

The Effect of Bathymetry Changes on Meridional Overturning Currents

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Abstract

1 Introduction

The geometry and resulting bathymetry of our planet is an ever changing phenomenon. In the last 120 Ma the earth moved from having one major oceanic system in the Pacific with a single large continent to the current 3 ocean system (Besse and Courtillot 2002). The Bathymetry changes that occurred in this time period are characterized by the opening and closing of certain passages through which exchange of water between the oceanic basins is observed. The exact timing of passage openings is a topic of rigorous debate in literature (Scher and Martin 2006, Schmidt 2007).

One of the changes on which there is general consensus, is the inception and expansion of the Atlantic ocean and the resulting decrease in size of the Pacific basin. The creation of the Atlantic basin has had major effects on the earth's climate, especially resulting in massive localized changes such as the temperate European climate, due to the north Atlantic meridional overturning current (AMOC). This creates the current Northern sinking oceanic throughflow in the Atlantic. However it is unknown when exactly this northern sinking started. With the past non-existance of the Atlantic it must have started some time in the last 40Ma with the advent of a larger Atlantic (Abelson and Erez 2017).

The result of these bathymetry changes on the oceanic stream function and the resulting overturning currents is something that has been previously studied by Mulder et al. 2017. They however found that using a Jacobian matrix for continuation in

each of the model years fails to simulate the onset of the Northern sinking AMOC that is physically observed. Here we instead propose to use a general circulation ocean model with only a changing bathymetry keeping the same initial forcing for each time step. This eliminates the need for a continuation using the Jacobian matrix method proposed in Mulder et al. 2017.

This paper will focus solely on changes in bathymetry using simplified zonally averaged global forcings. The results of the model will be used to estimate global changes in oceanic through flow at the critical passages. Furthermore the strength of the meridional overturning currents (MOC) will be studied.

2 Methods

2.1 Simplified Forcings

The domain chosen is bounded by longitudes $\phi_E = -180^\circ$ and $\phi_W = -180^\circ$ and latitudes $\theta_N = 80^\circ$ and $\theta_S = -80^\circ$ with periodic boundary conditions in the zonal direction. Furthermore the model uses restoring boundary conditions first proposed by Haney 1971. Restoring the boundary at the surface of the oceanic basin to be a certain value based of a forcing field for Sea Surface Temperature (SST), Sea Surface Salinity (SSS), and wind stresses (τ). The depth profile has 15 layers with grid stretching. There are 90×40 grid points to make a $4^\circ \times 4^\circ$ resolution model. The forcings are

prescribed as in Mulder et al. 2017 by highly idealized zonally averaged forcings using current day values. The SST and Zonal wind stress are chosen as the analytical model in Bryan 1987. While SSS is chosen as a zonal average of current day val-

ues (from ECMWF but not sure how to cite). The meridional wind stress is set to zero. The maximum ocean depth is 5000m. The model also requires initial conditions for salinity and temperature, for this zonally averaged present day values are again used.

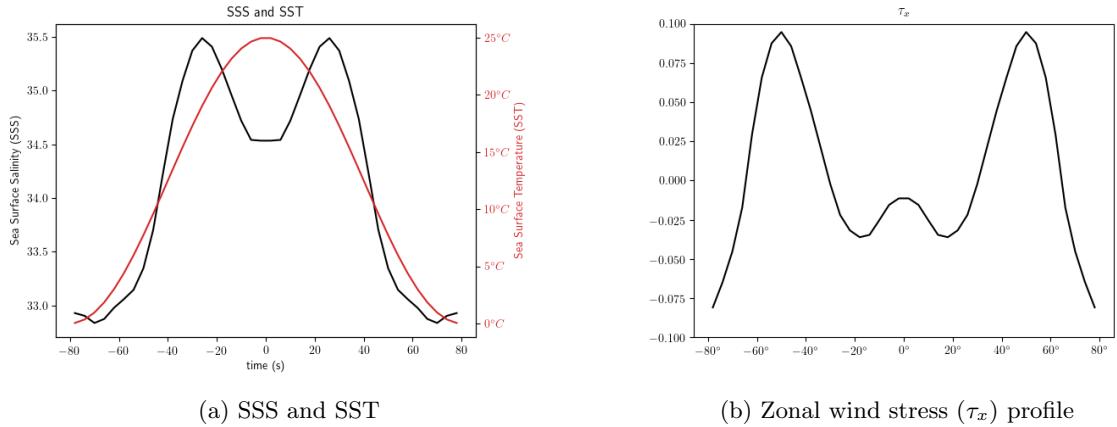


Figure 1: Idealized forcing profiles

2.2 Creating Bathymetries

To facilitate the model a set of 14 bathymetries were created in 5Ma time steps. These run from 65Ma to the present day configuration. These were reconstructed from bathymetries gained in Baatzen et al. 2016. These bathymetries were subsequently scaled to a 4 degree model and changed to address passage openings in the 4 degree case. Due to the low resolution of the model, choices have to be made with respect to the opening of certain passages. One of the choices that was made is that the northern Arctic sea is closed off in all of the bathymetries. This is mainly due to the fact that 4 degree models do not have enough resolution to facilitate this sea and Veros lacking the ability to have polar flow. The main events that shape the oceanic passages can be divided into time periods. These time periods are defined as follows in this paper. This deviates from their definitions in literature but serves only as a means of applying a name to the time steps.

