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NUMERICAL STUDY OF CIRCULATION AND THERMOHALINE STRUCTURE IN THE SÃO SEBASTIÃO CHANNEL

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ABSTRACT. The Princeton Ocean Model (POM) was adapted to São Sebastião Channel (SSC) by nesting three numerical grids so as to study the seasonal changes of its circulation and thermohaline structure. Through monthly average conditions, the numerical model simulated reasonably the typical conditions of spring, summer, autumn and winter, filling the bottom channel with South Atlantic Central Water (SACW) in spring and in summer. In autumn and in winter this mass of water is not found, nevertheless its weaker signs appear in autumn, season in which the stronger signs of Tropical Water (never more than 50%) are found. Northeasterly winds on the Southeast Continental Shelf (SECS) grid are essential so that the SACW enters SSC. The bottom circulation obtained in SSC is essentially to northeast and associated to the intrusion of the SACW forced first by the northeasterly winds in SECS and second by the pressure force always bigger at the south entrance than in the north entrance and always bigger in summer than in winter. The superficial currents are southwestward, weakening in autumn and intensifying towards summer, with its maximum in this season.

Keywords: Numerical modeling, thermohaline structure, currents.

RESUMO. O *Princeton Ocean Model* (POM) foi adaptado ao Canal de São Sebastião (CSS) através do aninhamento de três grades numéricas para estudar as variações sazonais de sua circulação e estrutura termohalina. Em condições médias mensais, o modelo representou razoavelmente bem as condições típicas de primavera, verão, outono e inverno, preenchendo o fundo do CSS com a Água Central do Atlântico Sul (ACAS) na primavera e no verão. No outono e no inverno esta massa de água não se encontra no canal, porém, seus sinais mais fracos são obtidos no outono sendo que nesta estação são encontrados os sinais mais fortes da Água Tropical. Ventos de nordeste na grade da Plataforma Continental Sudeste (PCSE) são imprescindíveis para que a ACAS penetre o Canal de São Sebastião. A circulação de fundo obtida no CSS é basicamente para nordeste e associada à intrusão da ACAS forçada em primeira instância pelo vento de nordeste na PCSE e em um segundo momento pela força do gradiente de pressão, sempre maior na entrada sul do que na entrada norte e sempre maior no verão do que no inverno. A circulação superficial é para sudoeste com relaxamento no outono, intensificando-se em direção ao verão com máximo nesta estação.

Palavras-chave: Modelagem numérica, estrutura termohalina, correntes.

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INTRODUCTION

The POM was created by George L. Mellor and Alan F. Blumberg around 1977 and has been constantly refined and updated in order to include better physical representations and higher numerical strength. A previous description of this tri-dimensional and weather dependant model of costal and estuarine circulation can be found in Blumberg and Mellor (1987).

This model has been applied to several studies, in different coastal regions, such as: the Gulf of Mexico (Blumberg and Mellor, 1985); Delaware Bay, including the estuarine region and the adjoining continental shelf (Galperin and Mellor, 1990a, b); Chesapeake Bay (Blumberg and Goodrich, 1990), and more recently Massachusetts Bay (Blumberg et al., 1993). The results of the model were widely compared to the available data, and the physical reality of each reproduction was well represented in all these studies.

The sigma-coordinate, POM, was configured for the North Atlantic Ocean between 5°N and 50°N as part of data assimilation, model predictability and intercomparison studies (Ezer & Mellor, 2000). The results showed that the use of closed boundaries together with near-boundary buffer zones where temperature and salinity are relaxed towards the observed values gave less realistic flows, weaker recirculation gyres, and less realistic Gulf Stream separation than did open boundary conditions.

The Princeton Ocean Model with generalized coordinate system was used to evaluate the diapycnal mixing, entrainment and bottom boundary layer dynamics in simulations of dense overflows (Ezer, 2005). One of the results is that the bottom Ekman transport associated with the Mellor-Yamada vertical mixing was found to be responsible for 20% of the downslope transport of the bottom plume.

POM was also configured for Mediterranean basin to investigate the outflow caused by the evaporation over that basin which produces a salt water mass that overflows the relatively narrow and shallow Straight of Gibraltar (Jungclaus & Mellor, 2000). The model results confirmed that the area of Cape St. Vincent is a prominent formation area for Mediterranean water eddies.

The South-Southeast region of the Brazilian coast is located between latitude 19° and 34°S. The prevailing coastal orientation is NE-SW, except in the regions located in the south of Cabo Frio (23°S), whose orientation is E-W, and in the south of Cabo de Santa Marta (28°40′S), whose orientation is N-S. These two capes, Cabo Frio and Cabo de Santa Marta, delimit the so-called Southeast Continental Shelf (SECS) (Fig. 1), whose widest part, about 230 km, is located in front of Santos, SP, and the narrowest ones are located in front of Cabo Frio, 50 km, and Cabo de Santa Marta, 70 km. The Southeast Continental Shelf is about 1000 km long. The depth of the shelf break ranges between 120 m and 180 m and the total area is approximately 150,000 km^2 (Zembruscki, 1979).

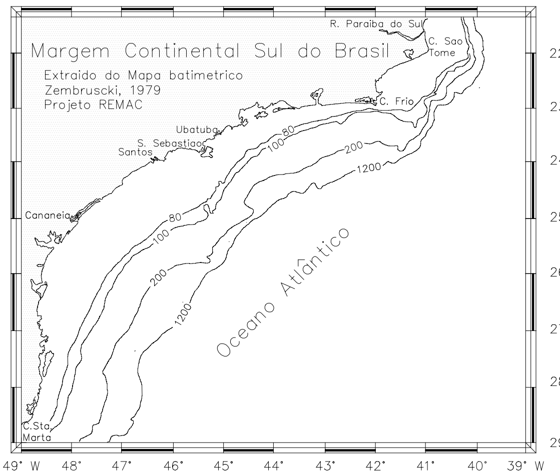

Figure 1 – Southeast Continental Shelf.

The São Sebastião Channel (SSC) and neighboring coastal regions (Fig. 2 and 3) are located in the central area of the Brazilian Southeast Continental Shelf, denominated Embayment of São Paulo (Zembruscki, 1979). It is characterized by the proximity of the Brazil Current, which flows along the continental slope, transporting water-masses from distinct origins: the Tropical Water (TW) and the South Atlantic Central Water (SACW). The influence of the TW predominates in surface layers and in deeper layers the SACW contributes with over 50% of the total volume of the continental shelf to form the water masses in the east of São Sebastião Island (Castro Filho et al., 1987).

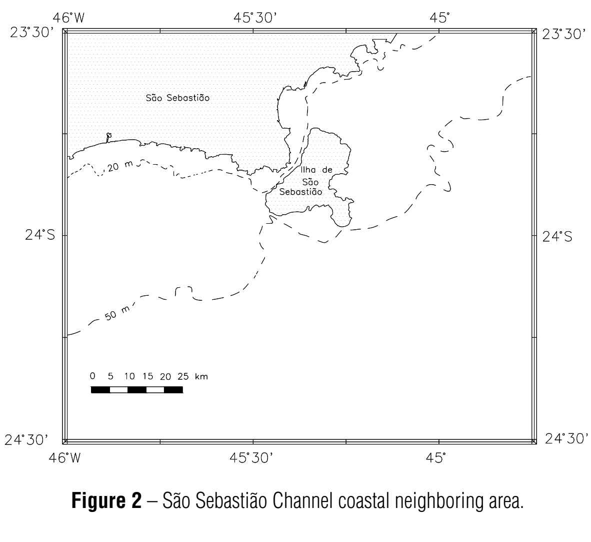

Figure 2 – São Sebastião Channel coastal neighboring area.

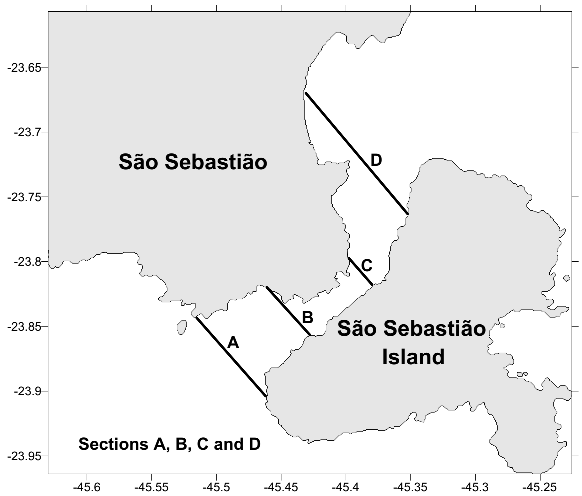

Figure 3 – São Sebastião Channel.

Piterskih et al. (2003) studied the volume and the heat transport by the Brazil Current (BC) south of the studied region and the authors found that the recirculation cells significantly increase the BC transport from -8.8 Sv at $25°$S to about -16.7 Sv. They also found that there is a southward increase in the heat transport by BC from 0.55 pw at $25°$S to about 0.92 pw.

The São Sebastião Channel (SSC) is located on the northeast of the state of São Paulo (SP) between the coastal plains and the São Sebastião Island. The channel is about 22 km long, stretching between latitude $23°41'$ and $23°54'$S. It has a curved shape which varies between NE and N, in relation to the geographical north, in its south and north entrances, respectively. These funnel-like entrances are about 7.2 and 5.6 km wide, the narrowest point, about 1.9 km is located in Ponta Araçá (Fig. 3). The channel deepest region is located on the insular side, where depth ranges from 20 m, in the north and south entrances, to approximately 50 m in the central area of the SSC. The insular side, referred to as main channel, where higher depths are found, presents a topography of ocean bottom with steep side inclinations. It is important to point out the uniqueness of the SSC in the Brazilian coast, not only because of its physical dimensions, but also because it is not an estuarine channel, which makes its physical oceanography quite specific.

Numerical models of wind generated circulation in the Embayment of São Paulo were developed by Harari (1985) and Castro Filho (1990). The latter developed a nest hierarchic and barotropic hydrodynamic model with three grids. The highest resolution one was found in the SSC. It showed that the circulation in the SSC resulting from this model in winter, when the water column is poorly stratified, is a local manifestation of a much bigger spatial scale movement, predominantly wind-generated.

Quasi-synoptic samples were used to survey the region between Ubatuba and the São Sebastião Island, in summer and winter, from 1985 and 1988. The results for the summer of 1985 and the winter of 1986 (Castro Filho et al., 1987) showed distinct patterns for water distribution in two domains (inner and coastal, and outer), separated by a well defined thermal frontal zone in winter.

