Regional Studies in Marine Science 38 (2020) 101389

Contents lists available at ScienceDirect

Regional Studies in Marine Science

journal homepage: www.elsevier.com/locate/rsma

Climatology of Maipo and Rapel river plumes off Central Chile from numerical simulations

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ARTICLE INFO

Article history:
Received 10 February 2020
Received in revised form 5 July 2020
Accepted 4 August 2020
Available online 8 August 2020

Keywords:
River runoff
Freshwater
Buoyant plumes
Modeling

ABSTRACT

River-influenced coastal areas are important ecosystems due to the critical influence of river runoff on nutrients and the structure of planktonic and benthic communities. Many studies have focused on the interaction among river runoff, wind, tides and river plume characteristics, and based on observations and modeling results. This study aims to improve our understanding about the circulation and seasonal pattern of river plumes off Central Chile, using climatological simulations in the Regional Ocean Modeling System (ROMS). Results were in reasonable agreement with satellite (MODIS) observations. The plumes exhibit a minimal area cover during summer-fall, with a northwest orientation as result of dominant southwesterly winds and low river discharges. A larger plume area is developed during June–September, as result of higher winter precipitations. The orientation of the plumes during winter is westward, driven by higher river discharges and winds blowing in the southeast direction. An interesting feature reproduced by the model was the trend to coalesce as observed in previous studies using satellite imagery.

1. Introduction

River plumes are essential features in some coastal ecosystems, given their impact on the biogeochemistry and the seasonal and spatial dynamics of planktonic and benthic communities (D'Sa and Miller, 2003; Mestres et al., 2003; Masotti et al., 2018). In general, river-influenced regions have comparatively higher nutrient concentrations than adjacent ambient waters and account for a higher planktonic productivity (Mallin et al., 2005; Peterson and Peterson, 2008; Kudela and Peterson, 2009). However, the most notorious and evident feature of these regions is a low salinity and high stratification along with high turbidity associated with elevated concentration of suspended matter. The seasonal variation of the areal extension and shape of river plumes mostly depends on river runoff (which, in turn, depends on the hydrological regime of the local rainfall and/or snowmelt), and the seasonal pattern of wind and surface currents over the continental shelf (Hickey et al., 2005). However, this general scheme varies with the effects of bottom topography and mesoscale processes. Some coastal areas, for instance, exhibit a rapid response to large freshwater and sediment discharges, showing a strong stratification and rapid sediment settling within 1 km of the river mouth (Warrick et al., 2004). On the other hand, modeling studies have shown that the mixing can be more intense near the river mouth because of the stronger vertical shear; however, wind is also able to intensify the mixing in the near and far-fields, but its efficiency is generally higher in the far-field (far from the river mouth) (Hetland, 2005; Horner-Devine et al., 2016). Regarding time scales, the variability of river discharge dominates the plume dynamics in a long-term (seasonal) scale. In contrast, higher frequency (few days) variability is mostly driven by wind stress (Lentz and Largier, 2006; Falcieri et al., 2013).

The hydrographic conditions along the river-influenced coastal zone exhibit high seasonal variability off central Chile (Strub et al., 1998; Sobarzo et al., 2007). Intermittent periods of upwelling and relaxation and high levels of stratification and intrusion of oceanic waters are observed during summer (Letelier et al., 2009; Aguirre et al., 2012). On the other hand, winter conditions are modulated by the passage of extra-tropical storms with strong southward winds (Hernández-Miranda et al., 2003). It is worth to mention that Central Chile is influenced by the so-called low-level

