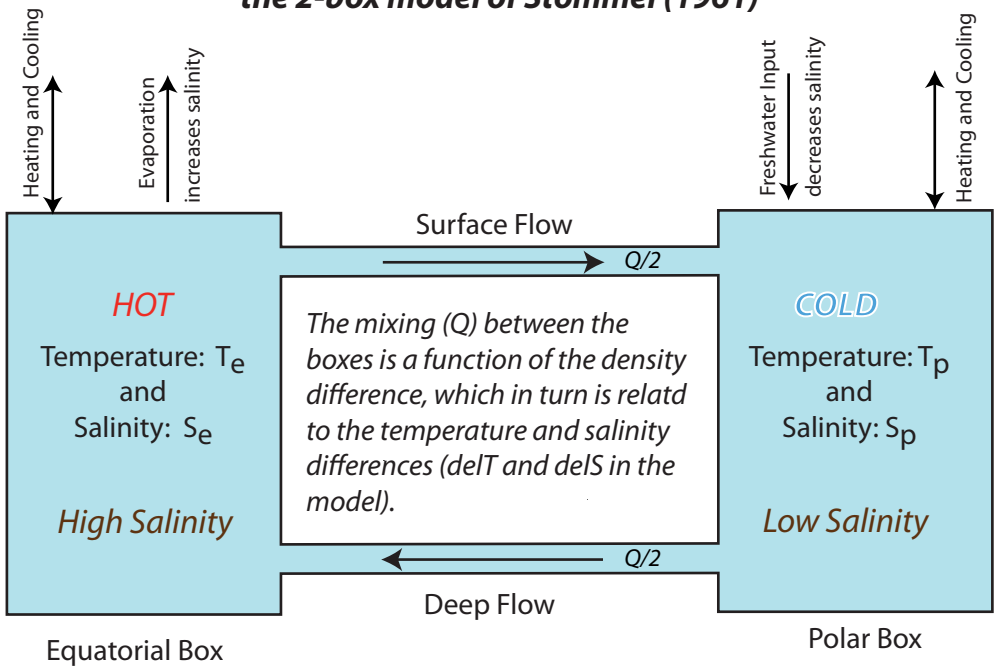
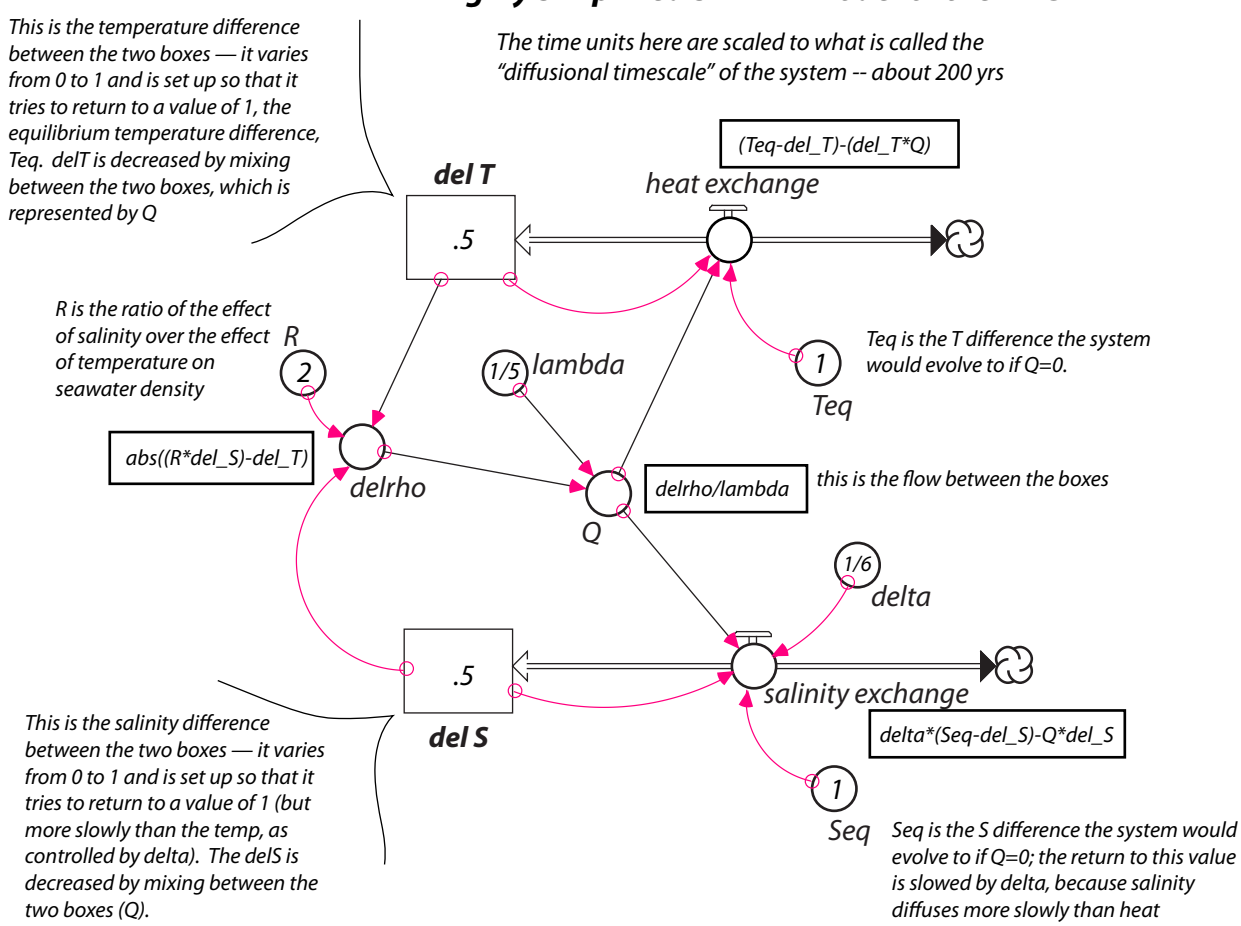
The following is from a lab project in Earth 202: Modeling the Earth System, taught by Dave Bice and Jim Kasting at Penn State University. Prior to this exercise, we spend a week talking about ocean circulation, the controls on seawater density, and some of the details of deep currents based on exploring datasets from the IRI/LDEO data library (http://iridl.ldeo.columbia.edu/). We also spend time going over the Younger Dryas and the D-O events and their implications Then, the students build the model, using the recipe included here.

