Driving of millennial oscillations in a two-dimensional ocean model

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Background and aim of research

Paleoclimatic records show that climate has undergone large and rapid fluctuations, called Dansgaard-Oeschger oscillations, during the last glacial period. With a typical period of about 1500 yr, they are characterized by rapid warming, followed by slow cooling (Fig.1).

Simple ocean models show that the thermohaline circulation can exhibit millennial-scale oscillations that might provide an explanation for the Dansgaard-Oeschger oscillations. However, these model oscillations are not yet well understood.

We try to give a general description of the physics of millennial oscillations in a two-dimensional model of the thermohaline circulation.

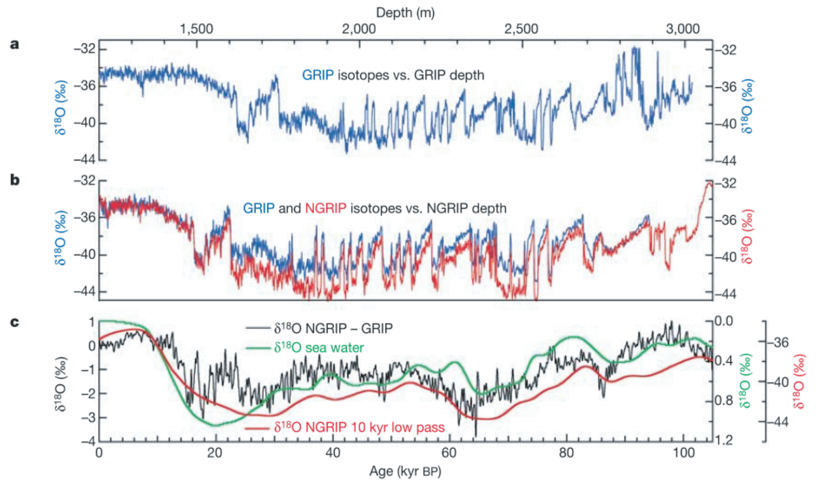

Fig. 1. Oxygen isotope ratio from two Greenland ice cores. (NGRIP members, Nature, 2004)

Physical mechanism of millennial oscillations

The model oscillations are characterized by a strong phase lasting for several centuries, during which the meridional overturning is thermally driven (sinking in the north), and a weak phase with a haline driven overturning (sinking in the south). The ocean takes up heat during the weak phase, which is released during the fast transition to the strong phase.