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https://doi.org/10.1016/j.rsma.2020.101389
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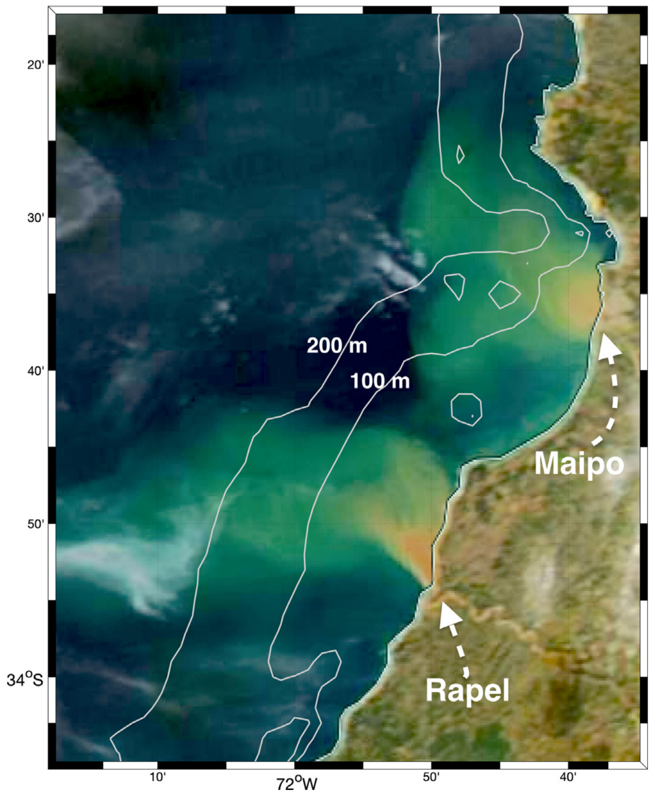

Fig. 1. Study area off central Chile in a MODIS true color image showing the Maipo and Rapel River plumes on May 24, 2008. The white contours denote the 100 m and 200 m isobaths. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

jet off the west coast of subtropical South America (Garreaud and Muñoz, 2005). This feature consists of southerly coastal jets (i.e., a maximum of wind speed) off central Chile (26°S-36°S), that occur year-round but whose intensity and frequency are higher during spring–summer (Muñoz and Garreaud, 2005).

Despite their relevance for local fisheries, ecological processes, and sediment supply to nearby beaches, the studies on river plumes in Chile are scarce and mostly focused on planktonic and benthic ecology. The low attention paid to river plume dynamics along the Chilean coasts is likely because these rivers are relatively small, given their small watersheds and the short distance between the mountains and the coast (Saldías et al., 2012). Piñones et al. (2005) concluded that, whereas the river discharge mostly modulated the Maipo river plume in wintertime, the influence of wind was dominant during spring–summer. This wind influence, in turns, exhibits a diurnal variation. On the other hand, Vargas et al. (2006) described the seasonal variation of the Maipo river plume hydrographic conditions and its influence on the distribution of chlorophyll and barnacle larvae in the inner shelf. Recent studies of river plumes in central Chile have used in situ observations in combination with MODIS imagery (Saldías et al., 2012, 2016). In these studies, a high seasonal and interannual variability in the plumes spreading and turbidity levels was observed. In austral winter, the plumes tend to merge in the downstream direction, whereas in austral spring–summer, the plumes are smaller and elongated relatively close to the coast.

River plumes along the Chilean coast have been studied mostly from ecological perspectives. Thus, their physics and the main forcings driving their seasonal dynamics are barely studied. This study aims to describe the climatology of the river-influenced circulation and hydrographic conditions off central Chile using numerical simulations.

2. Materials and methods

2.1. Study area

The study area covers the coastal ocean between the latitudes 32°30′S and 34°00′S, an area influenced by the Maipo and Rapel rivers outflows (Fig. 1). These rivers are relatively small due their small watersheds (14.939 km^2 and 13.576 km^2, for Maipo and Rapel watersheds, respectively) and the short distance between the mountains and the coast (∼150 km) (Saldías et al., 2012). However, they are among the most important rivers in central Chile because of their discharges and their path across several cities that account for the country's largest population. These snow- and rain-fed rivers move across transverse and longitudinal valleys. The resultant river plumes spread under the influence of tides and topography, and a strong seasonal influence from the wind and river discharges.

2.2. Numerical model

The velocity and hydrographic conditions were simulated with the Regional Ocean Modeling System (ROMS) AGRIF version (Penven et al., 2006). This model resolves the primitive hydrodynamic equations of ocean dynamics and uses the terrain-following coordinates (Shchepetkin and McWilliams, 2005). The model was configured with a 2 km horizontal resolution and 20 vertical levels, increasing the vertical resolution toward the surface and bottom levels to better resolve the boundary layers. This configuration helps to resolve sub-mesoscale features of the river

