Modeling of marine circulation and hypothetical discharges in Callao Bay, Peru

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Abstract

The objective was to simulate the marine circulation and hypothetical discharges in Callao Bay, taking into account climatological seasonal variations and considering the direction and intensity of wind forcing. ROMS (Regional Oceanic Model System) model with the nesting tool AGRIF (Adaptive Grid Refinement in FORTRAN) were used. An hybrid bathymetry was used from ETOPO2, GEBCO, DHN and IMARPE; winds from MWF-Quikscat, tides from TPXO6.2, initial conditions from WOA, boundary conditions from COADS, and information of rivers, aquatic quality and domestic effluents. The model represented adequately the patterns of temperature, salinity and circulation at large scale and small scale in Callao Bay. The hypothetical domestic effluent discharges were transported predominately towards north, with seasonal variations (to northwest in summer, due to rivers discharges). Simulations with northern winds scenarios, showed a transport of hypothetical discharges to Miraflores Bay. During this study period, observed pollutants concentration in Callao Bay exceeded the environmental quality standards of the Water Law, so the introduction of additional effluents should be avoided, and an adequate treatment and disposal system (i.e. treatment plant and submarine emissary) should be implemented.

Keywords: River hypothetical discharge; ROMS; Callao Bay; Marine circulation; Wind forcing.

1. Introduction

Callao Bay is located on the central coast of Peru, north of La Punta, and includes the port of Callao, and the mouth of the rivers Rimac and Chillon. The geo-morphological conformation of La Punta and the presence of the islands San Lorenzo and El Fronton, give a semi-protegida characteristic to this bay, which is protected of the effects of the remote swell and the action of the winds of great scale .Between La Punta and San Lorenzo Island there is a shallow channel about 4.5 km wide ,known as El Boqueron, where the bay of Callao communicates with the

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bay of Miraflores The seabed of Callao Bay is very complex, presenting a canyon to the slope and prominent tip elevations (DHN, 1999). There is some background on coastal zone modeling in Peru from environmental impact studies.

CCW (2002) used the steady state spectral wave (STWAVE) model to determine significant wave height and wave direction .In the area of Taboada (with a wave height Hmo= 6 m and a period Tp=20 s, direction SW), the model showed a direction of waves towards the northeast, but when passing the island San Lorenzo, the waves changed direction to the east.

JICA (1990) used a box mixing model based on flow volume flow formulas to simulate contamination of the drains of the Surco collector .The model allowed us to conclude that fecal coli form contamination caused by the discharge of raw drains from the Surco collector would be directed to the north, reaching the Chorrillos Regattas Club, both in the base simulation of 1990 and in the simulation projected for 2000 .In case of not reducing the effluents, the contamination would extend even more to the north, until Agua Dulce beach, in the following years.

PESI (2000) evaluated alternative disposal of domestic effluents from northern Lima .They used RSB models for initial dilution, RMA2 for hydrodynamics of discharges, and RMA11 for water quality, concluding that the primary alternative was the primary treatment with an 8-km submarine emitter .The results of the Callao Bay environmental monitoring carried out during 2006 to evaluate the state of the coastal marine environment have already been presented (Sanchez *et al*., 2007).

The objective of the present work is to simulate the marine circulation and hypothetical discharges in Callao Bay, taking into account the seasonal variations in climatology and considering the direction and intensity of the wind forwards, in order to have scientific bases prior to taking Of decisions regarding the treatment and disposal of domestic discharges in the bay of Callao.

2. Materials and methods

The spatial domain of the model lies between latitudes 11° 50’ S and 12°10’ S, and longitudes 77° W and 77° 20’ W (Figure 1). The input information for the model was obtained from international databases, satellite and on-site observations of the study area .The information on the rivers was obtained from INRENA (2008), the aquatic quality of IMARPE (2006) and domestic effluents from SEDAPAL (1998) and IMARPE (2006).

Initial conditions referred to sea surface temperature (SST) and sea surface salinity (SSS) fields, extracted from the WOA database (2007). The boundary conditions were collected and processed for the three open borders (North, East, and South), obtained from the database COADS (2006).

Realistic bathymetry included the coastline and the seafloor, combining the bathymetries of international databases such as: ETOPO2 (2008) with resolution of 2 minutes, General Bathymetric Chart of the Oceans (IOC *et al.*, 2003) with resolution of 1 , 0 minute, DHNM (1993) and IMARPE obtained by high resolution soundings performed with coastal vessels (Velasco com pers.). The hybrid bathymetry was obtained by combining the data using Objective Analysis (AO) techniques that allowed the creation of a regular grid of 150 m resolution (Figure 2). The hybrid bathymetry served as a pattern to obtain the grids of successive nesting to be used in the ROMS model.

The wind climatology to force the model was calculated from the MWF-QuikSCAT database (CERSAT IFREMER, 2005), and the flows of heat, fresh water, shortwave radiation, net heat and specific humidity from the COADS database (2006). In the Callao Bay there is a local forcing (local winds) and a large-scale surface atmospheric circulation forced by the South Pacific Anticyclone (APS), whose geostrophic component is modified by friction with the continent, Giving rise to prevailing winds of the south and southeast, responsible for the coastal outcrop. The APS is centered between 25°-30° S and 90°-105° W, ranging between 38° S and 12° S. In winter, the APS approach to the continent generates strong pressure gradients that intensify the winds. In summer, the APS moves away from the coast, weakening the winds (Fuenzalida, 1971). In the Callao Bay, the presence of coastal hills and the island San Lorenzo, constitute an important topographic restriction that modifies the direction of the field of winds, channeling the wind in direction

