Institut Pythéas
Observatoire des Sciences de l'Univers
Aix*Marseille Université

Mediterranean Institute of Oceanography

Three-dimensional modeling of the ocean circulation of the Caribbean Sea with ROMS model

LAMANI Bouabdellah

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Responsable : DOGLIOLI Andrea

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Abstract

Numerical modeling of ocean circulation is a major and powerful tool used by scientists to represent and understand the evolution of physical, chemical or biological processes in a specific ocean area. This study examines the circulation in the Caribbean Sea using the Regional Ocean Modeling System (ROMS). The model domain covers the region between 99 and 56°W and between 6 and 24°N, with two horizontal resolution of 1/2 °, then 1/4 °. In this practice, at first, we try to understand the fundamental principles of the physical oceanic circulation, particularly the mathematical laws that describe it, and the approximations that have been proposed and used, especially in ROMS model, in order to find the closest numerical solutions for primitive problems. Secondly, we try to imply this model to simulate the Caribbean Sea's circulation under different conditions, while explaining all the steps followed in manipulations. Finally, some results are compared with another scientific literature, which is here, the final results produced by the Exp-CS model (Yuehua et al 2011), in which a 1/6° spatial resolution has been used.

I. Introduction

The Caribbean Sea is a sea of the Atlantic Ocean in the tropics of the Western Hemisphere. It is bounded by Mexico and Central America to the west and south west, to the north by the Greater Antilles starting with Cuba, to the east by the Lesser Antilles, and to the south by the north coast of South America (Fig.1). The Caribbean Sea plays an important role as a conduit for mass, heat, salt, and other tracers in the Atlantic circulation system (Yuehua et al 2011). The existence of a strong mesoscale activity in the Caribbean Sea is receiving increasing attention (Jouanno et al 2008). First, the generation of large and energetic eddies poses very interesting dynamical questions. Second, the local and global implications of this mesoscale activity still have to be determined.

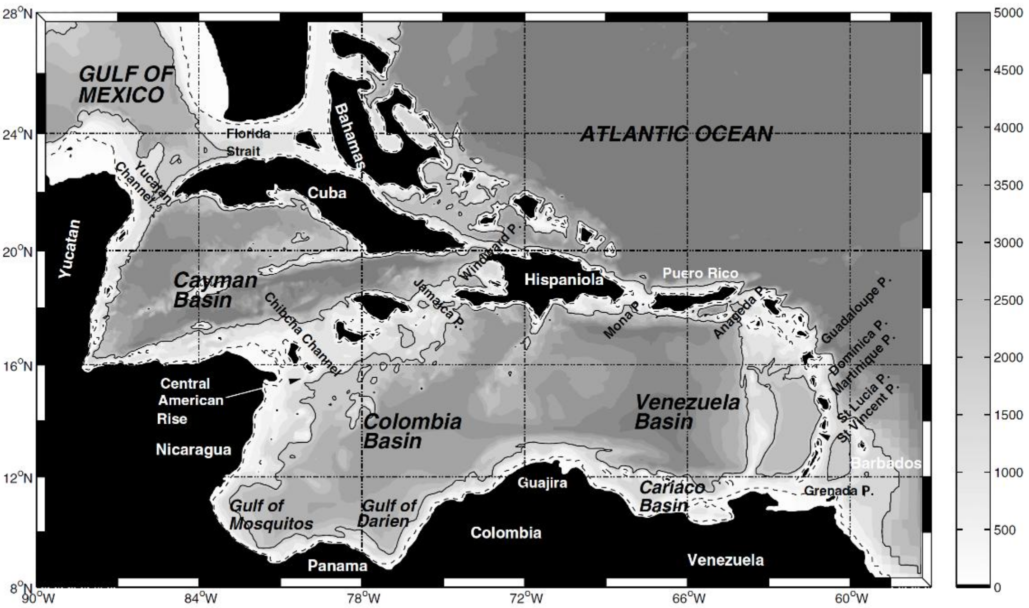

Fig.1 : Map and bathymetry of the Caribbean Sea. The dashed and full lines indicate respectively the 200 and 1000 m depth isobaths. (Jouanno et al 2008).