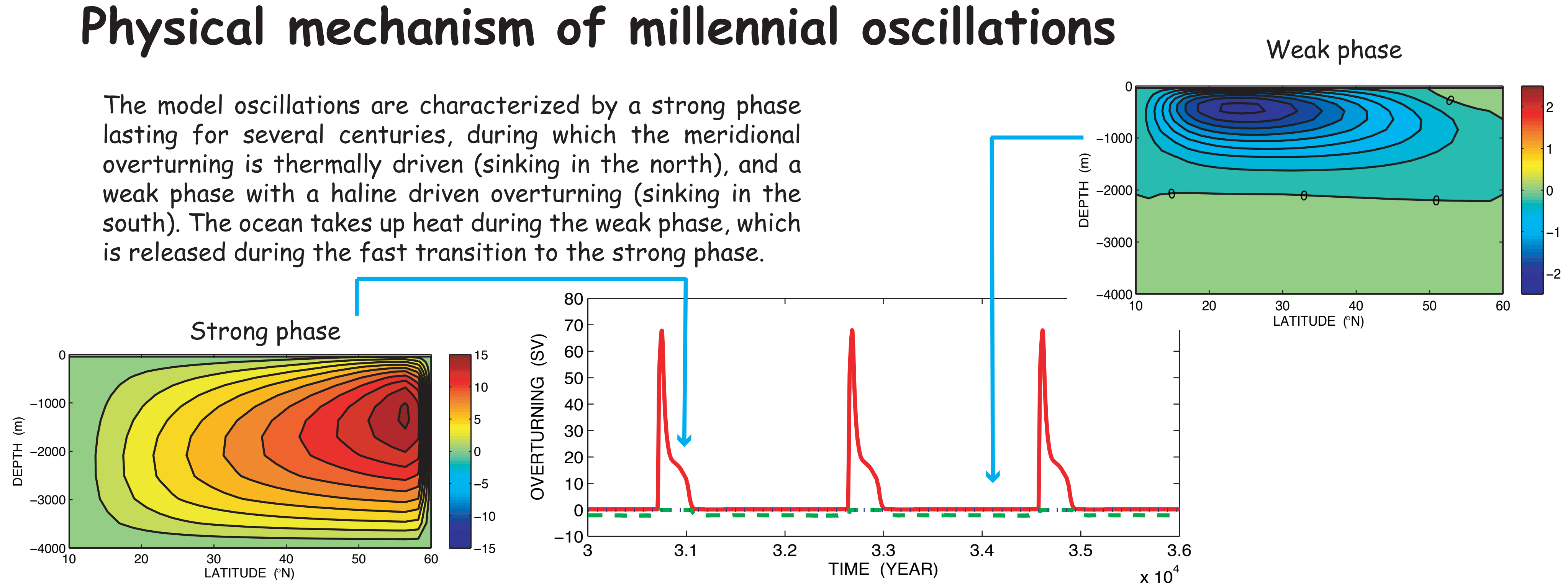

Fig. 2. Maximum (solid) and minimum (dashed) meridional overturning for the standard case. The oscillation period is 1915 yr.

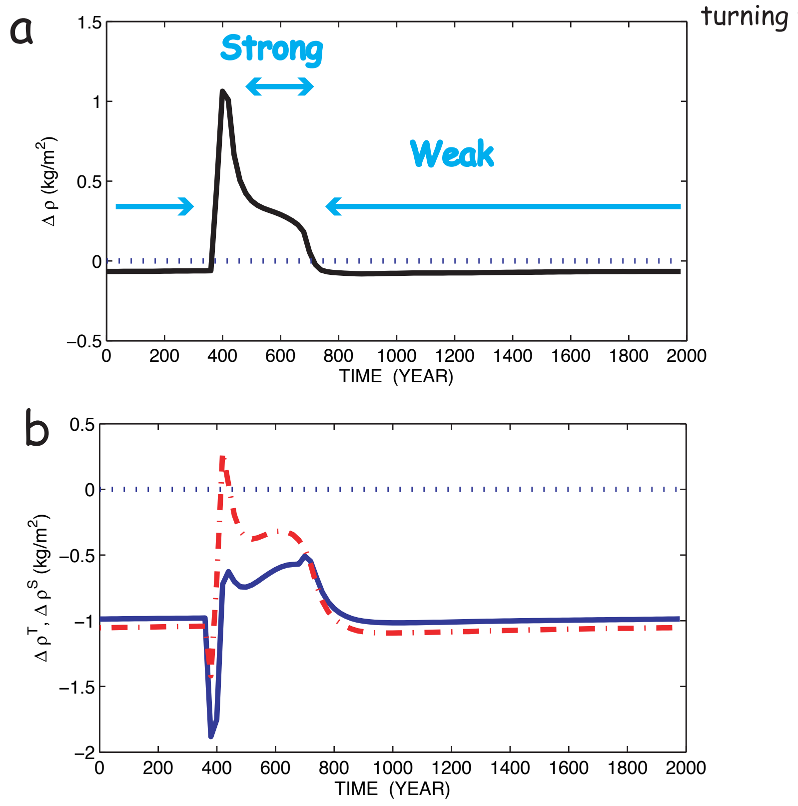

Fig. 3. a) Vertically averaged north-south density gradient $\Delta\rho$ (ρ at the northernmost grid point minus ρ at the southernmost grid point) for the standard case. b) Contributions of temperature (solid) and salinity (dash-dotted) to $\Delta\rho$.

