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 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 bathymetrys. 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)

2.2 Model Setup

2.2.1 Model Domain

The domain of the model is bounded by longitudes $\phi_E = -180°$ and $\phi_W = -180°$ and latitudes $\theta_N = 80°$ and $\theta_S = -80°$ with periodic boundary conditions in the zonal direction. Furthermore the model uses restoring boundary conditions. Restoring the boundary at the surface of the oceanic basin to be a value based of a forcing field for Sea Surface Temperature (SST), Sea Surface Salinity (SSS), wind stresses (τ) and heat flux. The depth profile has 15 layers with grid stretching (figure 1). There are 90×40 grid points to make a $4° \times 4°$ resolution model.

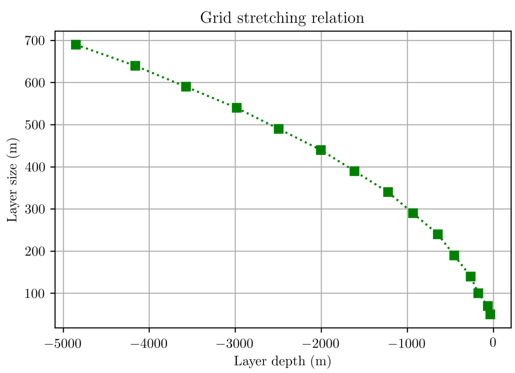


Figure 1: Grid stretching relation used

2.2.2 Surface Forcings

Choosing the correct forcing for the ocean is very important. It is known that the MOC in general circulation models is highly sensitive too even small changes in surface forcings (Milliff et al. 1999). Attempts at making these forcings highly idealized have often been made in the past with varying rates of success. In this paper we will however use idealized forcings. Noting the fact, that this will probably induce the aforementioned errors in deep ocean circulations.

There were several methods that are explored when it comes to creating these idealized forcings. In the Mulder et al. 2017 paper an analytic forcing profile was used for wind flux, SST and SSS. This however fails to capture seasonal changes in each of the forcings due to the earths axial tilt. Something that can bring about a huge effect on the strength of the MOC. To combat this change a compromise is proposed. The SSS, SST and heat flux profiles are taken as zonal means for each month in the earths rotation. While the Zonal wind stress is set to the simple profile proposed by Bryan 1987. The analytic profile used in the paper is not specified specifically. but it can quite easily be deduced from the profile's plot. The choice of this analytic profile was made over a zonally averaged and equatorial averaged forcing $\mu(\tau_x)$. These were both tested on the present day configuration to see which of these forcings most accurately captures the present day MOC. In section 2.2.3 a comparison with the present day MOC and BSF is made.

2.2.3 MOC stream function

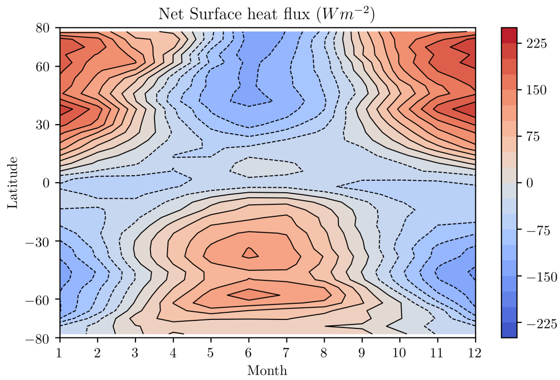
The global Meridional Overturning Circulation Ψ_{MOC} is defined as the zonally integrated meridional volume transport of water in the worlds oceans. It can be written down as:

$$\Psi_{MOC}(y,z) = \int_z^0 \int_{-180°}^{180°} v(x,y,z')dxdz'$$

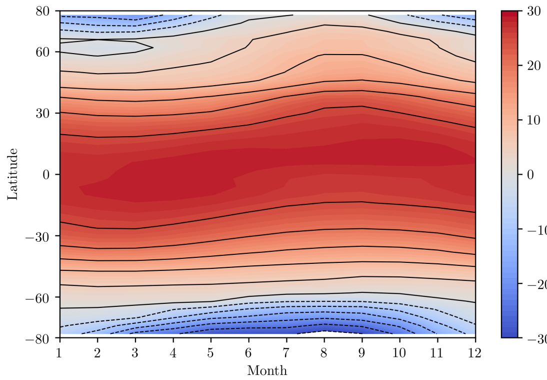
Where v is the meridional component of the velocity. Ψ_{MOC} is thus a stream function of the zonally integrated volume transport in the Earth's water basins. Plotting this stream function can give a lot of insight into the deep water transport associated with the thermohaline circulation. In this paper we hope to capture these deep water transport formations as a

