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Synchronization and Causality across Time Scales in ENSO

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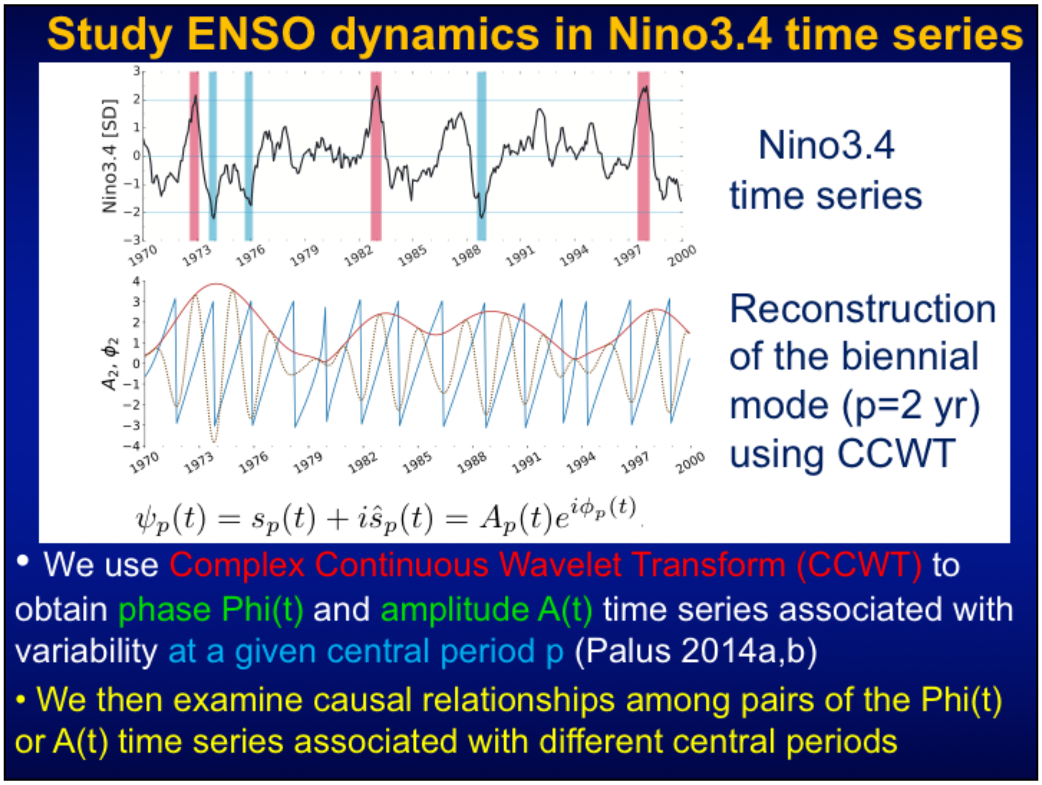
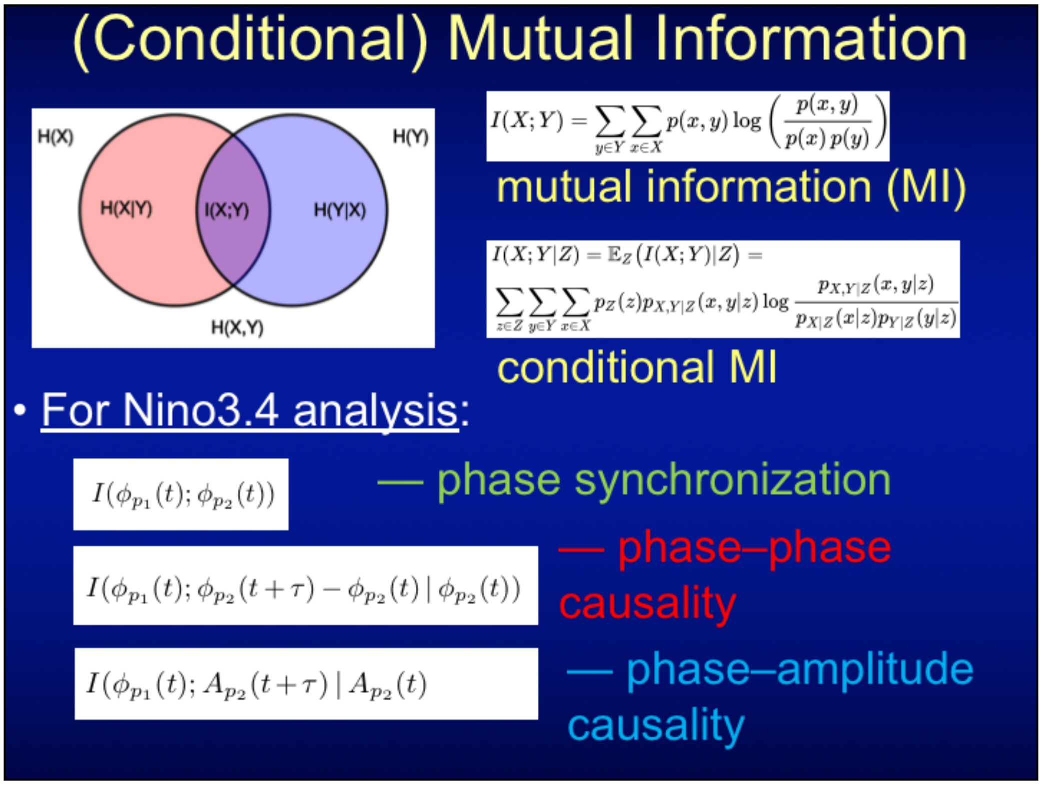
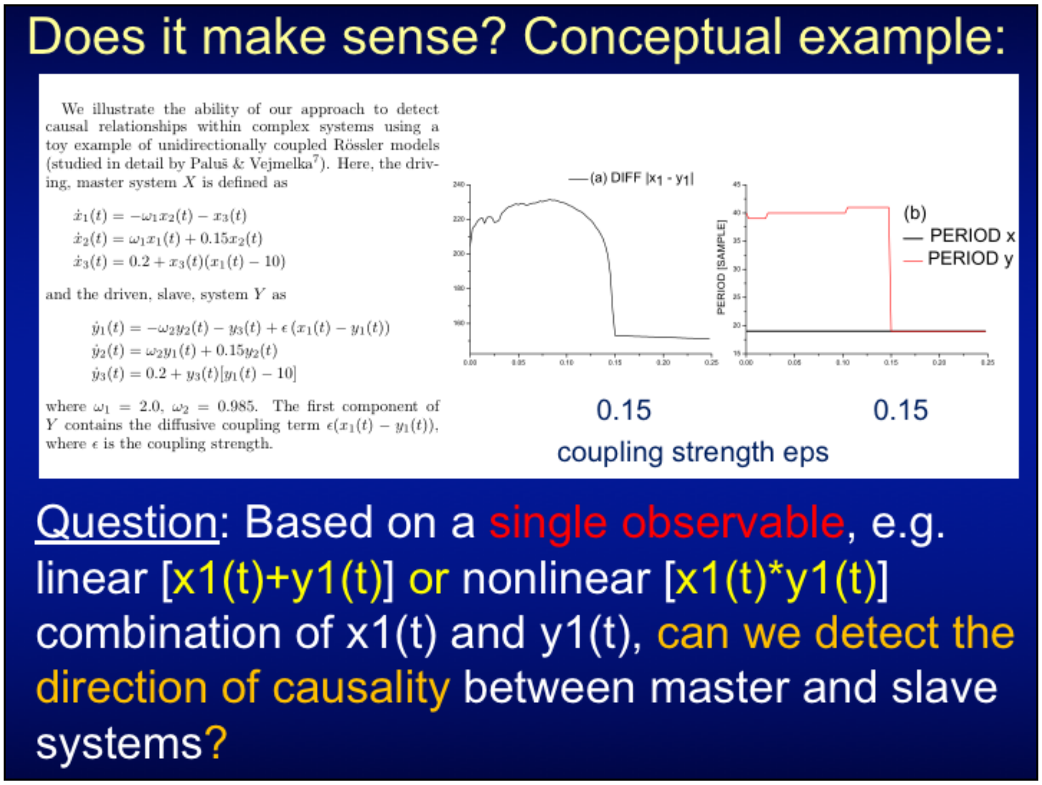
https://people.uwm.edu/kravtsov/



