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PHYSICAL SCIENCES

Upwelling-driven variation of sound speed profile in a Brazilian bay monitored by a coastal acquisition system

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Abstract: Sound speed profiles in the ocean are determined by seawater properties, where horizontal variability of thermal stratification modulates sonar detection distance. This work assesses the impacts of upwelling dynamics on sound speed profile in enclosed coastal areas by means of temperature observations acquired with a low-cost platform in Anjos Cove, Cabo Frio, Brazil. The Integrated Acquisition System for Research in Acoustics (IARA) consists of a customized 10-meter-long chain of smart temperature sensors (±0.1°C accuracy) mounted in an anchored vertical cable and an echo sounder for tide level measurements. From 2021 to 2023 a number of intrusion events of the cold South Atlantic Central Water (SACW) took place along the Cabo Frio continental shelf, some of which were recorded in the inner region of the Anjos Cove by IARA. Sound speed profiles computed by applying TEOS-10 standards indicate that the sound propagation within Anjos Cove varies often, i.e., several orders of magnitude, under the influence of SACW intrusion events. The phenomenon reflects information from deeper waters on a coastal scale, even at small depths.

Key words: coastal monitoring, sensor array, upwelling, thermal stratification, sound speed profile.

INTRODUCTION

The behavior of acoustic waves in the ocean is regulated by sound speed, which varies following seawater density, i.e., salinity, temperature, and hydrostatic pressure (depth). Since the ocean is far from homogeneous, regional acoustic propagation properties are ultimately determined by local dynamics and the state of seawater. For instance, in contrast with the strongly stratified surface waters, where temperature stratification modulates sound speed, deep water acoustic propagation is mainly determined by pressure. On the other hand, seawater density is much more sensitive to changes in temperature and salinity fields in shallow waters. Enclosed bays are subjected to local oceanographic regimes whose dynamical processes can rapidly change seawater properties, affecting sound speed profiles in a very short span of time.

Coastal upwelling systems have long been recognized as relevant mechanisms causing temporary yet intense anomalies in seawater properties over continental margins distributed worldwide (Smith 1968, Hidaka 1972, Miranda 1982). The phenomenon is characterized by the rise of deep and cold waters onto coastal regions due to either coastal divergence caused by zonal and meridional wind stresses or current-driven dynamics, such as the horizontal variation of the Brazil Current (BC) core flowing southward along the Brazilian continental slope, often closer to the continental shelf break (Castelao & Barth 2006, Silveira et al. 2000, 2004). These waters carry nutrients from deep layers to the euphotic zone, thus enhancing primary production (Coelho-Souza et al. 2013, Calil et al. 2021).

The coastal margins of southeastern Brazil sustain a well-known quasi-seasonal upwelling system located between Cabo de São Tomé (CST, ~22°S) and Cabo Frio (CF, ~23°S) (Signorini 1978, Castro & Miranda 1998). Within the CF oceanographic domain, the region of Arraial do Cabo is the most investigated site concerning the upwelling system dynamics and variability (Castro et al, 2008, Coelho-Souza et al. 2012, Dottori & Castro 2009, 2018, Fontes & Castro 2017) primarily due to local economic relevance.

The combination of wind- and current-driven forcing processes allows for the nutrient-rich South Atlantic Central Water (SACW) carried southward by the BC to penetrate the continental shelf adjacent to Arraial do Cabo eventually surfacing in its innermost extent (Stramma & England 1999, Silveira et al. 2000, 2004). In contrast, the outer shelf is mostly dominated by BC dynamics and to a lesser degree by atmospheric forcing (Castro et al. 2008). The inner shelf circulation is believed to be driven by the synoptic wind regime (Castro 2014), which responds to both the large-scale South Atlantic Subtropical High (SASH) and the passage of mesoscale cold front systems (Castro & Miranda 1998).

In spite of the multiple study efforts, smaller-scale features of the upwelling system dynamics are yet to be fully uncovered. For instance, although SACW surfacing may be easily observed with remote sensing and cold-water intrusion events can be recorded by moorings in deeper regions, monitoring the column stratification may still prove challenging in shallow waters. In that fashion, taken from a strategical perspective, one of the remaining questions in coastal oceanography rovers around the impact of rapid changes on physical properties such as sound speed, and how to monitor these changes in semi-restrict environments in real time.

The coverage of these dynamic changes in a large area, like coastal regions, depends on integrating data from many acquisition platforms to generate long and continuous time series. The oceanographic scientific community has proposed several measuring platform alternatives. Solutions range from integrated instruments for on-site observation systems to remote equipment, each with a specific purpose. These platforms comprise towed and autonomous measuring vehicles, underwater gliders, onboard ship sensors (Jones et al. 2019), profilers such as XBT (Expendable Bathythermograph), the arrays of temperature/salinity profiling floats from the Argo program (Abraham et al. 2013), CTD (Conductivity, Temperature, and Depth) that can measure the whole water column from ships, fixed positions in moorings (Venkatesan et al. 2018), or coupled to automated profiling systems (Walter et al. 2018). Moorings lines are highly valued for their ability to host a variety of oceanographic sensors and meteorological systems. It supports the collection of these datasets at appropriate time and space intervals (Bailey et al. 2019). Unfortunately, these systems are not easily found in the local market, and reliance on imports of sensors and embedded systems comes with a prohibitive cost. (Laney 2017). Satellite sensors are mainly used for this purpose (Yang et al. 2013). However, in coastal regions with intense air-sea interaction, there may be discrepancies in magnitude and temporal variability between satellite-derived sea surface temperature (SST) observations and on-site measurements (Emery et al. 2001, Pereira et al. 2020).