During the summer the inner domain shows mass stratification in two-layers, generated by the development of seasonal thermocline, which intensifies itself due to the advective effect of SACW during this season. In winter its thermal structure is almost vertically homogeneous. Using methods to analyze the T-S curves, researchers (Castro Filho et al., 1987) have calculated the contribution percentage of TW and SACW to the formation of Coastal Water (CW).

The data analyzed by Silva et al. (2001, 2004a), throughout six hydrographic research cruises collected from February 1994 to March 1995, confirm the homogeneity of SSC waters during winter and suggest the influence of SACW in the south entrance during summer (mainly NE winds) which may, under ideal circumstances, lead to form two layers.

Coelho (1997) analyzed data collected in 16 research cruises in the SSC and 4 in the Continental Shelf neighboring SSI between 1992 and 1993. The author points out the predominance of CW in autumn, winter, and early spring, and the intrusion of SACW in the bottom of the channel in summer and late spring. The SACW flows NE in the bottom, whilst the CW flows NE on the surface.

Leandro (1999) devised the region's climatology, through hydrographic and current meter data, collected in 37 hydrographic research cruises between January 1992 and March 1997, in thirteen stations in the SSC. The author describes the low values for temperature average on the insular side of the south entrance of the channel during spring and summer, and water homogeneity during winter.

The SSC circulation and thermohaline structure have been studied in several works: articles, Master's dissertations and Doctorate's thesis. These studies were developed through out the analysis of hydrographic and current graphic data. Only two presented numeric models of its circulation. As these models show SSC circulation in winter, when the water column is quite homogeneous, they can therefore be classified as barotropic models. The natural sequencing is to show a model depicting the SSC circulation and thermohaline structure during a complete annual cycle, which is possible through a baroclinic model. A question frequently discussed, concerning the region being studied, is the penetration of cold waters through the south entrance of the channel, which has been confirmed in many studies. Would these waters be part of SACW or would they be under its influence? In relation to the two-layer vertical stratification formation in the SSC, is it a result of SACW, or is there an unknown cause?

In an attempt to answer these questions, this study aims to:

- Apply a baroclinic model in the São Sebastião Channel in order to study its circulation and thermohaline structure in seasonal scale;
- Study the origin of cold waters and its penetration mechanisms in the São Sebastião Channel, particularly in the summer;
- Identify the formation and relaxing processes of the two-layer vertical stratification in the area.

METHODOLOGY

To model the São Sebastião Channel, following Castro Filho (1990), the 1997 version of POM was configured for the Southeast Continental Shelf which was forced to obtain boundary conditions in the channel. The grid presents three levels: a large grid of 13,200 m square blocks, stretching from Cabo Frio to Cabo de Santa Marta; a medium grid of 2,640 m square blocks, in the region of the São Sebastião Channel, from Parati (north) to Santos (south); and a small high-resolution grid of 528 m blocks covering the São Sebastião Channel. The larger grid has a total number of points of 2520, the intermediate of 2640, and the small of 2064. Figure 4 shows that these grids present a $51°$ clockwise inclination in relation to the geographic north. This rotation, besides lowering computing time (since it has a lower number of points than a north-south oriented grid involving the same region), presents its v component of current velocity approximately along the coast, consequently, the u component is perpendicular to the coast.

The thermohaline data regarding the shelf are from the Program for Assessment of Sustainable Potential of Living Resources in the Exclusive Economic Zone (REVIZEE) which has a great data bank systematically collected since the International Geophysical Year (1957) along the Brazilian Coast. After careful studies, these data generated the water climatology of the Southeast Continental Shelf with spatial resolution of at least $1°$ in latitude and $1°$ in longitude. The organization of the data basically consists of the following steps: (a) identification and elimination of spurious data through the analysis of the TS diagram; (b) data organization according to sets of observation level (to obtain horizontal sections representing different depths), by sets of straight lines perpendicular to the coast, and by sets of isobaths (considering the local station depth); (c) obtainment of data average and standard deviation for each one of these sub-sets.

Sequentially, and in this study, the data were horizontally interpolated in patterned depths through 'kriging' for grid points in the SECS and in the Inner Continental Shelf (ICS). After that, the data were vertically interpolated through 'cubic spline' and described with sigma coordinate system with 11 levels. These levels have logarithmic distribution on the surface and in the bottom, which allows higher resolution, and linear distribution in the remaining water column.

The thermohaline data used to start the model in the small grid (in the SSC) are from Climatology in the São Sebastião Channel (Leandro, 1999), based on the data from Projects HIDROCASS (Hidrodinâmica do Canal de São Sebastião) and OPISS (Oceanografia da Plataforma Interna de São Sebastião), which have been systematically sampled since 1992, in 40-day intervals, and in 13 stations along the SSC.

Besides the thermohaline data, the model is also forced with data representing monthly averaged heat and salt fluxes, shortwave radiation and wind stress. These data were obtained from COADS (Comprehensive Ocean-Atmospheric Data Set).

The chosen laterally boundary condition for the large grid was the implicit radiative condition form by Orlanski (1976), which is a schema centered in time and advanced in space, along with a technique of relaxation in the region of the grid. This relaxation technique was originally implemented by Martinsen & Engedhal (1987) as an open contour condition, using a linear model of shallow water. The performance evaluation of these contour conditions can be found in Chapman (1985) and Palma & Matano (1998). These conditions were used for the properties sea level and the velocity components parallel to the contours; a non-gradient condition was used for the velocity components perpendicular to the contour. The data generated by the large grid were stored in the contours of the medium grid, interpolated in time and space and, after the experiment, were then stored in the small grid contours, characterizing the active contour condition in inner grids. In this model, the data stored in the inner grid contours were: sea level, current velocity components (either those considered vertical average or those inside each sigma layer), temperature, and salinity.

The thermohaline indexes of TW and SACW do not present significant seasonal variations on the edge of the continental shelf. Therefore, the thermohaline indexes of SACW and TW used in this study to calculate percentages were those used by Coelho (1997), through the analysis of spread T-S diagram from 16 oceanographic cruises in ICS and SSC. These indexes are: SACW

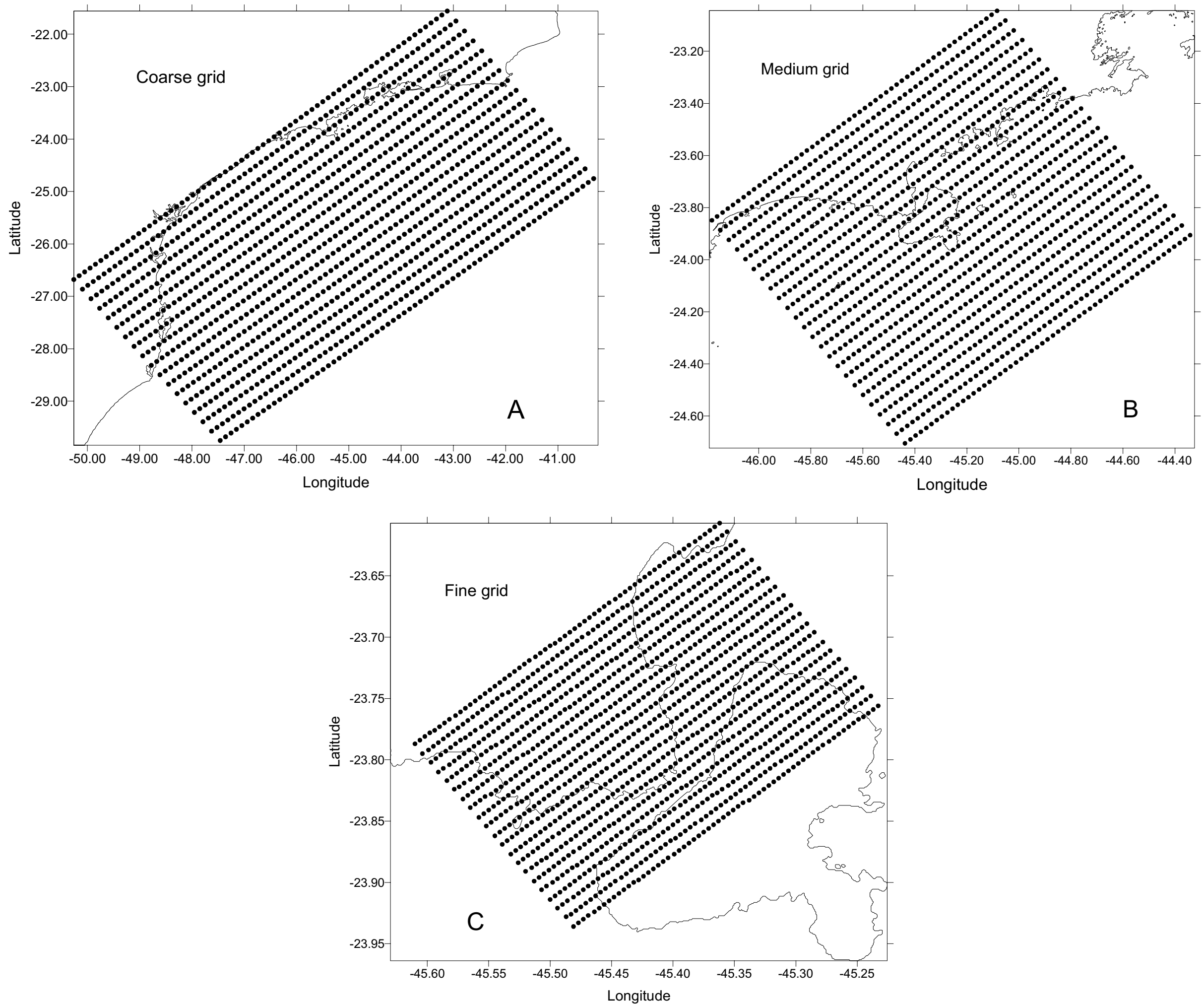

Figure 4 – The coarse grid (A), the medium grid (B) and the fine grid (C).

(13.2°C; 35.27) and TW (24.11°C ; 37.18). The thermohaline index of CW was obtained through spread T-S diagram after each experiment, identifying in the curve the points with higher temperature associated to lower salinity.

In order to better view the transversal and longitudinal data sections were made in the SSC. There are four transversal sections: south (section A), north (section D) and two intermediate (B and C). These sections were set as close as possible to the sections of data collection to better compare the results with previous experiment studies.

Simulations of spring, summer, autumn, and winter were performed using average temperature and salinity data, for each season, monthly average data of heat and salt flow, short wave radiation, and wind stress. Each simulation lasted 30 days. The months of November, February, May, and August were chosen to represent the seasons of spring, summer, autumn, and winter, respectively, when the data resource is monthly average. The simulations were performed prognostically.

