SWEATS and SHIVERS:

Precursor to Stadium-Wave Hypothesis

Could ocean-atmosphere coupled dynamics act as Earth's Thermostat?
Is Solar Variability its Metronome?

By Marcia Glaze Wyatt
(Circa 2008 with updates 2016)

Abstract:
A hypothesis attempting to explain a portion of natural global climate variability throughout the past several centuries is presented. It comprises two aspects, described here as being interlinked. One aspect involves internal variability of coupled oceanic-atmospheric circulation. The other proposes solar variability as nudging this internal variability, thereby setting its rhythm, preference-of-state, and amplitude.

Interannual to multidecadal climate variability in the North Atlantic Ocean is dominated by the atmospheric pattern, the North Atlantic Oscillation (NAO). In the North Pacific Ocean, the sea-surface-temperature pattern, termed the Pacific Decadal Oscillation (PDO) dominates on multi-decadal scales. Oscillation between positive and negative phases of these dominant modes of circulation influences regional and global climate. Climatic patterns are modified through phase-accompanying changes in atmospheric advection, oceanic advection, cloud-cover, precipitation, and inventory of subsurface ocean heat content. Through latitudinal changes in distribution of warming, positive circulation phases warm the globe; negative ones cool it.

A second aspect of this hypothesis offers a mechanism that excites these modes of circulation – that mechanism being solar variability on a variety of timescales. Through a Rube-Goldberg-type chain of dynamics, with western boundary currents and the tropics playing key roles, a low-frequency solar signal nudges the coupling of the ocean and atmosphere on multi-decadal scales, thereby governing the rhythm of internal oscillations.

Non-linear systems are distinguished from linear systems by possessing internally defined preferred states. External forcing on a non-linear system affects preference of state and/or residence time in the state occupied. The effectiveness of forcing can be amplified through resonant coupling. Whether the Rube-Goldberg-type physical mechanism described in this paper as leading to regime changes is slave to these mathematical descriptions of non-linearity, or instead, whether this physical mechanism is delicately orchestrated as a feedback response to damp extremes of external forcing, thus conveying relative stability to the climate system, is worth examination. Such is the goal of my research.

A first step is to examine the legitimacy of the proposed physical sequence leading to regime change. The second step is to justify a physical process that explains solar's tangible influence on the oscillating climate states. A last step is to explore the response of the regime-changing mechanism to the solar-"nudge" mechanism, first to see if there is a relationship and second, to determine if the response is more one of mathematical probability, one of regulatory feedback, or perhaps a combination of the two. Combined use of statistics and modeling would be the best approach in tackling this task.

What follows is a description of my current (2008) and evolving vision of how the system works and the justification of that vision with related study results from numerous researchers.

Introduction:

Variability is a signature of climate throughout Earth's history. Numerous scales of variability – tectonic, orbital, and sub-orbital - dot the paleoclimate record. Some of this variability has been remarkably abrupt. Recognition of abrupt onsets of millennial-scale oscillations of atmospheric temperature during the last glacial period, captured in oxygen isotope ratios in Greenland ice cores, brought the past rapidity of climate change to the public attention[1, 2]. Marine-sediment cores have revealed oscillations in SSTs[4] and in ice-rafting episodes[7] – all on millennial scales and all during glacial intervals. These large-amplitude variations of various components on suborbital scales during glacial conditions gave support to early speculation that warm climates were devoid of similar fluctuations, prompting an assumption that large ice sheets played a key role in millennial-scale oscillatory behavior.[1, 8, and 13]

Further examination of records has revealed otherwise [9, 28, 29, 53]. Millennial-scale oscillations have been found in the interglacials MIS-11 (~423 – 360 ka)[81], MIS-5e (~132 to 116 ka)[13], and MIS-1 - the current interglacial known also as the Holocene (~11.5 ka to now) [10]. While these climatic fluctuations are of a far lesser magnitude than their glacial-age counterparts, this persistent pattern speaks to an equally persistent mechanism.

Variations in deep-water production are thought to govern these suborbital fluctuations in climate, both during glacials and interglacials[11, 12, 90]. Shifts in the position of the ITCZ and variations in strength of the Atlantic sector of the meridional overturning circulation (AMOC) likely coincide with variations in deep-water production. Ice-sheet coverage may contribute to amplitude and timing of observed climate variability, but is not a pre-requisite for the variability to occur [78].

Variations in deep-water production, and its accompanying changes, likely contributed to the temperature excursions of the Little Ice Age and the Medieval Warm Period[10, 14]. Bond et al. '01[10] suggest that millennial-scale deposits of ice-rafted debris throughout the Holocene represented climate changes resulting from fluctuating deep-water formation driven by millennial-scale variations in solar output – the LIA/MWP representing the last drift-ice cycle on record.

It is not unreasonable to imagine this variability in deep-water production works not only on these millennial scales, but to a less extreme degree on shorter scales, as well. Indeed, within the last century, abrupt reversals of climate trends have been noted. Moderate by comparison to the LIA, MWP, or other millennial-scale excursions, these shorter-scale, lower amplitude fluctuations, of multi-decadal character, host globally averaged temperature deviations on the order of several tenths of a degree Celsius. Locally, the effects are magnified and they vary according to region. Observed climatic changes are consistent with changes associated with fluctuations in deep-water production.

A glance at the globally averaged surface temperature over the last century is instructive. Holding in mind the numerous caveats concerning measuring a globally averaged temperature, a pattern emerges, nevertheless. This pattern reveals two warming episodes interrupted by one of cooling. The first warming period occurred from ~ 1917 to 1944, the second, from ~ 1976 to at least the late 1990s. A cooling period between the two warm intervals spanned from 1944 to ~1976. Global temperature increases were similar for both periods – about 0.7°C. The intervening global temperature decrease was ~ 0.5°C.

Occam's razor begs for a streamlined explanation for this pattern of abrupt reversals of warming and cooling. None is immediately forthcoming. While tremendous effort has gone into modeling a feasible combination of external forcings (natural and anthropogenic) – greenhouse gases, aerosols, volcanics, land-use change, and solar variability – much uncertainty about the legitimacy of the modeled scenarios persists. Undoubtedly, all these forcings contribute, but what explains the *pattern*? Is it entirely externally forced?

Solar-output's pattern, alone, *resembles* the global temperature pattern over long segments of temperature history, but the many discrepancies in match between the two lead to solar's dismissal as a viable candidate. In addition, when considering radiative forcing, the magnitude of change in solar output is too little to effect the changes observed. History is cluttered with attempts to reconcile that which seems so obvious a climate factor, but whose inconsistencies are profound.

Piazzi Smyth [89] analyzed borehole measurements in the mid-1800s. He identified three cycles, the strongest of which was an 11.1-year cycle. The relationship he found was that increased sunspots correlated with decreased Northern Hemisphere temperature. He concluded that these counterintuitive temperature variations were solar related, but communicated through a weather influence.

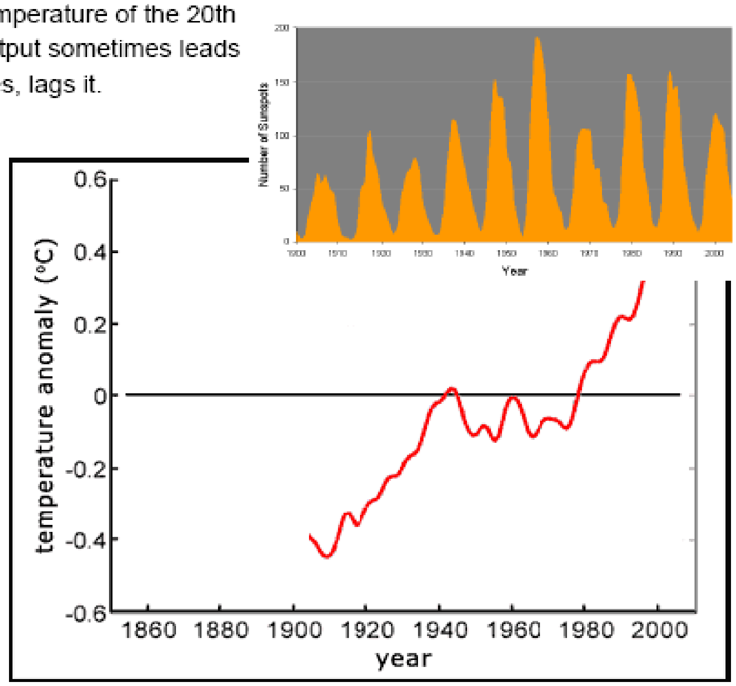
In 1914, *Wladmir Koppen*[20] reported a similar conclusion, noting that an inverse scale of sunspot numbers closely tracked the averaged Northern Hemisphere surface temperature between 1810 and 1910. Numerous other scientists came up with the same inverse relationship between sunspot numbers and atmospheric temperature – both for the Northern Hemisphere and globally. *Sir N. Shaw*[88], in 1928, published sunspot correlations with a diverse collection of geographical regions. The overwhelming majority showed strong negative correlations – the average correlation coefficient being -0.35. Shortly after Shaw's publication, the sun-climate community was confounded. For the next 30 years, researchers came up with conflicting results for the years after 1925. Some correlations that had been negative between sunspot numbers and temperature were now positive. Not all reversals of correlation were simultaneous. Interval of sunspot activity, length of interval, and geographical region appeared to determine the sign of the correlation.

When juxtaposing trends of atmospheric temperature and sunspot activity, a similarity in trends is clear, but they do not align. Furthermore, the temperature trend often appears to lead the solar trend. Sometimes the trend of solar coincides with the trend of temperature; sometimes it is lagged or reversed, but a pattern is still apparent.

Some would assert, and justifiably so, that such inconsistencies point to an absence of relationship between solar and recent trends in surface temperature. Yet, the pattern of warming and cooling compels further investigation.

A straight-forward correlation between solar output and Earth's globally averaged surface temperature is not apparent. Instead, visual inspection of juxtaposed time-series of sunspot activity and Earth's surface temperature of the 20th century suggests that solar output sometimes leads temperature and at other times, lags it.

Some would fairly conclude from this apparent absence of consistency that solar output is not correlated with Earth's surface temperature. I offer a different assessment.



Observations:
The temperature record shows surface warming begins in the early 1900s and peaks in the 1940s. The solar record shows output was increasing throughout this period. For the three following decades, temperatures dipped or remained steady. Solar output continued to increase until ~ 1960. Warming resumed in the mid-1970s, just as the solar signal was once again increasing, after a pronounced dip. Many climate scientists assert solar's contribution after 1940 to have been minimal, citing greenhouse-gas and aerosol emissions as best capable of explaining the trend. Not all agree.

While few would fail to acknowledge mankind's effects on climate – land-use change and emissions of aerosols and greenhouse gases - similarities in temporal and spatial patterns between today's changes and those in historical times – those attributed to solar variability – haunt the skeptical. If solar variability catapulted Earth's climate into one extreme and then another, could it be contributing in a similar manner to what is seen today? Could a more significant portion of observed warming be attributed to solar output? If so, how can it be explained?

Direct radiative forcing from the Sun can account for little of the observed temperature change over the last one-hundred years – perhaps 0.2°C, at most. Clearly, if solar does force significant changes in Earth's climate on historical and modern timescales, direct radiative forcing is not the method. An amplifying mechanism would be necessary. The ocean may be the place to look.

Possible Mechanism:
Connecting the external to the internal:
Could solar's influence be the timing, amplification, and damping of a naturally occurring internally oscillating system? Could solar variability govern both rhythm and amplitude of the NAO, and through the NAO, influence intensity of the meridional overturning circulation (AMOC) and position of the Intertropical convergence zone (ITCZ)? In short, could solar variability affect climate through its

choreography of deep-water formation – the culprit identified in past abrupt millennial temperature excursions?

