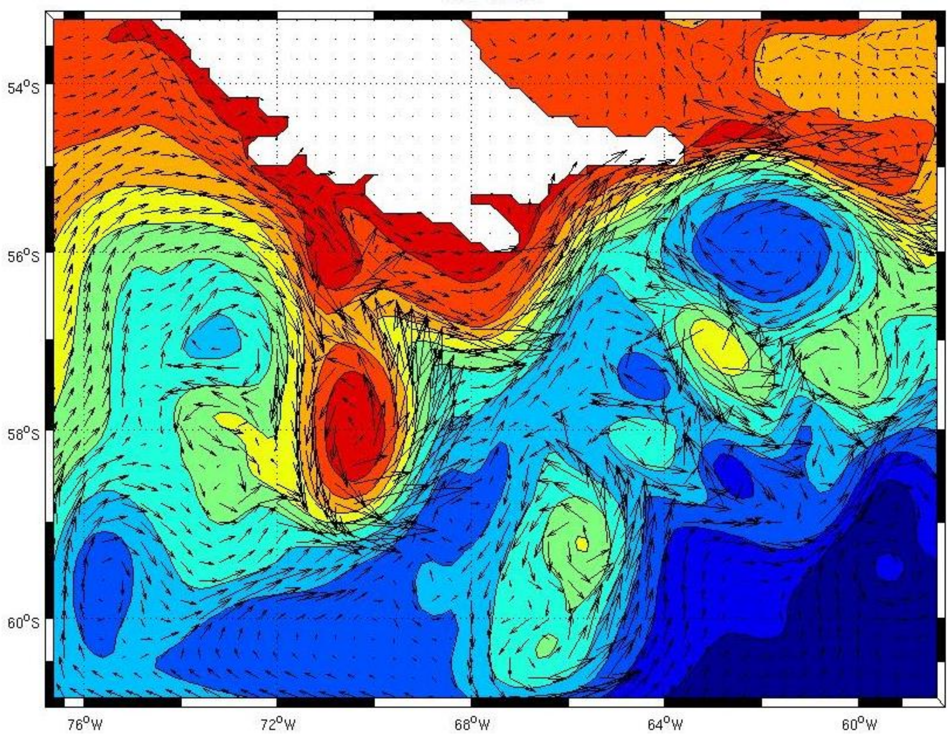
Simulation of current dynamics and disintegration in Drake Passage with the Regional Ocean Modelling System (ROMS)



OPB205 **MODELISATION OF OCEAN CIRCULATION**

Master Oceanography, first year 2015 – 2016

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Abstract

The influences of current dynamics and disintegration on the Drake Passage in the Southern Ocean is expected to be significant. A boundary current that originates in the South Pacific is entering the Drake Passage in the east and disintegrates inside it in a set of anticyclonic eddies. The integration might be essential for the mixing in the passage and the formation of the Circumpolar Deep Water and thus be necessary for the inducement of the Antarctic Circumpolar Current (ACC) which effects the global Meridional Overturning Circulation (MOC). This theory is assembled and further investigated by J. Alexander Brearley et al. (2014). In dependence of their findings, this work focuses on the same dynamic processes in the Drake Passage. With the regional ocean model simulation (ROMS) software, simulations shall give information about the extremely complex regional activities and the possible impact on MOC.

Obtained results with ROMS show deep water masses of low salinity and high temperature originated in the east pacific, flowing partly along the Cape horn but mainly entering the passage directly. This indicates the disintegration of Pacific Deep Water. The integrated current is also visible in the passage in form of a major anticyclonic eddy which with similar temperature and salinity properties and an appearance over the whole water column. Furthermore, a set of smaller anticyclonic eddies related to the current disintegration and complex bathymetry indicates the strong mixing in the area. All this indicates the strong influence of the arrival of the boundary current in the Drake Passage. According to the extensive influence of the current and the restricted space, an impact on the ACC and so, on the MOC can be derived. These results stands in strong accordance with the work of J.Alexander Brearley et al.

Summary

1. Introduction

With only about 480 nautical miles at its smallest width the Drake passage (named after Sir Francis Drake, 16th century) is an oceanic region with strong dynamics and strong influence on the global ocean circulation system. Located between Cape Horn at the very tip of the South American Continent and the Antarctic Peninsula and between the southern Pacific, southern Atlantic and Weddell Sea, it is effected by all its boundaries. In addition, two major climate fronts cross this region, the Polar Front and the Sub Antarctic Front. Many island chains and complex bathymetry cause a high local hydrodynamic. One of the major kinetic factors in the region is the Antarctic Circumpolar Current (ACC) with a transport capacity of 100-150 Sverdrups (Sv) which circulates clockwise around the Antarctic continent.

Dynamic mixing processes in the Drake passage influence strongly the meridional overturning circulation (MOC) of the southern hemisphere which is essential for head transfer with the atmosphere and the global climate. Deep boundary currents guided by complex bathymetry flow into Drake passage associated with strong eddying build together the Circumpolar Deep Water (CDW). A boundary current that originates in the south east pacific, which flows along the west coast of the south American continent enters the Drakes passage in the east and hits a series of anticyclonic eddies that are low in salinity in their center, in the west. This current, containing low saline and poorly ventilated warm waters transports approximately 6 Sv and is a related of the Pacific Deep Water (PDW). According to J. Alexander Brearley et al. in the article "Deep boundary current disintegration in drake passage" (2014), this current is responsible for transporting PDW along the ACC and its homogenisation and is thus an important factor in the Southern Ocean Overturning Circulation.