RESULTS AND DISCUSSION

The results of the simulations performed in the medium grid throughout the four seasons were previously published and they can be seen in Silva et al., 2004b and the results of the simulation of the thermical structure of São Sebastião Channel during a cold front passage can be seen in Silva et al., 2005.

Spring

Sea level on the west side of SSC ranges from –0.219 m in the north, to –0.232 m in the south. The higher sea level in the north, on the continent side, was also observed in barotropic mode.

The surface currents flow southeast and intensify in the channel strait. Velocities reach 0.45 m/s. In barotropic mode, although the currents flow the same way, they present lower intensity (maximum 0.03 m/s).

Surface temperatures (Fig. 5A) range from $17°$ to $21°$C, the highest ones are found in the north of the channel, on the west side, and the lowest are in the south, also on the west side. The lowest surface temperature at the south entrance of the channel, on the west side, was found in several spring and summer research cruises (Coelho, 1997; Silva et al., 2001) and confirmed by Leandro (1999). Salinity (Fig. 5B) ranges from 35.3 to 35.6. The highest salinities are in the south of the SSC, on the west side, and the lowest in the north, on the west side. In places were the lowest temperatures and the lowest salinities occur, the highest density gradients (Fig. 5C) are found, they range from 24.6 to 25.8 kg/m^3.

Figure 6 shows the vertical temperature profiles in sections A, B, C, and D. Temperature ranges from $19.5°$C, on the surface, to $13.5°$C, in the bottom, in section A. Temperature goes up on the surface and in the bottom from section A to D, according to what is observed in the horizontal distributions of this property. In the same sections, salinity ranges from 35.55, on the surface, to 35.7, in the bottom, in section A. These figures do not change a lot in the other sections. However, it was observed that from section A to section D both superficial and bottom salinities decrease slightly. The highest densities are found in the bottom of section A, next to São Sebastião Island, and the lowest are observed on the surface in all sections.

The analysis of longitudinal profiles of temperature, salinity, and density in the SSC shows that the highest gradients in these areas are observed in the south, where temperatures lower than $15°$C are found in the form of a thermal front. In this same area the highest salinities are found (35.65). Salinity decreases towards the edge of the channel, and increases towards the bottom. The configuration of isopycnals is close to the isothermal, with its maximum in the bottom of the south entrance of the channel (27 kg/m^3) and its minima on the surface (25.2 kg/m^3). The percentage analysis of water masses shows that the CW is found on the surface to profundities of 5m, in the south, and of 15m, in the north. The SACW is found right below, 90% in the bottom, in the south of the SSC. There are no traces of TW in the channel. However, isoline percentage of this water mass with 20% maximum are very much alike salinity field.

Figure 7A, B, C, D presents vertical profiles of components of parallel velocity (v) and perpendicular (u) to the channel. Fig. 7A and 7B show profiles in transversal sections while Fig. 7C and 7D show profiles in sections longitudinal to the channel. In section A, it is possible to notice that on the surface and throughout the west side currents flow southwest, and northeast on the east side; however, southwest surface currents are more intense than those flowing northwest. On the surface, values of –0.30 m/s are obtained for component v. Component u has maximum values of –0.15 m/s and are associated to the maximum positive of component v, which indicates that the waters entering the SSC through the bottom flow from the east. In longitudinal sections, component v (southwest bound) intensifies from the central area of the channel, due to the narrowing which occurs there. In the south and below 10 m deep currents flow northeast, deepening as they progress. Component u shows that in the south of the channel currents flow west.

After 30-day integration using average and historical thermohaline data for spring, wind forcing, heat, salt and short-wave radiation flows from average and historical data for November, surface circulation in the SSC was southwest, while the bottom circulation was northeast. These results are in accordance with Leandro (1999), whose work presents 6 in 11 cruises with surface circulation heading southwest and 3 in 11 cruises with bottom circulation heading northeast; 3 other cruises presented bottom circulation heading northeast in the south half of the area and southwest in the north half area. Fig. 7 shows that in the south half of the area currents intensify southwest, diverging in this area; that in the north half surface currents are less intense southwest, and that the bottom ones, heading northeast, are very close to zero. On the other hand, SSC wind is the same that flows in the shelf, only interpolated for the channel grid.

SSC temperatures in this season range from $14°$C in the bottom to $20°$C on the surface. Leandro (1999), in his climatology for the SSC waters, found average temperatures for this season ranging from $22.5°$C to $18.5°$C, in the south entrance of the channel. Standard deviations are around $1.5°$C for the surface and $3.0°$C for the bottom. According to Coelho (1997) and Leandro (1999), early spring cruises are similar to the winter ones, that is, SSC waters are quite homogeneous in relation to temperature. Late spring cruises are quite similar to the summer ones: low temperatures in the bottom and high temperatures on the surface. This study presents intermediate results, that is, low temperatures in the bottom and not so high temperatures on the surface. Two points must be taken into consideration: the thermohaline data for initializing the model were an average for the spring months and the forcing wind stress was the average for November. Average November winds on the shelf show close configuration and intensity to February average winds, mainly in the north area of the shelf, with winds basically parallel to the coast, which favors cold

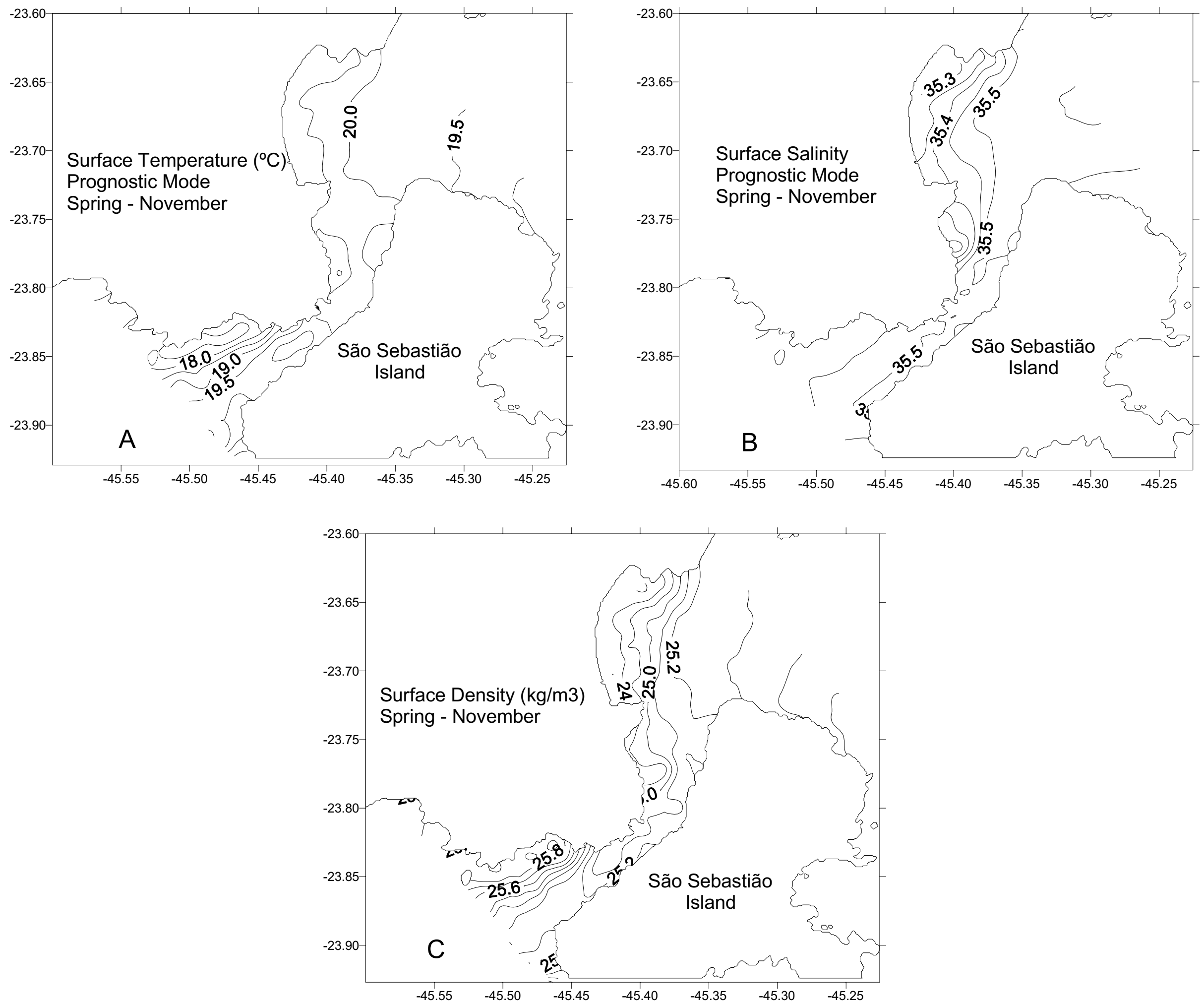

Figure 5 – Surface temperature contour (A), surface salinity contour (B) and surface density contour (C) in the São Sebastião Channel. Spring simulation – November.

water transportation to the coast. A counter example can be observed in the cold front simulation: these winds do not favor cold water intrusion on the coast. The 17°C initial bottom temperature lowers to 14°C, after 30-day integration, which causes cooling on surface waters. In the summer months surface temperatures of 29°C in the SSC have been found. However, with SACW intrusion through the south bottom of the channel, temperatures decrease to around 24°C (Coelho, 1997). As surface temperatures to initialize the model are low, since they are the average for the whole spring, and the forcing wind favors cold water penetration, the final results obtained are as follows: surface temperatures around 20°C and bottom temperatures around 14°C. The bottom thermohaline pictures, obtained in research cruises in the SSC, are the result of wind action on the shelf in immediately previous days. As the average wind on the shelf is northeast, it is natural that the SSC presents low bottom temperatures; this scenario is only modified with the arrival of a cold front in the area. Consequently, the results of a research cruise in the SSC depend on the day it is performed in relation to the passage of the cold front. In the average case simulated by this model, cold waters are present in the bottom of the channel, cooling surface waters.