Systems, by their very nature, are resistant to reduction into quantifiable parts. Interaction among components of a system generates a synergy within that system that optimizes its functioning. It is the significance of the interaction among components that compels examination of the "whole", not just individual links in isolation. Clearly, this is a daunting task. Finding analogues can facilitate understanding. Patterns in nature tend to repeat in a variety of systems. Internal climate regulation is no exception. The human body carries off this feat daily. Similarities give insight into Earth's own climate regulating mechanisms.

The human body, as does Earth, works to maintain a stable core temperature. For a human, the core is "control central" – the heart, lungs, and brain. For the Earth, the core is also "control central"; it is the tropics*. In either system – human or earthly – a narrow range of temperature is required by the core in order to operate properly. The response mechanism to variability in core temperature is export or storage of core heat. In the body, blood coursing through arteries and capillaries carries out this task. In the case of excess warmth, heat is shuttled out of the core. Vessels carrying the blood dilate, pumping warm blood to extremities where heat can be more effectively radiated away from the body. In the case of a forcing deficit, heat is held tightly within the core. Blood vessels constrict, storing the warm blood closer to the core, preventing easy escape of heat to the surroundings. On Earth, in response to preferential warming or cooling of its "core", currents in the oceans, and their synchronization with atmospheric, oceanic, and atmospheric-oceanic circulation patterns – e.g. NAO, PDO, and ENSO (El Nino Southern Oscillation) - fill a major portion of this function.

It is not a trivial matter to note that with no change in rhythm of external forcing variability, a regularly-paced response of heat export and heat storage is established. *Hengyi Weng '05* [107], studying Earth's climate response to variability in external forcing, noted in a simple numerically forced non-linear model that, without an 11-year modulation of seasonal forcing, the signal manifested is regular. In addition to the direct forced seasonal response, harmonics and sub-harmonics develop – none longer than ten years, repeating at a consistent rhythm.

This regular pattern does not persist when the forcing involves a changing solar "constant". Seasonal forcing, modulated by an 11-year cycle, provides an example. A small change in the amplitude of external forcing – about 0.1% in total solar irradiance over a quasi-decadal cycle (~ 0.15W/m^2) - changes the pattern of response. Numerous cycles develop. Regime changes are triggered[107]. The numerous harmonics that evolve, each non-stationary and each occurring with quasi-regularity, occur on a variety of timescales – interannual to centennial. Curiously, the timescale one such harmonic mimics is a dominant low-frequency solar signal – the Gleissberg cycle. This forcing was absent in the model run.

Observations of *Lohmann et al. '04* [73] lead to a similar conclusion – that an internal cycle found in the climate data is of a similar timescale to that of a low-frequency solar cycle. Through empirical orthogonal function (EOF) analysis of sea-surface-temperature (SST) data, they find a 67-year internally generated pattern and an 83-year externally forced pattern. The 67-year pattern is related to the meridional overturning circulation (AMOC), resulting from interactions of other cycles operating in the system. The 83-year pattern is the Gleissberg cycle modulation of the 11-year cycle.

**Not only does the tropical region maintain thermal stability of its low-latitude home-base through highly changeable atmospheric/oceanic dynamics* [63,68,75,112,113]*, but those changes that convey stability to the tropics send signals to high latitudes and upper levels of the atmosphere, forcing changes in those regions, some of which are ultimately communicated back to "control central".*

Tobias and Weiss [99] note from their 2000 modeling study that in many non-linear systems, a weak external forcing can have a dramatic effect if resonant coupling occurs, where internal and external phases align. In cases where both internal and external phases are chaotic, resonant coupling is strong and persistent. Matching of exact frequencies is not required for resonance to occur.

Through implementation of Lorenz equations, where solutions oscillate about either of two fixed points, representing warm and cold states, flipping sporadically between them, *Tobias and Weiss* show various responses of climate's chaotic system. In the case with no external forcing, no preference for a warm or cold state exists. With external forcing, there can be a preference, although not always. With non-resonant forcing, strong or weak, no preference for state exists. On the other hand, with resonant forcing, even where the forcing is weak, the effect is pronounced. Duration of time spent oscillating about either the warm state or the cold state increases, with a slight preference for the warm state [99].

Thus, if the period of solar variability resonated closely with the internal period of SST variability, the warm state would be preferred slightly. The degree of asymmetry is not strong, as the timescale of flipping merely increases. Duration of oscillation around *either* state increases. Warm states persist longer; cold ones do too. Thus, *resonance amplifies the solar signal, but damps it at the same time*. The net long-term effect is slight warming with a resonant solar signal.

Khatiwala et al. [57] had examined the Lorenz-type equations for their 2001 study and found that a change in mean residence times did occur, but the more dramatic consequence of external forcing was the increase in frequency of extremely persistent events. Significantly, they concurred with earlier conclusions of *Rossby '41*[83] that the spatial structure of the states, themselves, did not change with increased forcing. This view appears to be widely held; although *Kodera '03* [59] cites observational evidence suggesting the NAO pattern does change with forcing. They state that with minimal forcing, the NAO remains confined to the Atlantic sector. In contrast, during high solar activity, the NAO becomes hemispheric in its influence. This may be explained by a subsequent study by *Sun and Wang '06,* suggesting, instead, that an atmospheric bridge through the polar vortex conveys influence of the NAO to the PDO. [93.]

Building on the reasoning of *Khatiwala '01*, *Ruzmaikin '07* [84] explain that non-linear systems respond to external forcing differently from linear systems. In linear systems, an external forcing correlates to a change in magnitude or sensitivity of response. Non-linear systems are distinguished by possessing internally defined preferred states – such as NAO-positive and NAO-negative; for these preferred states he uses the term attractors – a mathematical term. External forcing of a non-linear system affects the probability that one pattern will persist over another. With increased forcing, the "well" of one state or another is made deeper, and the barrier inhibiting flipping to that state is decreased. Thus, according to this research, it is not so much the residency time that is increased or decreased with the application or withdrawal of external forcing as it is the tendency to go to one state over another. In this manner, a positive NAO could be the "preferred state" during increased solar, and NAO-negative preferred during decreased solar, particularly on longer timescales. Note: In contrast to work by *Tobias and Weiss '00*, discussed previously in this section, the work of *Ruzmaikin '07* does not introduce resonance as a factor.

Much remains unclear, most significantly, physical mechanism leading to the state changes. What is apparent is the feasibility that solar can influence climate through oscillatory circulation patterns. As will be suggested later in this paper, an envisioned mechanism effecting reversals of state argues for a statistical assessment of probability-of-state, supported by a proposed physically based explanation for the "choice" of circulation phase.

A human body becomes acclimatized to different climates. It is the transition between climates that is difficult. This could be likened to the responses found by *Weng '05*. Constant forcing elicits a regular pattern of response. A change to a new level of constant forcing demands an alternate pace and amplitude of response. In the case of initial exposure to intense heat, a human body will be slow to respond. When it does, the reaction is strong. Anyone who has exerted himself on a searing hot day recognizes this scenario. Vessels shunt blood to extremities. Sweat pours from the skin. The strategy is extreme, but effective; perhaps too effective. Without further change in external forcing, with change occurring only within the internal machinery, the core temperature drops below its ideal level. The cooling response was "too" efficient. Blue lips, goose bumps, and intense shivering supplant the sweating. The core is attempting to regain stability. The body soon steadies itself. With repeated hot days and high activity, such episodes become less frequent. A "new norm" is adapted to.

The body eventually acclimatizes to continued exposure to this new and higher level of external forcing, establishing a new rhythm and amplitude of dilating and constricting, exporting and conserving heat. After acclimatizing to the warmer regime, the body's response – vessel dilation, and if necessary, sweating – becomes quicker, and thus more efficient. The oscillation between heat export and heat conservation intervals becomes more rapid; it is governed by a higher frequency fluctuation.

On Earth, the analogue of dilating and constricting blood vessels to cool and warm the core can be found in the oscillating ocean-atmospheric circulation phases. Positive phases result in export of heat from the tropics, cooling the core. Negative phases minimize export, warming the core. The "extremities" are the mid-to-high latitudes. In the face of transition, response is initially slow. Then the system overworks until it settles into an efficient new pattern – regime change.

Changes in SSTs, considered both globally and regionally, can give insight to these responding oscillations. Observations of past changes, as evidenced in 430 years of tree-ring records, show the transition between regimes is not smooth. *Gray et al. '04* [40] observe that five to ten-year "organizational phases" precede regime changes in the North Atlantic circulation, after which a strong preference for one state or another is established. Through examination of paleoclimatological data, *Hubeny et al. '06* [50] identified cycle-length changes in conjunction with changes in external forcing. They found that cyclic variations in SSTs operated on scales of ~ 96 years during the Little Ice Age, whereas they cycled faster during warm periods, such as today and during the Medieval Warm Period (~950 A.D to 1250 A.D).

SST response to constant external forcing should result as *Weng '05* observed in her model study – with the directly forced signal plus lower-frequency harmonics. *Weng '05* examines observed SST response to observed variability of the solar constant over quasi-decadal cycles. She notes that an increase of solar output along the upward trend of the low-frequency solar cycle – the approximate 88-year Gleissberg cycle – results in the intensification of the multi-decadal signal and in slight lengthening in their timescales – from 44 years to 60.

Again, an analogy might help to illustrate.

Describing the Internally Oscillating Pattern as Nudged by External Forcing:
Where inertia of motion is minimal, oscillatory patterns are common. Consider a fluid, where impedance of its movement is minimal. If this fluid, say water, is bounded by a container, the response of the water to an imposed mechanical force is to flow in one direction and then another. In other

words, it sloshes. The forcing need not be large; nor does it need to be frequent. A kid in a bathtub is a great analogy. Stillness is broken by an enthusiastic lunge forward. That lunge sets off a wave in the direction of the lunge. Water hits the front of the tub and rebounds in the opposing direction, passing the forward-moving waves in the process. An oscillation is set up. If said "kid" times his lunges just right, he will reinforce the oscillations, amplifying them. The forward slosh becomes bigger; the backward slosh does as well. The timing of his lunge, as well as the energy behind the lunge, both play roles in the choreography of the oscillations. These variables determine amplitude of slosh-oscillation and length of time a slosh spends in the front of the tub and length of time a slosh spends in the back of the tub. In short, the lunging kid, through his continued forcing, can set the pace of, and influence the amplitude of, internally operating bathtub oscillations. A parallel is not difficult to see in Earth's "bathtubs".

Clearly, size of the bathtub plays a critical role in the pace of the oscillation, as does the character of the fluid being sloshed. Breadth and depth of the water's container affect an oscillation's rhythm, as does the density of the water within the container. Atmospheric idiosyncrasies play significant roles, as well. The bathtub sloshing is ponderous; by comparison, the air above the tub is swirling and diving, seemingly to a dance of its own. Over time, were one to be able to measure all the capriciousness of the system, a connection would become vaguely apparent between the slow-responding sloshes within the tub and the rapid twists and turns of the air above – a connection that, in actuality, is far greater than appears from limited scope of observation.

The beauty of the interrelatedness of a system is what makes it so difficult to study. Were I to sit by the lunging kid's bathtub, taking data measurements in hopes of isolating the key factor in why my floors were getting soaked, I would quickly be daunted by the apparent non-linearity of the situation. What statistical parameters could I apply? Correlations would appear non-existent. Statistical significance would be minimal. I could visualize what was happening – the kid was moving, water was splashing, and on occasion, my floor was getting wet. This pattern of relatedness would be apparent; yet quantifying it would pose a tougher challenge. So it is with coupled ocean-atmospheric systems, in particular, these internally oscillating systems operating in conjunction with a varying, albeit persistent, external forcing – a forcing such as solar output – a forcing that is sometimes obscured by other variables, natural and anthropogenic. The task is enough to compel the hardiest of the curious to narrow the quest. But it is the complexity and interrelatedness that hold he key to what is observed.