The mathematical models of physical systems, as for fluid dynamics or thermodynamic problems, are usually expressed by a system of partial derivative differential equations (Fabbri 2012). Usually it is not possible to find a closed form solution for equations, but it is possible to find out an approximate solution by numerical methods. Numerical modeling of the ocean circulation has begun to come of age only in the last decade (Pond 1976) The early models were developed with the limited aim of extending earlier analytic results into a nonlinear range.

Numerical ocean models have become increasingly valuable tools as we strive to understand the nature of the ocean's dynamics (Miller 2007). They have progressed from the necessarily crude and idealized tools of decades past to capture much of the complexity and beauty of the real ocean. As computers continue to increase in speed and availability at ever lower cost, this trend will clearly continue.

II. ROMS model implementation

ROMS is a free-surface, terrain-following, primitive equations ocean model widely used by the scientific community for a diverse range of applications. ROMS includes accurate and efficient physical and numerical algorithms (Power et al 2006, Fennel et al 2006). The algorithms that comprise ROMS computational nonlinear kernel are described in detail in Shchepetkin and McWilliams (2003, 2005). However, in this part, the main principles about how and which equations are based on and approximations that are taken into consideration, as well as the steps followed, in order to implement the ROMS model to simulate the Caribbean sea's circulation.

1. Theoretical foundations

The primitive equations are described in a Cartesian coordinate system (O, x, y, z), with the Ox axes oriented southward, the Oy axis towards the east and the Oz axis towards the Zenith. The origin O is at the rest level of the sea surface. The evolution of the mean horizontal velocity of the particles of the geophysical fluid is described by the Navier-Stokes equations (Eq.1, 2). Where, u, v and w are the horizontal and vertical non-turbulent or average components of the speed of movement, u', v' and w' are the turbulent components of the velocity of motion, f is the parameter of Coriolis, P is the pressure and ρ_0 is the reference density of seawater in the sense of the Boussinesq hypothesis (explained later).

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z} = -\frac{1}{\rho_o}\frac{\partial P}{\partial x}+f\,v-\frac{\partial\overline{u'u'}}{\partial x}-\frac{\partial\overline{u'v'}}{\partial y}-\frac{\partial\overline{u'w'}}{\partial z} \quad (1)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z} = -\frac{1}{\rho_o}\frac{\partial P}{\partial y}-f\,u-\frac{\partial\overline{v'u'}}{\partial x}-\frac{\partial\overline{v'v'}}{\partial y}-\frac{\partial\overline{v'w'}}{\partial z} \quad (2)$$

Secondly, Eq.3 and 4 describe the heat and salt's conservation respectively. The turbulent heat and salt flows are modeled using the concept of turbulent diffusivity, H_c is the incident solar flux, C_p is the specific heat coefficient (3950 J / kg.K), I (z) is the fraction of this flux that reaches the z level.

$$\frac{\partial T}{\partial t}+\vec{v}.\vec{\nabla}T = -\frac{\partial\overline{(T'u')}}{\partial x}-\frac{\partial\overline{(T'v')}}{\partial y}-\frac{\partial\overline{(T'w')}}{\partial z}+\frac{H_c}{\rho_o C_p}\frac{\partial I}{\partial z} \quad (3)$$

$$\frac{\partial S}{\partial t}+\vec{v}.\vec{\nabla}S = -\frac{\partial\overline{(S'u')}}{\partial x}-\frac{\partial\overline{(S'v')}}{\partial y}-\frac{\partial\overline{(S'w')}}{\partial z} \quad (4)$$

Finally, the equation of state of seawater (Eq.5) is the empirical relation defined by the International Equation of State of Seawater (IES 80). The final equation (Eq.6) expresses the continuity equation for an incompressible fluid.

$$\rho = \rho(T, S, z) \quad (5) \qquad\qquad \frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z} = 0 \quad (6)$$

The first approximation used by the model is the hydrostatic hypothesis on the vertical. According to this hypothesis the pressure at a point in the water column is equal to the weight of the water column present above the particle (Eq.7). Where P_a is the atmospheric pressure, g is the acceleration of the gravity and η the elevation of the surface with respect to the zero of the Oz axis.

$$P(z) = P_a + g\int_z^{\eta} \rho \mathrm{d}z \quad (7)$$

One of the important simplifications that are made to the complete Navier-Stokes equations is the fact that the differences in density in the ocean are small in comparison with the mean density. Thus the mean density can be used everywhere except in the buoyancy term. This is the Boussinesq approximation and is even valid for small scales.

