The Various Components of the Circulation in the Singapore Strait Region: Tidal, Wind and Eddy-driven Circulations and Their Relative Importance

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ABSTRACT

To obtain a better understanding of environment-related physical oceanography in Singapore Strait Region, numerical experiments are implemented to study the circulation in SSR. The three important components, tidal, wind and eddy-driven circulations are identified. It is shown that the tidal circulation is dominant in the region. Even though the wind and eddy circulations are relatively small, they may have significant effect on the local circulation and material transport.

KEY WORDS: circulation; tides; wind; eddy; Singapore Strait.

INTRODUCTION

The Singapore Strait Region (SSR) located between the Strait of Malacca in the west and the South China Sea in the east, is of significant importance within global shipping routes. Due to the increase of shipping and port activities, the marine environmental protection of the Singapore Strait has become more and more critical. Unfortunately, there are only few research activities focusing on this special region in the scientific literatures. The only joint broad survey in the strait was conducted thirty years ago (JTCS, 1979), and showed the potential interaction between the dominant M2 tide and other tidal components and the complex topography. The numerical studies of the hydrodynamics in SSR started with 2D models in 1980s (Shankar, et al. 1997), and have evolved to 3D modeling since last decade (Chen, et al. 1997, Zhang and Gin, 2000, Pang and Tkalich, 2003). These studies gradually increased the accuracy of prediction by improving the boundary conditions and refining the grid resolution, but they mainly concentrated on the tidal properties within the strait. As shown in Fig. 1, SSR includes many small islands resulting in an extremely complex topography. Even though the currents in SSR are predominantly driven by tides (Pang and Tkalich, 2003), they are influenced by topography as well as wind forcing and coastlines. All these factors contribute various components to the total circulation in the region. Therefore, thorough and deeper studies of the mechanisms of generations and interactions of these components are fundamental for the understandings of the dynamics of the circulation within SSR. Field observations include all these components which affect each other through linear or nonlinear interactions. It's difficult to divide the field measurement data into each component. However, with numerical modeling, it is possible to quantitatively separate each component's effect by an elaborated design of numerical tests.

This paper will present the numerical studies and their results in order to understand and quantify the various components of the circulations within SSR. It will facilitate the near future studies of the circulations in local region around Singapore coastlines as well as in far field region in South China Sea. The paper is organized as follows. The numerical model and numerical experimental set-up will be first introduced. The model validation follows by the comparison with experimental data. The subsequent section will introduce the different components of the circulation and present the numerical results for each component. A brief conclusion will be given in the last section.

NUMERICAL METHOD AND MODEL SETUP

The numerical simulation is carried out with an unstructured-grid, free-surface, 3-D primitive equation Finite Volume Coastal Ocean Model (FVCOM). Its horizontal grid is comprised of unstructured triangular cells and the irregular bottom is represented using terrain-following coordinates. It is solved numerically by a second-order accurate discrete flux calculation in the integral form of the governing equations over an unstructured triangular grid. A detailed description of FVCOM is given by Chen, et al. (2003). The applied domain covers the entire SSR, which is 105km long, and 16km wide. It is discretized into the non-overlapping triangular grids as shown in Fig. 2, which consists of 58,248 nodes and 108,229 elements. The resolution near the Singapore coastlines and groups of islands is about 100m, while for the region far away from Singapore and near to domain boundaries, the resolution varies from 300m to 500m. Vertically, the whole depth was divided into 5 layers. The SSR domain is driven by the tidal harmonics predictions Total Tide (2002) at six open boundaries. As shown in Fig. 1, the boundaries are set far away from the interior part of the Singapore Strait in order to minimize the influence of the boundaries. The selected modeling period is from Jun 12th 2006 to Jul 14th 2006 during the southwest monsoon season and from Jan 3rd 2007 to Feb 8th 2007 during the northeast monsoon season. However, due to the constraint of space, only the results of the northeast monsoon period will be presented here in the following analysis. To conduct the component decomposition of the current circulation, two kinds of numerical experiments are conducted. One is without wind effect on the sea surface, while the other use the real NCEP reanalysis wind stress on the surface. The wind vectors of the modeling period are shown in Fig. 3 in terms of magnitude and direction.