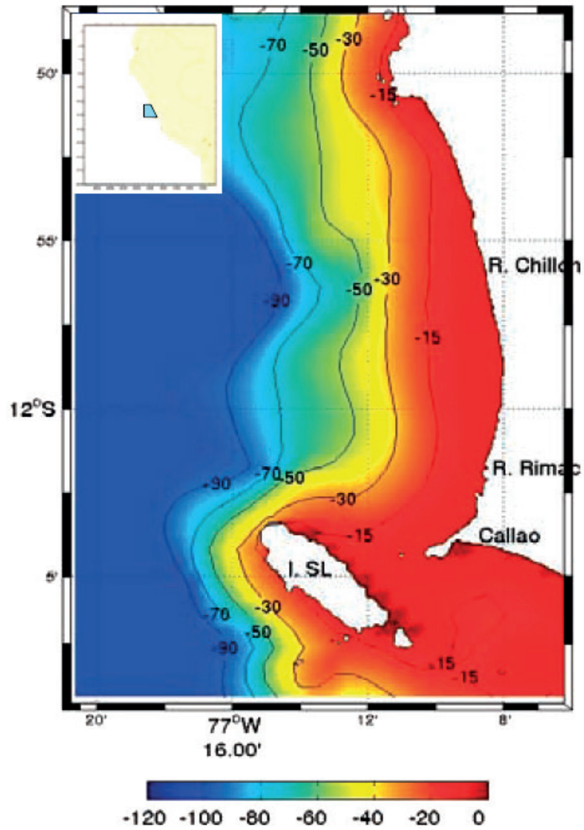

Figure 1. Domain and bathymetry (m) of the two-dimensional model

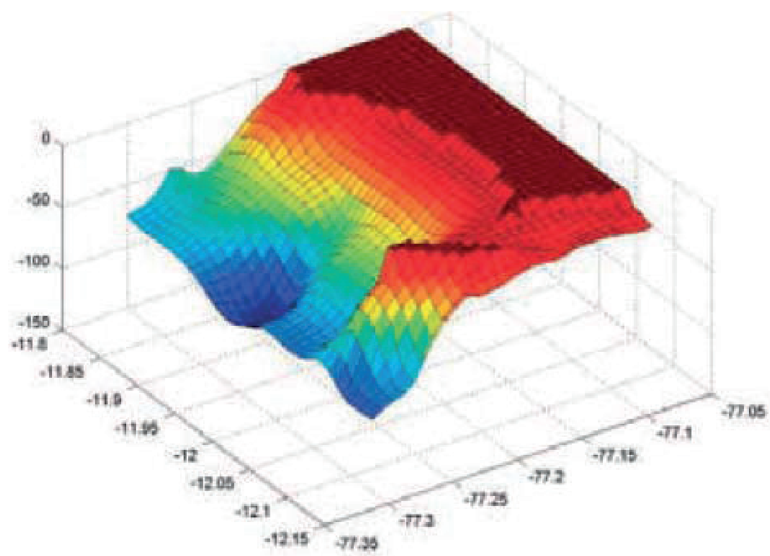

Figure 2. Domain and bathymetry (m) of the three-dimensional model

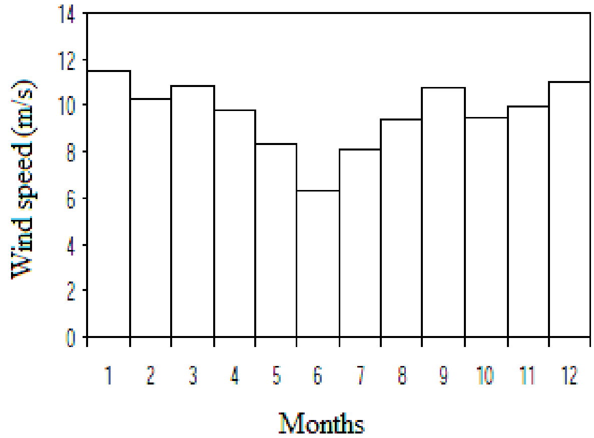

Figure 3. Monthly climatological variation of the wind in Callao Bay (data from IMARPE during 2006-2007)

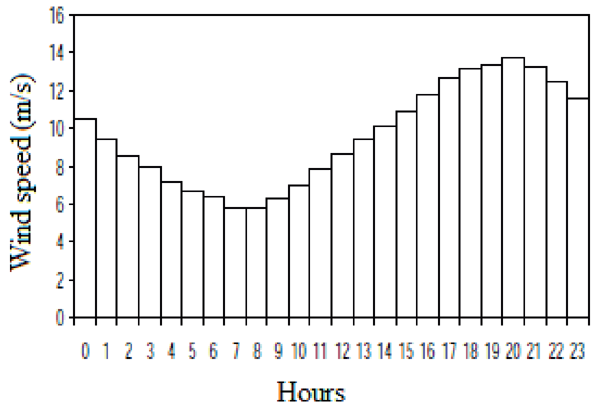

Figure 4. Hourly climatological variation of wind in Callao Bay (data from IMARPE during 2006-2007)

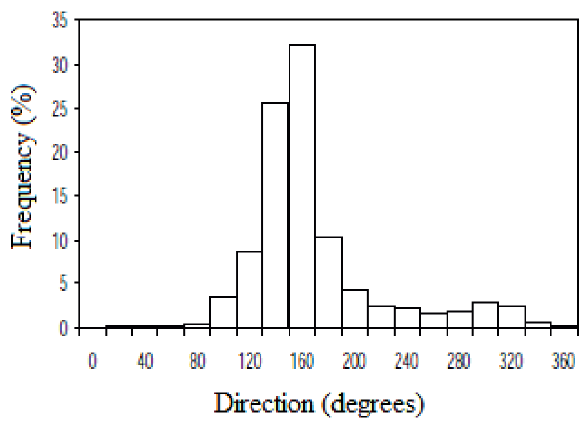

Figure 5. Frequency distribution of the hourly winds in Callao Bay (data from IMARPE during 2006-2007)

south-north. The change of direction of the coastline to the north of the bay causes a change of direction and reduction of the intensity of the winds (Bakun and Nelson, 1992).

The analysis of wind data from Callao between 2006 and 2007, from the IMARPE meteorological station, showed a predominance of southeast winds, with an annual cycle with minimum values in winter and maximums in summer, and with a parallel direction to the line (Figure 3). The hourly variation showed higher wind intensity in the afternoon and lower intensity in the mornings (Figure 4). The frequency distribution of the wind presented an average percentage of north wind of 6.7%, associated to events of winds from the north and/or to periods of relaxation of the trade winds (Figure 5).

To simulate the tides, the parameters obtained from the global barotropic tide model TPXO6.2 (2002), which has a horizontal resolution of 0.25° and uses the inverse modeling technique from altimetry data obtained from TOPEX (Egbert and Erofeeva, 2002). We considered 8 tidal constituents of diurnal and semidiurnal frequency (M2, K1, O1, S2, N2, P1, K2, and Q1). In the Callao Bay, the intensity (co-range) and phase (co-tidal lines) of the M2 component showed tidal amplitude of approximately 21cm and a phase of 226° (Figure6).

In order to simulate the Rimac and Chillon Rivers, the flow data were analyzed and greater flow was observed in the months corresponding to the summer season, when precipitation occurs in the central part of the sierra of the province of Lima. Between April and December the rainfall is scarce and the flow is substantially reduced. The average fluvial contribution of both rivers in the summer months was $39m^3/s$.

In order to simulate hypothetical domestic effluent discharges, the flow data were analyzed and the weighted average concentration

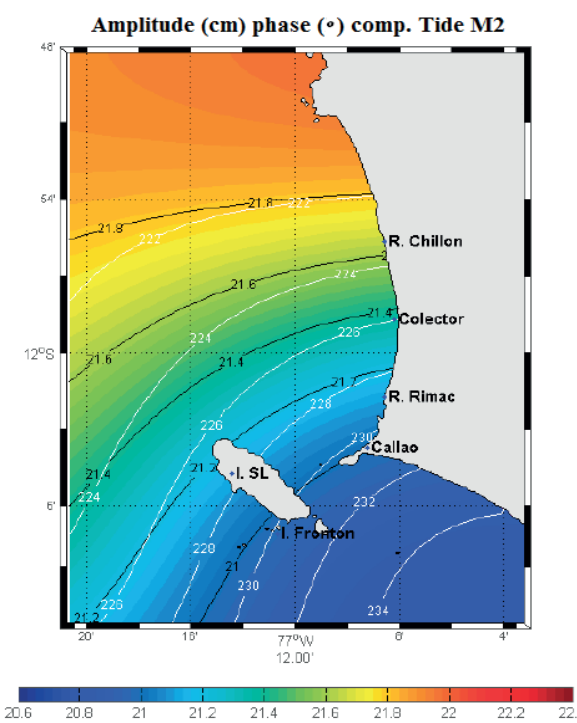

Figure 6. Amplitude and phase of the M2 component of the tides in the model

of effluents from the northern interceptor collectors, calculated to be discharged in the Taboada area, was calculated. The average flow of the hypothetical discharges was $12m^3/s$.

The computational equipment used for the execution of the model comprised Workstations of 2 (Sun) and 4 (Dell) processors Opteron, under Linux platform. The computational efficiency of the equipment using the nested model resulted in simulated 1.5 days/year (parent grid with 1/40° spatial resolution) and 3 simulated day/year (child grid with spatial resolution of 1/120°).

The model used was ROMS (Regional Oceanic Model System) (Shchepetkin and McWilliams, 2005) with the AGRIF (Adaptive Grid Refinement in FORTRAN) nesting tool developed in Fortran 90 (Penven *et al*., 2006). The AGRIF subroutine allows including the characteristics of a refined mesh within a numerical model of finite differences. The main advantage of AGRIF in static nested grids is that it has the ability to handle a varied number of fixed grids by arbitrary numbers of nesting levels. The nesting process is implemented to preserve the efficiency of the ROMS model over simultaneous computations on high performance computers. Both grids exchange information across borders in both directions, the lateral boundary conditions of the fine grid is fed with information from the thick grid, and then updated with the solutions of the fine grid.

