Klimageschichte Übung 9
Thermohaline circulation - the Stommel box model

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1 Introduction

As opposed to wind-driven currents and tides (which are due to the gravity of moon and sun), the thermohaline circulation (THC) (Fig. 1) is that part of the ocean circulation which is driven by density differences. Sea water density depends on temperature and salinity, hence the name thermo-haline. The salinity and temperature differences arise from heating/cooling at the sea surface and from the surface freshwater fluxes (evaporation and sea ice formation enhance salinity; precipitation, runoff and ice-melt decrease salinity). Heat sources at the ocean bottom play a minor role.

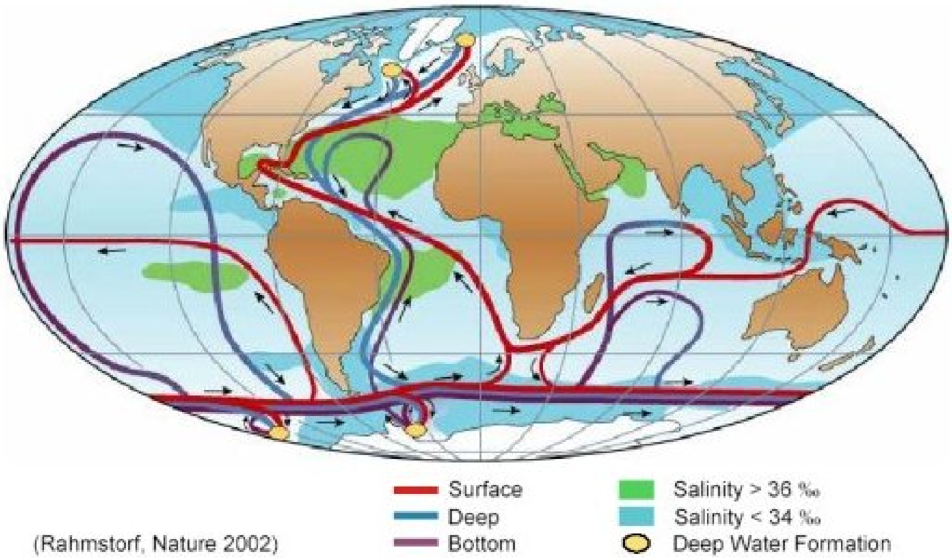

Figure 1: Ocean circulation. (Rahmstorf, 2002).

In contrast to the wind-driven currents, the THC is not confined to surface waters but can be regarded as a big overturning of the world ocean, from top to bottom. The thermohaline circulation consists of:

- Deep water formation: the sinking of water masses, closely associated with (but not to be confused with) convection, which is a vertical mixing process). Deep water formation takes place in a few localised areas: the Greenland-Norwegian Sea, the Labrador Sea, the Mediteranean Sea, the Wedell Sea, the Ross Sea.
- Spreading of deep waters (e.g., North Atlantic Deep Water, NADW, and Antarctic Bottom Water, AABW), mainly as deep western boundary currents (DWBC).
- Upwelling of deep waters: this is not as localised and difficult to observe. It is thought to take place mainly in the Antarctic Circumpolar Current region, possibly aided by the wind (Ekman divergence).
- Near-surface currents: these are required to close the flow. In the Atlantic, the surface currents compensating the outflow of NADW range from the Benguela Current off South Africa via Gulf Stream and North Atlantic Current into the Nordic Seas off Scandinavia. (Note that the Gulf Stream is primarily a wind-driven current, as part of the subtropical gyre circulation. The thermohaline circulation contributes only roughly 20% to the Gulf Stream flow.)

Several simple box models were used to study the changes in THC caused by e.g. changes in freshwater fluxes. We will discuss one of these models next.

2 The Stommel model

The Stommel model ((Stommel, 1961)) consists of two well mixed boxes (1: high-latitude; 2: low-latitude) of equal volume, each characterized by its own uniform temperature T_i and salinity S_i (Fig. 2). The density of ocean water can be approximated by linear dependencies on temperature and salinity:

$$\rho = \rho_0 - \alpha(T - T_0) + \beta(S - S_0) \tag{1}$$

α and β are the thermal and haline expansion coefficients, respectively and the subscript '0' indicates a reference state.

1. Given eq. (1), what is the effect on density of a temperature increase? And a salinity increase?

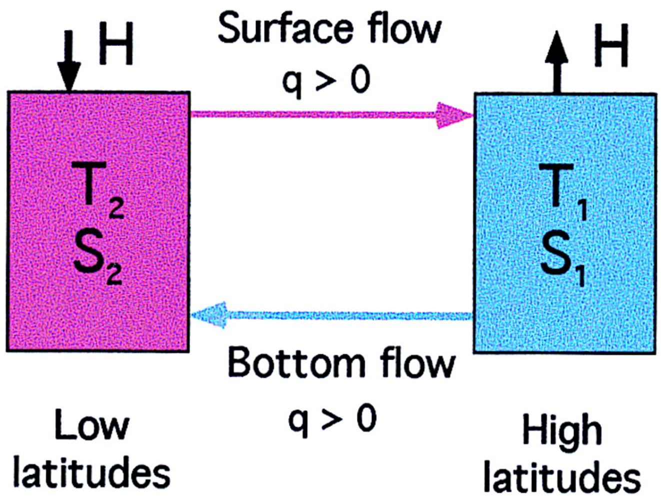

Figure 2: Stommel's conceptual model of the THC. (Marotzke, 2000).