In a joint effort between the Admiral Paulo Moreira Institute for Sea Studies (IEAPM) and the Brazilian Center of Physical Research (CBPF), a series of experimental sensor integration systems are being developed and tested at Anjos Cove, Arraial do Cabo. It aims to present a reliable platform for real-time assessment of physical parameters in support of underwater acoustic experiments in shallow waters: the Integrated Acquisition System for Research in Acoustics (IARA). Such assessment supports the monitoring of the local underwater soundscape, which is very relevant for operational purposes in acoustical oceanography. It also provides primary input parameters for sound propagation modeling in seawater, as well as for the prediction of the very near future state of the sea (nowcasting), which, in turn, assists opportunity coastal operations. Besides being essential for research in applied underwater acoustics, this region is a privileged location for detecting and monitoring SACW. The main objective of this work is to investigate the SACW intrusion into Anjos Cove and its consequent influence on the variation of the sound velocity profile from long-term in situ measurements.

MATERIALS AND METHODS

Study site

The thermographic profile and tide levels were taken at a vantage point for observing the continuous movement of SACW from deeper levels towards the ocean surface on the west side of the Atlantic Ocean off the coast of Rio de Janeiro, Brazil. One of its main characteristics is its geographical position, where the Brazilian coast changes its orientation from Northeast-Southwest to East-West in the approximate coordinates 23°S, 42°W. The measurement system was installed at the end of Pier 65 at Forno Port, sheltered by the calm waters of Anjos Cove (Figure 1). Three openings connect the Cove to the open ocean, two facing north and one facing south. The south opening

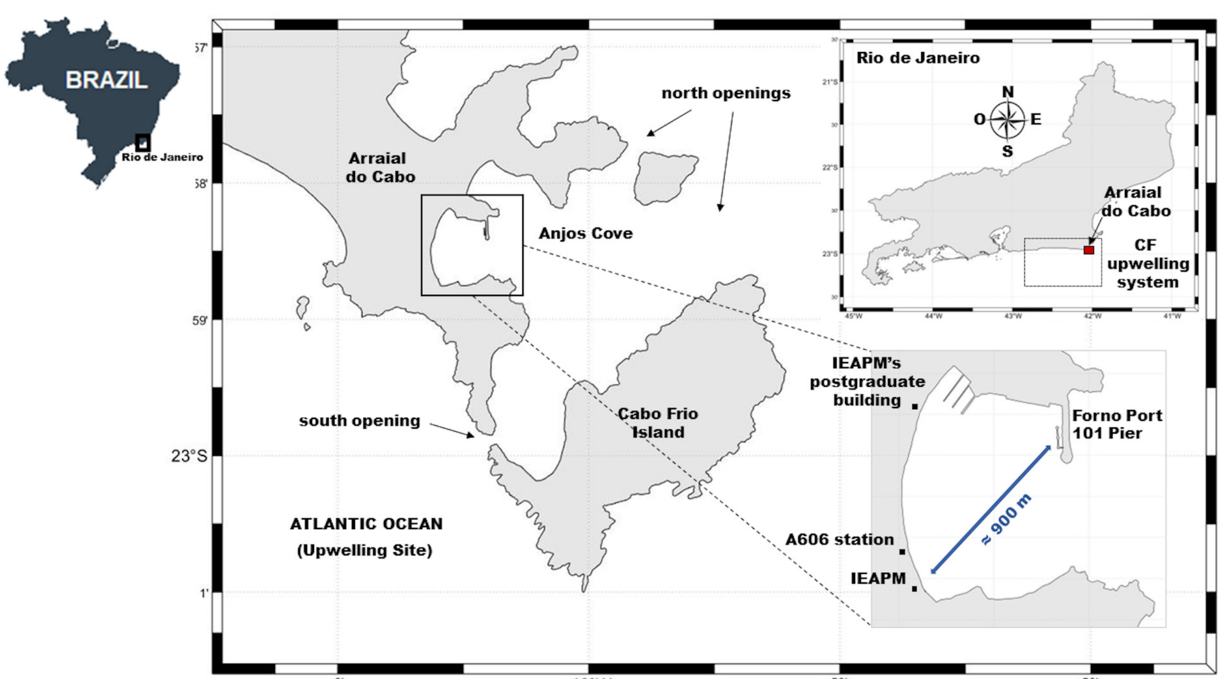

Figure 1. The study area where the seawater monitoring was carried out. The upper right panel shows Arraial do Cabo's location in Rio de Janeiro. The lower right panel depicts the breakwater where the measurement system station was installed within Anjos Cove.

connects the embayment to the place with the highest incidence of upwelling events on the southeast coast of Rio de Janeiro (Coelho-Souza et al. 2012). Furthermore, islands and coves provide a protected environment where tropical reef flourishes rich fauna and flora. The local marine ecosystem is regarded as a hot spot for biodiversity conservation (Ferreira et al. 2006). In addition to the ease of access on foot through the Port, the system can be visually monitored both from IEAPM laboratories and the IEAPM postgraduate building at the northern corner of Praia dos Anjos. There is also locally available data from the A606 station from the National Institute of Meteorology, located at 22°58'31" S / 042°01'17" W. The pier guarantees the mechanical stability of the device, and its installation position does not interfere with the flow of currents. The data processing and acquisition center is located inside IEAPM, approximately 900 meters from the pier.

Sound Speed Profile (SSP)

The data assessed in this study comprises seawater temperature observations collected by IARA system and the A606 meteorological station. IARA temperature sensor array measured the in-situ seawater temperature, and the tide gauge recorded the sea level height. The A606 obtained the wind speed and direction at a 3-meter height. All observations comprise a 2-year period from March/2021 to March/2023.

Salinity data were obtained from dated simulations using the Advanced Circulation Model (ADCIRC Luettich et al. 1992): *"...a system of computer programs for solving time-dependent, free surface circulation and transport problems in two and three dimensions. These programs utilize the finite element method in space allowing the use of highly flexible, unstructured grids"*. Temperature data from IARA were assimilated into the simulations, which were forced with atmospheric fields from the European Centre for Medium-Range Weather Forecasts (ECMWF, Zuo et al. 2019) and used boundary conditions from the Finite Element Solution tide model (FES2014, Carrere et al. 2016), and HYCOM-NCODA (Barton et al. 2021). The depiction of our simulation domain with variable grid resolution run is provided in the Supplementary Material (Figure S1). The model results were validated against observations: tide gauge sea level height data (Figure S2), ADCP velocity data (Figure S3), and CTD temperature and salinity data (Figure S4).

