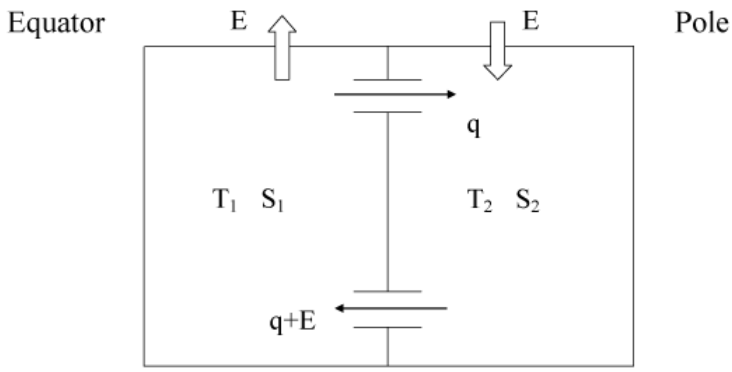
Thermohaline Circulation Model

Thermohaline circulation refers to the circulation of water in the oceans that occurs due to changes in density, changes which are themselves created by both surface heat and freshwater fluxes. "Thermohaline" comes from "thermo" (temperature) and "haline" (salt content); both of these factors determine the density of sea water. Wind-driven surface currents (such as the Gulf Stream) head polewards from the equatorial Atlantic Ocean, cooling and eventually sinking at high latitudes. This dense water then flows into the ocean basins and most of it upwells in the Southern Ocean. On its journey in the oceans, the water transports both energy (in the form of heat) and matter (solids, dissolved substances and gases) around the globe. As such, thermohaline circulation can have a large impact on the Earth's climate.

Evidence from ice cores and sediment records suggests that thermohaline circulation may have changed abruptly in the past. Many mathematical models have been developed to try to model thermohaline circulation, perhaps the simplest being the so-called "2-box model" developed by Stommel (1961), reviewed and augmented by many since then. Multiple equilibria of the thermohaline circulation are found in a wide range of these models.

In its simplest form, Stommel's box model consists of two well-mixed boxes, with prescribed temperatures T_1 and T_2 (maintained by air-sea heat fluxes), and salinities S_1 and S_2. The boxes are connected by two pipes, and additionally, there is a closed freshwater cycle, involving evaporation at low latitudes and precipitation at high latitudes, of transport E:



Key assumptions are:

1. within each box, T and S are well mixed;
2. a thermohaline circulation, strength q, flows through the pipes connecting the two boxes;

3. the transport of the thermohaline circulation through these pipes is a linear function of the density gradient,

$$q = k(\alpha \Delta T - \beta \Delta S),$$

where $\Delta T = T_1 - T_2$, $\Delta S = S_1 - S_2$, α and β are expansion coefficients, and k is a prescribed constant.

It can be shown mathematically that there are two equilibrium states:

Equilibrium 1: fast, thermally-driven circulation (present-day North Atlantic)

If the circulation is strong ($|q|$ is large) then evaporation and precipitation have insufficient time to modify the salinities significantly so $S_1 \approx S_2$, and hence the density gradient is controlled by $\Delta T = T_1 - T_2$.

Equilibrium 2: slow, salinity-driven circulation (present-day North Pacific)

If circulation is weak ($|q|$ is small) then $T_1 \approx T_1^*$ and $T_2 \approx T_2^*$, where T_1^* and T_2^* are the equilibrium values of T_1 and T_2 respectively. However, evaporation and precipitation have sufficient time to modify the salinities significantly so $S_1 \neq S_2$ and the density gradient can reverse.

Task 1

1. Write down a 'salt budget'for each of the two boxes in a steady state (i.e. balance the flux of salt in with the flux of salt out, for each box). Hence show that

$$|q|\Delta S \approx ES_0,$$

where $S_0(\approx S_1 \approx S_2)$ is a mean salinity. Why is there a modulus sign in this relation?

2. By eliminating ΔS, show that the equilibrium transport, q, is determined by the quadratic equation

$$|q|q - k\alpha\Delta T|q| + k\beta E S_0 \approx 0. \quad (1)$$

Equation (1) is the key equation which forms the basis of Stommel's 2-box model. In the following task you will investigate certain features of this equation for given parameter values.

Task 2

In this task you should use the following parameter values:

$\alpha = 2 \times 10^{-4}\text{K}^{-1},\ \beta = 0.8 \times 10^{-3}(\%)^{-1},\ k = 0.5 \times 10^{10}\text{m}^3\text{s}^{-1},\ \Delta T = 20\text{K},\ S_0 = 35\%.$

1. Plot a graph of the equilibrium transport q as a function of the freshwater transport E, for -0.5 Sv $\leq E \leq 1.5$ Sv. (Sv is the sverdrup, used almost exclusively in oceanography, to measure the transport of ocean currents. It is equivalent to 10^6 cubic metres per second.) Which part of the curve corresponds to solutions that are unstable?

2. What is the likely effect of increased atmospheric CO_2 on the freshwater transport E, and why?

3. Using the graph, describe how the thermohaline circulation is likely to respond to increasing levels of atmospheric CO_2.

4. What is likely to happen to the thermohaline circulation if atmospheric CO_2 levels are subsequently reduced to present-day values?

Task 2 should have given you a feel for how it might be possible for the thermohaline circulation to change abruptly from one state to another. Indeed, evidence from ice cores are sediment records suggests that the thermohaline circulation may have changed abruptly in the past. The is no clear consensus on whether the North Atlantic theermohaline circulation is likely to collapse or not over the next century, although most climate models show a weakening.

<u>Task 3</u>

Read Stommel (1961) and Marotzke (2000).

Having completed the three tasks above, you are now free to extend your project as you wish. Suggestions include:

- Using Stommel's 2-box model above, investigate how a finite perturbation, for example an injection of freshwater to the high-latitude box, can flip the circulation into the other state.

- Marotzke and Willebrand (1991) took an ocean general circulation model in an idealised domain containing two identical ocean basins (intended to represent the Atlantic and Pacific) connected by a circumpolar Southern Ocean. They were able to obtain four of the potential sixteen equilibria. Reproduce their results, or produce results for different parameter values and discuss any similarities or differences observed.

- In a warming climate, increased precipitation is likely to lead to a freshening of the high latitude oceans. Manabe and Stouffer (1994) studied the effect of increasing atmospheric CO_2 levels on the North Atlantic thermohaline circulation in a coupled ocean-atmosphere general circulation model. They performed three experiments in which CO_2 levels took different values. Reproduce their results, or produce results for different parameter values and discuss any similarities or differences observed.

The key paper on which this project is based is:

- Stommel, H (1961) *Thermohaline Convection with Two Stable Regimes of Flow*, Tellus XIII, 2.

Other papers include:

- Manabe, S., and R.J. Stouffer (1994) *Multiple Century Response of a Coupled Ocean- Atmosphere Model to an Increase of Atmospheric Carbon Dioxide*, Journal of Climate, 7(1):5-23.
- Manabe, S., and R. Stouffer (1993) *Century-Scale Effects of Increased Atmospheric CO2 on the Ocean-Atmosphere System*, Nature, (364) 215-217.
- Marotzke, J (2000) *Abrupt climate change and thermohaline circulation: Mechanisms and predicatability*, PNAS Februay 15, vol.97 no.4, 1347-1350.
- Marotzke, J. & Willebrand, J. (1991) *Multiple Equilibria of the Global Thermohaline Circulation*, J.Phys. Oceanogr. 21, 1372-1385.

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