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TOPICAL PROBLEMS OF NONLINEAR WAVE PHYSICS
(NWP-2017)

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8:30, Hall C

Insights into decadal climate variability from the synchronization of a network of major climate modes

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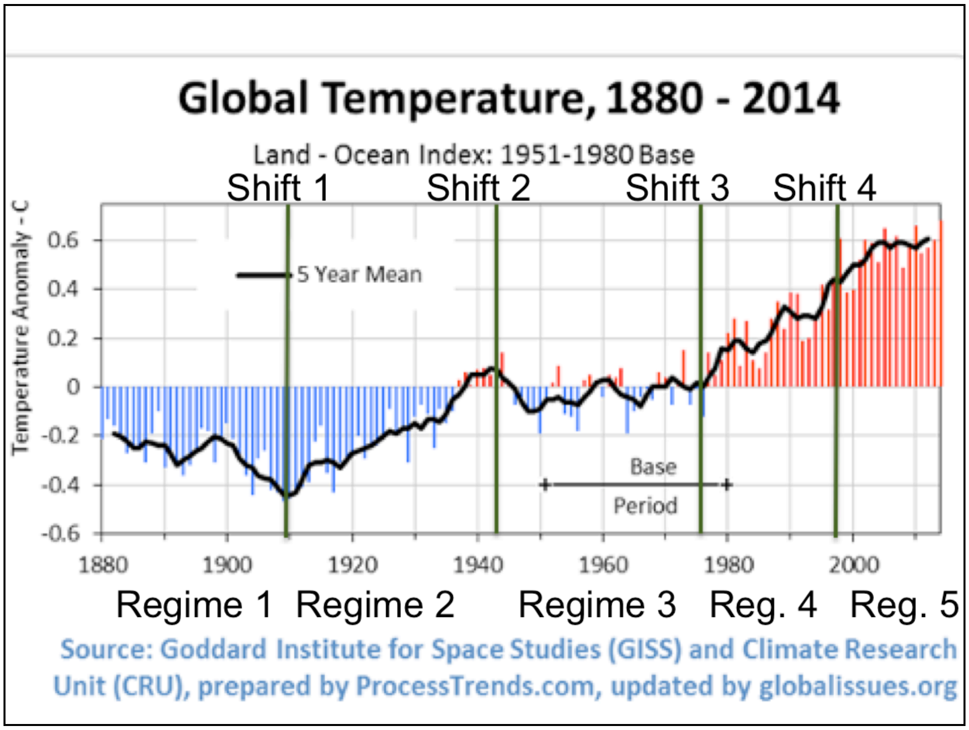


Global warming of the twentieth century was non-uniform, with two periods of fast warming (1910-1940, 1970-2010) and a pause in between (1940-1970). In general, there exist two major explanations for this multudecadal climate variability, with the latter being either due to non-uniformities in the external forcing, or the result of internal climate variability. These three periods, however, were characterized by major changes in their overall climate regime (in particular, non-zonality of atmospheric circulation and character of ENSO), which adds weight to the interpretation involving internal climate variability. Hereafter, we will refer to the phases of multidecadal climate variability as “climate regimes,” and to the transitions between climate regimes as “regime shifts.”

Climate Regime Shift of the 70s

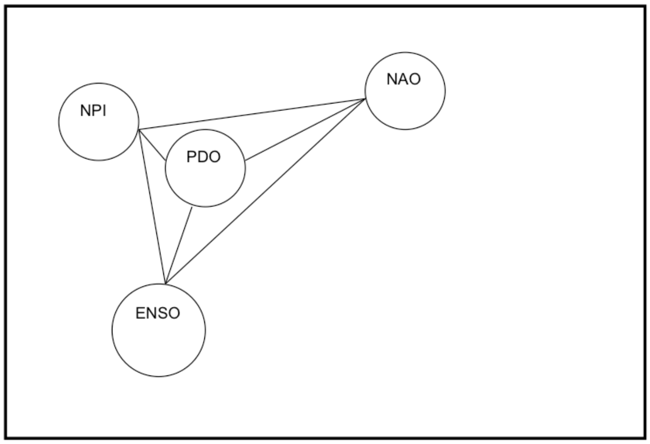
"One of the most important and mysterious events in recent climate history is the climate shift in the mid-1970s [Graham, 1994]. In the northern hemisphere 500-hPa atmospheric flow the shift manifested itself as **a collapse of a persistent wave-3 anomaly pattern and the emergence of a strong wave-2 pattern.** The shift was accompanied by sea-surface **temperature (SST) cooling in the central Pacific and warming off the coast of western North America** [Miller et al., 1994]. The shift brought sweeping long-range changes in the climate of Northern Hemisphere. Incidentally, after ''the dust settled,'' a **new long era of frequent El Niños superimposed on a sharp global temperature increase** begun."

