TD3 — Conceptual model of the Atlantic Meridional Overturning Circulation

We study a simple model of the Atlantic Meridional Overturning Circulation (AMOC), after Stommel (1961): the ocean is composed of two boxes characterized by temperatures T_1, T_2 and salinity S_1, S_2 (expressed in g.kg^{-1}), representing the polar and tropical regions, respectively (see Fig. 1). A meridional circulation transports heat and salinity: the mass flux in the upper ocean, denoted m, is proportional to the density difference $\Delta\rho = \rho_2 - \rho_1$: $m = -\mu\Delta\rho$, with $\mu > 0$ a constant coefficient. We impose a salinity flux Σ in the tropical ocean box. To ensure global conservation of salt, a salinity flux $-\Sigma$ is applied to the polar ocean box. We assume a linear equation of state: $\rho = \rho_0(1 - \alpha(T - T_0) + \beta(S - S_0))$ with $\alpha, \beta > 0$.

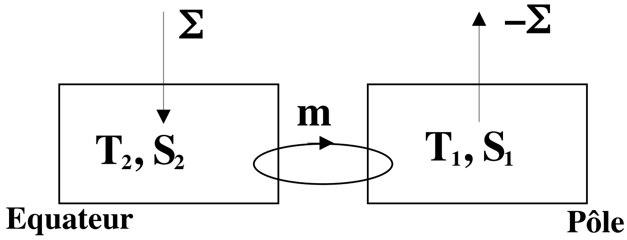

Figure 1: Schematic of the Stommel model.

1. Show that the evolution equations for the salinity in each box are:

$$\frac{\partial S_1}{\partial t} = |m|(S_2 - S_1) - \Sigma, \quad \frac{\partial S_2}{\partial t} = |m|(S_1 - S_2) + \Sigma. \tag{1}$$

   Deduce the equation for salinity difference $\Delta S = S_2 - S_1$:

$$\frac{\partial \Delta S}{\partial t} = 2(\Sigma - |m|\Delta S). \tag{2}$$

2. Let $x = \frac{\beta\Delta S}{\alpha\Delta T}$ and $F = \frac{\beta\Sigma}{\mu(\alpha\Delta T)^2}$. We assume that ΔT is constant. Show that, after introducing an appropriate non-dimensional time, the equation becomes

$$\dot{x} = F - x|1 - x|. \tag{3}$$

3. Draw the curve with equation $y = x|1-x|$. Show that for $0 < F < 1/4$, there are three fixed points $0 < x_T < 1/2$, $1/2 < x_I < 1$ and $1 < x_S$, and otherwise, only one fixed point. Study the stability of these fixed points.
4. Show that, in the new time units, $m = \frac{1-x}{2}$. Plot m at equilibrium as a function of F.
5. What would be the sign of F in the current climate? The sign of m? To which equilibrium state of the Stommel model would it correspond?
6. We now consider models which resolve the dynamics of the ocean, undergoing so-called "hosing" experiments: a freshwater flux is imposed in a specified region in the North Atlantic, and the strength of the AMOC is monitored as the flux is slowly increased and decreased. Fig. 2 shows the results of such experiments, for models averaged in longitude (top panel) and for 3D models (bottom panel). Is the qualitative behavior of these models consistent with the Stommel model? Discuss the agreement among models regarding the position of the two bifurcation points. Is current climate within the bistability regime?
7. Estimate the order of magnitude of the time in which the Greenland ice sheet would have to melt to collapse the AMOC, assuming that the behavior of the models shown in figure 2 corresponds to reality. The total mass of the Greenland ice sheet is roughly 3 000 000 Gton.

