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Klimarealistene
Michelets vei 8 B
1366 Lysaker,
Norway

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Correspondence:

h_masson@hotmail.com

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From Correlations to Causalities between Climate Proxies at the Pacific Ocean-Atmosphere Interface

Henri A. Masson

Em. Professor, University of Antwerp, Belgium

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1. Introduction

The Climate system is an extremely complex one, and it is necessary to *understand its structure before analysing its dynamics and trying to make some projections of it*.

A *key component* of the Climate system is the *ocean-atmosphere interface*. The oceans cover 70 % of the Earth surface, and the Pacific Ocean is the largest among them. At its interface with the atmosphere, heat and mass transfer of water vapor and CO_2 take place. In its seat, complex phenomena like El Nino - La Nina oscillations, changes in thermohaline interface depth, conveyor belt and circum-polar circulations develop and spread. While in the atmosphere, above the ocean, Trade Winds, Walker Circulation, Hadley and Polar Cells move considerable masses of humid air, contributing, by this way, to changes in the local cloud coverage. Underwater and surface volcanism, and underwater hot vents, along the ring of fire and at the junction of tectonic plates, emit, intermittently and rather at unpredictable interval, enormous quantities of heat, water vapor, and smaller quantities of Sulphur dioxide and CO_2 in the ocean and /or to the atmosphere. Also, the incoming solar radiative energy changes itself over time in a cyclic way, and is modulated by the albedo of the cloud coverage. All those *factors* may be combined and represented as *nodes* (or "*concepts*") in a tentative complex *network;* in which these nodes are linked by tentative *causal edges (Fig. 1 overleaf)*.

2. Methods

This paper presents a new approach for studying the edges of such a comprehensive Climate system network; it is focused on the *causal interactions* that could exist among the nodes of the network, which are the proxies for potential significant natural triggers of the Climate.

Deliberately, in order to avoid the justification of more or less explicit hypotheses and approximations, we did not use any kind of theoretical model for analyzing the Climate system, but *focused exclusively on data and complex network analysis techniques*. For forecasting purposes, it is not needed to understand the exact mechanisms happening inside each "concept"; a black box approach for each of them is suitable, as, at this early stage of the analysis, the links between concepts are more important than knowing exactly what happens within each concept. The exact nature of the interactions between nodes along edges is mathematically defined by a transfer function. Defining the exact nature of such transfer functions is beyond the scope of this paper. At this stage of development, we will only consider that such a transfer function may not necessarily be linear, but will be monotonically continuous.

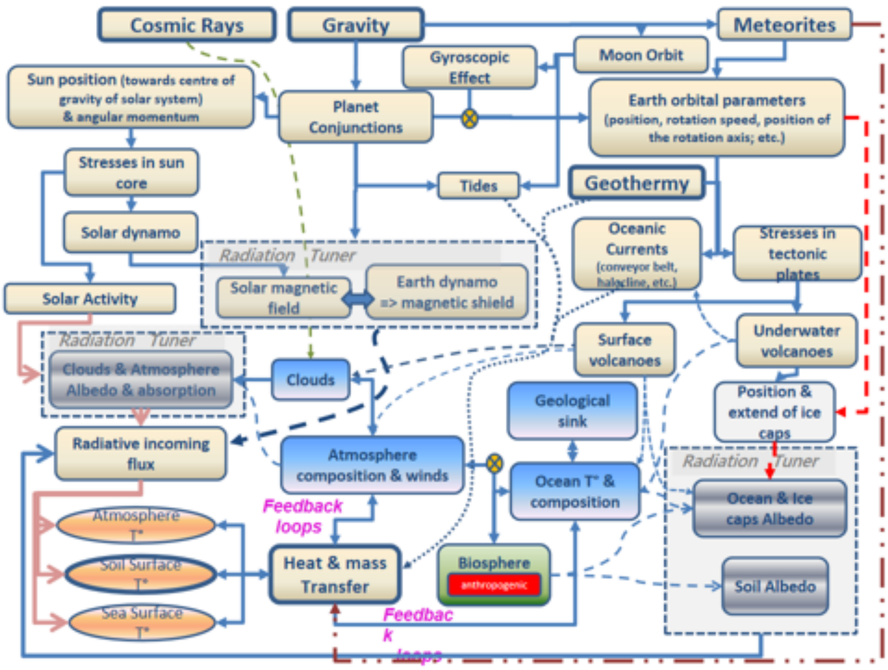

Figure 1. A tentative climate meta-model (presented as a causal network)

Causal analysis in complex systems is still a hot topic in data mining. Presently, there does not yet exist any satisfactory *sufficient* causal condition related to *complex systems with feedbacks*. We can only focus on a set of *necessary* conditions. We have developed an algorithm combining three methods:

1- A *Precedence analysis*, based on time shifts observed in the cross-correlation function between two concepts.

2- An mRMR (*minimum Redundance Maximum Relevance*) analysis combining *Spearman* correlations (not *Pearson* correlations which are strictly linear) and *Spearman partial* correlations (correlation between two variables when all the other variables have been maintained constant). A coherence analysis between correlations and corresponding minimum partial correlations is further made, and significance triggers are used to identify the most relevant correlations

3- A Granger causality analysis which is actually more a predictability than a causality analysis, but this is well suited to support causal inference and *forecasting* of time series. The results of the Granger analysis are used as a final filter for selecting not only the significant causal links existing in the network, but also the *direction* of the causal links, bidirectional causal links corresponding to the existence of some equilibrium between the linked concepts, or corresponding to the existence of one or many feedback loops.