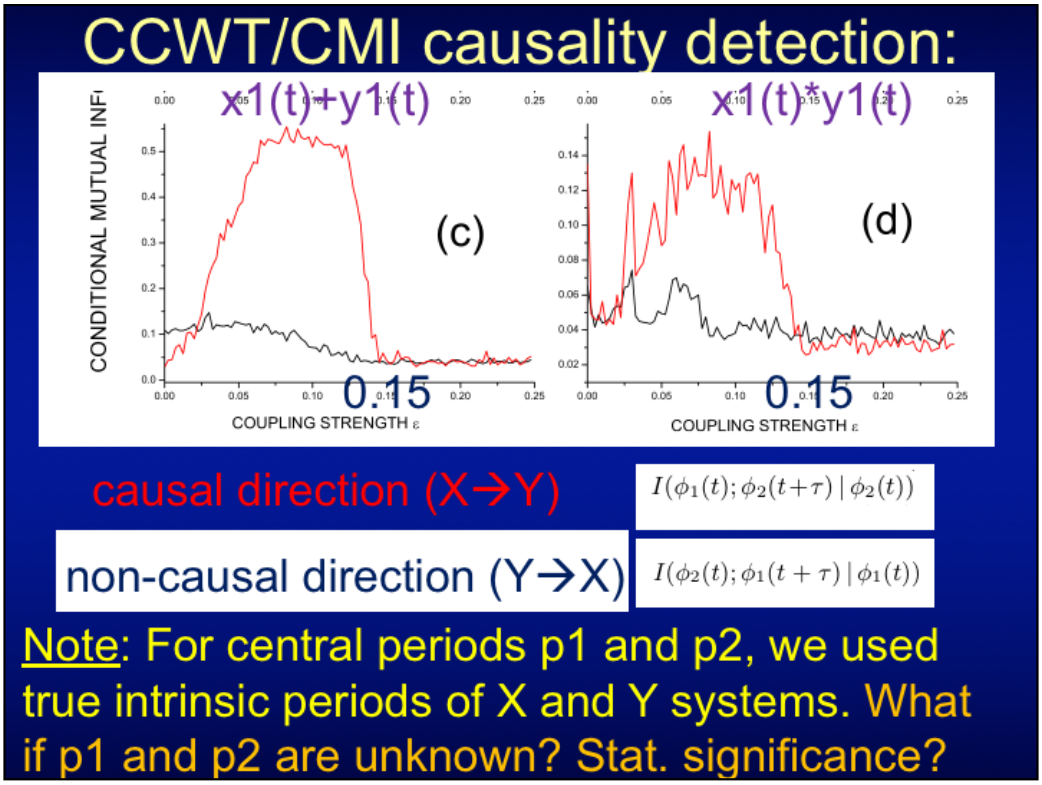
Minimal amount of input data to study a very complex phenomenon - just a single time series! It is amazing how much can be deduced via this methodology!