Thermohaline Circulation(THC) in the North Atlantic Ocean: the 2-box model of Stommel (1961)

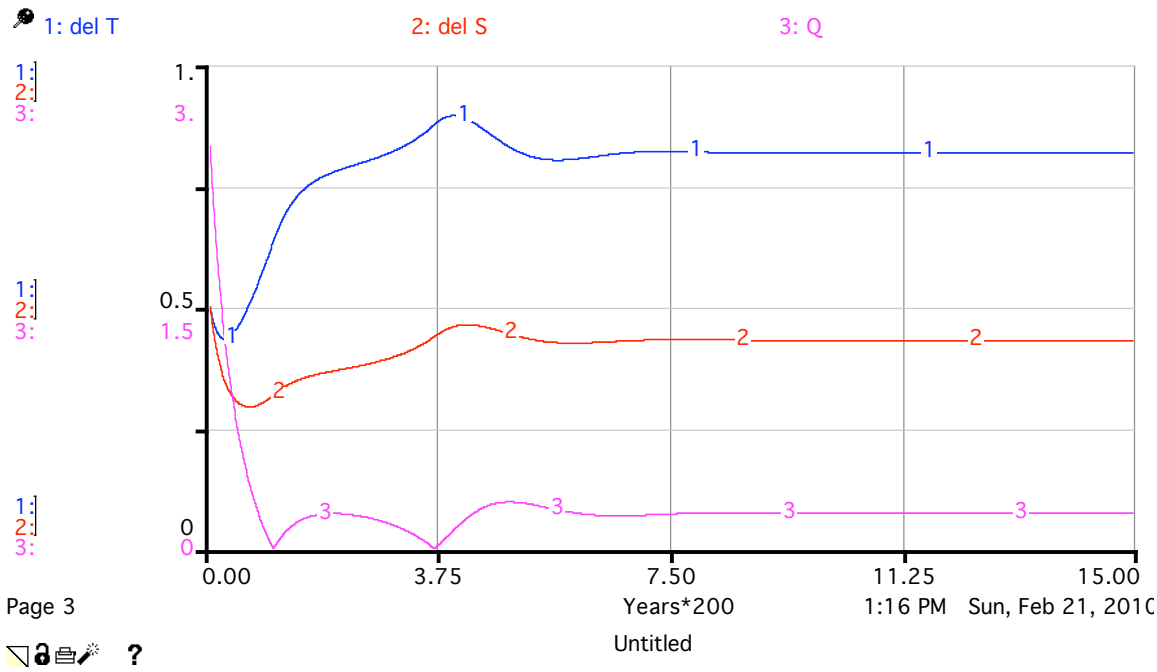


Highly Simplified STELLA Model of the THC



Experiments with the Thermohaline Circulation Model

Construct a STELLA model of Stommel's THC system following the design provided. 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 2 method. Here is what your model output should look like (note that I've got the delT and delS plotted on the same scale):