The ROMS model has been successfully used in aquatic quality studies (Cucucie, 2003) solves primitive equations in a free surface rotational system using the Boussinesq approximation, hydrostatic approximation and vertical momentum balance. The basic equations that the model uses are as follow:

The balance of momentum in the x and y direction:

$$\frac{\partial u}{\partial t} + \vec{v} \cdot \nabla u - fv = -\frac{\partial \phi}{\partial x} - \frac{\partial}{\partial z}\left(\overline{u'w'} - \nu\frac{\partial u}{\partial z}\right) + F_u + D_u$$

$$\frac{\partial v}{\partial t} + \vec{v} \cdot \nabla v - fu = -\frac{\partial \phi}{\partial y} - \frac{\partial}{\partial z}\left(\overline{v'w'} - \nu\frac{\partial v}{\partial z}\right) + F_v + D_v$$

where, x and y are the horizontal coordinates, z is the vertical coordinate, t is the time, u, v, and w are the components of the vector speed, u', v', and w' are the components fluctuating velocity, F is the Coriolis parameter, f is the dynamic pressure, F_u, and F_v are the forcing terms, D_u, and D_v are the diffusive terms.

The continuity equation for an incompressible fluid:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

where, x, y and z are the spatial coordinates, u, v, and w are the velocities of currents.

The model is discretized horizontally on a rectangular structured grid and isotropic type Arakawa C, vertically discretized in a system of curvilinear sigma coordinates that follow the shape of the bottom and the coastline (Song and Haidvogel, 1994). It uses rigorous numerical schemes compatible with the method of finite differences to approximate with a Eurilian approach, the primitive equations for the momentum and the transport of the salinity and the temperature. It uses two time steps, one for the barotropic external oscillation mode (with a smaller time interval) that satisfies the continuity equation and the other baroclinic internal one (with a longer time interval), both fulfilling the Courant Friedrichs Lewy (CFL) convergence condition.

The system of equations is temporally discretized using two algorithms, a third order predictor of approximation (Leap Frog), and a multipath corrector (Adam Molton) making it robust and stable. The model includes a KPP (K Profile Planetary) turbulence scheme to parameterize the vertical turbulence, through a sub-model that solves the sub-grid order processes and also allows solving the turbulence closure equations (Large *et al.*, 1994). The Flather radiative boundary condition implemented in the model code for the barotropic components of the velocities perpendicular to the boundaries, is formulated according to a combination of the Sommerfeld equations and the one-dimensional continuity equation. For the baroclinic velocities the Orlansky radiation equation was used (Marchesiello *et al.*, 2001).

The model was configured with the following characteristics: horizontal spatial resolution parent grid of 1/40°, horizontal spatial resolution child grid of 1/120° (<1 km), vertical spatial resolution with 20 sigma levels, temporal resolution of 135s, And numeric scheme nested with 3 iterations of the child grid for each iteration of the parent grid.

3. Results and Discussion

3.1. Model execution

The model was started from a standby state, to determine the spin-up stage and to obtain a "re-start" state. The stabilization stage lasted 5 years of simulation, achieving stability in the total kinetic energy. The nesting technique was performed sequentially, testing first with the parent grid and then nesting the child grid. Climatological simulations of the nested model were performed, representing fields of temperature, salinity and currents of the Callao Bay from the state of restart.

3.2. Temperature simulation

The influence of large-scale circulation was analyzed with simulations of the parent grid (Figure 7). The presence of anticyclonic eddies north of the Callao Bay could orient currents towards the coast as a retention mechanism. Other anticyclonic eddies south of the bay could orient currents away from the coast, reinforcing currents northward. PESI (2000) also observed eddies in the Callao Bay during winter 1995, a cyclone north of San Lorenzo Island, probably driven by the net flow to the shore of the coastal stream, and an anticyclonic one in the coastal region, perhaps driven by the swirling existing more outside in the coast. The simulation in the child grid represented the seasonal temperature cycle, with Ekman projection and transport offshore, in response to the action of the southeast wind during the months of July to October (Figure 8c). The model also represented higher temperatures in Miraflores Bay than in Callao Bay (Figure 8a). The model also reproduced the mesoscale activity associated with the outcrop, with the occurrence of very intense filaments that transport cold water from the coast to the ocean. This marked mesoscale activity occurred as a result of the baroclinic instability produced by the interaction of water masses with different properties (cold waters from the outcrop and warm waters from ocean waters) that give rise to strong temperature gradients. In summer the vertical structure of temperature showed a layer of mixture in the first 20 m of depth, and below stratification in the thermal structure and haline. In June, under the forcing of intense wind fields and with relaxed heat flows, destruction of the stratified structure occurred, followed by a mixture of the water column. In

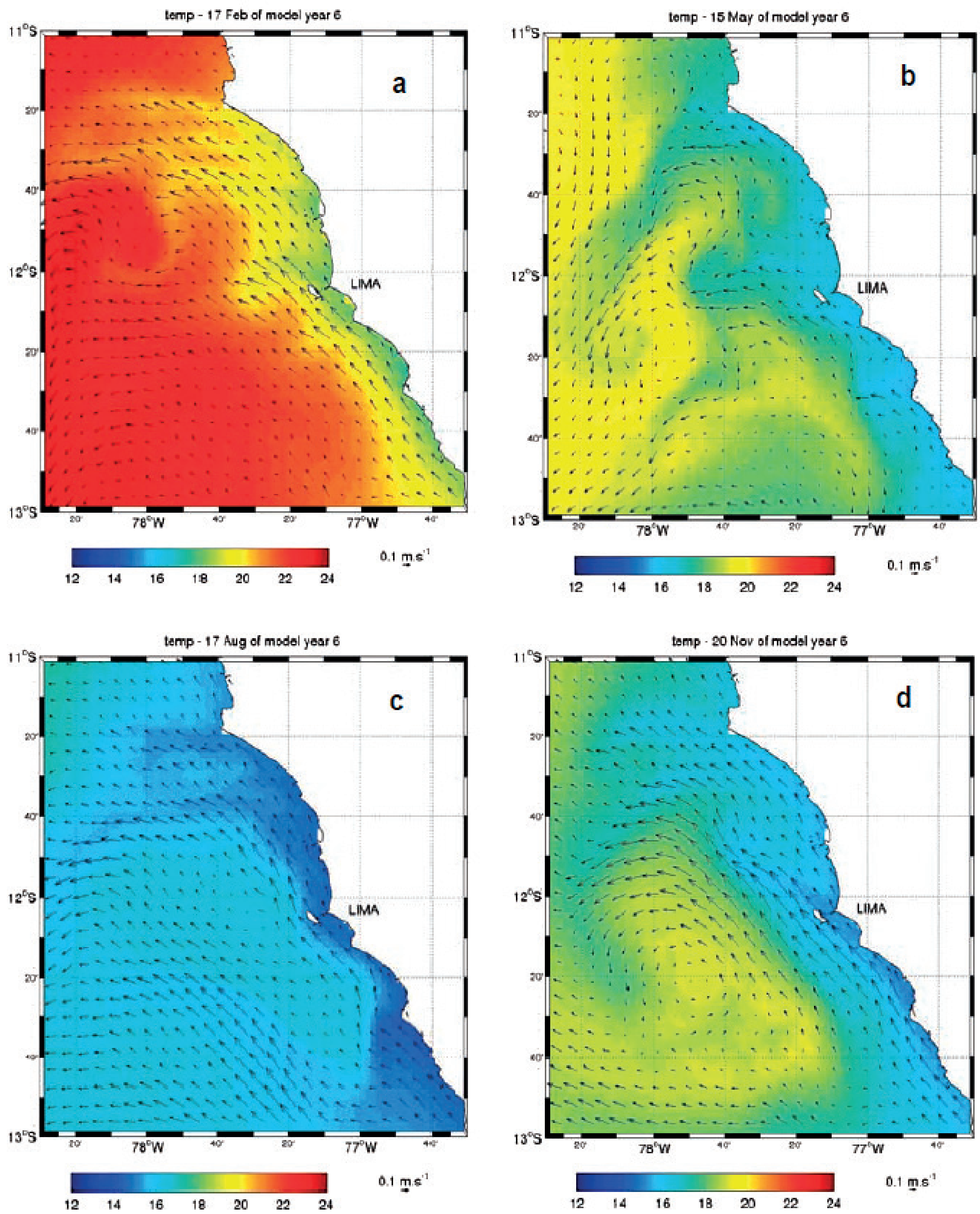

Figure 7. Climatic variation of temperature and currents in Lima during the months of (a) February, (b) May, (c) August and (d) November.

the winter months the mixture was remarkable throughout the water column, with occurrence of outcrops.

