Abrupt Glacial Climate Changes due to Stochastic Resonance

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Using an ocean-atmosphere climate model we demonstrate that stochastic resonance could be an important mechanism for millennial-scale climate variability during glacial times. We propose that the glacial ocean circulation, unlike today's, was an *excitable system* with a stable and a weakly unstable mode of operation, and that a combination of weak periodic forcing and plausible-amplitude stochastic fluctuations of the freshwater flux into the northern North Atlantic can produce glacial warm events similar in time evolution, amplitude, spatial pattern, and interspike intervals to those found in the observed climate records.

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Stochastic resonance (SR) was first proposed to explain the 100 000 yr periodicity of glacial cycles by Benzi *et al.* [1]. However, this original idea has not been supported by subsequent evidence. Meanwhile, the concept of stochastic resonance has found numerous applications in physics, chemistry, the biomedical sciences, etc. [2]. Recently, there appear stochastic resonance applications to climate. In an analysis of the Greenland ice core record (Fig. 1), Alley *et al.* [4] found that the statistical properties of abrupt warmings (Dansgaard-Oeschger events, in short DO events) are consistent with stochastic resonance, but inconsistent with the more straightforward stochastic mechanisms such as a simple white-noise response. The waiting times between consecutive DO events cluster around 1500 yr and, with decreasing probability, 3000 and 4500 yr. The small sample makes more detailed conclusions from the Greenland data set difficult.

The physical mechanism of DO events is not yet fully understood. We have recently proposed a mechanism [5] based on numerical simulations with a coupled ocean-atmosphere climate model which shows encouraging agreement with the available paleoclimatic data, in that the key features of these events are reproduced: the three-phase time evolution, the spatial pattern centered on the North Atlantic, and the relative phasing of the Antarctic response. The mechanism is based on a stability analysis of the Atlantic ocean circulation in the glacial climate. In the model, which produces a rather realistic simulation of glacial climate [6], the Atlantic ocean circulation possesses a stable and a weakly unstable (i.e., lasting several hundred yr before it spontaneously ends) circulation mode in glacial conditions (see Fig. 2). We also found a second unstable mode in which North Atlantic deep water formation shuts down altogether, but this is accessible only through a large freshwater input into the Atlantic, e.g., a Heinrich event [8,9], and is not relevant here.

Physically, the glacial Atlantic is thus an *excitable system,* in which a suitable perturbation can trigger a temporary state transition to the unstable circulation mode. (For warm climates like the present, in contrast, the model climate is *bistable:* as in most other models [10] there are two stable solutions which correspond to the two unstable glacial circulation modes.)

We proposed that DO events are such a temporary state transition, triggered by a small perturbation to the salinity balance of the northern North Atlantic, which causes a transient jump of the climate from the stable cold (or stadial) mode to the unstable warm (or interstadial) mode. This corresponds to a startup of convection in the Nordic Seas and a sudden incursion of the warm North Atlantic current into this area (see Fig. 2). Such an excitable system can be subject to coherence resonance and stochastic resonance [11]; a well-studied example is the Fitz-Hugh-Nagumo system [12]. Here we present a study of this mechanism in our climate model.

The model (described in detail in [13]) is a global climate model of intermediate complexity and includes submodels for atmosphere, ocean (including sea ice), and land surface. It contains a dozen independent prognostic variables and $\sim 10^2$ diagnostic variables computed on a global geographical grid. The atmosphere is resolved on a grid of 10° in latitude and 51° in longitude and includes a planetary boundary layer and a free atmosphere. The ocean [14] is zonally integrated for the three main basins (Atlantic, Pacific, and Indian Ocean) and resolved

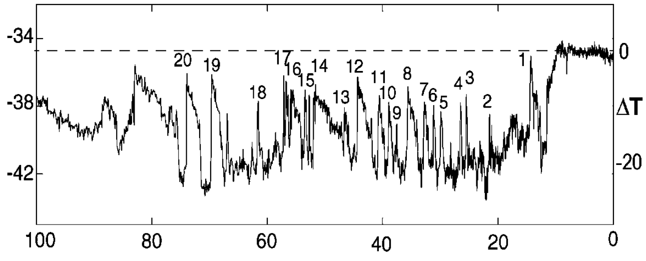

FIG. 1. Record of δ^{18}O [per mille (0.1%), scale on left] from the GRIP ice core, a proxy for atmospheric temperature over Greenland (approximate temperature range [3], in °C relative to Holocene average, is given on the right). Note the relatively stable Holocene climate during the past 10 kyr, and before that the much colder glacial climate punctuated by Dansgaard-Oeschger warm events (numbered).