Indeed, statistical analysis cannot easily capture these patterns. The resonant case is particularly difficult to capture, as widely differing conclusions can result. If the length of time series studied is short, or if the time series used does not span an entire resonant interval, resonant phenomena may be missed. Simple correlations, significance tests, and regressions – multiple or linear - fail to reveal robust relationships between solar variability and climate.

By employing a novel approach to the problem – the use of composite-mean-difference- projection (CMD), *Camp and Tung '07* [15]attempt to overcome this challenge of statistical shortcomings. Spatial characteristics of surface temperature patterns are used. The spatial differences between solar maxima and solar minima of the 11-year (Schwabe) cycle from 1959 to 2004 are assembled into a composite. The secular trend and punctuated influences of El Nino and volcanic eruptions are removed from the composite. The original detrended data is projected onto the spatial pattern, acting as a spatial filter, removing high-frequency variability. A time series is generated from this and is subjected to a statistical significance test (Monte Carlo test). The result is 99.8% (confidence level). This spatial pattern differs from previous model-generated spatial patterns, whose solar signal is small over the poles as compared to the tropics. *Camp and Tung* show pronounced warming of the poles - the Arctic, in particular (especially the Northwest Passage) - with solar forcing. This is not unlike the signature of the "export" response of the externally forced "core" presented in this paper. They point out that transport of excess heat to the poles is carried out by the upper ocean and atmosphere. This is done within five years or less of the solar maximum.

The observed solar spatial signal is not unlike the "global warming" signature gleaned from climate models. Warming at the surface in the tropics is minimal. Instead, the warming occurs at altitude ~ 200 hPa (~12 km or 38,000 feet). This is where latent energy from convection is deposited. Convection is enhanced in the tropics with increased solar[102]. This observation would also "fit" with *Labitzke and van Loon's '97a,b* [64,65] observation that changes in lower stratospheric ozone transport in the low latitudes causes the geopotential height and temperature in that region to increase. This forces a change in lapse rate that *White '06* [111] has shown to force excess heating, from the stratosphere down, of the upper 400 meters of tropical upper ocean in concert with fluctuating total solar irradiance (TSI).

Seidel et al. '08 [87] observe a poleward extension of the tropical belt. They suggest a connection to greenhouse-gas warming, citing model studies that find poleward displacement of jet streams and wind and precipitation patterns. But here again, the modeled greenhouse-gas warming signature and the solar signature are difficult to distinguish. Low-latitude heating of the stratosphere, as occurs with amplified solar output, forces the subtropical jet and Hadley cells poleward, thereby expanding the tropics. In contrast, latitudinally uniform heating would force the Hadley cells equatorward [39, 60, 116].

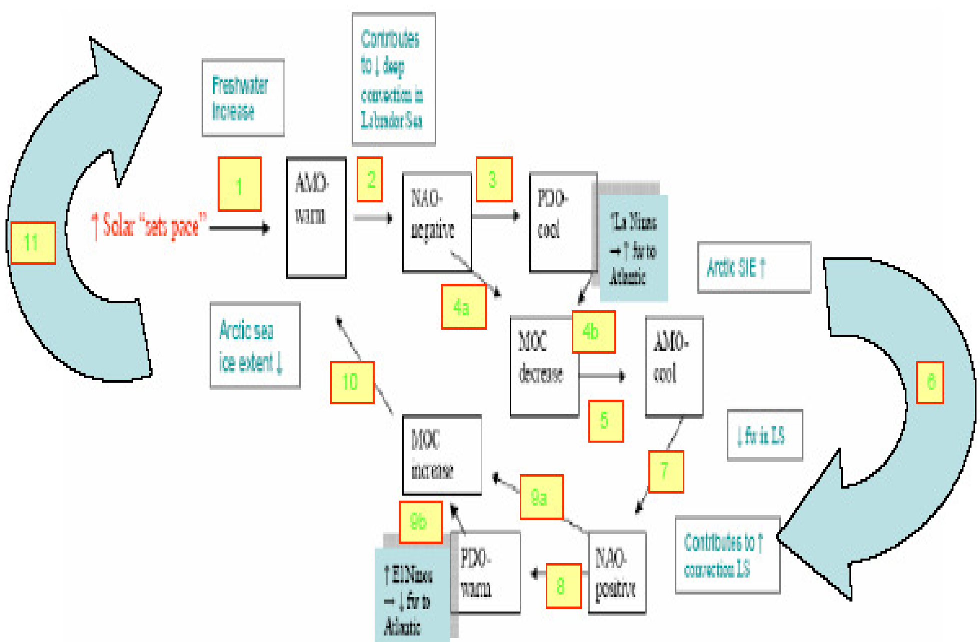
Finding a mechanism that pulls together observations and modeling studies, and reveals how solar variability might be involved in forcing certain climate patterns and climate extremes, would lend credence to a relationship where statistical analysis cannot. I suggest that internal circulatory oscillations, nudged by occasional resonance with the solar signal, in particular, the low-frequency signal of the Gleissberg cycle, provide that mechanism of amplification and damping.

Possible Physical Scenario:
Invoking the bathtub analogy one last time can facilitate explanation of internal oscillations – a critical player in solar's amplifying/damping mechanism. If we pare the list of variables down to a skeletal framework, we are left with the Sun, coupled ocean-atmospheric oscillations, and climate anomalies (temperature, winds, and precipitation). The Sun is the lunging kid. The sloshes in the bathtub, along with the twists and swirls of the air above, describe multi-scaled oscillations in Earth's ocean basins. These force [16, 24,31,35,62], and are forced by [63,114], accompanying oscillations in the overlying atmosphere. Two dominant coupled oscillations - the focus of this paper – are the atmospheric pattern, the NAO, and the sea-surface-temperature pattern, PDO (North Atlantic Oscillation and Pacific Decadal Oscillation). The water spilling out of the tub onto the floor represents anomalies of climate, governed by the oscillations.

Through a Rube-Goldberg-type chain of dynamics, with the tropics, atmospheric quasi-stationary waves, western boundary ocean currents, ocean gyres, and meridional overturning ocean circulation playing key roles, a low-frequency solar signal nudges the coupling of the ocean and atmosphere on multi-decadal scales, thereby governing the rhythm of internal oscillations and their consequent climate manifestations. During positive modes of circulation, heat is exported from the "core" - the low latitudes - to the "extremities" – the high latitudes. During negative modes, heat is stored [115], removed through subduction of SSTAs from the extremities and channeled to the low latitudes. The internal system – the bathtub - has its own set of timescales on which the oscillations occur – interannual ones superimposed upon decadal ones, superimposed on multi-decadal ones. These can interact with the multiple quasi-cycles of external forcing from solar variability – the kid in the bathtub. With resonant coupling, the result is a sequence of coupled ocean-atmospheric dynamics that initially amplifies, then subsequently moderates, the trend of solar output. It is conceivable that with a dramatic change in external forcing, or "temporal nudging", the sweats and shivers of the export/storage process can fall short of maintaining the ideal core temperature. Following the analogy to a logical conclusion, hypothermia or heat stroke might result. But this is unlikely. The vast expanse of oceans on Earth explains that. Water's high heat capacity assures relative stability of the core, despite the relatively large swings experienced by the extremities.

A schematic below provides a visual tool to capture this interwoven mechanism that appears to modify the solar signal. Details of each "part" can be found in the appendix.

The schematic shows that an internally quasi-periodic oscillating system, whether it is coupled to an external forcing or not, has no beginning and no end. To assume one point or another can be misleading.



Description of Sequence in figure above **(NOTE: precursor to stadium-wave hypothesis):**
The *warm* phase of the AMO sets the stage for the *negative* phase of NAO. The negative phase of NAO leads the cool phase of PDO by several years. Negative-phase NAO contributes to a slowing of the Atlantic-sector meridional overturning circulation (AMOC) through reduced Labrador Sea Water (LSW) formation; the cool phase of PDO contributes to a slowing of the AMOC via increased La Nina episodes and consequent freshwater increase in Atlantic. A slowed AMOC ultimately leads to the cool phase of AMO, which sets the stage for NAO-positive. PDO-warm lags by several years. Amplified LSW convection, associated with the positive phase of the NAO, hastens the MOC, as does freshwater export from the Atlantic due to increased El Nino events during the positive phase of PDO.

Putting the Pieces Together:

The Parts:

Parts to this globally integrated Rube-Goldberg puzzle include: a low-frequency solar cycle (likely the Gleissberg scale), the Meridional Overturning Circulation (AMOC), the Atlantic Multi-decadal Oscillation (AMO), the North Atlantic Oscillation (NAO), and the Pacific Decadal Oscillation (PDO). Within these parts are the links: the oceanic gyres - the subpolar gyres (SPG), the subtropic gyres (STG), the ITCZ, the West African monsoon, the Gulf Stream, the North Atlantic Current (NAC), Meridional Heat Transport (MHT) the Labrador Sea Water formation (LSW), the Iceland-Scotland Overflow Water (ISOW), Greenland- Sea Deep Water Formation (GSDW), sea-surface salinity (SSS), sea-ice extent (SIE), the Aleutian Low (AL), the Kuroshio Current, El Nino Southern Oscillation (ENSO), and the polar vortex. The quasi-biennial oscillation (QBO) and its influence on the polar vortex during different stages of solar output likely plays a role in boosting solar's efficacy.

Juxtaposition of time series of the +AMOC, +AMO, -NAO, and -PDO reveals a coherent pattern. Each leads the other in this given sequence. The time step is always less than a decade. Feedbacks among these components, as well as among the ancillary links in the sequence, regulate SST and sea-surface salinity (SSS) on both interannual [69, 85] and multi-decadal time scales [30,49,105,106], setting the rheostat on the AMOC[74,103], which influences the onset of the AMO phase[56], which sets the stage for the propagation of near-surface thermal anomalies[31,35,44,56,96], which ultimately trigger a phase change in dominant circulation (NAO) both through SST-forcing on the SLP[63,68,75,112,113] and through changes in LSW convection [21,63]. LSW convection helps plant the seeds of future change via deep-level transportation of thermal anomalies[23]. PDO follows suit within several years of NAO, possibly by way of an atmospheric bridge via the polar vortex[93]. AMOC strength is slave to these changes [27,58,70], and in turn, the succession of mode-onsets is slave to the AMOC. (**Note:** subsequent research by author showed multidecadal variability in sunspot numbers negatively correlates with NAO (and ENSO); while the geomagnetic proxy index of solar output (aa) correlates positively with AMO. Applied, this reflects increased solar correlates with a warm phase of AMO, a north shift of the Atlantic Intertropical convergence zone (ITCZ), and leads by a few years the negative phase of NAO, etc.)

The Possible Role of Solar:

Defining the role of solar is complicated by the fact that much about solar variability remains enigmatic. To define variability, numerous methods have been employed. None are immune from justifiable criticism. Some methods measure sunspot numbers; some measure sunspot groups; others take into account sunspot cycle length [38]; others have used sunspot structure[46] and sunspot decay [47]; and yet others have used level of solar maxima/minima average or the level of just solar minima – the latter correlating well with Earth's geomagnetic variability over the last century-plus [17].

Equatorial solar rotation rate is another proxy of activity [48]. As equatorial rotation is related to solar convective activity, it, along with the other proxies mentioned, has been put forth as an indicator of total solar irradiance (TSI) fluctuations. Gleissberg, for whom the quasi-periodic secular cycle of ~ 88 years is named, constructed the eponymous trend using a combination of sunspot numbers and length of cycle to determine this longer-term trend. This cycle reflects a gradual increase, followed by a less gradual decrease, in sunspot-cycle amplitude over a multi-decadal period.

Although sunspots are cool regions – as much as 1500°C cooler than the Sun's surface – their numbers increase when solar activity increases. Faculae – sources of energy emission from the Sun – increase also. Competing effects between these superposed features result in little change of the solar "constant", no more than about 0.04 to 0.1%, but a significant change - ~ 0.7 to 1.0% - occurs in the blue, ultra-violet, and extreme ultraviolet wavelength emissions – more than an order of magnitude greater than the change in solar constant - escaping from the faculae's exposed edges[48].