	From	Until
Paleocene	65Ma	55Ma
Eocene	50Ma	35Ma
Oligocene	30Ma	20Ma
Miocene	20Ma	Present

In the paleocene a vast Pacific exists almost serving as a single basin. This period is largely characterized by the growth and development of a larger atlantic basin. Serving to decrease the size of the pacific basin. We thus expect that the main flows here are concentrated in the pacific. There is probably no possibility for northern sinking in the atlantic due to the smaller size of this basin.

The Eocene in contrast to the Paleocene is distinguished by The opening of certain passages connecting oceanic basins. These effects are often studied extensively for each individual passage in the literature. Choosing the exact timing for opening the passages is done manually by looking at often active research. This was done taking into account big uncertainties in the exact timing of the openings often making choices such that the differences in passage openings can be seen in the final integrations.

The first of such passage changes that occurs is the Indian continent colliding with the Eurasian continent. This has the effect of closing the deep water formations between the Thethys sea and the Pacific ocean. The first throughflow over the indian continent is possible at 45Ma.

Next the Tasman passage is opened at 35Ma as a shallow passage slowly growing in size(Lawver and Gahagan 2003). The Tasman passage opening

is believed to have had a large impact on the onset of the ACC. The Total circulation of water around the Antarctic basin is finalized by the opening of the shallow Drake passage at around 30Ma. 30Ma is specifically chosen to differentiate between the opening of the drake and Tasman passages. Especially since there is still some debate on the exact timing of drake passage opening (Scher and Martin 2006). These openings will probably result in the onset of the Antarctic circumpolar current that has had major effects on the global climate variability.

The next time period is the Oligocene Which is largely characterized by the deepening of the Tasman and drake passage and further expansion of the Atlantic basin. Here we expect to see the onset of further strengthening of the ACC.

The Miocene is Characterized by Some more passage closures. The Thetys seaway had been decreasing in size in the previous 20Ma. Also the Indonesian passage is significantly decreasing in size due to the onset of multiple islands and the further displacement of the australian continent. This results in a narrower and shallower passage. Furthermore the Tethys seaway is finally closed at 15Ma(Hamon et al. 2013), Making northern flow over Africa between the Atlantic and Indian oceans impossible from this point onward. Then another major change occurs with the closure of the panama seaway (Molnar 2008; Pindell et al. 1988). Stopping the mid latitude throughflow between the Atlantic and Pacific basins.

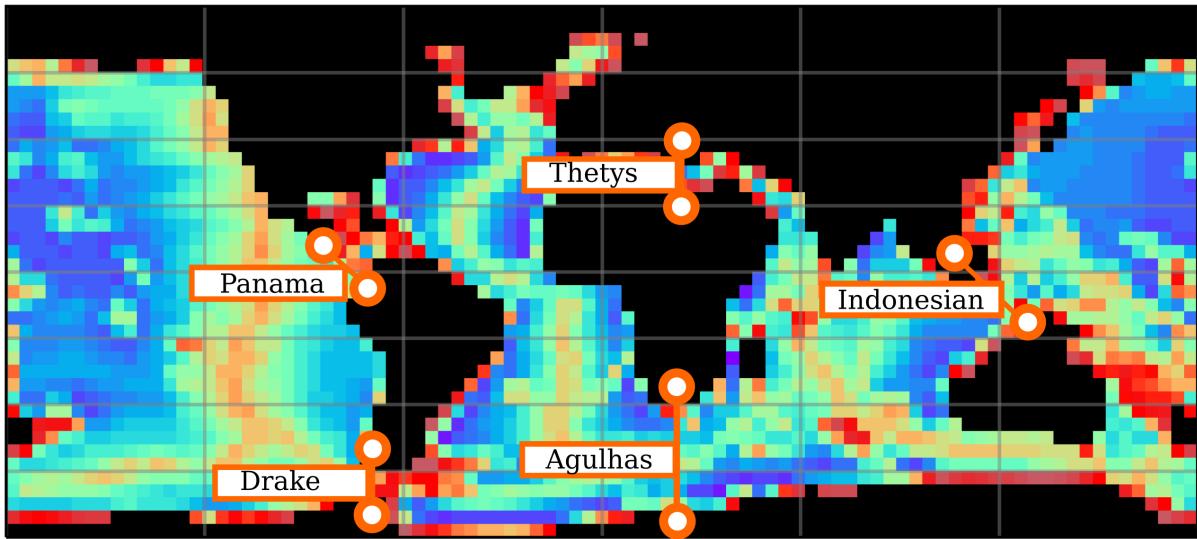
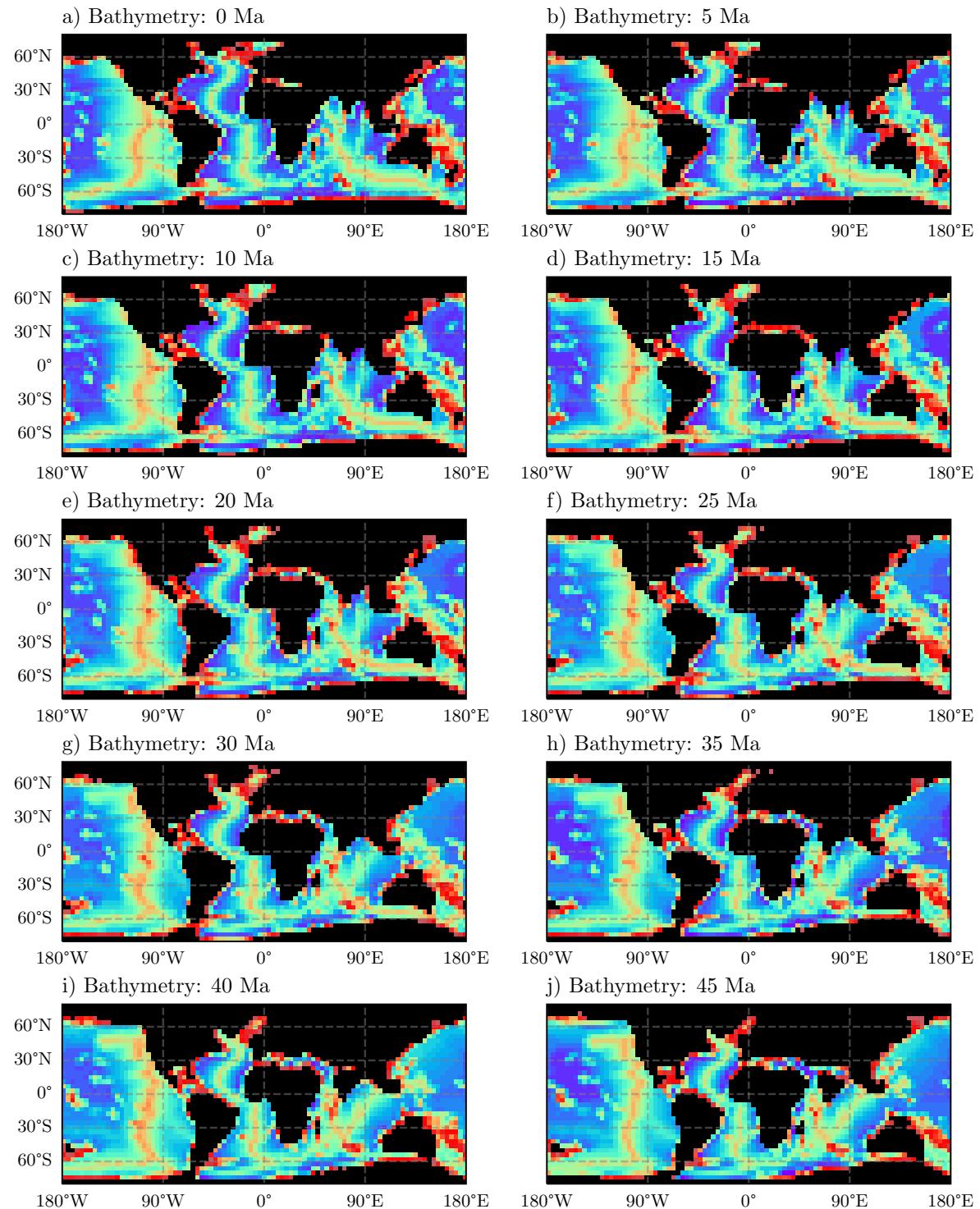


