Dansgaard-Oeschger and Heinrich events

climate dynamics (EPS 231)

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Outline:

1 **Introduction, observed record of DO events:** IRD, Greenland warming events.

2 **Winton model:** Convection, air-sea and slow diffusion: Relaxation oscillations/ Thermohaline flushes/ "deep decoupling" oscillations (Winton, 1993, section IV).

3 **MOC/THC flushes and DO events:** DO explained by large amplitude THC changes (Ganopolski and Rahmstorf, 2001): hysteresis diagrams for modern and glacial climates demonstrating the ease of making a transition between the two THC states in glacial climate; these oscillations are basically the same as Winton (1993) deep decoupling oscillations and flushes.

4 **Alternatively, sea ice as an amplifier of small amplitude MOC/THC variability:** Preliminaries: sea ice albedo and insulating feedbacks; simple model equation for sea ice (Sayag et al., 2004).

Li et al. (2005) AGCM experiments, showing small sea ice changes leading to a large atmospheric temperature signal. Then, sea ice as an amplifier of *small* MOC/THC variability (Kaspi et al., 2004); Possible variants of the sea ice amplification idea: Stochastic excitation of THC+sea ice leads to DO-like variability (Timmermann et al., 2003); similarly, self-sustained DO-like events with sea ice amplification in Loving and Vallis (2005).

5 **Precise clock behind DO events? Stochastic resonance?** First, Rahmstorf (2003). (Time permitting: clock error, triggering error and dating error); is it significant, or does the fact that we are free to look for a periodicity for which some "clock" might fit the time series makes it more likely for the time series to seem as if it is driven by a precise clock? Next, D/O events as a stochastic resonance: (Alley et al., 2001) which would lead to a histogram of waiting time between DO events showing multiples of 1470 yrs. The bad news: no clock, (Ditlevsen et al., 2007), based on better dating of ice cores and a careful Rayleigh criterion analysis.

6 **DO teleconnections:** Observations: Wang et al. (2001) show a strong correlation of Hulu cave in China with Greenland ice cores. Similarly, Denton and Hendy (1994) show a correlation between Younger Dryas and glaciers in New Zealand. What is the mechanism? (1) Atmospheric teleconnections via atmospheric Rossby wave teleconnections. (2) MOC/THC teleconnections: weaker NADW import to the Southern Ocean due weakening of MOC (Manabe and Stouffer, 1995); MOC/THC seesaw (Broecker (1998), and this). (3) Teleconnections via ocean wave motions, Johnson and Marshall (2004): essentially equatorial and coastal Kelvin waves propagate anomalies due to changes in convection rate very fast from the north-west Atlantic and spread the information along eastern boundaries, and then slower Rossby waves transmit the information to the ocean interior on a decadal time scale. This mechanism also allows for inter-basin exchanges.

7 **Heinrich events:**

1. Observations: IRD layers, the cold climate during events, precursor events, synchronous collapses.
2. MacAyeal's binge-purge mechanism: MacAyeal (1993)a's argument that external forcing is not likely to play a role (section 2, Eqns 1–5, p 777);
3. Difficulties with this argument: Moulins and collapse of ice shelf due to melt water accumulation in cracks leading to the elimination of buttressing and acceleration of ice streams.
4. Heuristic argument for the time scale (section 5, p 782, Eqns 19–25, note that LHS of Eqn 23, the b.c at the ground, should be $\tilde{\theta}_y(0,t)$).
5. Equations for the more detailed model of MacAyeal (1993)b (slides or Kaspi et al., 2004), and numerical solution for temperature and ice height (slides), explaining all temperature maxima and minima of temperature during the cycle.
6. An alternative: the Marine Ice Sheet Instability, MISI. See slides, plus the following derivation of the grounding line flux formula from appendix B of Hindmarsh (2012) and from Alex Robel. Let u be the along-stream velocity, in the x direction. The general rate of strain tensor is,

$$\dot{\epsilon}_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right),$$

while Glenn's law relates it to the stress in a simple lab experiment as,

$$\dot{\epsilon}_{xz} = A(T)\tau_{xz}^n.$$

This is generalized to a general relation between the two tensors that is invariant to coordinate transformation as,

$$\tau_{ij} = A(T)^{-\frac{1}{n}} E^{\frac{1}{n}-1}\dot{\epsilon}_{ij},$$

where the second invariant of the rate of strain tensor is used here,

$$E = \left(\frac{1}{2} \sum_{i,j=1}^{3} \dot{\epsilon}_{ij} \dot{\epsilon}_{ij} \right)^{1/2}.$$