The results for salinity range from 35.3, on the surface, to 35.7, in the bottom. These results agree with Leandro (1999) if standard deviations are considered, for they are in the average maxima obtained by the author. Coelho (1997), in an early December cruise, obtained 35.6 salinity in the bottom south entrance of the channel. Results in relation to temperature can also be considered. Initial salinity data in the south of the SSC, either in the SECS or in the ICS, range from 35 to 36; besides that, November average wind forces the transportation of more sa-

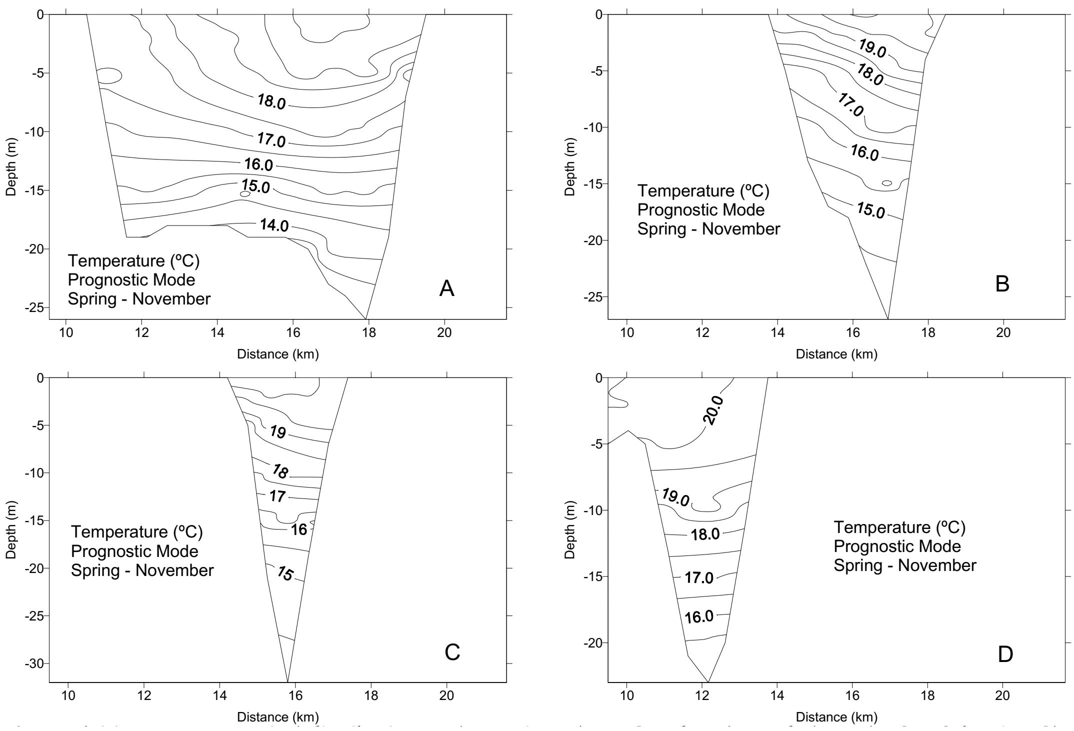

Figure 6 – Temperature vertical distribution at the sections A, B, C and D, located along the São Sebastião Channel. Spring simulation – November.

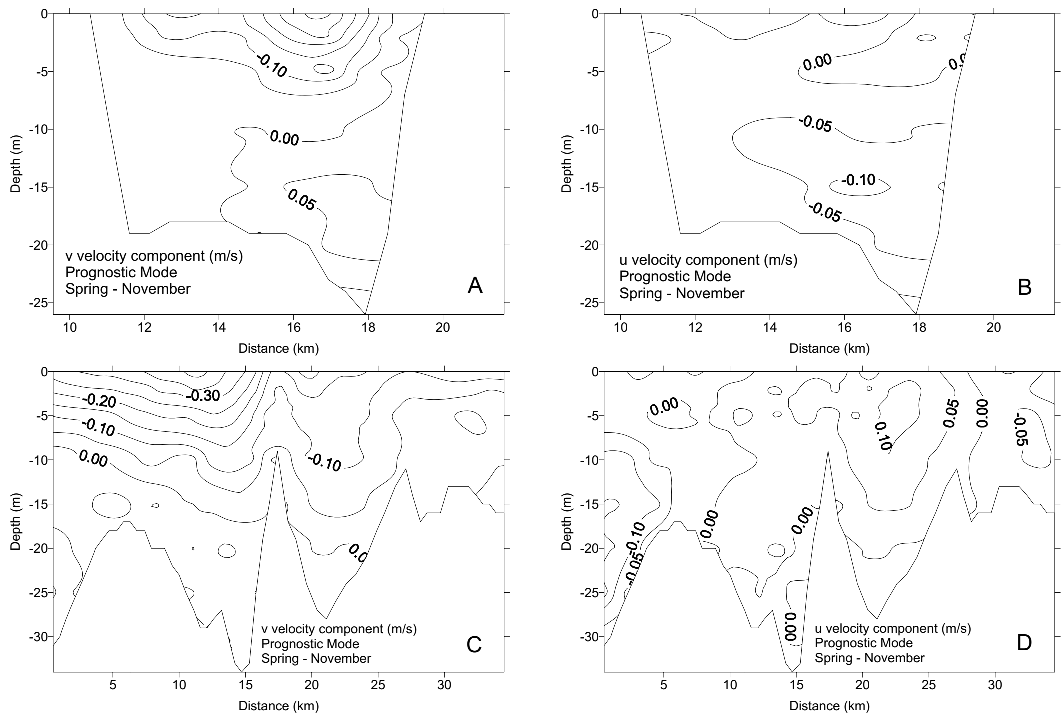

Figure 7 – Along-channel (A) and cross-channel (B) velocity component vertical distributions in the section A. Along-channel (C) and cross-channel (D) velocity component vertical distributions along the São Sebastião Channel. Spring simulation – November.

line waters offshore to the coast, counter-exemplified by the experiment with southwest wind, which presents salinity ranging from 34.2 and 35.0 and temperatures from 24°C and 30°C, after 10-day integration.

November average wind, along with the average thermohaline structure, in spring, on the SECS, makes the SSC to be filled by SACW in the bottom. All spring cruises in which there was SACW intrusion in the SSC, analyzed by Coelho (1997), occurred with northeast wind, similar to the one used as forcing in this model. More specifically, Dec. 93 cruise revealed SACW levels over 88% in the bottom, and 50% at 5m deep. Bottom circulation is northeast and surface circulation is southwest, the latter can be affected by local wind while the first is moved by factors external to the SSC.

Summer

After 30 days integration, the sea level in the SSC, as in spring, resulted in a minimum difference between the extremities, around 0.02 m. The lowest level is in the south, on the west side, –0.30 m. The surface currents flow south, intensifying in the center of the channel. The maximum values are around 0.55 m/s, slightly higher than those found for spring (0.45 m/s).

The analysis of surface horizontal distributions of the properties temperature, salinity and conventional density (sigma-stp) shows that the highest temperature (27°C) is found in the north, on the continental coast, in an area stretching to the center of the channel; from there, temperature lowers to the north, east and south, where the minima of 21°C is found. Salinity ranges from 35.3 and 35.45. The minimum is found in the central area of the channel, on the continental side, at the same point where the highest temperatures were found. The highest salinities are found in the north and south entrances, decreasing towards the center and the shallow areas. Density ranges from 23.0 kg/m^3, in the central area, to 24.5 kg/m^3, in the south and north of the channel. Density behavior is analogous to salinity: higher densities in the north and south entrances, decreasing towards the center and the shallow areas.

Horizontal distribution of water mass percentage shows that on the surface CW is found all over the channel, with the highest levels in the central area, and the lowest in the north and south entrances. The CW percentage, decreasing from the central area of the channel towards its extremities, on the surface, was found by Coelho (1997) in several summer research cruises. SACW percentages complement CW, since TW are very low. Therefore, SACW highest percentages are in the extremities of the channel; however, they do not go beyond 50%. The lowest percentages are found in the central area of the channel.

Along channel distribution of hydrographic properties in the SSC is shown in Fig. 8 A, B, C. In the south of the channel, temperatures (Fig. 8A) range from 23°C, on the surface, to around 12°C, in the bottom. In the north, they range from 22°C, on the surface, to around 19°C, in the bottom. The highest temperatures (24°C) are found on the surface, in the central area. Salinity (Fig. 8B) has its minimum in nucleus form in sub-surface layers (35.4), increasing to extremities and to the bottom of the channel, where a maximum of 35.7 is found. Density (Fig. 8C), which ranges from 23.5 to 27.5 kg/m^3, has its maximum in the bottom of the south entrance of the channel, while its minimum is on the surface, in the central area. Densities higher than 25kg/m^3 deepen towards the north; however, they do not reach that extremity. These figures show the adjustment of properties isolines to the bottom topography, which is characteristic of a sigma coordinate model.

The analysis of water mass percentages in section A shows the presence of CW over 7m, below which SACW is found, the percentage of 90% is found in the bottom of the south area. There are no traces of TW in the channel during this season.

Velocity components v and u are shown in transversal and longitudinal sections (Fig. 9A, B, C, D), observing that the configuration of velocity isolines is similar to the corresponding ones in spring (Fig. 7 A, B, C, D), but intensity is higher at this time of the year. The maximum value of longitudinal component on the surface, indicating movements towards the south, is equal to –0.30 m/s, while the maximum of transversal component u is –0.15 m/s. Like in spring, there are two distinct areas regarding currents: one where currents flow south, comprising the surface and the west part of the channel to the bottom, and another where currents flow north, with lower velocities, 0.10 m/s maximum, comprising the east part of the channel below surface. The nucleus of this current is approximately 15m deep. In the spring simulation it is also at this depth. The longitudinal section (Fig. 9 C, D) shows the intensification of currents in the narrowest part of the channel and the current null zone, which ranges from 5 and 15m deep, from south to north, delimits opposite movement (to the north). Component u positive (to the east) intensifies on the surface in the central area of the channel. Component u negative (to the west) intensifies in the south entrance of the channel. This means that the currents enter the SSC through the north, contour SSI (component u positive), intensify in the center of the channel, and then move to the coast. The same can be observed in spring.

