Horizontal dispersion in a two-layer Coriolis-affected tortuous flow

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Abstract

The southern coast of Chile (43°S - 47°S) is a unique region with a complex marine system of fjords and channels that receive melted waters from the glaciers of the southern Patagonian ice field. Interior waters of this region are characterized by a salinity induced two-layer density structure with a sharp interface located at about 20 m-depth, and homogeneous salt concentration of about 30 ppt below it. Estuarine circulation characterizes the horizontal transport with a superficial net flow toward the open ocean and a deep-water net flow towards the fjords. The low salinity in the surface layer is the result of fresh water inflows coming from rivers, glacial melting and coastal runoff. Besides this general estuarine circulation; wind, tides and the complex geomorphology, govern in together the hydrodynamics of this region. The objective of this research is to define which are the dispersion mechanisms that dominate horizontal transport in the upper layer of this region. Particularly, the focus is placed on tide dispersion, estuarine dispersion and wind dispersion. For doing this, the hydrodynamics of the region was simulated with CWR-ELCOM, considering daily inflows discharge, meteorological data reconstructed from the NCEP-NCAR reanalysis information, and tide height measurements. In order to define which dispersion mechanism dominates the horizontal transport, different scenarios were simulated considering changes in the external forcing, and the horizontal dispersion coefficient of the upper layer was then computed using the simulated flow velocities. It is shown that estuarine dispersion has an important role in the horizontal shear dispersion during the floods, but more important were the combined effects of tide and wind dispersion during the entire simulation. Particularly, the wind counteracts the effects of tide dispersion, showing an increase on the horizontal dispersion when the wind speed is reduced.

1 Introduction

The southern coast of Chile (43°S - 47°S, Figure 1) is a unique region with a complex marine system of fjords and channels that receive melted waters from the glaciers of the southern Patagonian ice field. Despite this region is almost uninhabited, it has been affected by harmful algal blooms called red tides that have increased in frequency, duration, extension and toxicity (Lembeye, 2008). Furthermore, recent events of virus ISA (Infectious Salmon Anemia) have stroked Salmon farms that operate on the region, with severe consequences on the Chilean economy. Considering these environmental trends, it is crucial to understand horizontal transport mechanisms that spread both algae and virus in the region.

The hydrodynamic of this region can be classified as fjord-like estuary, formed by the glacial action, with a complex system of branching channels that are very deep (400 m-depth), narrow (5-15 km-width) and highly stratified. Estuarine circulation characterizes
the horizontal transport with a superficial net flow toward the open ocean and a deep waters net flow towards the fjords (Silva et al., 1995). Interior waters of this region have a two-layer density structure with a sharp interface located at about 20 m-depth, and homogeneous salt concentration of about 30 ppt below it (Silva et al., 1995). The low salinity in the surface layer is the result of fresh water inflows coming from rivers, glacial melting and coastal runoff. This two-layer density structure, the complex geomorphology, and the high latitude that gives extreme meteorological conditions and important Earth rotation effects, define a unique region with a unique hydrodynamic structure.

The objective of this research is to define which are the dispersion mechanisms that dominate horizontal transport in the upper layer of this region. Particularly, the focus is placed on tide dispersion, estuarine dispersion and wind dispersion. For doing this, the hydrodynamics of the region was simulated with CWR-ELCOM (Centre for Water Research - Estuary and Lake Computer Model), considering daily inflow discharge from the main rivers measured by DGA (Chilean Governmental Water Agency), meteorological fields reconstructed from NCEP-NCAR (National Centers for Environmental Prediction - National Center for Atmospheric Research) reanalysis information, and tide height measured by SHOA (Chilean Navy Agency).

2 Methods

In order to capture the fluctuations associated to longer-term variations in tide amplitude as well as the seasonal fluctuations in meteorological and river inflows forcing, the complete 2008 was simulated.
Numerical model - Three-dimensional hydrodynamic simulations were carried out with ELCOM. This model solves the Reynolds averaged Navier Stokes equations with the Boussinesq approximation for density differences, using a semi-implicit formulation on a finite-volume framework (Hodges and Dallimore, 2010). ELCOM represents the turbulent fluxes of mass and momentum with a 3D mixed-layer approach based on the mixing energy budget derived for 1D lake modelling (Hodges et al., 2000). A detailed description of ELCOM is presented in Hodges et al. (2000). The numerical grid was generated using the bathymetric and coastline data of the Chilean Navy Agency (SHOA, 2001) shown in Figure 1c. The horizontal size-grid was 1000 × 1000 m$^2$, while vertical grid spacing was arranged such that the finest resolution was 4 m in the surface down to 20 m-depth, and the coarsest resolution was 10 m in deep waters. The time step was fixed to 360 s, which satisfy the Courant-Friedrichs-Levy stability condition.

Boundary conditions - For the open boundaries condition at the north and east of the domain (Figure 1c), sea level measured by SHOA (2008) in Puerto Montt (41.5°S, 73°W) was used (Figure 4a). Furthermore, 50 vertical CTD profiles were measured in Aysén fjord during January of 2008 (point (3) in Figure 1c), which were averaged in order to obtain the characteristics profiles shown in Figure 2. In absence of further information, these profiles of Figure 2 were used as both open boundary and initial conditions. Regarding the inflows discharge, the study area has three main rivers: Palena, Cisnes and Aysén rivers (see numbers in Figure 1c) with catchment areas of 11590, 5047 and 12745 km$^2$, respectively. Daily inflow discharges from Aysén river are available for 2008 (shown in Figure 4b), and this information was used to estimated the inflow discharge of the other two inflows by simple basin-transposition among basins. Furthermore, the inflows temperature was estimated based on correlations between water and air temperature measured in Aysén river. Finally, meteorological data was obtained from the 4-times daily NCEP-NCAR reanalysis (Kalnay et al., 1996). The surface data for the point in the middle of the domain (45°S, 73.5°W) is presented in Figure 3.

