NUMERICAL EXPERIMENTS OF THE HYDRODYNAMIC COASTAL OCEAN OFF PAITA AND SECHURA

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ABSTRACT

The hydrodynamics and transport processes of the Peruvian marine region off Paita and Sechura is studied using a finite element model for open and limited regions, which allows analyzing the response in days and weeks of circulation, in opened and limited marine regions, forced mainly by wind fields, maintaining low frequency dynamics in the model. The Petrov-Galerkin variational formulation of the non-permanent governing equations is used to obtain the numerical solution of the approximate variables by linear polynomials in the domain discretized by triangular elements. Observational data of both the wind fields and the surface temperature have served to suggest hypotheses about the role of non-uniform winds on the surface dynamics of the region and the generation of cold plumes that are dispersed in a northwest direction. To clarify the response trends observed in the region, some numerical experiments have been carried out, considering schematic wind fields patterns, including northeast wind deflections in the northern side as observed. In this way, the dynamic sensitivity of the region is analyzed. The results confirm the role of non-uniform wind fields in the evolution of cold-water plumes, a characteristic of the region.

Keywords: Hydrodynamic, Finite Elements, Ocean Model, Coastal Upwelling, Perú.

1. INTRODUCTION

The dynamics of the coastal regions depend on various factors, among which are mainly the irregular configuration of the coastline, the variability of the seabed, the forcing winds and their spatial distribution, the characteristics of surface and subsurface waters between other factors Given the existing complexities, the hydrodynamics and thermodynamics of the waters in coastal regions need mathematical tools that allow their approach in a reliable way. In the present work the problematic is approached by means of a dynamic description based on the first internal mode which is associated with temporary changes of days and weeks (reduced gravity).

In this article, the study region is framed between 2.5°S – 7°S and longitudinally up to 90°W. This region has a particular geographical configuration, where the capes at Paita and Punta Falsa (around 3°S and 5°S) and the Bays of Paita and Sechura are the most salient geographical features. Observed SST and Wind distributions in the region is presented in Figure 1, as a reference of the upwelling pattern in the region.

Dynamically this marine region is usually influenced by SE winds favorable to coastal hydrodynamic upwelling (Fahrbach and Brockman, 1981), but interacts with the equatorial front of hot waters. The hydrodynamics of the region is accompanied by outcrops of primary biomass generating high fishing production, on the other hand the variations in surface water temperature in the region are a consequence of the forcing and boundary conditions of the region.

In this context, the need to explore the dynamics of the numerical region is a way to understand reasons and response patterns. The numerical models are of great help in the conceptual studies of permanent and non-permanent qualitative and quantitative assessments of the circulation and transport processes in the coastal areas. On the other hand, it is considered in the present approach, that low frequency behavior has been indicated as the main factor associated to the transport of concentrations in the coastal regions, thus supporting hydrodynamic circulation studies based on low frequency circulation .

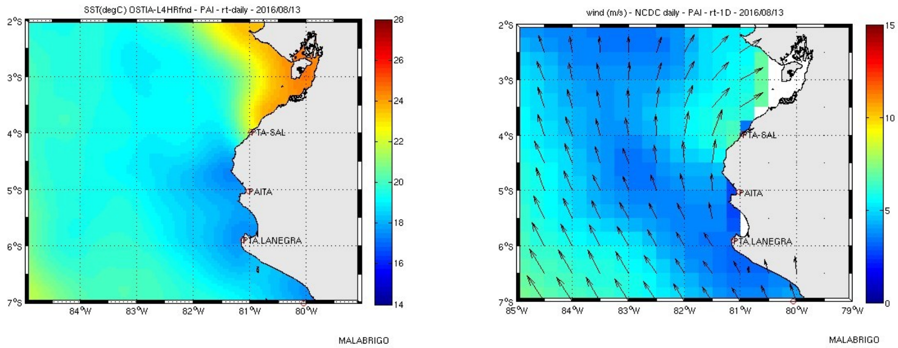

Figure 1. Region showing SST (ºC) and wind velocity field (m/s) observed at 13-08-16. Source: http://satelite.imarpe.gob.pe/

The present investigation is based on different numerical references about the model in a limited and open area domain applying finite element techniques (Carbonel and Galeao, 2010; Carbonel and Galeao, 2007; Carbonel, Galeao and Loula, 2000) and including dynamical open boundaries conditions (Verboom et al., 1982) which a demonstrated applicability in upwelling regions (Carbonel, 2003). The numerical solution is a variational Petrov-Galerkin formulation for the momentum equations for velocities, upper layer thickness and transport equation for the SST.