2.2.4 Barotropic Stream Function

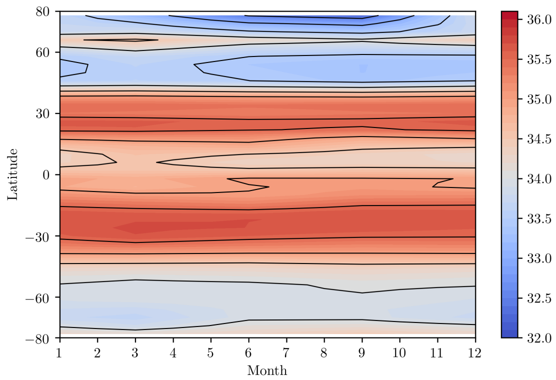
The Barotropic stream function Ψ_b is defined as the depth integrated volume transport in the Earth's water basin. It is a usefull tool to look at the shape and Gyres associated with the major ocean current systems. These Stream functions can be a useful tool to compare this simplified model to an existing 4° model.



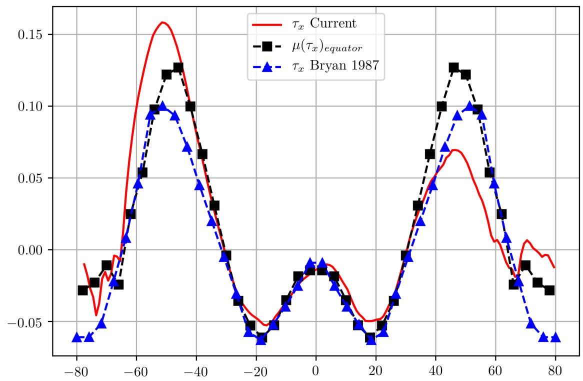
(a) Net Heat flux



(b) SST profile



(c) SSS profile



(d) τ_x profile

Figure 2: Idealized forcing profiles

2.3 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 Baatsen et al. 2016. These bathymetrys 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 of in all of the bathymetrys. 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 devided 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 probaby 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 choises such that the diffirences 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 Thetys 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.

