Final report of numerical modelling

Etudiant :
Erwan PINEAU

Encadrants :
Mr. Jonathan GULA
Mr. Quentin JAMET

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1 Abstract

2 Introduction

A major driver of the global oceanic circulation is the Antarctic Circumpolar Current. The Austral Ocean connects Atlantic, Pacific and Indian Oceans. Tasmania and Australia coasts make the link between the Indian and the Pacific oceans and, it is also the place where the mid-latitude gyres of these oceans meet. The upwelling of the overturning circulation is made in Southern Ocean, this convection process impacts the freshwater, global heat, carbon and nutients budgets. Knowing the circulation of this area is important due to the importance of it on global climate and global biogeochemical cycles (Herraiz-Borreguero and Rintoul 2011).

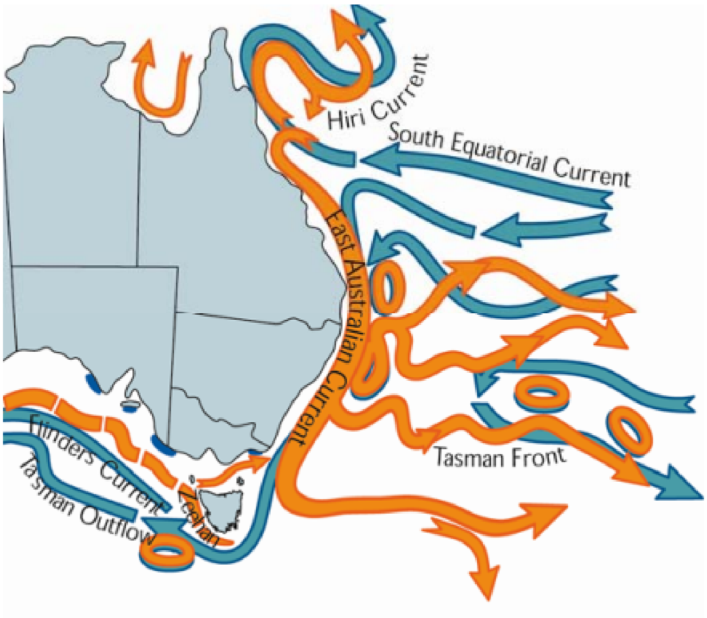


Figure 1: East-Australia map with the majors ocean currents represented with the orange (blue) arrows for the surface (subsurface) currents (Ridgway and Hill 2009).

The general circulation in this area is governed by two major currents, the East Australian Current and the Zeehan Current at surface (Figure 1). The EAC brings northern tropical water to the south from Fraser Island to the east of Tasmania. This current is stronger in summer and transports warmer water masses, and also tropical species like tuna. The ZC reaches is maximal flow in winter, it is in the continuity of the Leeuwin Current. It is southward oriented along the Tasmania west coast and turns around the island to flows northward until the middle of Tasmania. Due to the phase lag between these currents, there is a particular seasonality (Ridgway 2007).

The bathymetry of this region is special, the continental shelf is very close to the Australian and Tasmanian coasts and the depth changes of more than 4000 m through the continental slope. Moreover, there are several seamounts and plateaus (Figures 2 & 3).

For this study, the area of interest is Tasmania and the south of Australia between 137-153°E and 37-46°S.

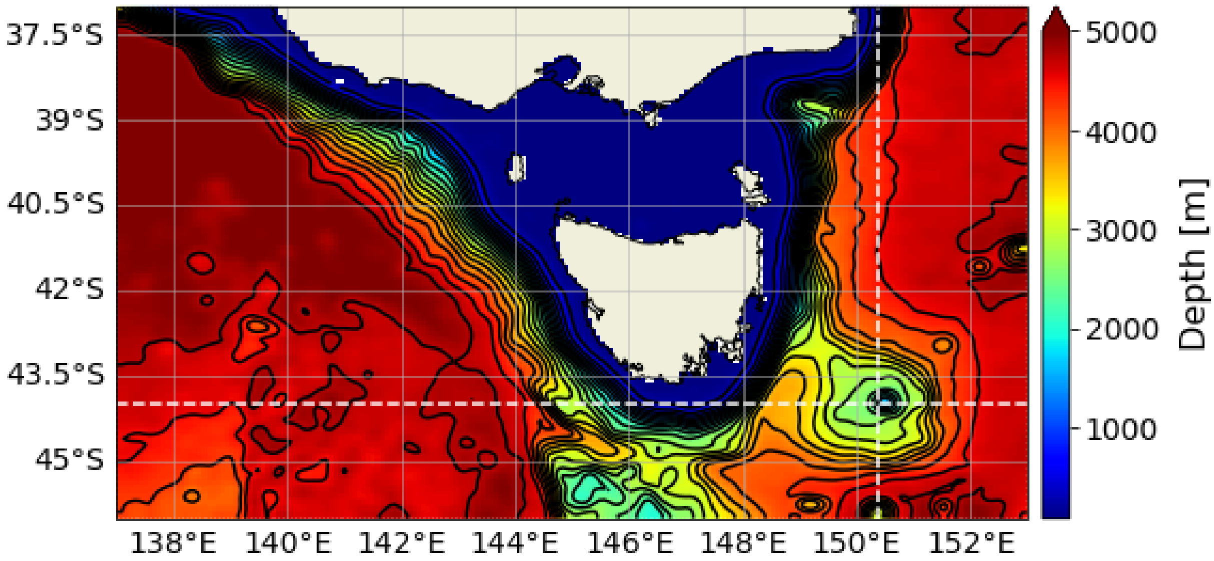


Figure 2: Bathymetry map with isobaths represented by the black lines and the meridional and zonal transects at 44.0°S and 150.5°E in white dashed lines.

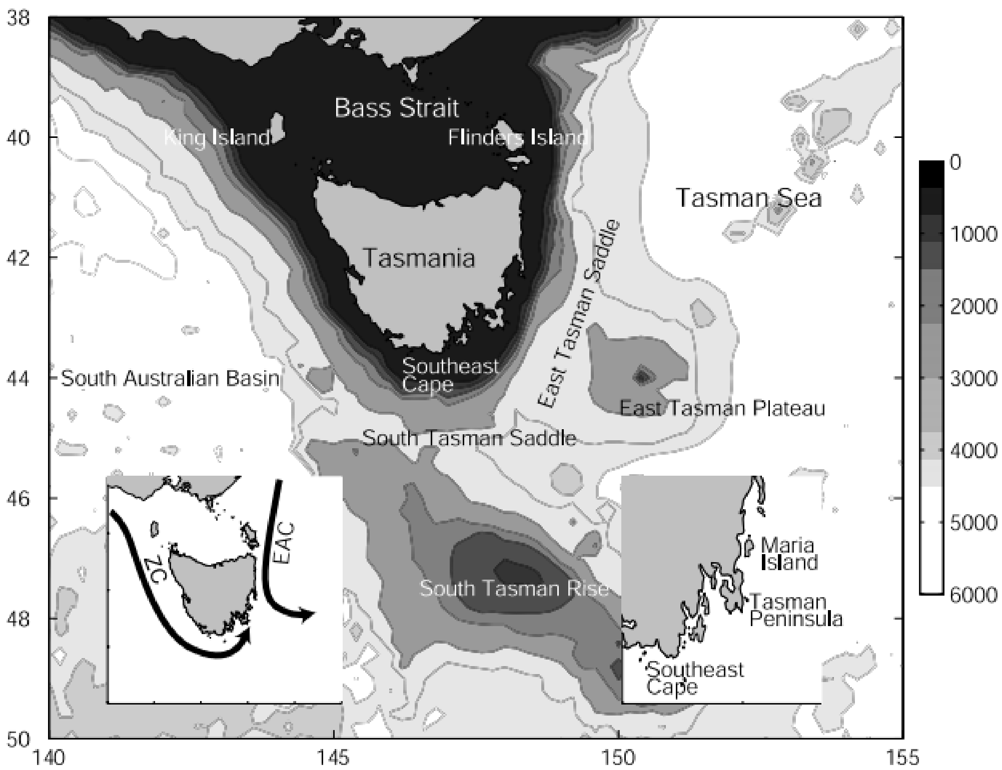


Figure 3: Bathymetric map with geographic names. The inset on the right shows the southeast coast in greater detail. The inset on the left shows a schematic of the major current systems in the region (Ridgway 2007).

