Stochastic Resonance in Glacial Climate

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It seems like magic. In an attempt to make it audible, you feed a faint signal, a wave of a particular frequency, through an amplifier - a strange black box which you bought at a junk yard, because your proposal to buy a proper one was turned down once again. Of course you hear nothing. The darn thing doesn't seem to work. Out of sheer destructive frustration you add some random noise to your signal, and voila: suddenly you hear it. The noise, rather than blurring your signal, makes it come through loud and clear. Take the noise away and the signal vanishes again.

This phenomenon is called ‘stochastic resonance’, and the climate system may behave just like that black box from the junk yard. Though counter-intuitive, stochastic resonance is actually quite simple. All it takes is an amplifier that does nothing with signals that are below a certain threshold, but strongly amplifies signals above it. Feed in a sub-threshold signal and nothing happens. But add noise, and the input strength (signal plus noise) can be lifted above the threshold value. The output then is noisy, but the signal also comes through. Too much noise drowns out the signal, too little noise and the signal doesn't make it through the amplifier at all, so there is an optimal amount of noise to produce the best results. This is why it is called stochastic resonance: the system resonates at a particular noise level. Your experiment thus tells you one thing about that black box: it must be quite a non-linear amplifier with some kind of critical threshold. Not as nice as that linear amplifier you wanted to buy, but still better than nothing.

The theory of stochastic resonance was first developed in an attempt to explain ice-age cycles [*Benzi et al.*, 1982], although subsequent data have not strengthened this early hypothesis. But biological evolution seems to have discovered stochastic resonance long before modern scientists did. Crayfish sensory cells detect weak pressure variations caused by the approach of predatory fish with the aid of environmental noise and noise between nerve cells themselves [*Douglass and et al.*, 1993]. On the predatory side, the ability of paddle fish to detect planktonic prey through their weak neurological electrical emissions is enhanced by appropriate levels of electrical noise, which in nature may arise from large aggregations of the prey [*Russell, Wilkens and Moss*, 1999]. Humans are better at detecting a weak periodic touch to their fingers when an appropriate level of random touching noise is added, opening the possibility of aiding those with impaired tactile sense [*Collins, Imhoff and Grigg*, 1996].

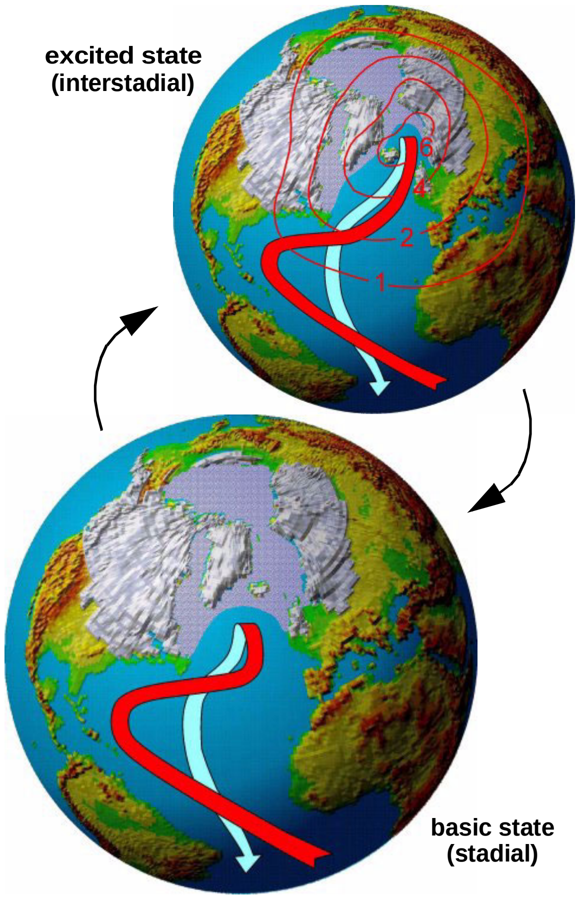

FIG. 1. Schematic of the two glacial climate states, from [*Ganopolski and Rahmstorf*, 2002]. Bottom: the stable ‘cold’ or ‘stadial’ mode. Top: the metastable ‘warm’ or ‘interstadial’ mode. Contours show the surface air temperature difference relative to the stable state. Ocean circulation is shown schematically, surface currents in red and deep currents in light blue. Ice sheets shown are prescribed from [*Peltier*, 1994].