The indeterminacy that resides in the turbulent flow terms of the primitive equations does not solve the system of equations. However, Reynolds-Averaged Navier-Stokes (RANS) equations apply the concept of mean flow and show turbulent terms. Thereafter, the Boussinesq approximation allows to close the RANS equations by parameterizing the Reynolds stresses and turbulent tracer fluxes (Eq.8, 9, 10), the overbar represents a time average, the prime represents a fluctuation about the mean and the coefficients A are called turbulent exchange coefficients.

$$\overline{u'u'} = -A_x \frac{\partial u}{\partial x} \quad (8) \qquad \overline{u'v'} = -A_y \frac{\partial u}{\partial y} \quad (9) \qquad \overline{u'w'} = -A_z \frac{\partial u}{\partial z} \quad (10)$$

2. Implementation on the study area

a. Discretization and Resolution

Spatial discretization : Horizontally, ROMS applies an Arakawa C-grid (Fig.2). Which does not define the variables of state and speed in the same place. Such staggered grid would better consider the conservation of mass (dotted square). Also, the model uses the orthogonal curvilinear grid arrangement.

Vertically, ROMS has a generalized vertical, terrain-following, coordinate system (σ). The coordinate σ thus makes it possible to follow the topography of the bottom and to keep a constant number of meshes on the vertical at every point of the domain (Fig.3). However, the fact that this coordinate system shall consider a same level, for points at different depths, that presents a problem concerning the pressure gradient.

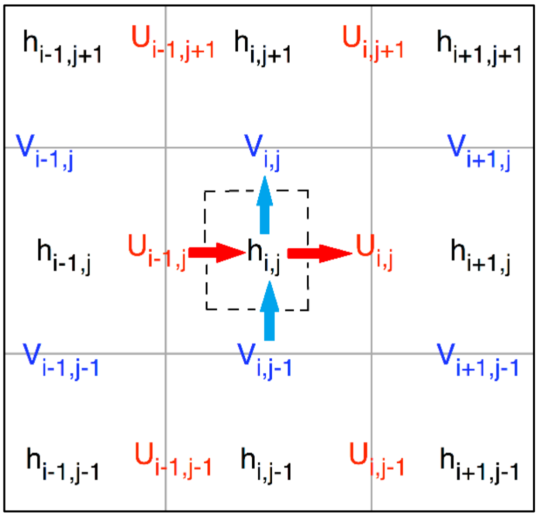

Fig.2 : The Arakawa C-grid.

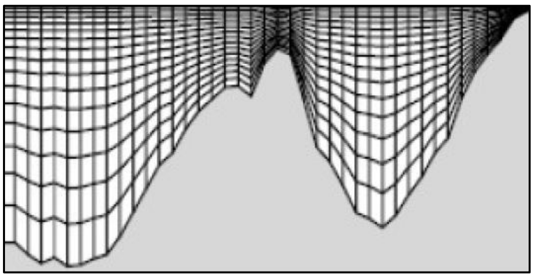

Fig.3 : Generalized vertical coordinate system (σ).

Time discretization : For computational economy, the equations are solved using a time-splitting method which requires a coupling between horizontal 2D-barotropic (fast) and vertical 3D-baroclinic (slow) modes. All 2D and 3D equations are time-discretized using the Leap-Frog scheme, and parametric filtering (Asselin Filter) time-stepping algorithm which is very robust and stable.