Assuming only along-stream variations, we can neglect other derivatives,

$$\tau_{xx} \approx A(T)^{-\frac{1}{n}} \dot{\epsilon}_{xx}^{\frac{1}{n}-1} \dot{\epsilon}_{xx} = A(T)^{-\frac{1}{n}} \dot{\epsilon}_{xx}^{\frac{1}{n}}.$$

We use, as the vertically integrated momentum equation, a balance between bottom friction and driving stress,

$$Hu_t = 0 = -\rho_i g H H_x - C|u|^{\frac{1}{\ell}-1} u.$$

The mass conservation equation, with a as the surface mass accumulation, is

$$a = \partial_x (Hu) = H_x u + H u_x.$$

Assuming a small accumulation rate, this simplifies to,

$$u H_x \approx -H u_x \approx -H \dot{\epsilon}_{xx}.$$

Using the last equation, substitute $H_x = H\dot{\epsilon}_{xx}/u$ in the momentum equation to find,

$$0 = \rho_i g H^2 \dot{\epsilon}_{xx} - C|u|^{\frac{1}{\ell}-1} u^2.$$

Use Glenn's law to express this in terms of the stress instead of the rate of strain,

$$0 = \rho_i g H^2 A(T) \tau_{xx}^n - C|u|^{\frac{1}{\ell}+1}.$$

For the boundary condition at the grounding line, let the longitudinal stress there be equal to the total ice pressure minus total water pressure. The floating condition is that the weight per unit area of ice at the ice margin bordering with the ocean is equal to the weight per unit area of ocean water $\rho_i H = \rho_w b$, where b is the ocean water level. This gives $b = \mu H$, with $\mu = \rho_i/\rho_w$. The hydrostatic pressure difference between the ice and ocean at the ice margin is,

$$\int_0^H g\rho_i z dz - \int_0^b g\rho_w z dz = \frac{1}{2}(1-\mu)\rho_i g H^2 = \frac{1}{2}\gamma H,$$

where $\gamma \equiv (1 - \rho_i/\rho_w)\rho_i g H$. The boundary condition is, therefore,

$$H2\,\tau_{xx}|_{\text{grounding line}} = \frac{1}{2}\gamma H^2,$$

(please don't ask me about the factor of 2 on the LHS:-) which gives an expression for the stress at the grounding line,

$$\tau_{xx}|_{\text{grounding line}} = \frac{1}{4}\gamma H.$$

We plug this into the momentum balance to find,

$$0 = \rho_i g H^2 A(T) \frac{1}{4^n}\gamma^n H^n - C|u|^{\frac{1}{\ell}+1},$$

and, therefore, the velocity at the grounding line is,

$$u = \left(\frac{\rho_i g}{C} A(T) \frac{1}{4^n}\gamma^n H^{n+2}\right)^{\ell/(\ell+1)},$$

and the volume flux at the grounding line is Hu, or,

$$Q_g = \left(\frac{\rho_i g \gamma^n}{4^n}\frac{A(T)}{C}\right)^{\ell/(\ell+1)} H^{1+(n+2)(\ell/(\ell+1))}.$$

Using $n = \ell = 3$, the power of the thickness is $1 + (n+2)\ell/(\ell+1) = 4.75 \approx 5$.

8 **Relation between DO and Heinrich events:** do major DO follows Heinrich events? Bond cycle (image in the slides is from here)? Do Heinrich events happen during a cold period just before DO events? When the ice sheet model is coupled to a simple ocean-atmosphere model, one can get the response of the climate system, as well via a shutdown of the MOC (leading to a cold event) followed by a flush (causing a warm event).

9 **Synchronous ice sheet collapses?** slides (33-47).

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