Dissertation Summary and Discussion (originally written May 2012**):**

A Multidecadal Climate Signal Propagating Across the Northern Hemisphere through Indices of a Synchronized Network, by Marcia Glaze Wyatt

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[Note: Three papers based on Wyatt's dissertation work have thus far been published (as of November 2013). One, Wyatt et al. 2012, was available online in April 2011. Two others were published subsequent to publication of the Wyatt dissertation (in May 2012). One of these papers is by Wyatt and Peters ((2012) re: model-based data analysis). The other is by Wyatt and Curry ((2013) a study based on spatially expanding the stadium-wave climate network, with particular focus on Eurasian Arctic shelf sea ice). Investigation of stadium-wave behavior continues, based on this body of work.]

As has been emphasized throughout this collection of studies, this research was motivated by the observation of an often-cited quasi-cyclic multidecadal signal that characterizes behavior of numerous geophysical indices - from commercial-fish populations to Earth's rotational-rate anomalies, to climate indices defining atmospheric and oceanic circulation patterns. This cadence is evident in a variety of proxy and instrumental records. Curiosity of this pervasive similarity led to preliminary analysis of raw time series of a variety of climate indices. Results of this pursuit suggested not only a shared quasi-cyclic multidecadal signal, but in addition, a propagation of this signal across the hemisphere.

Was this just an unsystematic low-frequency signal in a noisy data set? Was this observation no more than a random occurrence? Three separate, yet related studies, each based on a different data set and guided by slightly differing motivations, have been conducted in an attempt to answer this question quantitatively.

Our strategy for all studies was to forego detailed examination of regional circulations; instead, we evaluated collective behavior – interactions among nodes of a network. Synchronization theory lies at the heart of collective behavior – whereby the behavior of a system of interconnected nodes is not necessarily what would be predicted, from a knowledge of each individual circulation in isolation. Self-oscillating systems can couple, with certain conditions met, after which their intrinsic frequencies adjust to a shared frequency – hence, synchronization. A phase-lag, sometimes minute, always exists between synchronized oscillators. And within some synchronized systems, a signal is propagated (Pikovsky et al. 2003). That system is consistent with my hypothesis here.

The original stadium-wave study, based on the 20th-century instrumental record to which multichannel-singular-spectrum analysis (M-SSA) was applied, characterized the dominant mode of climate variability shared among all indices considered. Eight indices were first analyzed. Seven additional ones were subsequently evaluated. All possessed the M-SSA-identified shared oscillatory signal with strong statistical significance. While periodicity could not be assigned, because defining its time-specific secular-scale variability is not possible within the short time series available to us, a cadence of approximately 64 years was suggested in the 20th century analysis. This timescale of secular variability is consistent with widespread observations of such; yet more significant here is the statistically significant succession of indices carrying this signal. This is what distinguishes this line of research from those that evaluate periodicity of a single index or variable.

Findings from the original study indicate an Atlantic-born signal manifests as an oppositely signed hemispheric signal about thirty years after initiation. The atmospheric, lagged-oceanic teleconnection sequence, as identified in the original study, comprises: -AMO → +AT → +NAO → +NINO3.4 → +NPO/+PDO → +ALPI → +NHT → +AMO. Lags of two to eight years temporally separate these regionally diverse nodal links. An extensive literature-base provides supports the numerous identified links within this described stadium-wave teleconnection sequence. Details are provided in the discussion section of our original study (Wyatt et al. 2012 and chapter 2). One particular detail is the significance of latitudinal/longitudinal shifts of large-scale centers-of-action and related effects on ocean and atmospheric circulation. Their inclusion in models appears to be a critical feature required in simulating realistic ocean-ice-atmospheric coupled behavior (e.g. Kirov and Georgieva 2002; Polonsky et al. 2004; Grosfeld et al. 2007; Dima and Lohmann 2007; Wang et al. 2007; Sugimoto and Hanawa 2009; Frankignoul et al. 2011; Kwok 2011). For example, sea-ice growth in the Bering Sea region depends upon location of the Aleutian Low. Dramatic shifts in latitude and longitude occur in the Aleutian Low from one climate regime to another determining dominant wind direction influencing the region. Wind direction determines conditions for sea-ice-growth (Niebauer 1998). Similarly, Dima and Lohmann (2007) find the regime-related shifts in atmospheric centers-of-action determine sea-ice-export through the Fram Strait, with ensuing modifications of the Atlantic's freshwater balance. Kwok (2011) found the same to be true for placement of the Arctic atmospheric center-of-action. Its location influences the Arctic freshwater balance. Additional examples can be found in Wyatt et al. (2011), dissertation chapter one.