The mains objectives of this study is to analyze the spin up model and the circulation around Tasmania and its seasonal variability. The model and its parameters are described in 3.1 followed by the simulation and studied parameters like the region of interests, its bathymetry. In the 4 section, simulations are compared to observations to validate the simulation. Then, the spin-up response of the model is analyzed and finally there is a focus on the averaged surface dynamics over one year.

3 Data & Methods

3.1 ROMS-CROCO model

The ocean model used for this study is the ROMS-CROCO (Coastal and Regional Ocean COmmunity model) model. It is a three-dimensional regional model developed around the ROMS model by French institutes: UPS, IFREMER, SHOM, CNRS, INRIA and IRD in association with the institutes that developed ROMS.

This model solves the primitives equations that are simplifications of the Navier-Stokes equations by considering horizontal resolutions larger than the kilometer, with a nonlinear equation of state depends on temperature and salinity, and by doing some approximations:

- Hydrostatics: The assumption that the horizontal scale is much larger than the horizontal scale (i.e. $H/L << 1$) allows simplifying the vertical momentum equation as a balance between the buoyancy force and the vertical pressure gradient. The non-hydrostatics processes are parametrized.
- Boussinesq: The density variations are considered small in comparison to the background density (i.e $\rho'/\rho_0 << 1$) except for the variations in the buoyancy force.
- Incompressibility: The velocity divergence is assumed to be zero.
- Spherical earth: The geopotential surfaces are assumed to be spheres so that gravity is parallel to the earth's radius.
- Thin-shell: The ocean depth is small compared to the earth's radius.
- Turbulent closure: The turbulent fluxes are expressed in terms of large-scale features.

The equations solved by this model are:

- The momentum balance in zonal and meridional directions:

$$\partial_t u + \nabla.(\vec{v}u) - fv = -\frac{1}{\rho_0}\partial_y P + K_h \nabla_h^2 u + K_v \partial_z^2 u \tag{1}$$

$$\partial_t v + \nabla.(\vec{v}v) + fu = -\frac{1}{\rho_0}\partial_x P + K_h \nabla_h^2 v + K_v \partial_z^2 v \tag{2}$$

  Where u and v are respectively the zonal and meridional velocities. f is the Coriolis parameter, P corresponds to the pressure, K_h and K_v are respectively the horizontal and vertical Reynolds stresses parameters.

- The temperature (T) and salinity (S) conservation equations:

$$\partial_t T + u\nabla(T) = K_h \nabla_h^2 T + K_v \partial_z^2 T \tag{3}$$

$$\partial_t S + u\nabla(T) = K_h \nabla_h^2 S + K_v \partial_z^2 S \tag{4}$$

The horizontal discretization is the grid C of the Arakawa Grids. The zonal velocities are computed in the middle of the left and right cell sides, the meridional velocities in the middle of the up and down cell sides and the parameters are computed in the center of the cells. The vertical discretization are sigma-coordinates that follows the bathymetry.

There is a stability criteria that depends on the scheme implemented in the model called the Courant-Fridrichs-Levy (CFL). With the Leapfrog scheme used for this study, the CFL is given by:

$$\Delta t \leq \frac{1}{c\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}}} \tag{5}$$

This equation tells that the time step (Δt) and the horizontal resolutions (Δx, Δy) have to be selected carefully according to the propagation speed of the processes of interest ($c = \sqrt{gH}$). A balance between the resolution and the time step is important to be able to observe the processes of interest in an acceptable computing time.

3.2 Simulation parameters

The region of interest for this study is the Tasmania, the area limits have been as well as the number of cells in x- and y-axis with a Matlab program. The "makegrid" command generates the grid with the coordinates of the four grid corners and the angle resolution (1).

Longitude (°E)	**Latitude (°S)**	**Resolution (°)**	**LLm**	**MMm**	**N**
137 - 153	37 - 46	1/12.5	199	150	20

Table 1: Grid parameters

The "make_forcing" command generates the surface forcing wind-stress, surface heat flux and surface freshwater flux The initial conditions of temperature, salinity, currents and sea surface height are generated with the "make_ clim" command. The oceanic boundary conditions of temperature, salinity, currents and sea surface height come from "make_bry".

The integration period of the simulation is set to one year and a half, according to the precedent parameters, the time steps have to be selected in agreement with these formulas:

$$\Delta t_{bt} \leq \frac{1}{c\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}}} \tag{6}$$

Where Δt_{bt} corresponds to the time step for barotropic flows. Then, the baroclinic time step is given by:

$$\frac{\Delta y}{U_{max}} \geq \Delta t_{bc} \leq \frac{\Delta x}{U_{max}} \tag{7}$$

The link between these two time steps is:

$$NDTFAST \geq \frac{\Delta t_{bc}}{\Delta t_{bt}} \tag{8}$$

Where $NDTFAST$ is the ratio between the time steps. In this study, the time parameters are presented in the Table 2.

Δt_{bc} **(s)**	**NTIMES**	**NDTFAST**	**NWRT**	**NAVG**
800	58320	60	324	540

Table 2: Time parameters

Where $NTIMES$ is the number of time integration for a one year and a half simulation with a time step of 800 seconds. $NWRT$ is the number of iterations to save data and $NAVG$ corresponds to the number of iterations during with data are averaged in another file.

3.3 Studied parameters

It is interesting to compute the surface kinetic energy averaged over the all domain. This parameter give information about the global kinetic energy, and it is computed with the following equation:

$$SKE = \frac{1}{2}\int u^2 v^2 \delta x \delta y$$

The ratio between the relative vorticity and the local Coriolis parameter is a good parameter to study the regional circulation, this parameter is obtained with this equation:

$$\zeta/f = \frac{\partial_x v - \partial_y u}{f}$$

The velocity used for figure 17 is:

$$|\vec{u}| = \sqrt{u^2 + v^2}$$

Where u and v are averaged over the last year of the simulation.

The surface Eddy Kinetic Energy over the last year is represented on the figure 19 and is calculated with the following equation:

$$EKE = \frac{1}{2}\left(u^2 - \overline{u}^2 + v^2 - \overline{v}^2\right)$$

Where $\overline{u}$ & $\overline{v}$ are respectively the zonal and meridional mean velocities over the all domain. The EKE represents the kinetic energy carried by the eddies only.

4 Results & discussion

4.1 Model validation

Before analyzing the data generated by the CROCO simulation, it is important to compare the data with observations as a validation. By using altimeter data of TOPEX/POSEIDON, Jason, ERS-1, ERS-2, ENVISAT and GEOSAT satellites between October 1992 and December 2006, Ridgway 2007 generates monthly Sea Level Anomaly maps (Figure 4). Similar maps are generated with the simulation output on one year, between May 2005 and April 2006 5figure 5). In this paper this is clear that there is a positive anomaly of the sea level from May to August at coastal boundaries, and a reverse anomaly between November and March. This observation is not obvious on the model despite the positive anomaly in August and the negative anomaly in February and March. The anticyclonic eddies position off the east coast of Tasmania are relatively coherent between the two dataset from January to May but then, there are negative anomalies on the altimeter maps not present on the model, dataset. These differences are maybe due to the spin-up latency of the model and the time averaged made only on one year only compared to 14 years with the altimeters.

The second comparison is made between SST maps monthly averaged between January and April 1999 from satellite data obtained from Advanced Very High Resolution Radiometers (AVHRR) taken from Ridgway 2007 and with SST maps coming from the simulation between January and April 2006 (Figures 6 & 7). First, the temperature range appears to be the same. The warm water tongue in the east of Tasmania propagates southward between January and February. From March to July (not shown) there is an advection of cold water coming from the south, that cools the coastal water. These seasonal signals are coherent on the two datasets.

