Is the stadium-wave propagation an illusion?

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Two contrasting views of multidecadal climate variability in the 20th century

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Abstract:
A relatively recent hypothesis of multidecadal climate variability has been challenged (Mann et al. 2014). The hypothesis is the "stadium wave" (Wyatt et al. 2012). Its distinguishing feature is hemispheric signal propagation through a network of synchronized climate processes, the pace of which is influenced by variability in sea-surface-temperatures in the North Atlantic (i.e. the Atlantic Multidecadal Oscillation (AMO)). Mann et al. claim that flawed methodology has generated an apparent, or false, propagation in the signal. The contended flawed methodology is linear detrending, a statistical step once innocent in its ability to highlight lower frequency behavior within a time series - a signal often associated with the AMO – but today, a source of controversy, a portion of which has been aimed at the stadium wave.

Kravtsov et al. (2014) consider the challenge, adopting a strategy that evaluates phase uncertainties of the propagation, as well as spatio-temporal patterns of the signal in modeled and observed databases. In the following memo, through the lens of the Kravtsov et al. work, evidence supportive of the stadium-wave propagation unfolds. Findings show: i) The propagation of the "stadium wave" is highly unlikely to be due random occurrence or flawed methodology; and ii) pronounced and fundamental differences occur between analyses using observation-based data and analyses using model-generated data. Differences involve spatial patterns of the signals: ocean indices of the Atlantic and Pacific and atmospheric indices across the hemisphere play significant roles in the observed stadium wave; while only the Pacific appears significant in model-generated data. Differences also involve temporal patterns: the model-based signals are in-phase, stationary ones, requiring only one mode of variability to explain its profile; while observation-based signals are not in-phase, requiring two modes of variability to explain their alignment.

Significantly, the stadium wave says nothing about another aspect of the controversy that the indicted detrend methodology invites – i.e. attribution of signal. The detrending method is criticized for its tendency to exaggerate the appearance of an intrinsic component of multidecadal variability (e.g. the AMO). This is because the forced trend, itself, may not be linear. The stadium-wave hypothesis has fallen subject to a similar assumption: that it speaks to attribution. But indeed, it does not. While dynamics of the stadium-wave signal-propagation are likely intrinsic, shuttling a climate signal around the hemisphere (and maybe the globe), and the signal, itself, likely originates in, and is paced

by, the AMO; the source that generates the AMO tempo and AMO amplitude is neither addressed by, nor relevant to, the stadium-wave hypothesis.

Introduction:
Controversy regarding climate has been framed mostly in terms of global warming and the causes for such - natural versus anthropogenic factors. Recent debate narrows focus to climate's low-frequency pattern of variability, and the relative contributions causing the behavior – external forcing versus internally generated. Methodology to deliver the final verdict is not forthcoming, thus, providing little resolution.

Models driven by estimated external natural and anthropogenic radiative forcings between 1900 and 2000 can reproduce an observed low-frequency "wiggle" in trend of 20th century global surface average temperatures: pronounced warming ~1910 to 1940 and ~1970 to the late 1990s, with slight cooling between[1]. Non-uniform temperature trends are not unique to the 20th century. Proxy data pre-dating an enhanced anthropogenic contribution reflect similar variability, and suggest a relationship to the North Atlantic, specifically the Atlantic Multidecadal Oscillation (AMO), the intrinsic component of which is uncertain.

To better "see" these undulations, researchers traditionally have removed the long-term linear trend of a time series so as to highlight the higher-frequency fluctuations, the multidecadal ones among them. Yet, with the attribution issue (i.e. forced versus intrinsic) unresolved, appropriateness of this technique has come into question.