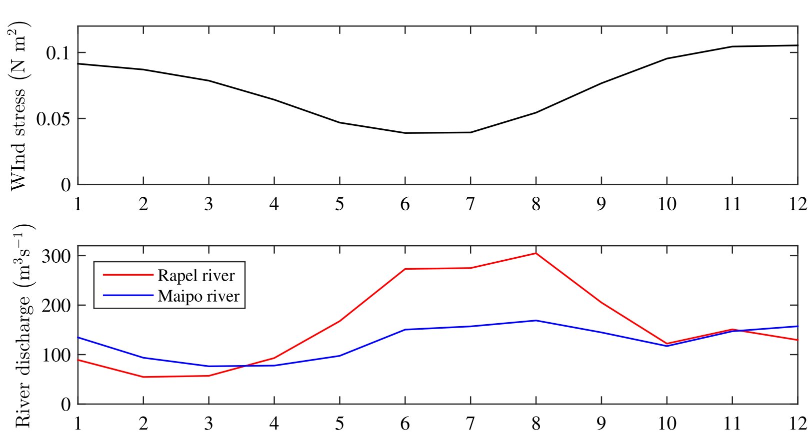

Fig. 2. Monthly mean (upper panel) meridional wind stress and (bottom panel) river discharges used to force the model in the study area.

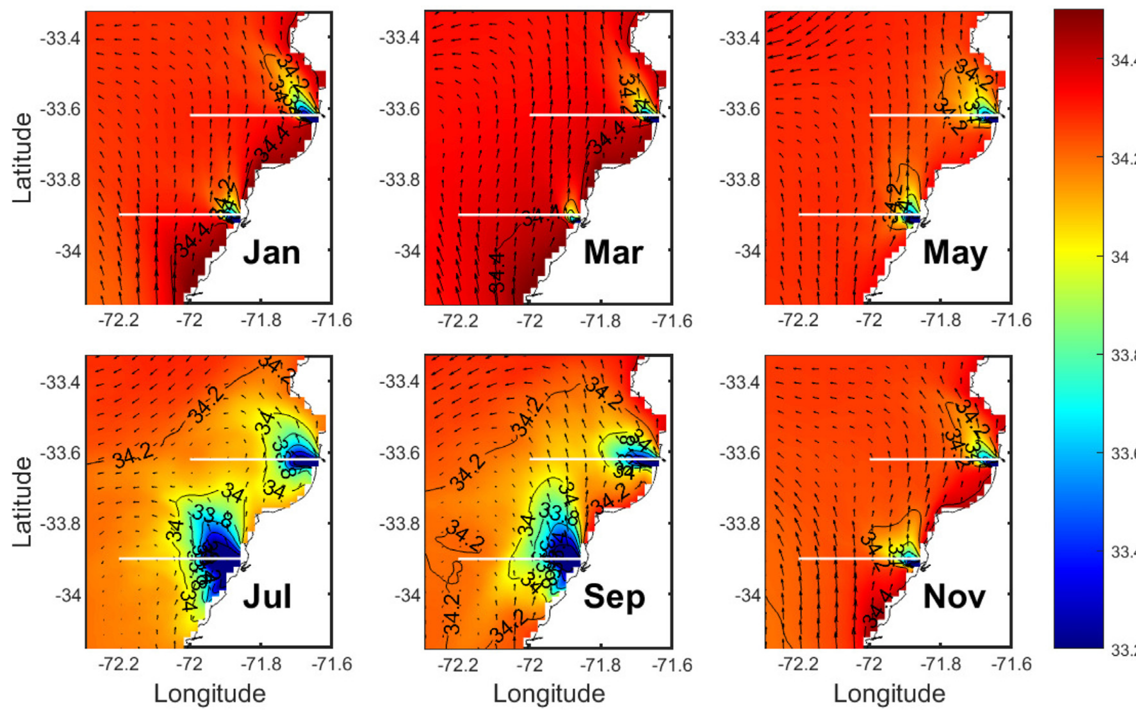

Fig. 3. Monthly mean surface velocity (vectors) and salinity (color scale) in the area under the influence of Maipo (upper) and Rapel (lower) river plumes. The white horizontal lines represent the zonal sections shown in Figs. 4 and 5 for the Maipo and Rapel river plumes, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