Surprisingly, while the field has grown in such diverse ways (see [*Gammaitoni et al.*, 1998] for a review), from quantum oscillators with tunneling noise to communications systems, applications in the climate sciences have been much slower to develop. Recently, however, modeling results and data suggest that stochastic resonance did exist in the glacial climate system (see Fig. 1), although in the millennial spacing of abrupt climate changes rather than the slower cycles of ice ages.

Abrupt Climate Flips

Large, abrupt and widespread climate changes punctuated the most recent ice age, and probably earlier ice ages

(Fig. 2). Some of these climate changes, such as the Younger Dryas cold interval and the cold event about 8200 years ago, immediately followed spectacular floods of ice-dammed lakes into the North Atlantic ocean, which could have shut down the heat transport of the Atlantic ‘conveyor-belt’ circulation. Yet the dozens of abrupt climate changes that occurred throughout the last ice age are difficult to explain with outburst floods. Sudden warmings from ice-age conditions were especially prominent (Dansgaard-Oeschger or D/O events). Furthermore, time-series analyses find a periodicity of about 1500 years (e.g., [*Grootes and Stuiver*, 1997]). If random variations in freshwater fluxes or other factors combined with some weak periodicity in the climate system, then stochastic resonance may provide an explanation for this puzzling behavior.

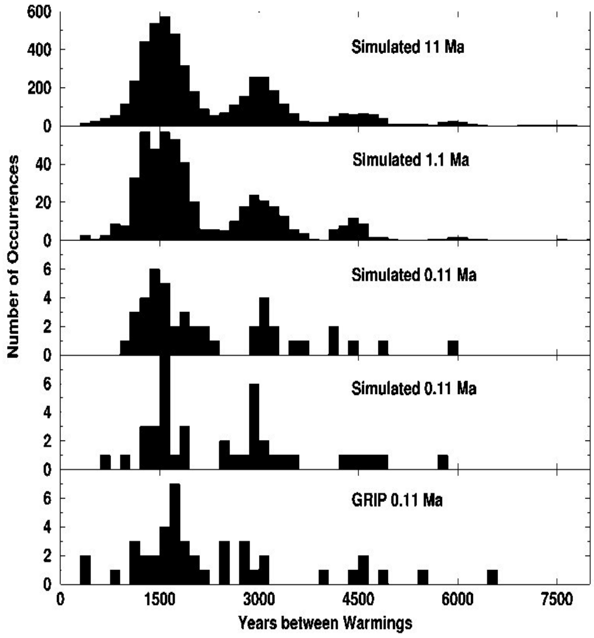

FIG. 3. Interspike interval distribution (or waiting time between warm events) for a simulated stochastic resonance process, for different lengths of the time series (1Ma = 1 million years). The bottom panel is from the 110,000 year-long Greenland ice core record. From [*Alley, Anandakrishnan and Jung*, 2001].

A simple test for stochastic resonance is to look at the waiting times between events. As shown in Fig. 3, a stochastically resonant system most frequently produces events separated in time by one period of the forcing. Transitions also are commonly observed spaced two, three, and more periods apart, with the number of occurrences decreasing exponentially with increasing waiting time and with few occurrences between. As shown in Fig. 3, one needs a rather long time-series to demonstrate this pattern clearly. The bottom panel, derived from the GRIP ice-core isotopic record, shows that the available data are fully consistent with stochastic resonance [*Alley, Anandakrishnan and Jung*, 2001]. A variety of other ocean and ice data sets yield similar results [*Alley et al.*, 2001].