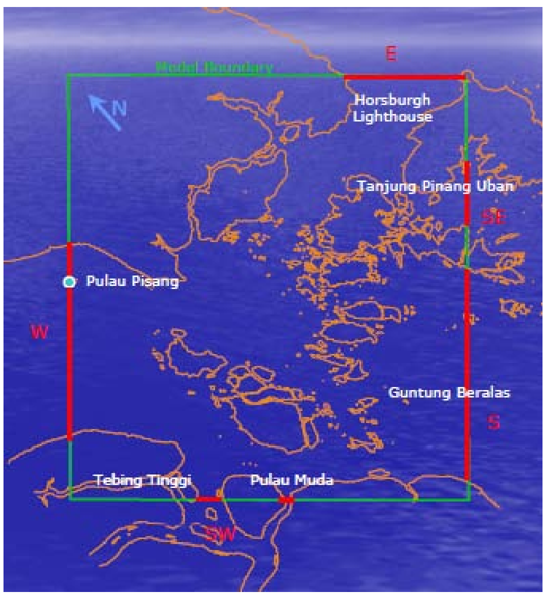

Fig. 1, Singapore Strait region and six open boundaries of the computational domain.

MODEL CALIBRATION

For the simulation period, field measurements were carried out at five positions in the Off Marian East of Singapore, shown in Fig. 4. Numerical results for the depth-averaged velocities are compared with the available measurements at c1~c5. Two of the comparisons are shown in Fig. 5. As shown in Fig. 5, the northward velocities (v-component) are relatively smaller. Thus, we focus on the eastward (u) depth-averaged velocity and the comparisons at the five points are shown in Fig. 6 for the first ten days. Generally, there is a good agreement between the model results and observations. The discrepancies occur at C4 and C5 when the flow is towards the east (positive value in u-direction). While the model simulations are smooth, the observations show noisy wiggles at the wave crests. This indicates high frequency waves generated in the lee side of the islands. Unfortunately, our relatively coarse grid meshes cannot resolve the extremely complex bathymetry around the Singapore coastlines. However, this will not have a significant effect on the following analysis of the circulations in the main body of the strait where the relatively larger islands are well resolved.

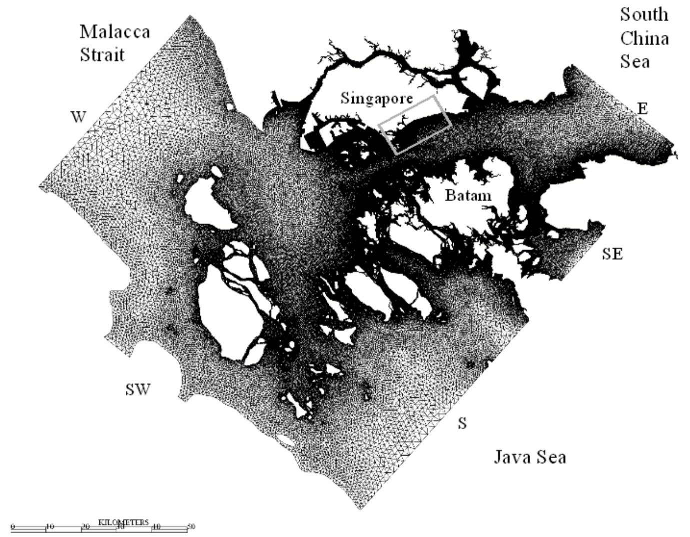

Fig. 2, Unstructured grid of the SSR. The local region having field measurement points is marked by a frame.

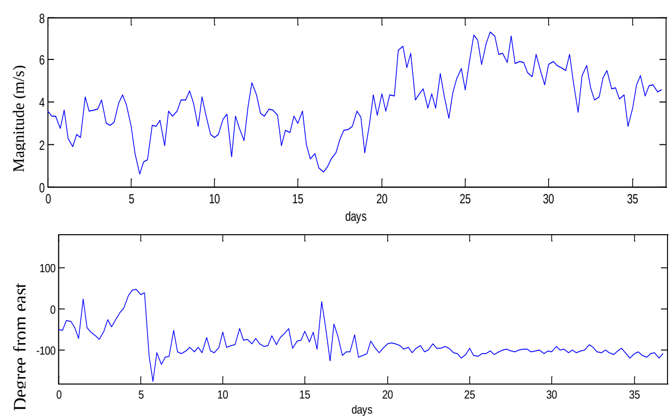

Fig. 3, the NCEP wind magnitude (up) and direction (lower) for the modeling period from Jan/3/2007 to Feb/8/2007.