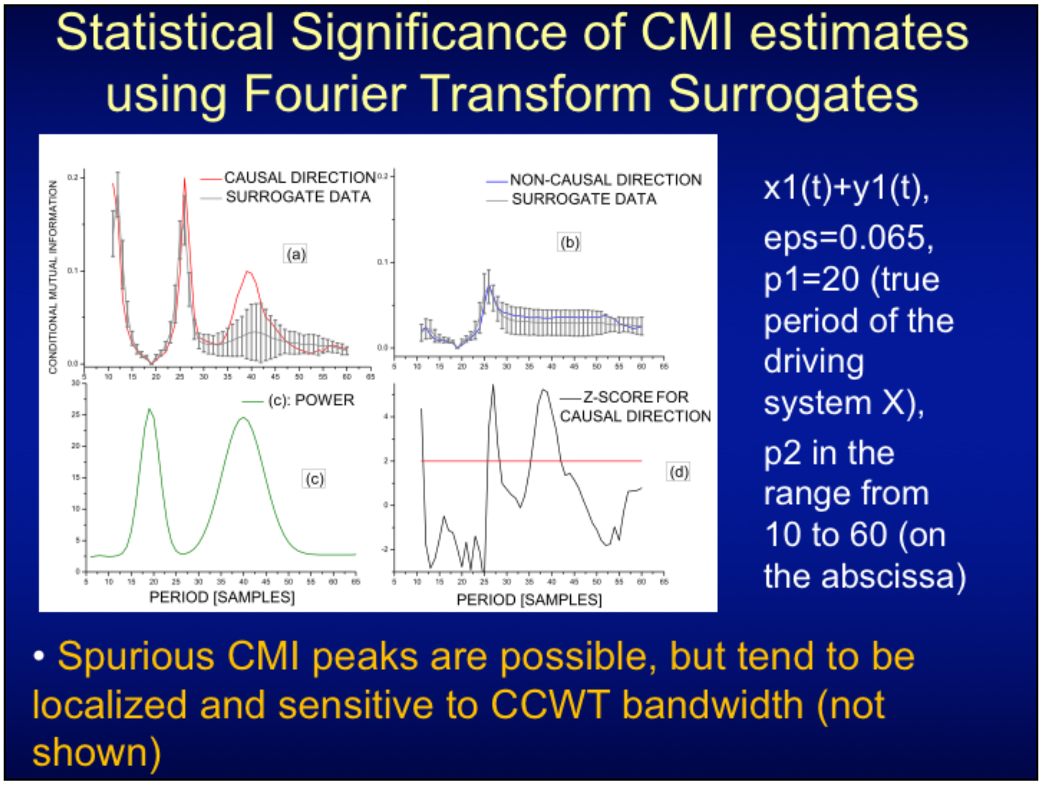
From Wikipedia. I(X;Y) measures a degree of similarity between the joint distribution of two random variables and the product of their marginal distributions. If these two are similar, variables are independent, if not – the uncertainty of one variable is reduced given the knowledge of the other. For phases, in extreme case, we can deduce the phase of one variable knowing the phase of the other – phase synchronization. Synchronization can be intermittent and still lead to large values of mutual information on average. For bi-variate Gaussian distribution, MI has a one-to-one relationship with linear correlation; MI, however, more general, and comprises both linear and non-linear dependencies. Conditional mutual information involving future values of one of the variables measures causality (directed information, flow of information). Analogy to Granger causality, but, once again, CMI is a more general measure of causality. All of these are comuted based on finite samples of data; need to bin and compute probabilities as frequencies of occurrence of events; advanced estimation methods have been developed.