Spatial resolution and temporal resolution are bound by the CFL (Courant-Friedrichs-Levy) stability criterion, so that a process does not propagate more than one mesh at each time step. The fastest propagations are those of the barotropic gravity-waves, for which the CFL criterion gives a conditioned time step calculated by the equation 11 :

$$\Delta t \leqslant \frac{1}{\sqrt{gh_{max}}}[\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2}]^{\frac{1}{2}} \qquad (11)$$

b. Initial and open boundary conditions

The differential equations underlying numerical models of ocean circulation give only the local structure of a surface in space and time, a global and unique determination of the solution on a domain also requires the values at the initial time and on the boundaries of the domain. The initial and boundary conditions are derived, first, concerning the external forcing (sea surface temperature, estimates of air-sea interaction and other meteorological variables), from COADS05 (Comprehensive Ocean-Atmosphere Data Set 2005) database. As for the internal forcing (initial seawater temperature and salinity) the data are obtained from WOA2009 (World Ocean Atlas 2009). Lastly, shoreline and coastline resources data are obtained from GSHHG (Global Self-consistent, Hierarchical, High-resolution Shoreline Database).

c. Manipulation and steps

All the necessary compressed tar files (XXX.tar.gz) containing the Matlab programs, several datasets and other toolboxes and softwares needed by ROMSTOOLS are download from CROCO's page (https://www.croco-ocean.org/download/), after being subscribed as ROMS user. Thereafter, all the files are uncompressed.

In this case study, the aim was to implement two different simulations for the Caribbean Sea. By using, firstly, a low spatial resolution (1/2°), and secondly a higher one (1/4°). The table 1 summarizes all the parameterizations preconfigured of the two simulations. Where obc presents the open boundaries (1=open, [S E N W]), dl is the horizontal resolution, LLm and MMm are the length and the width respectively of the grid in mesh numbers, N presents the number of the vertical levels, dt is the baroclinic time step for the 3D-equations (conditioned by the CFL criterion), NTIMES is the total number of timesteps (dt) and NDTFAST is the number of 2D timesteps within each 3D step.

Tab.1: Simulation grid parameters.

Parameter	obc	dl (degree)	LLm	MMm	N	dt	NTIMES	NDTFAST
Simulation 1	[0 1 1 1]	1/2°	67	37	32	4320	600	60
Simulation 2	[0 1 1 1]	1/4°	135	74	32	2160	1200	60

The diagram (Fig.4) resumes, in an understandable way, the steps followed during each simulation in chronological order and which parameter to modify before each step and in which file is this parameter.