The present study uses schematic spatial configurations for the wind patterns with the purpose to separate influences and roles of the composed wind parts on the dynamics response. Experiments are conducted and the resulting SST fields and associated velocity patterns are analyzed, considering observed wind configuration for comparison.

2. THE MODEL

The mathematical model is practically the same as the described by Carbonel and Galeao (2010). Here only a brief description is provided about the mathematical model formulation. To simulate the ocean behavior we adopt a gravity reduced model with an active hydro-thermodynamic upper layer of density ρ^u, thickness *h*(x,y,t), and an inert lower layer of density ρ^l (pressure gradient is zero). The dynamic mean variables are temperature field $T(x,y,t)$, velocity components $u(x,y,t)$, $v(x,y,t)$ positively oriented to the East and North direction respectively. The vertically integrated system of equations reads:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+\int\frac{1}{\rho^u}\frac{\partial p}{\partial x}dz-fv-A_H\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\frac{\tau_x}{\rho^u h}=0 \tag{1}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+\int\frac{1}{\rho^u}\frac{\partial p}{\partial y}dz+fu-A_H\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-\frac{\tau_y}{\rho^u h}=0 \tag{2}$$

$$\frac{\partial h}{\partial t}+u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}+h\frac{\partial u}{\partial x}+h\frac{\partial v}{\partial y}-w_{ed}=0 \tag{3}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}-K_H\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\frac{1}{h}(Q_I-Q)=0 \tag{4}$$

where , *p* is the pressure, the Coriolis parameter *f*, *g* is the gravity acceleration, A_H, K_H, are the constant horizontal eddy coefficients for momentum and temperature respectively. The vertical velocity w_{ed} which appears in equation (3), represents the entrainment-detrainment velocity given by $w_{ed}=(H_{ed}-h)|H_{ed}-h|/t_{ed}H_{ed}$.

Concerning the boundary conditions it is assumed that land type boundaries give rise to the classical non-slip conditions:whereas Neumann type boundary conditions are prescribed for the upper thickness *h* and for the temperature *T*. On the sea side boundaries we prescribe a weakly reflective boundary condition, based on the characteristic method. This is done assuming that on a normal direction (x_n) to the open boundary

$$\frac{dR^{\pm}}{d\acute{t}}=0 \tag{5}$$

Where *R* is the quasi-invariant of Rieman. A quasi-symmetrization is done introducing a new set of dynamic variables. After the variables change, the set of equations, in matrix form, for the unknown vector $V = (u,v,d,b)$ could be written as:

$$\underline{I}\frac{\partial V}{\partial t}+\underline{A}\frac{\partial V}{\partial x}+\underline{B}\frac{\partial V}{\partial y}+\underline{C}\,V+\underline{D}\left(\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}\right)+F=0 \tag{6}$$

For the present numerical ocean model, continuous interpolation in space and time will be adopted. Under this assumption we will say that the approximate solution of equation (29) is the particular unknown vector approach $V^h \in U_n^h$, if it satisfies the variational formulation

$$\int_{S_n}\hat{V}^h R^h \acute{d}\Omega\,\acute{d}t+\sum_{e=1}^{N}\acute{}\int_{S_n^e}\overline{\Psi}_e\,G^h R^h\,d\Omega\,dt=0\ , \qquad \text{for } n=0,1,2....nodes \tag{7}$$

where R^h represents the residual of the equation system approach and G^h is the space-time operator. $\overline{\Psi}_e$ is the matrix of intrinsic time scales, containing free parameters, normally known as upwind functions (Hughes and Mallet, 1986)

3. SIMULATION OF FORCED DYNAMICS

For the numerical study of the North-Peru ocean dynamic, a Finite Element Mesh was produced and is presented in Figure 2 (Left).