The flow strength, $q[s^{-1}]$, between the boxes can be related to the density difference by a linear law,

$$q = k[\rho_1 - \rho_2] \tag{2}$$
$$= k[\alpha(T_2 - T_1) - \beta(S_2 - S_1)] \tag{3}$$
$$= k[\alpha\Delta T - \beta\Delta S] \tag{4}$$

where k is a hydraulic constant.

2. Discuss the temperature and salinity conditions necessary to have a poleward surface flow ($q > 0$).

Assuming that the temperatures of the boxes relax to some reference temperatures imposed by the atmosphere with a timescale γ^{-1} and that $H > 0$ is the salinity flux out of the high latitude box, the conservation equations governing the system can be written as:

$$\frac{dT_1}{dt} = -|q|\Delta T + \gamma(\overline{T_1} - T_1) \tag{5}$$
$$\frac{dT_2}{dt} = |q|\Delta T + \gamma(\overline{T_2} - T_2) \tag{6}$$
$$\frac{dS_1}{dt} = |q|\Delta S - H \tag{7}$$
$$\frac{dS_2}{dt} = -|q|\Delta S + H \tag{8}$$

3. Assume that the temperature relaxation time-scale $\gamma^{-1} << |q|^{-1}$. This is equivalent to assuming that the temperature relaxation time scale is fast compared to the time scale of the overturning circulation. In this case, what are the steady state solutions for the temperatures T_1 and T_2?

We further assume that in a plausible limiting case the surface freshwater exchange (expressed through an equivalent surface salinity flux H) is imposed by the atmosphere. The conservation equations governing the system then are only those for salinity:

$$\frac{dS_2}{dt} - \frac{dS_1}{dt} = \frac{d\Delta S}{dt} = -2|q|\Delta S + 2H \tag{9}$$

The time evolution of the circulation q is goverened by:

$$\frac{dq}{dt} = -k\beta\frac{d\Delta S}{dt} \tag{10}$$

4. Substitute eq. 9 in eq. (10) and use $\Delta S = (-q + k\alpha\Delta\overline{T})/(k\beta)$. Show that the resulting steady state solutions of the equation are:

$$\begin{cases} q_{1/2} = \frac{k\alpha\Delta\overline{T}}{2} \pm \sqrt{\left(\frac{k\alpha\Delta\overline{T}}{2}\right)^2 - Hk\beta} & q > 0 \\ q_{3/4} = \frac{k\alpha\Delta\overline{T}}{2} \pm \sqrt{\left(\frac{k\alpha\Delta\overline{T}}{2}\right)^2 + Hk\beta} & q < 0 \end{cases}$$

The solution q_3 is discarded, because it contradicts the assumption that $q < 0$. Further it can be readily shown that solution q_2 is unstable. This simplest possible model of the THC has two stable equilibria, with sinking either at high ($q_1 > 0$, thermally dominated, poleward near-surface flow) or at low latitudes ($q_4 < 0$, salinity dominated, equatorward near-surface flow).

5. Assuming that $\Delta\overline{T}$ is given, the solutions for q depend only on the value of H, the salinity flux. Sketch the q_1, q_2 and q_4 solutions as a function of $H > 0$.

6. What is the critical value H_c of H for which $q_1 = q_2$. This is a bifurcation point.

7. Starting from the system in the state q_1, what happens if H is increased above the critical value H_c?

8. Temprature proxies indicate that during glacial times the temperature in the North Atlantic dropped abruptly during episodes of Heinrich events and the Younger Dryas (Fig. 3). Considering the role of the ocean circulation in redistributing heat meridionally, can you explain possible reasons of this abrupt changes?.

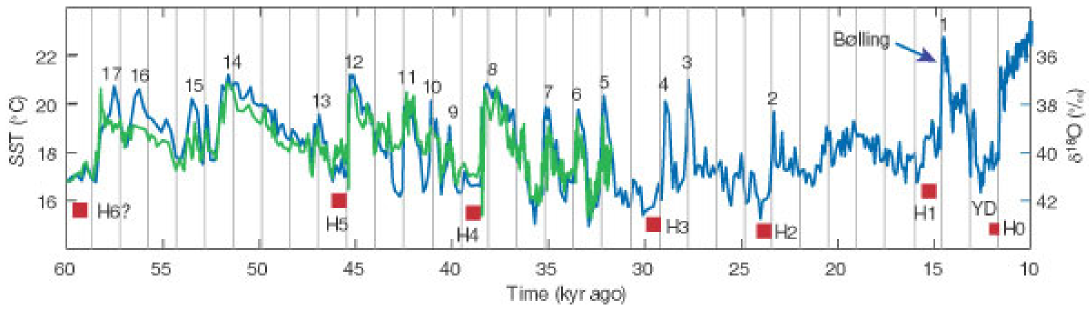

Figure 3: Proxy data from the subtropical Atlantic (green) and from the Greenland ice core GISP2 show several Dansgaard–Oeschger (D/O) warm events (numbered). The timing of Heinrich events is marked in red. The Younger Dryas (YD) event is also shown. (Rahmstorf, 2002).

Supplementary information:
`http://www.pik-potsdam.de/~stefan/thc_fact_sheet.html`

References

Marotzke, J. (2000). Abrupt climate change and thermohaline circulation: Mechanisms and predictability. *Proceedings of the National Academy of Sciences*, 97(4):1347–1350.

Rahmstorf, S. (2002). Ocean circulation and climate during the past 120,000 years. *Nature*, 419(6903):207–14.

Stommel, H. (1961). Thermohaline Convection with Two Stable Regimes of Flow. *Tellus*, 13(2):224–230.