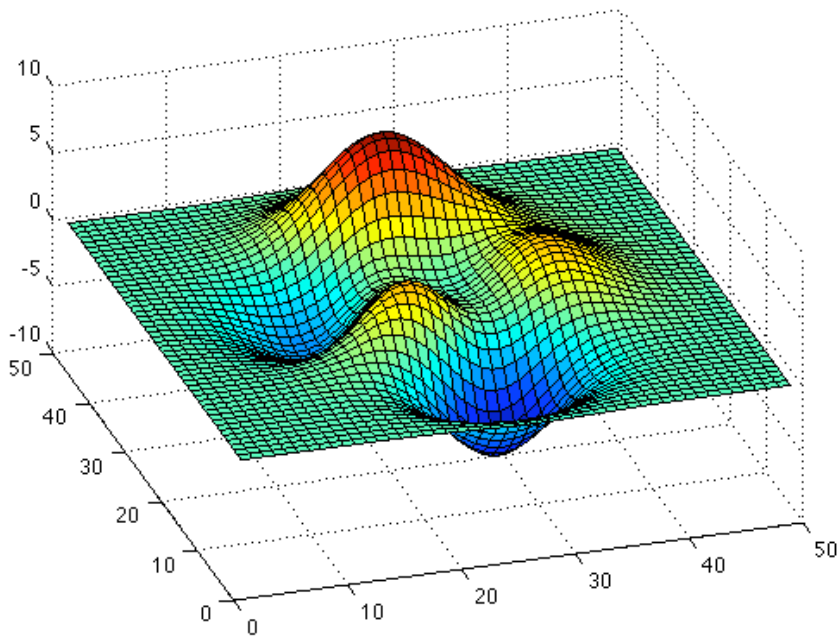
If you get results like this, then your model is ready to experiment with. If you don't get these results, go back and check the model construction carefully.

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. 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 Teq and Seq 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. Before running the model, take note of the steady state values of delS, delT, and Q from your first model run. 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? Run the model and see what happens, then describe the results.

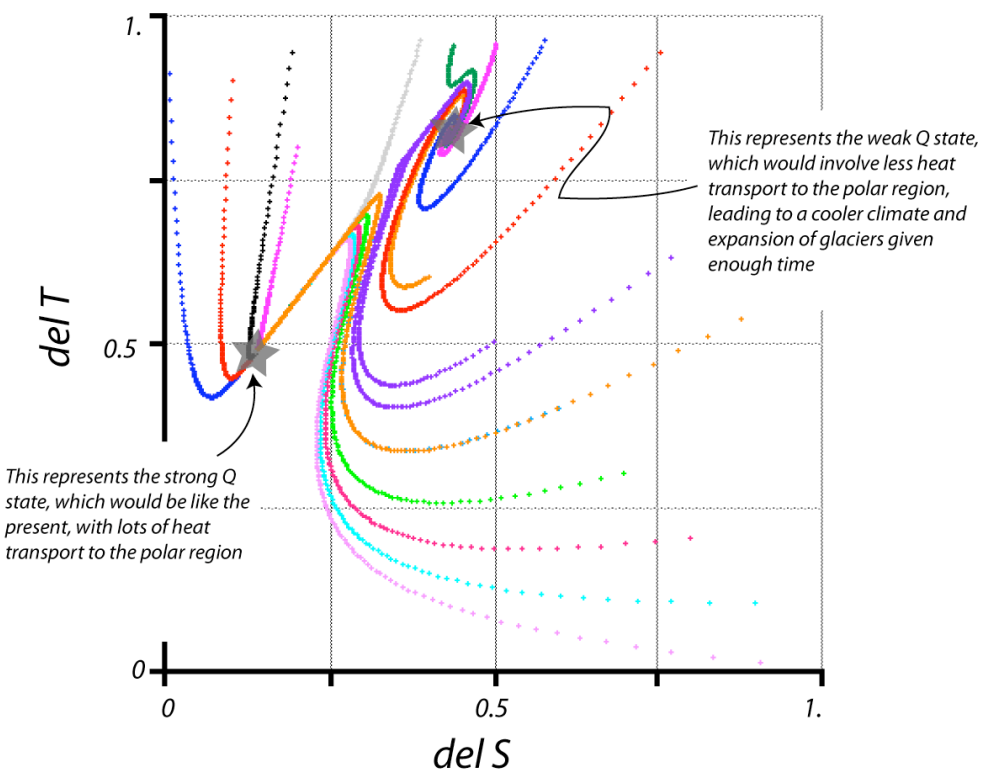
b) Now we will explore a wider range of initial values to better understand the steady states of this system. Go to the Sensi Specs window, from the Run menu and send both reservoirs over to the selected column. Make 11 runs, and have delS start at 0 and end at 1 and delT go from 1 to 0; be sure to hit 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.

Here is what they see:

Varying Initial Conditions Reveals 2 Stable States (marked by stars)



c) 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.

Experiments 2 and 3 to be done as homework, due next Friday.

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 (***Teq*** in our model), which is set to 1. If we reduce ***Teq***, that will tend to drive the system to a lower ***delT*** value.

So, set ***Teq*** equal to time and make it a graphical function of time. 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 ***Teq*** *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). So, after about 8 time units, make ***Teq*** step down to a lower value and then have it remain at that value for a brief period of time and then return it to 1. There are two questions to answer here:

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

b) 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. How does it react to the periods of decreased ***Teq***? Is this steady state more sensitive or less sensitive to ***Teq*** changes than the other steady state?

3. Freshwater pulses.
Recall from lectures that the Younger Dryas is believed to have been triggered by a change of state in the THC due to a pulse of freshwater 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.

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. Does this pulse knock the system into the colder of the two steady states? In other words, does it stay in that other state even after the pulse of freshwater has ended? Again, delve into the inner workings of the model to understand what is going on.

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