Disentangling forced from intrinsic variability: Implications for the "stadium wave" and Northern Hemisphere climate variability.

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I. Introduction:

The observed Northern Hemisphere temperature trend over the last 100-plus years increases non-uniformly, with multiple-decade intervals of strong warming alternating with multiple-decade intervals of stalled warming or slight cooling. Similar behavior emerges in proxy data, dating back several centuries (Black et al. 1999; Gray et al. 2004). A question of attribution emerges. What is the source of this non-uniformity? Does the climate system's intrinsic (internally generated) variability script this pattern or are external forcings (natural and anthropogenic) of the climate system in charge[1]? One may ask why it is necessary to know, or what one gains by knowing. Isolating an intrinsic signal from a forced one is not a matter of sorting out anthropogenic from natural, the value of this distinction more readily apparent. But debate does exist regarding the observed temperature trend - intrinsic versus forced. And debate exists regarding how to disentangle the two components.

Mann et al. 2014 address this attribution issue. Their approach is two-fold: **i)** to evaluate the current instrumental surface average temperature trend in context of modeled temperature histories; and **ii)** to evaluate methodology used in studies whose findings are consonant with the view that intrinsic variability plays a non-trivial role in multidecadal climate behavior. The hypothesis underpinning the Mann et al. work is that the low-frequency component of variability in Northern Hemisphere surface average temperatures (NHT) is dominantly a product of a radiatively forced signal.

In the Mann et al. study, an estimate of the forced component is computed via the use of a simple energy-balance model. Subtracting this component from observed NHT yields their estimated intrinsic component. They combine this estimated internal variability with model-simulated data from the fifth version of the Coupled Intercomparison Model Project (CMIP5) database to generate a collection of 'alternate' temperature histories. They use the alternate temperature histories to evaluate the currently observed NHT. With their estimated intrinsic component, they evaluate methodology employed in studies whose findings support a non-trivial role for intrinsic variability in the low-frequency climate signal.

Mann et al. submit that: i) the recently observed NHT falls within their computed ensemble of temperature histories; ii) the intrinsic component is minimal and regionally confined; iii) the method of linear detrending overestimates the amplitude of internally

[1] **Intrinsic variability** is not devoid of external forcing. Internal variability emerges with a constant force applied. In addition, an inconstant external forcing can influence the intrinsic character of an intrinsic system. An applied time-varying force, with a frequency close to that of the intrinsic system, can potentially nudge the oscillatory time scale of that system if interaction between the forcing and the system interact sufficiently. In contrast, a forced system oscillates or varies only in direct response to the applied force.

generated climate variability; and iv) an apparent hemispheric signal-propagation – the "stadium wave" – is no more than a statistical artifact of that method. This memo examines the Mann et al. conclusions and presents counter-arguments that lend perspective to the debate.

II. Framing the debate: how to interpret low-frequency climate variability:

Low-frequency behavior is evident in surface temperatures across the Northern Hemisphere, with particular focus on sea-surface temperatures (SSTs) in the North Atlantic. Instrumental and proxy data of the North Atlantic SSTs reflect a multi-decadally repeating pattern. While regularly repeating, it is not strictly periodic (Vincze and Janosi 2011). This North Atlantic variability has been termed the Atlantic Multidecadal Oscillation (AMO: Kerr 2000). Its timescale of variability is thought to be influenced by the Atlantic sector's Meridional Overturning Circulation (AMOC) (Knight et al. 2005). Similar timescales of variability have been identified in different climate patterns across the Northern Hemisphere (Enfield et al. 2001; Goldenberg et al. 2001; Sutton et al. 2003; Sutton and Hodson 2003, 2005, 2007; Knight et al. 2006).

These observations have spawned speculation that a North Atlantic-born signature (AMO) is imprinted on the hemispheric (possibly global (Lee et al. 2011; Feng He 2013)) climate record. If one assumes a relationship to the AMOC, *and* if one assumes the AMOC to be internally generated, then one might infer the hemispheric (global) temperature signature to contain an intrinsic signal. Herein lies the debate – is the observed low-frequency climate behavior of the AMO forced or intrinsic. And herein lies the crux of the Mann et al. argument. While they do not deny the existence of an intrinsic component of the AMO, they find its spatial reach minimal and its amplitude low, giving internal variability little influence over hemispheric (global) climate. Mann et al. argue that estimations of non-trivial amplitudes and broad teleconnected influence of the intrinsic component of AMO are functions of a flawed statistical methodology - in particular, the method of linear detrending - and not of a physical reality.