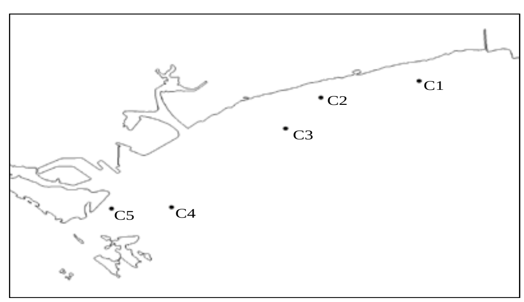

Fig. 4, Field measurement points next to Singapore coasts. Its position in the whole SSR domain is framed in Fig. 2.

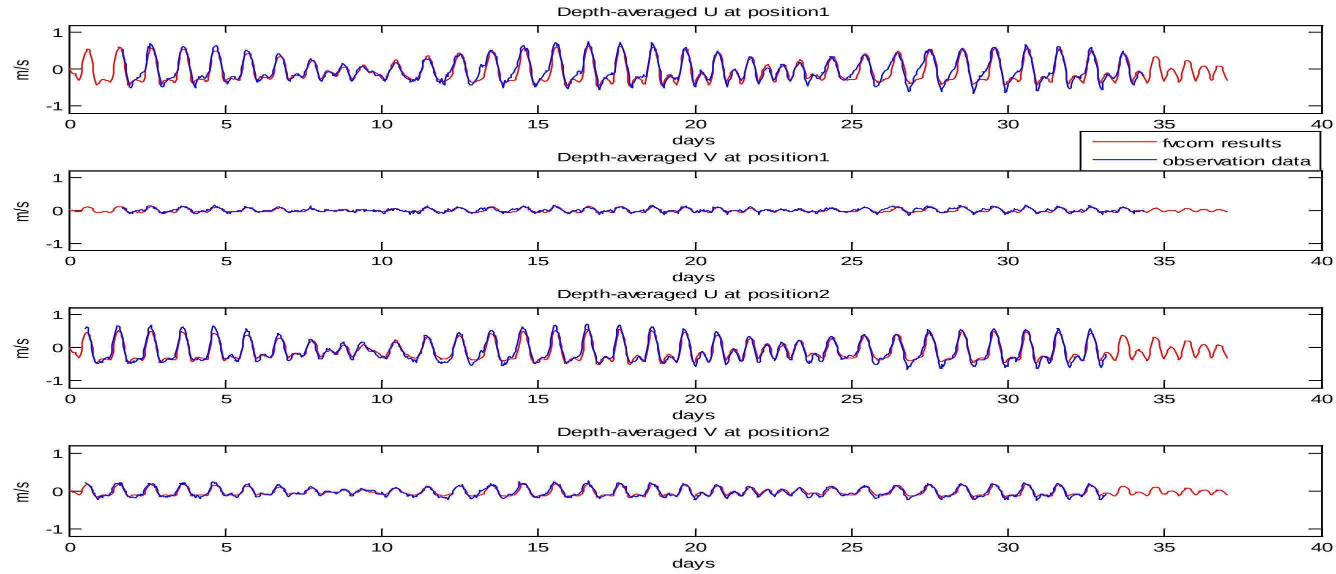

Fig. 5, Comparison of horizontal velocities at point 1 and 2. The red line is the numerical results and the blue line is field measurement.

NUMERICAL RESULTS: VARIOUS COMPONENTS OF THE TOTAL CIRCULATION

It is generally agreed that the current circulation in SSR is dominated by tidal forcing (Pang and Tkalich, 2003). Nevertheless, the total current circulation in SSR is actually composed of the tidal current and the other components due to the persistent wind in the monsoon season and the complex topography and coastlines. The former generates the wind-driven currents, i.e., the oceanic response to the wind stress. The latter generates the eddy components whose vorticity is induced by the horizontal shear and inhomogeneity in bottom stress (Dong, et al, 2009). These sub-dominant components modify the tidal current through linear and nonlinear interactions. They will significantly affect the diffusion and dispersion of materials disposed in the strait such as oil spills.