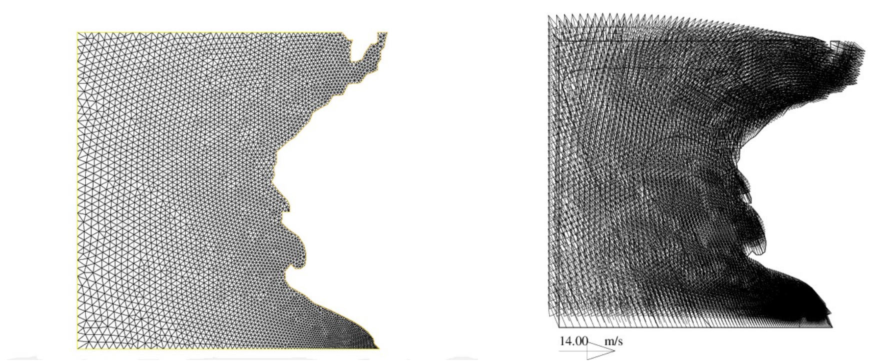

Figure 2. Left) Finite Element Mesh; Right Schematic wind field used for the Study case: Nonuniform Wind from SE

The numerical results are obtained defining a cold start for the dynamic variables at time instant t=0, considering a initial upper layer thickness of 60m and initial SST of 28^oC and 15^oC for the upper and lower layer respectively. Two wind field cases were considered to study the upwelling evolution : a uniform wind and a non-uniform wind.

3.1 Study case: Uniform Wind from SE.

The performed numerical experiments indicated that by uniform wind pattern (7 m/s from SSE), the dynamic response is influenced by the coastal configuration, producing sources of upwelling (Fig. 3, Right panel) and a convergence region located offshore (greater upper layer thickness, Fig. 3, left panel). The calculated colder SST in the north side (Ecuador side) is unrealistic and is a consequence of the considered uniform forcing.

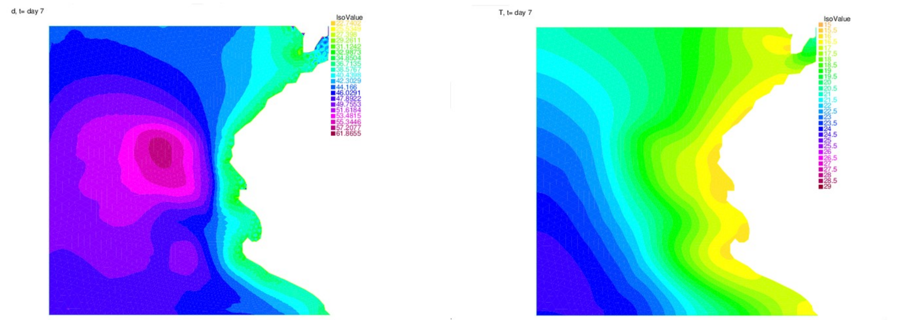

Figure 3. Uniform wind (7m/s) case. Left) Upper layer thickness field in meters; Right) SST field in ºC

3.2 Study case: Non-Uniform Wind from SE.

The response of the coastal region is different when a non-uniform wind pattern similar to observed (Winter 08-2017) is considered for the dynamic evolution (Figure 2, Right). In this case, the upwelling source has particular dispersion format as presented in Figure 4. The SST plume is extended in NW direction and the upper layer thickness field show the same format. This SST pattern is commonly observed in the region during winter (e.g 15-08-16 of Figure 1). The velocity field shows a band of higher velocities associated to thickness pressure gradients.

