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Summer/winter stratification variability in the central part of the South Brazil Bight

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ABSTRACT

Analysis of the hydrographic data collected during seven consecutive high resolution summer/winter cruises in the central part of the South Brazil Bight off the coastal city of Ubatuba confirmed an observable summer/winter stratification variability of the shelf waters. The maximum bulk stratification occurred at mean distances of 85.6 km and 39.1 km from the coast in the austral winter and summer cruises, respectively. Estimates of the equivalent mixing power of the physical processes that increase or decrease the stratification in the inner and middle shelves showed that both shelf regions would be vertically well mixed were it not for buoyancy advection. In the inner shelf, buoyancy advection was associated with the along-shelf transport of low salinity waters originating from river runoff. In the middle shelf, buoyancy advection was due to the oceanic South Atlantic Central Water intrusions toward the coast.

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1. Introduction

Subtropical continental shelf waters usually exhibit a strong annual stratification signal. Maxima occur during summer (high stratification) and winter (low stratification). This finding is particularly noticeable on medium-width and wide shelves, including the South Atlantic Bight (Atkinson et al., 1983), the Bering Sea Shelf (Coachman, 1986), the Georges Bank (Bisagni, 1992) and the Patagonian Shelf (Rivas and Piola, 2002). Stratification is increased by surface heating and salinity depletion due to fresh water injection (river runoff and rain) and decreased by surface cooling, salinity increase due to evaporation, and vertical mixing caused by surface and bottom stresses (Atkinson and Blanton, 1986). Buoyancy advection from oceanic waters is another mechanism that may be important either for increasing or decreasing stratification.

According to the classification of Loder et al. (1998), the South Brazil Bight (SBB) is a wide shelf with a western boundary current on the shelf edge. Bound by two Capes, Cabo Frio (23°S) and Cabo de Santa Marta (28°40'S), the SBB is located on the southeast coast of Brazil (Fig. 1). Due to its crescent moon shape, the shelf width varies between 50–60 km in the northern and southern reaches and 200–230 km in the central part. The shelf-break depth varies between 150 and 180 m. The region receives relatively small contributions of fresh water locally from the land due to the absence of large estuarine systems.

The shelf-edge western boundary current off the SBB is the southward flowing Brazil Current (BC). This current mostly flows along the continental slope, although part of its transport takes place on the continental shelf, near the shelf break (Silveira et al., 2000). The general hydrography of the SBB was described by Emilsson (1961), who defined the warm ($T > 20$ °C; T is temperature) and salty ($S > 36$; S is salinity) water carried along the shelf break by the BC in the upper mixing-layer as Tropical Water (TW). He also noted the importance of subsurface intrusions toward the coast by the upper part of the South Atlantic Central Water (SACW), which has salinities between 35 and 36, temperatures below 20 °C and flows below the TW within the BC pycnocline. SACW intrusions toward the coast are particularly noticeable off Cabo Frio, where coastal upwelling events are frequent, especially during summer (Mascarenhas et al., 1971), and sustain the local shelf ecosystems (Valentin et al., 1987). The Coastal Water (CW), a result of mixing among the TW, SACW and the low-salinity river-runoff water present near the coast, is the third water mass occupying the SBB (Castro and Miranda, 1998).

During winter, there are equator-ward along-shelf intrusions into the SBB by waters with relatively low temperatures and salinities that originate south of the SBB (Campos et al., 1996; Stevenson et al., 1998; Lentini et al., 2001; Moller et al., 2008). Piola et al. (2000, 2005) have shown that these cold waters, which define a surface subtropical front farther south, usually reach down to 28°S (near the southern part of the SBB) during winter and down to 32°S during summer. However, during severe winter wind anomalies they can reach lower latitudes within the SBB.

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Miranda and Katsuragawa (1991) found significant along-shelf differences in the SBB stratification, taking the city of Santos (Fig. 1) as a reference coastal position for a subsurface cross-shelf front that separated regions of higher and lower stratifications that were located northward and southward of the front, respectively.

The objectives of this paper are to qualitatively and quantitatively analyze the water masses that occupy the central part of the SBB northward from Santos and off Ubatuba city during winter and summer and to identify the mechanisms that cause the observed summer/winter stratification variability. The organization of the paper is as follows: Section 2 describes the data set and methods; Section 3 presents the results of the analysis; Section 4 introduces a discussion of the physical mechanisms; and Section 5 contains the main conclusions of the paper.

2. Data and methods

The hydrographic data set for this analysis was collected along five or six sections across the shelf (Fig. 1) during seven consecutive austral summer/winter cruises aboard the R/V Prof. W. Besnard (six cruises) and the R/V Almirante Saldanha (one cruise). The austral summer/winter cruises took place in December/July, starting in December 1985 and ending in December 1988. The cruise duration was 5.9 days on average, depending on the number of sections and stations (Table 1). Sections were labeled A, B, C, etc., from south to north (Fig. 1).