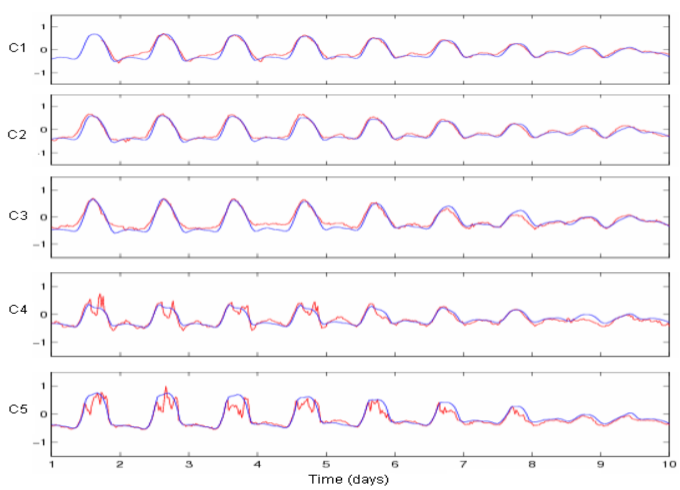

Fig. 6, Comparisons of x-component of velocities at all the field points for the first ten years. The red line is the numerical results and the blue line is the experimental results.

In general, the tide, wind, and eddy currents may have different importance depending on the time and location. The measured Eulerian current (total velocity) at a fixed position, can be decomposed as follows:

$$U_{Euler} = U_{mean} + U_{tide} + U_{wind} + U_{eddy} + U_{resi} \quad (1)$$

In the above equation, U_{tide}, U_{wind}, U_{eddy} are the tide, wind, and eddy induced currents, respectively. U_{mean} is the mean value of the total velocity. It represents the background current in that season and its variation reflects the seasonal or climatological changes. U_{resi} is the residual current after subtracting the above four other components from the total current. It may include the effects of atmospheric pressure, land runoff and other factors. This term is normally much smaller than eddy current and could make a tiny contribution to the eddy component through the nonlinear interactions with the other components and the complex topography. Thus, in our analysis, it is included into the eddy component.

To obtain the tidal component with numerical modeling, SSR model is first driven by the tidal forcing alone. The obtained time series of velocity are de-tided to get the de-tided residual. The tidal component is the difference between the numerical velocity under the tidal forcing alone and the de-tided residual. In the second run, the SSR model is forced by both the tidal boundary forcing and the surface wind forcing, which generates the total currents in the strait. Subsequently, the wind component (wind residual) can be simply obtained by taking the difference between the total velocity and the only tidally-forced velocity. The most interesting residual is the eddy component of the circulation. This component is calculated by subtracting the three above-mentioned components (tidal, wind, mean currents) from the total velocity.

Fig. 7 shows the various components of the total velocity at one point in the strait. It is confirmed that the dominant component is the tidal circulation. In Singapore, this component is dominated by the semi-diurnal tides (Zhang and Gin, 2000). The wind current is much smaller than the tidal current. However, when the wind magnitude becomes larger (referring to Fig. 2), the wind current will increase and has a larger variation. It can be expected that during a strong monsoon season or a gust, this component may become large enough to have a significant effect on the current in the Singapore Strait and on the coastlines. The eddy circulation is also relatively small, but has the same order of magnitude as the wind residual. The eddy component has an oscillation period of roughly 15 days. This is due to the spring/neap tidal interaction. The eddy circulation as well as their interaction with topography and coastlines is an important factor influencing the local circulation, and might have significant effect on the local biogeochemical transport and mixing. The last component shown in the figure is the mean current. It's negative in the modeling period indicating that the background current in the strait is westward. The similar dominant mean westward current in the northeast monsoon has been reported by Chia, et al. (1988).