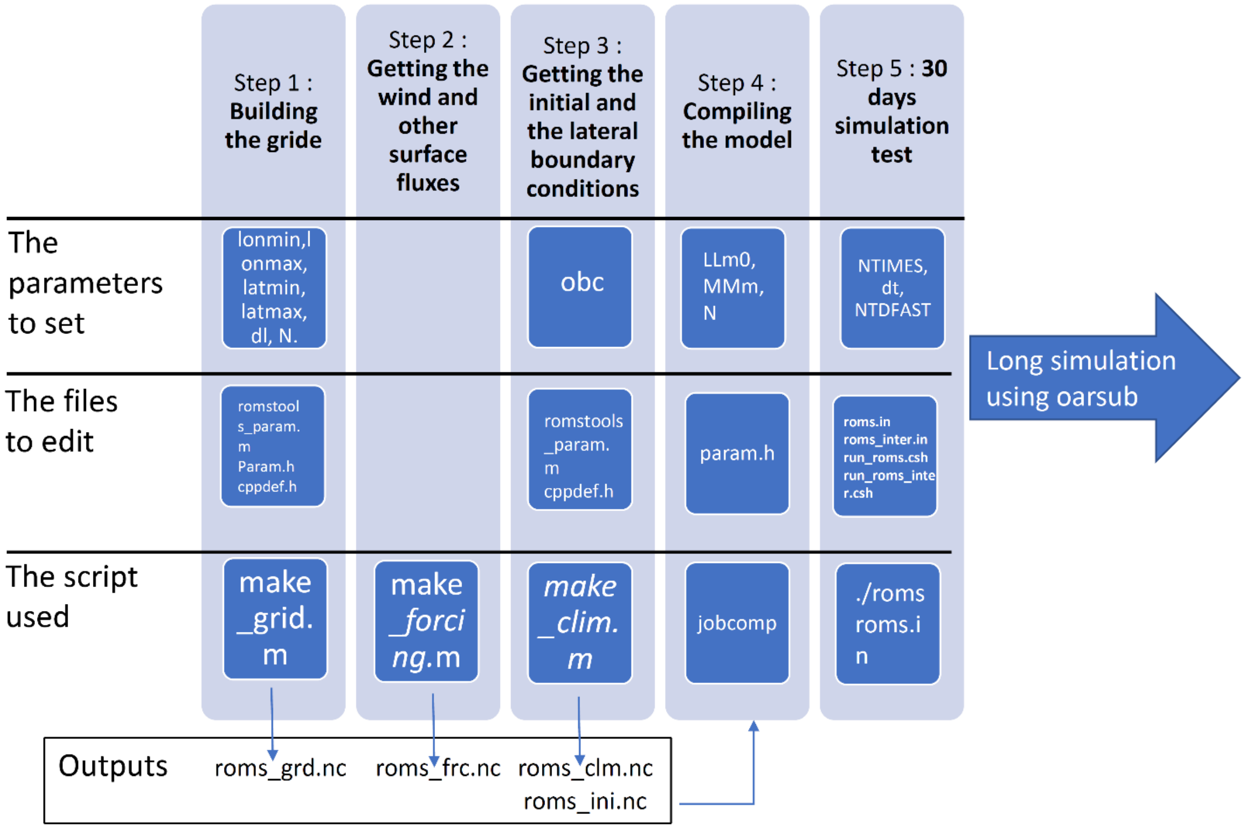

Fig.4 : Diagram of manipulation steps.

III. Results and discussion

1. Diagnostic

To analyze the two long simulations, a few scripts have been added from 'Diagnostic tools', which contains 'roms_diags.m' and 'plot_diags.m', programs that allow to perform a diagnostic of the simulation. The interpretation of the diagnosis makes it possible to determine when the model is stabilizing, and thus to determine the outputs to be studied, in fact, the ROMS model generally takes several years to stabilize (when the calculated values start to vary around the mean). This diagnosis indicates the volume anomaly (km^3), the average surface kinetic energy, the average water volume ($cm^2.s^{-2}$) and the average salinity and temperature (C) of the water volume (Fig.5). Besides all the other quantities, the average salinity of the water volume determines the sixth year as the first year of stability of the model.

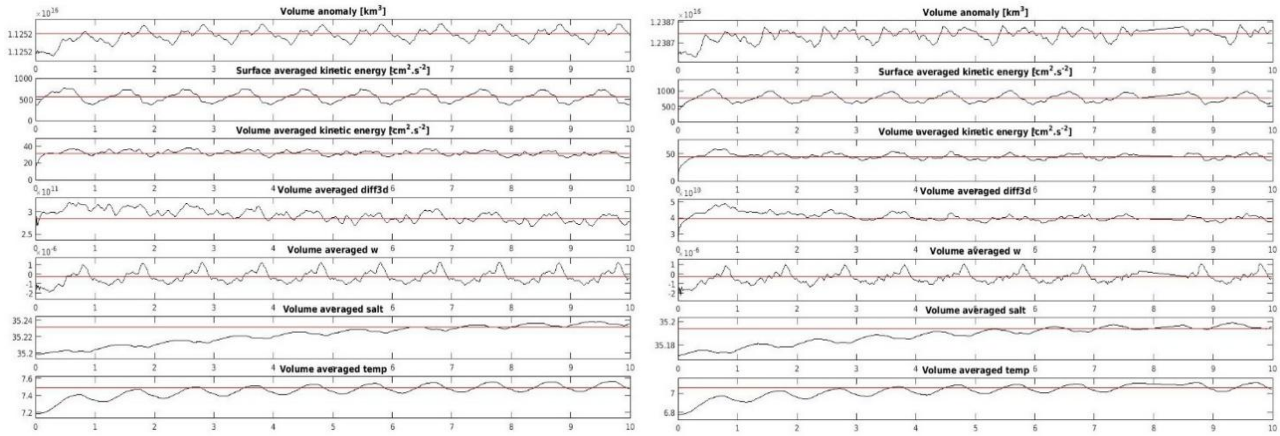

Fig.5 : Diagnostic curves for the simulation with a resolution of 1/2 ° (left) and 1/4 ° (right).