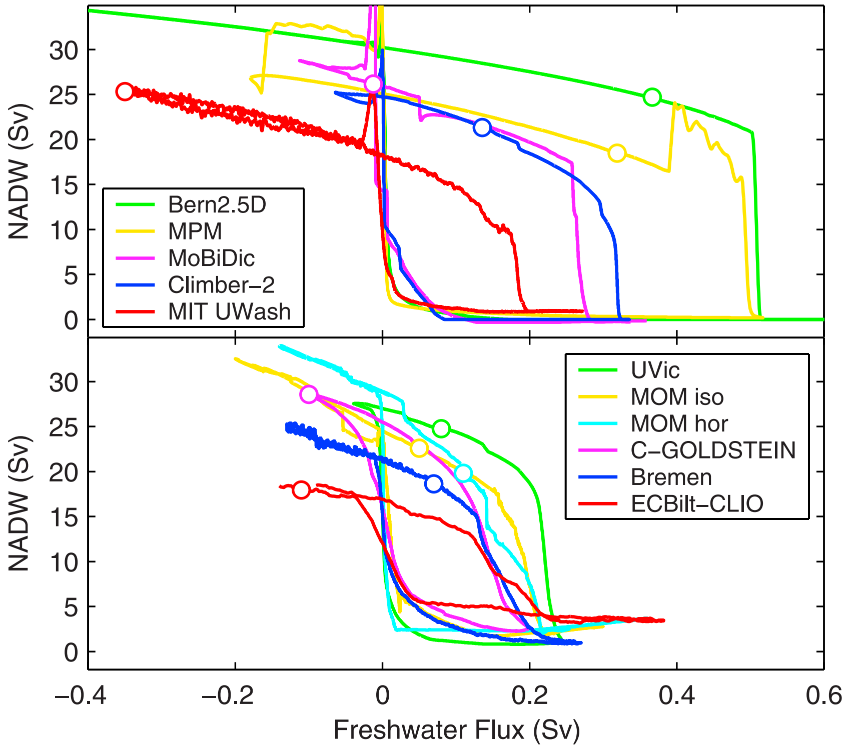

Figure 2: AMOC strength as a function of imposed freshwater flux in the North Atlantic in models of intermediate complexity (Rahmstorf et al. 2005). The dot indicates the position of current climate.

8. It remains debated whether the real AMOC exhibits multiple steady-states or not. Regardless, paleoclimate proxies indicate that it has varied substantially in the past, and it might have played an important role in abrupt climate changes over the last glacial period, such as those shown in Fig. 3. Relying on what you have learned in the paleoclimate lecture, describe the features of these climate changes qualitatively (context in which they occur, timescale, amplitude, etc).

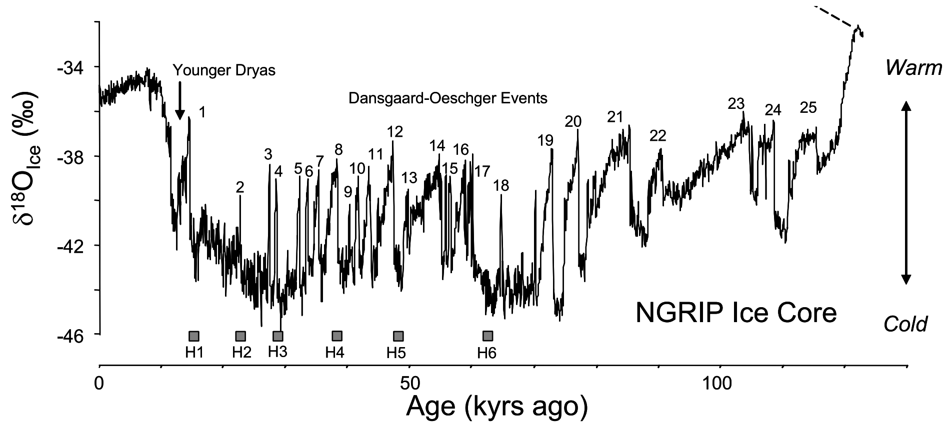

Figure 3: Oxygen isotopic ratio δ^{18}O from Greenland ice cores (Clement and Peterson 2008).

References

Clement, A. C. and L. C. Peterson (2008). "Mechanisms of Abrupt Climate Change of the Last Glacial Period". *Rev. Geophys.* 46.4, RG4002.

Rahmstorf, S. et al. (2005). "Thermohaline Circulation Hysteresis: A Model Intercomparison". *Geophys. Res. Lett.* 32.23, p. L23605.

Stommel, H. (1961). "Thermohaline Convection with Two Stable Regimes of Flow". *Tellus* 13.2, pp. 224–230.