Along with this increase in activity come increases in activity-related events. Two that are considered to be potential drivers of climate include high-speed solar streams (HSS) from coronal holes (open magnetic field) and coronal mass ejections (CMEs) (closed magnetic field), Magnetic clouds and solar flares are significant events related to CMEs.

HSSs vary little across the sunspot cycle peaks and appear to be affected more by angle of tilt of the heliospheric current sheet and the underlying interplanetary magnetic field rather than level of activity on the Sun (i.e. the sunspot cycle) [118]. On the other hand, CMEs and the related by-products vary closely with the sunspot cycle[118]. That observation suggests numerous solar drivers influence climate. This observation increases the difficulty of determining which proxy of solar activity to employ. This challenge becomes more vivid by comparing two key proxies – sunspot cycles and the aa-index (geomagnetic activity, as controlled by the solar magnetic field). Correlation between them historically has been strong. That changed after the past century's highest peak in the sunspot cycle. Since 1960, correlation between the two proxies has steadily declined, with geomagnetic activity continuing to increase as sunspot numbers have not; although the aa-index does share resemblance to the trend in solar minima. Solar activity related to CMEs is reflected well by the sunspot cycle. Solar activity related to HSSs is better captured by the aa-index. This suggests that CME activity is decreasing, in accord with the presumption that the recent Gleissberg cycle peaked in the 1960s, and that HSS activity is not as strongly overshadowed, or has perhaps increased.

On timescales relevant to circulations such as the NAO, *K. Georgieva et al. '07* [39] discuss the importance of solar flares and magnetic clouds – related to CMEs and whose closed-magnetic-field activity follows long-term variations in sunspot-cycle amplitude (Gleissberg). Their influence directly affects large-scale pressure systems on Earth, – the Icelandic Low and the Azores High, for example. These centers-of-action in the North Atlantic govern the NAO. Thus, solar's influence on them presents one mechanism that indirectly ties solar variability to climate change. While seemingly simple, this influence on pressure systems is complex. Some forms of solar activity strengthen the centers-of-action; other forms of activity weaken them.

Solar flare activity intensifies the pressures in these centers-of-action, thereby promoting a zonal circulation in the Atlantic – NAO-positive. Magnetic clouds *can* exert an opposing effect, suppressing zonal circulation, but the situation is not so straight-forward. The influence of magnetic clouds as a driver of climate on Earth depends on the solar hemisphere from which they are ejected. The reasoning involves the rotation direction of the magnetic field embedded within the ejected cloud. Left-handed clouds spew from the northern hemisphere; right-handed from the southern. Solar flares are not similarly selective. Their influence on Earth is independent of hemisphere of solar activity.

"Left-handed" magnetic clouds weaken the pressure systems, competing with the effects of solar flares, suppressing zonal circulation and enhancing meridional circulation – NAO-negative. "Right-handed" clouds have no effect on tropospheric circulation; solar-flare effects prevail when activity is strong in the Sun's southern hemisphere.

Georgieva et al. '07 find support for the notion that solar-hemispheric activity varies over the long-term Gleissberg cycle. They propose that the dominating hemisphere of activity switches between north and south with each Gleissberg cycle, much like the 22-year Hale magnetic cycle, where magnetic polarity reverses with each successive sunspot cycle. When the northern hemisphere dominates, as solar output increases on the centennial cycle, meridional (negative NAO) circulation develops. When the southern hemisphere is the more active, solar-flare activity has no competition. Zonal circulation governs the NAO with increasing solar output.

Sunspot numbers and the NAO index are strongly negatively correlated (>-0.73) over the 20th century. When lagged by ten years, the correlation between sunspot numbers and the NAO jumps to -0.90. Following the reasoning given above, this suggests that during the 20th century, solar magnetic activity was strongest in the Sun's northern hemisphere. Using proxy data, *Georgieva et al. '07* find positive correlation during the 19th century, negative for the 18th century, and positive for the 17th [39].

The effect of HSSs – products of an open magnetic field, and whose occurrence is fairly uniform across the sunspot cycle - is to increase zonality of circulation – a result of a high-pressure wave propagating from high to low latitudes. The NAO index slightly precedes the NAM index as the wave transits. Phase of QBO affects the onset and duration of the positive index. This influence of HSSs on Earth's climate is a short-lived event – on the order of a week or two. Whether the cumulative effect is significant or not is unknown.

Kirov and Georgieva '02 [117] found solar influence on centers-of-action in the Pacific and Indian Oceans. Using data – both instrumental and proxy - from 1821, they find robust results in the Pacific and Indian Oceans. With increased solar output, the Aleutian Low and Hawaiian High weaken. The Aleutian Low shifts to the north and west, the Hawaiian High to the north and east. The East Pacific High strengthens, while the West Indian Ocean High weakens. These patterns are not unlike PDO-negative and an ENSO cool event. Van Loon et al. '07 [102] and Christofou and Hameed '97 [119] have made similar observations.

Van Loon et al. '07 [102] found solar's influence in the Pacific during the boreal winter at solar peaks. At the peak years of decadal solar output – the year prior, the year of, and the year after - the climatological mean in the Pacific is enhanced. Southeasterly trade winds are intensified, ushering along increased upwelling of cool waters in the east equatorial Pacific. The cold tongue extends westward. Convection in the ITCZ and South Pacific Convergence Zone (SPCZ) increases. The convergence zones migrate poleward, the ITCZ northward, the SPCZ southward. Redistribution of diabatic heating and associated convective heating anomalies produces anomalies in related circulations: enhancement of the zonal Walker Circulation and diminishment of the meridional Hadley. Quasi-stationary waves emanating from increased convective activity in the warm pool weakens the Aleutian Low. The system shifts to the west. While the characteristics resemble a "cool event" - a La Nina episode - critical differences can be found in the stratospheric response[120].

Complications are not confined to determination of potential drivers of climate. To add to the complications of defining what aspects and what temporal trends of solar variability are relevant to Earth's climate, determining the behavior of the physical mechanism through which the solar influence is communicated is formidable. Direct radiative forcing plays only a minor role. Most of solar's power over Earth's climate is indirect – likely through changes in stratospheric dynamics, resulting from changes in stratospheric ozone inventory. Changes in the stratosphere are thought to propagate downward to the troposphere and surface [60,116].

As solar output increases, its short wavelength component increases at a disproportionately large rate. The substantial increase in ultra-violet radiation is thought to be key in solar's influence on Earth's climate. Complex ultra-violet interactions with ozone – creating ozone through photolysis; destroying it with heat – modify the Brewer-Dobson equator-to-pole transport of ozone, and thereby alter stratospheric circulation patterns, which then affect tropospheric circulations. Quasi-biennial winds (the QBO) contribute to the obfuscation of a clear solar-climate signal, as the oscillatory stratospheric wind strength and duration is affected by solar[43, 100] and the wind direction of the QBO affects the integrity of the polar vortex by governing trajectories of mid-latitudinal, vertically propagating, planetary-scale waves [3, 71,104]. Convection in the tropics both governs the QBO and is indirectly governed by the QBO. The vortex is both victim and dictator. Through this set of characters, the high latitudes are intimately connected to the low ones. Solar variability adds an overlay of variability within this intertwined set of dynamics.

The polar vortex and the equatorial stratospheric winds volley wave-forcing between them. Vertically propagating, planetary-scale waves, born of topographic highs and land-sea thermal contrasts in the mid-latitudes, provide the wave forcing. Once in the stratosphere, the vertically propagating waves break meridionally, coursing toward the equator. If they gain entry into the tropical region, they lower the tropopause there, suppressing tropical convection. If instead, they are deflected from the tropics, they travel poleward, where they impact the vortex. Tropical convection is enhanced and the vortex is weakened. The regimes of the QBO owe their existence to deep tropical convection. From equatorial convective activity, Kelvin, Rossby, and gravity waves propagate into the stratosphere, depositing momentum that gives birth to the oscillating wind directions. Without deep tropical convection, there would be no QBO. *(Refer to Baldwin[3] for a full review of the QBO.)*

A general rule is that when QBO is in the easterly phase, wave forcing cannot penetrate the flow. If the QBO is in the westerly phase, wave forcing reaches the tropics. In addition to wave forcing, thermal effects of each phase enhance the outcome – QBO-east hosting strong tropical convection and a weakened vortex, QBO-west hosting weak tropical convection and a strengthened vortex. Vortex strength plays a major role in wintertime tropospheric circulation; it also plays a role in distribution of stratospheric ozone.

If the wave forcing impacts the polar vortex, particularly in late fall or early winter, and the vortex weakens, air from the mid-troposphere invades the cold stratospheric air within the vortex. Air within the vortex heats tens of degrees in sudden stratospheric warmings (SSW). Subsequent radiative cooling leads to sinking of air at stratospheric levels in the vortex. This sinking motion at the pole forces enhanced uplift in the stratospheric tropical zone. The Brewer-Dobson ozone circulation is intensified. More ozone is carried poleward. The reverse situation is true for a strong polar vortex; the Brewer-Dobson circulation weakens. Ozone continues to be created in the tropical stratosphere; yet it is not quickly carried poleward, instead accumulating over the low latitudes.

Tropospheric circulation is not isolated from this upper-level freeway. Lane closures and detours to alternate routes result in consequences "upstream". *Labitzke and van Loon (LvL) '97* [64-65] find quasi-decadal changes in the production and transport of stratospheric ozone during a hemisphere's summer. A traffic jam, of sorts, occurs in the low latitudes. Production at low latitudes is increased, yet the transport of ozone poleward is inhibited. An increase in both temperature and geopotential height occur in the ozone layer within the stratosphere between 5° and 30° in each hemisphere during the hemisphere's summer. The result is a forcing from the stratosphere downward. The quasi-decadal pattern of ozone-transport changes hints at a solar influence.

While the *LvL'97* finding involves a summer event, *Labitzke '87* [121] observe a solar influence on the QBO during the northern hemisphere's winter. At solar peaks in the northern winter, if the QBO is in the west phase, this phase will be strengthened. In non-peak-solar years, a westerly phase would coincide with a strong vortex. Such is not true during peak years of solar output. *Van Loon et al. '08* [120] find the strengthened west phase of QBO during peak solar occurs in conjunction with a weakened polar vortex. If the QBO is in the east phase, this phase will be weakened and the vortex strengthened.

Gray et al. '04 [41]and *Hameed and Lee '05* [43] note similar observations of the solar effect on QBO and the QBO effect on the vortex with increased solar. This QBO manifestation persists over an approximate three-year period surrounding the solar peak year.

The QBO's thermal and dynamic influences on ozone distribution via the QBO's impact on planetary-wave forcing ultimately determine tropical convection and vortex integrity. Through these indirect mechanisms, solar forcing is amplified and affects tropospheric climate. The changes in ozone distribution, and therefore stratospheric heating, alter both tropospheric circulation patterns (e.g. Arctic Oscillation (AO), NAO, and PDO) and influence the lapse rate, and thus the loss of heat from the planet's surface [111].

Phases of QBO are rarely, if ever, parameterized in computer modeled climate change. It is not easy to quantify. But QBO phase is critical to many climatic features, and crucial to the solar influence. Its omission allows for a hugely inaccurate assessment of solar's impact.

White et al. '97 [122] found that the quasi-decadally oscillating global average SSTs between 40°S and 60°N was dominated by the tropical global average SST, from 20°S to 20°N. They further found that these quasi-decadal signals fluctuated in tandem with the quasi-decadal total solar irradiance (TSI) signal. In *White et al '98*, [108] the focus was on upper-ocean heat versus SST. The anticipated connection to solar variability was not found. While the pattern of variability hinted at solar's influence, the surface radiative forcing from solar, ~ 0.10 to 0.15 W/m^2 was too small to explain the upper-ocean-heat anomalies – diabatic heat storage (DHS). Furthermore, phase-lags existed that could not be explained.