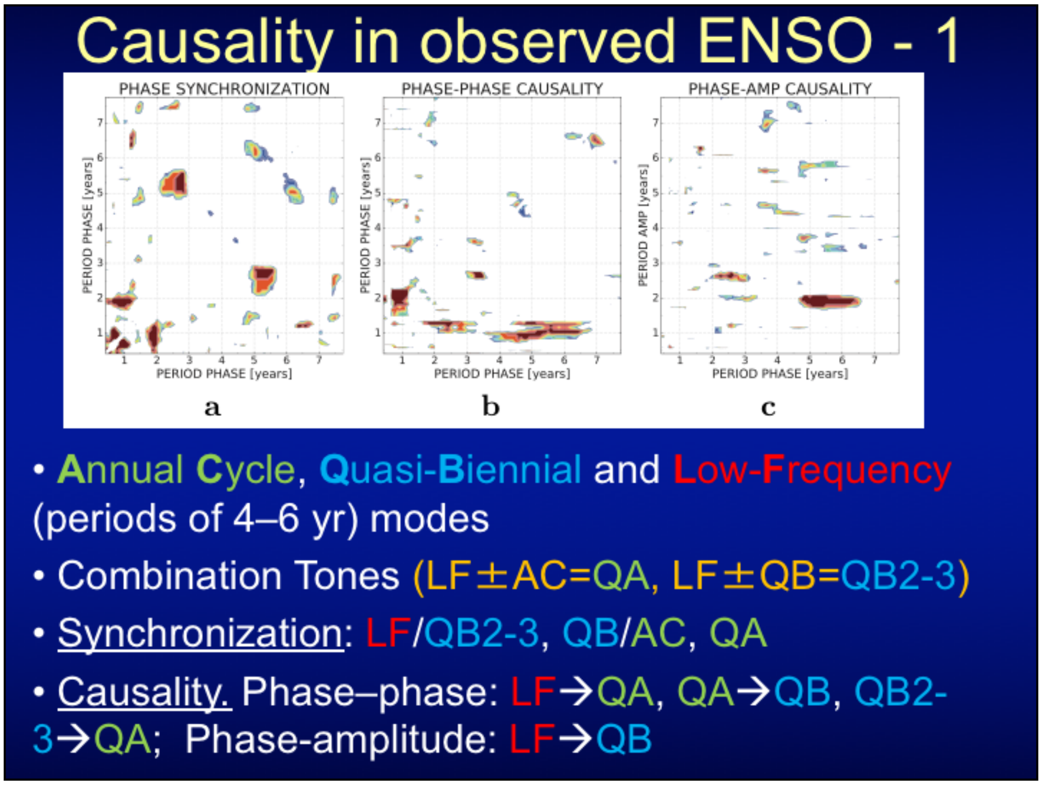
At large coupling strength the slaved system synchronizes with the master system and starts to oscillate with the period of the master system. Before this happens, can we deduce the causal direction by analyzing a single (linear or nonlinear) observable?



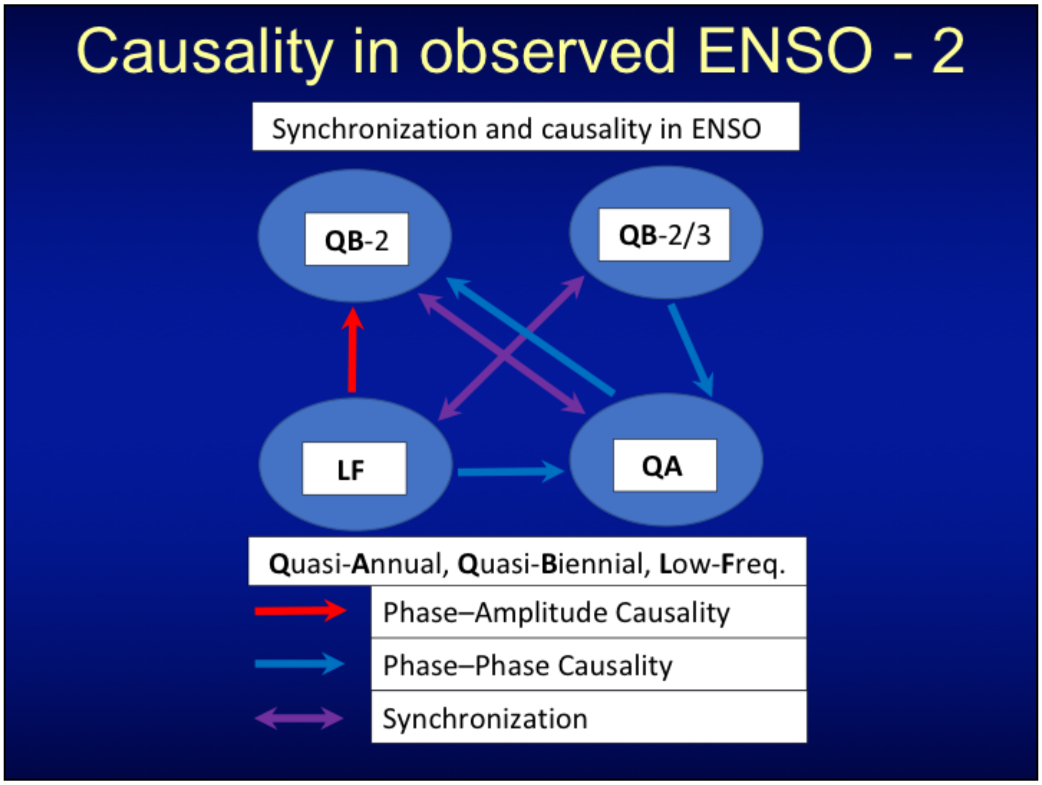
Yes we can! Be mindful of spurious peaks though. Note that causality cannot be estimated in the synchrionized regime (large coupling strength).