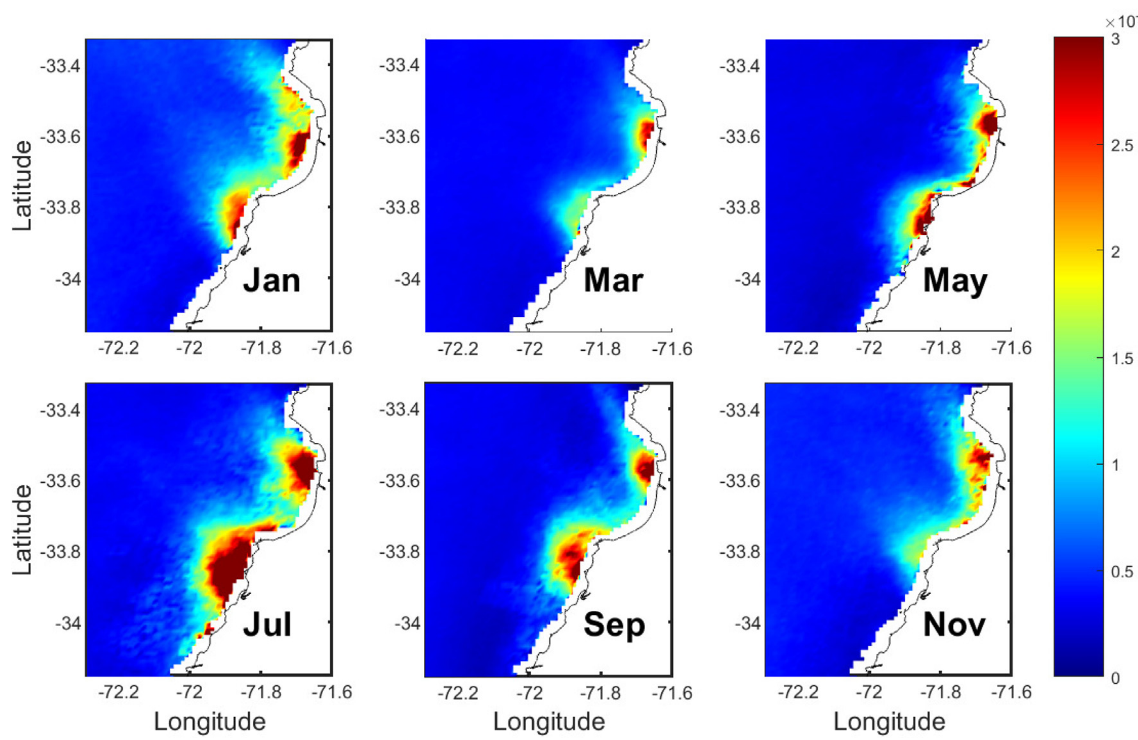

Fig. 4. Monthly mean reflectance at 645 nm (Rrs(645)) from MODIS-Aqua imagery in the area under the influence of Maipo (upper) and Rapel (lower) river plumes.

plumes and their interaction with regional mesoscale processes. The model momentum and buoyancy fluxes were forced with the Scatterometer Climatology of Ocean Winds (SCOW) and the Comprehensive Ocean–Atmosphere Data Set (COADS) 25 km resolution climatology. Boundary conditions were obtained from the 10 km resolution Ocean General Circulation Model for the Earth Simulator (OFES), which was forced with National Centers for Environmental Prediction (NCEP) fluxes. After analyzing the climatological data of global rivers from Dai et al. (2009), Dai and Trenberth (2002), a time-lag was noted. Consequently, climatological monthly discharges from the Maipo and Rapel rivers were obtained from the General Direction of Waters (Dirección General