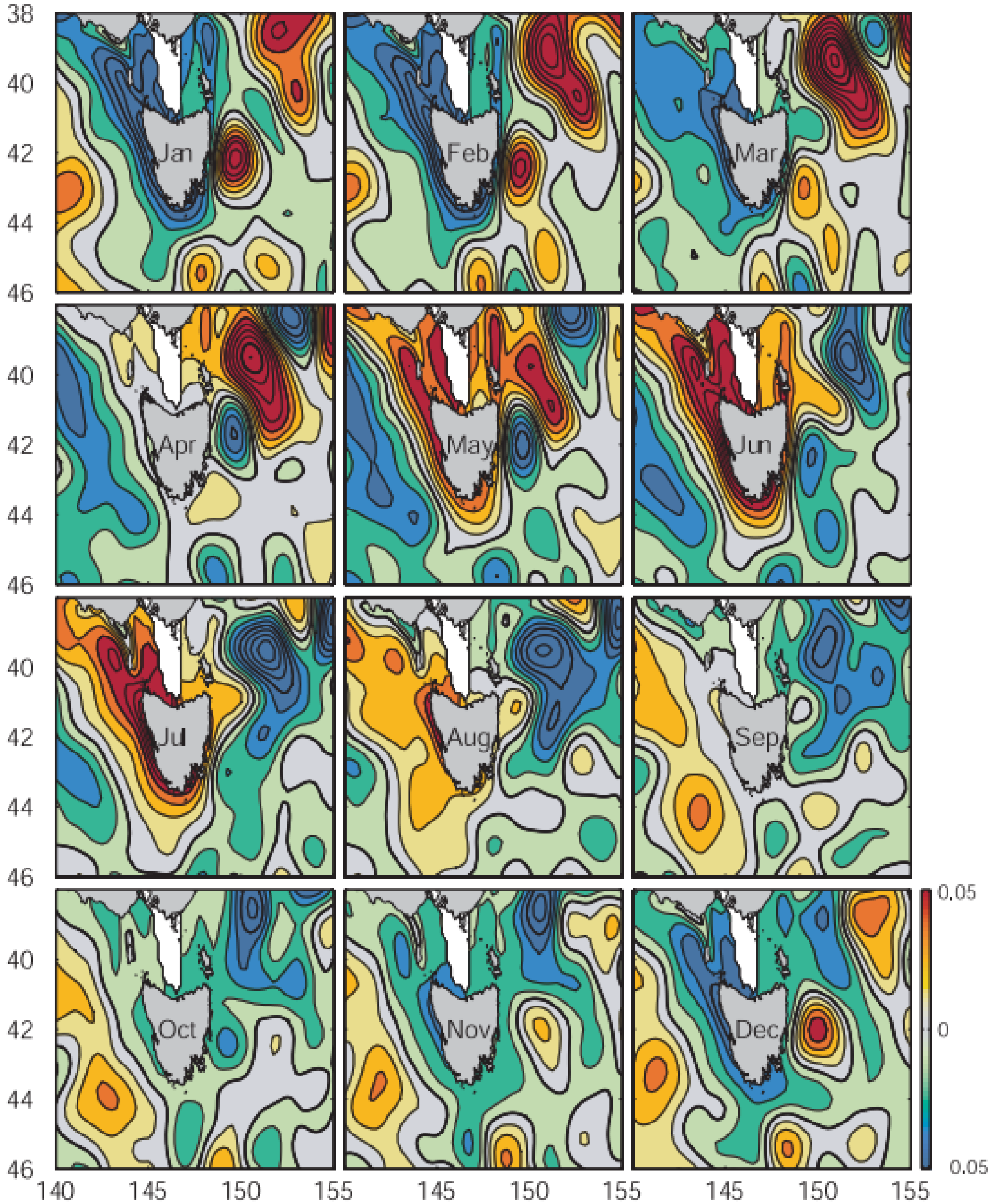


Figure 4: Monthly SLA from the merged altimetry data set. The contour interval is 0.02 m (Ridgway 2007).

As explained before, the EAC reaches is maximal flow during summer, from December to March. This current advects warm and saline water southward, along the east Tasmanian coast. This current is observable between September to March, is initially weak and turbulent. Then, the flow intensifies between January to March. The current splits in two branches at the Southeast Cape of Tasmania, the first one turns to the West by following the bathymetry through the South Tasman Saddle and the second, less important, continues to the Southeast (Ridgway 2007).

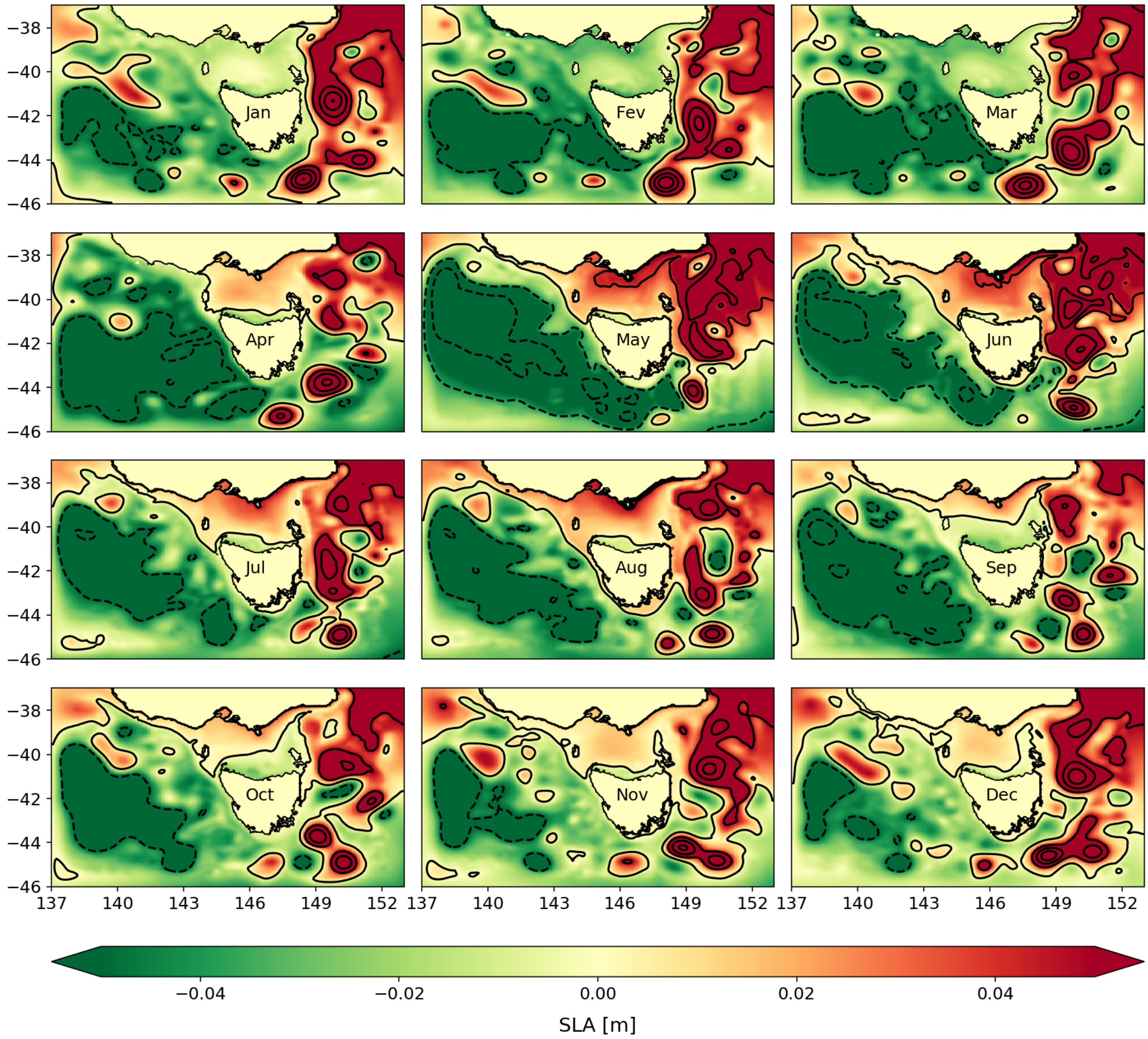


Figure 5: Monthly SLA from CROCO simulation from May 2005 to April 2006. The contour interval is 0.02 m.