In *2003a, White et al.* [110] found that the DHS anomalies were driven not by direct solar radiative forcing, but instead from the lower troposphere. The atmosphere was warming the ocean. Approximately 0.5W/m^2 of anomalous diabatic heat was being lost from the troposphere, while approximately 0.5W/m^2 was being gained by the upper ocean. It had been transferred downward across the air-sea interface via turbulent transfer of heat and moisture (sensible (Q_S) and latent (Q_L) heat). The flux of energy between atmosphere and ocean was being altered at a quasi-decadal rhythm, with the maximum 0.5 W/m^2 flux into the upper ocean occurring not at maximum TSI, but rather between the troughs and peaks of TSI. Changes were occurring from the top down.

On a quasi-decadal timescale, the tropical lower stratosphere showed the most temperature increase, ~ 0.80K. The upper tropical troposphere showed an increase of ~ 0.25K, the lower troposphere ~ 0.15K, and the tropical upper ocean showed an increase of ~ 0.05K. The question remaining was what was warming the troposphere?

Labitzke and van Loon (LvL) 1997a, '97b and '99 [64,65,123] found that lower stratospheric temperatures in the tropics varied in synch with fluctuations in the TSI. Stratospheric ozone absorbed an enhanced amount of ultra-violet radiation during peak solar output. Thus it appeared that the quasi-decadal change in upper-ocean-heat storage was consistent with changes initiated by solar variability's effects on stratospheric ozone, subsequently communicated downward.

White'06 [111] examined changes in Hadley cell circulation, SSTs, upper ocean heat storage, air temperatures from two kilometers above the surface through the troposphere into the lower stratosphere. They observed that with increasing TSI, air temperatures at two kilometers were greater than the SSTs below. The lower troposphere had to be losing diabatic heat, though, as the flux anomaly of latent and sensible heat was positive – i.e. into the ocean across the air-sea interface. *White* '06 concluded that a change in vertical gradient of potential temperature (i.e. change in vertical lapse rate), in combination with a weaker mean Hadley circulation, promoted diabatic heat gain of the lower troposphere. The heat gain in the lower troposphere balanced the heat lost from the lower troposphere – "lost" diabatic heat that is fluxed into the upper ocean via turbulent transfer. This re-charging of the lower troposphere with heat from the top-down fuels the "supply chain" of heat flowing from the lower stratosphere into the upper ocean – with temperature increases decreasing with each link in the supply chain. The forcing of this supply chain of change is the ultra-violet spectrum of the TSI. An increase leads to increased ozone production, changes in ozone transportation, and increases in lower tropical stratospheric temperature. In this way, solar output's influence on Earth's surface is amplified. This upper-ocean-heat gain during increases in solar output supports the observation years ago by *Ellis et al.'78* [36] that on the seasonal scale the upper ocean gained heat with an increase in solar and lost it with a decrease. Similarly, *White and Liu '08* noted that in conjunction with decreasing TSI, flux of latent and sensible heat flowed from the upper ocean into the atmosphere. The consequence of increased mixed layer/upper ocean heat storage carries implications for tropical convection and tropical and extra-tropical circulation patterns. The work of *White et al. '03 and '06* and *Ellis et al. '78* suggests that similar dynamics occur on different timescales.

Prior to the study by *White '06, Tourre et al. '01* examined SST and SLP signatures in the Pacific basin from 30°S to 60°N – interdecadal, quasi-decadal (e.g. the QDO), interannual (ENSO), and quasi-biennial (e.g. the QBO). *Tourre et al.* '*01* hypothesize that evolution of the SST and SLP signals reveals a similar physics underlying three of these four signatures.

Decadal, ENSO, and the biennial signatures share similar regional and global SST and SLP characteristics – all suggestive of Rossby wave physics. As the signals progress between warm and cool states, SLP anomalies closely coincide with SST anomalies. Strong SST anomalies first develop in the equatorial region. A weaker extratropical anomaly of opposite sign around 40°N follows by a slight lag. In addition, communication between the central tropical Pacific to the NW Pacific generates an anomaly there. There is a difference that distinguishes the decadal signature from this trio of similar patterns. The decadal signal evolves in the central Pacific and expands to the east; whereas the higher-frequency signatures - ENSO and QBO tend to emerge in the eastern tropical region and expand to the west.

The interdecadal pattern differs from the QDO, ENSO, and QBO patterns. SLP anomalies precede SST anomalies in the interdecadal pattern. SLP anomalies develop in the North Central Pacific around 45°N (Aleutian Low), followed by SST anomalies of the same sign between 25°N and 45°N in the central Pacifc (subtropical gyre region). Coupled atmospheric-oceanic interactions in the region of the Sub-Arctic Frontal Zone likely maintain the signal. Subduction and subsequent vertical and lateral advection of the signal via gyre circulation appears to provide basin-wide communication, and through this feedback, influences the rhythm of the oscillation [66, 67, 125, 126].

Subsequently, *White and Liu '08* [125, 126] found a role for solar in the decadal-scale oscillation. Through modeling, ENSO and QBO signals evolved, but not the decadal mode, aka quasi-decadal oscillation (QDO). With the addition to the model of a solar signal, the QDO was generated. Not only was the QDO generated, with a SLP and SST evolution and signature similar to the ENSO and QBO signals (reflective of a Rossby wave delayed action oscillator mechanism (DAO)), but the ENSO and QBO rhythm was found to be paced by the QDO. This finding could be explained by resonant excitation; ENSO and QBO timescales are T/3 and T/5 harmonics of the QDO. Despite SLP and SST similarities among the three signals, there are differences. Although all three patterns can be explained by the delayed action oscillator (DAO), there is a significant difference; the speed of propagation of the Rossby waves differs for the QDO. The latitude of westward propagation is higher in the QDO than in the ENSO and QBO (18°N versus 12°N), thus they are slower (~0.06 m/s vs ~ 0.20 m/s). This affects the eastward propagation of equatorial coupled waves. In addition, the DAO mechanism is more symmetric about the equator in the QDO as opposed to its position in the ENSO and QBO. These differences between QDO and the higher frequency oscillations suggest differing coupling thermodynamics of the equatorial coupled waves that accompany these patterns.

In order to meet requirements of resonant excitation, a phase lag of between 60° and 120° must exist between forcing and response *(Georgi '92 (?))* [127]. *White and Liu '08aand White and Liu '08b* (in press) suggest that this condition is met if one considers how the solar forcing is effected. As found in *White '06*, on the rising limb of TSI, forcing from the stratosphere-down through anomalous flux of sensible and latent heat into the upper ocean from the lower troposphere, the warm-SST phase of the QDO response is forced. On the descending limb of TSI, the maximum flux of anomalous sensible and latent heat is upward – out of the ocean. The phase lag of this response is ~ 70° to 90°. It thus appears that the peak of the QDO is almost aligned with the peak of the TSI. This is merely coincidence, as the forcing occurs along the increasing trend of TSI output.

Solar forcing not only triggered the evolution of the QDO, but triggered also a rhythm of ENSO [126]. Strong El Nino/La Nina pairs and La Nina/El Nino pairs straddle the peak of the QDO. Less intense, more prolonged phases occur at the QDO peak. *White and Liu* conclude that these ENSO pairs are phase-locked to the QDO.

The response is explained through the behavior of off-equatorial Rossby waves and equatorially-confined Kelvin waves. Together, their interaction governs the depth of the equatorial thermocline. Through the depth of the thermocline, SSTs and SLPs are indirectly governed. As mentioned earlier, the mechanism is called the delayed action oscillator (DAO). Without solar forcing, the modeled DAO produces a few high-frequency SST signals – 2.1 years and a broad interannual band around 2.9 to 4.5 years – the QBO and ENSO, respectively. With solar forcing, varying on an eleven-year timescale, added to represent 0.5W/m^2 due to sensible and latent heat flux, a different set of SST signals are excited – narrow-band signals at around 11 years, 3.6 years, and 2.2 years – the QDO, ENSO, and QBO. This solar-forced signal triad corresponds to observed global SST variability.

Fourier series expansion of the non-sinusoidal normal response of the Pacific DAO to the 11-year period harmonic of solar variability reveals that the first three harmonics align with the signals within the triad generated, the higher-frequency harmonics – T/3 and T/5 – phase-locked to the first harmonic, T/1. Due to constructive interference and this phase-locking, strong El Nino/La Nina pairs tend to align with the increasing limb of the QDO, while strong La Nina/El Nino pairs align with the decreasing limb of the QDO. Destructive interference of T/3 and T/5 align with the peaks and troughs of the QDO, producing a broader, yet lower amplitude, response.

White and Liu '08b suggest that findings by *van Loon et al. '06* [102] align with this hypothesis. *Van Loon et al. '07* found that at the peaks of solar variability – the year prior, the year of, and the year after – a La Nina-like condition occurs. Van Loon calls it a "cold event" – an enhancement of the climatological mean, as its signature differs from other La Ninas in that its stratospheric signal (the QBO and polar vortex responses) differs [120]. *White and Liu* note that during the increasing transition of the QDO, an El Nino/La Nina pair is excited. On the down limb, a La Nina/El Nino pair is excited. The La Nina of the ascending phase and the La Nina of the descending phase, along with the broad, lower amplitude phase that occurs at the peak in between these two higher amplitude events, represents the cool event observed by *van Loon et al. '06*. In short, cool events in the tropical Pacific straddle the peaks of the warm phase of the QDO; warm events (El Nino-like) straddle the troughs of the QDO – its cool phase. The timing of these events appears to be a lagged response to the indirect solar forcing, with a maximum flux of sensible and latent heat into the upper ocean preceding the peak of the QDO by 90° and the maximum flux of sensible and latent heat out of the upper ocean preceding the trough of the QDO by 90°.

While *White and Liu '08b* cannot offer a mechanism for the thermodynamic coupling of this wave packet excited by solar variability, model results and observation support the pattern. During the 20th century, the time-sequence sum of ENSO and QBO signals (~3.6 and 2.2 year-periods) can explain ~ 60% of the Nino-3 SST index variability. This variance is higher than the modeled variance of ~ 43%. Furthermore, peak phases in this constructive interference of T/3 and T/5 harmonics align with ~ 78% of the peaks in the Nino-3 SST index. This means that over three-quarters of the El Nino episodes during the 20th century fall on this phase-locked pattern of the solar-excited QDO.

The role of solar in its influence on the tropics is not confined to heating tropospheric and upper-ocean temperatures indirectly through stratospheric dynamics. Solar variability also can influence tropical convection directly through heating, and indirectly through changes in tropopause height, as governed by the QBO and planetary-wave propagation, and modified by solar. Tropical convection can force sea-surface-temperature-anomaly (SSTA) patterns that might lead to a regime shift in circulation mode. The NAO is one to consider.

Position of the ITCZ reveals much about the circulation pattern of an ocean basin. In the Pacific, the ITCZ shifts southward of its mean position when an El Nino event occurs. A PDO-warm mode in the North Pacific features a more southerly displaced ITCZ. In the Atlantic, the ITCZ shifts northward when the northeasterly trades subside and the southeasterly trades strengthen. An NAO-negative hosts a northward-shifted ITCZ; an NAO-positive hosts a southerly displaced convection zone. The ITCZ is also found to shift with strength of AMOC. This should come as no surprise, as the NAO and AMOC are closely related. Can a relationship be found between the ITCZ and solar output?