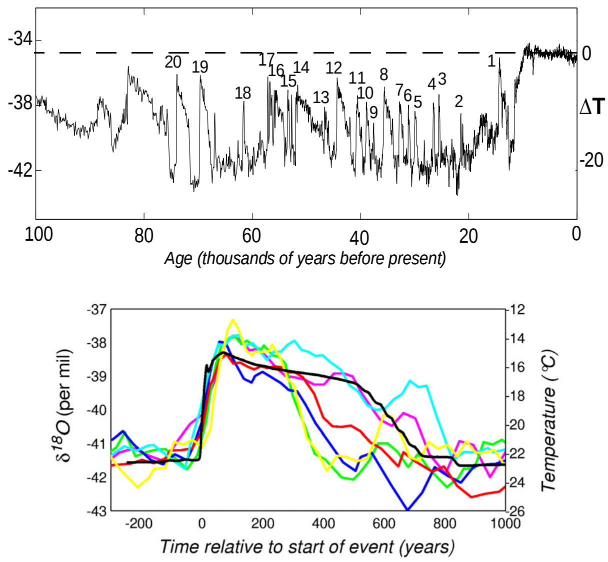

FIG. 2: Record of $\delta^{18}O$ (per mil, scale on left) from the GRIP ice core, a proxy for atmospheric temperature over Greenland (approximate temperature range, in °C relative to Holocene average, is given on the right). Note the relatively stable Holocene climate in Greenland during the past 10 kyr, and before that the much colder glacial climate punctuated by Dansgaard-Oeschger (D/O) warm events (numbered). The lower panel shows a close-up of several of the more recent events superimposed (coloured lines). The black line shows a model-simulated D/O event [*Ganopolski and Rahmstorf*, 2001].

In order to get stochastic resonance, we need the following three ingredients: a feeble periodic signal, noise, and a threshold-type amplifier. The origin of the periodic signal should ultimately be revealed by further paleoclimatic data. A possible cause could be a weak periodic variation in the output of the sun. Noise, on the other hand, is ubiquitous in the climate system due to the variability of weather and other processes. But what could the non-linear amplifier be?

Shifty Currents

A number of clues point to the Atlantic ocean circulation. Since the seminal work of Stommel [*Stommel*, 1961], we believe that the thermohaline (i.e., temperature- and salinity-driven) circulation is a highly non-linear system. Stommel's simple model showed two possible stable climatic states, with or without deep water forming in the north. The Atlantic would thus be a bistable system, like a ball in a double-well potential. Recently, Vélez-Belchí et al. [*Vélez-Belchí et al.*, 2001] demonstrated that oscillations from one to the other state in this model could occur as a result of stochastic resonance. The forcing required to push the Atlantic circulation between North Atlantic Deep

Water (NADW) formation 'on' and 'off' states is however rather large, so that it is debatable whether ordinary climatic noise could do the trick, or whether this does require large episodic forcing events like the meltwater floods mentioned above.

A more subtle mechanism for D/O events was recently proposed by Ganopolski and Rahmstorf [*Ganopolski and Rahmstorf*, 2001]. Rather than switching NADW formation 'on' and 'off', this mechanism involves geographical shifts in the location of NADW formation; these can be triggered much more easily. Based on experiments with a coupled climate model of intermediate complexity, the authors argue that the stability of the Atlantic currents was fundamentally different in cold and warm climates, and that this accounts for the climatic roller-coaster ride of the glacial climate as compared to the (at least in Greenland) warm stable Holocene. Present-day climate is bistable in their model, but glacial climate is not: it has one stable and an unstable state as pictured in Fig. 1. Physicists call this an *excitable system*; by perturbing the system, you can excite it to go to the unstable state for a while. Such a system is prone to stochastic resonance.