Figure 2: Passages



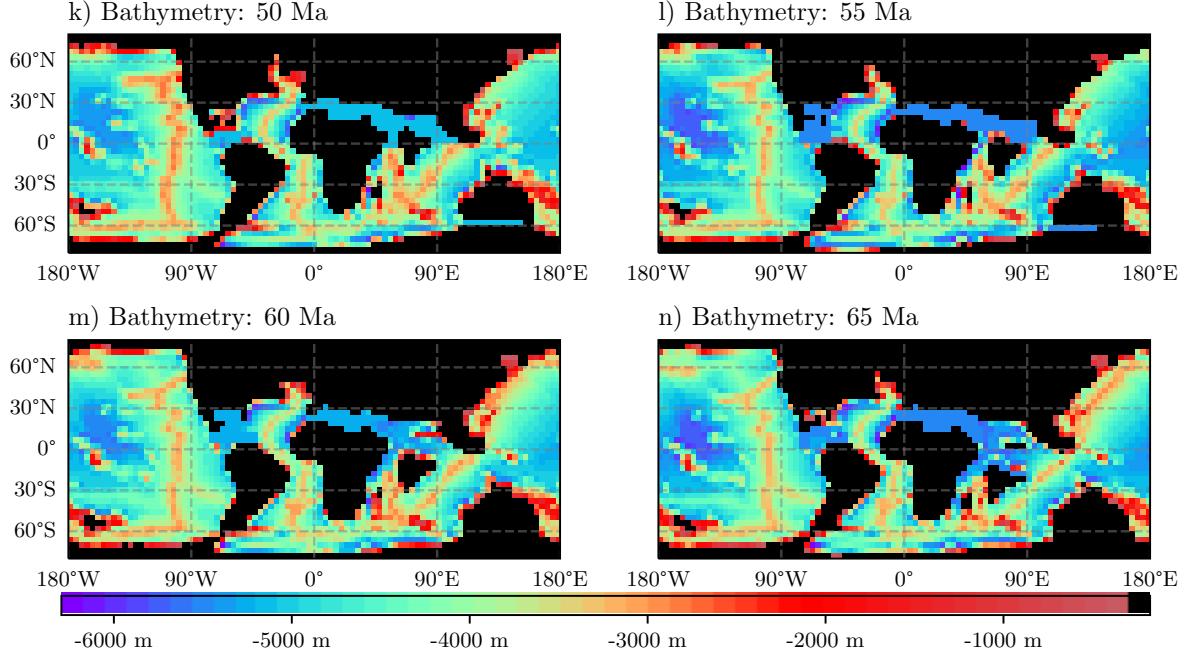


Figure 3: Bathymetries for each of the time steps studied in this model.