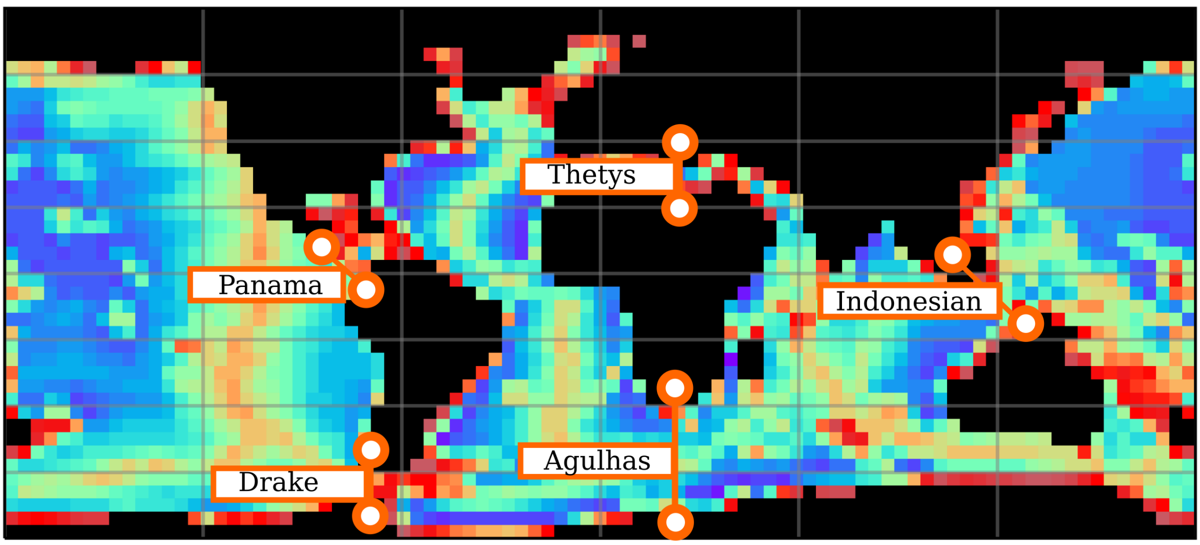
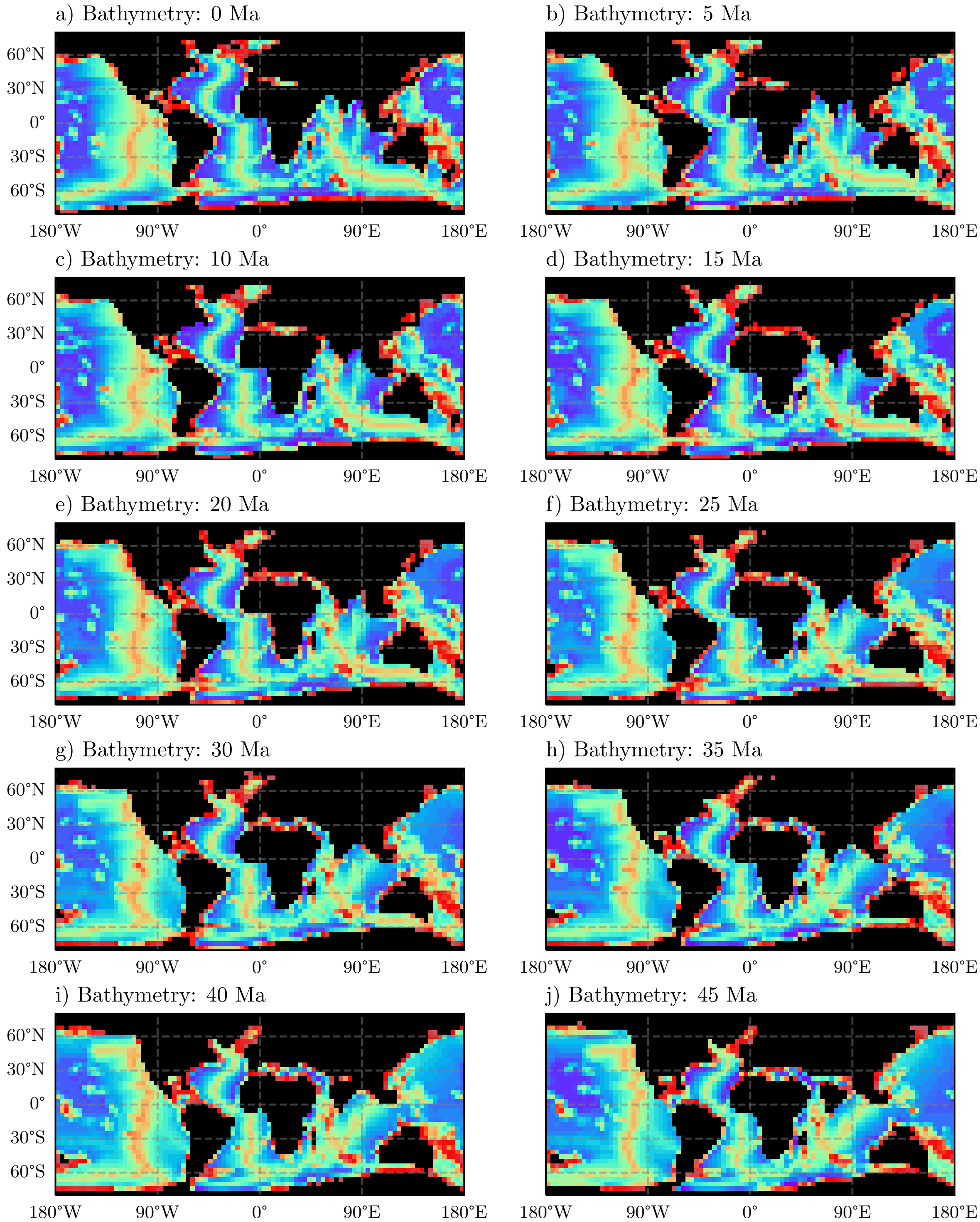


Figure 3: Passages


a) Bathymetry: 0 Ma
b) Bathymetry: 5 Ma
c) Bathymetry: 10 Ma
d) Bathymetry: 15 Ma
e) Bathymetry: 20 Ma
f) Bathymetry: 25 Ma
g) Bathymetry: 30 Ma
h) Bathymetry: 35 Ma
i) Bathymetry: 40 Ma
j) Bathymetry: 45 Ma
60°N
30°N
0°
30°S
60°S
180°W
90°W
0°
90°E
180°E