Figure 10 A, B, C shows vertical profiles of water mass per-

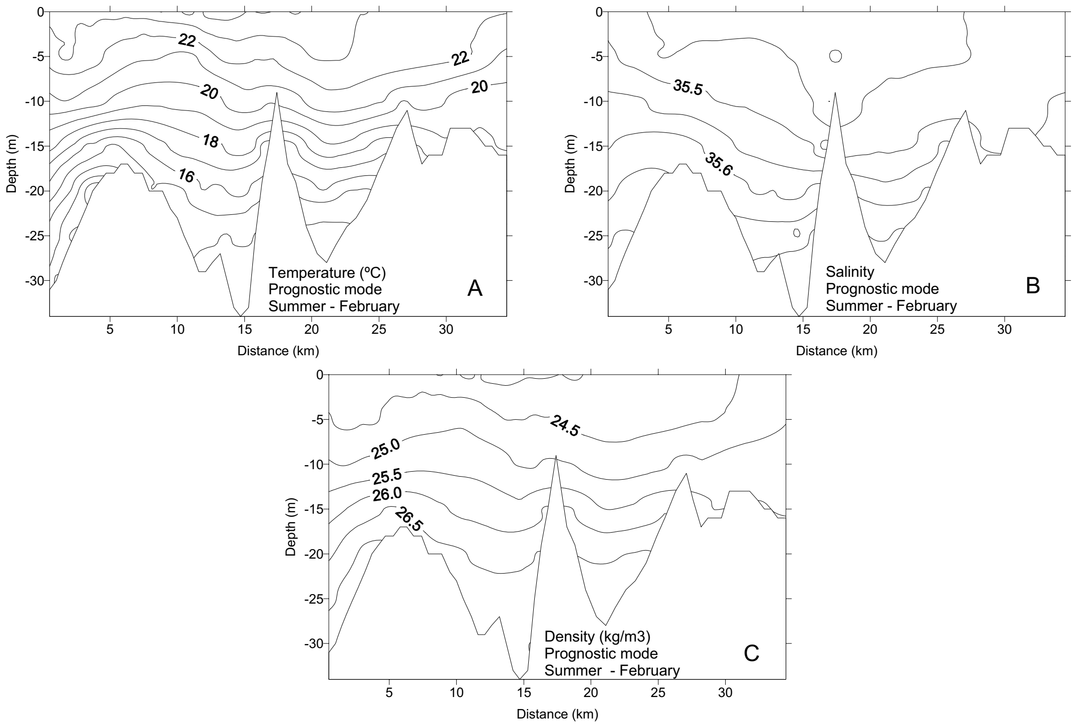

Figure 8 – Temperature (A), salinity (B) and density (C) vertical distributions in a cross-section along the São Sebastião Channel. Summer simulation – February.

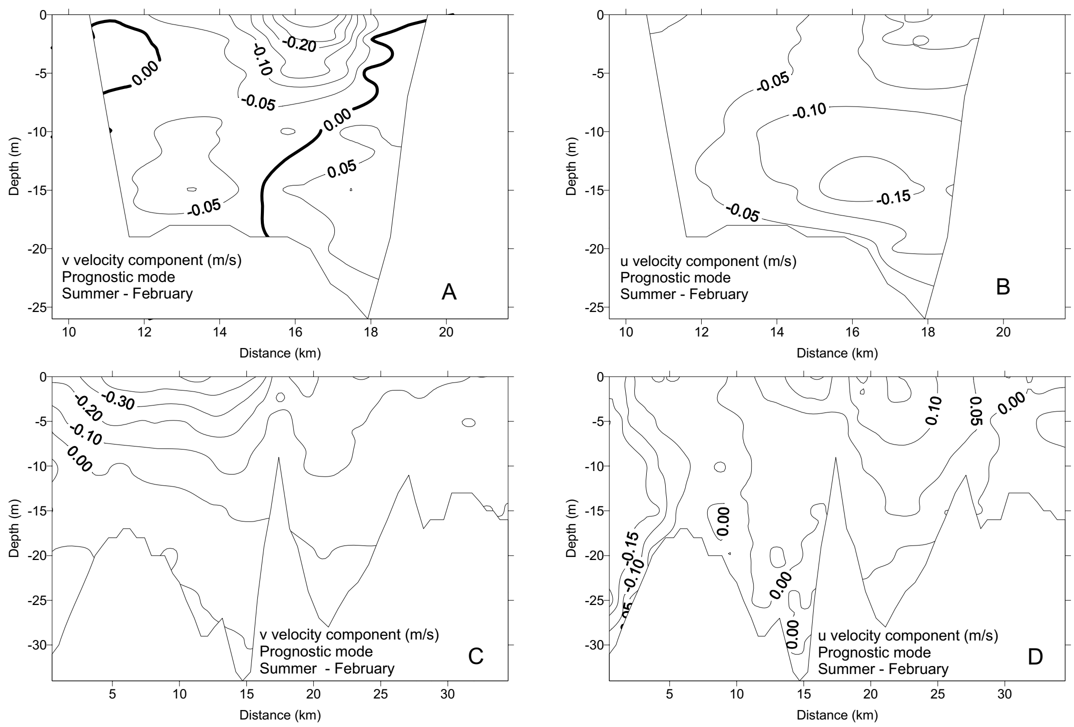

Figure 9 – Normal (A) and parallel (B) velocity component distributions to the section A. Along-channel (C) and cross-channel (D) velocity component vertical distributions along the São Sebastião Channel. Summer simulation – February.

centage in section A, in the SSC. The CW is found from the surface to 7m deep approximately, on the east side, SACW is found in the water mass right below. These two water masses mix on the surface, in the west. The highest TW percentages (20%) are found in the bottom, in the insular side. The highest CW percentages are on the surface (60%), in the east side, while the highest SACW percentages (95%) are found on the same side in the bottom. In these same places, Coelho (1997) found the highest indexes of CW and SACW in a spring cruise (Dec. 93) and summer cruise (Feb. 92). The author also obtained depths from 5m to 7m as a limit between these two water masses in both occasions.

The average circulation obtained in this season is very similar to the one for spring: southwest surface circulation and in the bottom a less intense circulation northeast up to the central area of the channel. In SSC section A, on the west side, currents flow southwest. Leandro (1999) points out 3 in 11 cruises in the SSC with southwest surface currents: two out of the three present northeast bottom currents, the third occurred in a day when a cold front had just left the Southeast Continental Shelf as stated by Fleet Numerical Meteorology and Oceanography Center (FNMOC) data from U.S. Navy. In 5 cruises with northeast surface currents described by the author mentioned before, at least 3 occurred during or very close to the passage of a cold front in the SECS (FNMOC).

SSC temperatures ranged from 12°C in the bottom and 25°C on the surface. This situation would correspond to an average situation for February. Leandro (1999) obtained as average for SSC section A temperatures from 19°C in the bottom and 27°C on the surface. However, standard deviation on the surface was of 2°C and 5°C in the bottom. Therefore, considering the standard deviation, the results presented in this model can be considered in the average. Bearing in mind that cold fronts causes the bottom water to increase at section A and as stated before, regarding circulation, a great deal of summer cruises analyzed by the author occurred next to cold fronts. The March 29, 94 cruise, for example, shows temperature profile in section A (Silva et al., 2001) close to the average obtained by Leandro (1999). On that day a cold front was leaving the Southeast Continental Shelf, which was practically covered by the cold front the previous day (FNMOC). The temperature picture obtained by this numerical model is very similar to the one obtained by Coelho (1997) on the February 21, 92 cruise, when bottom temperature was 14°C and surface temperature was 25°C. There were no fronts on the days preceding this cruise. Some days after that, a cold front arrived in the area.

Salinities in this season ranged from 35.3 on the surface to 35.8 in the bottom. Considering the average field in section A obtained by Leandro (1999): 33.8 (standard deviation = 1.2) on the surface and 35.4 (standard deviation = 0.8) in the bottom, it can be concluded that the salinities generated by the model on the surface are slightly above, even considering standard deviation. Some factors can be listed: 1) salinity initialization data in SECS and ICS generally show higher salinities than those corresponding to SSC, provided that the sources are different; 2) the model is efficient in relation to Ekman model, leading colder and more saline water from deeper areas offshore to more shallow areas on the coast. This is also a consequence of February favoring winds, since in autumn and winter salinities are much lower; 3) the absence of estuary source of discharge in the model can explain also the slightly high salinities, although there are not big rivers in the region.

South Atlantic Central Water is present in the SSC below 10m deep in the average situation created by the model: summer average thermohaline field, February average winds. All summer cruises which had northeast winds a few consecutive days immediately before the cruise analyzed by Coelho (1997), Silva et al. (2001) and Leandro (1999) came to the same conclusion. Fortunately, summer cruises were on days with southwest wind or right after the cold front had left the region under study. February average wind (COADS) favors SACW penetration in the SSC. This wind was replaced by one from another source (Hellerman-Rosenstein wind stress climatology) and the results were similar. November average wind shows close intensity and direction to the February average wind. The November wind is slightly less intense and its direction turned to the coast, mainly in the south area of the shelf; however, in the north area and in the north of SSC, the wind is practically identical to the February one, which explains the Ekman transport equally effective.

Autumn

Sea level differences in the SSC were of 0.01m. The minimum was found in the south, on the side of SSI, and the maximum, as in the other seasons, in the north on the continent side. Sea level is positive all over the channel.

Superficial currents flow generally southwest, intensifying in the central area. Close to the south entrance, currents flow offshore perpendicularly to the coast; maximum values reach 0.35 m/s. In spring and summer, currents flow offshore to the coast, close to the south entrance, and are more intense all over the channel.

Surface temperatures (Fig. 11A) range from 22.8°C (south of the channel on the continent side) to 23.9°C (north of the channel

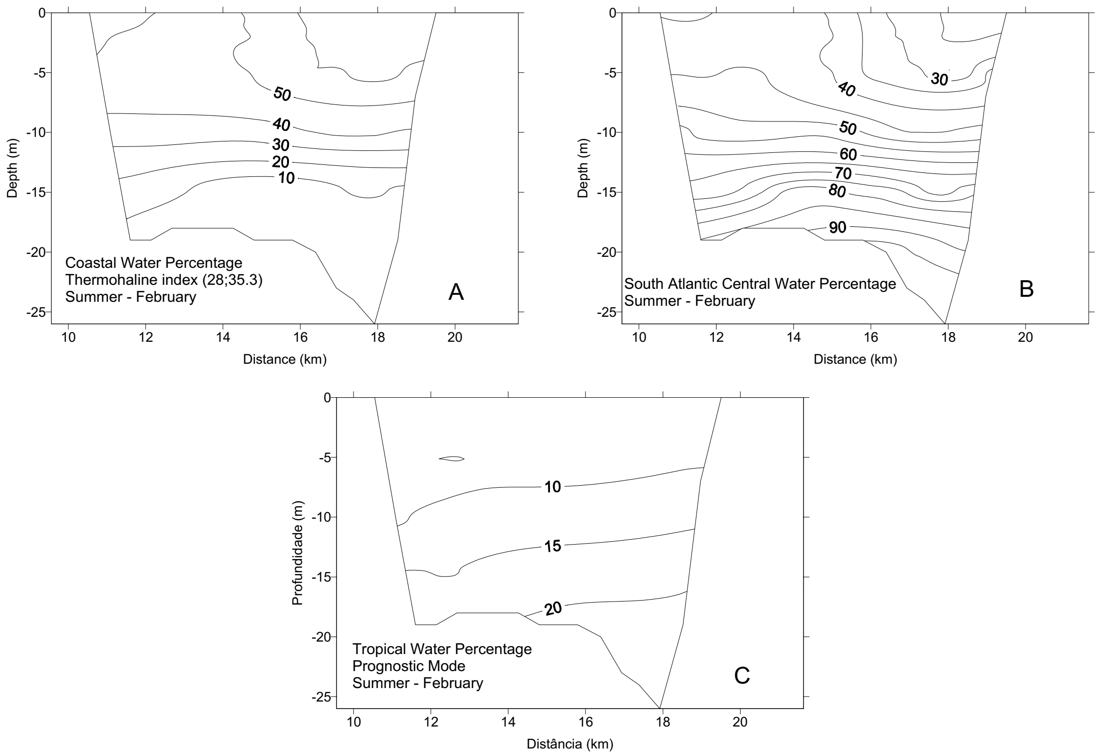

Figure 10 – Coastal Water (A), South Atlantic Central Water (B) and Tropical Water (C) percentage vertical distributions in the section A, located in the inner region of the São Sebastião Channel. Summer simulation – February.

on the continent side). In the other seasons, spring and summer, extremes were also found in these areas. However, in autumn, temperature values are between those of spring and summer. Surface salinity (Fig. 11B) is lower than those for spring and summer, the minimum of 34.6 is found in the north, on the continent side, and the maximum of 35.0 in the south. Density ranges from 23.4 kg/m^3, in the north on the continent side, to 24.0 kg/m^3, in the south on the continent side.

