Modeling the Thermohaline Circulation

Background

Surface ocean currents are driven mainly by the winds, but the deeper circulation of the oceans is mainly driven by density differences caused by changes in salinity and temperature. This kind of temperature and salinity driven flow is often called thermohaline circulation and it is a very important feature of the oceans, exchanging water (along with all of its dissolved constituents) between the surface and the vast deep water reservoir.

From the relationship between temperature, salinity, and density (Fig. 1) we see that colder waters are denser than warmer waters, and saltier water is denser than fresher water.

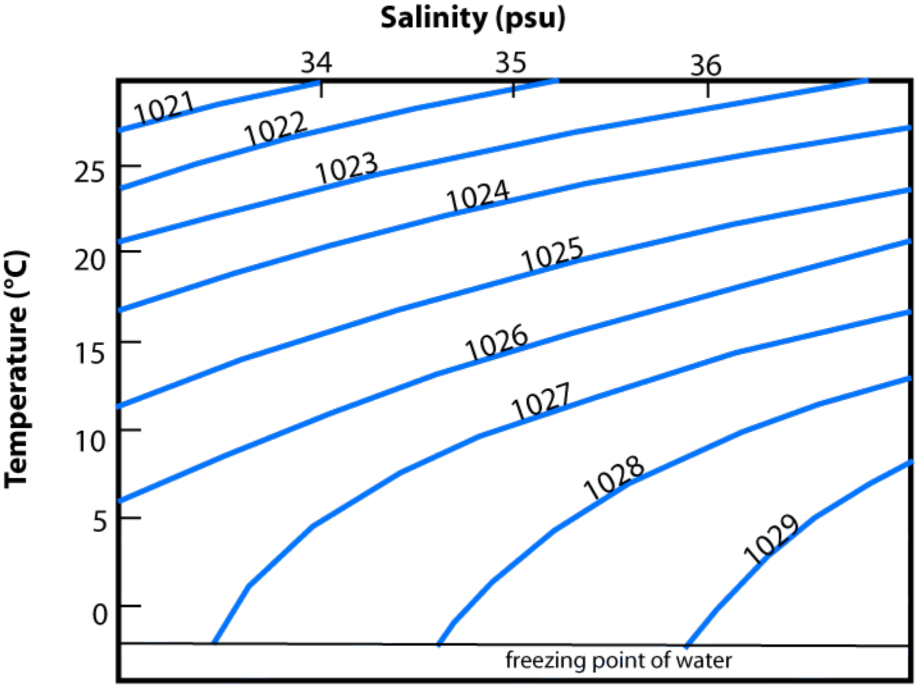


Figure 1. Changes in the density of seawater caused by changes in salinity and temperature. The blue lines are lines of equal density; density contours are in units of kg/m³.

In the North Atlantic, the salinity of the surface water is significantly higher in the south than the north (Fig. 2), which is largely due to differences in evaporation and precipitation. Evaporation increases salinity, while precipitation and river input decrease salinity.