Black et al. '99 [5] studied an 825-year upwelling history of the Cariaco Basin in northern Venezuela to determine the paleo-location of the Atlantic ITCZ. Suppressed upwelling, as inferred from positive SSTA anomalies teased out of the isotopic proxy record, suggests a northward shift of the ITCZ. This would imply reduced northeasterly trades. Black's team also found warm SSTAs at higher latitudes in the Atlantic, at about 50° to 60°N. Cool SSTAs were found in the Sargasso Sea. This is a tripole SST-pattern not unlike that of NAO-negative. In addition, *Black et al.* '99 find that several periodicities of ITCZ shifts and related SST-patterns emerge from the data – interdecadal, decadal, and centennial periodicities. Carbon-14 (C-14) quantities – a proxy for solar activity (negatively correlated) – align with the centennial-scale upwelling behavior; high solar (low C-14) correlated with diminished northeasterly trades and low solar (high C-14) with enhanced northeasterly trades.

The inferred relationship between solar output and strength of the northeasterly trade winds in the North Atlantic may offer insight into more recent observations: It has been shown through observation and modeling studies by *Cassou et al.'04* [16] that summer warming along the entire Atlantic tropics generates an SST footprint. Warming in the western equatorial Atlantic spawns quasi-stationary waves

(QSW) through increased convection and anomalous precipitation along a northerly shifted ITCZ, much as solar activity promotes the spawning of QSW in the western Pacific [102]. In the case of the Pacific, the resulting wave train weakens the Aleutian Low. In the case of the wave train in the Atlantic, through influence on geopotential heights in the NE Atlantic basin and resulting anomalous cyclonic wind patterns, resulting perturbations in surface turbulent and radiative fluxes force a pattern of SST change. Cyclonic wind anomalies generate warm SSTAs in the NE Atlantic and cool SSTAs in a lobe centered in the western Atlantic at ~ 40°N. In addition, Hadley circulation in the eastern basin is altered. This causes a weakening of the northeasterly trades. Weakened NE trades allow the ITCZ to shift northward. Upwelling of cool waters from depth diminishes. Low-level cloudiness is decreased, thereby lowering albedo. Temperatures in the SE basin increase accordingly. The "horseshoe" SST pattern is established – a central lobe of cool SSTAs surrounded by a horseshoe-shaped region, open side facing west, of warm SSTAs. This horseshoe pattern (HS) transforms from a passive role (baroclinic) in summer to an active (barotropic) one in winter, modifying synoptic-eddy (storm) activity in the extratropical atmosphere due to intensification of the jet stream. In the winter, such intensification typically occurs. Convection-generated atmospheric Rossby waves from the western tropical Atlantic intensify the jet's response.

During summer, SSTs in this horseshoe pattern influence the atmospheric pressure systems. This is a baroclinic response. Such a response entails the evolution of a high-pressure system over cool SSTs and a low-pressure system over warm SSTs. In late fall/early winter, when the jet stream intensifies, due partly to the development of a wintertime meridional thermal contrast and partly due to the generation of Rossby waves in the Caribbean, vertical shear is intensified. The shear disrupts the local baroclinicity and promotes geopotential height changes. This is the barotropic response. Now the atmosphere can influence the SST pattern. The horseshoe is thus thought of as an extratropical footprint of summer tropical convection. The horseshoe pattern of SSTs is not unlike the tripole pattern of NAO-negative, with positive SSTAs at higher latitudes and in the lower latitudes and negative SSTAs in the western basin at about 40°N. (Refer to schematic of NAO in appendix).

Bjerknes [4], in 1964, suggested that on an interannual basis, the atmosphere forced SSTs, but on a decadal and multi-scale timescale, SSTs forced the atmosphere, creating a coupled oceanic-atmosphere system, with the subtropical gyre as the key link in the mechanism. *Kushnir '94* [62] suggests the same, with the AMOC, instead, as the mechanism. *Timmerman et al. '98* [98] suggest that a warming trend along the Gulf Stream from 1894 to 1924 could be explained by an increasingly enhanced AMOC. Indeed, this period was a time of a cool North Atlantic, with a signature of AMO-cool underlying the tripole imprint of the NAO-positive pattern – cool in the subtropics and high latitudes of the North Atlantic and a warm sub-tropical gyre region ~ 40°N in the western Atlantic basin. An NAO-positive, through strong deep-water formation in the Labrador Sea, promotes an enhanced AMOC (*Kushnir and Held '96* [63], *Curry and McCartney '01* [21], *Delworth and Greatbatch '00* [27]) as the phase progresses, sowing the seeds of regime change.

Sutton and Allen '97 [96] describe a situation of propagating SSTA anomalies that *McCartney '97* [75] sees as being instrumental in slowing deep-water formation in the Labrador Sea and forcing a regime change. Decadal fluctuation is exhibited by SSTAs in this region. *Sutton and Allen* propose they result from storm activity in the western central Atlantic basin area. It is possible they are once-subducted anomalies resurfacing from the subtropical gyre. A similar phenomenon is seen in the Pacific, where anomalies subducted in the sub-tropical gyre (STG) are carried westward at depth and re-surface near the western boundary current (in the Atlantic, the Gulf Stream) (*Kelly '04* [55], *Latif et al. '94, '96* [66, 67], *Latif '00* [68]). In the Atlantic, SSTAs are also subducted in the Labrador Sea region in concert with the different phases of NAO. Warm SSTAs are subducted to shallow to intermediate depth during NAO-negative. These reach the STG region after about six to ten years [32, 86] .

The warm SSTAs off the southeastern coast of North America are associated with cool anomalies in the low latitudes between 5 and 20°N and in the vicinity of the North Atlantic Current at 40 to 55°N. This SST pattern is the characteristic tripole pattern of the NAO-positive. (Refer to appendix) This pattern is not stationary. The warm SSTAs propagate to the northeast. Sequestration of the anomalies during the summer surface stratification allows re-emergence of the propagating thermal signatures each successive winter; in this way, the anomalies persist throughout each year. The patch of SST anomalies, wider than the width of the Gulf Stream, continues its journey NE. Within two to four years, the SLP dipole that characterizes NAO-positive begins to weaken, becoming more characteristic of a lower index NAO. The SSTs are forcing a change in SLP. Warm anomalies reach the subpolar gyre (SPG) after about a decade of propagation from the mid-latitudes. Within the SPG, the anomalies are channeled to the Labrador Sea Region – a critical region of deep-water formation that feeds a portion of the North Atlantic Deep Water (NADW). Deep-water formation in the Labrador Sea weakens with the arrival of warm anomalies. The AMOC slows. The NAO-index weakens.

Backing up in time, about four years after the initial warm anomaly formed in this storm-formation region, a cold anomaly develops further southwest in the Gulf of Mexico. By six years later, this cold anomaly from the western tropical Atlantic has migrated to the Cape Hatteras region. (Could this be what *Cassou et al.'04* detected?) This, according to S&A, stimulates an atmospheric response that resembles the horseshoe pattern described by *Cassou et al* in 2004 – warm anomalies north and south of a west-central lobe of cold anomalies, an NAO-negative tripole pattern. *Czaja and Frankignoul '01* [24] also noted this pattern. *McCartney* [75], in his review of *Sutton and Allen's* work, shows the string of propagating warm SSTAs with a timescale marking their position. He shows them next to the timeline of the declining NAO index from the 1940s to the 1970s. The decreasing NAO index coincides with the strongest warm anomaly propagation. In contrast, the increasing index of NAO coincided with the propagation of the coldest SSTA from 1970 to 1995. Eden and Jung '01[35] found interdecadal changes in SSTs lead the NAO switch by a few years.

It was discussed earlier in this memo that an external forcing could adjust the pace of an oscillatory system and/or modify the residence time or preference of state in an oscillating system. This discussion related to behavior of non-linear systems. But could there be a more physically based mechanism operating in tandem with this statistical underpinning? Could the observation that heating in the tropics, propagation of anomalies, and subsequent establishment of SST patterns that force the atmosphere, which in turn force the SSTs, which in turn allow the system to couple, give insight into a possible physical role for solar's orchestration of rhythm? In addition, the external influence of solar activity on pressure systems – aka centers-of-action involved in these coupled oscillations – may well enhance the physical mechanism of SST patterns as related to tropical heating. Both pathways suggest a tendency toward NAO-negative and Pacific cool events at peak solar output and "normal" or positive phases during low solar output (keeping in mind the aa-index, which appears to reflect HSS activity).

Thus far in this paper it has been established that non-linear systems respond to increasing external forcing with a tendency to occupy one state or another, either with a longer residence time in each or with a tendency to persist in one state over another. It is likely that the "state" is an oceanic-atmospheric circulation phase, the most likely candidate being the NAO followed by the PDO. Mechanistically, relating the NAO and PDO to solar, the NAO appears to be at the helm. With solar's effect on the tropical upper ocean, modulated by the solar-influenced QBO, amplified through dynamic processes in the stratosphere, resulting from the approximate 1.5% increase in ultra-violet radiation over a decadal solar cycle with stratospheric ozone, propagated down through the troposphere via a changed lapse rate, it ultimately results in increased convection along the ITCZ. In turn, increased convection triggers a wave train of planetary-scale waves that interfere with the jet stream, leading to a barotropic response and evolution of an SST tripole pattern that resembles NAO-negative. Propagating warm SSTs, from subduction or storm formation, also appear to force the atmosphere and ultimately the deep-water formation, forcing either a NAO-positive or NAO-negative, depending on the sign of the anomaly. Mechanistically, with amplified solar, it appears that the system, if it were to persist in one state over another, would choose to "linger" in the NAO-negative state. Van Loon (personal communication) has shown through statistical analysis that this seems to be the case. In his words, "with increasing low-frequency solar forcing, the system goes to NAO-negative; with a decrease in forcing, the system does what it wants." Whether this will be shown consistent with time or not, is yet to be determined. But what does seem possible is that with increasing solar, the signal is initially amplified by a positive NAO state (followed by PDO-warm), only to flip to a persistent NAO-negative through SST-forcing on the atmosphere and SST propagation into the Labrador Sea region.

Because NAO-negative is associated with a decreasing AMOC, which sets the stage for a regime shift, it is of interest to note that a model study by *Cubasch et al '00 and Cubasch and Voss '00* [19,20] show that with increased solar, the AMOC slows with a lag of 25 to 30 years.

It has thus far been shown that solar variability influences Earth's climate system in ways other than direct radiative forcing. Solar activity has been found to have influence at a variety of latitudes. Solar variability is linked to changes in sea-level pressure within centers-of-action at a variety of latitudes and with changes in diabatic ocean-heat storage in the tropical latitudes. The latter is effected through changes in Hadley circulation and vertical lapse rate. These indirect solar effects speak to non-trivial mechanisms that amplify solar influence on Earth's climate.

Conclusion:
Solar output varies on a variety of scales – scales of periodicity, magnitude, and duration. Furthermore, solar output varies non-uniformly in output of radiation; increases of ultra-violet emissions far exceed those of other wavelengths of energy emitted during amplified output. This adds to the complexity of the situation, as the ultra-violet emissions add a chemistry component to our already complicated physics conundrum. With a quasi-periodic forcing on numerous timescales interacting with an internally fluctuating system, also with quasi-periodic cycles operating on a variety of timescales, the task of teasing out any solar influence is daunting. Statistical analysis is met with limited success. Spatial filters offer the best insight, allowing a geographical pattern of solar influence to be examined.

Proposed Approach to Testing the Idea:
A modeling study of the "Rube-Goldberg" schematic, allowed to operate with various versions of external forcing – an approach similar to *Weng '05* [107]- would likely be the most effective way to test the validity of this idea. The approach of *Camp and Tung '07* [15]– examining a spatial composite – applied to the model results would also be instructive.

Follow-up note (2016):
Multichannel Singular Spectrum Analysis (MSSA) was used in the stadium-wave study – the research focus that grew out of this review (dissertation and publications 2011-2015). Several proxies for solar activity were used in post-dissertation work: geomagnetic aa, sunspot numbers, and the Hoyt-Schatten 1993 five-proxy composite index among them. From all, a quasi-periodic, multidecadal-scale cycle of variability was extracted; all these fluctuations shared the same time scale; this was the same time scale

(approximate 60-year oscillation) as that shared by the collection of stadium-wave indices (e.g. AMO, NAO, ENSO, PDO, Arctic temperature, Northern Hemisphere surface temperature (averaged), fish populations, and Earth's rotational rate).