III. Identifying the AMO:

Many methods have been used to identify the multidecadal nature of the AMO – principal component analysis (PCA) (Parker et al. 2007), linear detrending (e.g. Enfield et al. 2001; Knight et al. 2005, 2006, 2009), and differencing (e.g. Mann and Emanuel 2006; Trenberth and Shea 2006; Kravtsov and Spannagle 2008; Knight 2009). If the goal in applying these methods is to isolate the intrinsic component from the forced, each carries weaknesses (Knight 2009). In the case of linear detrending, if the forced signal is time-varying, then a portion of it will be retained in the detrended product, thereby modifying the residual. Depending on the time-varying structure of the forced signal, the residual's variability may be enhanced or dampened. In the case of differencing, there are various versions. In one version, a global signal is subtracted from an Atlantic signal (e.g. Trenberth and Shea 2006). In this case, if an Atlantic fingerprint exists within the global signal, the risk of overfitting leads to underestimation of the residual, as a portion of the Atlantic fingerprint is subtracted from itself. And in differencing versions where modeled terms are used in conjunction with the differencing method (e.g. Mann and Emanuel 2006; Kravtsov and Spannagle 2008; Knight 2009), whereby a modeled forced signal is generated and subtracted from the observed hemispheric signal, results of the end-product depend upon the modeled forced signal. Forcing profiles, climate sensitivity used to generate them, and successful removal of the model's own internal variability from the simulated data (where applicable) are all subject to assumption and uncertainty. All influence the residual that is termed intrinsic.

IV. Mann et al 2014 – isolating the "AMO":
One goal of Mann et al. is to isolate the intrinsic component of the AMO. Assuming the NHT is a combination of a forced signal and an intrinsic one, they apply their differencing method: From the observed Northern Hemisphere temperatures, they subtract a model-estimated signal, which is forced by natural and anthropogenic contributions. The residual of this operation is their intrinsic component. Smoothing the residual with a 50-year low-pass filter generates the low-frequency expression of this intrinsic component. They term this expression the "AMO", in reference to the AMOC-driven portion of climate variability.

They compare this "AMO" to one obtained by linearly detrending the Northern Hemisphere mean temperature data[2] (not the North Atlantic SSTs), followed by a 50-year filter. They compare the two constructed "AMO" terms and find differences: The linearly detrended version has greater amplitude and 'biased' (shifted) phasing when compared to its differenced counterpart. Mann et al note that this is particularly true for recent years – the 'hiatus' years. In the mid-1990s, the differenced "AMO" began decreasing; while the detrended AMO peaked several years to a decade later.

V. Mann et al. and the stadium wave:
Mann et al. further pursue their argument by focusing on a relatively recently introduced hypothesis (Wyatt et al. 2012 (first online in 2011)) involving a climate signal that propagates across the Northern Hemisphere through a synchronized network of geophysical indices, geographically and sequentially communicated by a chain-like signal transmission through the coupling of ocean, ice, and atmospheric patterns. This propagation is called the "stadium wave", the underlying mechanisms of which are detailed in Wyatt and Curry 2014 (online 2013). Mann et al. claim the propagation identified as the stadium-wave signal is no more than a statistical artifact – a product of flawed methodology – i.e. linear detrending.

To address the potential role of linear detrending in generating false propagation, Mann et al. take their model-simulated forced signal and add to it a random white noise time series. They repeat this operation, generating a collection of surrogate climate indices. Five of these surrogates constitute their "climate network". The assumption underlying this procedure is that all climate indices in nature are a combination of a common externally forced signal plus interannual climate variability represented by white noise. They call these constructs "AMO teleconnections", even though there is no AMO, only a forced signal plus noise. They then linearly detrend all surrogate indices, followed with a 50-year filter. Results are plotted. The paper shows some interesting propagation

[2] This procedure is *not* typical of most studies that use a linearly detrended AMO. In traditional methodology using detrended AMO, basin-wide North Atlantic SSTs 0 to 70º N are detrended, not NHT.

scenarios that actually do resemble the Wyatt et al. plots in that there are phase shifts between filtered surrogate indices, creating an appearance of propagation. The supplementary section hosts additional plots; although their phase-shift sequences are less suggestive of the stadium wave. The basic premises of Mann et al. are: one, there exists an attribution problem, with assessment of intrinsic contribution to NHT largely a function of methodology; and two, that propagation patterns can emerge as statistical artifacts if the methodology applied is flawed (i.e. if linear detrending is used), and that uncertainty exists in lag times between index members.

VI. The stadium-wave:

To clarify a point that might get lost in the Mann et al. argument, the stadium-wave hypothesis does not address the attribution issue. The propagating dynamic is envisioned to be intrinsic with the current boundary conditions of Earth systems in play. AMO sets the tempo. Whether the AMO variability is intrinsic, forced, or a combination is irrelevant to this hypothesis. The stadium-wave describes the communication of a climate signal across the Northern Hemisphere, *paced* by the AMO. In the stadium-wave studies, all indices were linearly detrended – not in order to isolate an intrinsic component, but rather to highlight multidecadal variability. Removing the secular-scale (century-length) trend is one step toward effecting this goal.