Sensitivity analysis - In order to define which dispersion mechanism dominates the horizontal transport, three different scenarios were simulated considering changes in the external forcing: without tide forcing, without inflows discharge, and with a reduction of
Figure 3: Surface meteorological data for the point in the middle of the domain (45°S, 73.5°W) of the 4-times daily NCEP-NCAR reanalysis (Kalnay et al., 1996): (a) wind speed, (b) wind direction, (c) air temperature, (d) relative humidity, (e) solar radiation.

wind speed in 90%. These scenarios are hereinafter called tide, inflow and wind, respectively. The results of these scenarios were compared with the complete case scenario that considers all measurements (called complete). For each simulation, the shear dispersion coefficient for the upper layer (20 m depth) was computed based on the dispersion tensor given by (Fischer et al., 1979).

\[
K_{ij} = - \int u_i' \int \frac{1}{\epsilon_t} \int u_j' dx_k dx_k dx_k, \tag{1}
\]

with \(u_i'\) the fluctuating velocity from the mean flow, with \(i\) and \(j\) the horizontal directions and \(k\) the vertical direction, and \(\epsilon_t\) is the vertical turbulent diffusivity of \(\rho\), that was estimated based on Ivey et al. (2008), considering that the turbulent Prandtl number is equal to 1, the rate of dissipation of turbulent energy is equal to the shear production, and the mixing regime is intense. This gives that:

\[
\epsilon_t = 4\nu \frac{S^2}{N^2} \tag{2}
\]

where \(\nu\) is the water viscosity and

\[
S^2 = \frac{\partial u_i}{\partial x_k} + \frac{\partial u_j}{\partial x_k}, \quad N^2 = -\frac{g}{\rho} \frac{\partial \rho}{\partial x_k}. \tag{3}
\]

Finally, the characteristic shear dispersion coefficient that is used in this analysis is the largest eigenvalue of the shear dispersion tensor. This value is called \(K^1\).
3 Results and discussion

Figure 4 (c-e) presents time series of the horizontally averaged ratio between the horizontal dispersion coefficient for each scenario and the complete simulation, $K^1/K^*$. In the inflow scenario (Figure 4c), it is observed a reduction in the horizontal shear dispersion during the floods events (Figure 4a), which is more notorious in the regions close to the inflows discharge as it is shown in Figure 5a that show the spatial distribution of this coefficient during a flood in the day 137 (see dashed vertical line of Figure 4). Moreover, an important reduction in the horizontal dispersion of the tide simulation was predicted during the entire simulation (Figure 4c), and the magnitude of this reduction depends on the longer-term variations of the tidal cycle (Figure 4b). Finally, contrary to the other two scenarios, wind scenario predicted both reduced and enhanced shear dispersion (Figure 4d) with respect to the complete scenario, and this behaviour is related to a coupling between tide- and wind-induced flow. That is, depending on the tide phase, wind may counteracts tide dispersion, so that a reduction on the wind speed results in an increase on the tide dispersion. This is seen in the shaded areas of Figure 4, which show that when there is a decrease on the horizontal dispersion in the tide simulation, the dispersion on the wind simulation increases, in correspondence to weakly harmonic in the tide. This opposite feedback between tide and wind can be seen in the spatial distribution of this coefficient shown in Figures 5b and c.

![Figure 4: (a) Daily inflow discharges from Aysén river measured by DGA during 2008. (b) Sea level measured by SHOA (2008) in Puerto Montt (41.5°S, 73°W). Time series of the horizontally averaged ratio between the horizontal dispersion coefficient for each scenario and the complete simulation, $K^1/K^*$: (c) without tide forcing, (d) without inflows discharge, and (e) with a reduction of wind speed in 90%.](image)
Because stratification could play a significant role on the horizontal shear dispersion, it is interesting to study changes on the two-layer density structure simulated by different scenarios (Figure 6). It is observed a two-layer structure in all cases but in inflow scenario (Figure 6b), for which no fresh water inflows were considered, so that the surface layer of low salinity disappears. However, this does not produce changes in horizontal dispersion as it is shown in Figure 4c. Moreover, it is observed an enhanced stratified condition in tide scenario (Figure 6c), thus showing that tide promote both horizontal dispersion and vertical mixing.

![Figure 5: Spatial distribution of the horizontally averaged ratio between the horizontal dispersion coefficient for each scenario and the complete simulation, $K_1^*/K_1^*$: (a) without tide forcing, (b) without inflows discharge, and (c) with a reduction of wind speed in 90%, during a flood in the day 137 (see dashed vertical line of Figure 4).](image)

**4 Conclusions**

Horizontal dispersion in a two-layer Coriolis-affected tortuous flow was studied in this paper. The focus was placed on tide, estuarine and wind dispersion. It was shown that estuarine dispersion has an important role in the horizontal shear dispersion during the floods, and this effect was confined to channelized areas near the rivers. More important than estuarine effects were the coupled dynamics between tide and wind dispersion during the entire simulation. Particularly, the wind counteracts the effects of the tide dispersion, showing and increase on the horizontal dispersion when the wind speed is reduced. Finally, it was not clear the role of the stratification on the horizontal dispersion, but clearly it governs the vertical mixing.
Figure 6: Two-layer density structure simulated in the area close to the Aysén river for different scenarios: (a) complete, (b) without tide forcing, (c) without inflows discharge, and (d) with a reduction of wind speed in 90%.

References


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