The argument against it contends that linear detrending *assumes* removal of the forced signal. This assumption harkens back to the earlier views, when anthropogenic greenhouse-gas forcing was reflected in a linearly increasing warming trend and estimating its role was of primary interest. But the non-uniformity of trend motivates a broader view. Indeed, models reproducing the wiggle of the 20th century do so only with incorporation of external radiative forcings other than greenhouse gases – natural and anthropogenic aerosols critical to that undulating pattern. Thus, it is argued that if a linear trend is removed, a vestige of the forced wiggle is imprinted upon the remaining signal. In that case, if one interprets that detrended product to be of intrinsic character, the role assigned to it will be overestimated. This point has been made often over the last decade, with suggested alternate methods, each with its own companion flaws (Mann and Emmanuel 2006; Trenberth and Shea 2006; Kravtsov and Spannagle 2008).

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[1] There are opinions that differ with this statement of Kravtsov et al. regarding the ability of models to capture this 20th century "wiggle", but the reason can be explained thusly: Some of the most respected models do simulate a two-step warming, with a 'pause' between during the 20th century (this does not speak to the current pause (1998 to the present)). Timings of these trends may differ slightly according to model. In ensemble averages of the modeled outcomes, these slightly different timings may cancel one another out a bit, thereby muting the ensemble-average mid-20th-century "pause", giving the impression that the "wiggle" is not reproduced. How the cooling trend is reproduced depends a lot on how the aerosol effects are represented. Some use an indirect aerosol effect in addition to the direct effect. Typically, in such scenarios, the aerosol cooling is too strong. The work by Kravtsov et al. makes no comment regarding these model differences.

Linear detrending is implicated as a fatal flaw in a relatively new hypothesis regarding multidecadal-scale climate variability – the stadium-wave hypothesis. The stadium-wave hypothesis of multidecadal-scale climate variability assumes that synchronized network behavior governs the low-frequency quasi-periodic oscillatory component shared among a collection of interacting ocean, ice, and atmosphere indices. Phasing-offset among the synchronized network members reflects hemispheric propagation of the signal, the pace of which appears to be governed by variability in the AMO.

There has been a long-suspected relationship of AMO with multidecadal variations in Northern Hemisphere temperatures, those in Europe, in particular. Proxy data and historical temperature records cast its role as pivotal; the modern era apparently supportive of it. Thus, because of this historical context, many studies have assigned AMO-related variability to intrinsic processes, a point that brings us back to the controversy of methodology. If AMO is linearly detrended, is there, or is there not, a vestige forced signature imprinted upon the residual, thereby exaggerating the perceived role of internal processes? We arrive back at the impasse. Yet this impasse is not to be conflated with fundamentals of the stadium-wave signal. Stadium-wave propagation is hypothesized to have an intimate connection with AMO – the latter being its pace setter. Perhaps not immediately intuited, this association says nothing about the driver of AMO. Propagation of the stadium wave proceeds, so the hypothesis goes, irrespective of the *source* of AMO oscillatory energy, be it external forcing, internally generated variability, or a combination of both.

Attribution-of-signal will continue to ignite active dialogue; yet the stadium wave hypothesis will likely offer little weight to either view. What it may offer is insight into how surface heat is hemispherically (globally?) re-distributed on multidecadal time scales associated with signal propagation – itself, likely an intrinsic process.

Mann et al. 2014 contend that this propagation is not real, that it is no more than an artifact of flawed methodology – once again indicting the linear detrend method. Through the lens of a new paper by Kravtsov et al. (2014), this challenge is examined. Taking center stage is the re-evaluation of the robustness of the stadium-wave hypothesis.

Overview: The Mann et al. challenge and Kravtsov et al. response:
Mann et al. (2014) contend that the propagation – the distinguishing signature of the stadium-wave hypothesis – is no more than a statistical artifact of flawed methodology – i.e. of linear detrending. Linear detrending is a step in the analysis used to document the stadium wave, the intended purpose to remove the centennial-scale trend to highlight multidecadal variability. But, regardless of intended use of the method, it is worth taking into account the findings of Mann et al.

Kravtsov et al. (2014) considered Mann et al.'s contention that the stadium-wave propagation is no more than an artifact of methodology. Mann et al. illustrated that a random realization of interannual variability (white noise), superimposed upon their artificial climate indices – an in-phase forced signal common to each – would, once linearly detrended and smoothed, produce a false appearance of propagation. Choice of noise realization would dictate propagation sequence and phase offsets. Thus, one could generate a variety of different "stadium waves" according to the nature of the white noise imprint, an outcome implying that the propagating stadium-wave signal identified by Wyatt and collaborators was illusory, and any apparent stadium-wave lags were statistically insignificant.