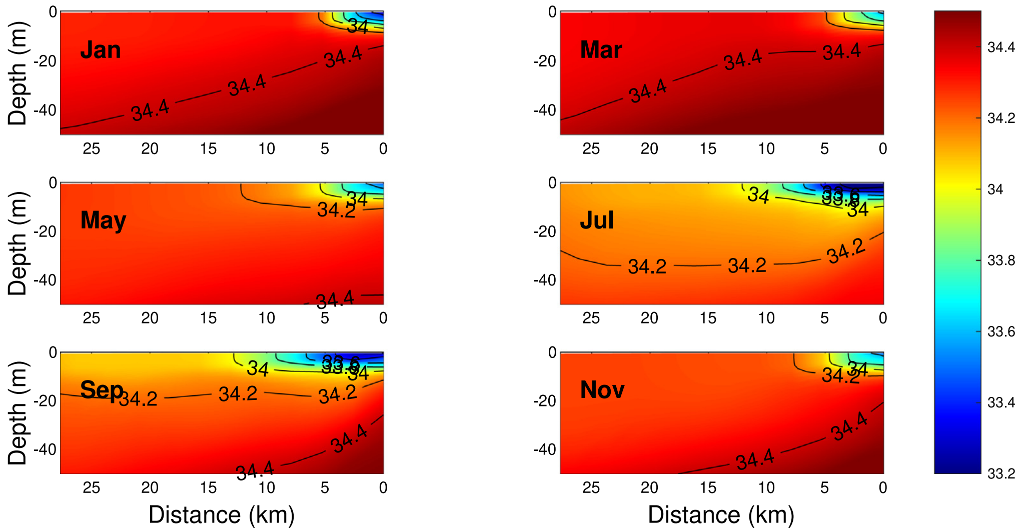

Fig. 5. Seasonal variability of cross-shore salinity structure off Maipo river mouth.

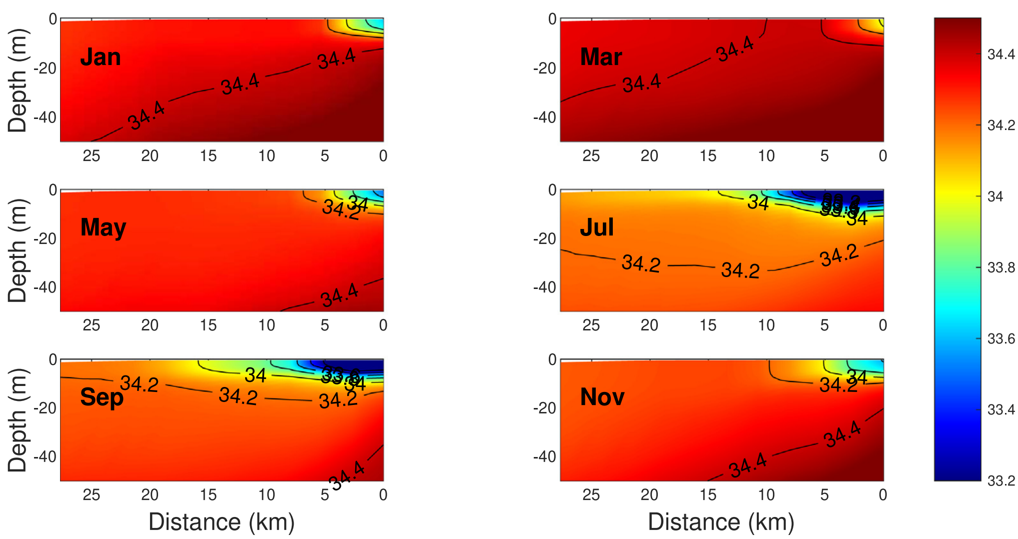

Fig. 6. Seasonal variability of cross-shore salinity structure off Rapel river mouth.

de Aguas, Chile), the Chilean government entity responsible for measuring and managing water resources. The monthly mean wind forcing and river discharges in the study area are shown in Fig. 2. Simulations were replicated ten times in order to capture the internal model variability. The first four years were not considered in the results as this period was the model spinup.

2.3. Remote sensing data

Monthly composites of level 3 Remote Sensing Reflectance at 645 nm (Rrs(645)) were downloaded from the MODIS-Aqua mission (http://oceancolor.gsfc.nasa.gov/), for the period 2003–2011. Fields of Rrs(645) were used to confirm and compare the seasonal variability of plume spreading in the study. Previous studies have used this ocean color band for mapping the spatial extension of turbid freshwater plumes in the coastal ocean as it presents low penetration in the water column and delineates coherent plume shapes (e.g. Aurin et al., 2013; Saldías et al., 2016; Fernández-Nóvoa et al., 2017).