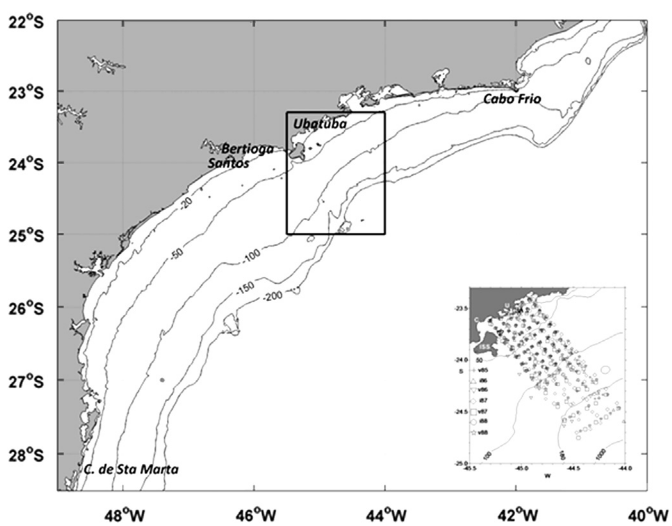

Fig. 1. South Brazil Bight with topography in meters. The insert shows the hydrographic station positions for the 7 seasonal cruises.

Table 1
Duration, number of stations and number of sections for each of the seven hydrographic cruises.

Research vessel	Period (dd/mm/yyyy)	Number of stations/number of sections
Prof. Besnard	11–14/12/85	64/6
Prof. Besnard	20–24/07/86	70/6
Prof. Besnard	11–19/12/86	61/6
Prof. Besnard	09–14/07/87	72/6
Alm. Saldanha	11–16/12/87	60/5
Prof. Besnard	06–12/07/88	70/5
Prof. Besnard	15–18/12/88	59/5

Seasonal T and S variabilities off Ubatuba are the most energetic, although there are also subinertial changes due to synoptic wind variabilities (Castro, 1996). The T and S data sampled during the cruises were considered synoptic when comparing the cruise duration with the synoptic wind time scale in the region (6–12 days; Castro, 1996). The data collected in each section were synoptic because all of the sections were sampled in less than 2 days.

Comparing the air temperature and atmospheric precipitation in the 30 days before the hydrographic cruises with long-term averages (30 years) for those variables, Castro (1996) found that the anomalies were usually less than one standard deviation, with the exception of the July 1986 and December 1986 cruises when the precipitation anomalies were almost twice the standard deviation, indicating heavy rains in the 30 days before the cruises. The salinity values were expressed without units because they were estimated using the definition presented by UNESCO (1978).

The data from these historical cruises were chosen for analysis due to two factors: (i) the high-resolution horizontal sampling, with average distances between sections and between stations of 9 km; and (ii) the seasonal sampling strategy, with cruises taking place in consecutive summers and winters over several years. The surface meteorological data and the sea surface temperature data collected at the Oceanographic Institute's Ubatuba Coastal Station (23°30'S; 045°07'W) were also used. To focus the study on the continental shelf, only stations located inshore of the 180-m isobath were used in the T and S analyses.

The bulk stratification ($\Delta\sigma_t$) was calculated by subtracting the surface water density (σ_t) from the near-bottom value of that variable (Atkinson et al., 1983). In the volumetric T–S analysis, the total horizontal area for each cruise was estimated using the northern and southern sections and the shallowest and deepest stations in each section. The mean horizontal area representative of each station was found by dividing the total horizontal area by the number of stations in each particular cruise; this mean varied between 64 km^{2}and 115 km^2, depending in large part on the number of sections in each cruise.

The buoyancy fluxes B [W m^{-3}] were estimated using the equation presented by Atkinson and Blanton (1986):

$$B = \frac{g\alpha_v(Q_s - LE)}{c_p} - g\beta(E-P)S + gF \quad (1)$$

where g [m s^{-2}] is the acceleration due to gravity, α_V [K^{-1}] is the thermal expansion coefficient, Q_S [W m^{-2}] is the heat flux due to radiation and conduction processes at the ocean–atmosphere interface ($Q_S > 0$ means that the sea surface is gaining heat), L [J kg^{-1}] is the latent heat of evaporation, E [kg m^{-2} s^{-1}] is the evaporation rate, c_p [J kg^{-1} K^{-1}] is the specific heat at constant pressure, β is the saline contraction coefficient, P [kg m^{-2} s^{-1}] is the precipitation rate, S is the salinity, and F [kg m^{-2} s^{-1}] is the approximate buoyancy generation by the low-salinity water flux due to the estuarine discharges. If $B > 0$, then the vertical stratification increases; $B < 0$ indicates a decrease in the vertical stratification. $Q_S - LE$ was estimated considering that the advective heat flux is small because the sea water's response to atmospheric heat forcing is rapid due to the small thickness of the water column (Pingree and Griffiths, 1977). Eq. (1) was applied to the inner and middle shelves to estimate the water response to the different physical mechanisms in changing the bulk stratification from summer to winter.

The Figs. 2–4 show the data values plotted against the distance from the coast. Fourth-order polynomials were adjusted to the data values using least squares. The envelopes containing the polynomials fitted to the data set show values of ± 2 standard deviations.

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