The analysis of vertical profiles of temperature, salinity, and density, respectively, shows that the vertical temperature gradients are much lower than those found for spring and summer. Temperature horizontal gradients on the surface are low, around $23.0°$C, in sections A and B, $23.2°$C in section C, and $23.6°$C in section D. In the bottom, the gradients are also low: $22°$C in the south entrance and 22.4 in the north entrance. The highest vertical gradients are found in the bottom, in the south entrance of the channel. Vertical salinity gradients, in section A, are lower than in the other sections of the channel. When comparing these values with those from other sections, it is possible to notice that salinity is much lower in winter. Salinity decreases on the surface from the south towards the north and increase in the bottom in the same direction. Density vertical profiles show the same features as those for temperature and salinity, the minimum is found in sections A and B on the surface, 23.9 kg/m^3, and the maximum in the bottom of sections B and C, 24.7 kg/m^3.

Figure 12A, B, C shows vertical profiles for temperature, salinity and density, in a section longitudinal to the SSC. This figure shows the homogenization of SSC waters, in relation to summer. The results confirm those obtained in the transversal sections.

Figure 13 A, B, C presents vertical profiles of water mass percentage in the same section. Fig. 13A confirms that the highest CW percentages (80%) are found in the north, and the lowest are found in the deepest area of the channel (45%). SACW percentages show its extremes in the same places; however, they are opposites, that is to say, the minimum is in the north, on the surface, and the maximum in the bottom, in the same place where the minimum of CW is found. The maximum of TW (40%) is found in the bottom, approximately between sections C and D.

Autumn surface currents flow south with much lower intensities than those found for summer and spring. The maximum for component v is –0.16 m/s, in the south entrance of SSC, on the side of SSI. Approximately below 7m deep, the flow is northward

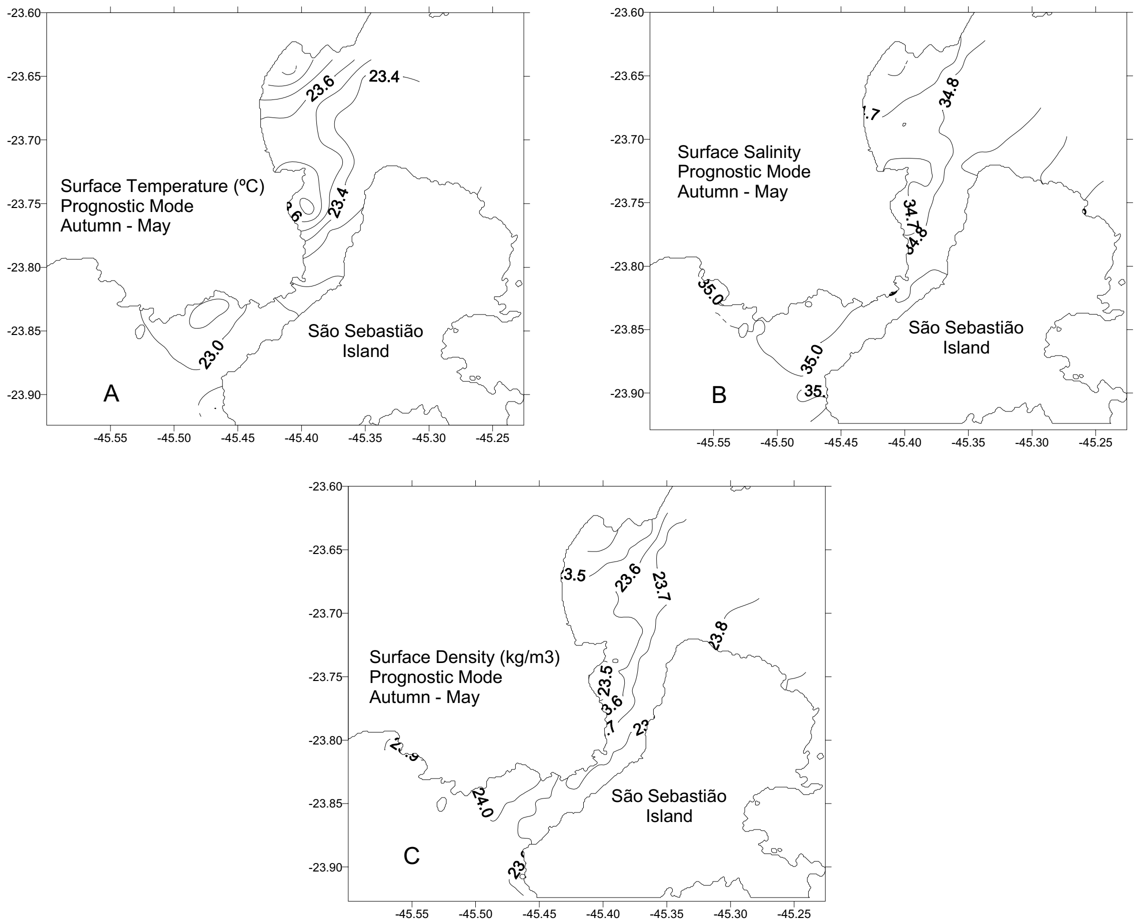

Figure 11 – Surface temperature contour (A), surface salinity contour (B) and surface density contour (C) in the São Sebastião Channel. Autumn simulation – May.

with maximum intensity of 0.06 m/s. Coelho (1997), analyzing data from a research cruise in May 92, obtained a vertical profile for component v in this section quite similar to the one found in this simulation, with surface currents southward, on the side of SSI, and currents flowing north in the other parts of this section, with nucleus 15m deep on the continent side. Water entrance in SSC in section A in this season is not the insular side through the bottom, like in spring and summer. The nucleus of the currents (0.06 m/s) to the north in this section is 10m deep, on the side of the continent; it is not associated to the penetration of colder waters (SACW). Currents in the south of section A of the channel flow northeast, going offshore around SSI. In spring and summer, the currents in this section flow offshore to the coast. This northeast current weakens southwest surface currents in the channel. This component u has a maximum of 0.18 m/s in the south.

The autumn circulation pattern obtained is very different from spring and summer. Currents flow west-east in the south entrance of the channel, while in spring and summer, they flow east-west. Surface currents, which flow north-south, join currents from the west, in the south entrance, and form one single current which contours the SSI. These currents present low intensities: the component longitudinal to the channel shows a maximum of 0.14 m/s in the center of the channel. In the north area currents are even lower. This might be a consequence of weak average winds in May and against the coast, reaching both entrances parallel to the channel. Bottom currents are equally low, flowing south-north. In the experiment without wind forcing in the SSC (Summer), surface currents decrease considerably in relation to the wind presence. Therefore, local winds sources, which were not considered in this model, are important with low surface currents. Local south wind would push currents north and vice-versa. Five out of seven autumn cruises analyzed by Leandro (1999) presented northeast currents (surface and bottom); two presented southwest currents. Among them, the March 94 cruise with northeast winds (FNMOC)

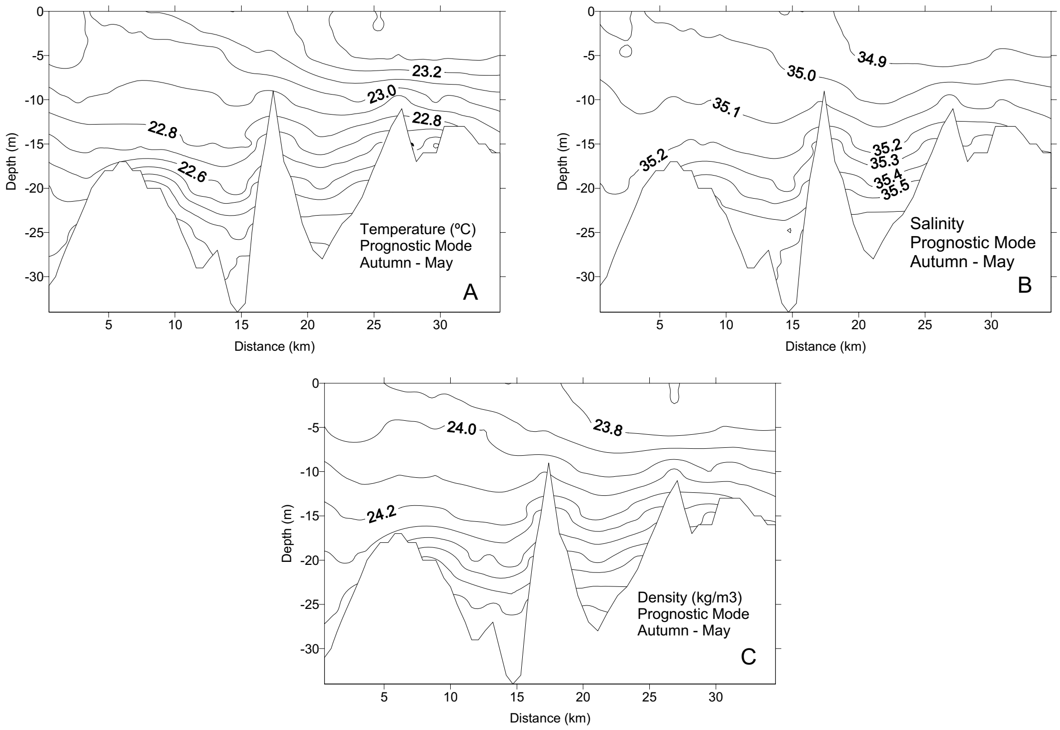

Figure 12 – Temperature (A), salinity (B) and density (C) vertical distributions in a cross-section along the São Sebastião Channel. Autumn simulation – May.