Indeed, when this climate model is driven by random noise of realistic amplitude, combined with a very weak climate cycle of 1,500 years, Dansgaard-Oeschger events result which are very similar to those recorded in the Greenland ice and other paleo-climatic archives (Fig. 2). What is more, the histogram of recurrence times resembles that shown in Fig. 3 [*Ganopolski and Rahmstorf*, 2002]. This shows how the Atlantic ocean currents can act like a threshold amplifier, turning a feeble signal into dramatic climate swings.

Earlier proposed mechanisms for D/O events have also invoked variations in the thermohaline circulation (e.g., [*Sakai and Peltier*, 1995]), but in the form of self-sustained oscillations in its strength, rather than shifts between different deep water formation sites triggered by stochastic resonance. Oscillating solutions can be found in ocean models in some parts of parameter space. Paleoclimatic data thus provide a benchmark for distinguishing between fundamentally different physical mechanisms: while state transitions through stochastic resonance show secondary maxima at multiples of the main frequency as shown in Fig. 3, internal oscillations do not share this characteristic.

We remain many data sets and simulations away from confident characterization of a stochastically resonant climate. But for the first time, data analysis has shown strong hints and model simulations have provided a possible quantitative mechanism for stochastic resonance causing some of the most abrupt climate shifts known. Identifying the source of the weak periodicity, and learning whether natural or human-caused noise might affect the system in the future, remain interesting challenges. In the meantime, after straying from ice-age cycles into widely diverse fields from biology to physics, stochastic resonance appears to be coming home to climate.

References

Alley, R.B., S. Anandakrishnan, and P. Jung, Stochastic resonance in the North Atlantic, *Paleoceanography*, *16*, 190-198, 2001.

Alley, R.B., S. Anandakrishnan, P. Jung, and A. Clough, Stochastic resonance in the North Atlantic: Further insights, in *The Oceans and Rapid Climate Change: Past, Present and Future*, edited by D. Seidov, M. Maslin, and B.J. Haupt, pp. 57-68, AGU, Washington, 2001.

Benzi, R., G. Parisi, A. Sutera, and A. Vulpiani, Stochastic resonance in climatic change, *Tellus*, *34*, 10-16, 1982.

Collins, J.J., T.T. Imhoff, and P. Grigg, Noise-enhanced tactile sensation, *Nature*, *383*, 770, 1996.

Douglass, J.K., and et al., Noise enhancement of information-transfer in crayfish mechanoreceptors by stochastic resonance, *Nature*, *365*, 337-340, 1993.

Gammaitoni, L., P. Hanggi, P. Jung, and F. Marchesoni, Stochastic resonance, *Reviews of Modern Physics*, *70*, 223-287, 1998.

Ganopolski, A., and S. Rahmstorf, Rapid changes of glacial climate simulated in a coupled climate model, *Nature*, *409*, 153-158, 2001.

Ganopolski, A., and S. Rahmstorf, Abrupt glacial climate changes due to stochastic resonance, *Physical Review Letters*, *in press*, 2002.

Grootes, P.M., and M. Stuiver, Oxygen 18/16 variability in Greenland snow and ice with 10^3- to 10^5-year time resolution, *Journal of Geophysical Research*, *102*, 26455-26470, 1997.

Peltier, W.R., Ice age paleotopography, *Science*, *265*, 195-201, 1994.

Russell, D.F., L.A. Wilkens, and F. Moss, Use of behavioural stochastic resonance by paddle fish for feeding, *Nature*, *402*, 291-294, 1999.

Sakai, K., and R.W. Peltier, A simple model of the Atlantic thermohaline circulation: internal and forced variability with paleoclimatological implications, *Journal of Geophysical Research*, *100*, 13455-13479, 1995.

Stommel, H., Thermohaline convection with two stable regimes of flow, *Tellus*, *13*, 224-230, 1961.

Vélez-Belchí, P., A. Alvarez, P. Colet, J. Tintoré, and R.L. Haney, Stochastic resonance in the thermohaline circulation, *Geophysical Research Letters*, *28*, 2053-2056, 2001.

A movie of computer-simulated Dansgaard-Oeschger events can be watched at www.pik-potsdam.de/~stefan