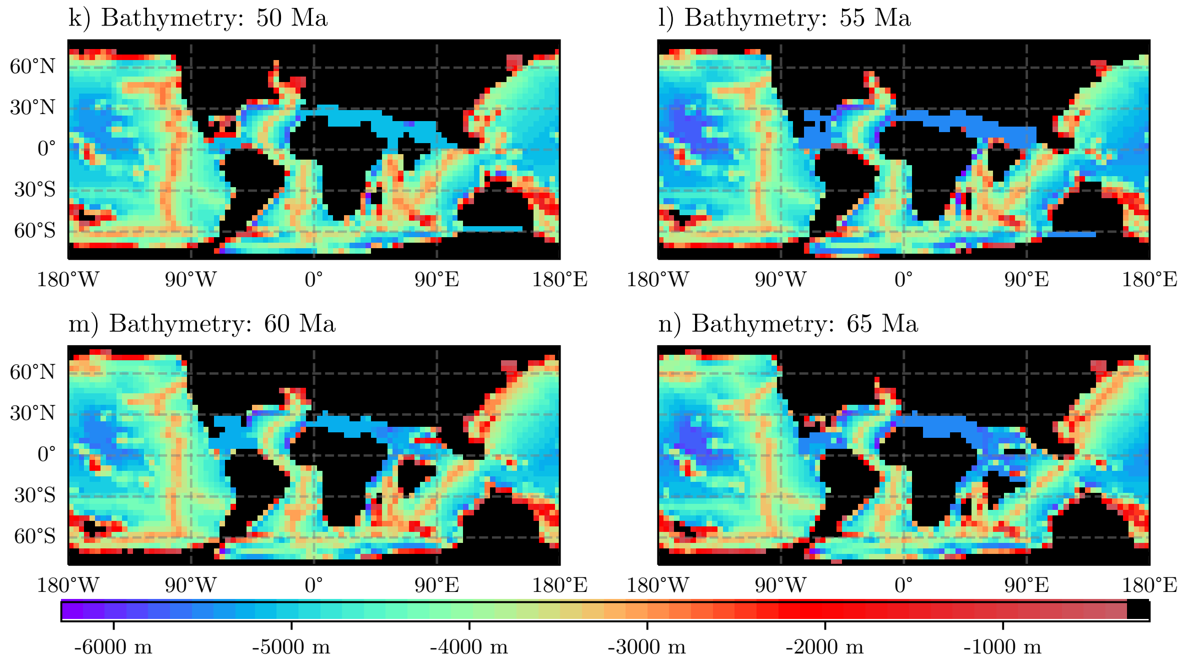


Figure 4: Bathymetries for each of the time steps studied in this model.

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

$$Q = \int \int_A \vec{u} \cdot d\vec{A} \tag{1}$$

For each passage a suitible 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 strenght 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 gridcells wide and, the nature of the 4 degree model. Resulting in discepencies due to boundary conditions. The passageways have been labeled in figure (figure of these) and results are plotted in figure (figure of these).

There is still some uncertanty in the method of calculating the throughflow. The method used in figure **??** on page ?? is calculated using the velocity field. Another method is using the Barotropic stream function discussed in section 3.3 on page 10. The stream fuction Ψ' is defined by

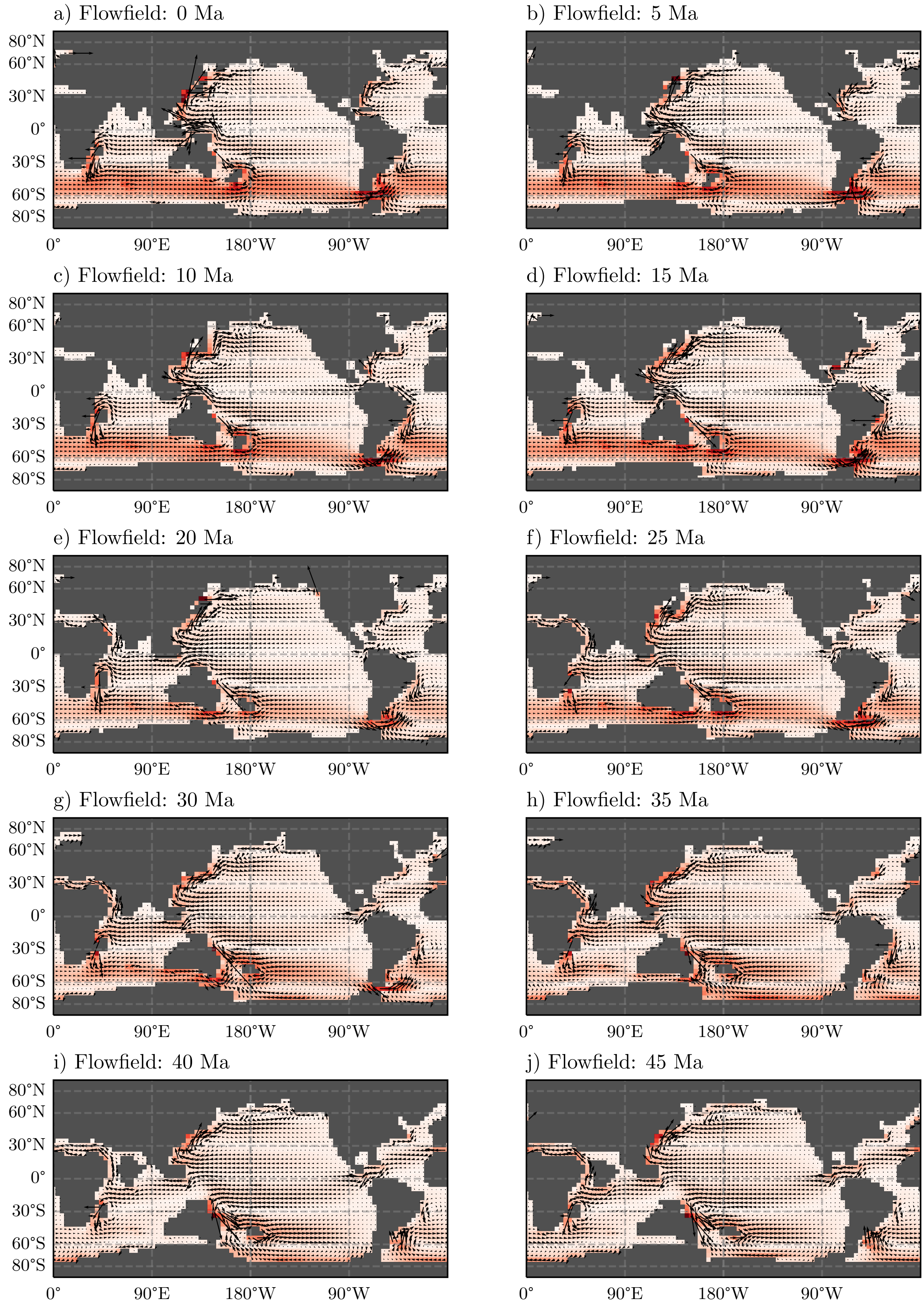
$$u = \frac{\partial \Psi'}{\partial y}, v = \frac{\partial \Psi'}{\partial x}$$