Kravtsov et al. concede that a collection of indices constructed from a commonly shared, in-phase, forced signal, whose only differences are those imposed by regional noise processes, do generate false "stadium waves", once linearly detrended and smoothed – as was done in Mann et al. In methodological contrast, Wyatt and collaborators, in their stadium-wave analyses, have sought to identify timescales of co-variability among network indices. Their use of Multi-channel Singular Spectrum Analysis (M-SSA) -- a generalized application of the more commonly known Empirical Orthogonal Function (EOF) analysis, adept at identifying propagating signals and shared variability among indices -- has documented multidecadal-scale stadium-wave propagation (a structure of M-SSA-generated phase-shifted signals) in a variety of geophysical index collections. The phase shifts between the "real" stadium-wave indices are, of course, subject to uncertainty, just as are the indices in the synthetic example of Mann et al. (2014). However, the real question is whether these uncertainties are so large as to render the stadium-wave propagation statistically insignificant. That is the point Kravtsov et al. first investigate.

Merging this view of M-SSA generated phase-shifted signals plus noise with the strategy of Mann et al. in constructing surrogate networks, Kravtsov et al. show that the phase uncertainties of each index are significantly smaller than the *actual* phase lags (lag time in years between propagating indices) among those indices in the "real" stadium wave. This finding supports the Kravtsov et al. counterargument to Mann et al's contention that artificial propagation is a product of sampling associated with climate noise. According to Kravtsov et al., such sampling variations are unlikely to explain the propagation observed in the "real" stadium wave; thus weakening Mann et al.'s challenge.

Details of Methodologies:

<u>Mann et al.2014 surrogate network and propagation using modeled data</u>:

Buried in the overview are the details of surrogate reconstruction. In the case of Mann et al., they begin surrogate index construction with a simple energy-balance model, driven by radiative forcing estimates. This is done to generate a core forced signal. This signal is their "Northern Hemisphere Temperature (NHT)". To five versions of this forced NHT signal, they add random realizations of model-generated white noise. The white noise realizations represent presumed regional contamination of the hemispherically shared forced signal. The resulting versions of NHT + noise are then linearly detrended, smoothed with a low-pass 50-year filter, and plotted. They refer to this collection as "AMO teleconnections". The result is a plot of five indices, each with a shared low-frequency "wiggle", yet each index with a slightly different phasing – a result of different noise processes superimposed upon an in-phase, forced signal – offsets of which are highlighted by linear detrending and subsequent smoothing.

Kravtsov et al. 2014 surrogate network and propagation using observation-based data:
In the case of the stadium-wave studies, isolation of the propagating signal (e.g. Wyatt et al. 2012) involves decomposing raw time series of network members into a linear trend, a multidecadal trend, and a residual time series – interannual-to-interdecadal. Step one involves the linear detrending of each network member, done to highlight frequencies of each index higher than centennial-scale. No attribution of signal is intended with this step. In step two, the remaining data of all detrended indices are decomposed into modes (patterns of shared variability) using M-SSA. The leading two M-SSA modes found in the observational data are of multidecadal scale. They both exhibit approximate 60-year oscillatory trends throughout the instrumental record. And although their patterns of variability are similar; they are not identical. Combined, these two multidecadal modes define what Wyatt and collaborators referred to as the stadium-wave signal. The leftover time series is the residual variability, and is of interannual-to-interdecadal time scale.