3. Results and discussion

Model results showed a marked seasonality in the direction and spreading of the plumes from the Maipo and Rapel rivers. Low river discharges predominate between November and April, forcing the plumes to spread in the northwest direction. This is coherent with the influence of spring–summer southwest upwelling winds. In June, the plumes from both rivers began to grow, reaching a maximum area in July–August and tending to coalesce. The plumes tend to spread westward around the river mouths, which is due to the weakening of the northward upwelling winds in winter (Fig. 3). This spatial extension, along with the decrease in the plume area during late winter and early spring, is also evidenced in satellite composites of Rrs(645) (Fig. 4). Note that the most substantial seasonal contrasts, with small plumes extending northward in January and the largest plumes in July, agree well with our modeling results (Fig. 4), and are in good agreement with previous observational studies (Saldías et al., 2012, 2016).

The vertical structure and offshore extension of the plumes off Maipo and Rapel river mouths are shown in Figs. 5 and 6. A strong vertical stratification is observed off both rivers (see

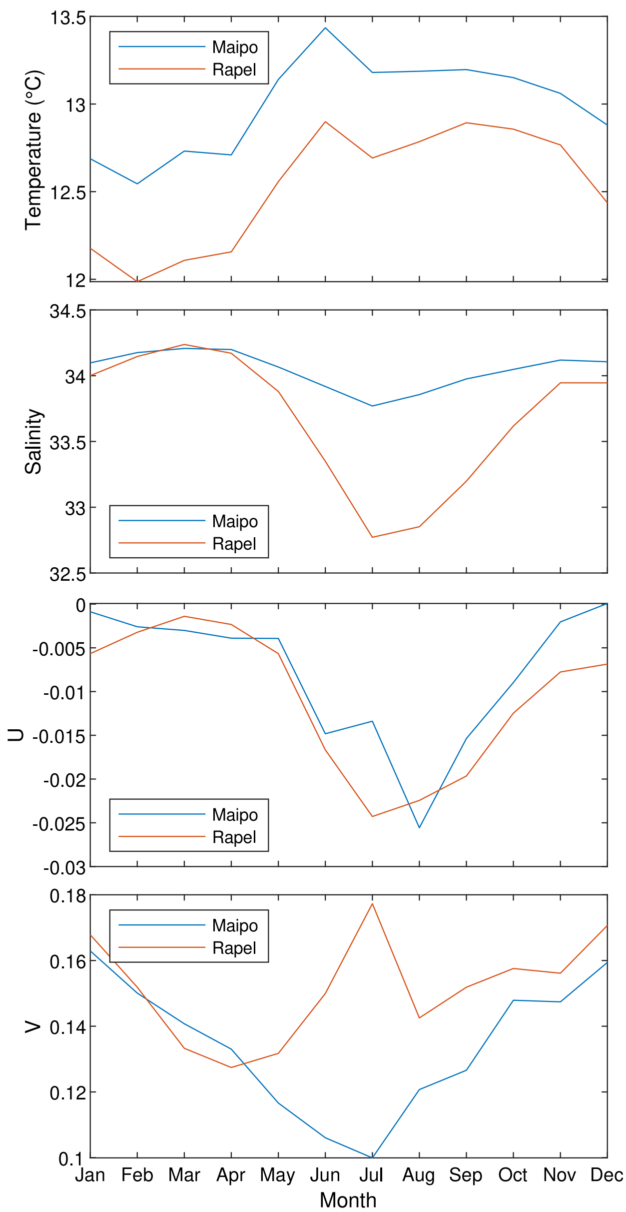

Fig. 7. Seasonal variability of mean (from top to bottom) temperature, salinity and surface zonal velocity (U), and surface meridional velocity (V) off Maipo and Rapel river mouths.

zonal sections in Fig. 3) during July and September. These zones of strong stratification due to the presence of the freshwater plumes can extend up to 10 km offshore (bounded by the isohaline of 34, which is located at 10–15 m depth), in agreement with the description given by Sobarzo et al. (2007). The stratification gets weaker as the freshwater plume is considerably reduced during the rest of the year, extending westward over less than 5 km in Summer (January–March). It is important to clarify that our results do not provide coastal-attached plumes flowing in the downstream direction as the climatological wind forcing did not switch to downwelling conditions (Fig. 2, upper panel). This is a major difference from previous studies off central-southern Chile and it is a consequence of the average persistence of northward wind stress year-round in the study area. Farther south in the coastal region next to Itata and Biobio rivers the seasonal variability of wind stress changes to a predominantly southward component during winter, which forces the plumes to rotate anticyclonically and merge with other plumes in the downstream direction (Saldías et al., 2012).