In this work the dynamics and the influence of the arrival of the PDW in the Drake Passage are investigated with help of the regional ocean model simulation software ROMS. The results are analysed and compared with the outcomes of the upon introduced article of J.Alexander Brearley et al.

2. Materials and Methods

2.1. Studied Zone and Bathymetry

The global studied zone and its bathymetry is illustrated in Figure 2 and Figure 2. With low depths of maximum 1000 m, the zones around the numerous islands at the tip of Chile are defined as not essential for this studies. Also a dividing by land masses might cause complications in calculating capacities with the model.

Lower depths of maximum 1000 m marked in deep blue follow around 100 km off shore the coast line around Chile and continue west along the Burdwood Bank until the Falkland Plateau. The maximum depth of almost 5000 m in the west of the model zone rise in the drake passage around 3500 m and drop slightly direction east. The area of the passage is covered with heights. Not illustrated in this figure is the Antarctic Peninsula that is just south of the studied area and continues with the South Shetland and the South Orkney Islands. These Island build together with the Antarctic Peninsula on the south side and the shallows between the Burdwood Bank and the South Georgia Island a kind of funnel. This funnel builds the east Drake passage witch leads into the area between Weddell Sea and South Atlantic Ocean.

From the east, the ACC arrives from the Southern Ocean and enters the Drake passage together with PDW. From the Weddell sea, the Peri Antarctic Coastal Current (PACC) which flows counter clockwise around the Antarctic, arrives south-east of the Drake passage follows the bathymetry and turns east.

From the north of the Flakland Plateau the Brazil Current arrives in the South Atlantic and turns east when hitting the Flakland Current that origins in the Drake Passage direction north.

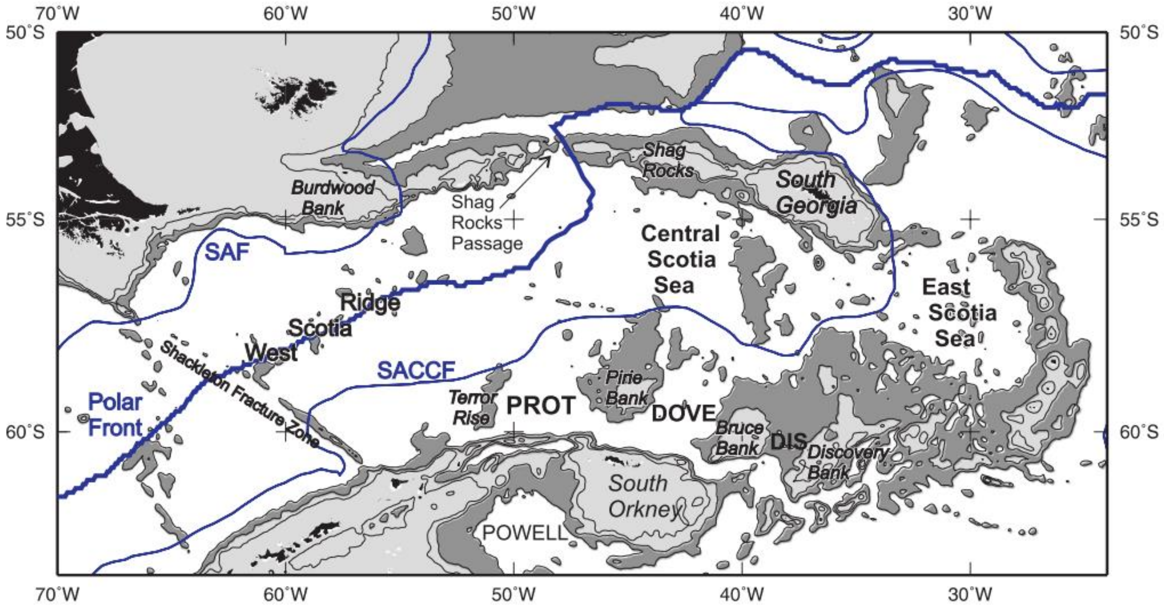

Figure 1: Drake Passage and the Scotia Sea. Bathymetric contours [from Smith and Sandwell, 1997] are shown at 1000 (filled light gray), 2000, and 3000 m (filled dark gray). Approximate positions of oceanographic fronts shown in blue. (Source: Roy Livermore, 2007)

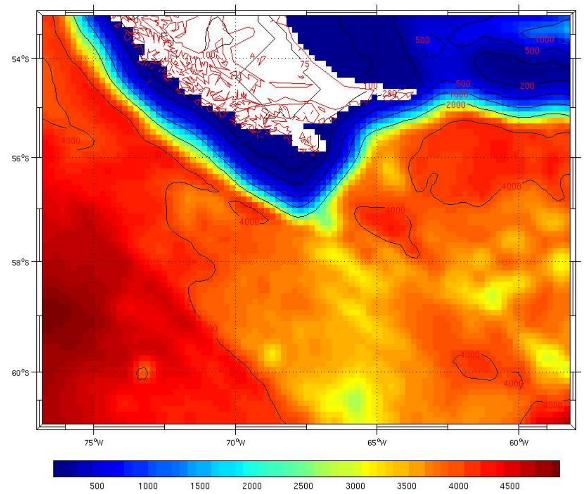

Figure 2: Bathymetry Map of the Southern Ocean and Drake Passage and its bathymetry. Depths are indicated with colour bar and values in meter. Longitude and latitude of map in °. Map generated with ROMS and plotted with Matlab.