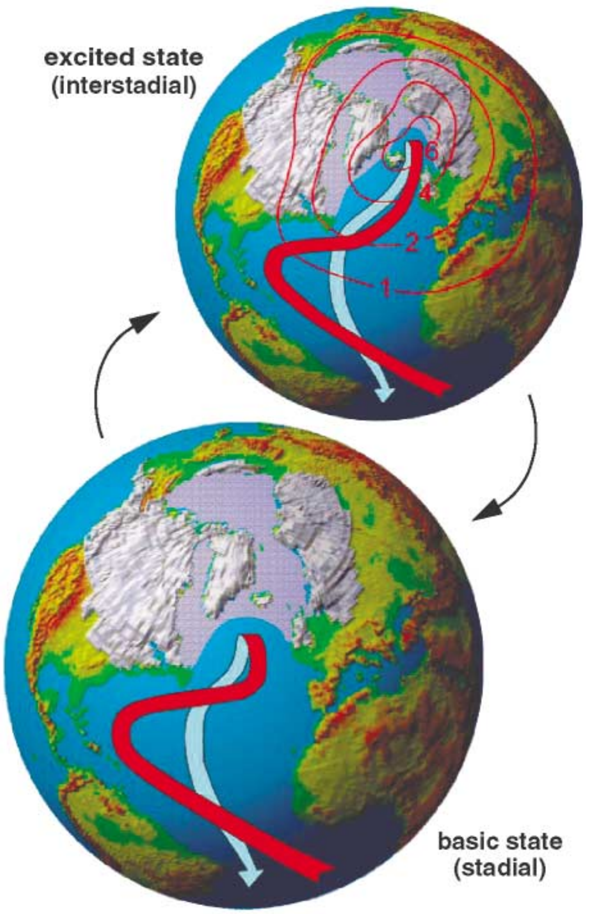

FIG. 2 (color). Schematic of the two glacial climate states described in Ganopolski and Rahmstorf [5]. Bottom: the stable "cold" or "stadial" mode. Top: the unstable "warm" or "interstadial" mode. Contours show the surface air temperature difference relative to the stable state. Ocean circulation is shown schematically, surface currents in red and deep currents in light blue. Continental ice sheets are based on the reconstruction of Peltier [7], prescribed in the simulations.

at 2.5° in latitude with 20 vertical levels. The time step is one day. Synoptic (i.e., weather) variability is not explicitly calculated (its effects being parametrized), only the large-scale, time-averaged climatic variables (e.g., average July temperature, cloudiness, or precipitation). In contrast to shorter time-scale variability, evolution of such averaged variables is not chaotic, neither in reality nor in the model.

When driven by present-day boundary conditions (i.e., solar insolation, atmospheric CO_2, and continental ice distribution) the model produces a rather realistic climate, including the seasonal cycle [13]. When the above boundary conditions are changed to their glacial values, the simulated climate is in agreement with paleoclimatic data reconstructions, including the changes in Atlantic ocean circulation [6]. A key feature relevant for the present discussion, namely the southward shift of deep water formation from the Nordic Seas to south of Iceland, has recently been reproduced also in a much more detailed coupled climate model [15]. Extensive sensitivity studies and validations of our model against more complex climate models and for different paleoclimates have been published elsewhere [16–18].

In our earlier study [5], we showed that episodic warm climate events resembling Dansgaard-Oeschger events in time evolution and spatial pattern can be triggered by small-amplitude sinusoidal freshwater forcing in the high-latitude North Atlantic. This is a threshold process: the details of the warm events do not depend on the forcing but merely on a critical threshold being exceeded. As expected, the regular sinusoidal forcing produces completely regular events; this is a rather artificial case which was used to demonstrate the basic mechanism of the events. Here, we investigate the more realistic situation of a noisy climate which includes some internal stochastic variability.

Given that our model does not explicitly simulate synoptic variability, i.e., the main stochastic component of climate, stochastic variability can be added in the form of random fluctuations of the air-sea fluxes. For the experiments reported here, we add a "white-noise" component to the freshwater flux (precipitation plus runoff minus evaporation, Fig. 3a) computed by the model for the Atlantic north of 50° N. The high-latitude North Atlantic is the crucial region for deep water formation. Decorrelation time of the noise is one year, and the standard deviation of the noise is varied between 0 and 0.1 Sv (Sv = sverdrup =