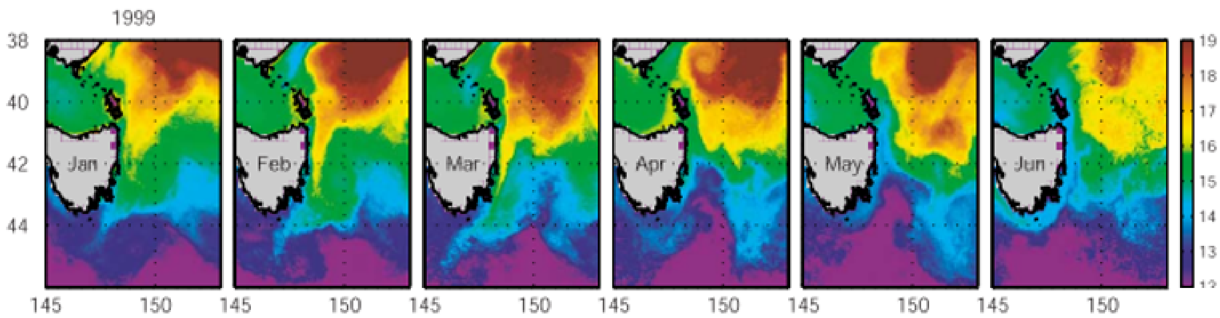


Figure 6: Monthly SST for 1999 from January to June (Ridgway 2007).

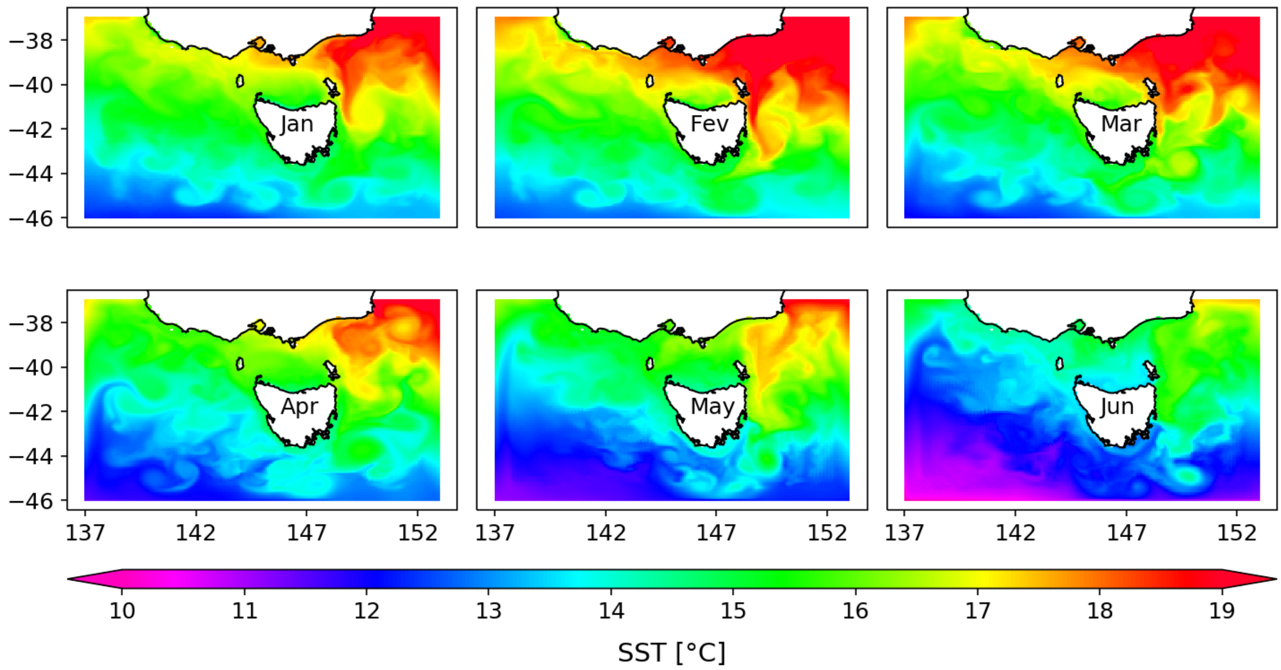


Figure 7: Monthly SST from CROCO simulation from January 2006 to April 2006.

4.2 Spin-up response

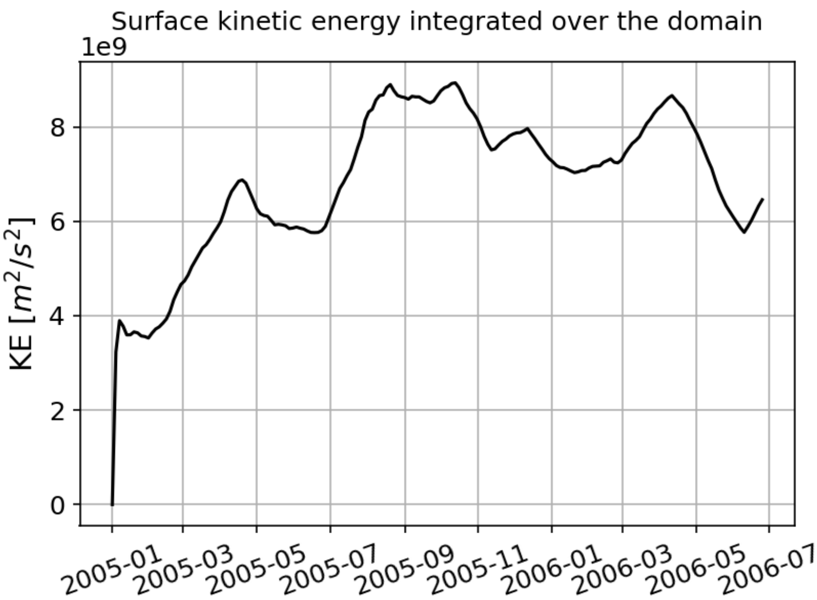


Figure 8: Temporal variation of the surface kinetic energy averaged over the all domain

The initial kinetic energy is equal to zero before the ocean spin-up caused by the different forcings. Then the kinetic energy varies with time with a mean value of 6.8 10^9 m^2/s^2. The maximal value is reached at the end of August and is equal to 8.9 10^9 m^2/s^2. The variations are due to the seasonal variability. This variability is very special, like Cresswell 2000 shown that the EAC is maximal in winter, while the Zeehan Current is more intense in winter. This phase lag means that the seasonality is controlled by one of its two currents. This is observable on the figure 8 because the surface kinetic energy stay high in summer, this is not the case in many other regions.