Sound speed profiles were calculated using the TEOS-10 (The International Thermodynamic Equation of Seawater – 2010) Gibbs function of seawater with an RMS error of ~0.067 m/s (Feistel 2018). TEOS-10 provides the currently accepted equation for sound speed as a function of Absolute Salinity S_A and conservative temperature formed from the observed variables Practical Salinity S_P and *in situ* temperature together with pressure, latitude, and longitude. This equation is based on laboratory sound-speed measurements made by Del Grosso (1974) and is consistent with the seawater densities reported by Chen & Millero (1977).

IARA system description

The Integrated Acquisition System for Research in Acoustics (IARA) prototype was developed to monitor the shallow water marine environment's physical parameters in real time. The measurement platform consists basically of four main subsystems (Figure 2): a microcontroller-embedded subsystem for processing the measurements; a sensing subsystem composed of a digital thermometer chain and an industrial sea level sensor; a solar-powered battery charger subsystem; and a subsystem for real-time telemetry to the land station. The solar panels and the antenna for radio transmission were installed on the ceiling. The instrumentation

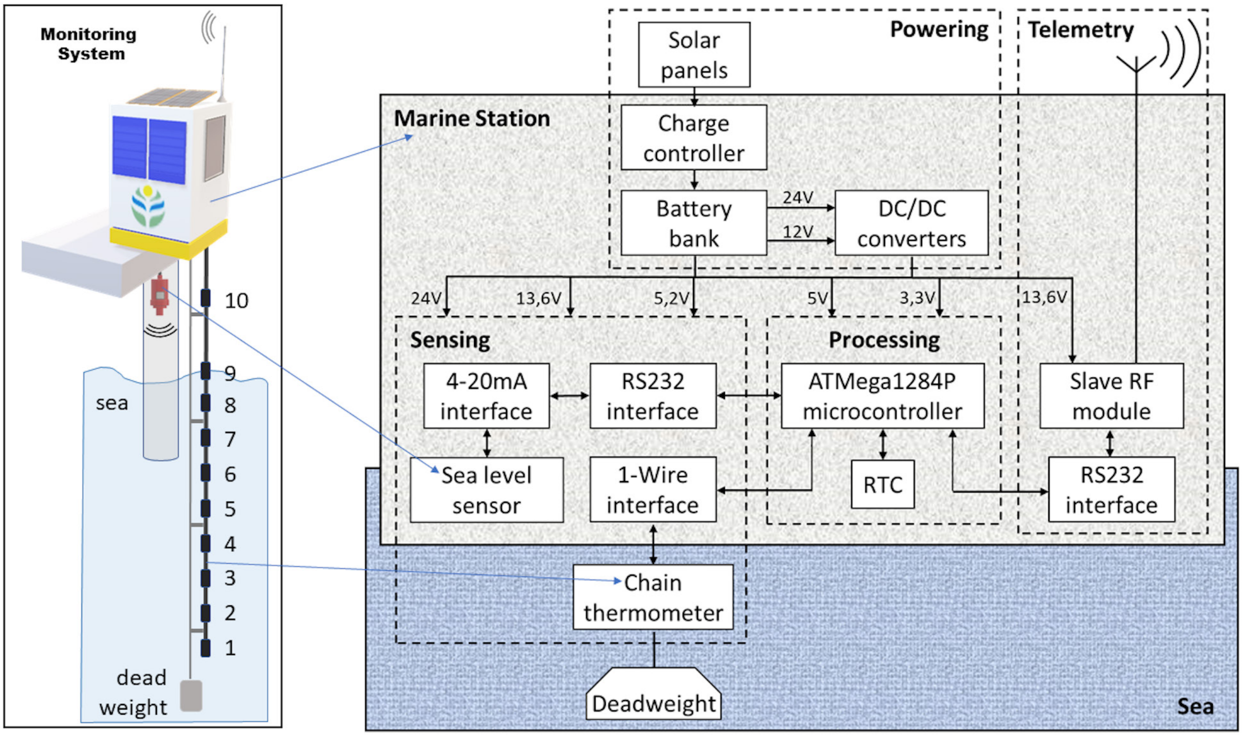

Figure 2. Representation of the measurement platform assembly scheme (left side panel) and the system's block diagram displaying the arrangement of the sensors, readout interface, and communication link (right side panel).

for powering supply, data acquisition, and telemetry control was installed inside a station compartment. A 6-meter-long PVC pipe runs through the housing floor and extends 3 meters deep for the sea-level transducer operation. The chain of thermometers crosses the station's side and extends vertically to the bottom of the sea. This configuration resulted in the permanent immersion of thermometers #1 to #8, equally spaced by 1 meter from each other. The first thermometer stays 1 meter from the bottom, and thermometer #9 depends on tidal variation, being immersed only during periods of high tide. Thermometer #10 was used as a reference for air temperature.