2.3 Veros and Runtime

Ocean modeling has been an area of continued progress. The resolutions of the models have been steadily increasing since the inception of the first computerized ocean models. However, due to the age of some of these models and the continued adaptation of often old legacy Fortran code, many models have become enormous hurdles to get started with often resulting in frustration. The Veros ocean model project is trying to tackle this problem with a totally new code base written entirely in Python (**Hafner2018Aug**). Veros is a General Circulation Ocean model based on the successful PyOM2 model. It was designed from the ground up with flexibility in mind. This flexibility cuts valuable time spent on figuring out the often cumbersome Fortran models of the past. Veros is specifically well suited for researching the effect of changes in both forcings and bathymetries. They can be easily edited using Python. These features in particular are heavily used in this paper. One of the most extensively used features for example is the fact that any bathymetry can, without further manual specifications of islands be used for stream function calculation.

In this case the models used in this paper were run on a 8 core (16 threads) machine using an MPI CPU configuration of 1 node. The Bohrium GPU

possibilities of Veros were also tried but failed to result in much improvement in speed. Figure (figure on speed) shows the model speed of the integration. The total time needed to run all of the models was approximately one week.

(some more on how fast the model is)

3 Results

3.1 Stabilizing of the models

(Section on when the integration was stopped. How good it is etc.) 60/100 done

3.2 Passage throughflow

For each of the aforementioned passages the throughflow was computed. This is done using a simple integration to calculate the volumetric flux through each passage.

$$Q = \int \int_A \vec{u} \cdot d\vec{A} \quad (1)$$

For each passage a suitable location was chosen such that there are no boundaries next to the passageways. Then the u component of the flow is used to compute the total flow. This method is the same for each of the passages and thus we can study the

effect of changes in bathymetry to on the relative strength of the flow. However, it should be noted that these values may not represent real physical values. As the passages are often only a few grid-cells wide and, the nature of the 4 degree model. Resulting in discrepancies due to boundary conditions. The passageways have been labeled in figure (figure of these) and results are plotted in figure (figure of these).

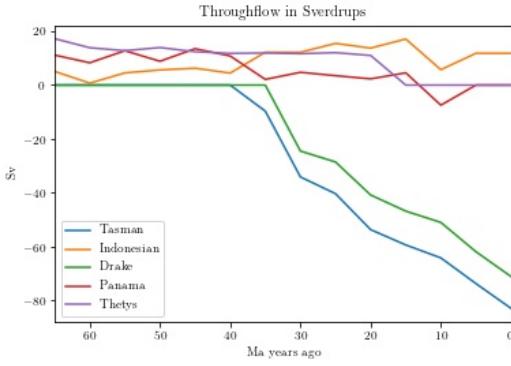


Figure 4: test caption

There is still some uncertainty in the method of calculating the throughflow. The method used in figure 4 is calculated using the velocity field. An-

other method is using the Barotropic stream function discussed in section 3.3 on page 8. The stream function Ψ' is defined by

$$u = \frac{\partial \Psi'}{\partial y}, v = \frac{\partial \Psi'}{\partial x}$$

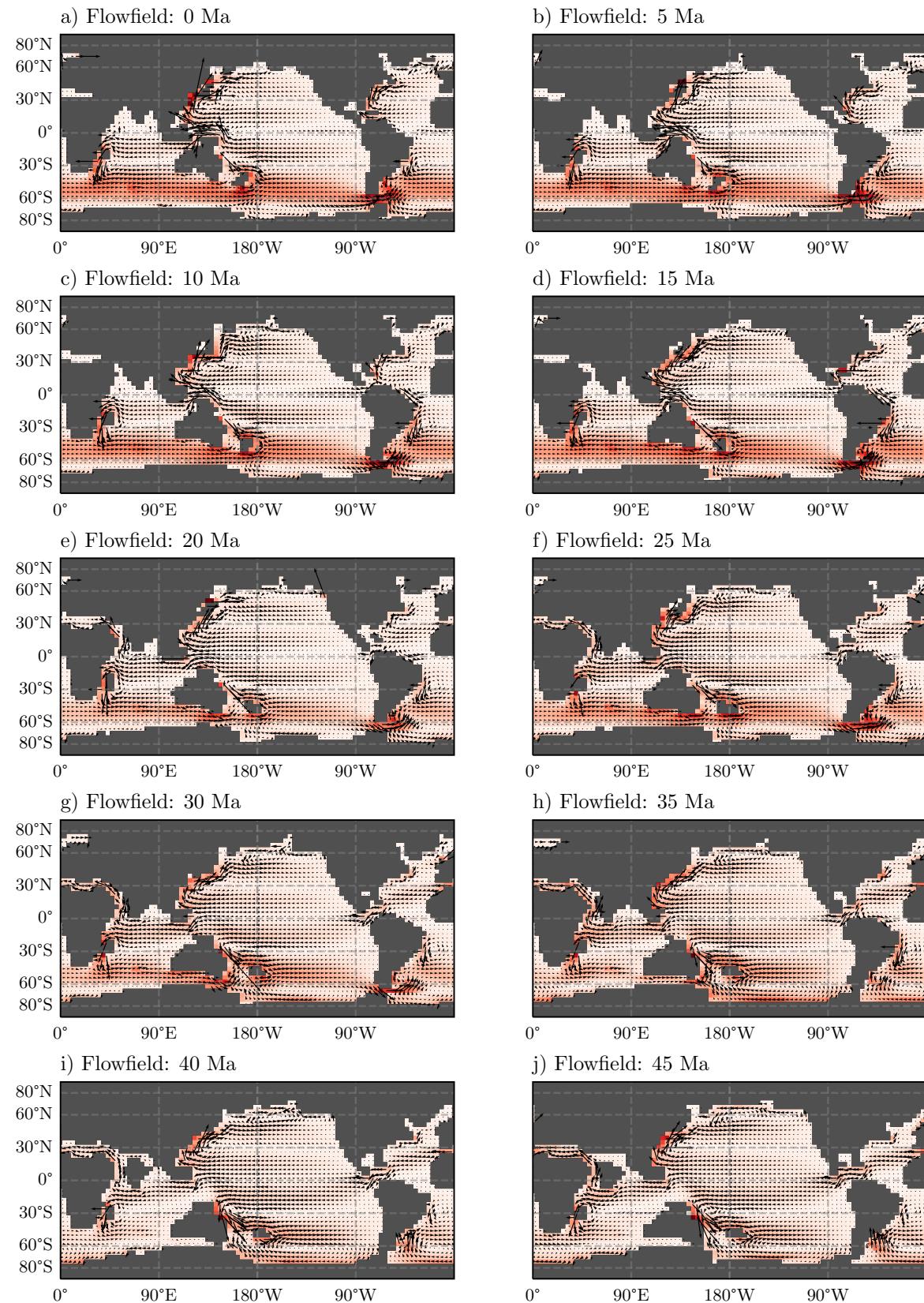
In veros it is computed by integrating the barotropic flow from north to south. This gives values for the volumetric flow of each gridcell. Where a positive value indicates clockwise flow and a negative value anticlockwise flow. This can thus also be used as a measure of the throughflow for each passage. These values are given in (figure)