As the model is two-dimensional and uses linear friction, the meridional velocity is directly related to meridional pressure and thus density gradients. Hence, we can understand the evolution of the meridional overturning by monitoring a measure of the meridional density difference (Fig. 3a).

During the strong phase, this density difference keeps decreasing, because the temperature contribution is increasing (becoming less negative) faster than the salinity contribution (Fig 3b). Advection and horizontal diffusion of heat cool the deep low-latitude ocean more than vertical diffusion can warm it. During the weak phase, advection and horizontal diffusion cause the intermediate low-latitude ocean to become fresher. The resulting increase in salinity difference causes the density difference to increase until the end of the weak phase.

Model:
- two-dimensional, ocean only
- linear friction
- linear equation of state
- mixed boundary conditions
- idealized, steady forcing
- single-hemispheric basin

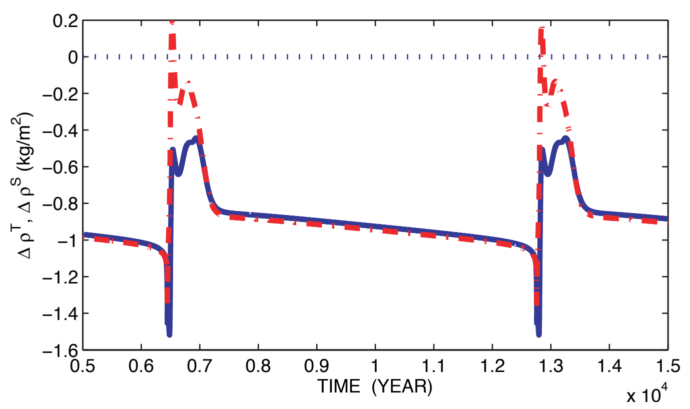

Fig. 4. Contributions of temperature (solid) and salinity (dash-dotted) to $\Delta\rho$ for a case where $\Delta\rho^T$ and $\Delta\rho^S$ decrease during the weak phase. This is a case without convective adjustment.

In other cases, the weak phase ends because the contribution of temperature to the density decreases faster than that of salinity (Fig. 4). In such cases vertical diffusion and convection dominate over advection and horizontal diffusion.

The oscillations are thus driven by a mismatch between advection and horizontal diffusion of heat and salt on one hand, and vertical diffusion and convection on the other hand.

The example in Fig. 4 also shows that even without convective adjustment oscillations can be found.

Bifurcation diagram

The bifurcation diagram of meridional overturning as a function of the freshwater flux strength has been computed for the case without convective adjustment. For this particular case, the window of millennial oscillations is confined by two narrow regimes of linear oscillations. No stable steady states are possible within the window of millennial oscillations.