From Tsonis et al. (2007), GRL

Main hypothesis

- We hypothesize that **multi-scale climate interactions** are centrally involved in **climate regime shifts**
- Conceptually, we view the climate system as a **network of nonlinear coupled oscillators**
- The regime shifts are caused or accompanied by **bifurcations in the collective state of these oscillators** as the coupling parameter changes (either in response to external forcing or via internal large-scale dynamics)

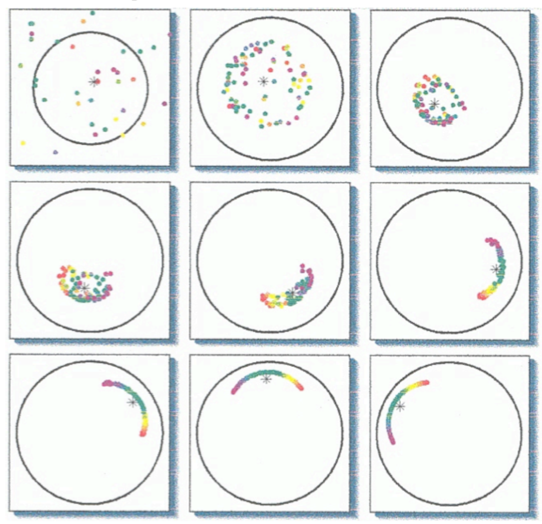
The network used



- Four major climate indices
- DJFM means
- Concentrate on measures associated with <u>interannual variability (fast time scale)</u>

We analyzed four climate indices (DJFM means), arguably representing distinctive oscillating climate subsystems, very likely coupled with one another: NAO (North Atlantic), PDO/NPI (North Pacific ocean/atmosphere), ENSO (tropical Pacific) to study their collective behavior. The statistical measures of this collective behavior we used emphasized the fast timescale behavior dominated by interannual variability (even in the slow PDO index). How this was achieved will become more clear later.

Synchronization in a network of coupled oscillators



We start with the concept of synchronization in a system of coupled limit-cycle oscillators. The instantaneous state of each oscillator is represented by a dot in the complex plane. The amplitude and phase of each oscillator corresponds to the radius and and angle in polar coordinates. The color of each oscillator corresponds to its natural frequency. If the oscillators are not coupled each oscillator settles down onto its limit cycle and rotates with its natural frequency. When they are coupled, however, they self-organized and rotate as a synchronized group with locked amplitudes and phases. The idea in our works is that such synchronization may occur also in a small number of nonlinear oscillators.

Distance a Measure of Synchronization

- Nodes – individual climate indices, 11-yr sliding window used

Mean distance:

$$d(t) = \frac{1}{N(N-1)/2} \sum_{d_{ij}^t \in D^t} d_{ij}^t$$

where

$$d_{ij}^t = \sqrt{2(1-|\rho_{ij}^t|)}$$

- d=sqrt(2): zero synchronization
- d=0: perfect synchronization

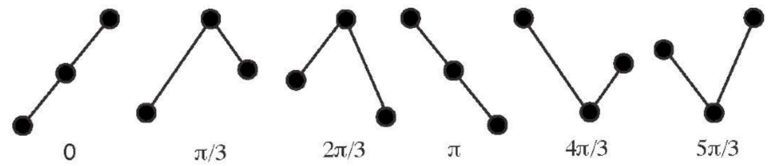
where ρ_{ij}^t is the correlation coefficient between nodes i and j in a window centered at t.

- According to the above definition of distance the maximum distance or no synchronization (which corresponds to all $|\rho|=0.0$) is $\sqrt{2}$ and the minimum distance or strong synchronization (corresponding to all $|\rho|=1.0$) is 0.0.
- Think of zero distance as instantaneous communication within the network, therefore synchronization.
- Note that values of $|\rho|$'s around 0.5 give $d \approx 1.0$
- **Note also that the 'local' in time correlations are dominated by fast dynamics**, i.e. <u>decadal climate variability is not explicitly considered</u>

Coupling strength in a network of oscillators

- In a data-driven approach taken here, we don’t have an explicit coupling parameter, so we need to infer the coupling strength directly from our multivariate time series
- Synchronization is not synonymous with coupling (think, e.g., of two oscillators in quadrature)
- We estimate the coupling strength based on how strongly the phases of different modes of variability are linked

Symbolic phases



- Define phases by comparing the neighboring values within each time series
- Non-parametric procedure
- <u>“Blind” to decadal variability</u>