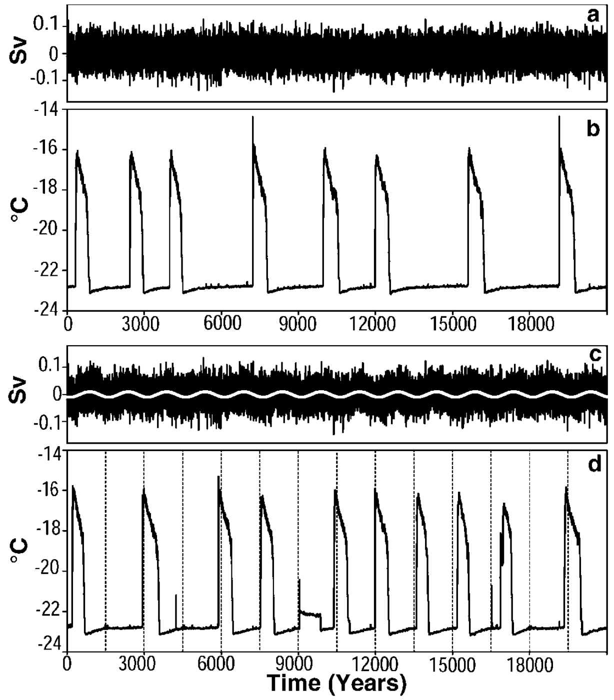

FIG. 3. Time series of freshwater forcing (a),(c) and simulated temperature over the northern Atlantic (b),(d). Upper panels show a case with "white noise" forcing only with a standard deviation of $\sigma_F = 0.035$ Sv (Sv = sverdrup = 10^6 m^3/s). Lower panels show the same noise plus a sinusoidal periodic signal of amplitude 0.01 Sv, shown by the white line on (c).

10^6 m^3/s). The middle of this range (i.e., 0.05 Sv) corresponds to 25% of the net freshwater flux to the northern Atlantic and to the magnitude of its interannual variability in the present climate. Freshwater variability in the glacial climate is unknown; it could have been smaller (due to a weaker hydrological cycle in a colder climate) or larger (due the presence of surrounding ice sheets calving glaciers at irregular intervals) than at present.

Figure 3b shows the response of the climate model to the simple white-noise variability of the freshwater inflow. This experiment demonstrates that

(i) The characteristic three-phase time evolution of the simulated DO events is retained also with stochastic forcing: a rapid warming phase, an unstable plateau phase with slow cooling, and a final rapid cooling back to stadial conditions.

(ii) There is an intrinsic time scale for the duration of these events of several hundred years. This is the advective time scale for salinity changes in the high-latitude Atlantic and is only weakly dependent on the forcing which triggers the events, but it depends (this is not shown here) on the background climate state, with a warmer climate leading to longer events.

(iii) There is an intrinsic waiting time after the end of one event until the next one can be triggered, as the water column retains a slowly fading "memory" of a previous event in the form of particularly high deep water density in the high latitudes, inhibiting the onset of another convection event.

Taken together, this means that for weak noise the mean interval between events decreases with increasing noise amplitude, while for stronger noise the interspike interval converges to being in the range 1000–2500 yr, with a very low probability of shorter or longer intervals (Figs. 4a and 4b). This fairly regular behavior is an example of coherence resonance.

The experiment was then repeated with the same noise forcing plus an added sinusoidal cycle (Fig. 3c) in the Atlantic salinity forcing north of 50° N, with an amplitude of 0.01 Sv and a period of 1500 years. This period is found in many observed climate records [19] and pervades both glacial times (where it is associated with DO events, Fig. 4e) and the Holocene (where no DO events occurred). Its origin is still debated, with solar variability being a prime suspect [20].

Figure 3d shows the outcome of this model experiment. The simulated DO events are now synchronized by the weak periodic forcing and occur preferentially near its minima, since a higher surface salinity makes it easier to trigger a convection event. This leads to preferred interspike intervals of 1500, 3000, and occasionally 4500 yr, as shown in Figs. 4c and 4d. This telltale sign of stochastic resonance is also found in the Greenland record (Fig. 4e). The periodic cycle amplitude is in itself only a fraction of the threshold value (~0.03 Sv) for triggering a warm event in this simulation; it is the noise which triggers the events and thus amplifies the weak cycle into major climatic shifts with global reverberations.

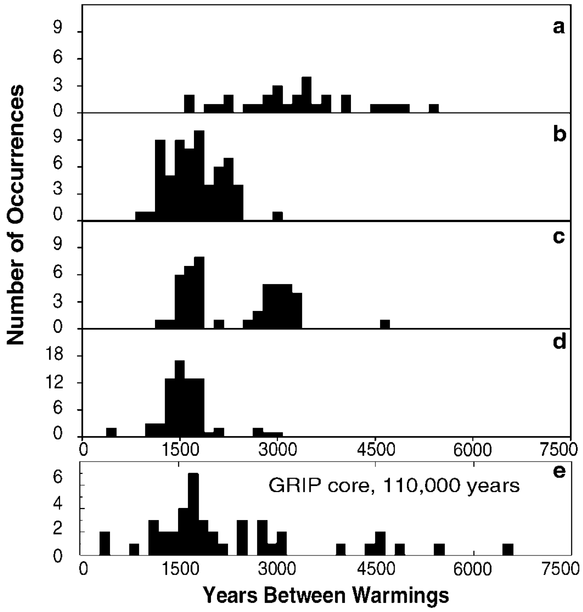

FIG. 4. Interspike interval distribution (or waiting time between warm events) for "noise only" experiments (a),(b) and "noise plus signal" [(c),(d); amplitude = 0.01 Sv]. Standard deviation of the noise is $\sigma_F = 0.035$ Sv in panels (a),(c) and $\sigma_F = 0.05$ Sv in panels (b),(d). Each distribution was obtained from a simulation of 110 000 climate years. The bottom panel (e) is from the equally long Greenland ice core record and is taken from [4].