3.3. Salinity simulation

Salinity simulation showed the effect of the Rimac and Chillon rivers during the summer months, forming a low salinity enclosure (<34 ups) heading north (Figure 9a). Vasquez and Campos (1996) mentioned the presence of an anticyclonic swirl in the bottom in front of the Rímac river. On the other hand, it was also observed the presence of higher salinity SSA

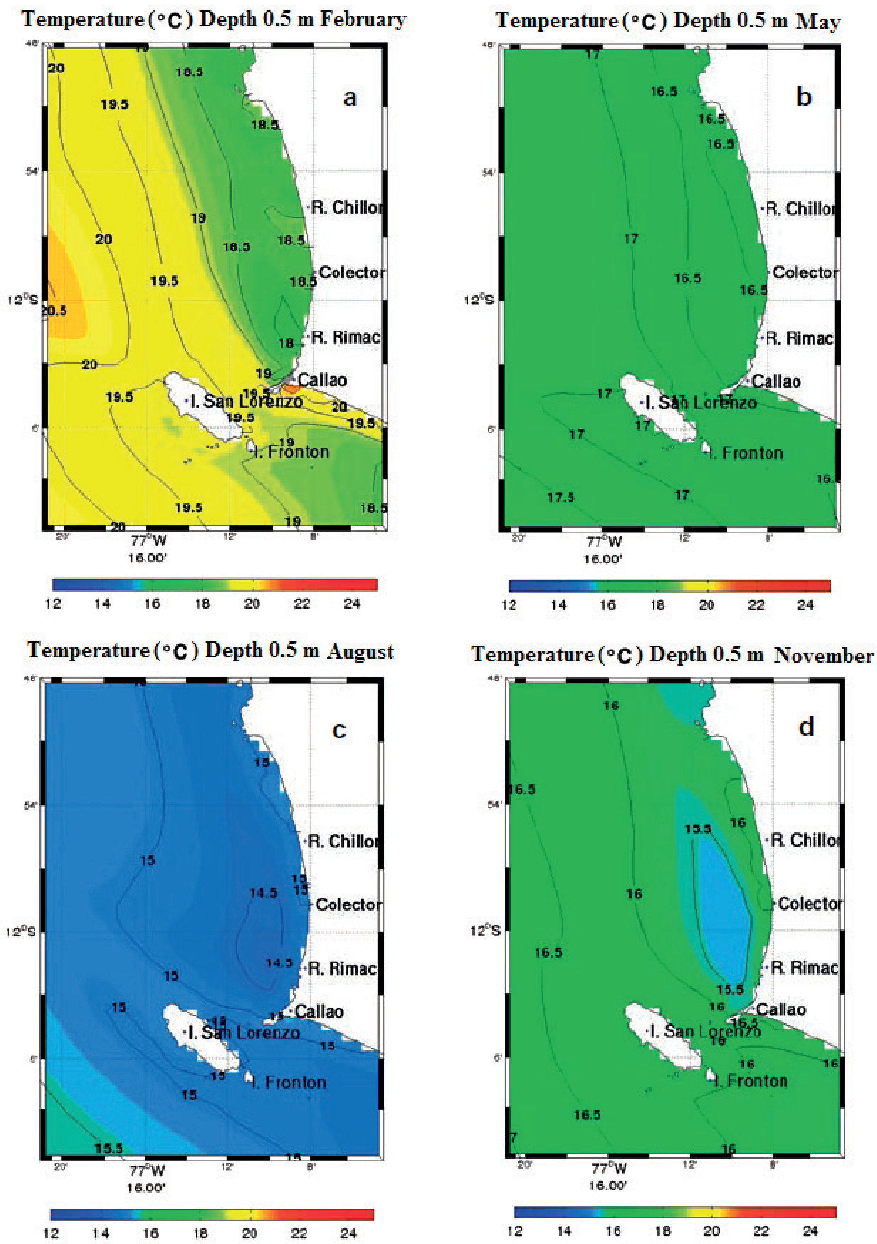

Figure 8. Climatic variation of the temperature at 0.5 m depth in the Callao Bay during the months of (a) February, (b) May, (c) August and (d) November

approaching the coast in the warm months, as well as the presence in the cold months of waters of lower salinity from southern outcrops (Figure 9c, d)

3.4. Simulation of currents

The parent grid simulated large-scale circulation, which provided information to the child grid boundaries. The Callao Bay is a coastal area that is strongly influenced by the dynamics of the region, where there are very