2. Seasonal variation of the salinity

The outputs of the model have been exploited using the tool 'roms_gui.m', which allows to present the parameters graphically. In this part, among the various parameters calculated by ROMS, only salinity was chosen in order to evaluate its seasonal variation, in the first 10 meters, estimated with two different resolutions simulations, by choosing average values for the month of the seventh year, whiche would present a specific season. February, May, August and November for winter, spring, summer and fall respectively.

A similar salinity distribution in the surface waters out of the two simulations (Fig.6); low winter values may be due to rainfall and high values may be due to evaporation during the summer, and mean values during the spring and fall. However, from a comparative point of view, the second simulation has presented more spiral forms.

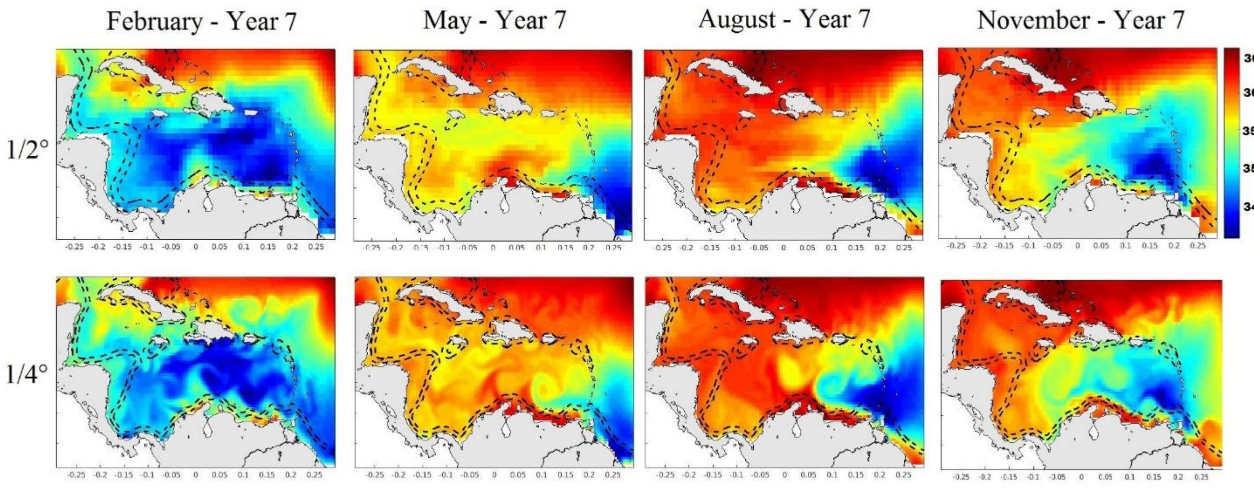

Fig.6 : The annual variation of salinity in the first 10 meters in the Caribbean Sea. From monthly mean values for February, May, August and November of the seventh year of simulation 1 (top) and 2 (bottom).

3. The resolution influence on detecting Caribbean eddies

In this part, a comparison of ROMS results with Exp-CS model (Yuehua et al 2011) products, demonstrates that the ROMS model has skill in simulating eddies in the Caribbean Sea. Nevertheless, the bigger the resolution is, the less small eddies are detectable.

In figure 7, there is a small-size anti-cyclonic eddy produced by Exp-CS model (labeled 'E'), wich coulde be also detected along its way by the second simulation (black circle), firstly in the eastern Colombian Basin on August, then it propagates westward with the Caribbean Current in the Colombian Basin and increases in strength and size. It is centered on the Nicaraguan Rise on December and passes over the Nicaraguan Rise and reaches the Yucatan Basin with the near-surface Caribbean Current flowing more westward in the western Colombian Basin region. The eddy squeezes through the Yucatan Channel in March.

It is quite possible that the small-size eddy could not be detected in the first simulation because the fact that the first resolution is not small enough for it to be feasible.