The dependence of the periodic component of the climate response on the noise amplitude is shown in Fig. 5 for two amplitudes of the forcing cycle. The figure reveals a clear stochastic resonance at noise amplitudes near 0.05 Sv. While this is the optimal level to bring out the 1500-yr periodic signal, only lower noise levels reveal the secondary maxima at 3000 and 4500 yr in Fig. 4. The presence of these maxima in the Greenland data (Fig. 4e) thus suggests that the stochastic variability of glacial climate was, in this sense, suboptimal for triggering DO events.

Stochastic resonance has recently been invoked in a simple conceptual, bistable model of the thermohaline circulation to trigger switches between thermal and haline circulation modes [21]. In contrast, we find that in our model the bistable Holocene climate is not susceptible to regime switches by stochastic resonance with plausible parameter choices and even unrealistically large noise amplitudes, and neither is it in conceptual models. The width of the hysteresis loop, i.e., the magnitude of the required freshwater forcing, is ~0.25 Sv in this case [5] and thus much larger than observed noise, and indeed there is no evidence for regime switches during the Holocene. In our model the occurrence of stochastic resonance is limited to the monostable, excitable glacial climate state, and the regime switch is neither between thermal and haline nor more

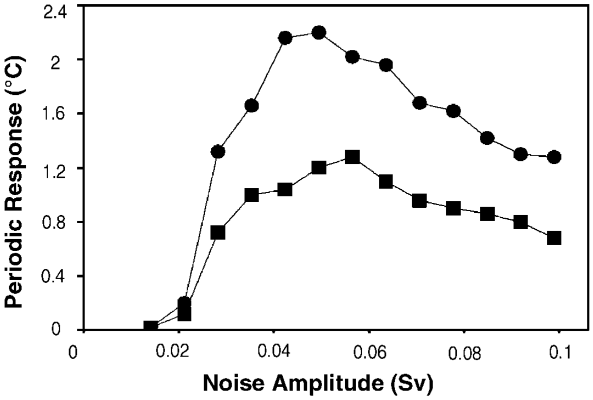

FIG. 5. Amplitude of the periodic component $T(\sigma_F)$ of the climate system response (northern Atlantic temperature) as a function of the noise intensity (standard deviation of the freshwater forcing, σ_F). Circles were computed with an amplitude of the periodic forcing of 40% of the threshold value for pure periodic forcing, squares correspond to an amplitude of 20% of the threshold value. Note that for a pure periodic forcing with an amplitude above the threshold value of 0.03 Sv, the amplitude of the periodic response is 3 K.

generally between North Atlantic deep water formation "on" or "off" modes, but between modes with different North Atlantic deep water formation sites. This type of transition requires much smaller forcing amplitudes than an "on/off" transition.

Is it unlikely that conditions would have been "just right" for stochastic resonance to occur in glacial climate? In fact, climate gradually cooled during ~100 000 years from the Eemian interglacial down to maximum glacial conditions, covering a large region in climatic "parameter space." The record (Fig. 1) suggests that fewer and longer-lasting DO events prevail in the early, warmer part of the glacial (when the warm mode was presumably more stable, as argued in [5]), and likewise few events occurred during the coldest time around 20 kyr b.p., when the cold mode was presumably more stable. In-between, climate passed close to the bifurcation point where stochastic flickers between the two modes can easily occur; in the presence of a weak regular 1500-yr cycle these took the form of stochastic resonance. Given the large range between interglacial and full glacial climate conditions, it is not unlikely that climate would pass a bifurcation point and respond in nonlinear ways somewhere within this range.

Our experiments demonstrate for the first time in a detailed, quantitative climate model that major climatic events could indeed have been triggered by stochastic resonance with plausible noise amplitudes and a very weak periodic forcing. The modeled warm events agree in many respects (e.g., amplitude, spatial pattern, time evolution in Greenland and Antarctica) with the properties of the Dansgaard-Oeschger events recorded in Greenland ice and other climate archives. By providing a quantitative physical mechanism, our results support the conclusion of a recent analysis of the Greenland data [4] that stochastic resonance is at work in these dramatic events.

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