As far as selection of statistical methods applied, in any study, these choices are guided by assumptions associated with the hypothesis being tested. The Mann et al. work is rooted in the assumption of a single forced component, whose various temporal expressions differ due to adulteration by noise. In contrast, the hypothesis underpinning the stadium-wave is that on long time scales, climate variability organizes into network behavior executed through coupled dynamics among ocean, ice, and atmospheric circulation patterns. Thus, different methods of analysis are required for these different views.

To examine collective behavior of the hypothesized stadium wave, the authors employed a multivariate approach - Multiple Channel Singular Spectrum Analysis (M-SSA: Moron et al. 1999; Ghil et al. 2002) - that identifies co-variability among network members. With this method, only the time scales at which *all* network members vary are identified. Single-variable methods cannot identify such timescales of shared variability among indices. For the stadium wave, only a time scale of between 55 and 70 years emerged as being shared by *all* network members. Numerous index networks were analyzed (Wyatt (dissertation: 2012) and Wyatt and Curry (2014)). All produced similar results, all with physical basis suggested.

<u>Support for Stadium-Wave propagation</u>:

Model-simulated data: After Wyatt et al. (2012) documented propagation characteristics of the 'original' stadium-wave network, Wyatt and Peters (2012) sought to find similar behavior in model-generated data. They used model-generated data from the third version of the Coupled Intercomparison Model Project (CMIP3) to investigate whether the models produce stadium-wave-like behavior. From the modeled raw variables (e.g. SSTs, sea-level-pressures, etc), climate indices that were used in the original stadium-wave study (Wyatt et al. 2012) were reconstructed. These simulated indices were then treated exactly like the ‘real’ indices used in Wyatt et al. 2012. In other words, it was assumed these indices would function as a network on multidecadal time scales.

Twenty-one of 22 models were represented (one model output was corrupted (http://pielkeclimatesci.wordpress.com/2011/06/28/comments-by-marcia-wyatt-on-cmip-data/)). Sixty-six runs were processed – the majority with prescribed “business as usual” CO2 increase; a few runs were pre-industrial control runs. None of the 66 runs produced a stadium wave. Of the models that produced a low-frequency signal, that signal was stationary and in-phase, with no propagation - reminiscent of an externally radiatively forced signal. In contrast, the leading secular-scale stadium-wave signal in observations is captured by two leading M-SSA modes, each reflecting an approximate 60-year quasi-periodicity. The stadium-wave signal is identified in a vast and diverse collection of geophysical instrumental and proxy indices – not just for the 20^{th} century, but prior to it Wyatt (dissertation: 2012), when anthropogenic forcing was not a factor; thus further suggesting that propagation is unlikely to be an artifact of linear detrending.

A question surfaces: If linear detrending generated a false propagatory signal in instrumental and proxy data, as Mann et al. suggest, then why did the same methodology applied to indices reconstructed from computer model-generated data – 20^{th} century data *and* pre-industrial model-generated data - not produce the same false propagation?

Mechanism: Propagation illuminated by statistical means is meaningless without dynamical foundation. The propagation patterns derived in Mann et al’s work have no physical basis. This stands in stark contrast to the stadium-wave phasing. In Wyatt and Curry (2014), a detailed set of mechanisms is offered, each step (ocean, ice, and atmospheric coupling) in the sequence discussed and supported by previous research. Furthermore, proxy data representing the various climate indices peak and trough at the same phasing as their instrumentally measured counterparts. Proxies used in Wyatt and Curry have been long observed to be correlated with certain ocean and large-scale wind patterns. That the phasing of these proxies fall at ‘expected’ times when evaluated separately from their climate-index counterparts, speaks to the mechanisms at play.

Spatio-temporal statistical analysis: Additional statistical evaluation (Kravtsov et al (submitted)) further weakens the Mann et al. argument that the stadium wave was a statistical artifact. To test this, Kravtsov et al. adopted and generalized the Mann et al. procedure to estimate the uncertainty of phase lags in their inherently multivariate-signal-detection approach, and found that the observed lag times between indices were larger than the lags expected from the random sampling at the 5% significance level. This is *opposite* from what Mann et al. concluded. And finally, Kravtsov et al. identified spatial structures of the observed stadium-wave signal that could not be duplicated with the forced signal generated by the state-of-the-art GFDL model.

VII. Summary and Discussion:

<u>The Stadium Wave:</u>

Failure of modeled data to produce a stadium wave (Wyatt and Peters 2012); mechanisms describing stadium-wave propagation through coupled ocean, ice, and atmospheric indices (Wyatt and Curry 2014); and rejection of Mann et al's null hypothesis (Kravtsov et al. submitted) combine to provide strong support for the stadium-wave propagation sequence in generating the multidecadal component of the Northern Hemisphere's observed climate variability. Thus, Mann et al.'s arguments against the stadium wave seem weak.