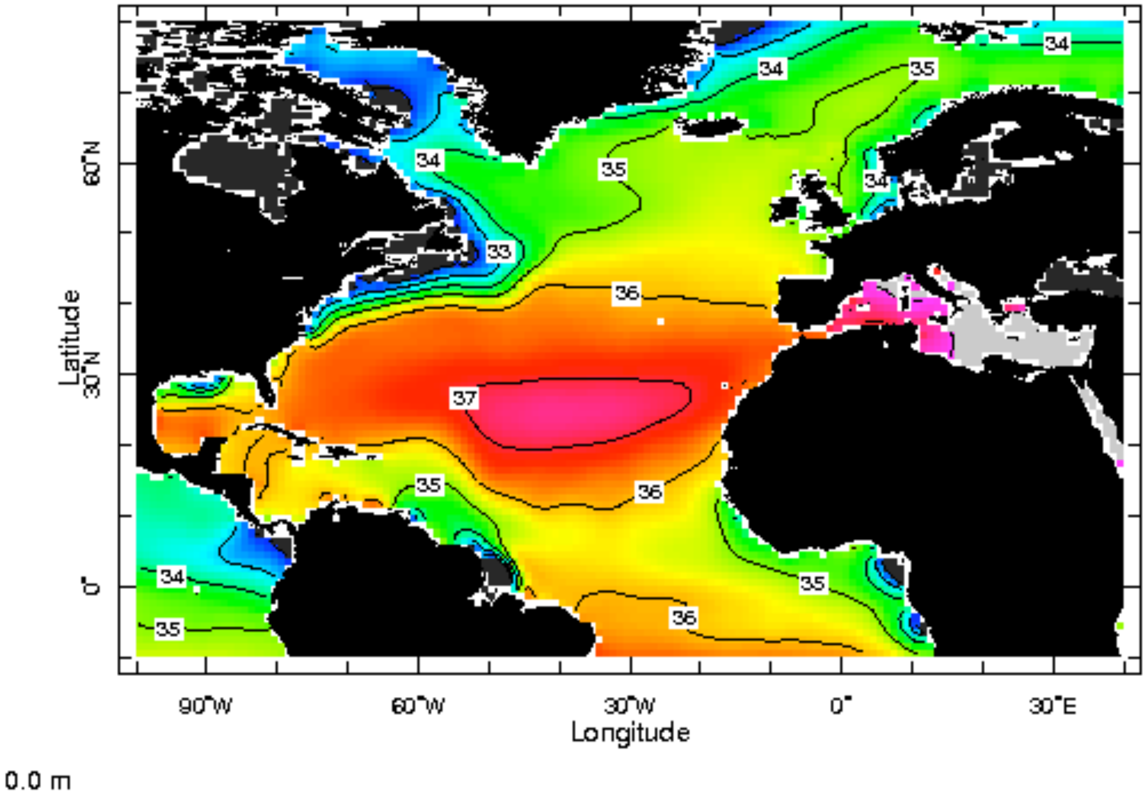


Figure 2. Annually averaged surface water salinity in the North Atlantic, from the NOAA NODC WOA05 database, accessed at: http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NODC/.WOA05/.Grid-1x1/.Annual/.an/.salinity

The Gulf Stream (Fig. 3) delivers some of this warm, salty water into the North Atlantic, where it cools and becomes dense enough to sink to the bottom of the ocean, initiating one of the main deep currents in the global ocean, the North Atlantic Deep Water (NADW).