With the goal being to test the role of noise in generating phase uncertainties in the propagation alignment, and in the spirit of the Mann et al methodology, Kravtsov et al. first generated random surrogates of residual variability. They did so using a linear stochastic model with a lag-0, lag-1 co-variance structure that reproduces the structure of the observed residual. This surrogate residual, the analogue to the Mann et al. noise component, was added to the combined product of ([original linear trend] + [original stadium-wave signal]). These now-formed three-component surrogate indices are ready for the original stadium-wave analysis: i) a new linear trend is computed and subtracted; ii) M-SSA identifies modes of co-variability among the surrogates; iii) leading modes of co-variability are extracted and combined for each surrogate network-index. This mode-combination represents the surrogate's stadium-wave signal; and iv) for the purpose of estimating uncertainty of phasing offsets among indices, this procedure is repeated 1000 times, in accord with classical Monte Carlo testing.

Results show the variations in phasing are considerably smaller than the phase offsets between each "real" index. This suggests the observed propagation is not a random occurrence – i.e. not a statistical artifact of flawed methodology. In fact, with application of this standard Monte-Carlo significance estimation, Kravtsov et al. formally argue a result strongly contrasting that of Mann et al. Specifically, Kravtsov et al. show that the observed stadium-wave lags are statistically significant at the 95% confidence level (i.e. the likelihood that stadium-wave signal propagation is false, and due to random sampling, is vanishingly small, 5% or less - the estimated uncertainties supporting this conclusion).

Kravtsov et al. 2014 surrogate network and propagation using model-generated data:
Kravtsov et al. repeat the same strategy (M-SSA) as described above, this time using the modeled data generated by the Geophysical Fluid Dynamics Laboratory Coupled Physical Model (GFDL CM3). Results between the two data sets – modeled and observational - are not the same. Instead of a propagating signal, as found in observation-based data, the result using GFDL CM3 modeled data shows an in-phase, stationary collection of "waves" with a period centered on ~75 years. No propagation emerges. Furthermore, while two leading modes of multidecadal-scale co-variability are identified in the model-simulated data, only one mode dominates. (See also Wyatt and Peters 2012)

This is noteworthy - noteworthy because in observational data, at least two leading modes of multidecadal-scale co-variability emerge, yet significantly, and in stark difference to modeled results, each leading mode in observed data reflects similar dominance.

Kravtsov et al. 2014 comparing spatio-temporal patterns, modeled vs. observational data: A fundamental distinction between observed and model-based multidecadal climate variations is clear. At least two spatial patterns underlie the observed stadium-wave signal; while only one pattern is needed to describe the model-simulated version of the multidecadal signal. Kravtsov et al. evaluate and compare spatial patterns of these two network renditions – modeled and observed. For both the modeled data and observation-based data they define the spatial patterns statistically by regressing the sea-surface-temperature (SST) fields onto normalized sine and cosine predictors. A period of 75 years defines the predictor curves, with the zero-phase set at 1920; the two curves in-quadrature, with the sine curve well aligned with the 20th century global-temperature wiggle. Roughly, it also corresponds to the GFDL CM3's stationary, in-phase "wave".

They find that the spatial pattern of the linear trend and the sine pattern of the modeled global SST time series are similar to the observational analogues. But the similarities do not extend to the cosine predictor pattern, which is distinct and pronounced in observations, but not so in the modeled data. It appears that a forced pattern is all that emerges in the spatial signature of the modeled data; while two patterns define the spatial character of the multidecadal signal in observed data.

Further breaking down the patterns, Kravtsov et al. focus on the fingerprints of individual network-index members. Kravtsov et al. show that most indices reconstructed from the GFDL CM3-generated data – e.g. the AMO, the Atlantic SST Dipole, the North Atlantic Oscillation (NAO), the North Pacific Oscillation (NPO), and the Aleutian Low Pressure Index (ALPI) – exhibit variances in the decadal-to-multidecadal range that are far *smaller* than observed variances; in some cases, up to an order of magnitude smaller. This means that these indices play an insignificant, if any, role in the *modeled* multidecadal climate variability. Exceptions to this minor-to-absent participation of modeled indices include the Pacific Decadal Oscillation (PDO) and the NHT. In these two cases, variances are similar to their observed counterparts. These results suggest that the GFDL CM3's simulated multidecadal signal is due to a forced signal. This forced signal is dominated by the Pacific sector, and synchronized to the NHT, with little to no involvement of Atlantic and atmospheric indices. Modeled multidecadal variability, where the Pacific role dominates, is unlike observed multidecadal behavior, where all discussed indices participate. This fundamental difference in outcomes between analyses using observation-based data and analyses using model-generated data may imply that dynamics operating in the observed climate variability – via stadium-wave signal propagation – are either poorly represented or absent from current model design.

