Script of

In Search of Simple Rules at the Heart of Climate's Complexity, By J.A. Rial

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Slides, 1,2,3 are self-explanatory

Slide 4

The earth's climate is driven by solar energy, but each part of the system responds in different ways both spatially and temporally.

Slide 5

The highly variable history of the climate is depicted in these two diagrams. In the top panel, the last 65 million years of stable oxygen isotope record shows that for the last 50My the earth surface temperature has decreased substantially. 50 million years ago the polar ocean was 12 degrees Celsius warmer than it is today and 20,000 years ago the temperature in Antarctica during the last ice age was 8 degrees Celsius lower than today. The lower panel shows the clear oscillatory character of the record, especially during the last 3 million years.

Slide 6

The oscillatory character of the records is in part created by astronomical, deterministic forcing and by the response of the climate to that forcing, which is usually nonlinear, chaotic, random or even linear and predictable. Shown are common features found in long-term time windows: a sawtooth shape of the time series and a bi-stable behavior between cold and warm stages. Intriguing is the fact that there is a certain fractal quality to the records as shown in the blow up of the ice core GRIP between 28,000 and 58,000 years ago.

Slide 7

A van der Pol oscillator can be used to represent the interaction between sea ice and ocean temperature. The nonlinear equations are solved by relaxation oscillations. The model was developed originally by Saltzman and has been used in many simplified climate models, including the ones reported here.

Slide 8

Two examples (independent realizations) of the forced noisy van der Pol oscillator produce close likenesses to the actual data. Note the important role the insolation forcing (summer at 65N) has in reproducing the main long period features of the data and the frequency modulation effect of the astronomical forcing on the prescribed (but otherwise arbitrarily chosen) 1400yr period of the oscillator.

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Slide 12

The advent of the great ice ages of the late Pleistocene is interpreted to be the result of synchronization of the long period response of the climate system to the eccentricity forcing. The modulator is obtained from the LR04 stack by using techniques of frequency demodulation. Synchronization occurs when the phase difference between the eccentricity and the modulator is small or zero. The modulator function represents the forcing as 'seen' from the climate system's reference frame. All calculations are performed using the complete 5-Myr record.

Slide 13

Theoretical low-frequency (period>300 kyr) and high-frequency (period>80 kyr) orbital eccentricity compared with the modulator (top). Their phase difference decreases monotonically (bottom) with time until phase locking occurs about 1.2–1.1 Myr ago. Mean value (solid) ± one standard deviation (dashed) are shown. In the insets it is shown that the Rayleigh R test and P values reject the null hypothesis of phase circular uniformity in the 1.2–0 Myr ago interval, so that the abrupt change in

$\Delta\Phi(t)$ at ~1.2 Myr ago is statistically significant.

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Slide 16

In the XVII century Huygens observed the synchronization of two pendulum clocks attached to a beam. The clocks could be set initially at any arbitrary phase but eventually, through the minute signals sent to each other through the beam their phases would synchronize in at least one of three modes.

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Slide 20

Inspired by the bold neuroscientists, we assume that the $\delta^{18}O$ time series of the two poles are generated by two synchronized oscillators. This results in relatively simple but often revealing climate models. Notice the consistency of phase relationships between South and North time series. aicc2012 age models are used. Other age models produce substantially identical results in the working time scale.

Slide 21

All North (top) and South (bottom) records used in the analyses. Three ice cores from the Arctic and four from the Antarctic produce 12 pairs of S-N combinations to study. Heinrich events approximate timings are shown.

Slide 22

(A) Phase difference between age-matched NGRIP (Greenland) and Antarctica's EDML $\delta^{18}O$ time series using the aicc2012 age model in both. (B) Methane-based Monte Carlo age model for series NGRIP and DomeC. (C) GRIP (Greenland) and Byrd (Antarctica) $\delta^{18}O$ methane-matched age model time series. Full-circle 2π jumps are likely caused by noise. These jumps usually occur in real, synchronized systems (Boccaletti et al 2002). The evolution of phase difference with the 2π jumps removed is shown in the bottom plots. Phase differences are calculated using the Empirical Mode Decomposition (EMD) described in Huang et al (1998) which allows decomposition of each series into Intrinsic Mode Functions (IMFs) (or mono-components). Gabor's method (Gabor 1946; Rial 2012; Rial et al. 2013) is then employed to obtain the phase difference on high-pass filtered records to attenuate periods longer than 10ky. A constant phase shift is a necessary condition for synchronization to occur between two coupled oscillators (Pikovski et al. 2001; Boccaletti et al. 2002; Izhikevich and Kuramoto 2006). Histograms show that the distribution of phase difference strongly peaks at π/2 (modulo 2π). Modified from Oh et al. (2014).