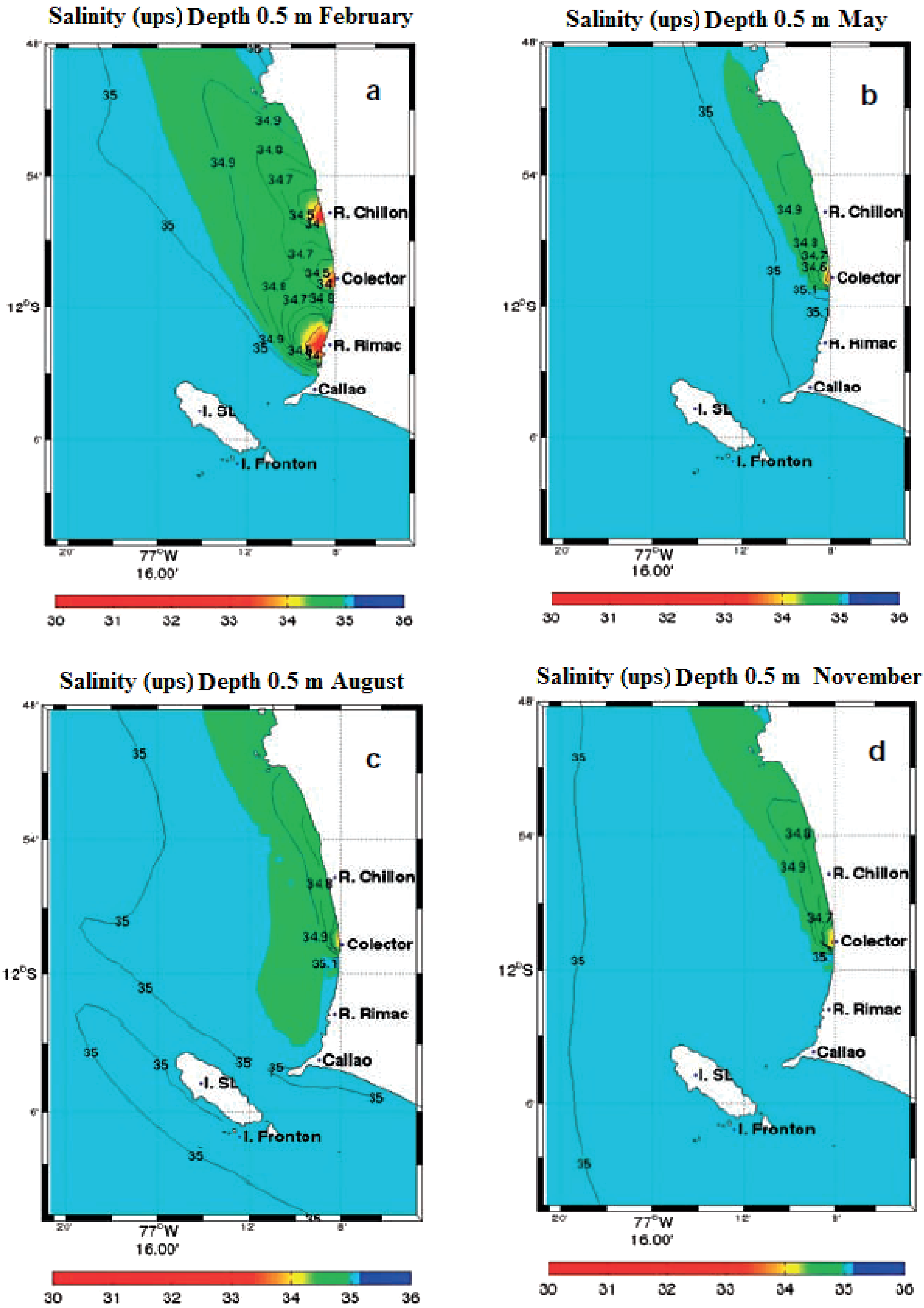

Figure 9. Climatological spatial variation of salinity at 0.5 m depth in the Callao Bay during the months of (a) February, (b) May, (c) August and (d) November

intense gradients of salinity and temperature with characteristics of very complex spatial patterns. The simulation adequately represented the Peruvian Coastal Current (PCC) with north direction, near the coast and interacting with the bay domain (Zuta and Guillen, 1970).

The semi-protected complex topography of the bay, with the interaction of San Lorenzo Island and the orientation of La Punta, generated a series of effects on the currents. On the surface, flows entered the south, and later due to the obstacle of the island San Lorenzo, separated in two flows, a flow passed through the geomorphological strait of 4.5 km between the island and La Punta, which produced an intensification of the currents, soon to the edge point into the bay, originating a cyclonic circulation; the other flow passed to the northwest. Behind the island, the flows converged leaving a region of calm. In this way, the "peninsula" effect can be recognized by friction with the topography of La Punta that produced a cyclonic circulation within the bay, generating a potential retention zone of contaminants (Leth and Middleton, 2004). On the other hand, the "canal" effect produced an intensification of the velocity of currents in the strait between La Punta and San Lorenzo Island (Figure 10). Finally, the

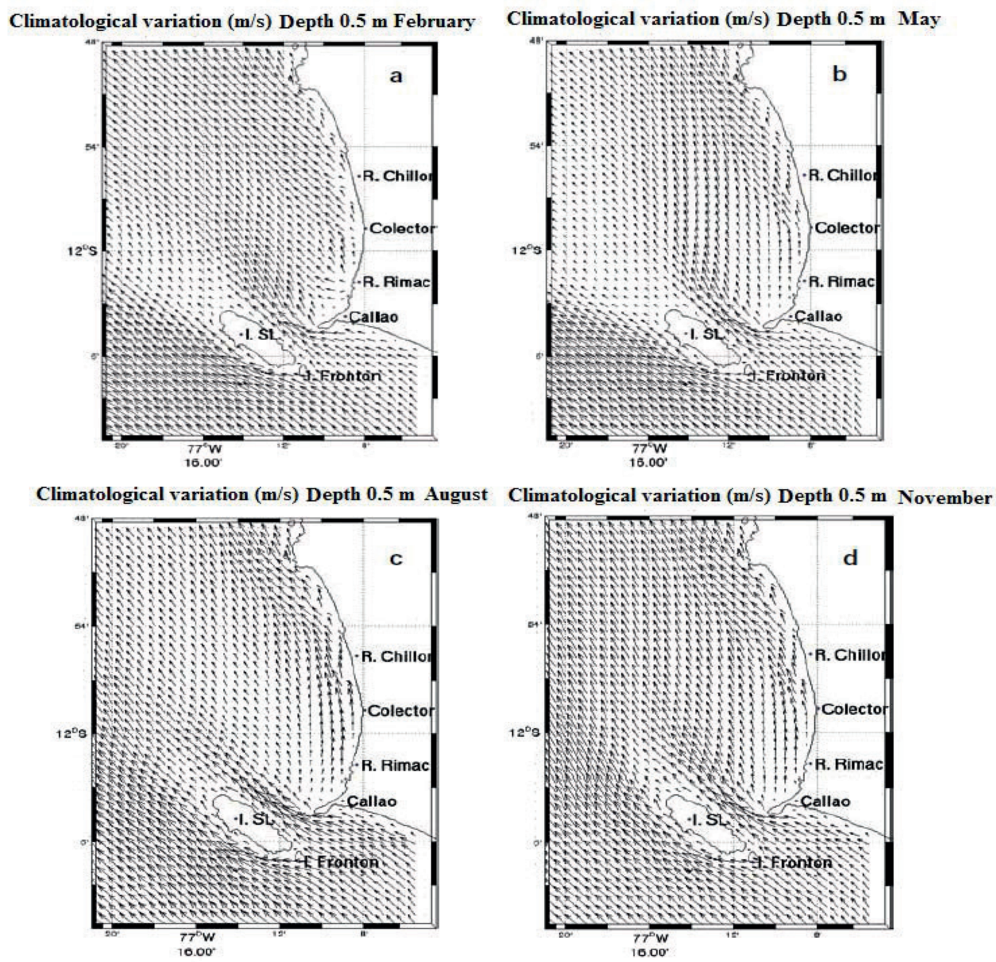

Figure 10. Climatological variation of the currents at 0.5 m depth in the Callao Bay during the months of (a) February, (b) May, (c) August and (d) November

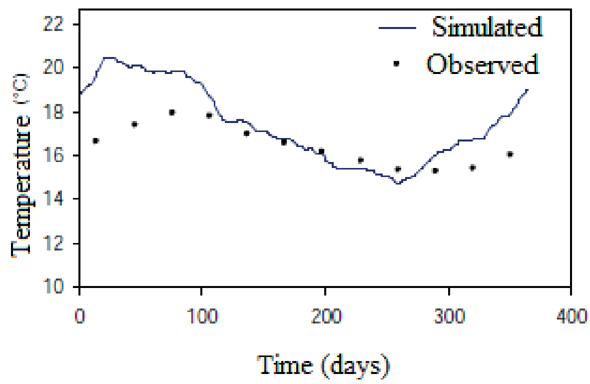

Figure 11. Comparison between observed and simulated sea surface temperature during a climatological year in the Callao Bay (r = 0.743, p <0.01)