Summary of Kravtsov et al. findings:
In summary, Kravtsov et al. use a variety of strategies to examine robustness of the stadium-wave signal. They address the Mann et al. challenge regarding signal propagation and then go further, comparing observed multidecadal behavior with

modeled analogues. Steps in their strategy include: i) Using instrumental data, and adapting Mann et al.'s approach, they construct surrogate indices and estimate uncertainties in phase offsets between observation-based indices to evaluate statistical significance of signal propagation; ii) with model-generated data, they repeat the previous step; iii) through SST regression onto sine and cosine predictors, they assess and compare spatial fingerprints of observed and modeled multidecadal variability; and iv) by examining signatures of individual indices, they compute the relative variances in multidecadal behavior.

They find and/or add support to the following: 1) propagation alignment of the stadium wave indices does not appear to be a statistical artifact of linear detrending and its documented hemispheric propagation is highly unlikely to be due to random sampling associated with higher-frequency noise; 2) no propagation is identified in model-generated data; instead, these data strongly reflect an in-phase, forced signal dominated by the Pacific sector and projected onto the NHT, with little variance in atmospheric and Atlantic-centered indices; and 3) two leading modes are required to explain the observed multidecadal variability and rationalize the observed stadium-wave propagation. Fundamental distinctions in the outcomes of analyses between modeled and observed data sets, as illustrated through the Kravtsov et al. study, may allude to climate-model design, potentially reflective of their omission of, or poor representation of, dynamics critical to the generation of climate variability on multidecadal timescales.

In Closing: **Some Comments on Stadium-Wave – Mechanism/Attribution**:

Mechanism:

The Kravtsov et al. study is based on statistical documentation and mechanism is not invoked. Observing behavior without explicating mechanism does not necessarily undermine a hypothesis; in fact, one could argue that elucidating phenomena through statistical analysis, without invoking mechanism, minimizes the tendency to see what one might expect to see, and allows one to view statistically documented behaviors with less bias, allowing mechanistic dynamics to unfold accordingly.

But indeed, mechanism underpinning the stadium-wave propagation has been investigated in previous work. As Kravtsov et al. point out in their paper, in addition to literature-based speculations on key index-linkages offered in previous works (Wyatt et al. 2012; Wyatt and Peters 2012), Wyatt and Curry (2014) offer significant insight into mechanism. Their findings detail a complex interplay among various geophysical processes, with sequential interactions among regional processes, carried like a relay baton-exchange across a diverse spatial landscape, transporting an Atlantic-born signal, irrespective of the Atlantic's source of variability, across the Northern Hemisphere. Climate-regime reversals coincide with trend reversal of the AMO, the phase-polarity of which manifests in an oppositely signed phase of Northern Hemisphere temperature approximately 30 years later, its profile scripted as the signal propagates through the processes outlined above.

Attribution of Signal:

And a final note is offered on something that perhaps has been lost in on-going discussion of the stadium-wave hypothesis. While AMO is thought to set the pace of the stadium-wave signal, the propagation of which is likely internally generated, the source of AMO variability – forced, intrinsic, or both – is not a matter addressed by, nor relevant to, the stadium-wave propagation. It is assumed that within the present-day boundary conditions, hemispheric propagation of signal will continue, its dynamics likely a product of self-organized, synchronized network behavior, involving ocean, ice, and atmospheric processes, paced by the variability of the AMO, regardless of AMO's source of variability, with positive and negative feedbacks enhancing, and subsequently reversing, its sign polarity, effecting the re-distribution of surface heat along its sequential journey, and scribing the associated low-frequency component of surface-temperature trend, at least within the Northern Hemisphere.

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