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 diffirent that the values obtained in figure ?? on page ??. 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...


a) Flowfield: 0 Ma
b) Flowfield: 5 Ma
c) Flowfield: 10 Ma
d) Flowfield: 15 Ma
e) Flowfield: 20 Ma
f) Flowfield: 25 Ma
g) Flowfield: 30 Ma
h) Flowfield: 35 Ma
i) Flowfield: 40 Ma
j) Flowfield: 45 Ma
80°N
60°N
30°N
0°
30°S
60°S
80°S
0°
90°E
180°W
90°W

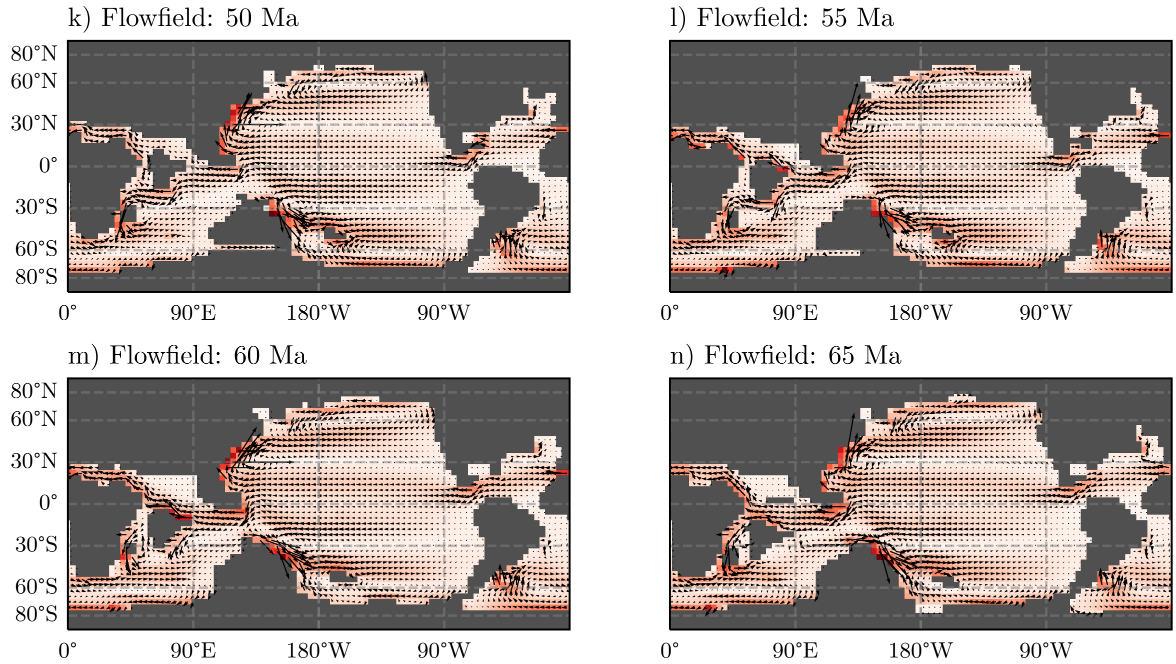
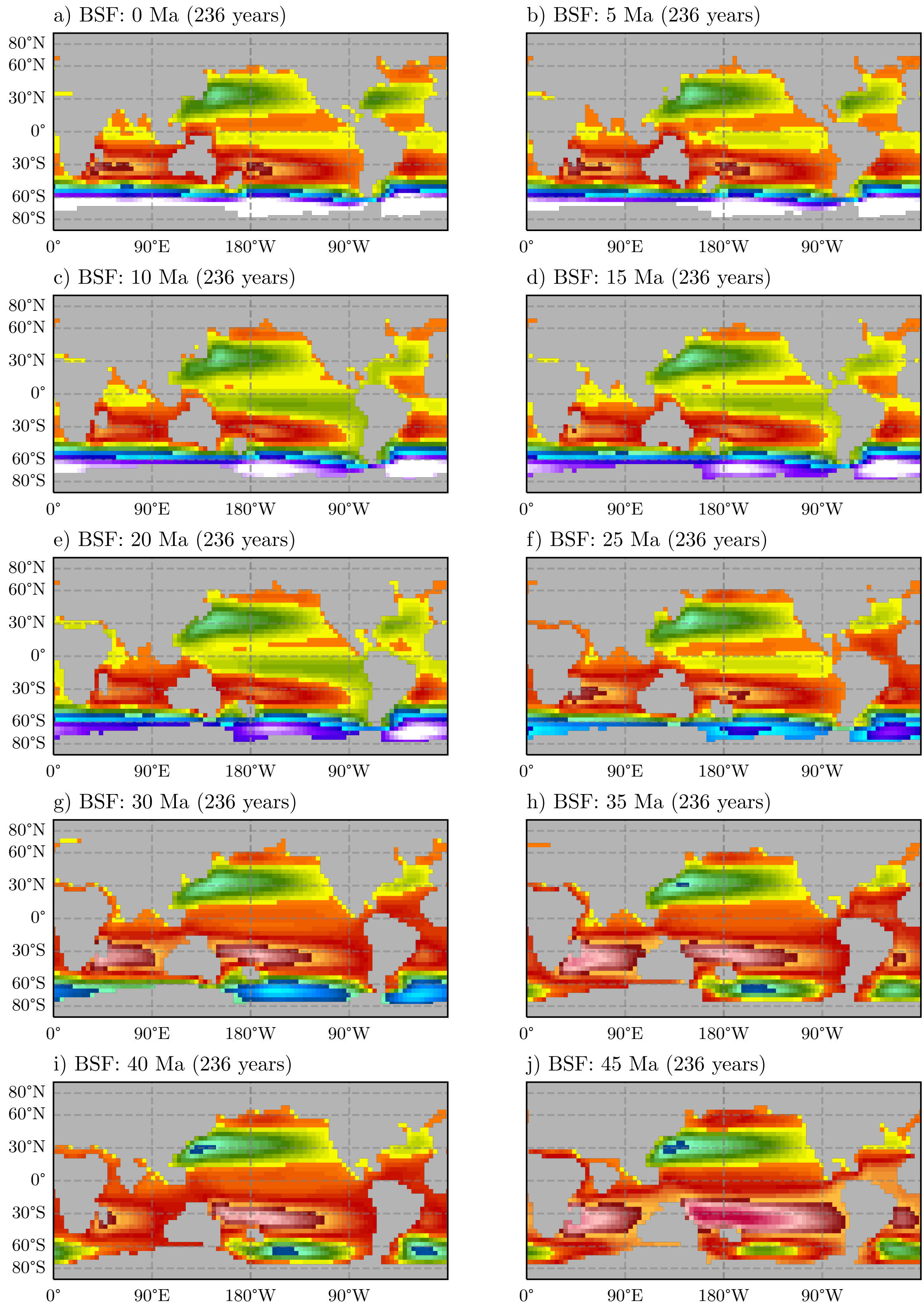


Figure 5: Flow field

3.3 Barotropic Stream function

Thee barotropic streamfunction is a usefull tool to see if the model we have created is representative of reality. The streamfunction is calculated each time step. Splitted into a barokline and barotropic mode. However due to interpolation the streamfunction is not defined everywhere.


a) BSF: 0 Ma (236 years)
b) BSF: 5 Ma (236 years)
c) BSF: 10 Ma (236 years)
d) BSF: 15 Ma (236 years)
e) BSF: 20 Ma (236 years)
f) BSF: 25 Ma (236 years)
g) BSF: 30 Ma (236 years)
h) BSF: 35 Ma (236 years)
i) BSF: 40 Ma (236 years)
j) BSF: 45 Ma (236 years)
80°N
60°N
30°N
0°
30°S
60°S
80°S
0°
90°E
180°W
90°W