Measure of coupling

The symbolic phase ϕ^j_n is constructed separately for the four climate indices, where j denotes the index and n the year. The phases for a given year n are represented by the complex phase vector $\vec{Z}_n$ with elements $Z_n^j = exp(i\ \phi^j_n)$. The predictability of this phase vector from year to year provides a measure of the coupling and is determined using the least squares estimator

$$\vec{Z}^{est}_{n+1} = \mathbf{M}\vec{Z}_n$$

where $\mathbf{M} = [\mathbf{Z}_+\ \mathbf{Z}^T]\ [\mathbf{Z}\ \mathbf{Z}^T]^{-1}$ is the least squares predictor. Here $\mathbf{Z}$ and $\mathbf{Z}_+$ are the matrices whose columns are the vectors $\vec{Z}_n$ and $\vec{Z}_{n+1}$, respectively, constructed using all years. A measure of the coupling then is simply $\left\| \vec{Z}^{est}_{n+1} - \vec{Z}_{n+1} \right\|^2$, where strong coupling is associated with small values of this quantity, i.e., good phase prediction.

We construct a least-squares estimator of the next-year phase of each index given the phases of the current year, based on the entire available time series of our four climate indices. The coupling strength is then defined based on the smallness of the regression residual in a given year, with the smaller residual corresponding to stronger coupling (more prediction skill of the next-year phase by our least-square linear model), and vice versa.

Intuitive Idea

- The theory of synchronized chaos predicts that in many cases when systems of coupled oscillators synchronize, an increase in coupling between the oscillators may destroy the synchronous state and alter the system's behavior [Heagy et al., 1995; Pecora et al., 1997] (leading, in our terminology, to a climate regime shift).

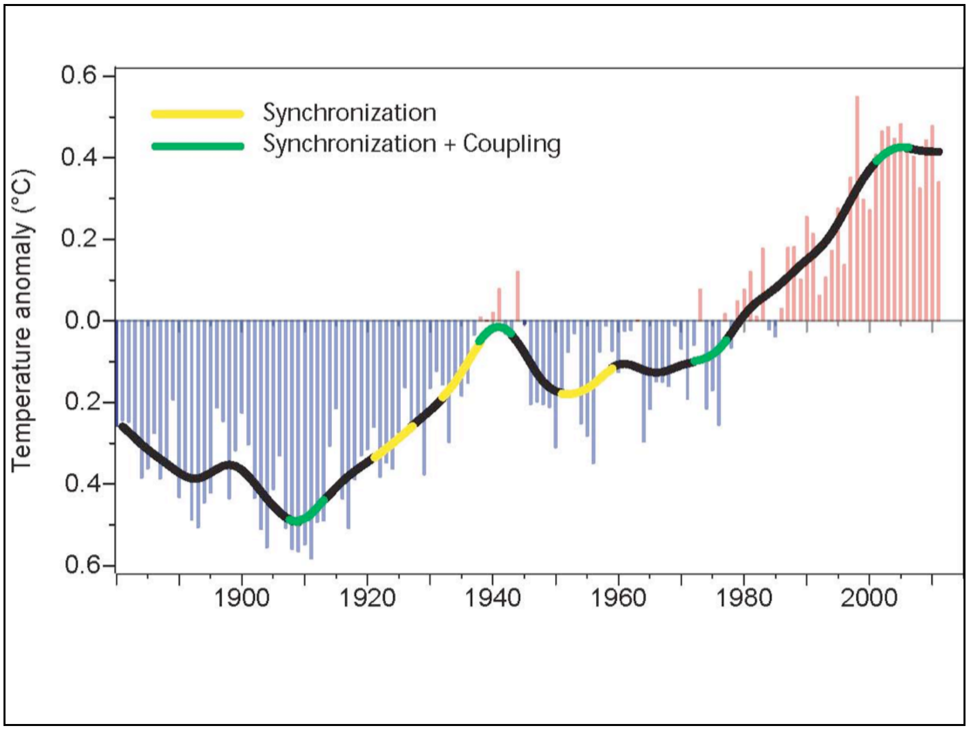
- We thus look to identify the cases when the synchronization of climate indices is accompanied by increased coupling within the index network

TSONIS ET AL.: MECHANISM FOR MAJOR CLIMATE SHIFTS

GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L13705, doi:10.1029/2007GL030288, 2007

- Figure 2: Analysis of Instrumental Record
- Figure 3: GFDL2.1 control run
- Figure 4: GFDL2.1 SRESA1B (business as usual future climate change scenario)

The results of this analysis in observations and a climate model are visualized in Figs. 2, 3 and 4 of Tsonis et al. (2007)