The climate in the Drake Passage is distinct by only little seasonal variations of temperature and air movement. Strong westerly winds blow constantly along the south of the south American continent into the arctic ocean where they hit the rising easterlies from higher latitudes. Constant meridional overturning circulation causes a very constant sea surface temperature (SST) (Figure 3).

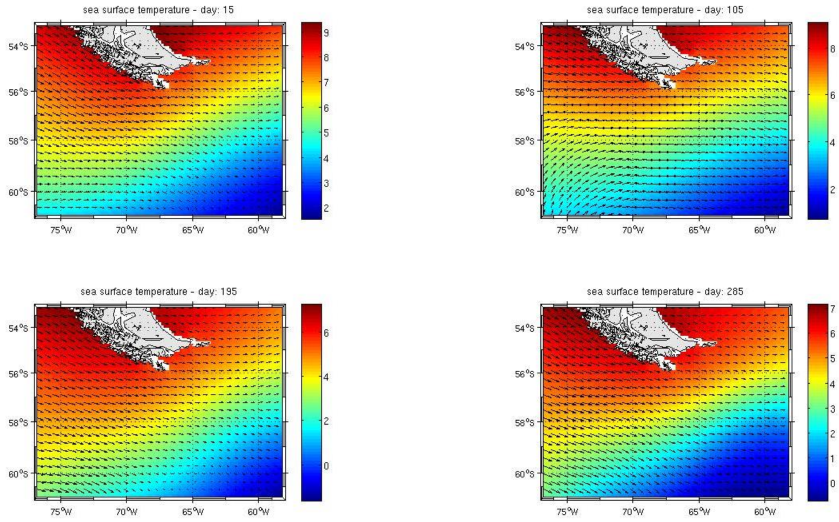

Figure 3: Map of Drake Passage with sea surface temperature in °C illustrated with a colour bar and wind direction illustrated with arrows. Each figure shows on moment of the year between 15th and 285th day. Longitude and latitude of map in °. Maps plotted with Matlab.

2.2. Generalities ROMS

The Regional Ocean Modelling system (ROMS) is a three dimension, free-surface model, based on primitive equations widely used in the climatologic and oceanographic communities. This model allows to determine the seasonal and annual variations of physical parameters of a chosen zone knowing the initial boundaries values.

2.3. Primitive Equations

The Regional Ocean Modelling System (ROMS) is fundamentally based on the primitive movement equations of Navier-Stockes (1)(2). With respect of the conservation equations for heat (3) and salinity (4) and ocean water properties via TEOS10 and continuity equation (5).

$$\frac{\partial u}{\partial t} + \vec{U}\nabla u - fv = -\frac{1}{\rho_0}\frac{\partial P}{\partial x} + A_h \nabla_h^2 u + A_v \frac{\delta^2 u}{\delta z^2} \qquad (1)$$

$$\frac{\partial v}{\partial t} + \vec{U}\nabla v + fu = -\frac{1}{\rho_0}\frac{\partial P}{\partial y} + A_h \nabla_h^2 v + A_v \frac{\delta^2 v}{\delta z^2} \qquad (2)$$

$$\frac{\partial T}{\partial t} + \vec{U}\nabla T = A_h \nabla_h^2 T + A_v \frac{\partial^2 T}{\partial z^2} + \frac{Q_c}{\rho_0 C_p}\frac{\partial I}{\partial z} \qquad (3)$$

$$\frac{\partial S}{\partial t} + \vec{U}\nabla S = A_h \nabla_h^2 S + A_v \frac{\partial^2 S}{\partial z^2} \qquad (4)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (5)$$

With:
u and v: horizontal speed,
P: Pressure,
T: temperature,
S: Salinity,
ρ0: volume mass at atmospheric pressure,
Ah and Av: horizontal and vertical viscosity coefficient,
f: Coriolis force

2.4. Grid parameters

The geo coordinates of the zone under study is selected with additional under program of ROMS, ad_findgeocoord.m. Via simple selecting on the earths map, the program gives precise coordinates which are used for the model. All grid parameters (Table 1) are settled with the under program romstools_param.m. The under program make_grid.m generates a low resolution map of the area (Figure 4). With an additional option in the under program the coastline is optimised, sea and land areas are selected. Finally, a map with the bathymetry of the region is plotted (Figure 2). Parameters are transferred to file param.h. With the under programs make_clim.m and make_forcing.m, low resolution climate and geophysics models from databank are plotted which give boundary conditions.

