Proceedings of 8 ICSHMO, Foz do Iguaçu, Brazil, April 24-28, 2006, INPE, p. 1269-1272.

IMPACT OF THE MERIDIONAL OVERTURNING CIRCULATION ON THE TROPICAL ATLANTIC CIRCULATION

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1. INTRODUCTION

The Atlantic Meridional Overturning Cell (MOC) plays a fundamental role in the earth's climate by its heat transport, which is associated with the amenization of the climate and control of the exchange of gases with the atmosphere. The MOC transports warm water towards the high northern latitudes where it sinks into depth to form the North Atlantic Deep Water and flows back towards the southern hemisphere.

Some studies which apply modeling and observations show that men have been influencing the variability of this transport through the carbon dioxide emissions, what can yield in a decreasing or even a complete shut down of this current (Dong and Sutton, 2002, Longworth et al. 2005).

The aim of this work is to investigate the effect of the variability of the MOC on the upper tropical Atlantic and its relationship with the wind-driven circulation. In order to do this a shallow water model will be applied where the MOC will be imposed as an inflow in the southwestern and an outflow in the northwestern boundary.

2. THE MODEL

The model constructed was a reduced gravity with 4 ½ layers, which solves the equations of movement using the Arakawa C-grid with a resolution of 0.25°. The upper layer is kept 50m deep, where the wind stress is applied, and the others are allowed to move. The tropical Atlantic basin is idealized by a square basin with 3000 km (lon)x 6000 km (lat) with the equator in the middle. The momentum equations were integrated in a leap-frog scheme and the continuity equation applied the Flux Corrected Transport algorithm (Salesak, 1979). No slip boundary condition was used and a sponge layer was applied onto the southern and northern open boundaries. Also the sponge layer was responsible for the prescription of the MOC by varying the restoring term for the layer thickness. The entrainment term was introduced in a way that once the layer is outcropped the mixed layer may exchange water with the subjacent layers.

The thermodynamic equation was solved diagnostically for the upper layer and the no heat flux boundary condition was applied.

Basically three experiments are done and compared. One is forced only by MOC, other is only forced by wind and a third experiment forced by wind along with the MOC.

3. RESULTS

3.1. MOC-only

In the MOC-only experiment a northward flow was introduced along the western boundary of the domain. The MOC flux is applied only on layers 3 and 4. Nevertheless, the model adjusts in a way that the flow is spread among all layers. From the point that the MOC flow is switched on, Kelvin and gravity waves are triggered. The Kelvin waves travel equatorward, flow along the equator until the eastern boundary where they split into 2 costal Kelvin waves traveling poleward. On the equatorial eastern boundary the equatorial Kelvin waves are also reflected westward as Rossby wave trains, carrying then the information into the interior, across the basin.

As the adjustment begun and the MOC flow increased on the western side of the basin, eddies started to be generated on the northern hemisphere (figure 1) in all layers. The eddies are anticyclonic because they are fed mainly by southern hemisphere waters, which reach the equator carrying a negative potential vorticity, displace the isoertels towards the north on the western boundary and create then a negative relative potential vorticity in that region.

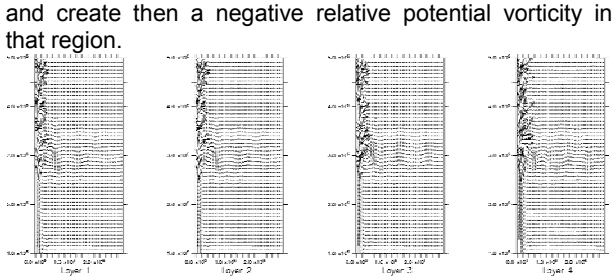

Fig. 1: Currents for each layer in the MOC experiment.

The increase of the potential vorticity close to the boundary results in an ideal situation for the growth of instabilities on the northern hemisphere (Fratantoni et al., 2000). The generation of eddies will be then related to the strength of the northward flow and also to the diffusion coefficient A_H. We can define, as in Edwards and Pedlosky (1998), a Reynolds number, which translates the competition of the advection against diffusion:

$$\mathrm{Re} = \frac{S_0}{A_H H_0} \qquad \textbf{(1)}$$

, where S_0 is the northward transport and H_0 is the initial layer thickness. This non-dimensional number represents the degree of nonlinearity of the system, and as Re increases more chances are for eddies production.

The mass balance in the boundary layer for the supercritical Reynolds number MOC-only experiment is shown on figure (2). For the zonal momentum equation (figure 2a) the balance consists basically of the geostrophic balance where the Coriolis force (green line) balances the pressure gradient (black line).

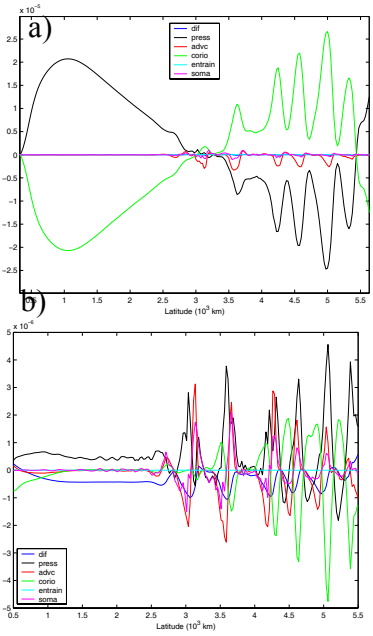

Fig. 2: Momentum balance in the boundary layer for a) x: direction and b) y: direction.