The processing subsystem has been configured to operate remotely and automatically. It controls the measurement rate, formats data, and sends them to the telemetry subsystem. The main component of the data acquisition interface is the ATmega1284P microcontroller. The microcontroller was populated on a custom-printed circuit board for its operation that houses the interfaces for serial communication and part of the power subsystem components (dedicated board voltage regulators). Once enabled, it continuously monitors and performs critical tasks such as sampling interval control, recording date and time measurements, sensor acquisition, storing configuration data in memory, and transmitting it. A peer-to-peer radio-frequency link establishes communication with the land station by the FRG2-CE-U radios. Each unit was connected to a CXMM900 marine mobile antenna designed to withstand winds up to 100 km/h. They can be expanded from a point-to-point network to a point-to-multipoint wireless sensor network with multiple slave units. It also offers automatic retransmissions on error detection, which is desirable to remedy antenna tilt errors in more agitated sea situations. All electronics in the processing, sensing, and telemetry subsystems were packed in a stainless-steel case. Rubbers were used on all holes and covered to protect the system from salinity. Connectors certified for harsh environments, and rated for water resistance up to IP68, were used for external devices. The system can be accessed in from the IEAPM station using control software in LabVIEW. The user interface displays the evolution of ambient temperature and thermal gradients in the water column in real time.

The sensor subsystem monitors the sea level and the thermal stratification of the water column. For sea-level measurement, the EasyTREK SP-300 was used. It is an ultrasonic-level transmitter manufactured by Nivelco. The transducer converts the measured distance parameter to a proportional current signal that varies linearly from 4 to 20 mA and corresponds to 0 to 100% of the configured measuring range. The Nivetec 487 series universal level indicator digitizes the signal and sends the information through an RS232 serial interface to the processing subsystem in real time. The temperature data is provided by DS18B20 digital thermometers built in a custom waterproof linear chain to monitor the variation of the thermal stratification on the water column and the ambient temperature. The DS18B20 provides a selectable resolution of up to 12 bits. It corresponds to increments of 0.0625°C, with an initial ± 0.5°C accuracy from –10ºC to +85°C. Each sensor has a 64-bit unique registration number in read-only memory (ROM) that is used to address them individually by a master device if many sensors are present in the network. It is based on 1-Wire technology, developed by Dallas Semiconductor, which allows a single master device to be connected to multiple slave devices using a single data channel conductor. The 1-Wire protocol was initially developed to enable communication between nearby components. The number of sensors and the maximum communication distance are limited to the cable's impedance contributions added to each sensor's impedance contributions. Lengths up to 200 m are possible using special drivers in conjunction with the microcontroller's digital port configured as the master device. A total of 10 sensors were soldered over a TSS DRAKA electric cable suitable for use at sea. It is neoprene-lined and manufactured specifically for use in submerged acoustic systems. To ensure the impermeability of the line and the sensors, they were covered with the Fiber MC109 epoxy-type adhesive compound in molds formed by shrinkable heat tubes, commonly used in electrical cable splices (Figure 3). The average response time of mounted thermistors is in the order of seconds. Therefore, it fits within the scope of our application.

Since temperature is the most influential parameter for the speed of sound at the upper layers of the ocean, a test was carried out to assess the accuracy of each sensor. The calibration procedure's primary purpose was to determine the correction to be applied to the indication of the digital thermometer to reference it to the International Scale of 1990 (ITS-90). Both devices were subjected to a temperature-controlled thermal medium. Consecutive and independent readings were done for each t90 set to the medium. Finally, the residual temperature was compared to the calibrating thermometer and the reference temperature on the ITS-90 scale. The transducers' accuracy was evaluated through 120 measurements at 10-second intervals. The temperature of the thermal medium varied within the range and the number of points desired. Nine temperature points were chosen within the reference thermometer's calibration range (10, 15, 20, 25, 30, 35, 40, 45, and 50 °C). The instruments' values were compared at each point to determine the correction and evaluate

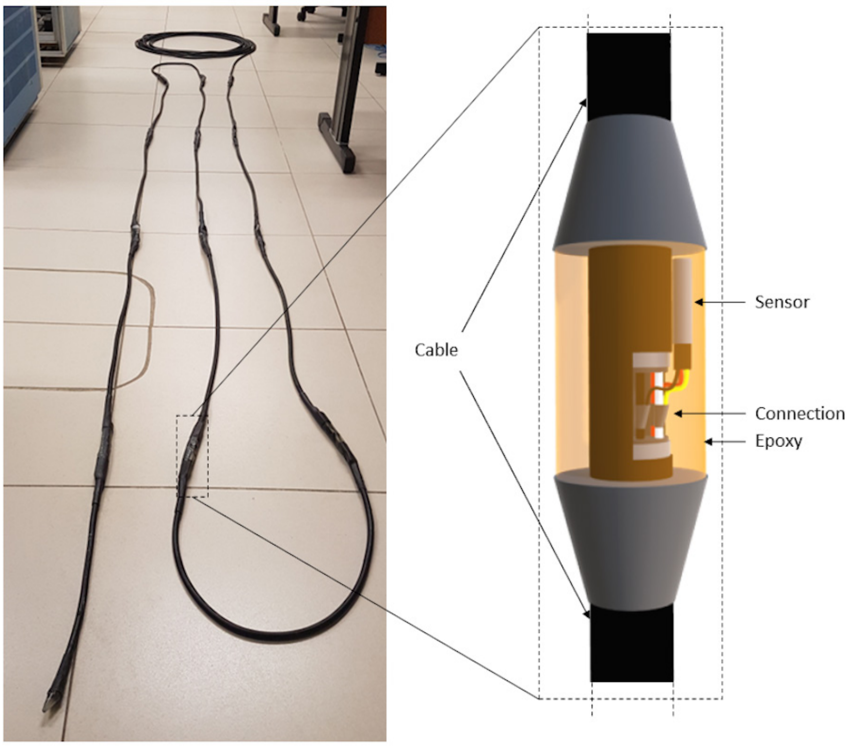

Figure 3. Photo of the thermometer chain installed in the measurement station in Anjos Cove. The zoom box details the encapsulation structure built to ensure waterproofing for each sensor.

the uncertainty components involved in the measurement process.

According to The Guide to the Expression of Uncertainty in Measurement (GUM), only a first-order Taylor series approximation was considered to assess uncertainties. A detailed description of the calibration procedure is presented by Lopes et al. (2019). The calibration methodology conducted in the laboratory resulted in calculated errors of less than 0.1°C for a coverage probability of 95.45%. Figure 4 shows the result of ±0.05°C inaccuracy (3σ) over the 0°C ~ 50°C temperature operation range.