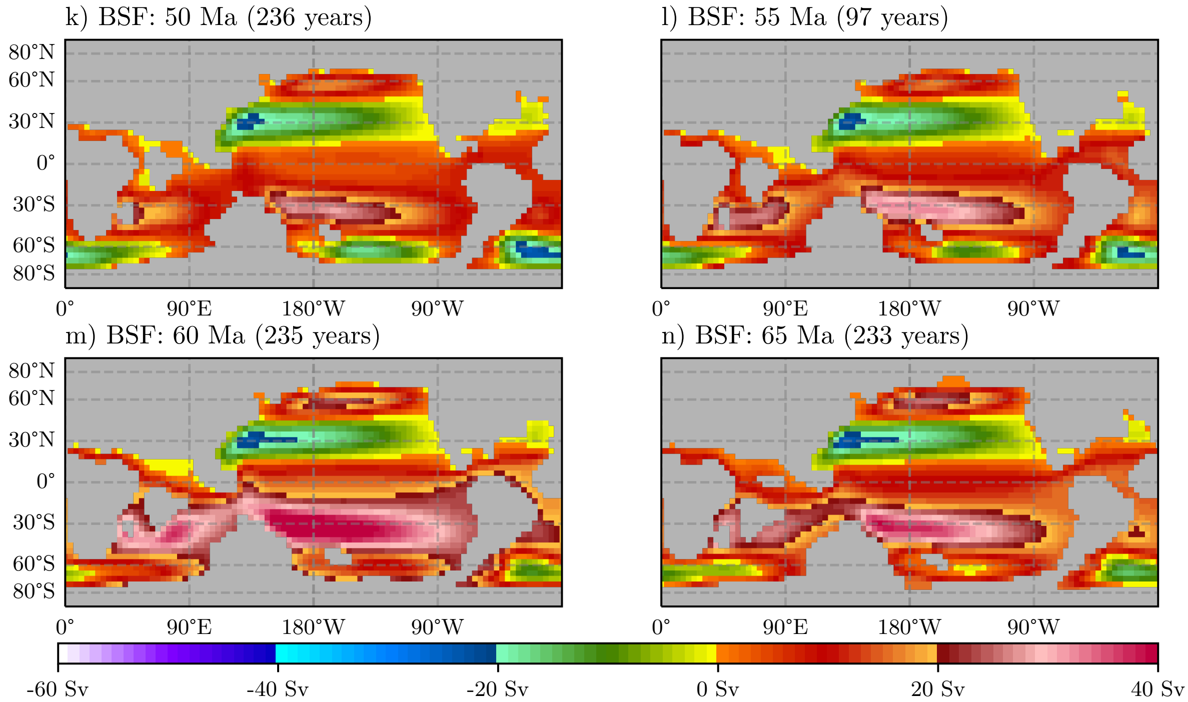
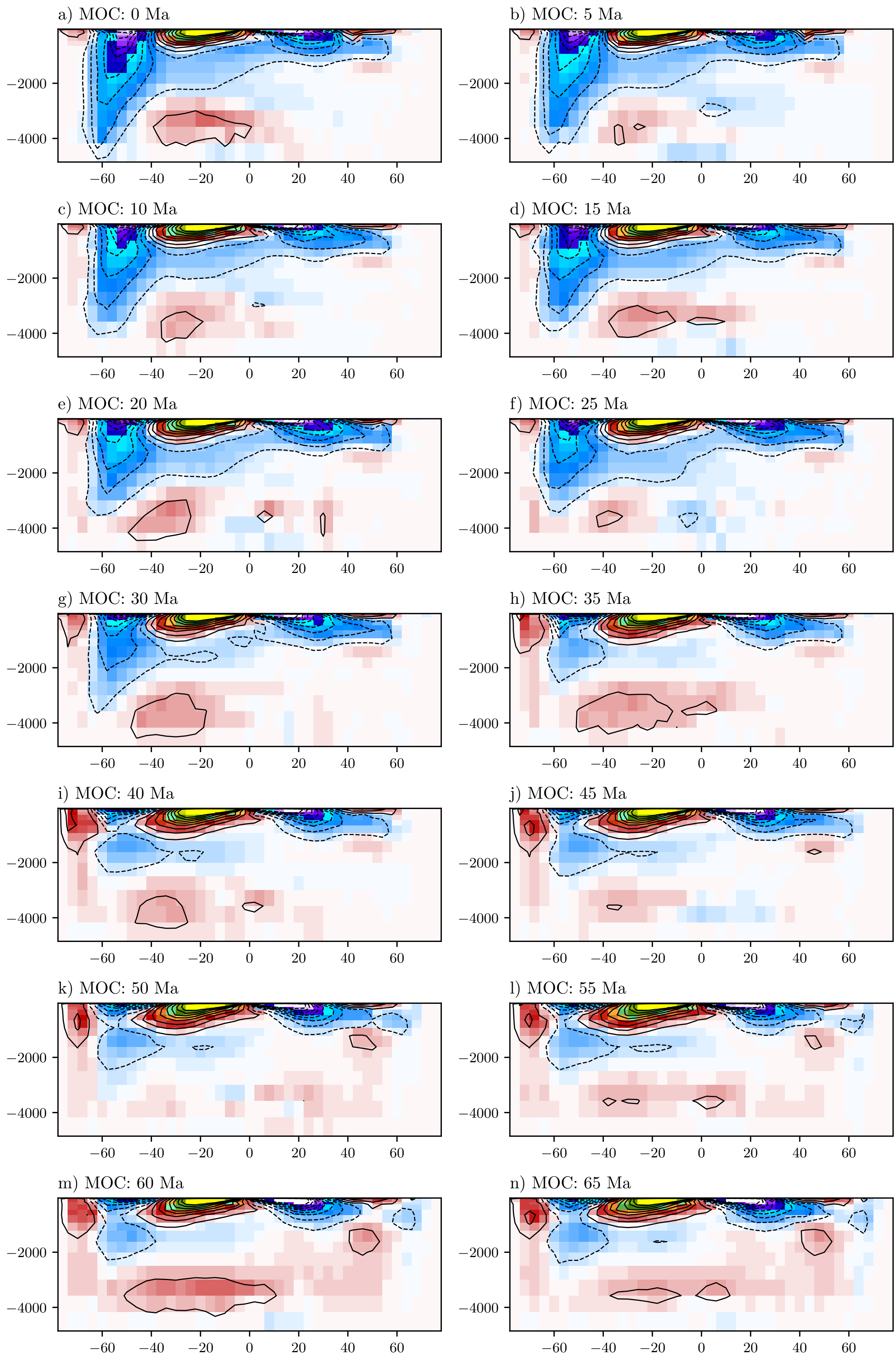