In the post-doc research, an unexpected obstacle emerged in this line of research. Using MSSA analysis, as in the original stadium-wave analysis, each solar index was shown to align with a different index within the lagged collective relationship: aa with AMO; negative sunspot numbers with NAO and ENSO, and the Hoyt-Schatten index positively with the Arctic temperature. Why all indices did not align temporally with the same geophysical index is unclear. Hence, without an understanding as to why the various solar indices aligned with different geophysical indices, the work ended. To adopt just one index out of the several would have been convenient; yet it would hide the uncertainty of what these various solar proxies actually represent. It seems reasonable to explore this curiosity, and I offer this observation to others who may wish to pursue similar research.

Handicapping the solar-link research further was a dearth of evidence at the time for a quasi-periodic sixty-year cycle of solar activity. Of course, it can be argued that an external forcing need not exhibit a 60-year oscillation to cause a 60-year oscillation in climate. Mentioned earlier (page 5) in this essay was the work done by *Weng '05*, where it was shown that a changing solar constant on quasi-periodic decadal time scales could trigger multidecadal oscillations, ones for which there was no direct physical link! Constructive and destructive interference of other oscillations can, under different circumstances, generate variability not tied to any direct physical forcing. This underscores the challenge of finding a convincing argument for a multidecadal external forcing involved either directly or indirectly in similarly timed variability observed in climate, especially over the last 150 years.

But still, observations compel investigation into origin – whether direct or indirect – for an approximate sixty-year oscillation. Indeed, a quasi-periodic oscillation was detected in the stadium-wave work that was consistent with this time scale; yet connecting it with variability in solar output was no small challenge. Without a direct multidecadal component of solar activity, an argument for a multidecadal forcing, or nudging, by solar activity was weak. During the years over which the stadium-wave hypothesis was unfolding, several researchers found possible sources for this apparent solar-activity cycle. *Nicola Scafetta* and *Nils-Axel Morner*, along with colleagues, are two examples of researchers who have published papers (See examples: *N. Scafetta*; Empirical evidence for a celestial origin of the climate oscillations and its implications; Journal of Atmospheric and Solar-Terrestrial Physics; 2010; 72; 951-970. *Morner et al 2014*; Pattern in Solar Variability, their Planetary Origin and Terrestrial Impacts; Pattern Recognition in Physics (book). *N. Scafetta*; High resolution coherence analysis between planetary and climate oscillations; Advances in Space Research; 2016) on their hypothesis that the detected solar cycle is linked to the changing location of the center-of-mass, or barycenter, of the solar system. That center-of-mass of the solar system is determined by the positions of the sun and the orbiting planets. The barycenter lies within the sun; yet it is not at the center of the sun. Instead, it is off-center. And it moves according to orbital changes. The movement of the solar system's center-of-mass results from gravitational interactions of planetary bodies (especially Jupiter and Saturn) and the sun. This line of reasoning allows us to give some foundation to an approximate sixty-year oscillation in solar activity; yet a mechanism for how that variability influences climate remains unclear.

Much of the discussion of this paper has pointed to the tropics as being sensitive to changes in solar output. Recall (from discussion on page 5 of this memo) studies that showed a tropical response to solar being communicated to high latitudes, allowing for an indirect mechanism connecting solar forcing to tropospheric climate. Of course, influence from external forcing by the sun need not be confined to one region or latitude. In fact, one must keep open to the possibility that the direct location/mechanism of solar forcing, paced at a multidecadal time scale, may change over time and with changing boundary conditions. It quickly becomes clear the complexity of ferreting out a simple explanation.

An explanation may be traced to the polar vortex. ((See essay (on Investigations Page of Web Site) on "Control Central" for discussion on polar vortex behavior.) Considering this possible vortex-solar connection, whether direct or indirect, an argument is made in two papers by *Veretenenko and Ogurtsov (2012 and 2013)*. They find an approximate 60-year oscillation in tropospheric (atmospheric) circulation. This quasi-periodic oscillation is found in the middle and high Northern Hemisphere latitudes and is tied to behavior of the polar vortex. This indicates stratospheric involvement in the observed tropospheric multidecadal cycle. *Veretenenko and Ogurtsov* argue that both solar activity and cosmic ray influx (the two being related due to changes in solar wind) influence the multidecadal evolution of the vortex in the polar stratosphere, and hence, the tropospheric circulation experienced at middle and high latitudes.

The studies alluded to above are not alone in this line of research. It is well worth keeping an eye on developments in this arena.

Postscript (2016):
The stadium-wave premise, for which this essay was a precursor, was that the ocean-atmospheric synchronized (matched rhythms, not necessarily "same-timed") network through which a climate signal passed, scripted approximate 30-year alternating trends of increasing and decreasing average surface temperatures across the Northern Hemisphere. In this manner, the network functions as a thermostat, operating on a multidecadal time scale. Lower and higher frequency components of variability co-exist with this approximate sixty-year, network-choreographed component; at least over the last 150 years, according to the hypothesis.

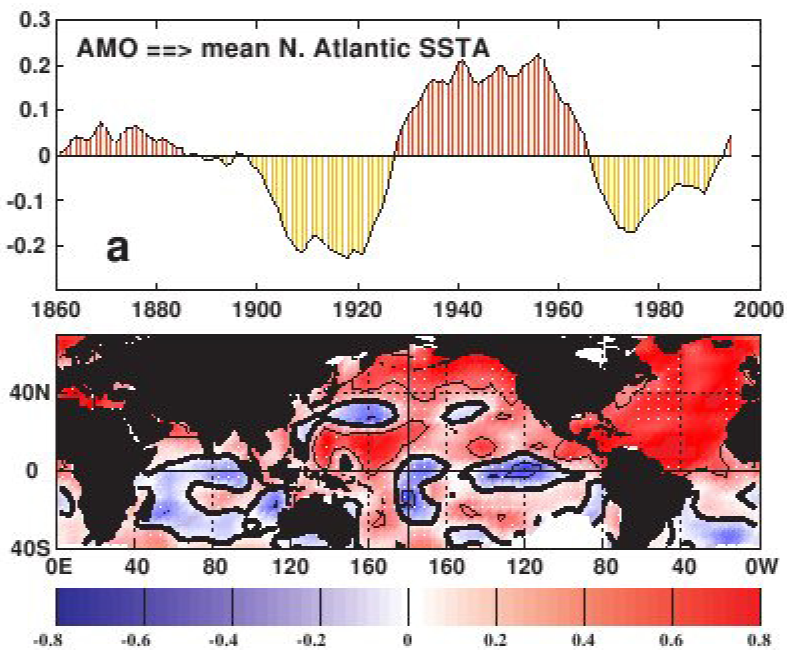
At the time of this essay's original writing (2008), research on the stadium wave was in its infancy. The idea of a role for the Western Eurasian Arctic sea ice – which *Wyatt and Curry 2014* found to be a fundamental component in the stadium-wave's propagating mechanism – had not yet materialized. My hunch, inferred from observation, is that a certain inventory of sea-ice extent in this specific region of the Arctic is critical to the function of the propagating signal. Another hunch is that the system is intrinsic; yet, it is sensitive to resonance – as is any self-oscillating system. Sensitivity to resonance suggests that an external forcing can hijack, or nudge, the rhythm of a self-oscillating system. If the pulse of the external system is close to that of the intrinsic system, and if the linkage between the external force and intrinsic system is not too strong, that external heartbeat can entrain the natural frequency of the self-sustained oscillator! In plain-speak, solar might nudge the timing of the stadium wave. And, my hunch is that sea ice cover in the Eurasian Arctic shelf seas enhances the sensitivity of the stadium-wave network so that its natural oscillation period is modified slightly. Whether the solar influence directly impacts the high latitudes at which the sea ice exists, or is an indirect communication from the tropics, is unclear. But the sea ice, in conjunction with stratospheric dynamics in the polar region is a topic worth further investigation.

In short, in specific cases, and on multidecadal timescales, the solar component can act as a metronome for Earth's intrinsic thermostat.

APPENDIX:

Definitions/Descriptions:

AMO = Atlantic Multidecadal Oscillation: a North-Atlantic basin phenomenon; a dipole pattern of sea-surface-temperatures (SST) between the North Atlantic and South Atlantic. Although it is often described as a basin-wide warming or basin-wide cooling of North Atlantic SST, the uniformity of pattern is not complete. Subpolar and tropical-subtropical SSTs tend to be of one sign with a slightly opposing sign of SST in the subtropical gyre. The ITCZ follows the warmth. When the warmth is mostly in the North Atlantic, the ITCZ shifts in tandem. The AMO operates on an approximate 65-year periodicity and appears intimately related to the AMOC – the meridional overturning circulation.



MOC = Meridional Overturning Circulation: A globe-girdling vertical and horizontal ocean circulation, with downwelling regions in the high latitudes of the North Atlantic and in the Weddell and Ross Seas off the Antarctic continent. Upwelling occurs in a few regions – much of it in the Southern Ocean, some in the North Pacific. The pace of the MOC is largely governed by downwelling strength in the Labrador Sea region of the North Atlantic – one of the few areas of intermittent deep-water formation in the North Atlantic that comprise the downwelling limb of the MOC. Deep-water-formation in the Labrador Sea and MOC strength are positively correlated.

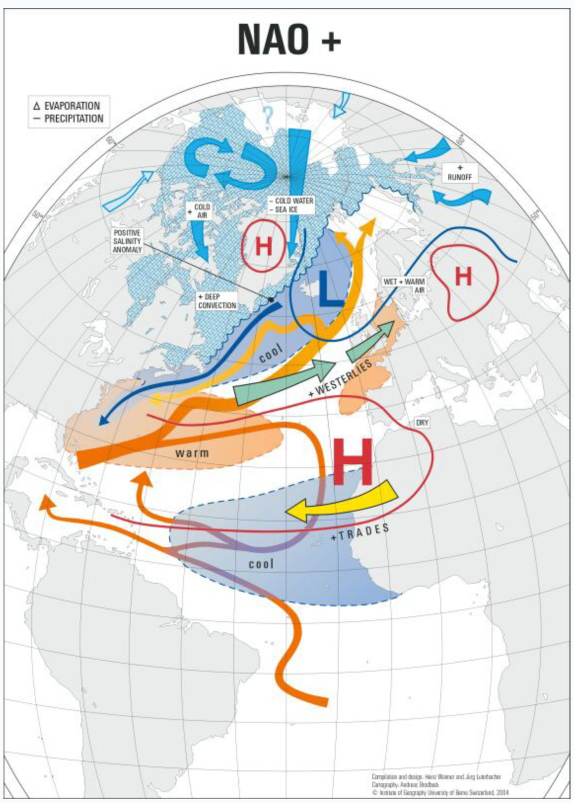
Strength of the MOC is also intimately tied to extent of sea-ice cover in the Arctic. With amplified currents advecting warm water northward, sea-ice is attenuated from below. Melting sea ice contributes freshwater to the region of deep-water-formation, exerting influence on the intensity of the process. (Atlantic sector MOC: AMOC)