The period of lowest river discharges in central Chile occurs during summer-fall, coinciding with the strongest winds from the southwest (Fig. 2). This effect of lower river runoff can be observed locally. The river plumes close to the river discharges exhibit lower temperatures and higher salinities from December to April (Fig. 7). On the other hand, the lower momentum flux is observed in the magnitude and direction of current surface velocity U–V components. During winter–spring, relatively higher temperature values are observed, whereas surface salinity is lower, because of higher freshwater discharges. The surface vector components reflect stronger discharges westward, although Rapel river discharge also shows a strong northward component (Fig. 7). This change in plume orientation as a response to the combination of river discharges and upwelling-favorable winds has been described by other authors (Sobarzo et al., 2007; Saldías et al., 2012). Southwesterly winds enhance coastal upwelling, whereas rivers runoff decreases in summer, which also favors coastal upwelling by weakening vertical stratification. Moreover, the summer hours of sunshine add surface buoyancy, which opposes coastal upwelling. During austral winter, downwelling-favorable winds predominate, along with higher freshwater discharges. Thus, river runoff increases, introducing buoyancy and increasing the vertical stratification, inhibiting coastal upwelling (Sobarzo et al., 2007). Sobarzo et al. (2007) pointed out that freshwater discharges determine the seasonal pattern observed in the first 20 m of the water column. At the same time, the higher freshwater discharges in austral winter influence the onset of the coastal upwelling for the coming spring season (Saldías et al., 2016). This seasonal pattern was described by Piñones et al. (2005), concluding that, whereas the river discharge mostly modulates the plume in winter, the influence of wind is more critical during spring–summer. This wind influence exhibits, in turn, a diurnal variation.

In particular, the local influence of Maipo river discharge is consistent with the description of Narváez et al. (2004). They observed vertically and horizontally homogeneous conditions during winter and a strong stratification in summer. Although there is a strong interaction between river plumes and wind-induced upwelling, tides are also important in the evolution of a river plume. Therefore, as MacCready et al. (2009) asserts, a full understanding about mixing and circulation in a river-influenced area must consider the estuary and the shelf, the river discharge, and tide forcing.

A strongly wind-influenced system is the Columbia River region (Fiedler and Laurs, 1990; Hickey et al., 2005; Saldías et al., 2020). Here, similar to the coastal region off central Chile, the surface circulation is mostly wind-driven, under the seasonal fluctuation of the atmospheric forcing (i.e. the plume is oriented according to the predominant winds and, in turn, its size depends on the river discharge). In winter, the plume is directed northward and is colder than the surrounding water (Hickey et al., 1998). In summer, the plume is oriented southward and is warmer than the coastal water (Hickey et al., 2005; Saldías et al., 2016).

A more complex interaction must be studied in detail, as some other factors can affect the plume behavior. For instance, Nikiema et al. (2007) modeled the Amazonas river plume under realistic conditions and found a permanent influence of the coastal current, which can be moderated by the wind. Additionally, tides were shown to influence the horizontal position of the plume front. Future studies are planned to include the tidal forcing in this study area. The dependence of the plume dynamics and structure on changing river runoff characteristics is another aspect worth of being further explored (Fong and Geyer, 2002; Yankovsky et al., 2001), considering the synoptic variability and interplay between river discharges and realistic wind pulses.

CRediT authorship contribution statement

Julio Salcedo-Castro: Project administration, Writing - original draft, Conceptualization, Methodology, Supervision, Funding acquisition. **Gonzalo S. Saldías:** Writing - review & editing. **Freddy Saavedra:** Reviewing and editing. **David Donoso:** Model configuration, Numerical experiments.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was funded by CONICYT FONDECYT, Chile grant 11160309 "Numerical modeling of river plumes in central Chile (32S-34S) and assessment of climate change scenarios". The first author thanks the valuable comments and observations of Ms. Catherine Córdova. GSS thanks the support from FONDECYT, Chile grant 1190805 and the Millennium Nucleus Center for the Study of Multiple Drivers on Marine Socio-Ecological Systems funded by MINECON, Chile NC120028.

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