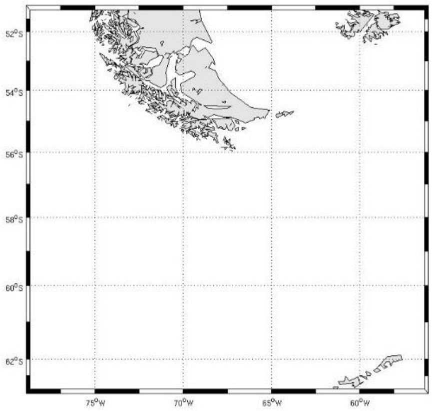

Figure 4: Low resolution map of studied are.

Table 1: Grid parameters of Drake Passage model, generated with file: romstool_param.m

Grid parameters	Model
Longitude min.	-74°W
Longitude max.	-62°W
Latitude min.	-61°S
Latitude max.	-53°S
Number of vertical levels	32
Grid dimensions LLm/MMm	94/73
Grid resolution	12 km
Resolution	1/5
Open borders	all

2.5. Model parameters

The under program ad_cfl.m gives a pre estimation for time parameters. All parameters (Table 2) are set and transferred to files: roms.in, roms_inter.in and run_roms.csh.

The simulation considers a model of 10 years. NTIMES describes the number of loops for the 3D equations, NTDFAST describes the number of loops for the 2D equations for each 3D loop. The time steps are described with Dt. The computation process is performed on the cluster of the Pytheas Institute of Marseille.

Table 2: Time parameters of Drake Passage model

Time parameters		
time of model simulation	-	10 years
Number of loops 3D	NTIMES	3600
Time steps	Dt	720 seconds
Number of loops 2D / (3D loops)	NTDFAST	60 seconds

3. Results and Discussion

The model records all basic kinetic values such as energy and volume changes, average salinity and temperature changes in order to detect over amplified oscillation and to control the models stability. The recorded data is plotted in Figure 5, with which a stable time period in the model can be chosen for further investigations.

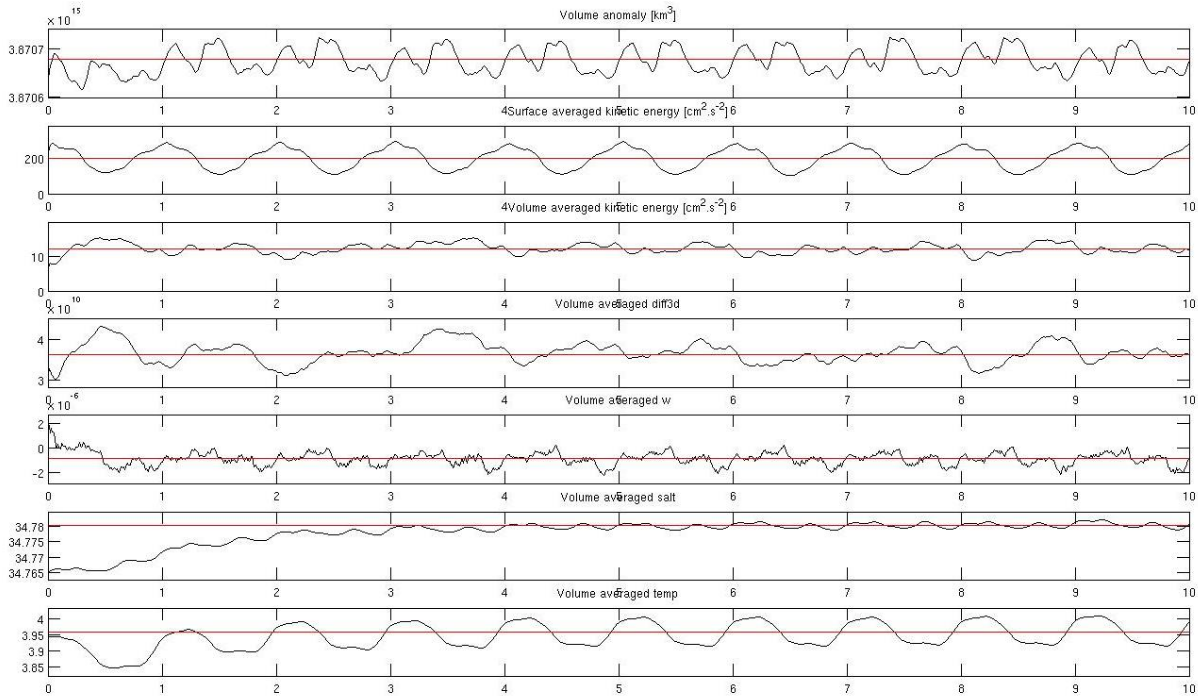

Figure 5: Simulation diagnosis of Irminger. Red line indicates the mean value of each curve, the black lines indicate the average values for the 10-year simulation.

The computing process of the model in Drake Passage as shown in Figure 5 had a constant seasonal oscillation in each year with greater differences in long term studies. In the beginning of the simulation, values had inconstant amplitudes. At approximately year five, the model started to swing in and became stable. For further investigations year eight is chosen concerning its very stable trends.