Yellow: synchronization but no coupling increase. Green Synchronization with the coupling increase

Summary of the results

- Four climate-regime shifts were identified in instrumental record (early 1910’s, early 1940’s, mid-1970’s and late- 1990’s), for which synchronization was accompanied by increased network coupling
- These shifts were characterized by the kinks in the global temperature trend and changes in the ENSO variability
- Similar climate shifts were found in GFDL2.1 model, *both* in **PI control run** and in the SRESA1B scenario simulation
- *The control run results argue that these shifts are internal*

Role of NAO as the instigator of climate shifts

- In all 4 synchronizations that led to climate shifts in the observed record (early 1910's, early 1940's, mid-1970's and late-1990's, NAO was found to be a major agent to increased coupling strength.
- In all other synchronizations which did not lead to a shift (1921-1925, 1932-1938, 1952-1957), NAO was not involved. This result is confirmed without exceptions for 12 other synchronization events in 3 climate model simulations.

One can break down contributions from different pairs of indices to the distance and coupling network measures. This analysis identifies the NAO as the major dynamical constituent of the climate regime shifts.

Dynamical mechanisms?

- Atlantic MOC variations linked with NH mean surface temperature variability (Zhang et al., 2007)
- Five-lobe circumglobal waveguide pattern (Branstator, 2002)
- Footprinting (Vimont et al., 2001, 2003)
- 3-D loop (Ineson and Scaife, 2009) NAO→PDO→ENSO→PNA→stratosphere→ NAO
- More details Wang et al., 2009, GRL, L07708 (download from Tasos' web site)

Conclusions

New “mechanism” for major climate shifts:

- First, the fast time scale components of major climate modes exhibit synchronization.
- When this synchronous state is followed by an increase in the coupling strength, the network’s synchronous state is destroyed and after that a new state emerges.
- The whole event marks a significant shift in climate, as reflected by the kinks in the global temperature trend and changes in ENSO variability.
- The changes in the coupling strength leading to climate shifts appear to be internal, rather than forced
- It appears that coupling of NAO with the modes in the Pacific is the necessary step for a major climate shift.

Issues/additional points

- Our statistical results are guided by intuition rooted in the theory of synchronized chaos, but the definitions of collective behavior of climate network associated with fast time scales are somewhat *ad hoc*.
- Causality: Is it a stand-alone large-scale low-frequency (LSLF) climate mode that affects the way fast subsystems interact? Or does this LSLF mode reflect by itself a change in the collective "state" of our coupled "oscillators."
- Predictability: Use fast-scale diagnosis to predict long-term climate trends?

Back-up slides

Shift in the 40s

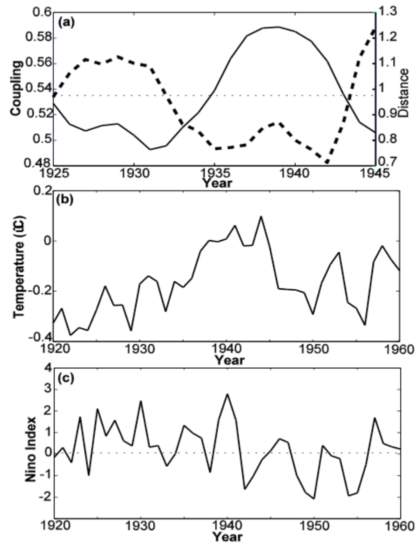
Contributing to synchronization

ENSO-PDO
ENSO-NAO
PDO-NPI
PDO-NAO
NAO-NPI

Contributing to coupling (NAO present in all pairs contributing to coupling increase)