RESULTS AND DISCUSSION

The time series of data collected throughout the 25 months reveals distinct conditions taking place in Anjos Cove (Figure 5), pinpointing subsequent events that reflect the role of ocean-atmosphere interactions modulating the local dynamics. The region is subjected to rapid changes in the atmospheric circulation (Figure 5a), which, combined with tidal oscillations (Figure 5b), yields significant changes within the Cove's oceanographic regime. Figure 5c displays the ocean's vertical thermal structure responding to atmospheric variations. Despite the higher frequency oscillation present in the signal, two main conditions/regimes seem to stand out: the establishment of a quasi-isothermal water column when SW wind is more persistent and a stratified situation where NE winds seem to favor cold water intrusions onto the inner Anjos Cove, which is in agreement with previous studies suggesting the Cabo Frio upwelling to be mostly wind-driven (Castro 2014, Fontes & Castro 2017).

In line with Carriére et al. (2010) and Calado et al. (2010), coastal upwelling happens more often and for longer periods (up to 36 hours) during the summer months due to favorable wind conditions, i.e., persistent NE winds (Figure 5). As discussed by Sun et al. (2017), during summertime the SASH is farthest poleward and its border is closest to the western South Atlantic

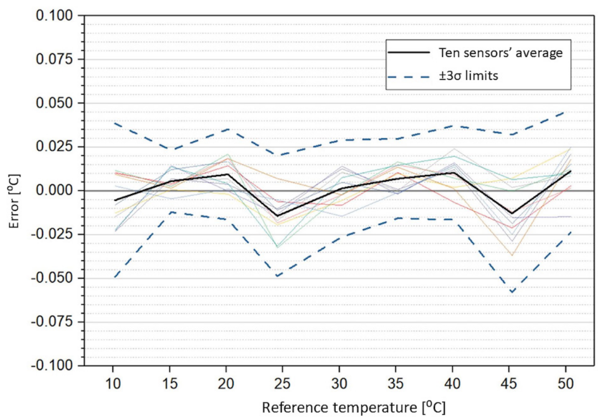

Figure 4. The temperature sensor error (standard deviation) after applying the calibration adjustment.

margin, thus promoting the establishment of several-day lasting NE winds over the study site. Combined with the break in the orientation of the coastline (Figure 1), this wind pattern yields offshore Ekman transport, boosting the upwelling of SACW due to coastal divergence, eventually producing high thermohaline gradients with direct impacts on the stratification of the water column.

Defined as a relatively cold (6°C – 20°C) and salty (34,6 – 36,2) water (Castro et al. 2008), South Atlantic Central Water intrusion events in the Anjos Cove are identified as the temperature drops below 20°C (red dashed line – Figure 5c).

The upwelling events that reached the inner Cove (i.e., temperatures below the threshold of 20°C), were identified and assessed in terms of monthly occurrence, duration (hours), and water temperature (Figure 6). Corroborating the literature (Carriére et al. 2010, Calado et al. 2010, Sun et al. 2017), these results pinpoint a well-defined seasonal variation; during warmer months in the Southern Hemisphere, the Anjos Cove is subject to more frequent occurrences, ranging from ten to 40 upwelling events per month, whilst colder seasons observe zero to ten events per month (Figure 6a).

Besides persistent NE winds, the seasonal variation of the BC position may also act to favor upwelling events in the summertime. Lorenzzetti et al. (2009) discuss that the BC moves closer to the continental shelf break with intensified current velocities during the summer, which increases bottom stress and develops a cross-shore transport along the bottom boundary layer (BBL) towards the coast, thereby favoring upwelling. In the same fashion, Roughan & Middleton (2004) discuss that the East Australian Current flowing closer to the coast favors the upwelling during summertime due to increased transport within the BBL, which was eventually

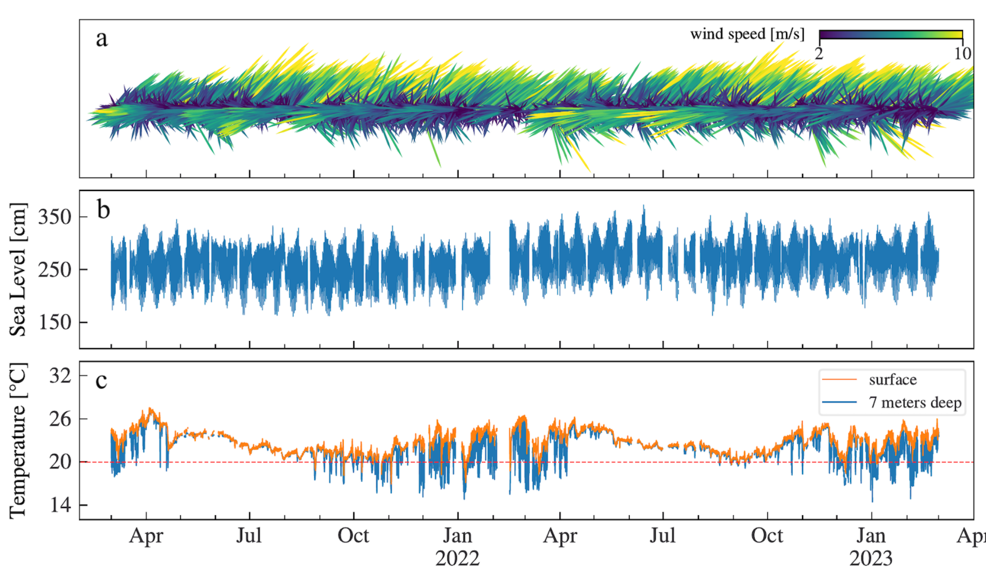

Figure 5. Hourly mean data observations from March/2021 to March/2023. Wind data measured by the automatic weather station at 3m height (a), sea level height (b), and seawater temperature (c) measured by IARA.

found to be the predominant forcing mechanism for upwelling in the region by Schaeffer et al. (2014).