Overall the seasonal variation in terms of water temperature, winds and salinity the model Drake Passage over the year eight was not intense and consider as not crucial. Over the first third of the year, currents and eddies are very sorted and clearly determinable. With ongoing time, during the middle of the year, overall mixing becomes slightly stronger and calms down again in winter. For investigating the influence by PDW´s on the ACC and the MOC in the Drake Passage the seasonal changes are evaluated as not essential. All further results consider early march (1. March, eights year) because of its well pronounced currents and eddies. Furthermore, tree different layers in the water give striking data for this studies, the surface layer (10 m), at 1000 m and 2000 m of depth.

3.1. Circulation and Currents

Figure 6 illustrates with colour levels the sea surface elevations. Vectors indicate water movements with speed and directions. Well pronounced is a positive elevation and strong currents into the Drake passage, at the western coastline of Chile that originate in the South Pacific and the Southern Ocean. These currents partly run into a major anticyclonic eddy and partly follow the Chile coastline direction Falkland Plateau where they build together with a set of anticyclonic eddies, a major cyclonic eddy. Well pronounced by sea surface elevation are the high pressure areas in anticyclonic eddies, and low pressure areas in cyclonic eddies.

The formation of the Falkland current can be observed in the north, where the major cyclonic eddy drives water masses over the Burdwood Bank into to South Atlantic. The elevation at the east Chile coastline can be interpreted by geostrophic down welling driven by currents, winds and the Coriolis effect. The arrival of a current from the east Southern Ocean can be graded as the ACC. The current that originates in the South pacific and is running down along the Chile east coast into the Drake passage can be interpreted majorly as PDW. Its influence is strongly illustrated by the formation of the major anticyclonic eddy and the current direction east. Strong mixing takes place in the Drake passage. This stands in correlation with the results of J. Alexander Brearley et al.

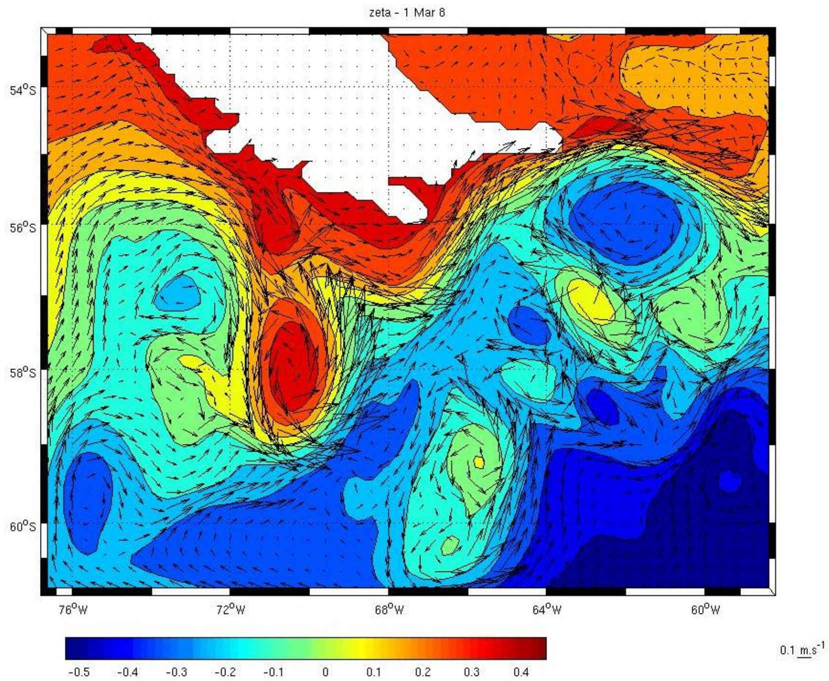

Figure 6: Zeta describes the sea surface elevation in the Drake Passage. In blue, the negative values, in red positive values. Vectors illustrate sea surface water movement, speed in m/s.

3.2. Temperature and Salinity

In the Figure 7 and Figure 8 vectors show overall the same dynamics as described in paragraph Circulation and Currents. Over the whole water column (Figure 7 and Figure 8) the PDW can be spotted (see vectors) in front of the Chile coastline. But with greater depth all current speeds decrease slightly. Hereby, also the same eddying dynamic takes place as seen in the surface waters. The main anticyclonic eddy exists with almost linear current speeds and dynamics over the whole profile.

Water masse with increased temperature flows along the Chile coast into the Drake Passage, where it runs into the main eddy which has also a clearly increased temperature profile. This matches with the PDW that brings warm water into this are in a depth of about 2000 m. This behaviour corresponds with the one in the article of J. Alexander Brearley et al. The low temperature area in the south east of drake passage is also remarkable and points out the arrival of the Peri Antarctic Coastal Current.