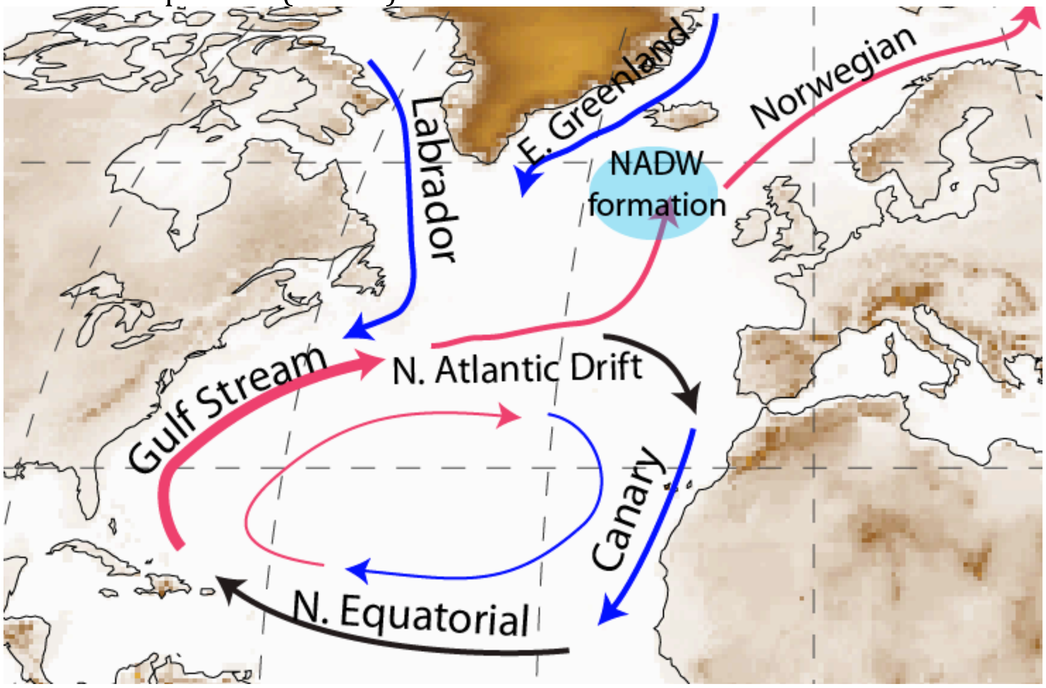


Figure 3. Simple representation of the major surface ocean currents in the North Atlantic. Red arrows are warm currents, blue are cold currents and black arrows are neutral in terms of movement of heat. The primary location of NADW formation is shown by the blue ellipse.

This NADW eventually returns to the surface and makes its way back into the North Atlantic, where rejoins the Gulf Stream, creating what Broecker (1991) calls the Great Ocean Conveyor, which is of great importance to the global climate system.

To provide a sense for how important this system (which includes the Gulf Stream and the NADW flow) is, consider the following rough calculation of how much heat is delivered to the polar region.

> Volumetric flux or discharge of NADW formation = 2e7 m^3/s
>
> Density of seawater = 1e3 kg/m^3
>
> Mass flux (F_m) = (2e7 m^3/s) x (1e3 kg/m^3) = 2e10 kg/s
>
> Temperature change during cooling (ΔT) = 25°C
>
> Heat capacity of water (C_p) = 4184 Joules $\cdot$ $kg^{-1} \cdot °C^{-1}$
>
> Energy flux = C_p x ΔT x F_m = 2.09e15 Joules/s (same units as a Watt)

This is a big number — a lot of energy — but what does it mean? If you take this energy and spread it out over the whole polar region above 60°N latitude, you come up with 61 W/m^2, and the sunlight up there provides an average of 190 W/m^2, so this process provides about 25% of the total energy for that region, which is enough to cause ice sheets to grow or shrink, and as they grow or shrink, they can change the albedo to the point where it could influence the climate over a vast area beyond the polar region.

Back in 1961, Henry Stommel studied this thermohaline circulation in the form of a simple model system, one in which there are two boxes or reservoirs of water — one warm and salty, the other cold and fresher — and water is exchanged between the boxes by means of both a surface flow and a deep flow. This system is a highly simplified version of the North Atlantic and by exploring the behavior of this system, Stommel discovered some unexpected complexity that is now widely believed to be related to some dramatic and abrupt climate shifts that have occurred in the last 100,000 years. Stommel realized that this seemingly simple system has two stable states (or conditions) that are characterized by very different flow strengths and that very small perturbations can cause it to flip from one stable state to another. These flips in state can have serious climatic consequences by changing the amount of heat supplied to the polar region. The flipping of this thermohaline circulation system is hypothesized to be the explanation for some abrupt climate changes revealed by the oxygen isotope record of temperature supplied by ice cores from Greenland (Fig. 4).