Figure 6: Barotropic Stream Function

3.4 MOC Stream function

The meridional overturning circulation (MOC) is characterized by large changes in the


a) MOC: 0 Ma
b) MOC: 5 Ma
c) MOC: 10 Ma
d) MOC: 15 Ma
e) MOC: 20 Ma
f) MOC: 25 Ma
g) MOC: 30 Ma
h) MOC: 35 Ma
i) MOC: 40 Ma
j) MOC: 45 Ma
k) MOC: 50 Ma
l) MOC: 55 Ma
m) MOC: 60 Ma
n) MOC: 65 Ma
−2000
−4000
−60
−40
−20
0
20
40
60

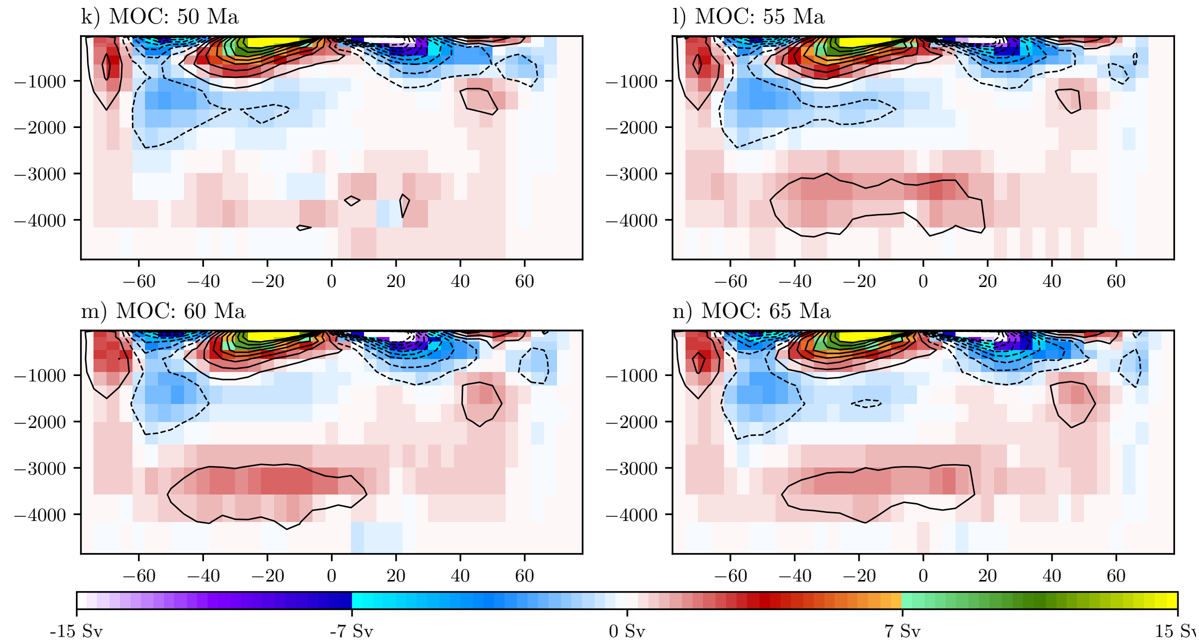


Figure 7: Barotropic Stream Function

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 trail and error in the model.

Discuss Climate changes and their major effects that have been ignored.

Discuss what can be concluded from these results.

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