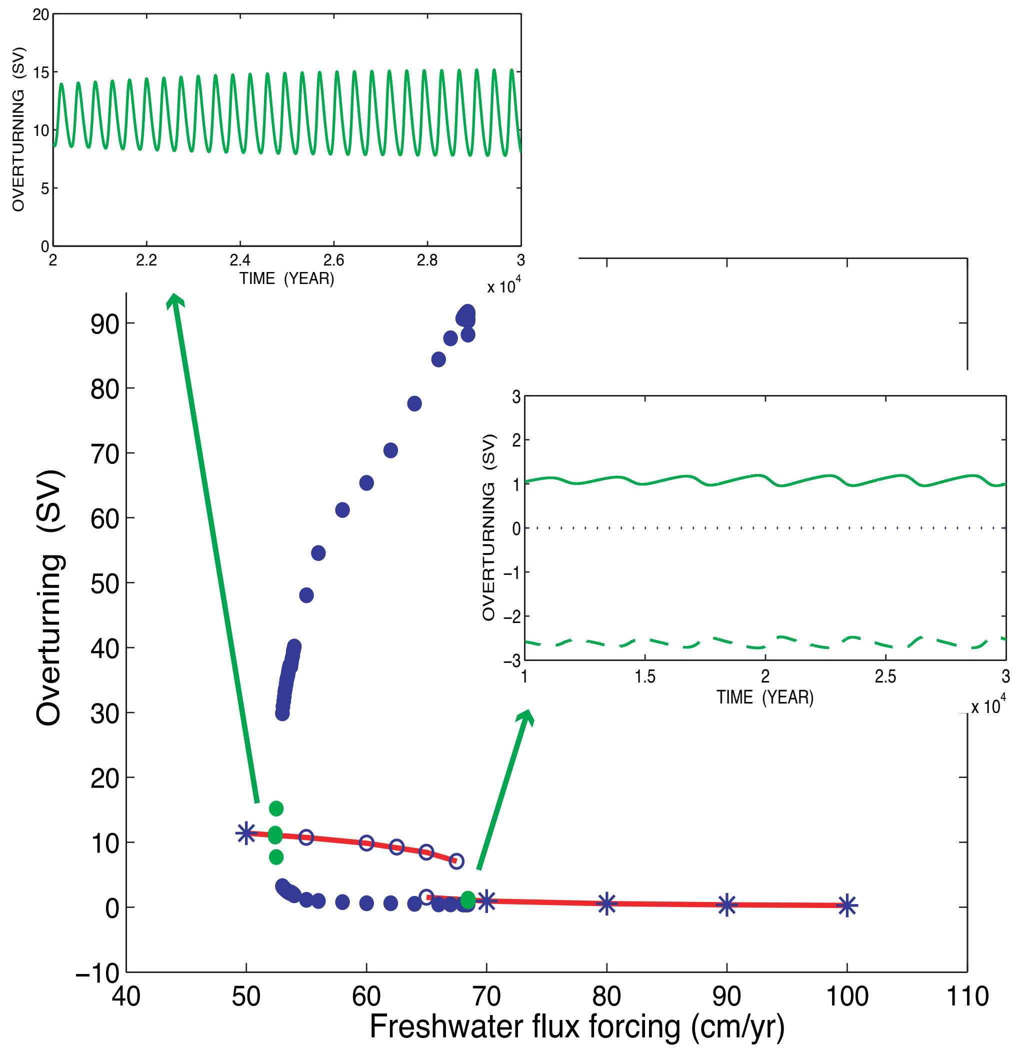

Fig. 6 Maximum meridional overturning as a function of the freshwater flux strength. Stable (stars) and unstable (open circles) steady states, maximum and minimum values for linear oscillations (green dots) and nonlinear millennial oscillations (blue dots) are indicated.

Sensitivity

As a function of various control parameters, the regime of millennial oscillations appears as a window in between the regimes of steady thermally driven flow or steady haline driven flow (Fig. 5).