Additionally, upwelling events during the summer tend to last longer, up to 36 hours (Figure 6b), and reach slightly lower (~2 °C colder) temperatures, also suggesting the summer events to be more intense (Figure 6c).

To better investigate the coupling between atmospheric variability and local ocean dynamics, we analyze shorter periods that represent these distinct conditions. Wind, seawater temperature, and sound speed profile data spanning two 4-month intervals (May to August) in consecutive years of 2021 and 2022 show rather similar conditions for both years (Figure 7). The upper panels (Figure 7a, b) show that, despite being consistently more intense, NE winds are not persistent during both 4-month intervals, rendering the isothermic water column conditions displayed in the mid-panels time series (Figure 7c, d), since this variable wind pattern seem unable to sustain upwelling events capable of reaching the inner shelf. As a result, sound speed profiles show no stratification throughout the 4-month intervals in both years (Figure 7e, f). However, it must be noticed that the underwater sound speed decreases during these intervals following the cooling trend observed in seawater temperature in both years, reflecting the seasonal cycle variability in the Southern Hemisphere.

The opposite scenario takes place when the combination of persistent NE (Figure 8a) winds and the dominant semidiurnal tidal cycle in the region (Figure 8b) support the intrusion of upwelled cold waters that flow inward along the bottom promoting the stratification of the water column in the Anjos Cove (Figure 8c). During this 5-day interval, each ebb tide peak (Figure 8b) is followed by a sudden drop in seawater temperature close to the bottom of the Cove within a 6-hour time lag (Figure 8c). Some of these drops record temperatures below

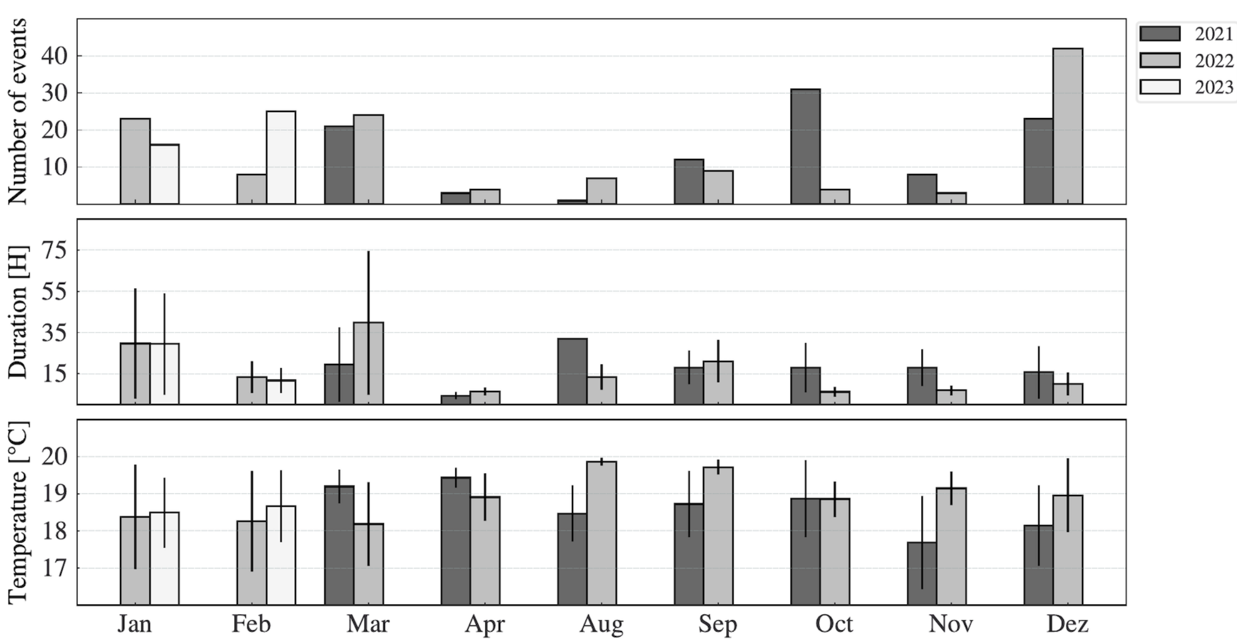

Figure 6. Upwelling events detected by IARA in the inner Anjos Cove: total number of occurrences (a); monthly mean of events duration in hours (b), and monthly mean of recorded temperatures in ºC (c). Months with no upwelling events detected were suppressed.

20°C, which is a local reference for upwelling events, whilst the surface displays no significant change. The sound speed profiles, in turn, reflect the cold-water intrusions instantly and the SSP becomes stratified as soon as this upwelled water reaches the inner Cove.

To illustrate the role of atmospheric circulation in modulating upwelling events, Figure 9 presents wind, seawater temperature, and SSP results within a 3-day interval in August 2021. Even though the intense NE winds come to a halt in the first half of the interval (Figure 9a), the amount of water advected offshore due to coastal divergence allows the upwelled SACW to spread and occupy the totality of the Cove's interior. Both surface and bottom layers go through a temperature drop below 20°C during the second half of the observed interval (Figure 9b), rendering stratified SSP accompanying the cold-water intrusion along the bottom, followed by a near-iso velocity condition as the cold water reaches the surface of the Cove. These results suggest that strong upwelling events followed by frontal passages may cause cold surface waters to pile up inside the Anjos Cove, despite the wind-driven Ekman transport onshore hampering vertical advection of SACW.