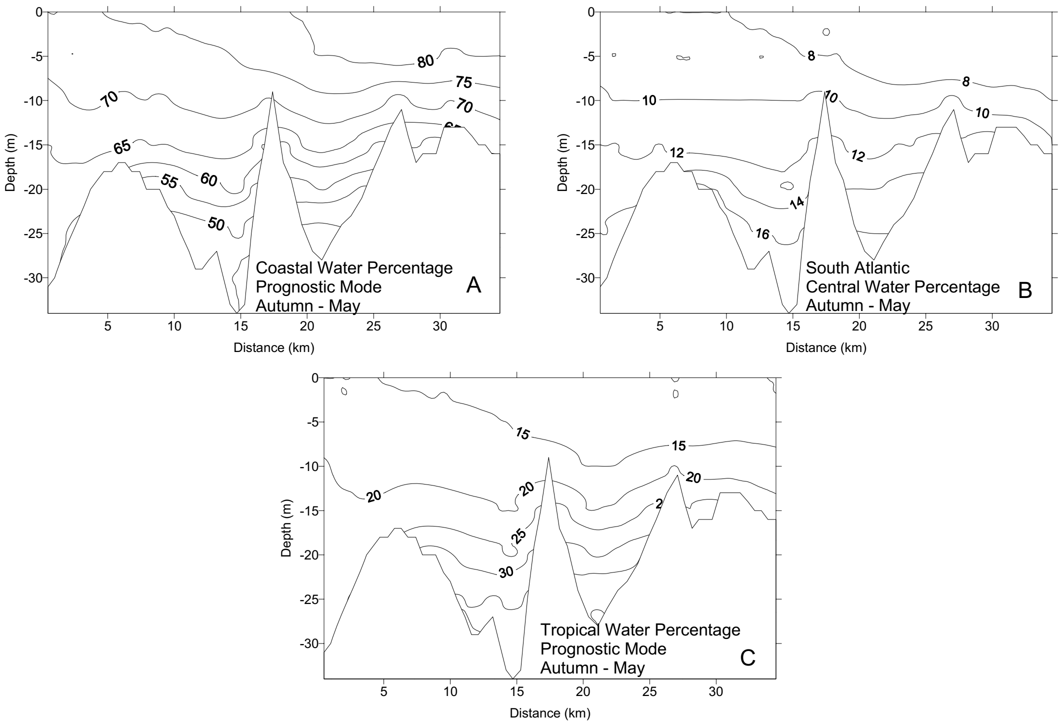

Figure 13 – Coastal Water (A), South Atlantic Central Water (B) and Tropical Water (C) percentage vertical distributions along the São Sebastião Channel. Autumn simulation – May.

would explain current direction, provided that these winds push surface currents southwest. Although the author did not mention, this cruise shows traces of bottom currents to the northeast, in the south entrance of the channel (Silva et al., 2001), which is due to the penetration of colder water through the south entrance of the channel, resulting from Ekman transport, favored by the northeast winds. The currents found in this model for autumn are basically northeast, with a small layer of weak currents southwest, which would be easily changed by overlaying local winds to climatological wind in the shelf.

In this season, temperatures range from 21.9°C (south entrance bottom) to 23.6°C (north entrance surface). Leandro (1999) analyzed seven autumn cruises and obtained in section A an average picture which ranges from 25°C on the surface to 22.6°C in the bottom. The results of this model are appropriate, considering standard deviations. The results for the other sections are also close, even in configuration, to the results obtained in this model.

Salinities range from 34.8 on the surface to 35.6 in the bottom. Leandro (1999) obtained salinities ranging from 33.9 to 35.1, with standard deviation around 0.7 both on the surface and in the bottom, in his statistical study for this season. May 92 and May 93 cruises analyzed by Coelho (1997) are very close to the results obtained in this model. In this season salinities are lower than those obtained in spring and summer, due to the winds that are less intense in May and are not parallel to the coast. Consequently, they do not favor Ekman transport.

Although SACW is present below 60 deep in the four seasons, it does not penetrate SSC in autumn, which demonstrates the importance of northeast winds for the approaching of this coastal water mass. However, it cannot be stated that SACW has never entered SSC in autumn. It will depend on the winds. Autumn average winds do not favor SACW entrance, but there are records of its approximation to the coast in autumn. In an April 12, 2000 cruise in Parque Estadual Marinho da Laje de Santos (Silva, 2001) found SACW levels of 74% at 40m deep.

Winter

The sea level in the SSC, whose amplitude is lower than 0.01m, presents its maximum in the north, on the continent side, and its minimum in the north of SSI. Surface currents flow southwest with maximum values of 0.33 m/s, in the channel strait.

Surface temperature maximum of 22°C is found in the same place were the sea level maximum was found; the minimum of 20.8°C is found in the north and south of SSI. This model found the north of SSC, on the continent side, for temperature maximum in the four seasons and the south area of the channel for the minimum. Surface salinity ranges from 34.6 (associated to temperature maximum) to 35.2 in the south. Density ranges from 24.0 kg/m^3, in the north on the continent side, to 24.8 kg/m^3 in the south.

The highest levels of CW, around 99%, are found in the north, the same area where temperature maxima and salinity minima were found. A CW minimum (55%) is found in the south, associated to temperature minima. SACW and TW maxima are in the south. TW percentages (25%) are higher than SACW (15%).

The vertical temperature profile (Fig. 14) shows a condition of thermal quasihomogeneity, since temperatures range from 19°C in the bottom of section A, to 21.4°C on the surface of section D. In the four sections, temperature amplitude is around 1.2°C. Salinity all over the channel ranges from 34.9, on the surface of sections C and D, to 35.7, in the bottom of section A. Bottom salinities decrease from section A to section D, the same happens to surface salinities. Density, reflecting thermal and haline conditions of the channel, decreases from section A (24.6 kg/m^3) to section D (24.3 kg/m^3); bottom densities decrease from 25.6 kg/m^3 in section A to 24.9 kg/m^3 in section D.

CW levels over 50% are found above 10m deep; below that there is a region of mixing, where none of the three water masses predominate. In the bottom, CW, SACW, and TW maxima are 25%, 40% and 30%, respectively. Coelho (1997) found, in the Aug. 92 cruise, SACW minimum (58%) in the bottom of the south entrance of the channel.

Temperatures (Fig. 15A) increase from south to north, in the section longitudinal to SSC, with 19.2° minimum and 21.2° maximum. Isothermals are concentrically arranged in the form of front, gradient vector indicates that it enters through the south entrance bottom of SSC. This feature is also observed for isohalines and isopycnals; the highest salinity is in the south, in the bottom of the south entrance (35.7) and the lowest on the surface (35.0). Density maximum (25.7 kg/m^3) is in the bottom of the south entrance and minimum (24.4 kg/m^3) on the surface. While the characterization of haline and thermal front, originating from the bottom of the south entrance channel, is also observed in spring and summer, it is not observed in autumn, which suggests that the northeast wind is associated to this feature.

Vertical profiles, in longitudinal section to water mass percentage (Fig. 16A, B, C), show isolines distributed the same as isothermals, isohalines, and isopycnals, which reveals signs of SCAW front in the south bottom of the SSC. Notwithstanding, CW occupies all SSC, except the south bottom entrance, where SCAW

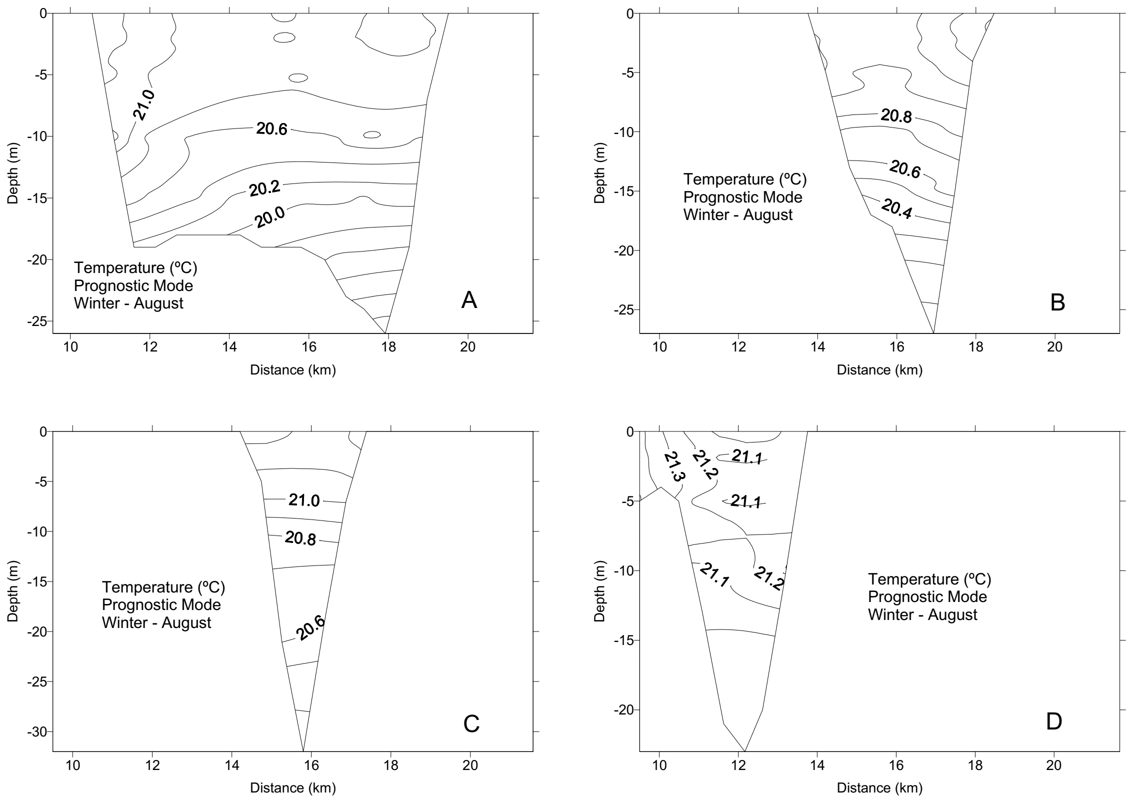

Figure 14 – Temperature vertical distribution at the cross-sections A, B, C and D, located along the São Sebastião Channel. Winter simulation – August.

percentage is 40% and TW 35%.