As is visible, these values are quite different than the values obtained in figure 4. They give an image of a much weaker flow. This can probably be attributed to the fact that interpolation is used at the coasts. resulting in the barotropic streamfunction being zero on the boundary of some coasts.

To get a better understanding of the flows we can look at a vector field showing the direction of horizontal water displacement. This is done by making a weighted mean of the horizontal flow field for each layer. Weighted by the volume of each grid cell. In this way each arrow actually represents relative flow velocity compared to other grid points.

This field is shown in figure ...

The flow field clearly shows that...



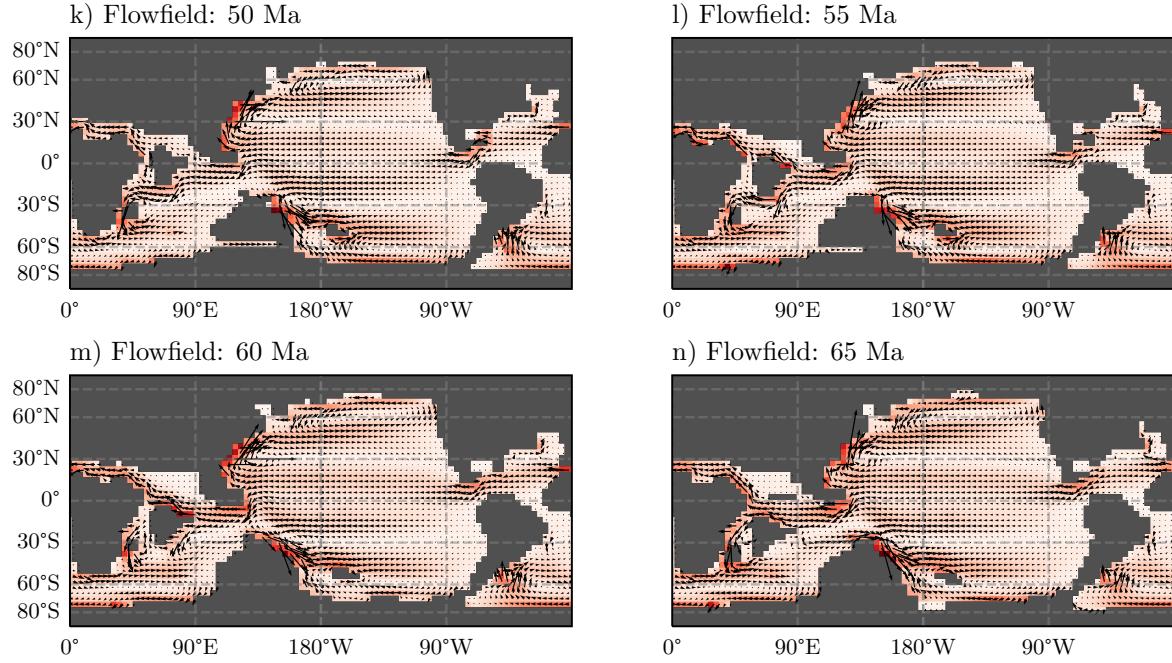
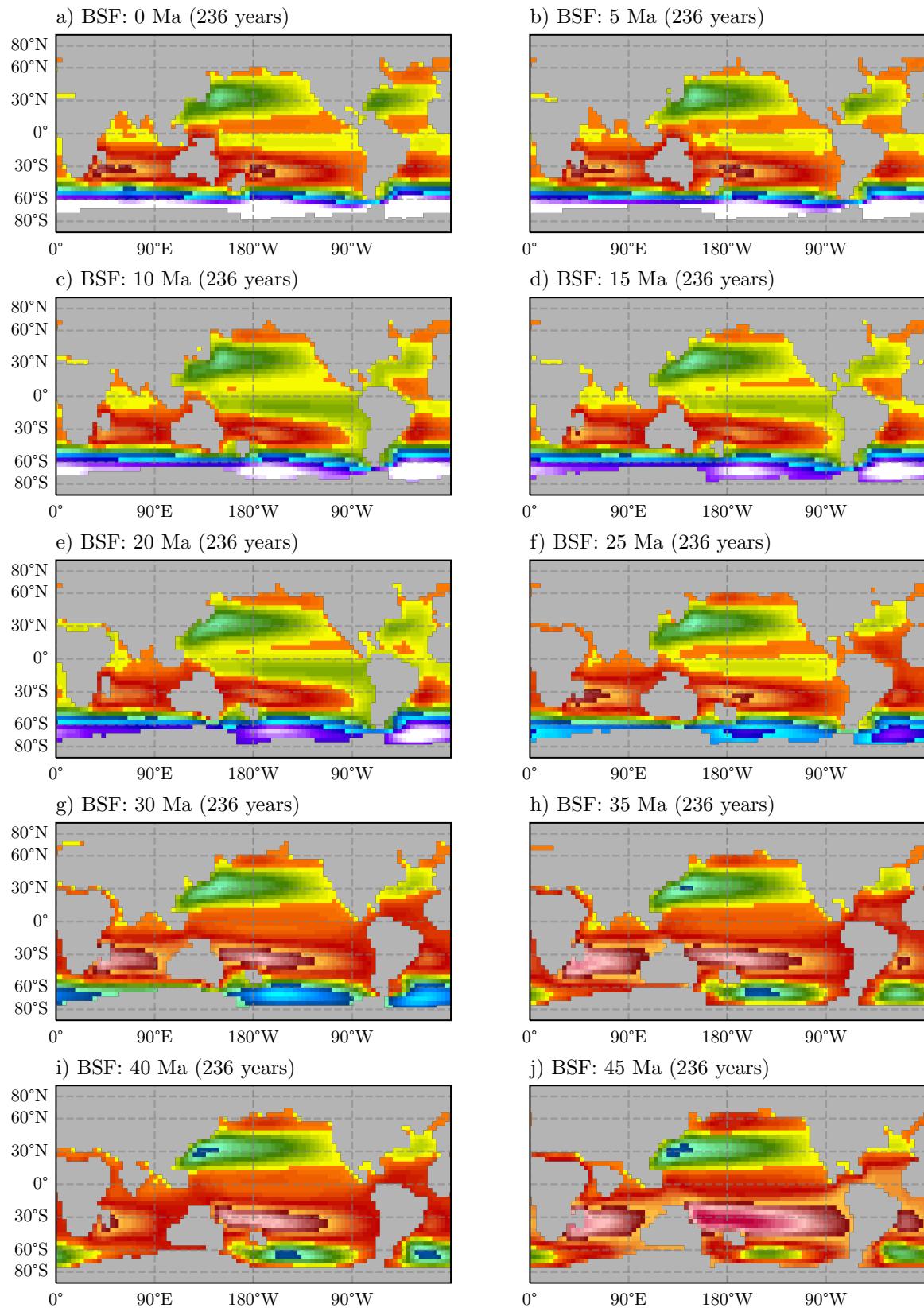


Figure 5: Flow field

3.3 Barotropic Stream function

The barotropic streamfunction is a useful tool to see if the model we have created is representative

of reality. The streamfunction is calculated each time step. Split into a barokline and barotropic mode. However due to interpolation the streamfunction is not defined everywhere.