However, on the equatorial region, the advective terms (red line) start to get importance and replace the Coriolis term on the balance. For the balance on the meridional momentum equation (figure 2b), on the southern hemisphere, where there is no production of instabilities, it is the diffusion-pressure gradient balance which dominates. Once the flow approaches the equatorial region this balance is broken. On the northern hemisphere, where there are constant generation and emission of eddies, the advection terms grow. Up north the Coriolis term start to have more importance and the flow becomes more geostrophic, although advection and diffusion are still important.

This way one can do a dimensional analysis for the momentum equations on the western boundary layer in terms of Rossby (Ro) and Reynolds (Re) numbers. Thus the equations are the following:

$$y: Ro(u'\frac{\partial v'}{\partial x'} + v'\frac{\partial v'}{\partial y'}) - u' = \frac{\partial h'}{\partial y'} + \frac{\partial^2 v'}{\partial x'^2} + \frac{Ro}{\mathrm{Re}}\frac{\partial^2 v'}{\partial y'^2} \quad \textbf{(2a)}$$

$$x: \frac{Ro}{\mathrm{Re}}(u'\frac{\partial u'}{\partial x'} + v'\frac{\partial u}{\partial y'}) + v' = \frac{\partial h'}{\partial x'} + \frac{Ro}{\mathrm{Re}}\frac{\partial^2 u'}{\partial x'^2} + \frac{1}{\mathrm{Re}^2}\frac{\partial^2 u'}{\partial y'^2} \quad \textbf{(2b)}$$

If we vary the strength of the MOC we can find a critical Re under which eddies started to be generated. We made the transport vary sinusoidally on both north and south of the basin, with the maximum transport reached 6 Sv and minimum close to zero. As the mean northward transport reach a certain value the anomalies start to have non-null values, which represent the turbulent flux on that latitude, transmitted by eddies. These eddies are generated by barotropic instabilities, caused by the horizontal shear of the flow, and they appear equally in all layers.

In the figure (3) the Reynolds number is calculated for each layer separately on the 4e6m latitude, a region on the northern side of the basin. The variation of the MOC in this figure is made slowly, with a period of 8 years. Re is calculated according to the equation (1), with A_H=300 and H_o is the respective initial thickness of each layer. For layers 1,2 and 4 the critical Reynolds number (Re_c) is about Re_c=40, and for the layer 3 (blue line) is about Re_c=50. After reaching the Re_c instabilities are then created. Figure (3) also shows that even when the mean flow approaches a null transport (or Re), eddies are still present on the western part of the basin. It suggests that even with a shutdown of the MOC, eddies may still transmit mass and heat northward until their complete spin-down.

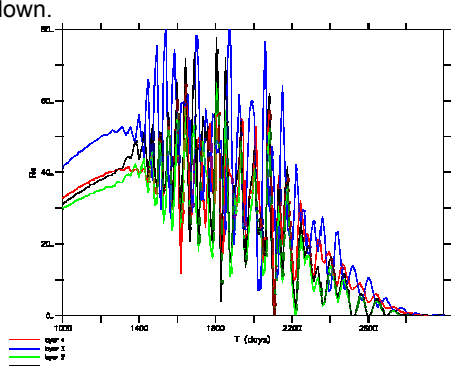

Fig. 3: Reynolds number (Re) for each layer in the MOC experiment while varying the strength of the MOC.

3.2.Wind-only

In the wind-only experiment the model is forced by the annual climatology from Hellerman & Rosenstein zonal wind stress. Before, the model is run for 15 years in order to be spun-up.

A strong feature of the circulation due to the wind forcing is the North Equatorial Counter Current (NECC), whose core is at the surface and has its signature on the zero wind stress curl region but only close to the western boundary.

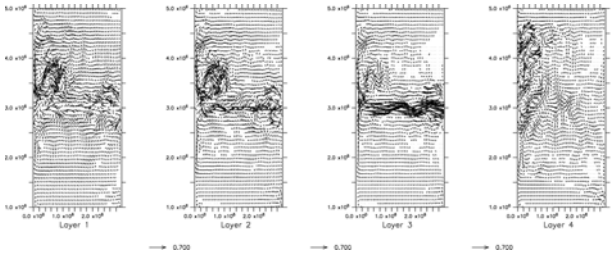

Fig. 4: Circulation in each layer for the wind-only experiment.

The NECC can't enter much further into the interior due to a strong mesoscale behavior, where many eddies are generated but not emitted, mixing eventually to the mean flow. The Equatorial Undercurrent (EUC) is present mainly on the layers 2 and 3 (figure 4).