In the following, we will only show the values of mutual information that are statistically significant at the 5% level relative to FT surrogates (Fourier transform time series, randomize phases of sines and cosines, transform back to the physical space). Small-scale “noise” in the parameter space of the plots is likely to be associated with spurious peaks in MI or CMI.

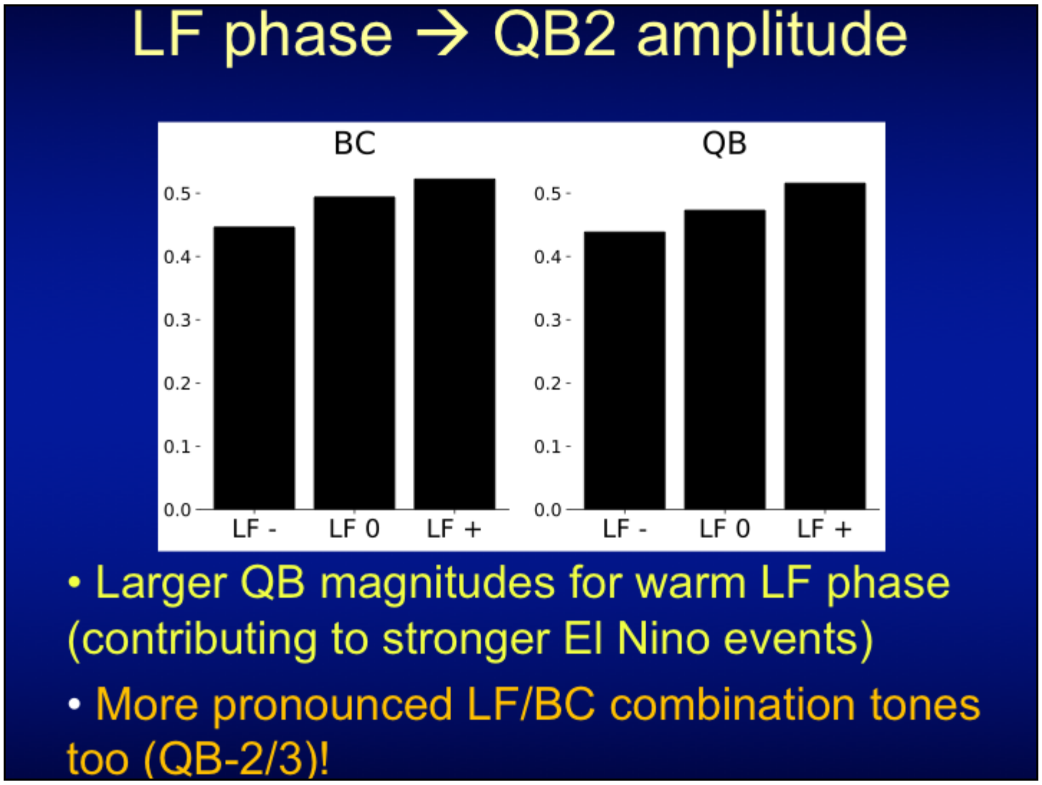


The analysis identifies processes at three distinct time scales important in ENSO dynamics (consistent with previous knowledge): QA, QB, LF. AC→QB synchronization (ENSO's biennial events tend to peak in winter). Combination tones between LF and AC/QB modes lead to QB2-3 and QA variability. QB2-3 is synchronized with LF, QA with AC. No direct causal connection between LF phase and QB phase, but indirect connections via annual cycle. The only pronounced phase-amplitude causal connection is between LF and QB. Schematic on the next slide summarizes these points.