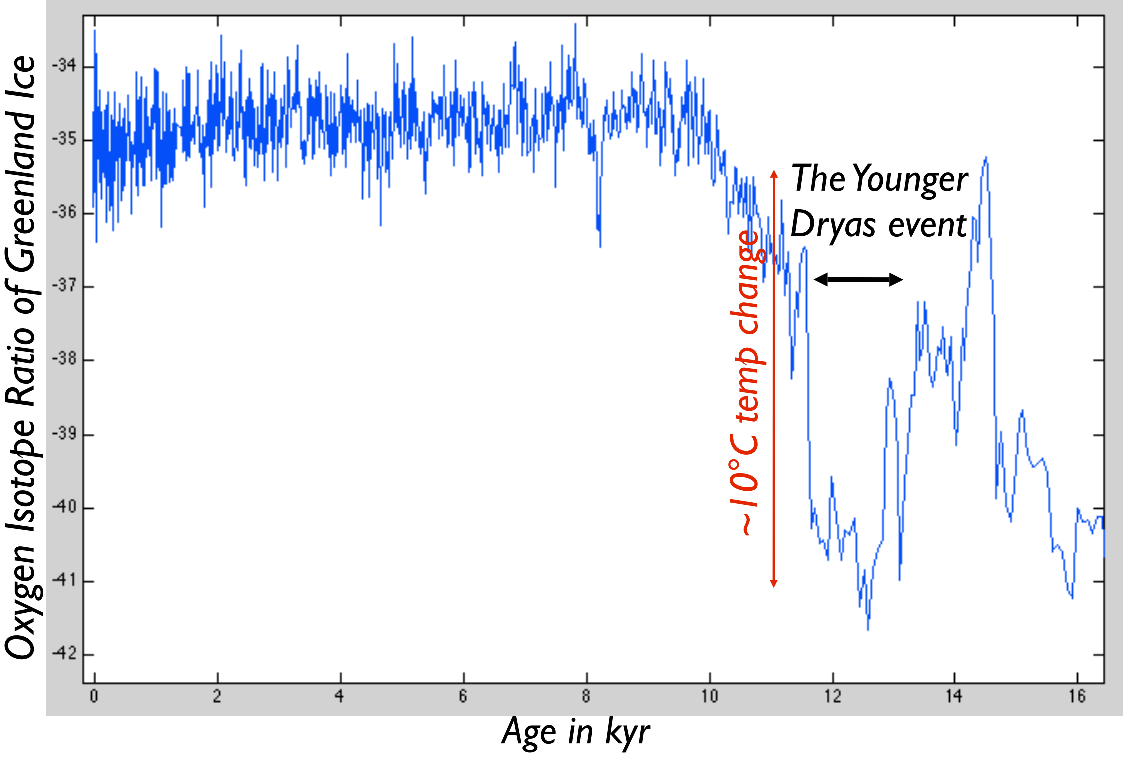


Figure 4. The oxygen isotope record from the GRIP ice core in Greenland for the last 16 kyr, showing the dramatic, abrupt cooling and warming that define the onset and end of the Younger Dryas event. The more negative values of the oxygen isotope ratio reflect colder temperatures.

The Younger Dryas event (Fig. 4) was marked by a sudden cooling, a thousand years of cold, and then abrupt warming, and the transitions appear to have occurred in a matter of years to decades. The magnitude of the temperature changes are shocking and the Younger Dryas is the only such event; there are at least four others in the past 50 kyr. This leads us to some important questions regarding the causes this flipping. What triggers the switch? How does it work? We can make some progress towards answering these questions with a simple model based on Stommel's work.

The STELLA Model of Thermohaline Circulation

The first step in making a model is to create a conceptual diagram of the system, which should be as simple as possible, and then from that diagram we can create a STELLA model with appropriate equations and values plugged in. The conceptual diagram below (Fig. 5) is adapted from Stommel's work, and the STELLA model is based on Stommel's mathematical description, which takes the form of two differential equations — flows in the world of STELLA models — that are interconnected.