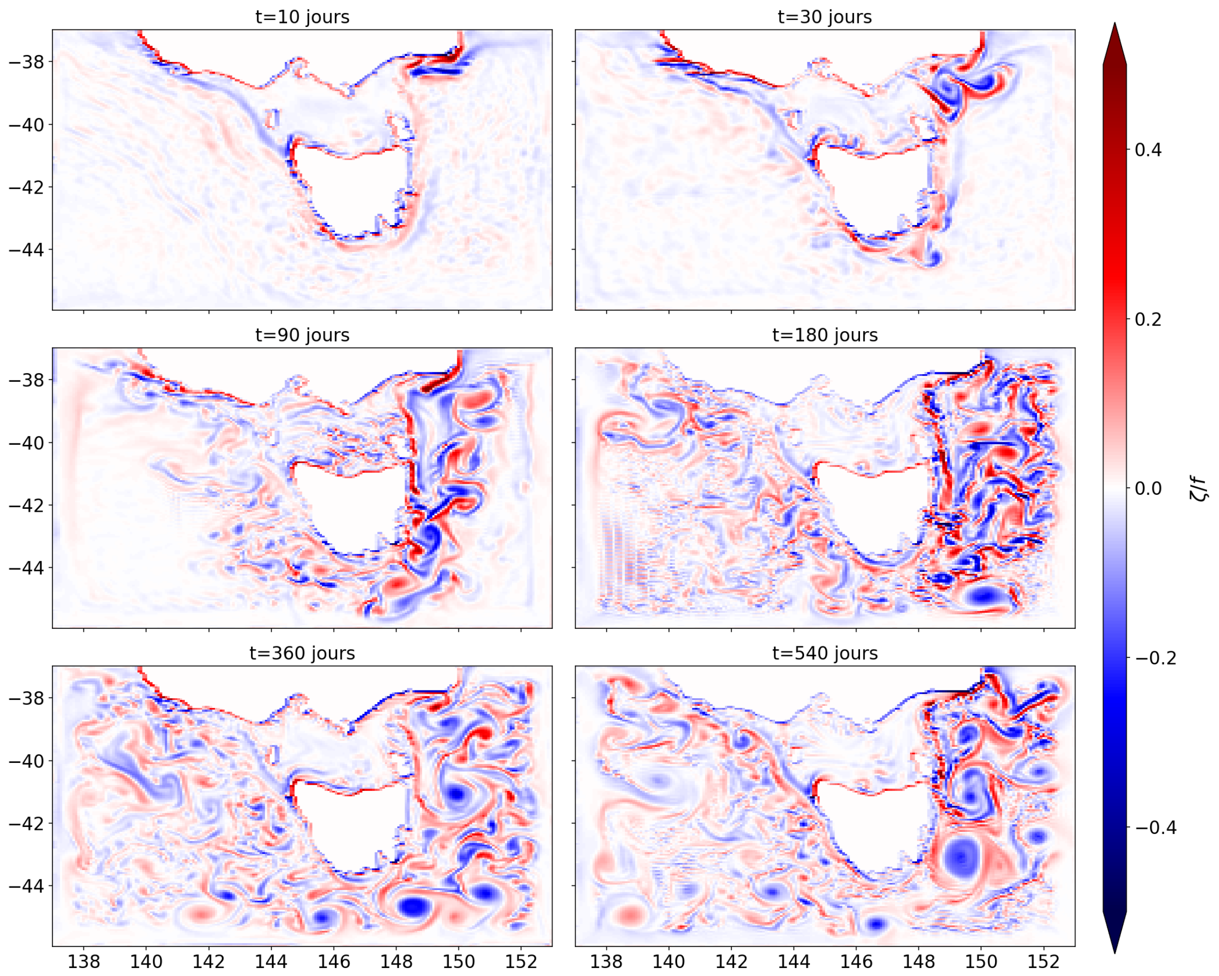


Figure 9: Relative vorticity normalized by the local Coriolis parameter ζ/f at the surface at t = 10, 30, 90, 360 and 540 day.

The relative vorticity can be generated by wind forcing and by bathymetric gradient and as presented before, there are important slopes in this region. Figure 9 represents the relative vorticity normalized by the local Coriolis parameter at the surface. Initially, the relative vorticity is globally null except near the coasts, especially at the South-Est of Australia. On the 30-day snapshot, an intensification of the relative vorticity is noticeable at the est of the studied area. This vorticity continues to increase at 90 days and 180 days with filaments structures. The West vorticity signals are less intense than the East patterns and that is due to the East Australian Current. Then, the relative vorticity reduces at 360 days because of the seasonal variation. For the next southern winter, at day 540, the vorticity value appears to be less important, but the eddies are larger and more structured with a negative sign, corresponding to anticyclones in the Southern Hemisphere, surrounded by "shields" composed by positive sign.

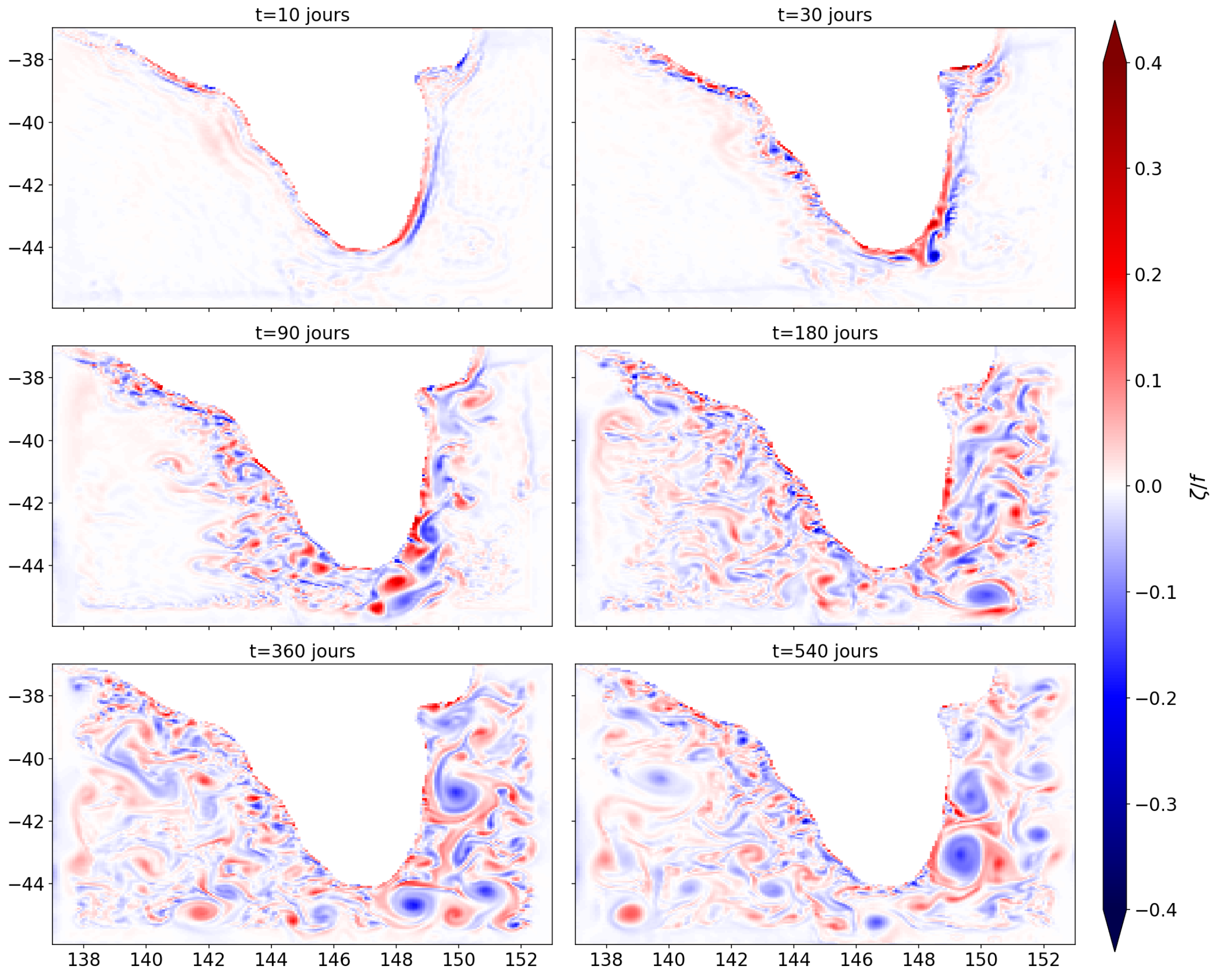


Figure 10: Relative vorticity normalized by the local Coriolis parameter ζ/f at 400 m at t = 10, 30, 90, 360 and 540 day.

The eddies described are also visible at depth, as the figure 10 shows. The ratio between relative vorticity and Coriolis parameter is generally weaker than at the surface, but is still important, the patterns and the dynamics are equivalent. These vortices will impacts water masses parameters at surface and depth.