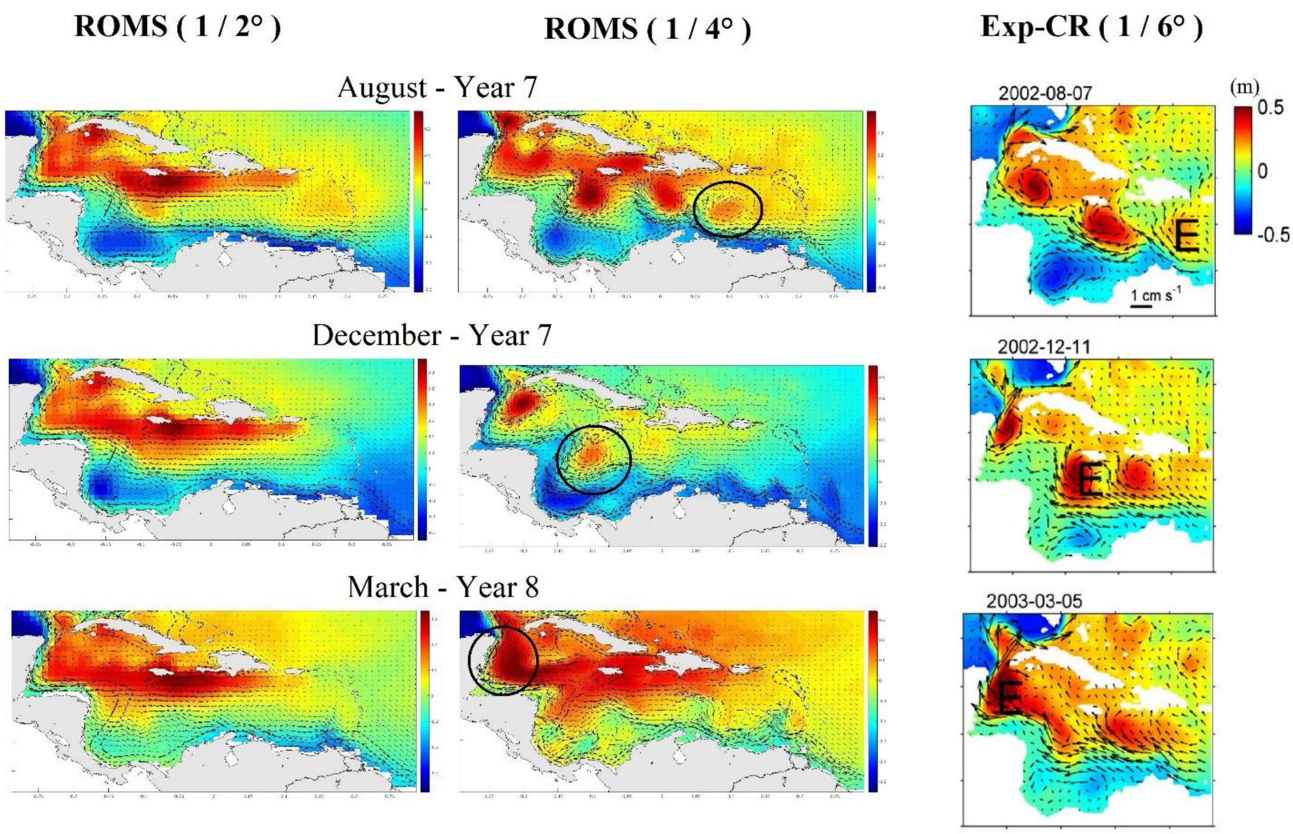

Fig.7 : Snapshots of near-surface currents (black arrows) and sea surface height fields (color) from simulation 1 (left) and simulation 2 (middle) of August and December of the seventh year of simulation and March of the eighth year. And produced by Exp-CR Model (left) (Yuehua et al 2011) during 07 August 2002, 11 December 2002 and 05 March 2003.

IV. Conclusion

ocean circulation modeling is fundamentally based on principles of fluid mechanics and thermodynamics. Over the course of many years of scientific researches, approximations have been proposed in order to make the mathematical problems that describe this circulation simpler and to find numerical solutions approached as much as possible.

The ROMS model, is one of the powerful numerical models and thanks to its computing power and its resolution of many equations, it made it possible to make a realistic simulation of the study area. Its stability depends on certain criteria, particularly the CFL condition. It is also controlled, in the way how it can present some physical phenomenon, by spatial and temporal steps taken on consideration.

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