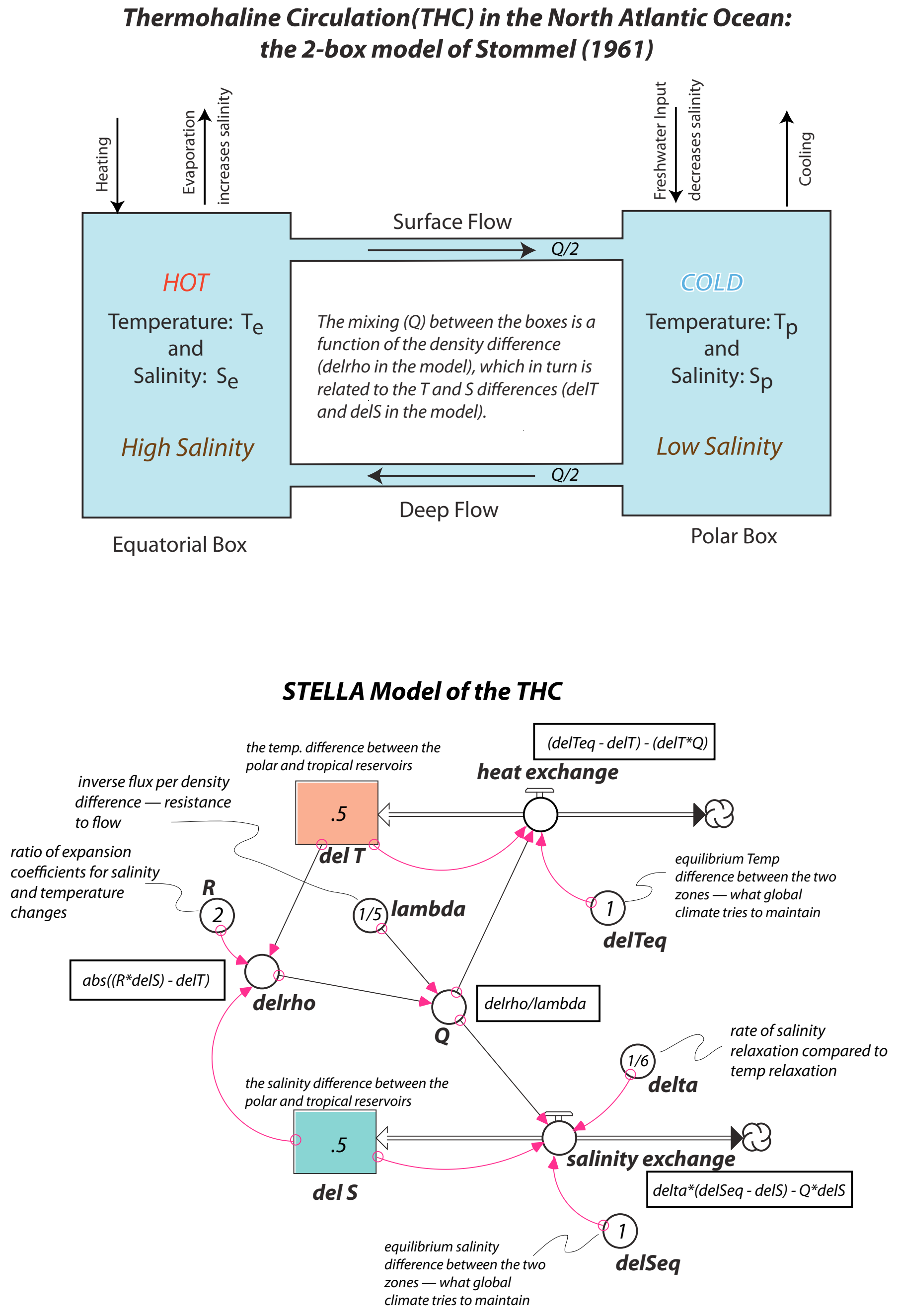


Figure 5. Conceptual diagram and STELLA model for thermohaline circulation (THC) based on Stommel's 1961 paper.

It helps to study Figure 5 carefully before starting to experiment with the model. The two reservoirs (equatorial and polar) have inherently different salinities and temperatures due to the global climate — the equatorial box is hot and salty, while the polar box is cold and less saline (fresher) — and the global climate will always try to maintain these differences. These differences are labeled delTeq and delSeq in the STELLA model (del = delta (difference), T = temperature, eq = equilibrium). But these inherent differences in salinity and temperature create a density difference between the two boxes (delrho; rho is the greek letter used for density), which then drives a flow between the two boxes (Q) which mixes them and thus tends to reduced the differences between the two. The mixing flow is divided equally into a surface flow (i.e., the Gulf Stream) and a deep flow (i.e., the NADW).