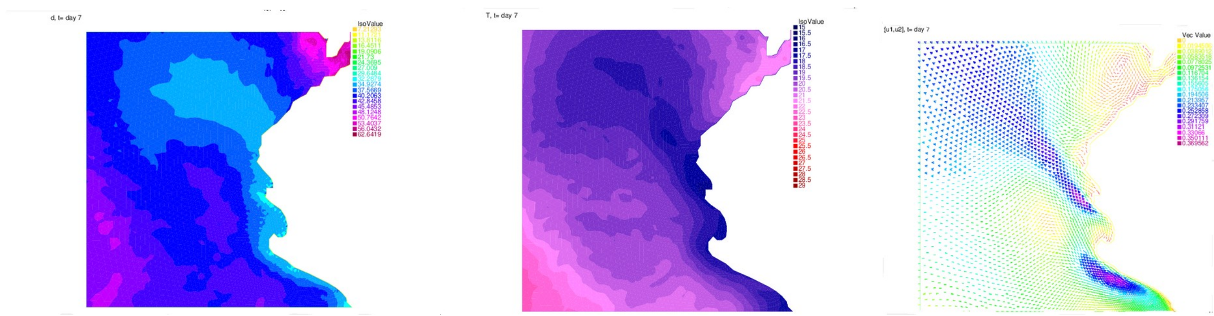

Figure 4. Non-Uniform wind (max. of 7m/s) case. Results at day 7. Left) Upper Layer tickness field in meters; Center) SST field in ºC; Right) Velocity field in m/s.

The role of patterns of wind patch, upcoast and downcoast patterns are an important issue in coastal ocean modeling. This topic was also numerically revised for another upwelling region[2], and the considered wind format of the present experiment, resembles the case "d" of Figure 3 of paper Carbonel et al. (2007)..

3.3 Downwelling possibilities

The upwelling along the Peruvian coast is practically permanent during the year with a small seasonal intensity variation and some regional intensity changes. Otherwise, in the 2018 year (Summer) after the weakness of the wind forcing off the Peruvian coast, a strong warming of coastal waters was observed. This fact, was the motivation for the present experiment.

The experiment considers a cold start for the variables and the wind forcing field is applied at the water surface of the model. After 4 days of a non-uniform wind field favorable to upwelling, directed to NNW, colder waters appears along the coast (Figure 5 Left). Then, the wind field initiates a progressive rotation up to 180º0 in 3 days generating a retraction of the upwelling plume. The resulting SST field at day 7 is showed in Figure 5 Right, indicating a resulting warming waters due advection directed to the coast. The model has described qualitatively, the relaxing of upwelling condition due wind direction changes.

4. CONCLUSIONS

To clarify the response trends observed in the Nort-Peru marine region, some numerical experiments have been carried out. It has been considered schematic wind fields patterns, including northeast wind deflections in the northern side, as observed in satellite data. The dynamic sensitivity of the region was explored with some runs. In this way the response along the coastal line was analyzed. The results confirm the role of non-uniform wind fields in the main pattern response, producing the evolution of cold-water plumes, which is a characteristic of the marine region.

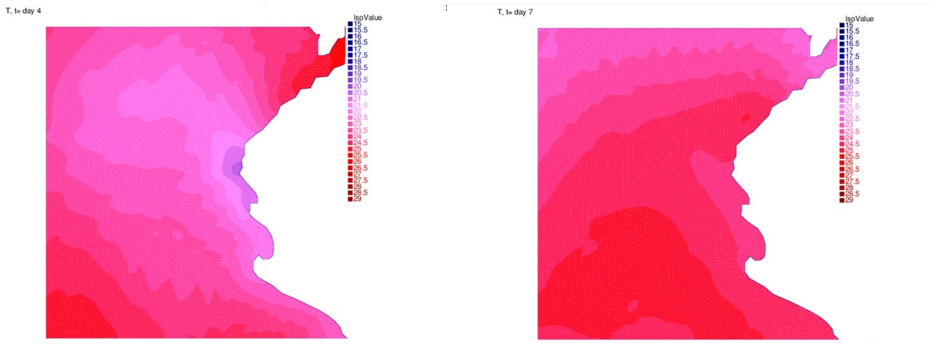

Figure 5. Non-Uniform wind (max. of 7m/s) case with rotation. Distribution of SST (ºC);field at: Left) day 4; Right) day 7

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