Mann et al's understanding of the stadium wave appears incomplete. Evolution of the idea may have obfuscated our message. Thus to clarify: The stadium-wave hypothesis describes a hypothesized intrinsic dynamic of hemispheric signal communication under boundary conditions extant throughout the 20th century (and perhaps for at least a century prior). It is paced by the AMO, regardless of the forced or intrinsic nature of AMO's variability. Thus, regardless of a forced signal's magnitude or temporal structure, the stadium wave derives its marching orders from the AMO. If radiative forcing weakens or slows the AMOC, and thus the AMO, then the stadium wave should reflect this. If sea ice in the Eurasian Arctic disappears completely, the stadium wave may cease to operate (see Wyatt and Curry 2014). These are points for further investigation.

Linearly detrending indices in the stadium-wave climate network removes the secular-scale trend. It is used not to isolate the intrinsic component of the AMO, but rather to highlight variability on time scales shorter than century-scale. M-SSA was then applied to the network of indices to detect co-variability among index members. In the stadium-wave analyses of instrumental and proxy data, *shared* variability among network indices occurred on multidecadal timescales only. Individually, climate indices exhibited additional timescales of variability – annual to interdecadal – but none of these timescales was shared by all network members. Thus, over long timescales, it is hypothesized that ocean, ice, and atmospheric systems across the Northern Hemisphere organize into synchronized (matched rhythms) network behavior. In the architecture of the hypothesized stadium-wave network, a climate signal is sequentially propagated across the Northern Hemisphere, its potential influence on the Southern Hemisphere not yet determined.

<u>Methods and Isolating the Intrinsic Component of the AMO</u>:
And beyond focus on the stadium wave, general arguments put forth by Mann et al. regarding methodology used to isolate forced and unforced components of climate variability serve only to highlight the debate over disentanglement of components, while promoting the tacit assumption that all studies using linear detrending use it to isolate the intrinsic component of NHT. In the case of the stadium-wave, this assumption is false.

There is value to Mann et al's method of differencing. It is one way to attempt to isolate an intrinsic component, if that is the goal. Others have used differencing with alternate terms being subtracted (Trenberth and Shea 2006; Mann and Emanuel 2006; Kravtsov and Spannagle 2008; Knight 2009), some with results divergent from Mann et al's, in fact, some with results that are not too dissimilar from those derived from linear detrending (Kravtsov and Spannagle 2008; Knight 2009).

VIII. Conclusion:
This memo addresses arguments set forth in Mann et al. 2014 regarding the statistical method of linearly detrending indices, and this method's purported role in generating a statistical artifact resembling that characterizing the hypothesized 'stadium wave'. The methodology of Mann et al. is described, their arguments outlined and addressed, and the debate put into perspective.

Mann et al. challenge the method of linear detrending in its ability to separate intrinsic variability that is often associated with the AMO from forced variability associated with radiative signals. No method – linear detrending or the differencing method – is free of uncertainties and weaknesses as applied to the goal of isolating the intrinsic component. Linear detrending removes a secular-scale signal. This highlights multidecadal variability, with no guarantee of separating components of a climate signal. Most who use this approach recognize this, including the authors of the stadium wave studies.

Information in this present memo weakens the case of Mann et al. as it pertains to the stadium wave. Indeed, through Mann et al's approach, they were able to plot indices that appeared to propagate, suggesting the propagating nature of the 'real' stadium wave was of similar specious derivation. A collection of arguments outlined in section VI counter this assertion. Further analysis reaffirms the assertion that the hypothesis of the propagatory nature of the stadium wave is highly unlikely to be due to random sampling.

Mann et al. interpret the stadium wave as a challenge to their forced signal. This conclusion seems unfounded. While the stadium-wave's propagation dynamic is likely to be intrinsic, AMO is the pace-setter. The stadium wave says nothing about the components of the AMO. It may be forced, intrinsic, or a combination; such is irrelevant to the stadium-wave propagation. The stadium wave represents a dynamic involving ocean-ice-atmospheric coupling sequentially transmitted across the Northern Hemisphere on multiple-decade time scales. A cool signal in the Atlantic leads to a warming hemispheric signal half-a-cycle later, feeding back upon the Atlantic throughout the cycle, continuously planting seeds of reversal (Wyatt and Curry 2014). Boundary conditions of ocean, ice, and atmosphere of the 20th century supported the stadium-wave propagation in its 20th century manifestation. If boundary conditions change, so might the stadium wave. Thus, this hypothesis invites more exploration than simply limiting focus to intrinsic vs. forced contributions. Earth systems appear to redistribute heat laterally and vertically, regardless of source.

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