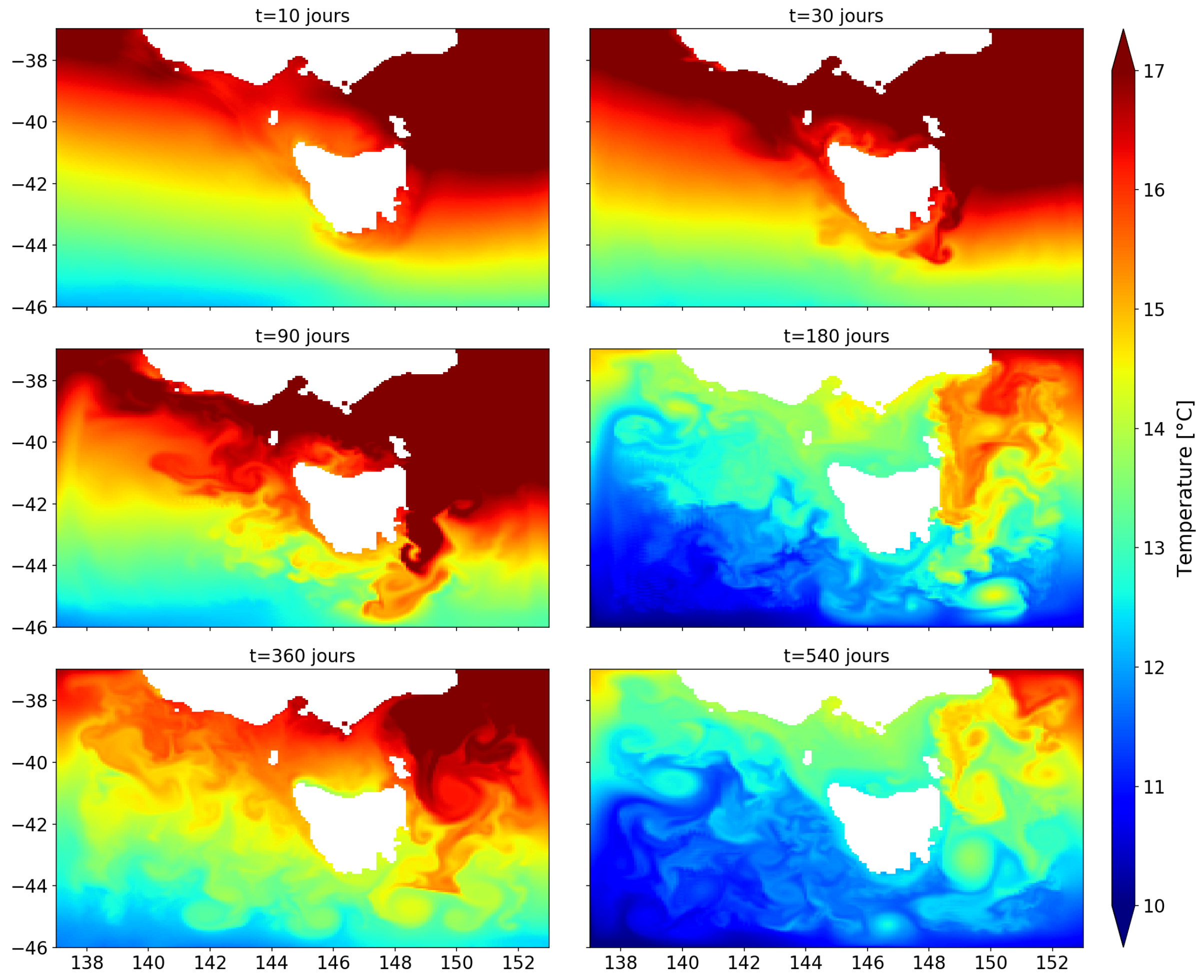


Figure 11: Maps of Sea Surface Temperature at day 10, 30, 90, 180, 360 and 540.

Initially the temperature varying globally with latitude with cold water in South and warm water in North of the area (Figure 11). There is an advection of warm water to the South between 10 and 90 day by the EAC, this motion generates turbulent processes highlighted by the filaments. In winter, at day 180, as said before, the ZC reaches is maximum flow and cold water is advected toward the East because of the intensification of the Eastward winds during winter (Ridgway 2007). The temperature structures one year later in summer (i.e 10 day and 360 day) are globally the same except that there are many more filaments and turbulent processes.

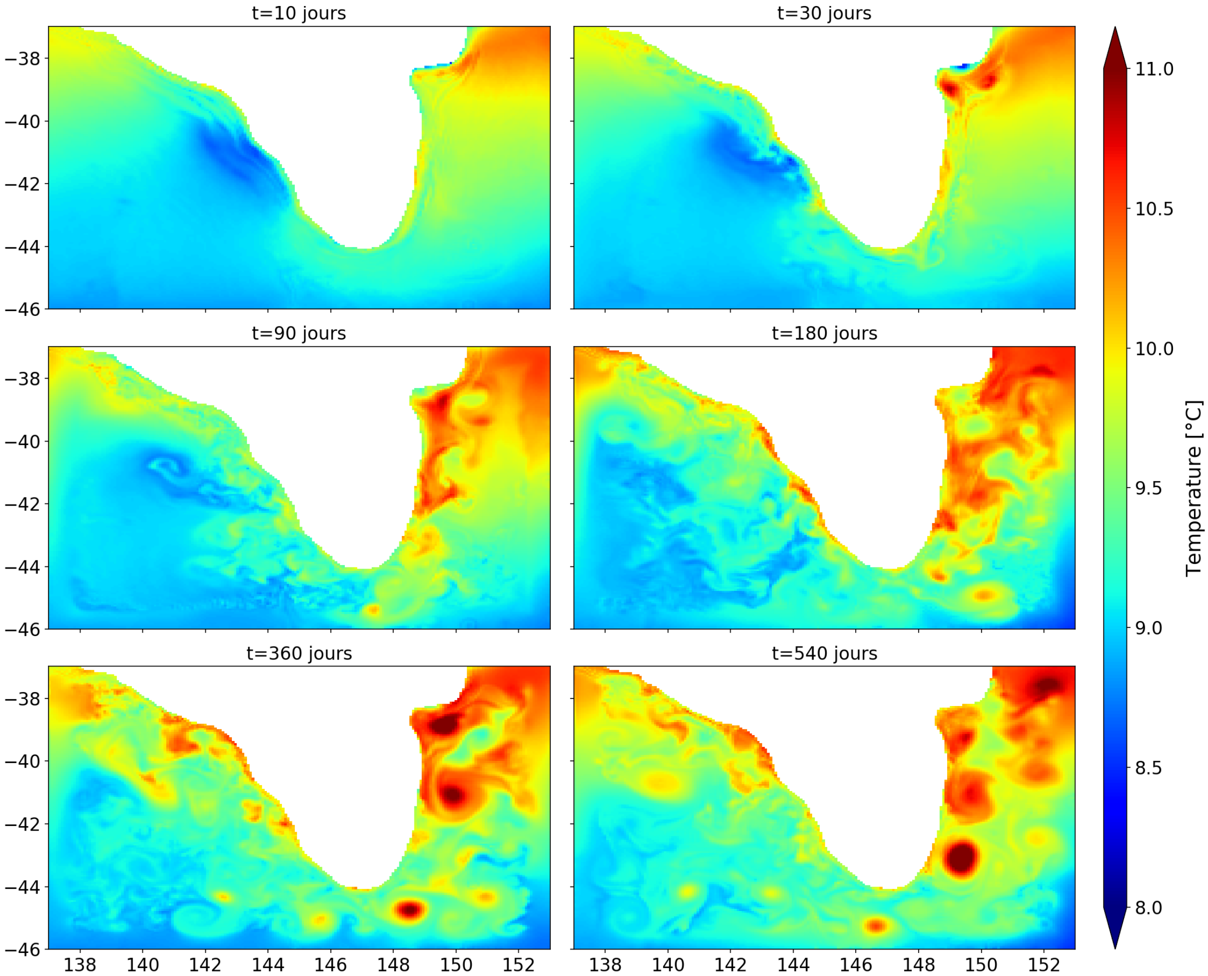
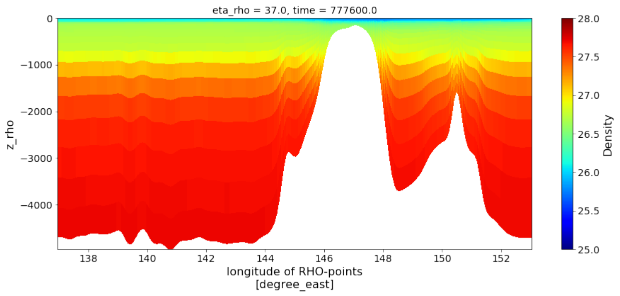


Figure 12: Maps of sea temperature at 400m depth at day 10, 30, 90, 180, 360 and 540.

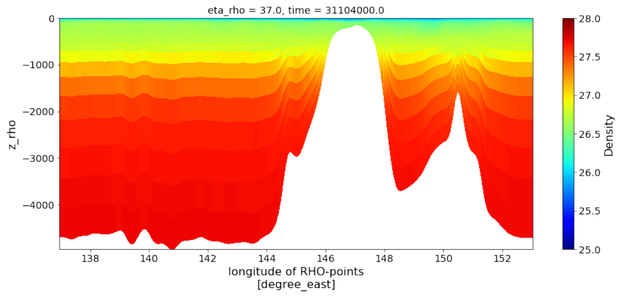
The temperature variation at 400 m depth is less than at the surface but the time variations are the same (Figure12). As expected, there are anomalies of warmer temperature visible at day 360 and 540 in the South and East of Tasmania. Their locations correspond to the anticyclonic eddies at 400 m (Figure 10).

The following figures represent the density and the velocities of a meridional and a zonal transect at 44°S and 150.5°E respectively at day 10 and 360. These transects are shown on the figure 2.