Turning our attention to the STELLA model, the first thing to note is that the reservoirs are the temperature and salinity *differences* rather than the actual values of each of the two zones (equatorial and polar) — Stommel realized that this would make the math easier and he did not have a computer to work with on this problem. The flows going in and out of the reservoirs are then *changes* to the temperature and salinity *differences*, and not just changes in temperature and salinity of each zone. The model includes a few parameters we have not yet discussed: R is the ratio of the affect of salinity versus temperature on density (density is twice as sensitive to salinity as temperature), lambda is something that expresses friction or resistance to flow, and delta expresses the rate of salinity relaxation (return to the equilibrium salinity difference imposed by climate) relative to the rate of temperature relaxation (temperature relaxes about 6 times faster than salinity).

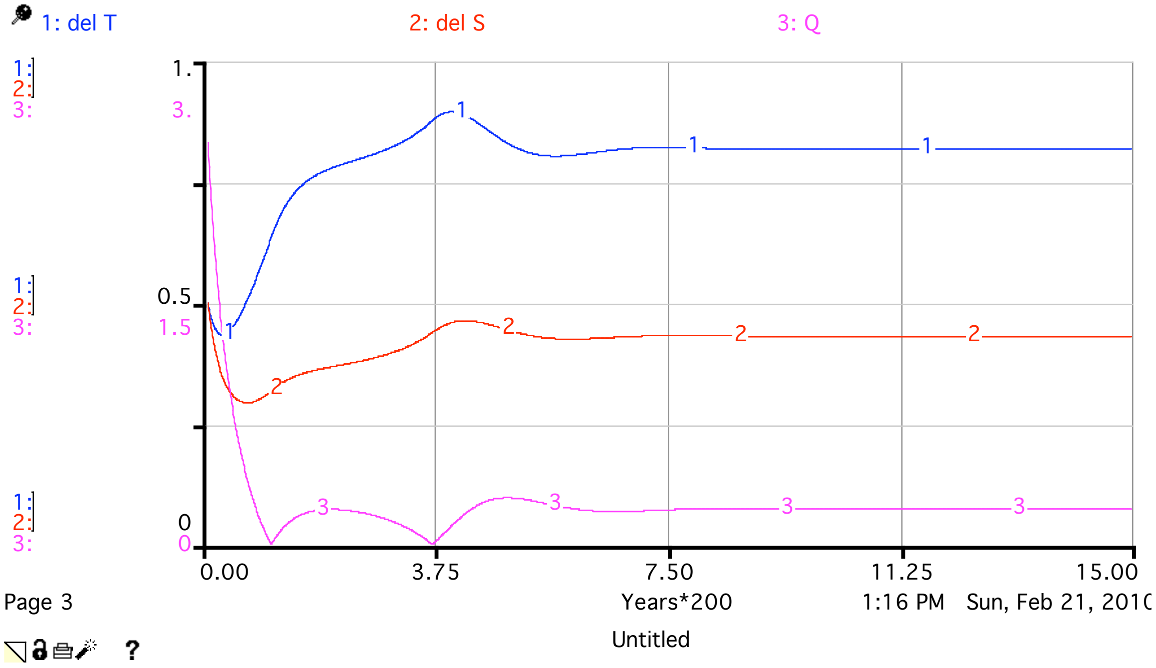
Experiments with the Thermohaline Circulation Model

There are a couple of options here. The best one is to get a copy of STELLA and build this model yourself; if you don't have a license for STELLA, you can work with a web-based version by following this link:

http://forio.com/simulate/dmb53/thc-stommel/simulation/

The web-based version is less interactive and the graphics are more limited, but you can still do these experiments and learn some interesting things.