Our results corroborate the association between wind/current direction and water temperature inside Anjos Cove. The settlement of persistent NE winds, referred to by locals as "good weather conditions", favors the upwelling of SACW onto the continental shelf of Cabo Frio and into the Cove. Although it has been discussed that these cold-water intrusions might not be able to break sharp bottom topography gradients (Louza et al. 2019), these records suggest otherwise. The integrated simultaneous sea level height and seawater temperature measurements showed that tides play a complementary role along with the wind pattern to induce these changes in the Anjos Cove water column structure. These are the first records of such interactions modulating the dynamics of the Cove.

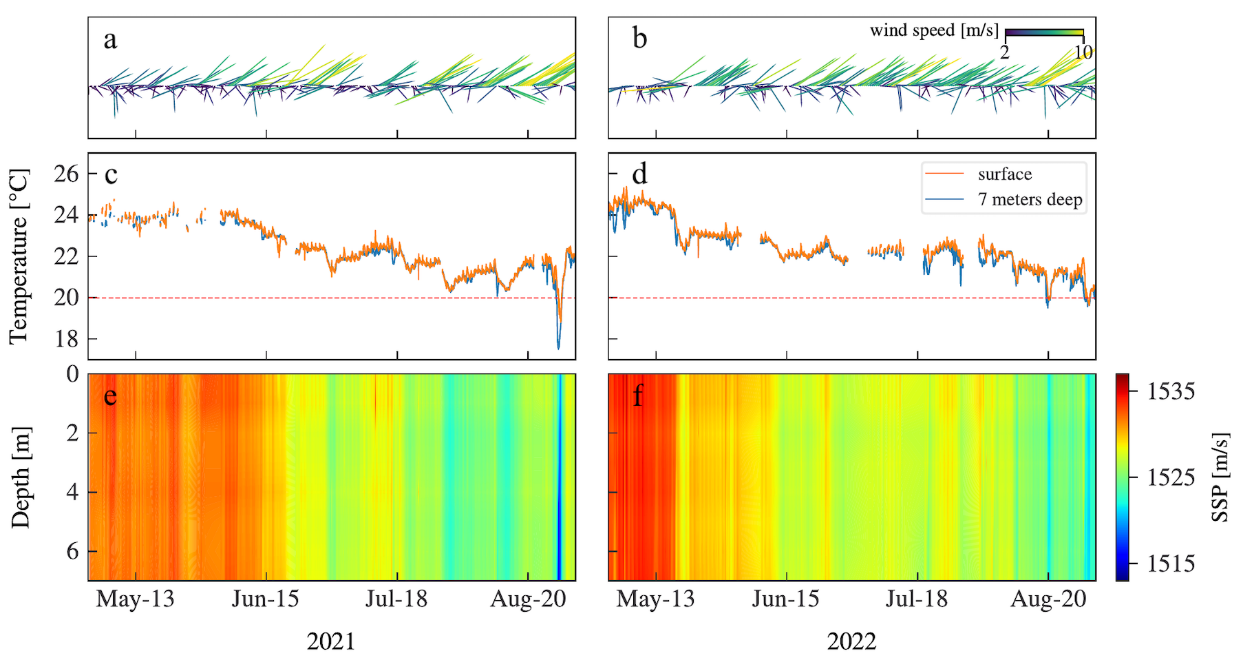

Figure 7. **Wind (a, b) and seawater temperature (c, d) data observed between May and August of 2021 and 2022 displaying environmental conditions inhibiting the establishment of upwelling events. The lower panels (e, f) show the sound speed profile calculated using the IARA thermometer system data for both time intervals.**

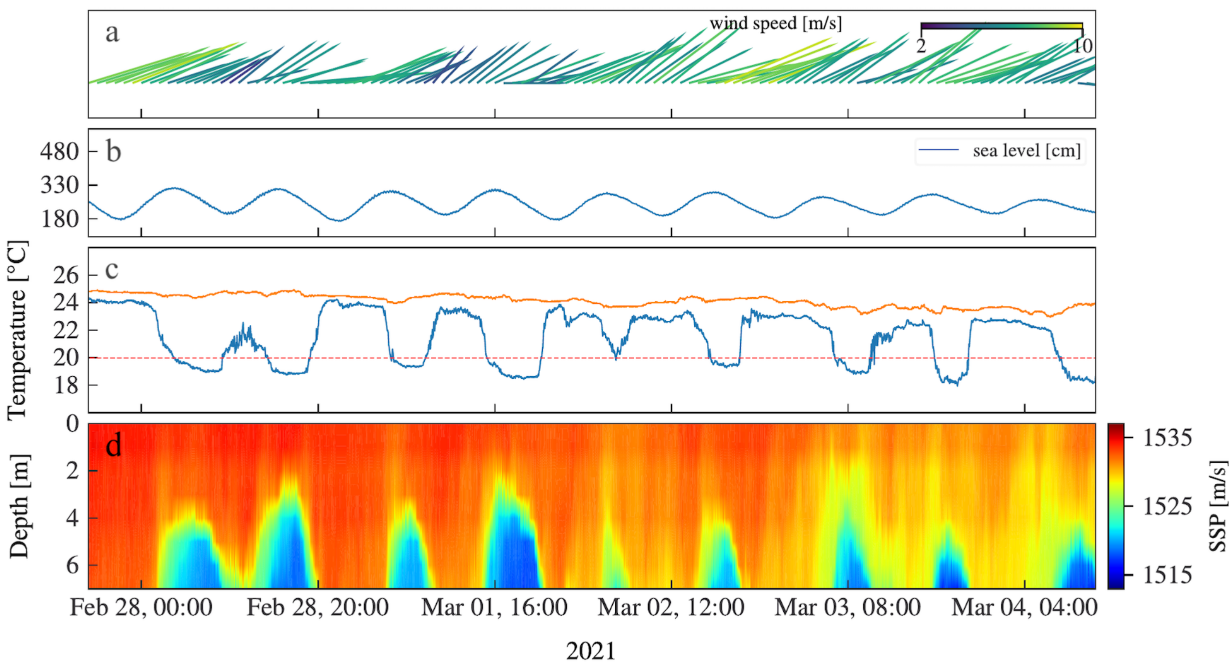

Figure 8. Wind (a), sea level height (b), and seawater temperature (c; orange/blue lines represent surface/bottom layers) data observed between February and March of 2021, illustrating environmental conditions favorable to the upwelling occurrence, i.e., consistent NE winds. The lower panel (d) displays the sound speed profile resulting from the intrusion of upwelled cold waters along the bottom layers of the inner Cove.