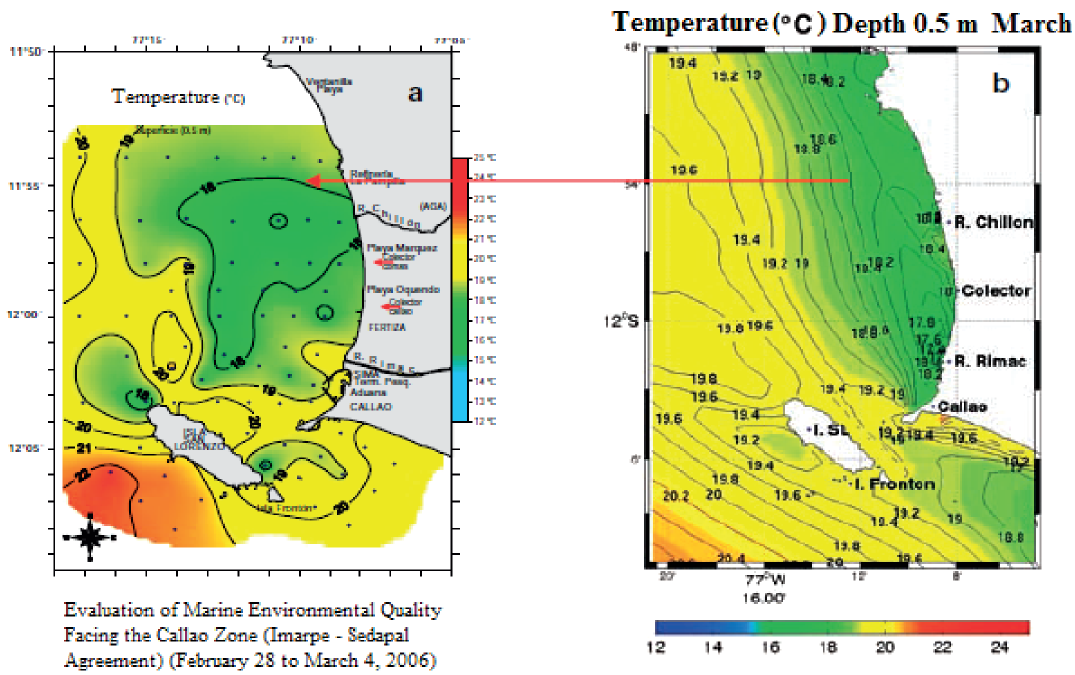

Figure 12. Comparison between the observed temperature (IMARPE 2006) in March 2006 (a) and the simulated temperature in March climatologically (b) in the surface of the Callao Bay

"island" effect produced a decrease in the velocity of the currents, behind San Lorenzo Island, generating another potential pollutant retention zone. The predominant flow direction followed the direction of the winds. Near to the coast, the currents were weak; to greater depths the currents followed the isobaths to greater speed. At the subsurface level, at a depth of 35 m, a flow towards the south was found, corresponding to the Chilean Peruvian Subsurface Countercurrent (CSSPCH) (Zuta and Guillen, 1970).

3.5. Validation of the model

The validation of the nested model was performed with simulation without domestic effluent discharges. The simulated temperature

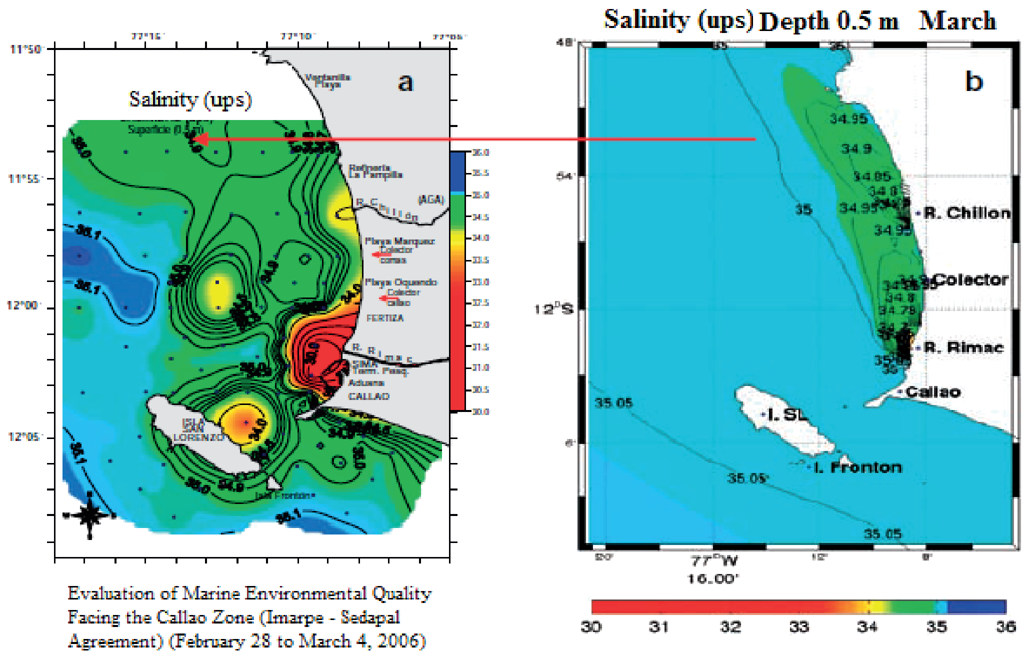

Figure 13. Comparison between observed salinity (IMARPE 2006) in March 2006 (a) and simulated salinity in March climatologically (b) in surface of the Callao Bay

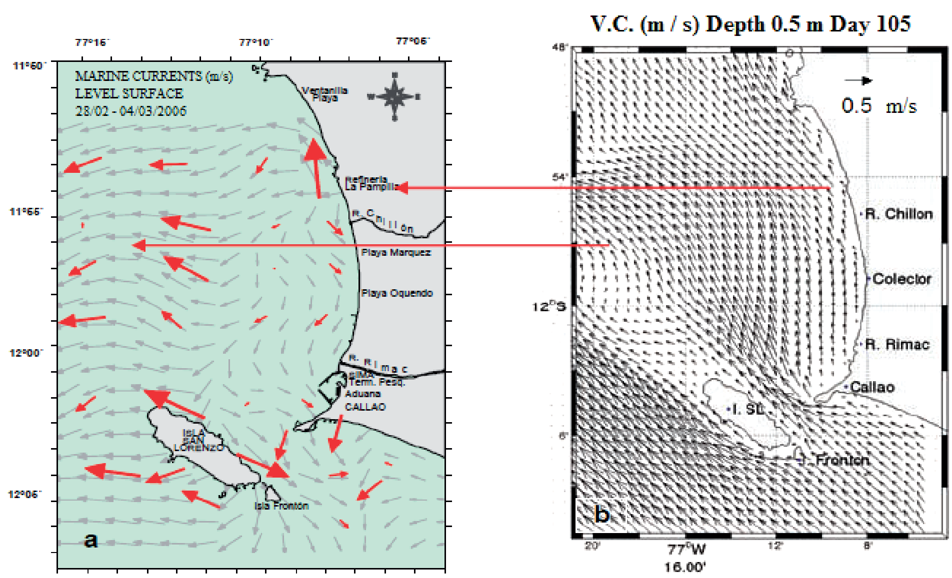

Figure 14. Comparison between the observed currents (IMARPE 2006) in March 2006 (a) simulated currents climatological (b) and in surface, in the Callao Bay

represented the seasonal variation in temperature with a significant correlation coefficient ($r=0.743$; $p<0.01$) (Figure 11). The spatial pattern of simulated temperature was in agreement with the pattern observed during March 2006 (Figure 12a) with the 25° C isoline located approximately 12 km from the coast (Figure 12b). The spatial pattern of simulated salinity showed concordance with the isoline of 35 ups, located about 15 km offshore (Figure 13a, b).

Circulation patterns showed concordance with flows observed to the north, especially along the coastline (Figure 14a). Far from the coast, differences were found in the direction of currents, with currents observed to the west and simulated currents towards the northwest (Figure 14b), which could be due to the observed pattern being a combination of measures of currents taken to different hours of the day. The parent model used at the boundaries of the nested model has been validated by Penven *et al.* (2005) who found a good concordance between the simulations and the observations of temperature and sea level.

The availability of on-site information on retrospective monitoring of IMARPE in the Callao Bay allowed comparisons with other circulation patterns. The predominance of currents to the north, especially near the coastline, coincided in the simulations and observations of April 1997 (Moron and Crispin, 1997). The intensification of the "canal" velocities between San Lorenzo and La Punta coincided in the simulations and observations of December 1996 (Vasquez and Campos, 1996) and May 2000 (Vasquez *et al.*, 2000). The generation of a cyclonic eddy by "peninsula" effect coincided in the simulations and the subsurface observations of February 1995 (Moron, 1995).