Construct a STELLA model of Stommel's THC system following the design provided in Figure 5. Be sure that your flows are biflows with the open arrows pointing towards the reservoirs. Set the model to run from 0 to 15 (time units are scaled to the diffusional time scale of the system, which is thought to be about 200 years), with DT =0.01, using the Runge-Kutta 4 method. Here is what your model output should look like (note that I've got the delT and delS plotted on the same scale):



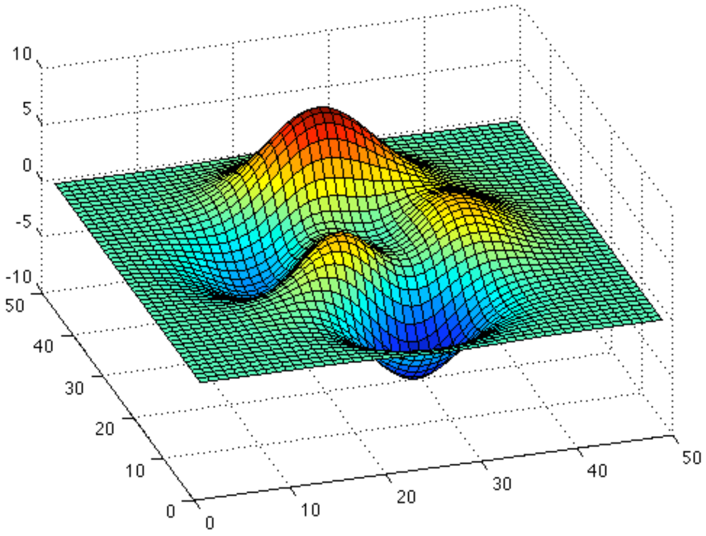
If you get results like this, then your model is ready to experiment with. If you don't get these results, go back and check the model construction carefully.

Notice that the system is not in steady state to begin with, but that it finds a steady state after about 5 or 6 time units (remember that each time unit here is about 200 years). The evolution of the system into the steady state is complex — the salinity difference overshoots the final steady state value and the temperature difference initially heads off in the wrong direction and then it also overshoots the final steady state value. Q, which you can think of as representing the combined Gulf Stream and NADW flows, initially starts off very strong and then declines to 0 at two points before eventually reaching a steady value. Q here is designed so that it cannot be less than 0 — it is a measure of the *magnitude* of flow and not the *direction* of flow. Note that when Q=0, both delT and delS increase — they will approach the delTeq and delSeq values. High values of Q mean strong mixing between the polar and tropical portions of the ocean and this will tend to make their temperatures and salinities more similar, thus making delT and delS be lower. *A high Q value also means strong transport of heat from the tropics to the polar region.*

Experiments

1. Varying initial reservoir values.
a) Change the delS initial value from 0.5 to 0.
b) Before running the model, take note of the steady state values of delS, delT, and Q from your first model run.
c) Then, make a prediction about how the reservoirs will begin to change at first and where they will end up at the end of the run — will the system return to the same steady state?
d) Run the model and see what happens, then describe the results.

e) Now we will explore a wider range of initial values to better understand the steady states of this system. Go to the Sensi Specs window (from the Run menu) and send both reservoirs over to the selected column. Make 11 runs, and have delS start at 0 and end at 1 and delT go from 1 to 0; be sure to hit the Set button after you define the starting and ending values. Then set up a graph to view the results — make it a comparative scatter plot, with delS on the X axis and delT on the Y axis. Make sure the Run Specs are set to run from 0 to 15 time units with a DT=0.01. Then run the model and see what happens. You can watch the trajectory of each run by following the dots — they move fast when the system is not in steady state, but they become stationary when a steady state is achieved. So if there is one steady state, all dots will converge on a single spot; if there are multiple steady states, then you'll see more than one convergence. These convergences, also known as attractors, can be thought of as similar to topographic depressions — imagine a topographic surface with some peaks and some depressions (see schematic illustration below) — the depressions represent conditions where the two flows in our model are both zero. If you toss a bunch of marbles onto this smooth surface, they will tend to find their way to the depressions, and the initial starting point of the marble determines which depression it ends up in.