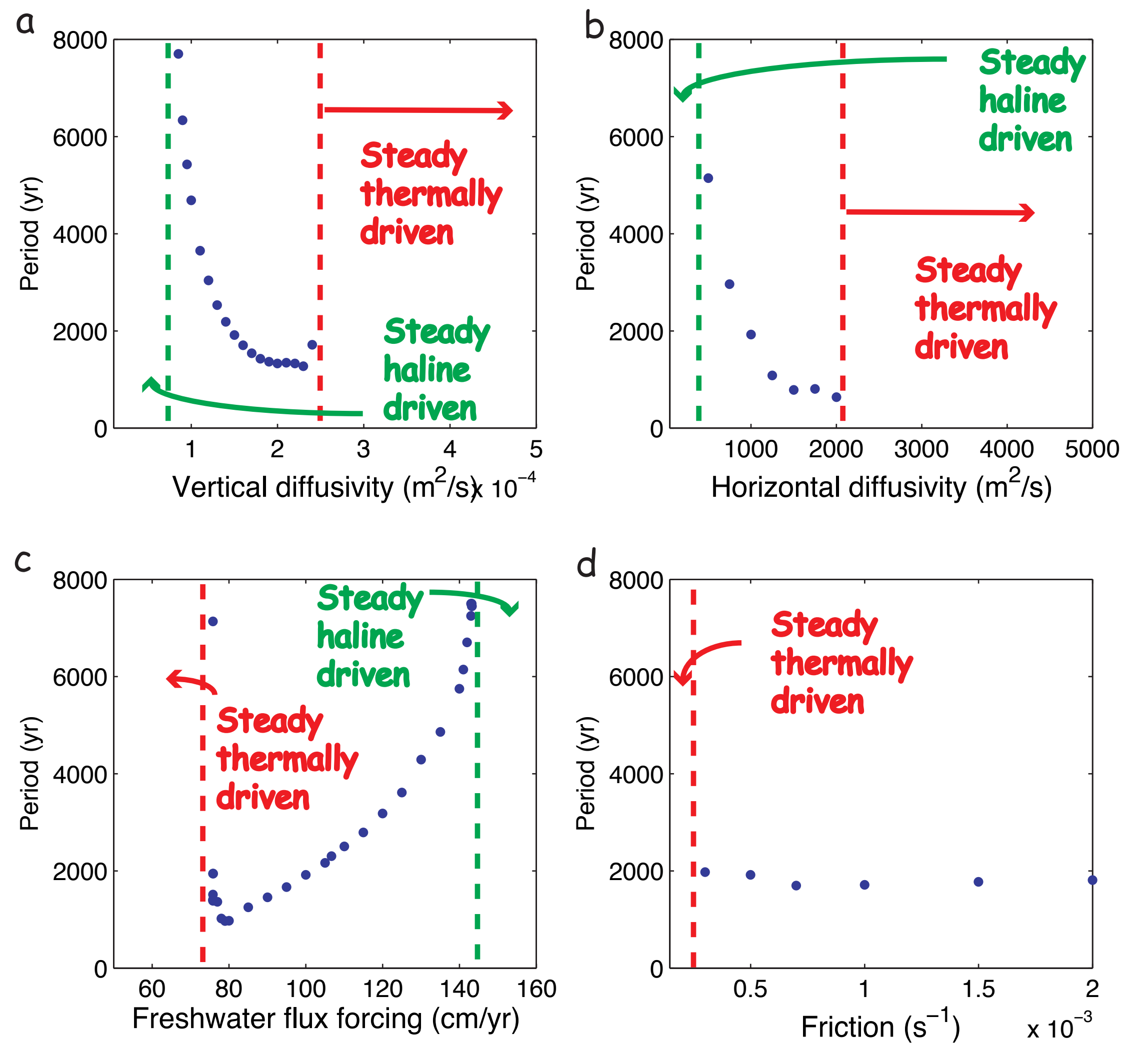

Fig. 5. Period of the oscillations as a function of: a) vertical eddy diffusivity, b) horizontal eddy diffusivity, c) freshwater flux strength, and d) friction parameter.

The oscillation period increases when the vertical or horizontal diffusivity is decreased, or when the freshwater flux strength is increased. In all cases, the imbalance becomes less and less pronounced, which increases the time needed for the density difference to change, and thus lengthens the period. It is unclear why the period is not sensitive to the friction.

The period is mainly determined by the duration of the weak phase. Exceptions are the cases with relatively high vertical or horizontal diffusivity, or relatively low freshwater flux strength, when the strong phase lasts longer than or as long as the weak phase.

Summary and conclusions

- The evolution of the meridional overturning can be understood from the evolution of the large-scale meridional density differences.

- The oscillations are driven by a mismatch between advection and horizontal diffusion of heat and salt on one hand, and vertical diffusion and convection on the other hand.

- In this two-dimensional model, convection is not essential for the oscillations to exist.