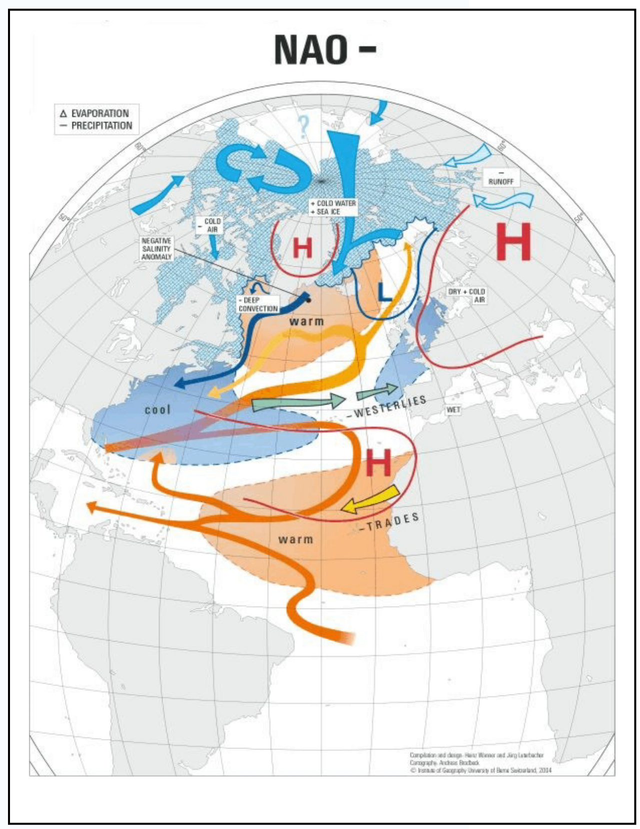
NAO = North Atlantic Oscillation: The NAO is described as a climatic phenomenon whose direct realm of influence lies in the North Atlantic Ocean. Wintertime fluctuations in the difference in sea-level-pressure between the Icelandic Low and the Azores High define the NAO-index. A large difference describes a high index of the NAO, a situation characterized by strong westerly winds that carry anomalously warm temperatures to mid and mid-high latitudes of Western Europe. During a high-index, or positive, NAO, the polar vortex above the Arctic region is intensified. Air locked within the vortex is frigid. Bounding the vortex are wintertime surface-to-stratospheric westerly winds that serve to isolate the polar air, resulting in accelerated stratospheric ozone loss and plummeting temperatures, typically between December and March.

When atmospheric pressure between the two systems is small, the index is considered to be low or in the negative phase. Westerly winds weaken. Western Europe cools. The wintertime polar vortex is weak, with its boundary further equatorward. Intrusions of frigid Arctic air into the mid-latitudes are more common when the vortex is weak.

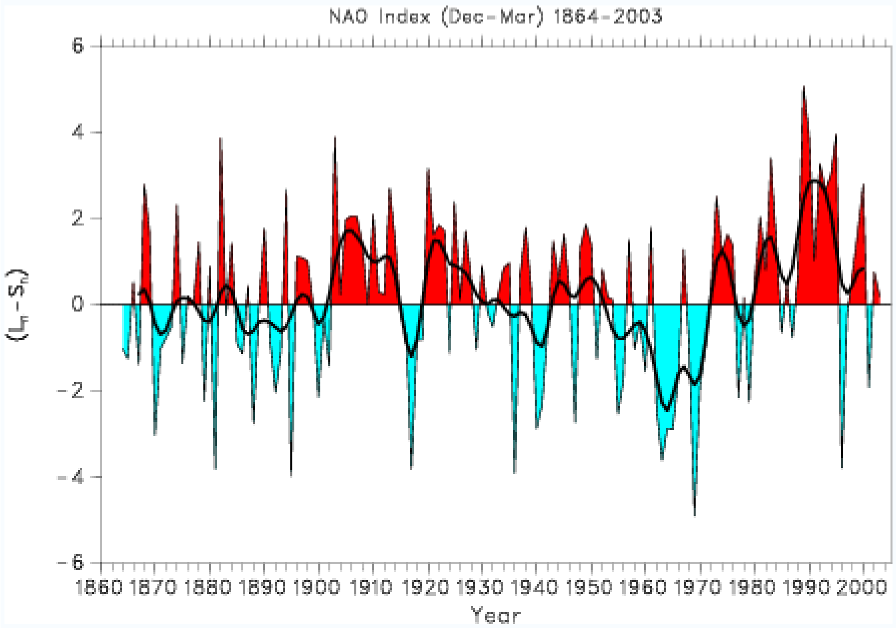
Because the vortex strength is a major component of the NAO, and because the vortex strength is tied to another oscillation called the Arctic Oscillation (AO) or Northern Annular Mode (NAM), the NAO and AO/NAM are often used interchangeably. In this paper, they are not.

A signature pattern of atmospheric pressure and SST characterize phases of NAO. Atmospheric forcing is shown to force these patterns. During a NAO-positive, SLP patterns generate a tripolar SST pattern of anomalously cool SSTS at subpolar latitudes (~50 to 60°N) and in the tropics and anomalously warmer SSTs in the mid-latitudes, particularly in the subtropical gyre region. The tripolar SST pattern is reversed during an NAO-negative phase.





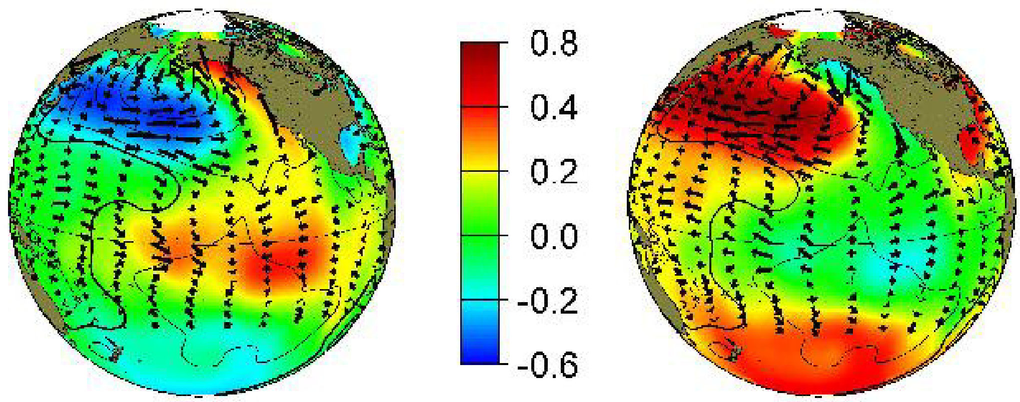
Computer models successfully model the interannual and interdecadal atmospheric fluctuations of the NAO. No ocean component and no external forcing is required for this oscillation to fluctuate. While this observation is not contested, further observation and study have shown that on decadal and multidecadal timescales, the ocean and atmosphere couple, so that one forces and reinforces the other, providing persistence to one phase or another. While interannual and interdecadal timescales continue, these shorter-term fluctuations are superimposed upon the longer timescales of multi-decadal periodicity.

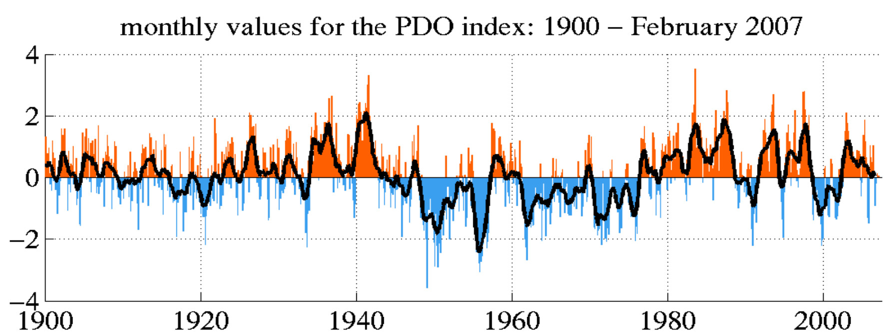


During times of a predominantly positive phase of NAO, intensified westerlies and a northerly-shifted jet stream leave Western Europe warmer and wetter than normal and the Mediterranean drier. Strong northeasterly trade winds push the Atlantic Intertropical convergence zone (ITCZ) further south. Coastal upwelling – a result of strong trade winds - cools SSTs in the eastern subtropical and tropical regions off the west coast of Africa. Enhanced southerly winds – a result of both intensified northeasterly trades and the consequent amplification of the subtropical gyre (STG) velocity – warm and dry the southeastern U.S. Cold air hovers over much of the northeastern section of North America and western Greenland. Cold air and cold SSTs in this region – the Labrador Sea region – lead to intensification of deep-water-formation and deep convection. This is the Labrador Sea deep-water-formation – LSW. When convection here is strong, more heat is released to the atmosphere from the descending water mass and the MOC strengthens, as well.

During times of predominantly negative NAO, all parameters – temperature patterns, wind patterns, ITCZ location, etc. - are opposite, including a slowdown of LSW. A reduction of LSW results in less heat being released from the water to the atmosphere and in a slowed MOC.

PDO: The Pacific Decadal Oscillation is defined as the leading principal component of SST variability in the North Pacific. It has been described as an ENSO-like pattern, in that the warm phase of the PDO resembles the El Nino SST pattern in the Pacific and the cool phase of the PDO resembles the La Nina SST pattern. The PDO is basin-wide in extent; whereas the ENSO patterns are more confined to the tropics. During a PDO-warm, SSTs in the eastern equatorial Pacific and along the west coast of North America warm. SSTs in the central and western basin cool. While the technical definition involves only SST- most likely due to the fact that its recognition was prompted by the abrupt appearance and disappearance of certain fish populations, clearly affected by SST conditions – distinct SLP patterns characterize the phases, as well. A strong, deep, easterly shifted Aleutian Low, with strong winds encircling the ocean gyres straddling the Low, is a signature of PDO-warm phases. A less deep, westerly shifted Aleutian Low is characteristic of a PDO-cool – a time when SSTs in the central basin are warm and those along the equator and along the western NA coast are cool. There appear to be two dominant time-scales of the PDO – a shorter one of 15 to 25 years and a longer one of 60 to 80 years. Observations suggest a connection between the PDO and AMO as well as one between the PDO and NAO. The prevailing thought is that the Arctic Oscillation bridges the two oceans, with the Atlantic leading the Pacific.





Studies suggest that during PDO-warm phases, El Nino events are more intense and more frequent. Likewise, during PDO-cool phases, La Nina events are more intense and more frequent. As the SST signatures in the tropics are similar, this comes with little surprise.

Shifts in atmospheric circulations alter precipitation patterns across the globe during ENSO events. El Nino episodes force changes in the Atlantic that lead to less freshwater input into the tropical/subtropical region. La Ninas lead to the opposite – a freshening of the low latitudes of the Atlantic. These salinity fingerprints propagate with surface currents poleward, ultimately affecting deep-water formation and thus the strength of the MOC. These changes occur on decadal timescales. El Nino and La Nina also affect salinity via oceanic processes, through the Bering Strait into the Arctic and through the Indian Ocean into the Southern Atlantic. These salinity changes are the exact opposite of the shorter-term effects; yet they occur on multi-decadal scales, most likely ensuring oscillatory behavior of the system.

El Nino events clearly elevate the global mean surface temperature. This is largely due to the eastward advance of warm waters from the west, extending the range of warm surface waters and diminishing or eliminating the effect of cool, upwelling waters in the eastern tropics. The greater frequency of El Nino events during PDO-warm phases explains, in part, the observation that global temperatures increase during a PDO-warm. In addition, basin-wide dynamics change between PDO phases. In a complicated scenario involving the subtropical gyre and the western boundary current, heat subducted into the STG and into the upwelling regions of the tropics during a PDO-cool is carried to the western basin during a PDO-warm where it is fluxed to the atmosphere.

Similarly, during NAO-positive, where deep-water formation is intensified in the Labrador Sea, more heat is expelled to the atmosphere than during the shallow subduction during a NAO-negative. Furthermore, the western boundary current and its STG partner in the North Atlantic, operate similarly to their counterparts in the Pacific, expelling heat to the atmosphere during the positive state and subducting it during the negative state.

Thus, changes in surface SST patterns, accompanying wind changes, and changes in ocean-heat uptake and release, contribute collectively to the climatic influences wielded by these ocean-atmospheric oscillations.

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Important papers to consider when re-visiting this topic:

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