Slide 23

(Top) South-to-North temperature difference from methane-matched, reconstructed time series GRIP and DomeC compared to the timing of Heinrich events (vertical colored bars). H0-H6 times are from Hemming 2004, Bond and Lotti 1995 and Rashid et al 2003. The timing of Heinrich events and even the timing of minor IRDs (labeled d-k) coincide with times at which the south pole-to-north pole temperature difference is the greatest. Age models are based on methane-matched records from which selected IMFs (Intrinsic Mode Functions) 2d to 8th were extracted, which filters off long period insolation (Milankovitch) forcing as well as high frequency noise (Huang et al. 1998). The S-N temperature difference function B-A has been rectified by adding to it its absolute value so that the N-S temperature differences do not show. (Bottom) The panel shows S-N average temperature differences for all 12 combinations of polar time series pairs with methane- and Monte Carlo-matched age models (three in Greenland, four in Antarctica), rectified as above and squared to lower the noise and enhance the larger amplitudes. Matched age models produce clear spikes at the HEs and IRDs times while age-unmatched (original) records fail to do so (not shown) in almost all instances. The time series are reconstructed using the sum of the 2d to 6th Intrinsic Mode Functions. This choice of IMFs produces smother records than those in the top panel.

The polar π/2 phase shift is climatically important because it makes the coldest times of the Greenland temperature coincide with the peak warming events of Antarctica (within age uncertainty), which causes the S-N temperature difference between poles to reach maxima of +10ºC to +15ºC during these times. More importantly, these maxima are coeval (within age uncertainty) with the Heinrich events as described and timed by Hemming (2004) and the quasi-periodic ~1.5ky smaller pulses of IRDs described and timed by Bond and Lotti (1995).

Slide 24

Estimates of the rate of energy arrival are obtained by squaring and adding the amplitudes of north and south $\delta^{18}O$ records (age models are matched using the methods described above). The sum of the squares is proportional to the instantaneous rate of arrival of the total energy (power). The timing of the energy peaks coincides (within estimated timing error) with all Heinrich events. From top to bottom the records used are: All southern records added, averaged and squared plus all northern records added, averaged and squared, Byrd squared plus GRIP squared, DomeC squared plus NGRIP squared, and Vostok squared plus Gisp2 squared. For any Greenland record g(t) and any Antarctic record a(t), the sum $|s(t)|^2 = a(t)^2 + g(t)^2$ appears as localized bursts. Squaring $\delta^{18}O$ amplitude measurements results in amplitude errors approximately double the original (in percent, for small error), but most original measurement errors are not reported or deemed too small to be discerned in time series plots. Errors in timing are not affected by the squaring of amplitudes and should be the same as the original age-matched data.

The estimate power results in episodic, pulse-like bursts of energy that occur at the times of the stronger Heinrich events (including the yet to be found H7 and H8) and at nearly no other time. The results require the contribution of both polar time series and thus are supportive of the assertion that the occurrence of HEs is tied to the climate of both Polar Regions and not to processes occurring only in the Northern Hemisphere. The relationships among peaks are essentially unchanged no matter what age model (methane-matched, methane-MonteCarlo, aicc2012) is used. Though absolute ages of HEs and IRDs may change slightly with age model their relative ages and phases do not significantly change.

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The polar temperature gradient (a), obtained by subtracting averaged polar records (aicc2012 age model) closely resembles the organic carbon record (b) offshore northern Brazil in the equatorial Atlantic. The Fe/Ca ratio (c) from the same core as (b) contains clear spikes coeval with the HE events H0-H6. Age model differences (core GeoB3912-1 uses C14-based age model) accounts for loss of correlation from 67ky to 85ky.

In order to quantify the apparent similarity between time series (a) and (b) and determine any lag/lead relationship it is necessary to carefully account for the difference in age models. The GeoB3912-1 core uses C^{14} ages at discrete points for the first 45ky with an overall sampling error of ±100years (Jennerjahn et al., 2004).

Assuming the aicc2012 model for the polar gradient is accurate we calculated lag correlations between the two time series directly and through a Monte Carlo approach that conservatively randomizes each sample in the organic carbon record to vary within ±200year, without overlapping. The result is that the organic carbon record lags the polar gradient record at all frequencies, with lags ranging from 300 to 680 years. This suggests that the organic carbon spikes (b) follow or are driven by the polar gradient spikes (a). The frequency dependence of the lags can be easily transformed into a dispersion curve, using 10000km (1/4 of the earth's circumference) as the spatial distance between the two time series. In consequence, the results strongly suggest that each peak in organic carbon is a record of a half-hemisphere-delayed passage of a wave-like climate disturbance through the equator carrying the S-N temperature maxima. And each of these occurs within timing error of the Heinrich events H0-H6.

Slide 27

Lagged correlation coefficients as a function of lag between the time series (a) the pole-to-pole temperature difference and (b) the organic carbon record from the Brazilian tropical Atlantic. The organic carbon record lags the temperature difference by 300 to 680 years. From this graph a group velocity curve is obtained. The signals on the lower right show an example of close correlation for filtered and lagged signals.