The resulting *outcome matrix* is finally transformed into a *causal network* for better readability and communication purposes.

3. Data

We have applied this algorithm to climate related proxies acting on the Ocean-Atmosphere interface, with special focus on interactions happening around the Pacific Ocean.

For each proxy, the underlying validity conditions have been tested and the time series of the considered proxies have eventually been detrended, differentiated to make them stationary, or submitted to a lambda transform for respecting the isoscedasticity condition. The residuals have been compared to a normal distribution of zero mean value; they were also compared by autocorrelation analysis to an ergodic white noise.

Separate analyses have been made on

1- Annual detrended proxies, as usually done with climate data
2- Trends (defined as annual moving averages in this study) for analyzing interactions involving some integration of the proxies
3- The residuals, for finding eventual traces of remaining stochastic and chaotic components
4- Some blends of factors coming from the three previous components, and also mixtures of some of these components and derivatives of other ones have also been submitted to a causal analysis. The underlying idea being that some concepts could be linked by a differential equation, as for example the derivative of the temperature of a reservoir (such as an ocean) and an incoming flux (such as the solar intensity reaching the surface of the ocean)

4. Results

The results (See Fig. 2), show that some bidirectional causality exists

- between GAT (Global Atmospheric Temperature) and SST Global (Global Ocean's Sea Surface Temperature), corresponding to convective-conductive heat exchange equilibrium mechanism at the interface,
- between change in PTWS (Pacific Trade Winds Speed) and TAT (Tropical Air Temperature),
- and between Indian Tr SST (Indian Ocean's Tropical Sea Surface Temperature) and TAT (Tropical Air Temperature). This result is interpreted as a result of intense turbulence in the atmosphere and the ocean, at a location where the conveyor belt splits, encounters the circumpolar current, and where monsoon weather patterns and associated extreme winds and rainfall develop.

Four unidirectional causal links have also been identified

- From TAT (*Tropical Air Temperature*) to GAT (Global Air Temperature), a causal link demonstrating the importance of the Walker circulation and the Hadley cells for the redistribution of tropical air and heat over the Planet.
- From TAT (*Tropical Air Temperature*) to CO_2 concentrations in the South Pole Atmosphere; a mathematical proof for the causal effect of CO_2 absorption- desorption in the Ocean on atmospheric CO_2 concentration. This effect is a significant addition to natural and anthropogenic terrestrial CO_2 emissions.
- From East Pac SST (*East Pacific's Sea Surface Temperature*) to GAT (*Global Air Temperature*). This is a mathematical proof that the East Pacific Ocean heats up or cools down the global atmosphere and not symmetrically. This East Pacific Tropical Ocean is the place where the up-swelling or the down-swelling of the thermohaline layer initiates El Nino-La Nina cycles.
- From Atlantic Tr SST (*Tropical Atlantic Ocean Sea Surface Temperature*) to TAT (Tropical air temperature), a causal link that confirms the mechanism of the formation of hurricanes.

The residuals are not assimilable to a Gaussian distributed white noise. Cyclic but aperiodic (thus chaotic) traces of El Nino and La Nina, as well as the effect of major volcanic eruptions remain clearly identifiable in their autocorrelation functions.

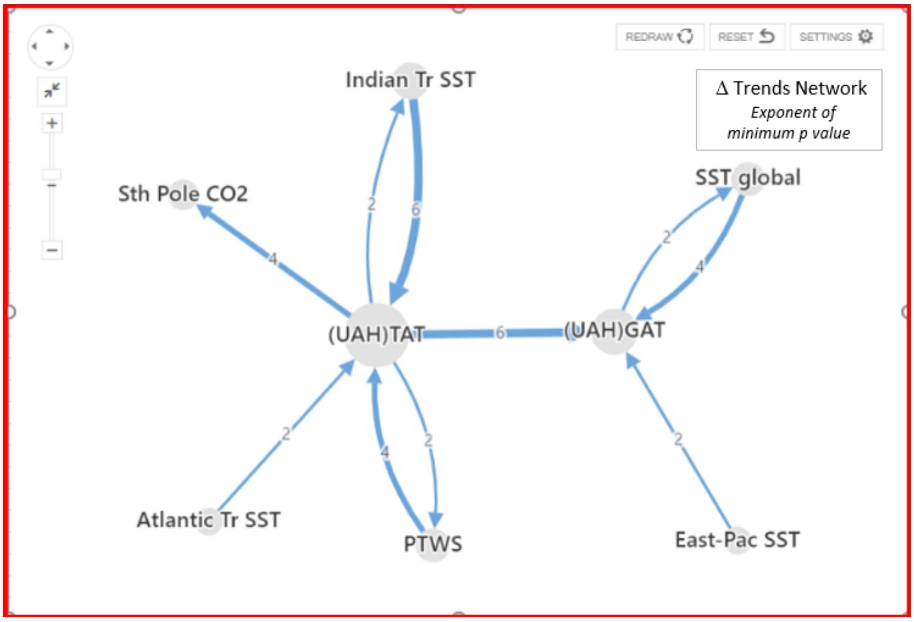

Figure 2. The resulting causal network

5. Conclusion and Recommendations

Obviously, the overall significance of the results obtained in this *explorative study* is somehow limited by the short length of some of the time series considered, as some of the data have been collected by satellites over a few decades only. However, this study demonstrates the use of some simple innovative method for making a causal analysis on a set of time series. This method can immediately be applied to longer time series, like paleoclimatic proxies for example, if wanted.

Guest-Editor: Stein Storlie Bergsmark