3.6. Simulation of hypothetical discharges

The physical sub-model was coupled to a scatter sub-model, based on an advection-diffusion equation; this equation did not include additional sources or sinks. A domestic effluent discharge of $12 m^3/s$ was simulated. The dispersion sub-model was parameterized with the flow data, and the results were expressed as percentage of effluent. The region with effluent concentrations higher than 0.5% represented significantly elevated effluent levels (Signell *et al.*, 2000). The model simulated the direction of the discharges being directed mainly towards the north (Figure 15), due to the prevailing direction of the winds from the southeast, and to the large-scale circulation influenced by the PCC. The seasonal variation in the circulation and flow of rivers causes changes in the direction and extent of the simulated discharges. During the summer months, the greater flow of the Rimac and Chillon rivers diverts the discharges towards the northwest, away from the coast, at approximately a 30 ° angle to the coastline (Figure 15a). However, the rest of the year, the discharges are directed to the north, striking the coast for more than 10 km, reaching the Chillon River and Ventanilla beach (Figure 15b). The width of the coastal region impacted by discharges, with significantly elevated effluent levels, is approximately 2 km. In this way, the PCC acts as a border that channels and confines the effluent near the coast. Additionally, the analysis of the mesoscale structures showed the presence of anticyclonic swirls that produce currents towards Callao Bay (Figure 7) and this mechanism can carry significant amounts of effluent towards the coast. At a greater depth, the effluent disperses in a spatial extent similar to the surface, indicating that the effluent is considered as a mass of water with high concentrations of effluents to more than 5 m depth.

Simulated discharges showed significantly elevated effluent levels extending up to approximately 10 km from the point of origin

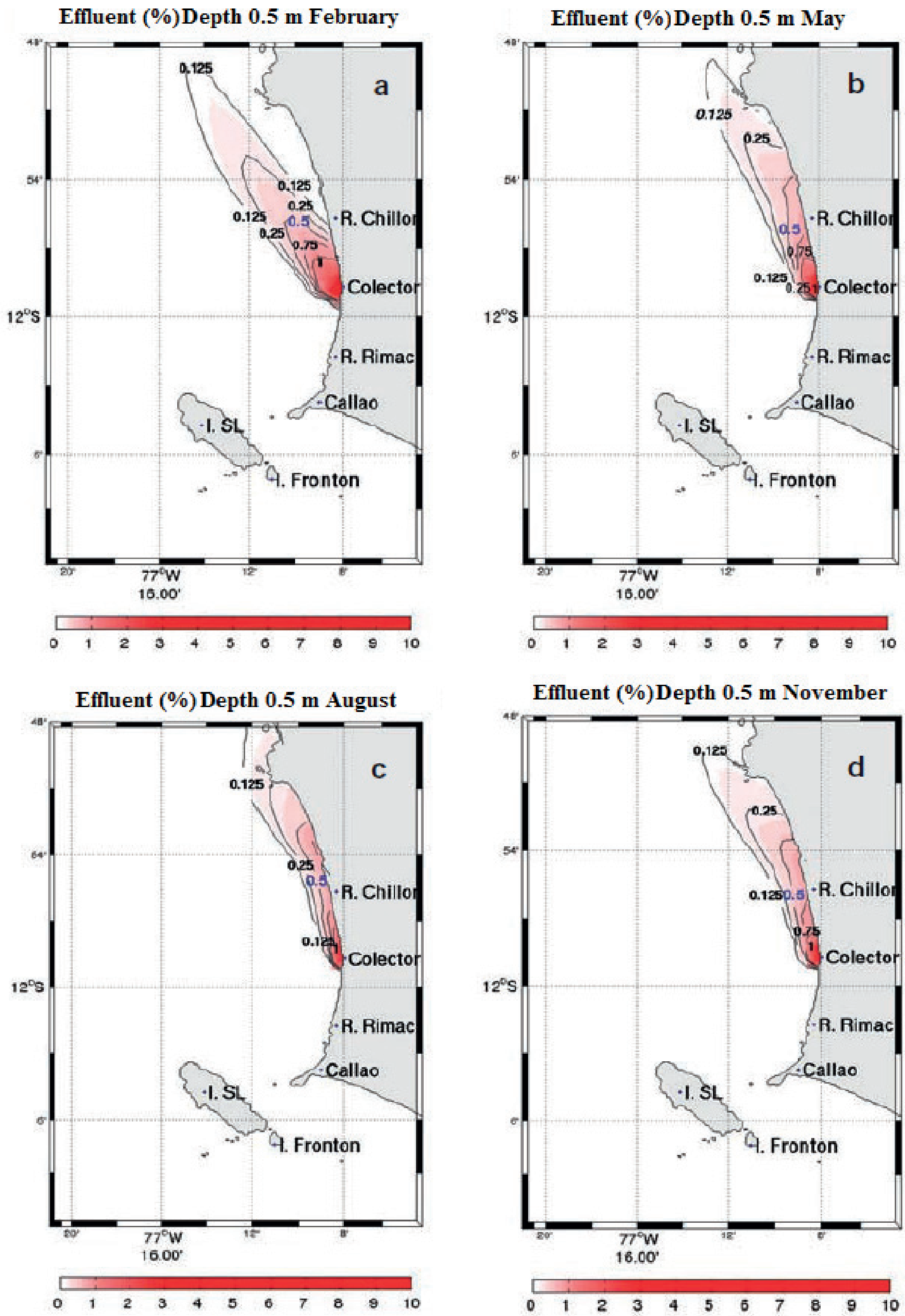

Figure 15. Spatial climatic variation of the effluent at 0.5 m depth in the Callao Bay during the months of (a) February, (b) May, (c) August and (d) November

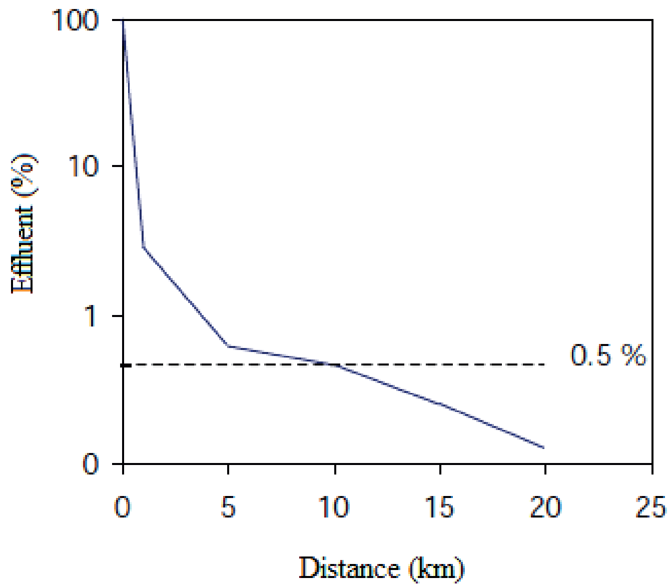

Figure 16. Spatial variation of simulated average effluent concentration from the point of discharge

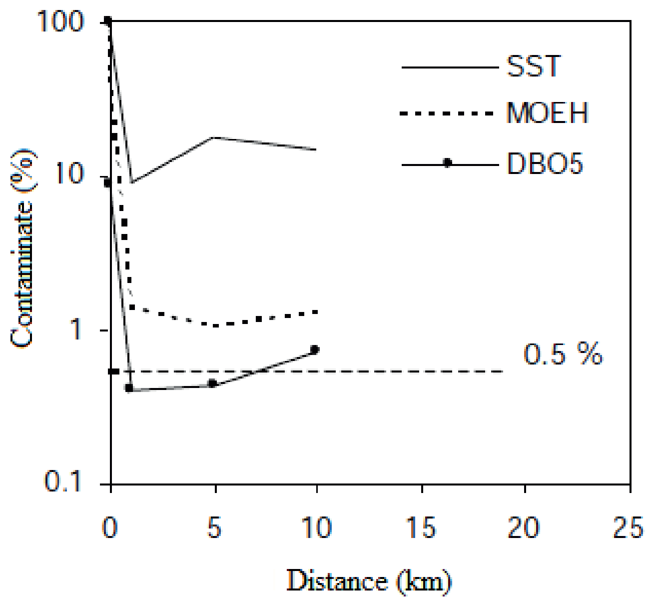

Figure 17. Spatial variation of the effluent concentration observed from the Callao collector