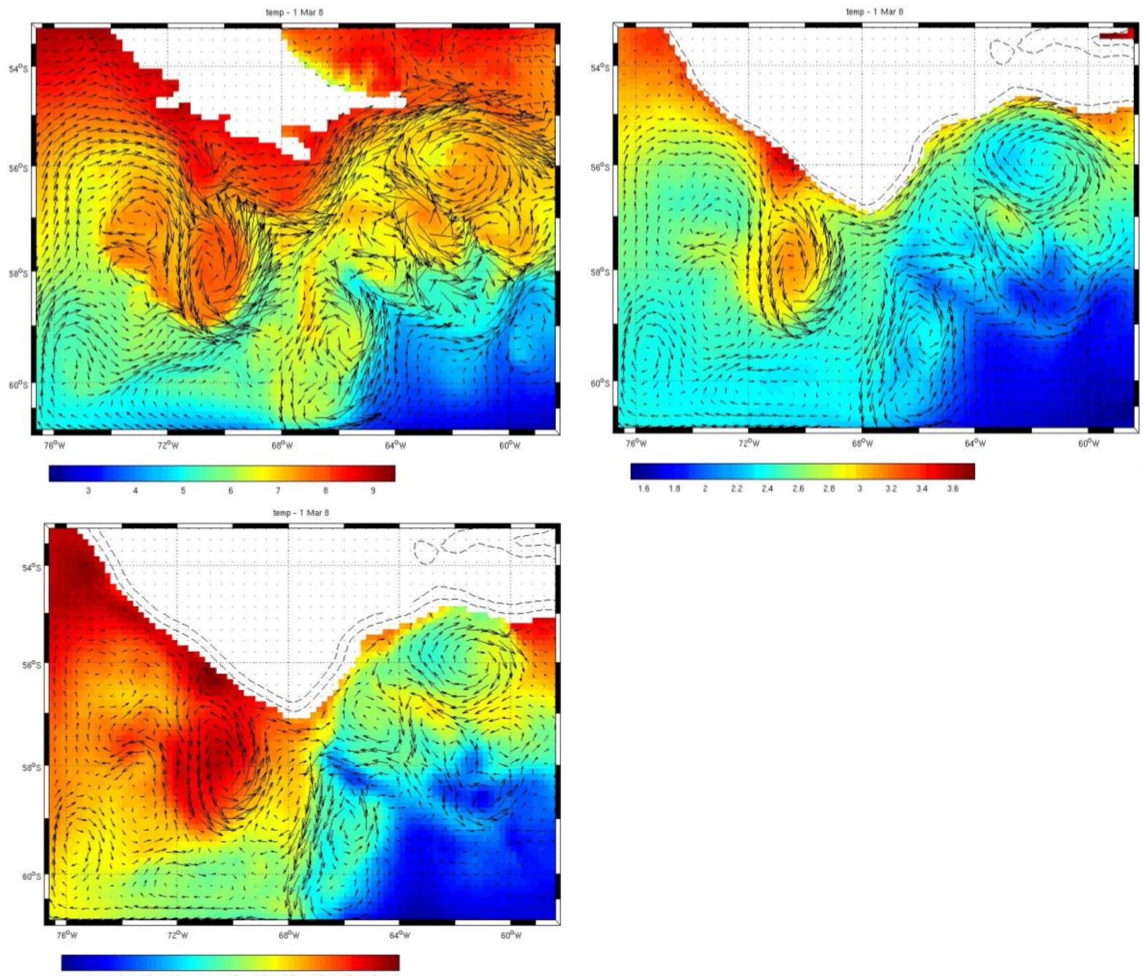

Figure 7: Maps illustrates temperature (°C) layers (with colour bar) and vectors indicate water movements at sea surface (up, left), 1000 m (up, right) and 2000 m (down).

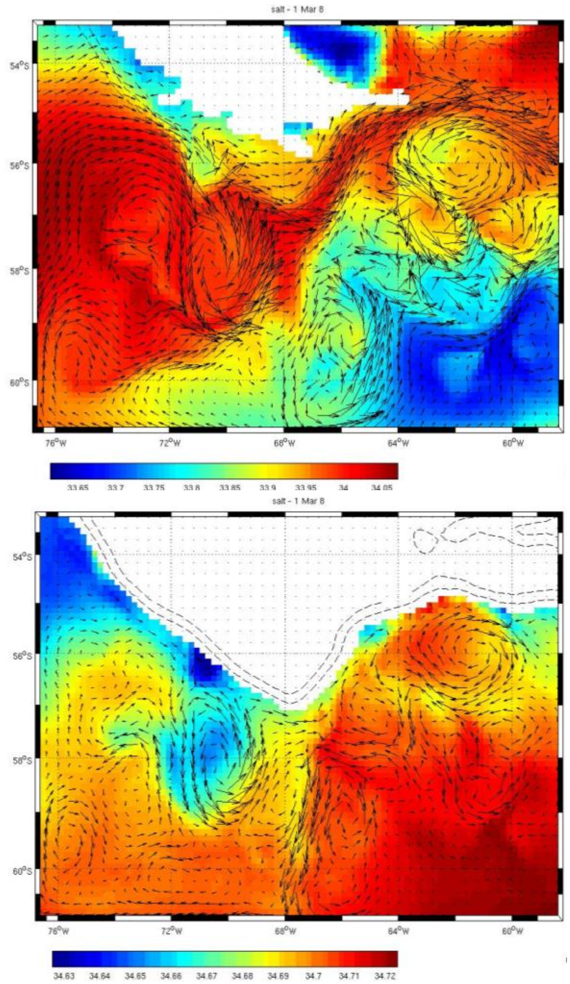

Figure 8: Maps illustrates salinity layers (with colour bar) and vectors indicate water movements at sea surface (up, left), 1000 m (up, right) and 2000 m (down).