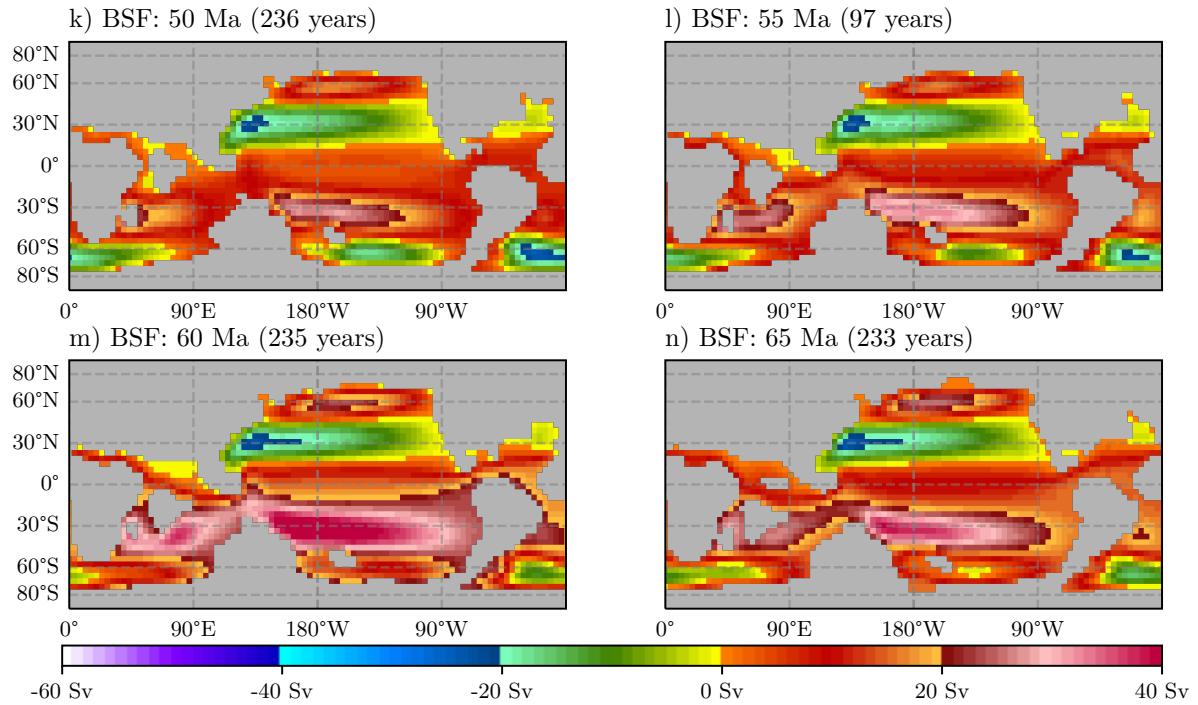
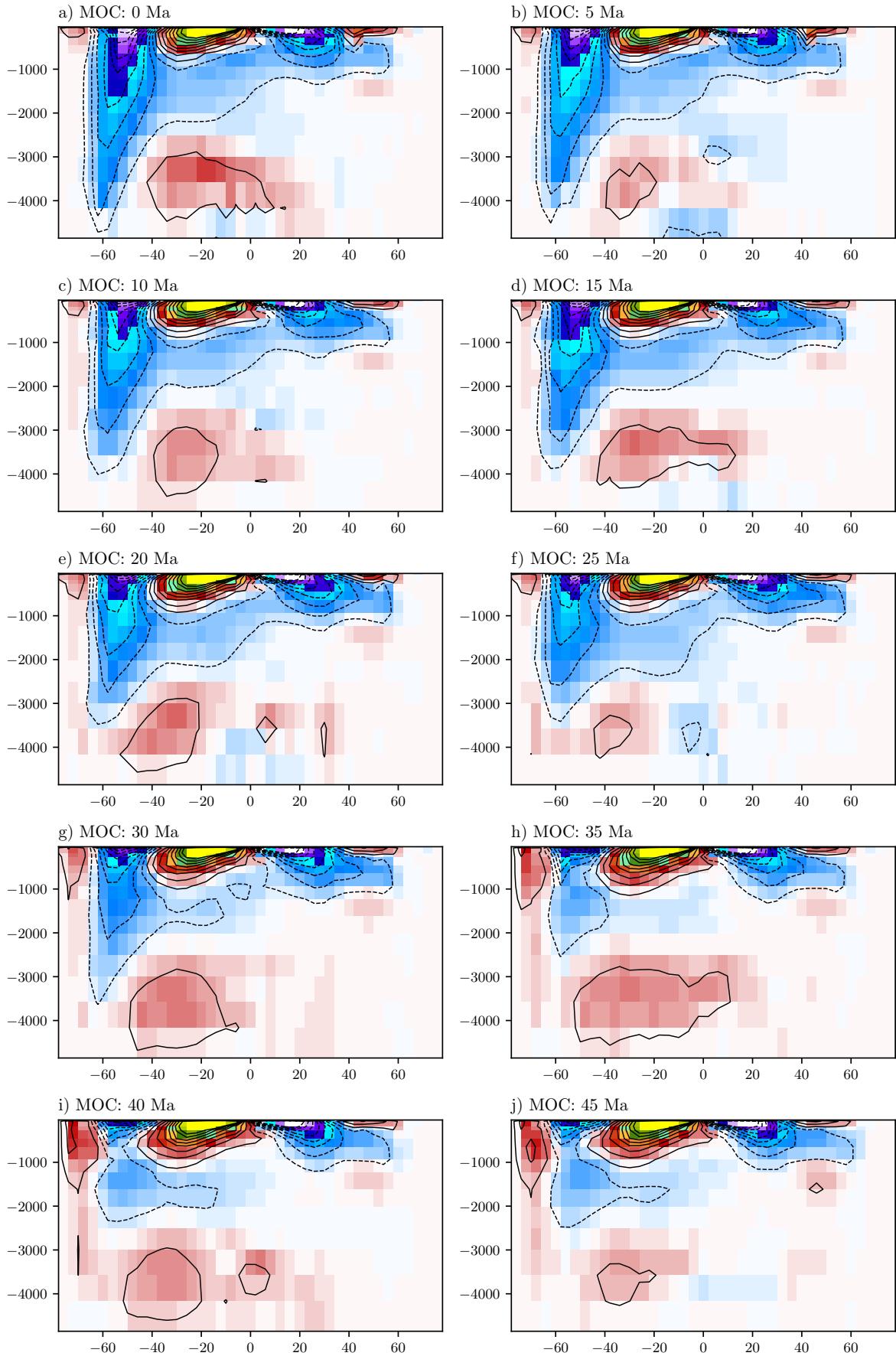