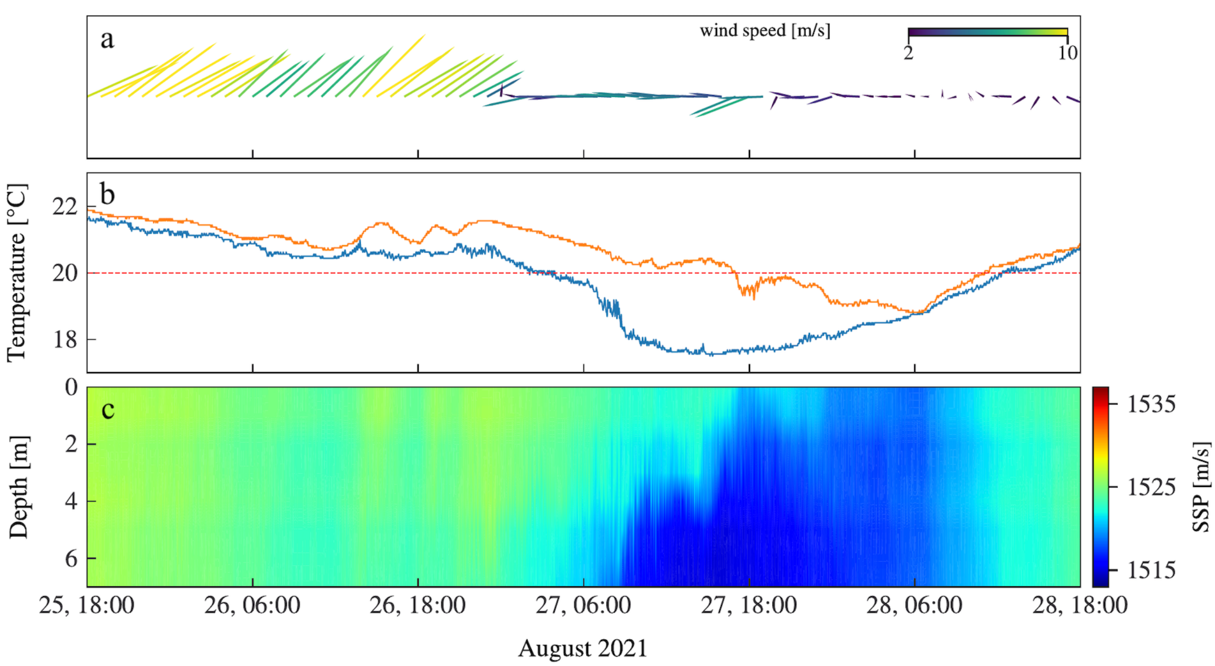

Figure 9. Wind (a) and seawater temperature (b) data observed during 4 consecutive days in August of 2021 showing the impacts of sudden changes in wind direction on the water column temperature caused by a cold front passage. The lower panel (c) shows the sound speed abrupt drop following the sea water temperature changes.

CONCLUSIONS

The development of an integrated system, consisting of a tide gauge and a custom array of thermometers, made it possible to observe for the first time the impacts of cold-water intrusion events on the thermal stratification inside the Anjos Cove, Arraial do Cabo, RJ. The results highlight the value of real-time monitoring of shallow water enclosed bays for investigations focused on underwater sound speed variability in support of regional ocean nowcasting, i.e., the numerical prediction of the very near future state of the sea, which, in turn, assists opportunity coastal operations. The results demonstrate that IARA efficiently records and transmits seawater multiple-layer temperature change data, with an accuracy of ±0.1 °C (within the 10-50°C range). Along with satellite observations, this prototype presents a viable alternative to examine the coastal upwelling phenomenon from a three-dimensional perspective, aiding the investigation of the impacts of deep water on enclosed coastal environments.

Even though several authors have reported the intrusion of SACW on the southeastern Brazilian coast, our results show the presence of the water mass in the innermost portion of Anjos Cove. Moreover, we were able to follow the intrusion and retreat of upwelled waters in the Cove. The cold water upwelled outside the Cove is carried to its interior, cooling either the bottom layers or the entire water column. These conditions only last for up to 36 hours due to the settlement of southwestern wind, which hampers the upwelling process. Tides seem to play a role in driving the cold-water advection inward but only under favorable wind conditions.

The cold water flows near the bottom and can generate strong temperature gradients with direct impacts on the sound speed profiles in Anjos Cove. We have shown that the spread of cold water inside the Cove can reach the interior sub-inlets, as is the case of Forno Port, but this intrusion's mechanisms are yet to be fully described as well as the extension of the cold water spread inside the cove. In the same fashion, the consequences of abrupt temperature and sound propagation changes on the diverse local marine biota are also subject for further investigation.

Finally, traditional oceanographic research often requires expensive and sophisticated instruments, making it challenging for researchers with limited budgets or resources to participate in meaningful studies. Low-cost robust equipment opens up opportunities for a broader range of scientists and students to contribute to oceanographic research, democratizing access to valuable data and insights. In terms of scalability, the deployment of multiple instruments simultaneously enhances the spatial and temporal resolution of data collection, leading to more accurate and detailed analyses of ocean processes and phenomena. This facilitates large-scale data collection across different regions and timeframes, thus allowing researchers to gather more comprehensive datasets without the need for whopping investments, improving the understanding of ocean dynamics, ecosystems, and climate patterns.

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SUPPLEMENTARY MATERIAL

Figures S1-S4.

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