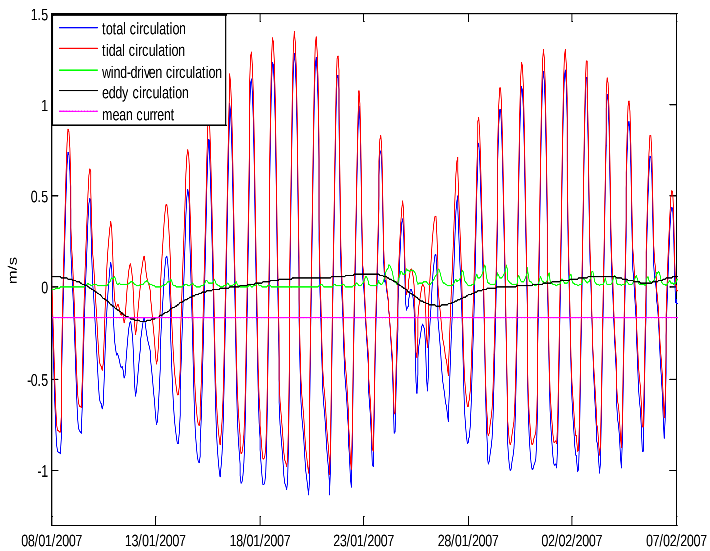

Fig. 7, Component decomposition of the total velocity at a point in Singapore Straits.

To examine the different components of the total velocity from the macro scale perspective, snapshots of each component are shown in Fig. 8 to Fig. 11. Fig. 8 shows the total current field in SSR on the day of a neap tide. Currents can reach up to 2m/s in the narrow part of Singapore Strait. Generally, during the northeast monsoon season, the currents in the Singapore Strait are westward. In order to show the detailed characteristics of each component clearly, the pattern is zoomed into the red-frame zone in the following snapshots. Fig. 9 shows the predominant tidal circulation component, which corresponds to the red line in the Fig. 7. This component has the same order of magnitude as the total circulation. The time shown for the figure corresponds to decreasing tide, the tidal flow in Singapore Strait is westward. The currents flow from the Horsburgh Lighthouse (Fig. 1) to the west and then bend to the Java Sea. On the other hand, when the tide is rising (figure not shown), the currents are easterly. The switches of current directions in each branch in SSR are complex and were discussed in details by Chan, et al. (2006). Fig. 10 shows the wind-driven circulation. This component is roughly one order smaller in magnitude than the peak tidal component. The magnitude and direction of the wind-driven residual are consistent with and governed by the sea-surface wind stress. Fig. 11 shows the eddy circulation. Many eddies are present and important when the tides are relatively weak during the neap periods. The evolution of eddies shows that when the tide currents are strong (say, spring tide), the eddies will be swept away and become small and few. The eddy contribution to the currents is relatively quite small compared with the dominant tidal circulation. However, it has the same order of magnitude as the wind stress and has substantial effect during neap tide period.

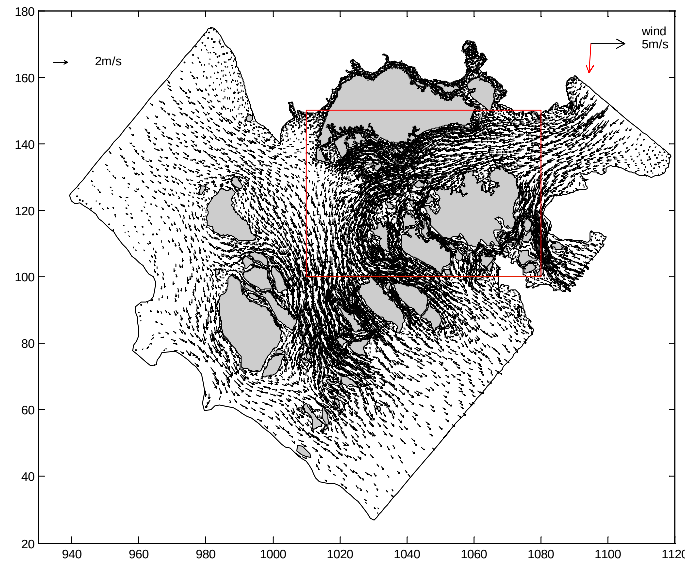

Fig. 8, Total circulation in SSR at 00:00 25/Jan/2007. The red frame is the zoom-in area for the following figures.

CONCLUSIONS

The different components of the total circulation in SSR so far have not been studied separately. Through the numerical experiments, three major components, the tidal, wind and eddy-driven circulations, are identified in SSR. Among three components, the tidal component is predominant (~1.5 m/s) while the wind and eddy-driven circulations are about of the same order (~10 cm/s). The decomposition of the total circulation is helpful to understand the local patterns. The effect of wind and eddy circulation on the material transport and oil spill in Singapore Strait needs further investigation.