Figure 8 illustrates salinity values in the Drake Passage at the surface, 1000 m and 2000 m. At 2000 m depth higher salinity in the south of the passage corresponds with Antarctic deep water arrives from west and the high saline deep water of the Peri Antarctic Coastal Current. PDW is specified by very low salinity over the whole depth and can be seen along the western Chile coast. Especially at 2000 m depth very low salinity underlines the presence of PDW in this region. The main anticyclonic eddy is influenced by high salinity at the surface originating from the arrival of high saline surface water from the ACC. At 1000 m and 2000 m, this eddy stands out by very low salinity. This underlines again the presence of PDW, that drives this eddy.

For further investigations a vertical cut (point a to point b) between the north east of the Southern Pacific and the south west of the Southern Ocean has been made (Figure 9) to examine salinity and temperature in this area.

The left side in Figure 9 which represents the Chile coast is clearly low in salinity and high in temperature in the surface are. This trend continues until a depth of around 2000 m, where it starts to homogenise with the rest of the basin. This concerns around the first 400 km of the Chile Coast to off shore. Again this underlines PDW that flows along Chile into the passage.

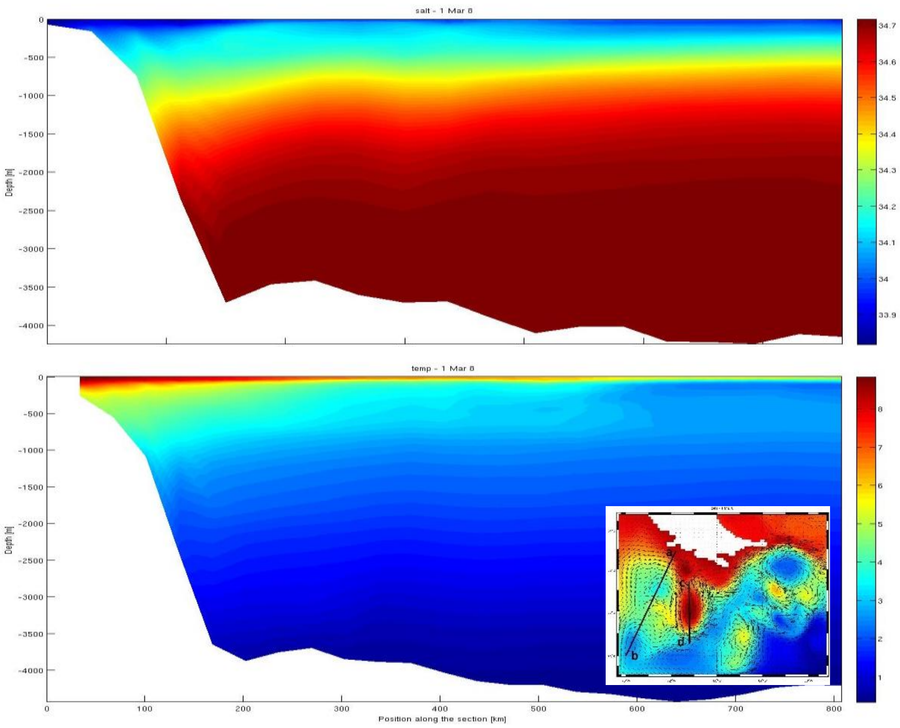

Figure 9: Vertical profile cut between point a and b. Salinity (up) and Temperature (°C) (down) profiles between 0 and 4000 m.

3.3. Eddies

All figures show a very dynamic eddying in the drake passage. A set of anticyclonic eddies cover the whole passage. In the east, anticyclonic eddies drive together with a strong current a large cyclonic eddy that measures around 250 km in diameter. In the west a large anticyclonic eddy, driven by pacific waters and the ACC is very pronounced. To analyse this main eddy, a vertical cut was made between points c and d (Figure 10). The vertical profile show temperature and salinity values.

A very well pronounced decrease of salinity and increase of temperature builds up in the middle of the eddy. This takes place until a depth of around 1500 m. Little peaks of temperature and salinity at the sides mark very well the boundaries.

The eddy corresponds very well with the one in the article of J. Alexander Brearley et al. in terms of dynamics, low salinity and higher temperature.