The analysis of vertical profiles of parallel (v) and perpendicular (u) velocity components demonstrates that component v shows surface currents flowing south all over the channel (0.30 m/s maximum), inverting flow below 10m deep (0.10 m/s maximum). Component u demonstrates that, in section A in the bottom of the channel, on the side of SSI, currents flow offshore to the coast, which indicates that this place is the entrance to water external to the channel. This feature was also found in spring and summer; however, it was not found in autumn.

In this season circulation is identical to summer and spring, with lower current intensities. Surface currents flow southwest, but below 10m deep they flow northeast. Leandro (1999) points out seven out of eight cruises with bottom circulation flowing northeast. All eight cruises present northeast surface circulation; however, August cruises in the same study show very low surface currents (some less than 0.10 m/s all over the channel). Average wind in the shelf generates weak southwest surface currents and the local winds can invert current direction.

Temperatures in the SSC range from $19.0°$C to $21.2°$C. In the northern extremity of the channel they range from $20.9°$C to $21.5°$C. The temperature average profile found by Leandro (1999) indicates temperatures that range from $20.5°$C to $20.7°$C, with standard deviations of about $1.4°$C. Although the results obtained in this model are contained in the average obtained by the author, it must be pointed out that the temperature profiles in July cruises are the ones that show the lowest gradients, sometimes the same temperature along the 22 km, from surface to bottom, in the SSC. June and August cruises show some stratification (Coelho, 1997), such as the August 92 cruise.

Salinities in the SSC range from 34.8 to 35.7. This stratification level was obtained by Coelho (1997) in an August 92 cruise, with lower salinities, however. The average salinity field found by Leandro (1999) in this season ranges from 32.6 to 33.3, with standard deviations of 1.6 on the surface and 1.0 in the bottom. What happens to salinity is the same that happens to temperature in winter months: low gradients in June and August and practically no stratification in July. Salinities vary a lot in winter in the SSC; values close to 30.0 have already been found; as well as values over 35.2, such as the June 93 cruise (Coelho, 1997). SACW was not identified in the SSC for the average conditions established in this model. However, its percentage is higher than in autumn.

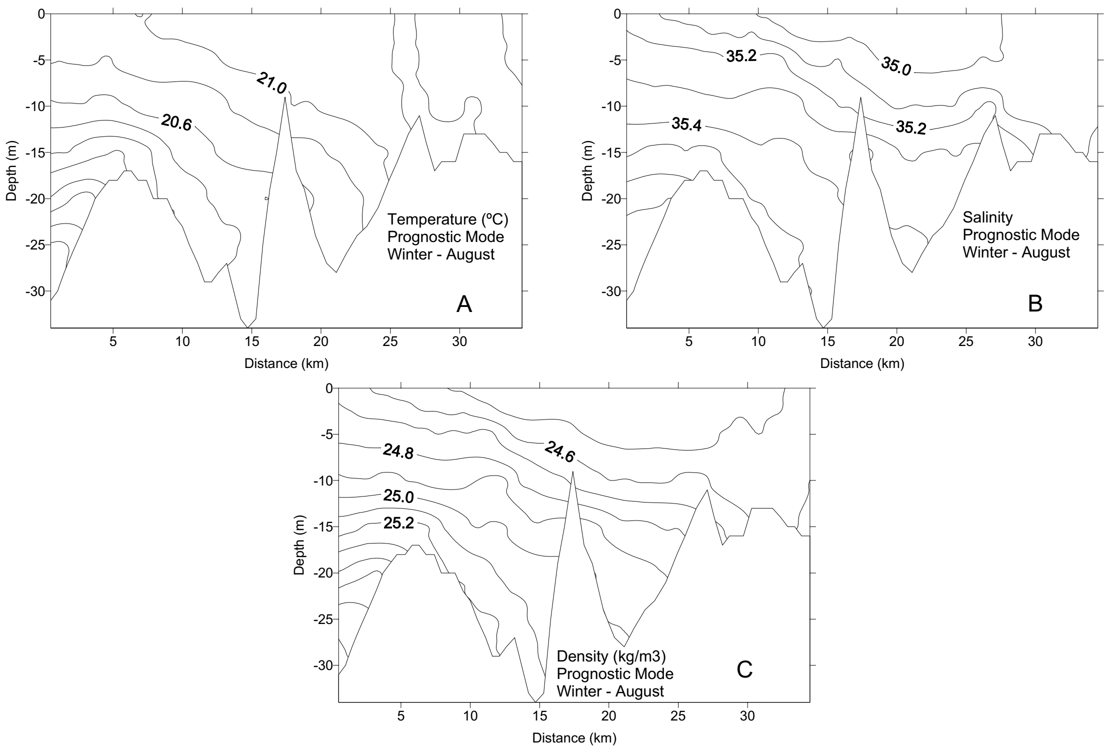

Figure 15 – Temperature (A), salinity (B) and density (C) vertical distributions in a cross-section along the São Sebastião Channel. Winter simulation – August.

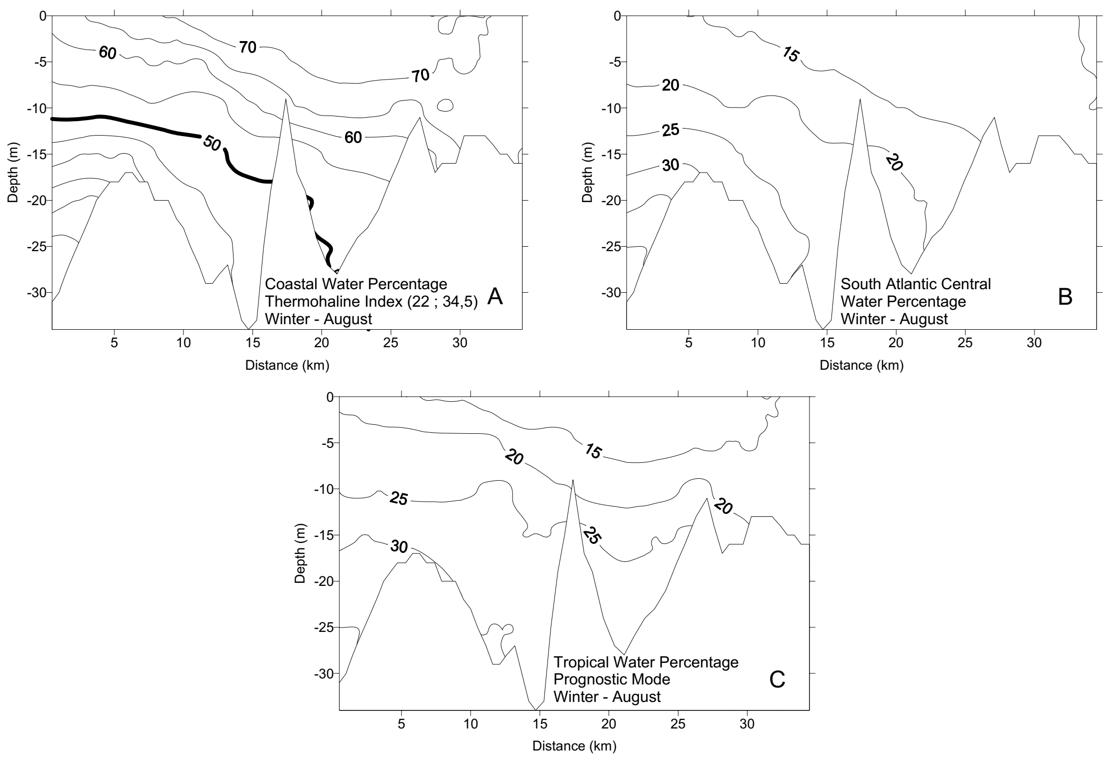

Figure 16 – Coastal Water (A), South Atlantic Central Water (B) and Tropical Water (C) percentage vertical distributions along the São Sebastião Channel. Winter simulation – August.

WHICH FORCE WOULD EFFECTIVELY PUSH SACW INTO THE CHANNEL?

To understand this process better, two force balances were analyzed in two sites on the coast: one in the north and another in the south of the SSC, in the three areas and two seasons: summer and winter. In the summer, it is noticeable that in the SECS, either perpendicular to the coast or along it, there is equilibrium between Coriolis force and pressure gradient force. In ICS, although there is equilibrium between these two forces, the wind has relative importance, especially along the coast. It is also noticeable that in the south of SSC pressure gradient force is much more intense than in the north in the balance perpendicular to the coast. In the SSC grid, in the south, the balance perpendicular to the coast is between the pressure gradient force and the advective and diffusive forces. In winter the same results occur in SECS and ICS, except that the force due to density gradients is more intense in the summer. In the SSC grid, with some differences, there is also the main equilibrium between the pressure gradient force and the advective and diffusive forces, however, they are much less intense than in the summer, they are also more intense in the south, both in summer and in winter.

CONCLUSIONS

The greater evidence that this model is reasonably calibrated is the results obtained from the analysis of the February 21, 92 cruise in the São Sebastião Channel. After 20 consecutive days with northeast winds over the SECS, SACW was observed filling the channel from south to north below 5m deep. The February winds, according to COADS, are very close to the winds on Feb. 21, 92; on that day the winds practically aligned with the coast. It can be concluded that SACW is present, in average, in the bottom of SSC in February. The November average winds are also very close to the February winds, which places SACW in the bottom of the channel in November either, with lower percentages, however. There was no trace of SACW either in May or in August. There is more evidence of SACW in winter than in autumn due to the fact that the winds in August are from northeast, but less intense than the February ones, and even less intense in the SECS south region. Autumn (May) was the season which brought TW closer to the coast. The model confirms the bottom south entrance as the SACW preferred entrance. The pressure gradient force, with the contributions of density gradients, forces this water mass into the channel. This situation is more intense in the summer than in winter, and more intense in the south than in the north of the channel.

The SSC circulation model with surface currents flowing southwest and bottom currents northeast reaches its maximum in summer, weakens in autumn, and intensifies in spring, reaching its maximum again in summer. This mechanism is clearly associated to the SACW penetration in the SSC, which has its maximum in summer, is absent in autumn, returns in spring, reaching its maximum again in summer. A natural sequencing for this study would adopt monthly initialization thermohaline fields, not seasonal ones, as it would also be interesting to work with data from the past ten years, so that more recent trends could be taken into consideration.

Despite low surface salinities in the SSC were not obtained, because they are not present in the initial fields, mainly in relation to ICS, remote estuary discharge sources must be considered in future studies. The southwest surface currents and the surface layer thermohaline characteristics in winter and autumn would have been better simulated with the presence of these two sources.

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