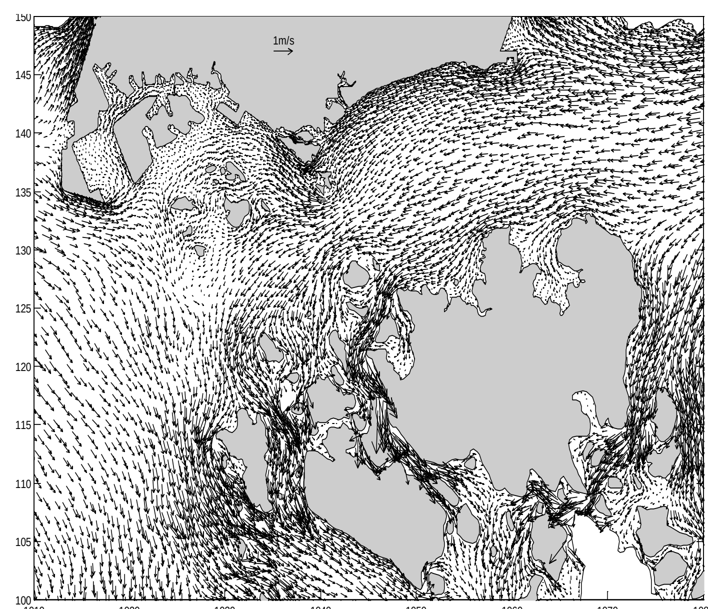

Fig. 9, The tidal circulation on 00:00/25 Jan 2007.

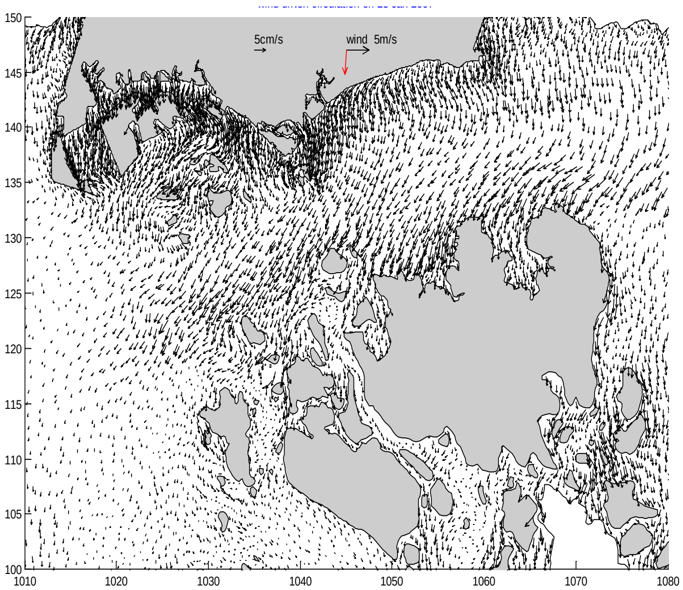

Fig. 10, The wind circulation on 00:00/25 Jan 2007. The red arrow indicates the real wind vector at the indicated time.

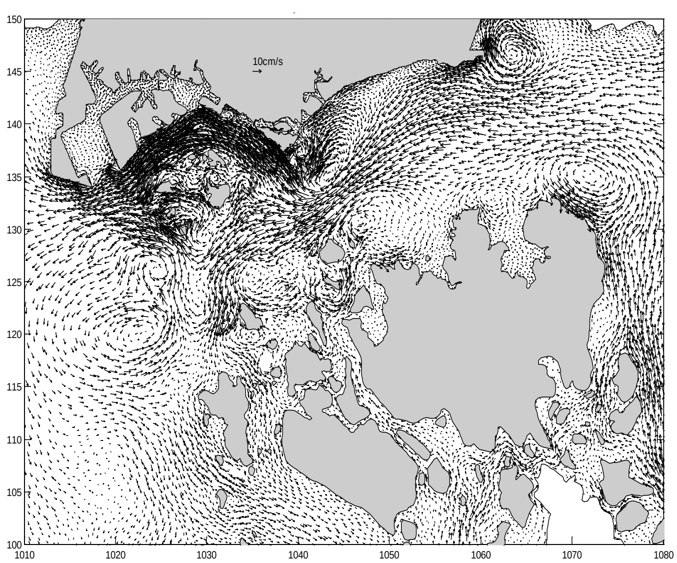

Fig. 11, The eddy circulation 00:00/on 25 Jan 2007.

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