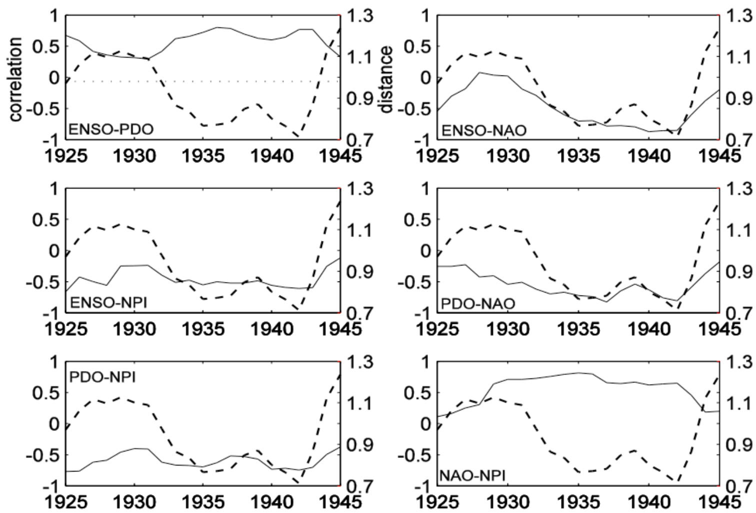
ENSO-**NAO**
PDO-**NAO**
NAO-NPI

The shift in the 40s

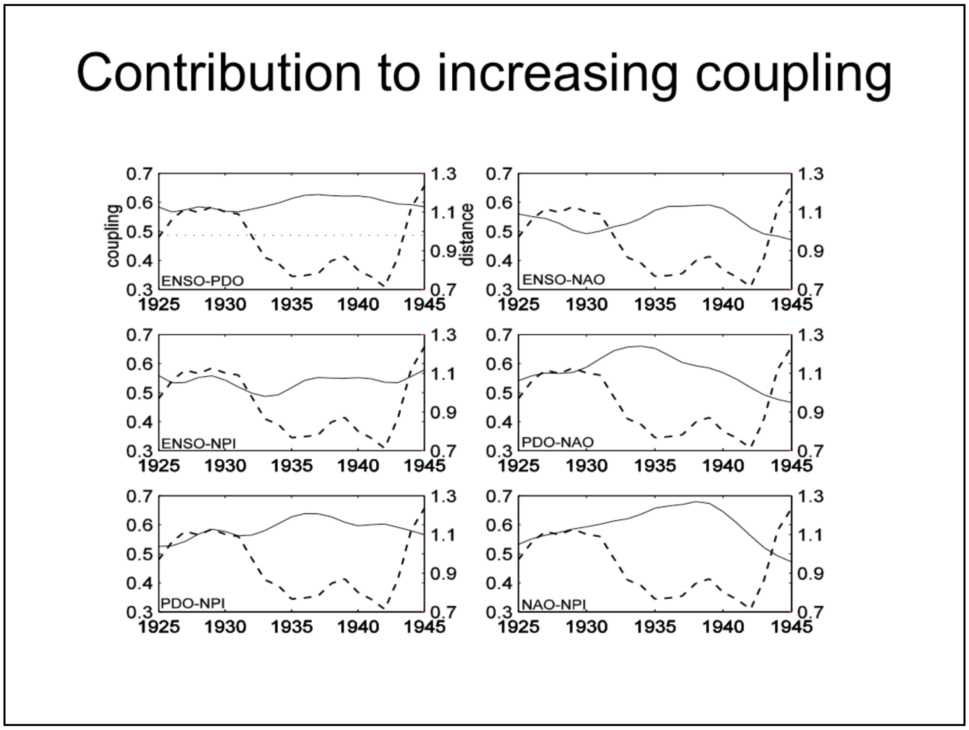


The broken line is the distance of the network. The dotted line indicates the 95% confidence level for the distance based on surrogate data analysis. For the distance a value of less than 1.0 signifies statistically significant synchronization. Solid line is the coupling measure. Network is synchronized 1932-1943 but the coupling during 1932-1938 is decreasing (NOTE that according to the definition of coupling higher values mean greater prediction of phases error or weaker coupling). No change of regime is observed. Then coupling begins to increase from 1938 on, until the network de-synchronizes around 1943 and a change in regime (temperature trend and ENSO variability) follows.

Contribution to synchronization



Contribution to synchronization broken down to all pair components in the network. The broken line is the distance as it was in the previous slide. The solid line is the correlation between the two indices of a given pair in a sliding window of 11 years. Recall from above that an absolute correlation value of 0.5 (which corresponds to a value of distance of 1.0) is more or less the threshold of synchronization. So, in this case the pairs contributing to synchronization are those with absolute values greater than 0.5 (i.e. >0.5 or <-0.5). Those pairs are ENSO-PDO, ENSO-NAO, PDO-NPI, PDO-NAO, NAO-NPI.



Contribution to coupling broken down to all pair components in the network. The broken line is the distance as it was in the previous slides. The solid line is the coupling between the two indices of a given pair. Recall from above that decreasing values indicate coupling getting stronger. So, in this case the pairs strongly contributing to synchronization are ENSO-**NAO**, PDO-**NAO**, **NAO**-NPI

Climate shifts in proxy records

- Since then, many other studies have used this slow climate modes paradigm to explain climate shifts and decadal climate variability
- This result has also been confirmed by a study using proxy ENSO, NAO, and PDO data going back a several centuries (1300-1900). Tsonis and Swanson, 2011, IJBC, 21, 3549-3556, download from Tasos' web site)

Mention Marcia's and your follow-up research and papers