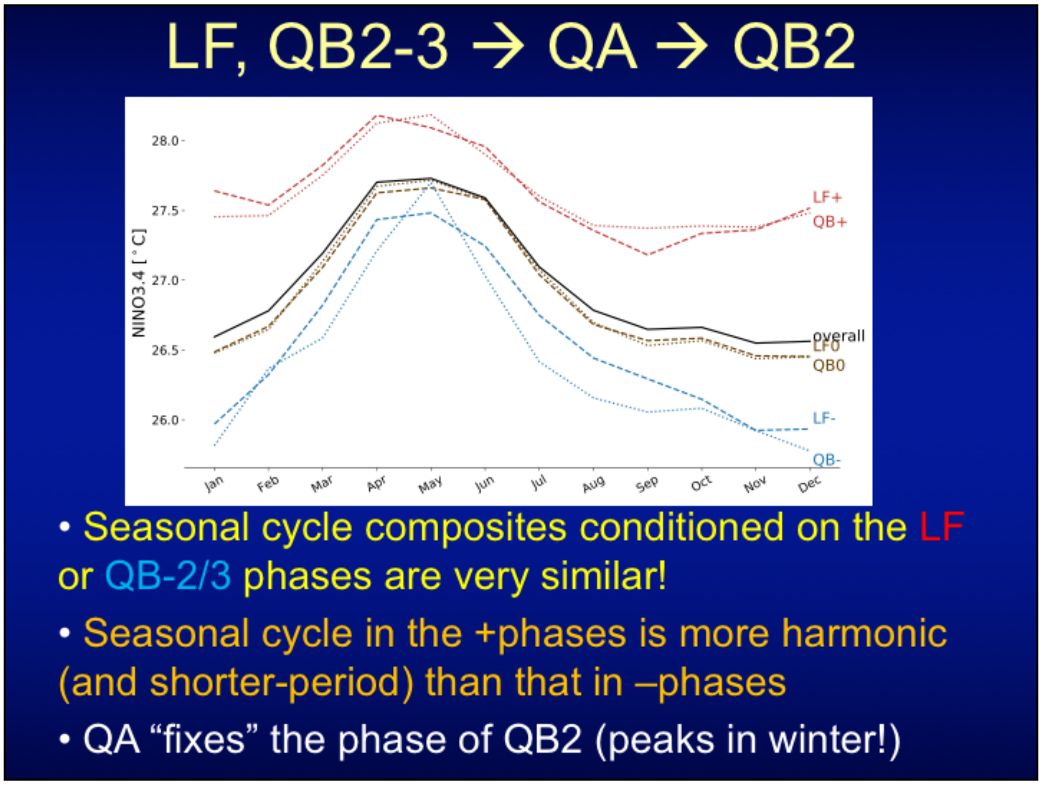


So, positive phase of LF, LF+ is associated with enhancement of biennial QB-2 variability and, through nonlinear interactions, enhancement of the biennial combination tones QB-2/3; the latter QB-2/3 variability is phase-synchronized with the LF variability, and both lead to changes in the shape of the annual cycle's main harmonic and combination tones (jointly QA variability), which fixes the phase of QB2 variability. Synchronization within a suite of different QB-2 modes leads to extreme ENSO events. This is the summary of causality in ENSO.

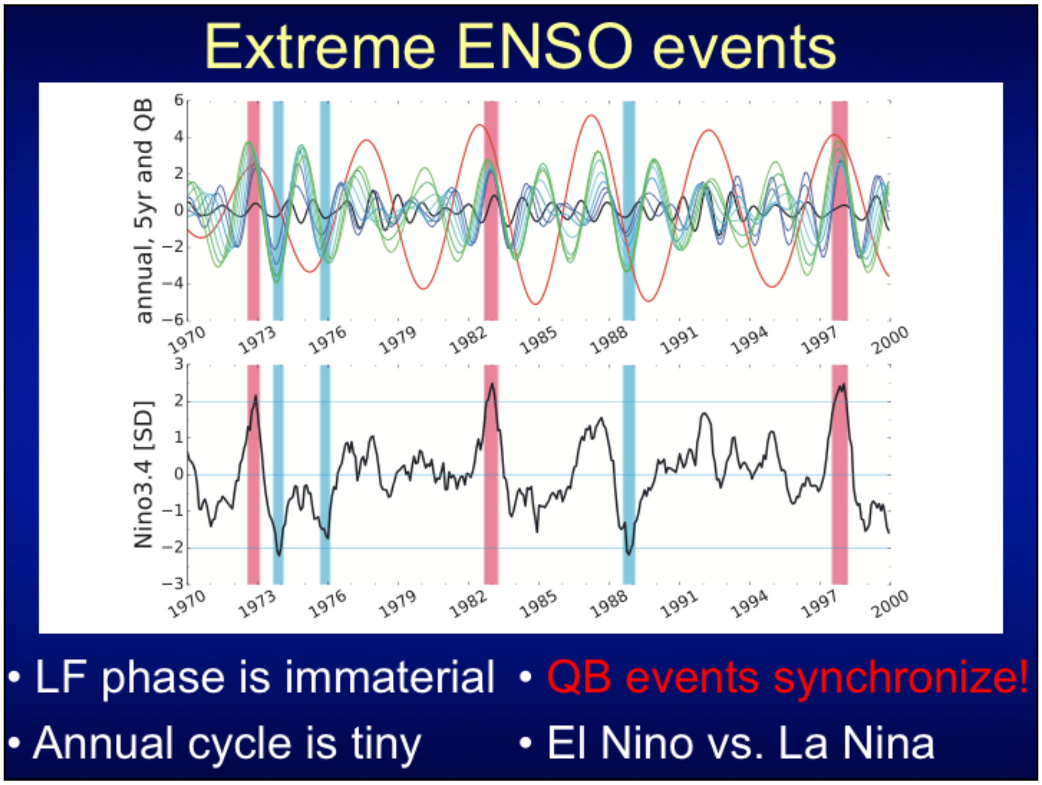
All of these points are illustrated, one by one, in the following three slides.