Figure 6: Barotropic Stream Function

3.4 MOC Stream function

Section on the meridional overturning current



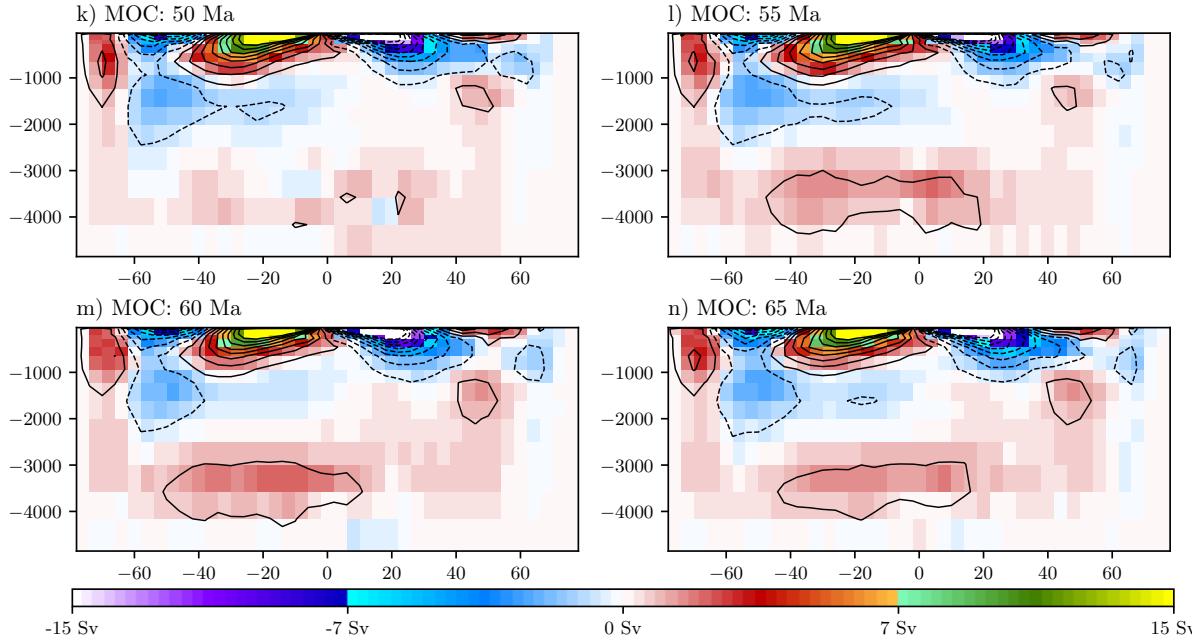


Figure 7: Barotropic Stream Function

4 Summary

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5 Discussion

- Discuss the results and flaws in these.
 - Discuss possible future research.
 - Discuss possible improvements.
 - Discuss possible 1 degree models.
 - Discuss troubles with the ACC strength due to the forcings.
 - Discuss the difficulty with trial and error in the model.
 - Discuss Climate changes and their major effects that have been ignored.
 - Discuss what can be concluded from these results.
- 0/100 done

References

- [1] Jean Besse and Vincent Courtillot. "Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr". In: *Journal of Geophysical Research: Solid Earth* 107.B11 (2002), EPM-6.
- [2] Howie D. Scher and Ellen E. Martin. "Timing and Climatic Consequences of the Opening of Drake Passage". In: *Science* 312.5772 (2006), pp. 428–430. ISSN: 0036-8075. DOI: 10.1126/science.1120044.
- [3] D. N. Schmidt. "The closure history of the Panama Isthmus: Evidence from isotopes and fossils to models and molecules". In: *ResearchGate* (2007), p. 429444. URL: https://www.researchgate.net/publication/282323290_The_closure_history_of_the_Panama_Isthmus_Evidence_from_isotopes_and_fossils_to_models_and_molecules.
- [4] Meir Abelson and Jonathan Erez. "The onset of modern-like Atlantic meridional overturning circulation at the Eocene-Oligocene transition: Evidence, causes, and possible implications for global cooling". In: *Geochemistry Geophysics Geosystems* 18 (May 2017). DOI: 10.1002/2017GC006826.
- [5] T. E. Mulder et al. "Efficient computation of past global ocean circulation patterns using continuation in paleobathymetry". In: *Ocean Modell.* 115 (2017), pp. 77–85. ISSN: 1463-5003. DOI: 10.1016/j.ocemod.2017.05.010.

- [6] Robert L Haney. "Surface thermal boundary condition for ocean circulation models". In: *Journal of Physical Oceanography* 1.4 (1971), pp. 241–248.
- [7] Frank Bryan. "Parameter sensitivity of primitive equation ocean general circulation models". In: *Journal of Physical Oceanography* 17.7 (1987), pp. 970–985.
- [8] Michiel Baatsen et al. "Reconstructing geographical boundary conditions for palaeoclimate modelling during the Cenozoic". In: *Clim. Past* 12.8 (2016), pp. 1635–1644. ISSN: 1814-9324. DOI: 10.5194/cp-12-1635-2016.
- [9] Lawrence A. Lawver and Lisa M. Gahagan. "Evolution of Cenozoic seaways in the circum-Antarctic region". In: *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 198.1 (2003), pp. 11–37. ISSN: 0031-0182. DOI: 10.1016/S0031-0182(03)00392-4.
- [10] N. Hamon et al. "The role of eastern Tethys seaway closure in the Middle Miocene Climatic Transition (ca. 14 Ma)". In: *Clim. Past* 9.6 (2013), pp. 2687–2702. ISSN: 1814-9332. DOI: 10.5194/cp-9-2687-2013.
- [11] Peter Molnar. "Closing of the Central American Seaway and the Ice Age: A critical review". In: *Paleoceanography* 23.2 (2008). ISSN: 0883-8305. DOI: 10.1029/2007PA001574.
- [12] James L. Pindell et al. "A plate-kinematic framework for models of Caribbean evolution". In: *Tectonophysics* 155.1 (1988), pp. 121–138. ISSN: 0040-1951. DOI: 10.1016/0040-1951(88)90262-4.