Slide 28

Account of the age uncertainty on the determination of lags at maximum correlation is done using Monte Carlo methods that generate 1000 runs with randomly perturbed data points and ±100 years of data uncertainty. The velocity is obtained by dividing the distance from pole to equator by the lag for each frequency.

The 'dispersion relation' shown is consistent with trains of dispersive water waves or thermal waves travelling at group velocities ranging from 33km/year to 17km/year from Antarctica to the equator and further north. Consistently, the group velocity of 33km/year for the fastest wave is nearly the same as that of the thermo-haline circulation (THC) speed of 10^{-3} m/s in the central Atlantic (Marshall and Plumb 2008). With these velocities the waves will propagate twice across the Atlantic basin (time to couple both poles) in 1.2ky to 2.3ky, which are close to Bond's estimates (1.5±0.5ky) for the recurrence of IRDs.

On physical grounds a wave propagation system is supported by the data, as follows. Since plankton population essentially regulates itself (Sigman and Hain 2012) population and primary production surges as revealed by the GeoB3912-1 spikes in organic carbon requires rapid, anomalous addition of nutrients over short periods of time (e.g., hundreds of years). This could be accomplished by upwelling, in which nutrients are carried up from the deeper layers of the ocean to the euphotic zone. Upwelling occurs primarily due to wind. Wind also carries nutrients from land sources in Aeolian iron fluxes. Rain, erosion, and fluvial sources similarly transport nutrients very effectively. This becomes evident in the Fe/Ca ratio (Slide 26, c) from the same core, which contains clear spikes of terrigenous detritus coeval with the Heinrich events H0-H6. These contributions of organic carbon together with strong Fe/Ca ratios suggest intense periods of upwelling, precipitation and erosion. These are consistent with episodic, vigorous hydrological cycles, characterized by frequent powerful storms, driven by temperature gradient anomalies that propagate across the Atlantic in a wave-like manner.

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Slide 31

Simulation (center and right columns) of the pair of polar ice core $d^{18}O$ records from NGRIP (Greenland) and Vostok (Antarctica) in the 5ky-20ky time interval (left column). The simulations are solutions to stochastic differential equations representing the two polar climates as van der Pol oscillators (Rial 2012). U_2 is the simulated temperature variation induced by changes in the sea ice extent in the north Atlantic and U_3 is the simulated ocean temperature in the southern hemisphere. The simulations are close to the actual records provided there is polar synchronization in the model. The right column shows that the two synthetic signals are a Hilbert transform pair, as shown by the color lines overlaid on the synthetics. Insolation (Milankovitch) frequencies have been filtered out. The close fit to the data disappears if there is no synchronization (Rial 2012). The prototypical example of abrupt climate change (Broecker 2010; Alley et al. 2003) the Bølling-Allerød and Younger Dryas events (BA and YD) are not an exclusively Northern Hemisphere phenomenon to be explained with NH physics but it occurs in synchrony with Antarctic climate variability. If synchronization is indeed at work, the system formed by the polar climates and the Atlantic basin is a self-sustained self-oscillating oscillator (Jenkins 2013) whose synchronized oscillations started probably a million years ago, when the great ice ages of the late Pleistocene began and the climate system's longer period natural oscillations synchronized with the astronomical forcing for the first time (Rial et al 2013). YD:Younger Dryas; BA: Bølling-Allerød; ACR: Antarctic cold reversal. Modified from Rial (2012).

Slide 32

Monte Carlo simulations of the same data interval as in the previous slide but incorporating the insolation forcing effect. The averages of ten MC runs (thick black curves) are shown along with one standard deviation (light blue dotted lines). The optimal values for the natural frequencies of the polar oscillators is deduced from a MC average of 500 realizations. For comparison the actual data (red dotted lines) are plotted with the simulations.

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Slide 35

(A) Correlation coefficients of sea surface temperature anomaly (SSTA) time series over the last ~100 years on a 2º x 2º grid results in the detection of sixteen dipole systems oscillating in synchrony, π radians out of phase (dipole, correlation ~ -1) in the geographic regions shown. Each dipole pair is marked with a white star. A dipole mode index (DMI) is calculated from the first principal components (PC-1) of a small neighborhood consisting of the nine closest neighbors time series. The correlation coefficient between the DMIs at each dipole center and the time series in the entire grid are then computed and displayed in the maps (scale on right of figure). The maximum correlation coefficient is given for each map (multiplied by -1). **(B)** Locations of the dipole centers and twelve detected synchronized centers with π/2 phase lock (red diamonds), just like the two poles. Understanding their origin and extent will be an important part of the proposed effort.

Slide 36

Dipoles in the South Pacific are synchronized to precipitation data from Australia and South America. Are teleconnections another name for what is really synchronization?

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