Go back and forth between this slide and slide 8 (ENSO causality schematic).



Go back and forth between this slide and slide 8 (ENSO causality schematic). The shape of the seasonal cycle depends on the phase of the LF and QB2-3 variability (the latter two tend to be synchronized). The amplitude of the seasonal cycle is small though (compared to that of extreme ENSO events), in all cases.



In particular, during all of the strong El Niño events of years 72/73, 82/83 and 97/98, the QA, QB and LF modes were characterized by synchronous pronounced maxima. Note, however, that strictly speaking, the synchronization with LF mode is not really necessary for an extreme ENSO event to materialize, since the ‘peak’ of this mode spans a good part of the year (for example, the peak of LF mode did not really occur in winter 1982/83, but the LF wintertime ‘background’ during that time was still abnormally warm), while the amplitude of the QA mode is, in general, small, so that this mode does not contribute much directly to the magnitude of a given event. Instead, what appears to be essential for an extreme ENSO to occur is the synchronization of multiple QB modes with each other. We believe that this ‘internal’ QB synchronization is what has been picked up by our conditional mutual information analysis in the form of LF→QA→QB phase connections and also LF phase→QB amplitude connections (since synchronization of phases of different QB modes should automatically result in a large-amplitude event.) By contrast, during a moderate El Niño of 87/88, the LF, QB and QA modes exhibited phase shifts, with lower-frequency modes leading the higher-frequency modes (in particular a suite of QB modes) instead of being ‘stacked’ on top of one another, thus limiting the magnitude of this event. Notably, strong La Niña events do not seem to be associated with the minimum of the LF mode, but instead occur during near-neutral LF conditions when the minima of the QA modes and the minima of the whole range of QB modes synchronize. Thus, in both El Niño and La Niña cases, the behaviour of the QB modes has a vital control on the magnitude of the ENSO events.

Summary and discussion

- Causality diagnosis of Nino3.4 time series points to a **dominant role of quasi-biennial variability in ENSO dynamics.**
- QB modes do not account for a large fraction of Nino3.4 variance on average, but **the spikes in QB variability can still lead to extreme ENSO events** when multiple QB modes synchronize.
- The **QB variability** during extreme ENSO events is clearly not due to alteration between week and strong annual cycle (Meehl 1987), which is weak in both cases. **What is it then?**
- The observed causal connections in ENSO are absent from the simulations of state-of-the-art climate models (CMIP5), as well as from conceptual models of ENSO interactions with seasonal cycle (e.g., PRO model). **Hence, the existing explanations of multi-scale ENSO dynamics are inconsistent with observations.**
- **Empirical LIM SST models mimic some of these dynamics**

Back-up slides: Wavelet spectra of Nino3.4, Summary figure of comparison with CMIP5 models, LIM figures.