Now, study the results of these model runs and find out how many steady states there are for this system (you may want to modify your sensitivity specs a bit to cover more of the space in the delS vs. delT plot) and then report the delT, delS coordinates of the steady states. ***[Note: the web-based version of the model does not allow the Sensi Specs feature, but you can simulate this by running the model many times and studying the comparative plots of delT and delS to see if there is one or more common steady state values]***

f) Characterize the steady states by looking at the magnitude of Q, the exchange flow between the two oceanic boxes. High Q would mean a vigorous Gulf Stream – NADW system, which would be associated with lots of heat transport from the equator to the poles. Which of the steady states (designated by the delS, delT steady state values) is associated with a warmer polar region?

2. Changes in temperature.

What will happen to this system if the climate warms? How can we modify the system to represent a warmer climate? As you may know, the recent climate change has been characterized by greater warming at high latitudes, which tends to reduce the gradient from the poles to the equator. In our model, the temperature difference between the polar and equatorial regions is represented by the ***delT*** reservoir. The value or magnitude of ***delT*** is a function of two things — the density-driven mixing that tends to even out the temperature difference (reducing ***delT***) and the climate-controlled temperature difference (***delTeq*** in our model), which is set to 1. If we reduce ***delTeq***, that will tend to drive the system to a lower ***delT*** value.

a) Set ***delTeq*** equal to time (just type in time; STELLA knows what this is) and then click the button that makes it a graphical function. Make the upper limit 1 and the lower limit 0.5 (anything lower would be too extreme). Set the time axis to go from 0 to 30 so that we can make the change in ***delTeq*** *after* the system has gotten into a steady state (it would be hard to understand the effect of the change during the adjustment to steady state). ***[the web-based version already has set as a graphical function of time]*** After about 8 time units, make ***delTeq*** step down to a lower value (try 0.8 to 0.5) and then have it remain at that value for about 2 to 10 units of time and then return it to 1 (you'll want to try a range of values here). There are two questions to answer here:

c) Working with the initial ***delT*** and ***delS*** settings of 0.5, how does the system respond to different magnitudes and durations of the excursion of ***delTeq***?

d) Does the system always bounce back to the original steady state, or can it get knocked into the other steady state?

e) If it does get knocked into another steady state, is it one of the same steady states that we found earlier, by just changing the initial values of the reservoirs without tampering with ***delTeq***?

f) In general, describe how this change affects the magnitude of ***delS***, ***delT***, and ***Q***. This will require some careful analysis of the model parameters, but do your best to explain why the system behaves this way.

g) With the two reservoirs initially set to 0.5, the system would find one of two steady states, and we've been tampering with that steady state. Now, let's do the same kind of tampering with the other steady state. Using your results from the first experiment, set the initial values of delS and delT to represent the other steady state.

h) How does it react to the periods of decreased ***delTeq***?

i) Is this steady state more sensitive or less sensitive to ***delTeq*** changes than the other steady state?

3. Freshwater pulses.

The Younger Dryas is believed to have been triggered by a change of state in the THC due to a pulse of freshwater (from melting glaciers) added to the North Atlantic. Cessi (1994) figured out that the pulse of water, in Stommel's model would represent a flux of 0.2 ***delS*** units for a period of between 3-5 time units. Find a way to modify your model to simulate this freshwater pulse — you want to *add to* the ***delS*** reservoir for a limited period of time, and you want to impose this on the steady state condition that represents the warmer (high ***Q*** and low ***delT***) of the two steady states. *For the web-based version, you can simply modify the graphical converter called pulse history and then turn on the switch labeled* ***pulse****.*

a) Show how you make this change to your model (make a sketch, or print out the altered model), and then carry out the experiment.

b) Does this pulse knock the system into the colder of the two steady states, or does it stay in the warmer (stronger Q, greater delS and delT) state?

c) Describe what happens after the pulse of freshwater has ended? Again, delve into the inner workings of the model to understand what is going on.

d) What is the minimum *magnitude and duration* of freshwater pulse that is needed to knock the system into the other steady state?