(Figure 16). This extension is considerably larger than the acceptable spatial extent (2-3 km) of discharges discharged through undersea outfall (Signell *et al*., 2000). Using the data observed during environmental monitoring conducted at Callao Bay in 2006 (IMARPE 2006), the current percentage of pollutants discharged from the Callao collector (Centenario) was calculated, observing a trend consistent with the simulated data, with a lower retention (BOD5), and higher retention of extractable organic material in hexane (MOEH) and total suspended solids (TSS) (Figure 17). Several studies indicate that the discharge to the Callao Bay of large volumes of domestic effluent without treatment would be detrimental to coastal residents. The Callao Bay has been classified as Class VI (area for preservation of aquatic fauna and recreational or commercial fishing) (DIGESA 2005). Environmental quality assessments carried out during monitoring in the Callao Bay (IMARPE 2006), have shown values of pollutants higher than the European Collaborative Action (ECA) of the Water Law (El Peruano, 1969). In this case the WSDE recommendation (2003) is applicable, where it is pointed out that, if a receiving aquatic body already exceeds the environmental criteria, authorization for new discharges must be denied.

The environmental impact study carried out for SEDAPAL by the consulting firm PMI (2003) concluded that: "as long as the works are not developed (treatment plant and underwater emitter) the impact will be negative, since the sea in this area is very impacted is say has many environmental liabilities." Previous studies have suggested conducting offshore treated waters through an 8 km long emitter (SEDAPAL, 1998). Several activities were proposed to develop north of Callao Bay, such as: (i) decontamination of Ventanilla Bay, (ii) control and monitoring of water quality in Ventanilla Bay, (iii) bio-ecological management and ecotourism development of the Ventanilla wetland, (iv) landscape protection and ecotourism use of cliffs, (v) decontamination of the river and Chillon valley between Puente Inca and Victor Raul, (vi) ecological adaptation of the hydrocarbon waste lagoons of the The Pampilla. Because the Ventanilla Sea is one of the ecosystems that host diverse hydro biological species, the CTPDC (2006) has planned to promote fisheries development, for which it is essential to have a good aquatic quality in this area. Ludwig (1988) indicated that Eutrophication can be an important factor when domestic effluent discharges are carried out in restricted-circulation marine waters, such as in the bays, so long-term permanent monitoring is necessary to evaluate the process of anthropogenic Eutrophication, before and during the discharges.

3.7. Simulation with scenario of North winds

The analysis of wind time series showed that in some days the northern winds in the Callao Bay predominated, and even currents have been measured with flows towards the south in the bay; for this reason it was necessary to simulate the impact of this scenario on the hypothetical discharges of domestic effluents. Simulations with northern analytical winds showed that northern winds would carry hypothetical discharges to the south, with significantly elevated levels of effluents, surrounding La Punta across the strait, and reaching as far as Miraflores Bay (Figure 18). This scenario also allows inducing that, in the Callao Bay, the circulation is governed mainly by the winds and to a lesser extent by the tides. In this way, there is a risk that events of north winds may cause impacts on areas of recreational spas (Cantolao, La Punta, Arenilla, etc.).

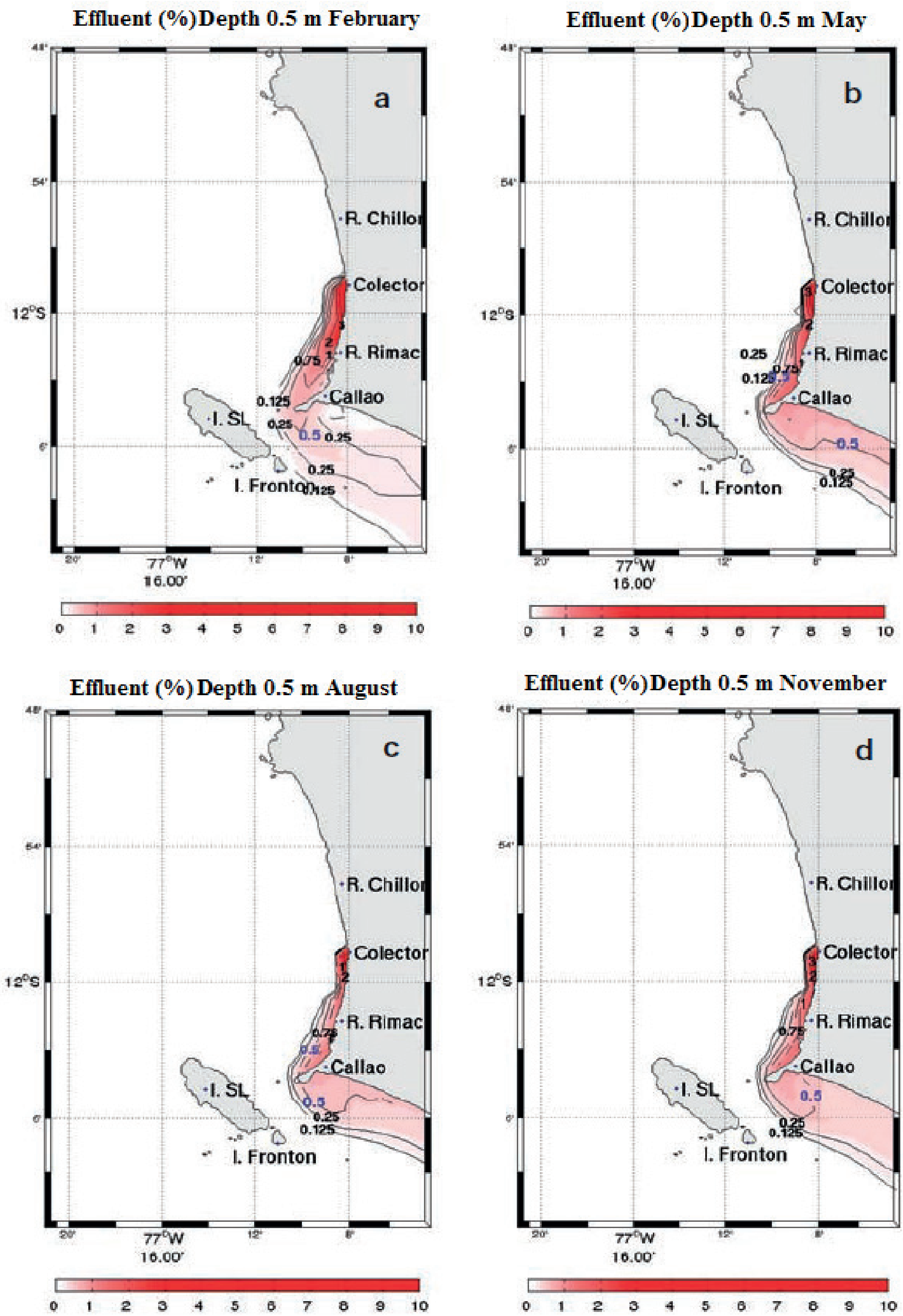

Figure 18. Spatial variation of the effluent in a scenario with a north wind, 0.5 m deep in the Callao Bay during the months of (a) February, (b) May, (c) August and (d) November

Conclusion

- The model adequately represented the patterns of temperature, salinity, large-scale circulation, and local circulation of Callao Bay
- The simulated hypothetical discharges were transported predominantly to the north, with seasonal variations (towards the northwest in summer by the discharge of the rivers)
- The spatial impact of the hypothetical discharges extended approximately over 10 km along the coast, 2 km wide and 5 m deep
- Mesoscale structures and topography increased retention in the Callao Bay
- The simulations with scenarios of north wind, showed the transport of the hypothetical discharges to the Miraflores Bay

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