References

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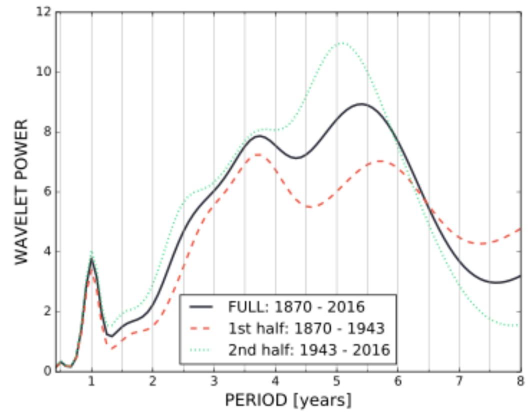
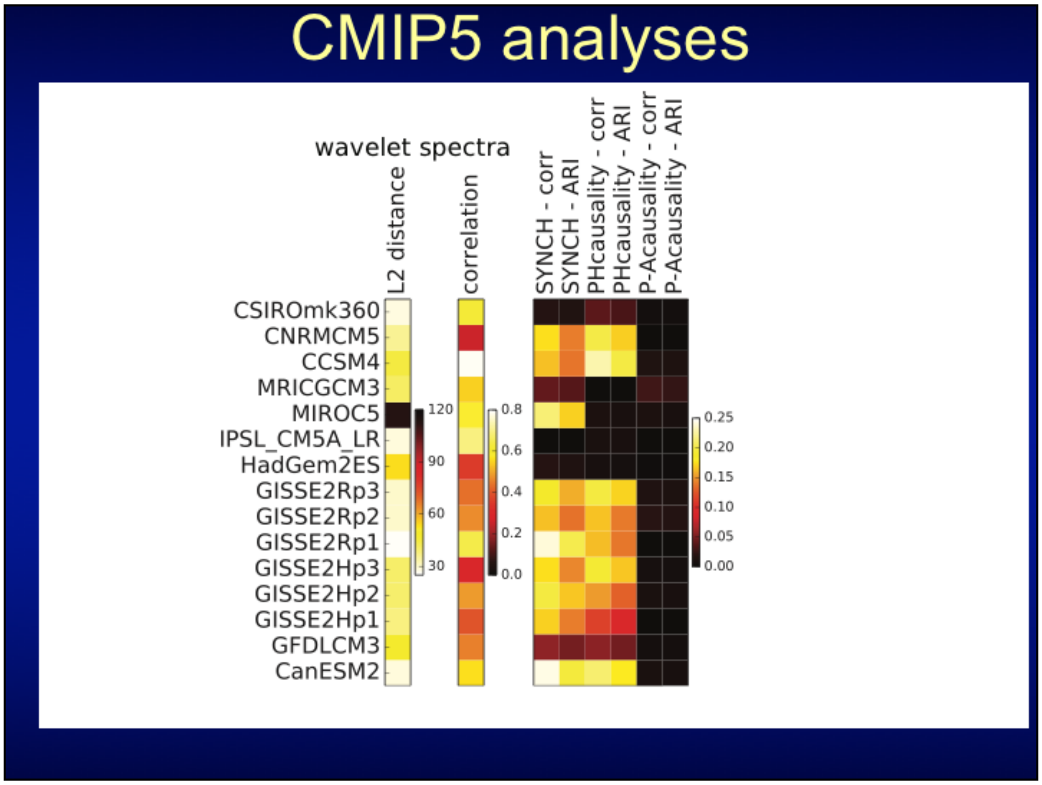
- Milan Paluˇs, "Cross-scale interactions and information transfer," Entropy 16, 5263–5289 (2014).
- Milan Paluˇs and Martin Vejmelka, "Directionality of coupling from bivariate time series: How to avoid false causalities and missed connections," Phys. Rev. E 75, 056211 (2007).
- Gerald A Meehl, "The annual cycle and interannual variability in the tropical Pacific and Indian Ocean regions," Mon. Weather Rev. 115, 27–50 (1987).
- Wikipedia: Mutual Information (https://en.wikipedia.org/wiki/Mutual_information)

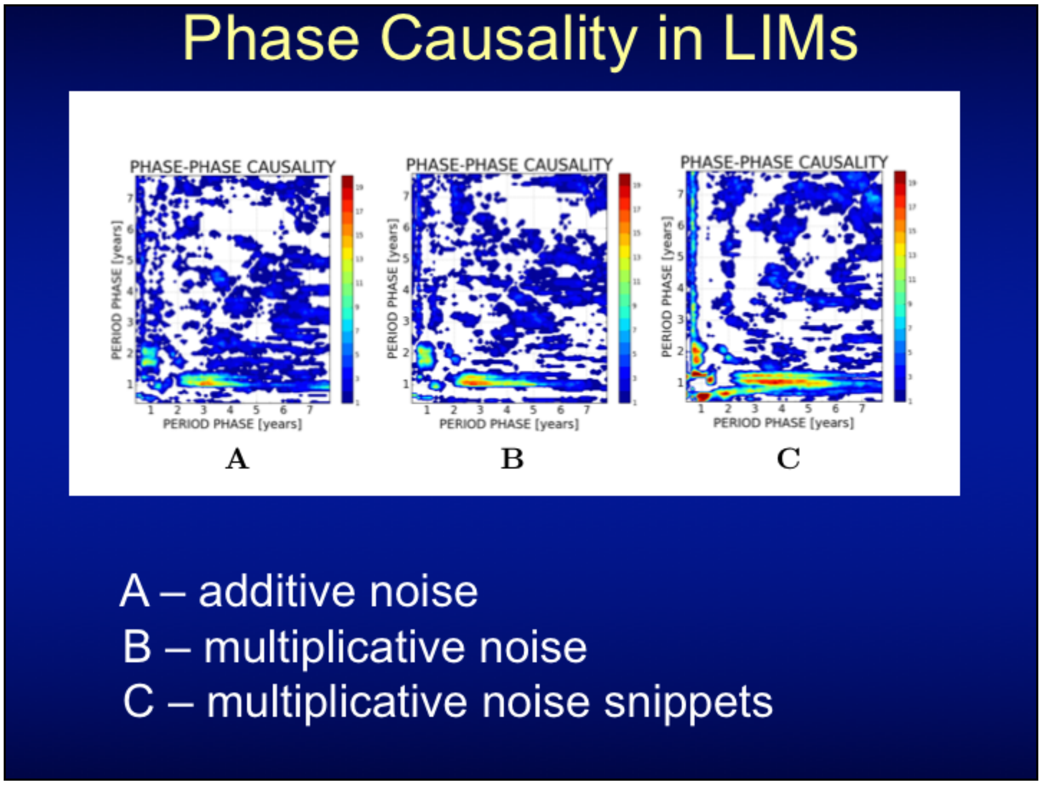
Back-up slides

Nino3.4 wavelet spectrum





The synchronization and causality comparisons are based on thresholded binary maps.



The Nino3.4 simulated in LIM models matches the observed causality much better than CMIP5 or conceptual models.