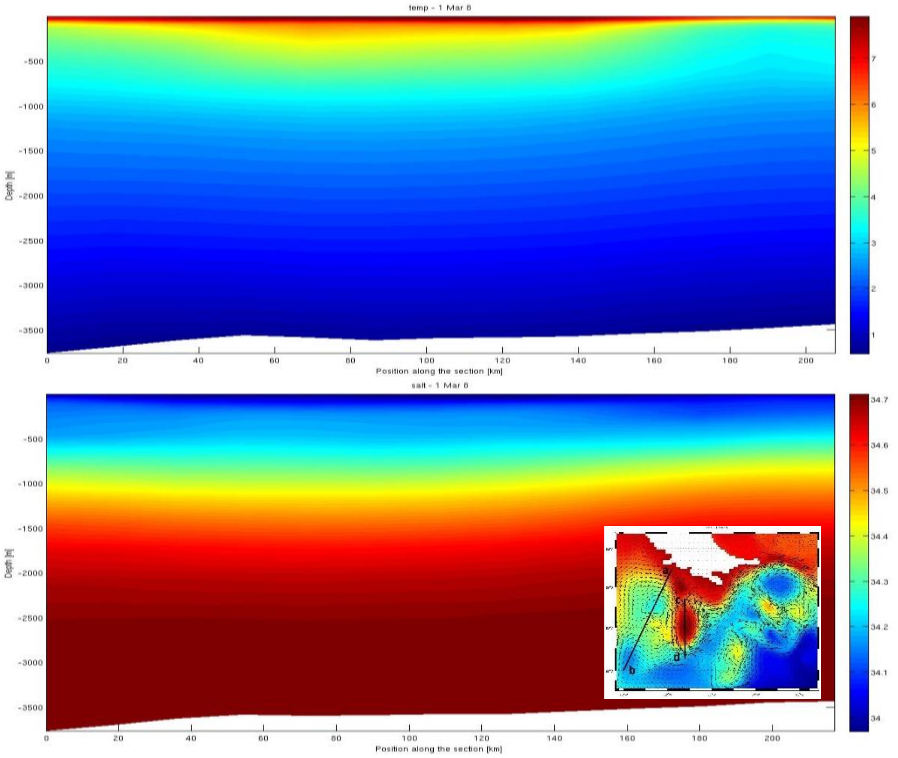

Figure 10: Vertical profile cut of main eddie between point c and d. Salinity (down) and Temperature (°C)(up) profiles between 0 and 3500 m.

4. Conclusion

The numerical simulation with ROMS has given lots of data about the physics in the Drake passage and the Southern Ocean. In this region of very high kinetics standing under the influence of many parameters, several processes and phenomena could be studied separately. Complicated bathymetry paired with the influence of several major currents and the neighbourhood of the two biggest oceans lead to these dynamics. A set of big eddies that exist over the whole water column give information of different current directions. Clear separation between major water masses can be found with help of salinity and temperature values. So are the Antarctic Circumpolar Current and the Peri Antarctic Coastal Current with its cold waters quickly identified. The arrival of the pacific current along the Chile coast and its PDW that is characterized by low salinity and rather higher temperatures find evidence in all of the model results. Especially the main eddy, in which the current leads to inside the Drake passage underlines this. Several results concerning PDW and general dynamics stand in direct correlation with the article of J. Alexander Brearley et al. and its described processes. Salinity and temperature values as well as current directions correspond together. Also the dynamics and values of the eddies in the passage are very pronounced. Low salinity and high temperature inside the main eddy mark PDW.

After a global view over the dynamics taking place in the Drake passage, it is very likely that the disintegration of the PDW and eddies driven by currents from the west pacific have a strong influence on the ACC. Consequently, it can be assumed that the global meridional overturning circulation which the ACC is part of is also impacted.

On a global scale, the simulation with the program ROMS brought results that correlates in a lot of points with the article of J. Alexander Brearley et al.

Bibliography

-Brearley, J. Alexander, Katy L. Sheen, Alberto C. Naveira Garabato, David A. Smeed, Kevin G. Speer, Andreas M. Thurnherr, Michael P. Meredith, and Stephanie Waterman. "Deep Boundary Current Disintegration in Drake Passage." Geophys. Res. Lett. Geophysical Research Letters41.1 (2014): 121-27. Web.

-Livermore, Roy, Claus-Dieter Hillenbrand, Mike Meredith, and Graeme Eagles. "Drake Passage and Cenozoic Climate: An Open and Shut Case?" Geochemistry, Geophysics, Geosystems Geochem. Geophys. Geosyst. 8.1 (2007): n. pag. Web.

- Stephenson, Gordon R., Sarah T. Gille, and Janet Sprintall. "Processes Controlling Upper-ocean Heat Content in Drake Passage." J. Geophys. Res. Oceans Journal of Geophysical Research: Oceans 118.9 (2013): 4409-423. Web.

- Meredith, Michael P., Philip L. Woodworth, Teresa K. Chereskin, David P. Marshall, Lesley C. Allison, Grant R. Bigg, Kathy Donohue, Karen J. Heywood, Chris W. Hughes, Angela Hibbert, Andrew Mcc. Hogg, Helen L. Johnson, Loïc Jullion, Brian A. King, Harry Leach, Yueng-Djern Lenn, Miguel A. Morales Maqueda, David R. Munday, Alberto C. Naveira Garabato, Christine Provost, Jean-Baptiste Sallée, and Janet Sprintall. "Sustained Monitoring Of The Southern Ocean At Drake Passage: Past Achievements And Future Priorities." Rev. Geophys. Reviews of Geophysics 49.4 (2011): n. pag. Web.

- Doglioli, A. M. (2015), Notes de Cours et Travaux Dirigés de Modélisation de la Circulation Océanique, Université d'Aix-Marseille, Marseille, France. Www.mio.univ- amu.fr/~doglioli/Doglioli_NotesCoursTD _ModelisationCirculationOceanique.pdf