The vertical variation of the density varies principally with the depth and the bathymetry and the isopycnal are following the seabed (Figures 13 & 15). The isopycnal slopes induced by the topography will generate zonal flow for the meridional transect and meridional flow for the zonal transect, considering the thermal wind balance. The figures 14 & 16 confirm this assumption with stronger velocities where the topographic slopes are important. The water is heavier on a sea mount so the water will fall and this motion, because of Coriolis acceleration, will be deviated to the left in the Southern Hemisphere. This is clear on the two transects at 360 day at 44°S, 150.5°E. Variations of positive and negative velocities are observable even in region without isopycnal slopes, that correspond to the anticyclonic eddies. These circular motions are visible in all the water column. The diameter of the anticyclonic eddy on figure 13 is about 220 km and that is close to the results of Ridgway 2007, they found a recirculation feature of 250-300 km diameter.

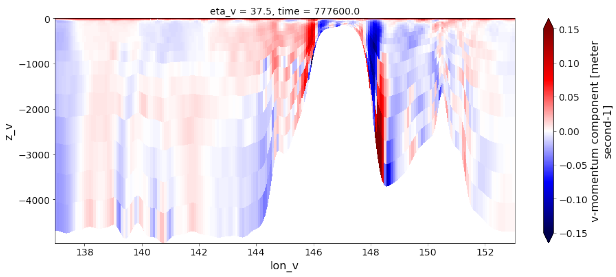


(a) t = 10 day

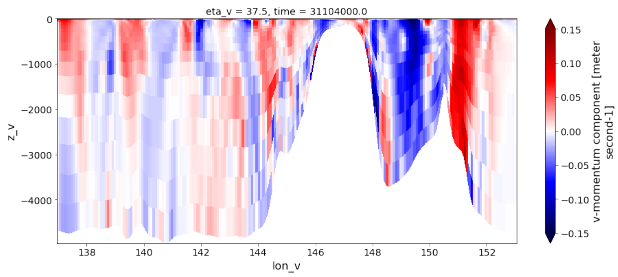


(b) t = 360 day

Figure 13: Zonal transect of density at 44°S at day 10 (360) on the left (right).

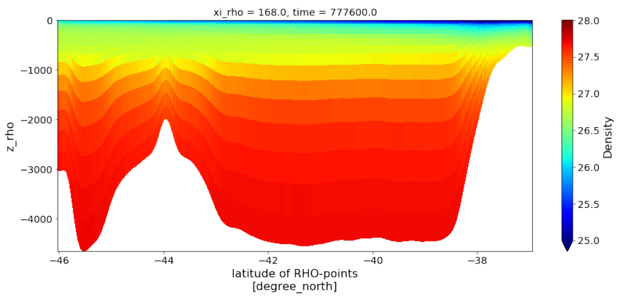


(a) t = 10 day

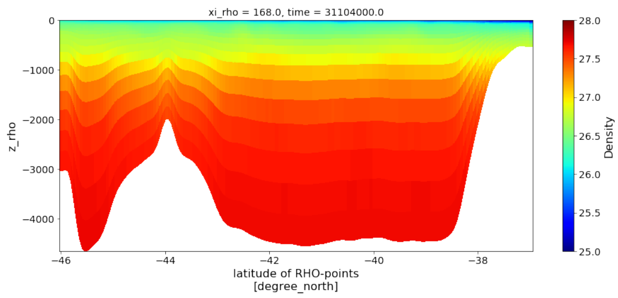


(b) t = 360 day

Figure 14: Zonal transect of meridional velocity at 44°S at day 10 (360) on the left (right).

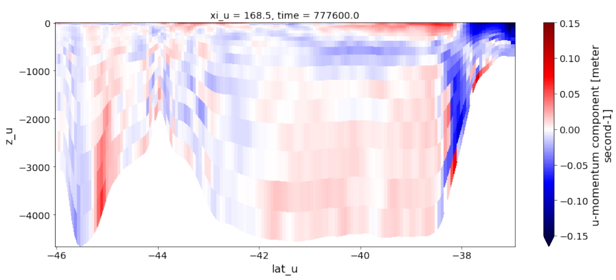


(a) t = 10 day

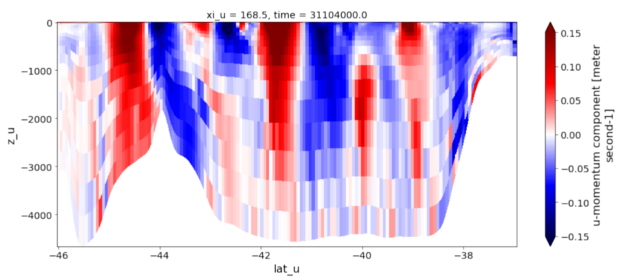


(b) t = 360 day

Figure 15: Meridional transect of density at 150.5°E at day 10 (360) on the left (right).



(a) t = 10 day



(b) t = 360 day

Figure 16: Meridional transect of zonal velocity at 150.5°E at day 10 (360) on the left (right).

The oceanic model response to the different forcing is about 180 days, after this integration period, the parameters are close to *in situ* data (Ridgway 2007).

4.3 Average surface dynamics over one year

The surface velocity averaged over the last year is represented on figure 17, the arrows correspond to the directions of the flow. The surface velocity on Bass Strait is North-East oriented like in the East of Tasmania, where the Zeehan Current is northward directed. This main direction is coherent with the surface wind stress is globally westerly regardless of the season (Ridgway 2007).

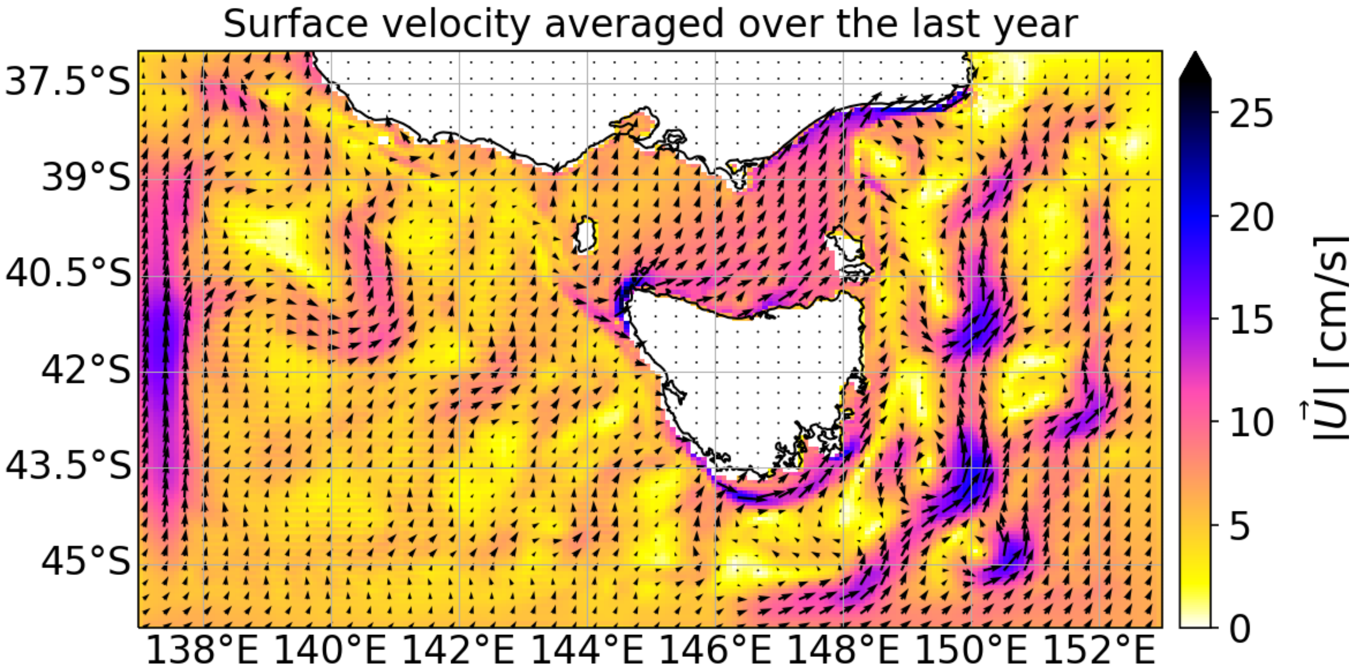


Figure 17: Map of surface mean velocities over the last year of simulation, the arrows represent the direction of the velocity.