In addition to the multidecadal contingent of the stadium wave, seven complementary indices, most dominated by higher-frequency variability, were also found to fluctuate at the identified signal's multi-decadal pace. In particular, it was found that intensity and frequency of the interannual-to-interdecadal variability altered according to prevailing climate regime, polarity shifts that are consequent of stadium-wave progression.

For Chapter 2, I attempted to ascertain historical persistence of the stadium wave and to gain insight into potential dynamics underlying the propagating signal. Appended to the original data set were proxy data and index sets representing the Arctic and the Intertropical Convergence Zone (ITCZ). From this extended data base, a variety of subsets were analyzed with M-SSA. In all cases for the 20th century, a statistically significant, secularly varying, quasi-oscillatory, shared signal was identified. For proxy data extending to dates prior to the 20th century, robustness of results depended upon proxy subset used; stadium-wave-like behavior was found, but statistical significance diminished with the longer the time series. Not clear are the reasons for this; whether they lie with the signal or with quality issues of proxy data is something I cannot conclude from this analysis. That said, evidence for a propagating signal exists back to at least 1700, the length of the study, with differences in stadium-wave amplitude and frequency, in particular, prior to 1750.

Insight into 20th-century stadium-wave dynamics came from the incorporation of Arctic indices. A distinct multidecadal character, in particular in the Eurasian Arctic sector, emerged in our results and is consistent with extensive literature support of this temporal-scale of variability (see Frolov et al. 2009 and references within). Eurasian

Arctic Shelf Sea ice appears to play a critical role in signal propagation, with ocean-ice-atmospheric coupling and indications of subsequent negative feedback from Pacific onto the Atlantic. A weak solar signal appears to be synchronized to the system, being in parallel alignment with negative polarities of Atlantic atmospheric circulations and positive inventories of Eurasian Arctic sea-ice. Entrainment of tempo by an external quasi-oscillatory system is common in synchronized networks (Pikovsky et al. 2001). This may be the avenue through which solar co-varies with atmospheric and ice-related indices, but its role in the stadium wave is not clear.

A large data set comprising model-generated data from the third version of the Coupled Model Intercomparison Project (CMIP3 (Meehl et al. 2007)) was analyzed in the third study. A total of sixty data sets from a collection of 22 models were examined – with most analyses being of 20th-century experiments, and several being of long-control (pre-industrial) experiments. Reconstructed climate indices from the raw simulated data gave us our climate-index network, a network analogous to the collection in the original study. Methods identical to the previous two studies for identifying a statistically significant, low-frequency, quasi-oscillatory, propagating signal were employed.

No statistically significant stadium-wave signal could be identified in this vast data base. Results from the two studies outlined above provide information to guide speculation regarding its absence. First, Eurasian Arctic sea ice was found to play a key role in the propagation of the stadium wave signal. In essence, increased sea-ice-extent leads to warm Eurasian temperatures, this being a result of an ice-induced basin-scale meridional temperature gradient (Outten and Esau; Petoukhov and Semenov 2010). CMIP3 models show a poor representation of this Arctic sea-ice (Izrael et al. 2001; Jun et al. 2008; Kwok 2011). Arctic sea-ice-motion, a function of geographical placement of the Arctic atmospheric center-of-action is centered too far in the Arctic in the CMIP3 models (Kwok 2011), and therefore is poorly simulated, which suggests that it is one likely factor in the failure. Shifting centers-of-action – oceanic and atmospheric – are critical to linking network communications (Wang et al. 2007, for example). Such nuances of circulation patterns are difficult to model. In a stadium-wave-like sequence, certain behaviors of a sub-process depend upon the sub-process it follows. Such non-linearity in responses is a challenge for models to simulate, but is a feature of a communicating network. Van den Berge et al. (2012) may have made strides toward overcoming this obstacle with their design of a network-like "super-model". Their super-model design allows communication among models. The models exchange information during simulations. Results of this rather novel modeling approach are far better than those from individual models and from multimodel-ensembles. Such a modeling strategy may illuminate more information about what we have attempted to describe here – a hemispheric network of coupled oceanic, ice, and atmospheric circulations.

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