Its core appears on the third layer with maximum speed of about 1.19 m/s, and as it flows eastward shoals to feed water for the surface layer through equatorial upwelling. On its beginning the EUC is fed by waters from both hemispheres that meet on the equator and then separate from the coast to flow along the equator. The meandering of the EUC is nearly absent.

The SST is higher on the tropics (figure not shown) with maximum value on the southern hemisphere. The equatorial region has lower temperatures due to the equatorial upwelling. The eastern equatorial region has the lowest values of SST because this is the region of outcropping of the third layer and is the region where the EUC is more present on the mixed layer.

In order to analyze the mass transport on the domain, the figure (5) shows the meridional transport in each model layer. On layer 1 (red line) the transport is poleward. In opposition, on the layers 2 (green line) and 3 (blue line) the transport is basically geostrophic and equatorward. We have then the formation of the Subtropical-Tropical Cell (STC) on the Atlantic. The mean transport for all layers is described by the black line, which is located almost over the line of zero transport, defining then that the net wind-driven transport along the basin is nil.

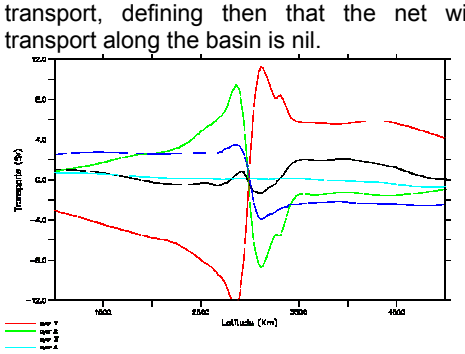

Fig. 5: Meridional transport for each layer in the wind-only experiment.

3.2. Wind+MOC

In this experiment a 6 Sv MOC is added to wind-driven run after 15 years of spin-up. On the first ˈer (figure 6a), eddies are generated and emitted rthward, but the wind makes the layer 2 outcrop at out 10° north of the equator, creating a region of high sitive potential vorticity what is a barrier for the eddies to w onto latitudes further north. On the third layer (figure) as the model starts its adjustment it's seen that the stern boundary current separation is displaced rthwards and once separated from the boundary the w turns southwards in order to meet the equator and feed the EUC.

Now the EUC is fed mostly by the southern hemisphere waters. The EUC becomes more meandric and stronger (maximum speed of about 1.3 m/s), and because of it the shear between the SEC and EUC, which flow in different directions, is also stronger causing an increasing of the diapicnal mixing and can decrease the SST on the equatorial region.

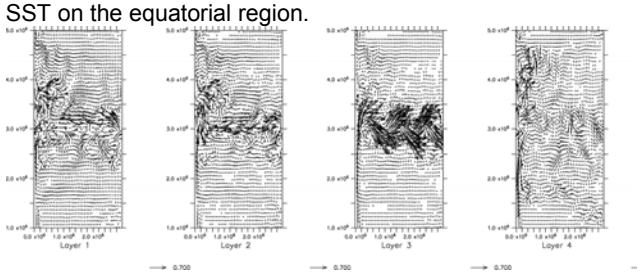

Fig. 6: Circulation in each layer for the wind+MOC experiment.

Looking at the STCs behavior for the region in the wind+MOC experiment (figure 7), one can see that layers 1 and 2 (red and green lines, respectively) don't suffer much variation in the transport comparing to figure (5). However, the layer 3 doesn't have a convergent pattern at the equator.

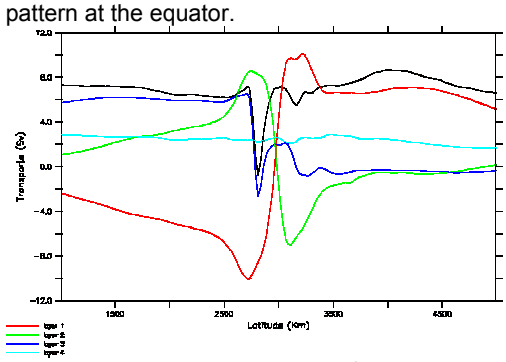

Fig. 7: Meridional transport for each layer in the wind+MOC experiment.

On the southern hemisphere its transport increases from 4 Sv to the wind-only experiment to about 7 Sv and for the northern hemisphere the transport becomes nearly zero. On the layer 4 (cyan curve), which had null transport before now has 2-3 Sv northward. The net transport (black line) goes to 7 Sv northward, value which corresponds to the total MOC transport for all layers.

4. DISCUSSIONS AND CONCLUSIONS

There is a critical Reynolds number under which eddies are created by the MOC flow. This number is about Rec=40/50.

An equation for the boundary layer was described here which is dependent on the Reynolds and Rossby numbers. Maybe it is possible to find the latitude that eddies start to be created.

The model represented well the main features of the wind driven circulation in this simplified of the Atlantic Ocean.

The wind play a role creating a barrier for eddies to move northward along the coast.

The addition of the MOC inhibits the southward flow from the northern hemisphere into the EUC. Thus, there is no more balance between Ekman and geostrophic flows.

Contrary to Fratantoni et al. (2000) an intensification of the EUC occurred with the addition of the MOC due to the fact that most of the southern MOC flux retroflects on the equatorial region.

5. REFERENCES

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