The Sea Surface Height variance map represents the variability of the SSH averaged over the last year. The level of the sea is also a good parameter to explain general circulation and stationary eddies with the hydrostatics and the shallow water hypothesis. The maximal values are localized in the East of Tasmania, along the continental slope, and above the East Tasman Plateau and reached more than 70 cm^2. The surface velocity and the Eddy Kinetic Energy maps are showing the same structures (Figures 17 & 19).

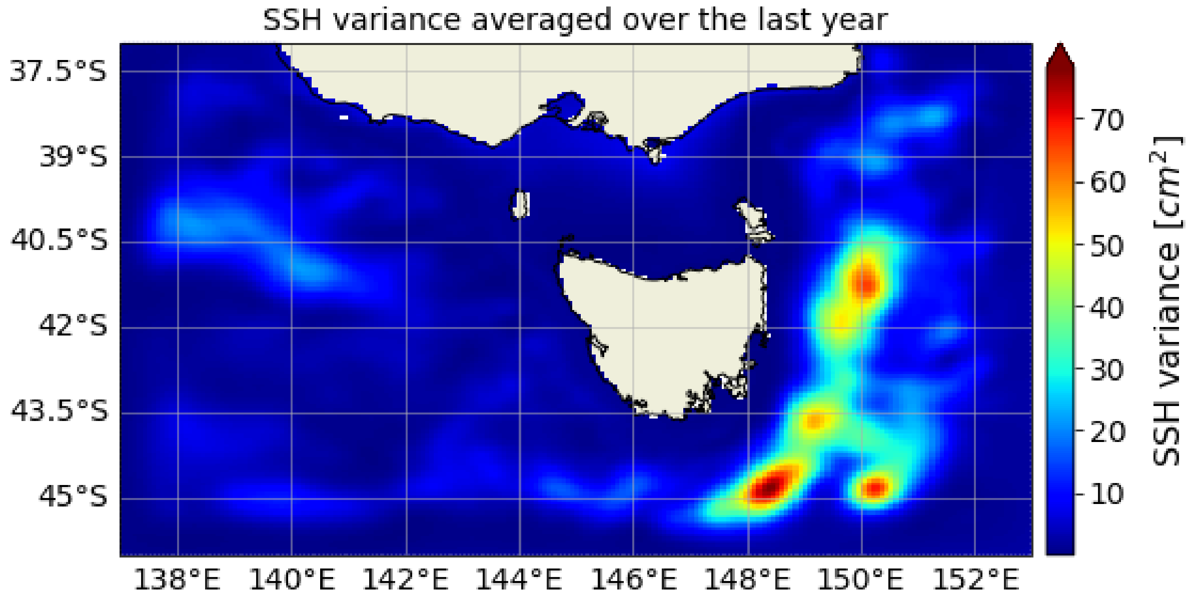


Figure 18: Map of Sea Surface Height variance over the last year of the simulation.

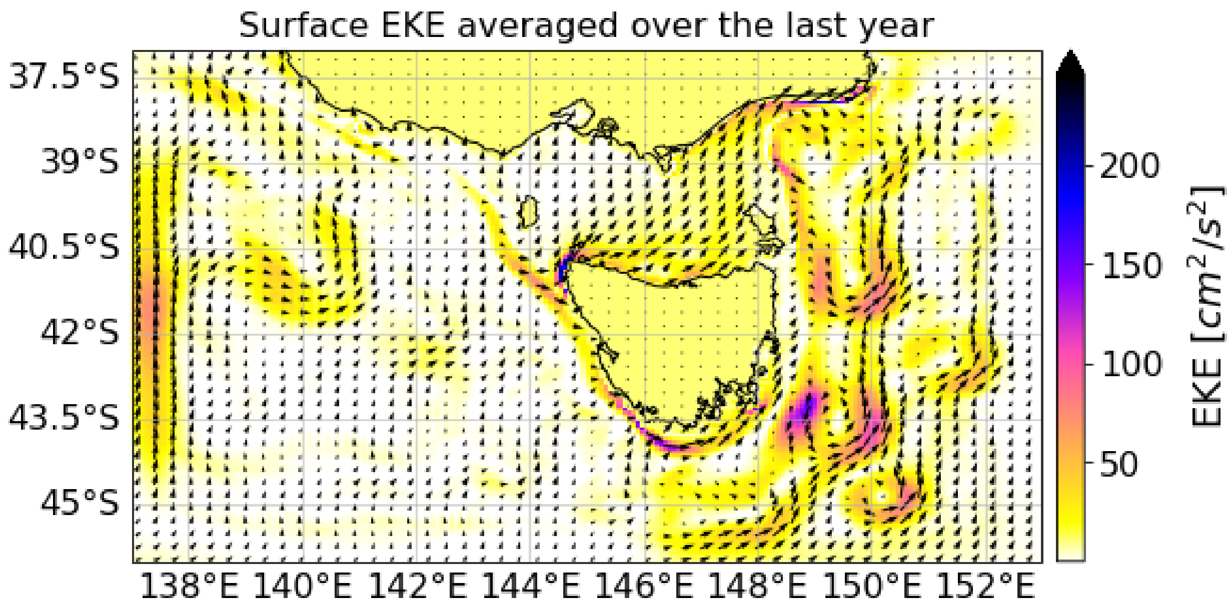


Figure 19: Map of Eddy Kinetic Energy over the last year of simulation.

5 Conclusion

The simulations made with CROCO model allow us to observe the three-dimensional circulation of the studied area: Tasmania. Despite the fact that the ocean motions are fast and meandering, the results seems to be consistent with *in situ* data obtained from satellites. The relatively small space scale allows to observe relatively high resolutions phenomena like meanders (11). The effects of the two currents, the East Australian Current and the Zeehan Current have been observed. The phase lag between these currents make the specificity of this region. During the summer, the EAC is stronger and brings warm and saline water southward. It is also during this time of the year that there is anticyclonic eddies at the Southeast of Tasmania. Then, in winter ZC reaches is maximal flow and advects cold water Westward. The temperature variations are about 9°C between the North and the South of the studied area and about 4°C along the Tasmanian coasts during the year.

The eddies are generates by wind forcing or by the topography, there are stronger near the surface where the relative vorticity is strong and decreases with depth except over topographic features like the East Tasman Plateau (150.5°E, 44.0°N) (Figure 16. The signature of this eddy is visible on annual mean (Figure 19).

The model spin-up is about 180 days to obtained coherent data compared to observations.

There are limitations with this simulation. The comparison with *in situ* Sea Level Anomaly monthly averaged and SLA obtained from the simulation are different principally around the coasts of Tasmania. Then, many parameters are parameterized like the diffusion and that could bring errors. A longer simulation could be a good solution to be more consistent with the observations and study inter-annual variations or with higher spatial resolution to observe smaller motions on the vertical and horizontal but the computation time would be long. A solution could be to do nesting simulation with the same area and a smaller one with higher spatial resolution on the King Island to observe the impacts of it on the circulation.

References

[Cre00] G. R. Cresswell. “Currents of the continental shelf and upper slope of Tasmania”. In: *Papers and Proceedings of the Royal Society of Tasmania, Proc. R. Soc. Tasmania, 133* (2000), pp. 23–30.

[HR11] Laura Herraiz-Borreguero and Stephen Rich Rintoul. “Regional circulation and its impact on upper ocean variability south of Tasmania”. In: *Deep Sea Research Part II: Topical Studies in Oceanography* 58.21 (2011). Biogeochemistry of the Australian Sector of the Southern Ocean, pp. 2071–2081. ISSN: 0967-0645. DOI: `https://doi.org/10.1016/j.dsr2.2011.05.022`. URL: `https://www.sciencedirect.com/science/article/pii/S0967064511001482`.

[Rid07] Ken Ridgway. “Seasonal circulation around Tasmania: An interface between eastern and western boundary dynamics”. In: *Journal of Geophysical Research* 112 (Oct. 2007). DOI: `10.1029/2006JC003898`.

[RH09] Ken Ridgway and Katherine Hill. “The East Australian Current”. In: *A Marine Climate Change Impacts and Adaptation Report Card for Australia 2009, NCCARF Publication* (Jan. 2009).