Influence of temperature and salinity on the sound speed in shallow waters of Tumaco Bay

Influencia de la temperatura y salinidad en la velocidad del sonido en aguas someras de la bahía de Tumaco

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Abstract

The present study establishes the horizontal and vertical variation of the sound speed in Tumaco Bay (department of Nariño, Colombia) and describes its behavior from data recorded in field surveys with the aim of identifying the effect of depth, temperature and salinity on its variability. Profiles with an approximate spatial resolution of 500m were distributed in the study area: 184 water column profiles for May 2019 and 165 profiles for April 2021. The results obtained show a variation in the sound speed between 1526.6 m/s and 1540.3 m/s for the 2019 profiles, and between 1518.5 m/s and 1542.82 m/s for 2021. The difference between the average values obtained for the two dates does not exceed 0.69 m/s. In 2019, the temperature ranged from 25.75°C to 29.21°C and no salinity data was obtained. For 2021, the temperature varied between 26.88°C and 29.84°C and the salinity values between 11.36 psu and 35.44 psu. In the maps of both dates, there was an area of significant variation in the sound speed, which was associated with the mouth of the Mira River.

Keywords: profile, sound speed , temperature, depth, salinity, Bay of Tumaco.

Resumen

El presente trabajo establece los rangos de variación horizontal y vertical de la velocidad del sonido en la bahía de Tumaco (departamento de Nariño, Colombia) y describe su comportamiento a partir de datos registrados en campo con el objetivo de identificar el efecto de la profundidad, temperatura y salinidad en su variabilidad. En el área de estudio se distribuyeron perfiles con resolución espacial aproximada de 500m, 184 perfiles de columna de agua para mayo de 2019 y 165 perfiles para abril de 2021. Los resultados obtenidos muestran una variación de velocidad del sonido entre 1526.6 m/s y 1540.3 m/s para los perfiles del año 2019, y entre 1518.5 m/s y 1542.82 m/s para el 2021. El valor medio obtenido para las dos fechas, no supera una diferencia de 0.69 m/s. En el 2019, la temperatura varió de 25.75°C a 29.21°C y no se obtuvieron datos de salinidad. Para el 2021, la temperatura varió entre 26.88°C y 29.84°C y los valores de salinidad entre 11.36 psu y 35.44 psu. En los mapas de las dos fechas, coincide una zona de variación significativa de velocidad del sonido que se asoció a la desembocadura del río Mira.

Palabras Clave: *perfil, velocidad del sonido, temperatura, profundidad, salinidad, bahía de Tumaco.*

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Introduction

Colombia has a privileged geographical position thanks to the great marine diversity provided by the Caribbean Sea and the Pacific Ocean, conditions that provide an important source of resources that are an economic backbone of the country. For this reason, variables are studied to identify, describe and characterize processes that contribute to oceanographic and hydrographic information for maritime transit.

The Pacific Oceanographic and Hydrographic Research Center (CCCP) is responsible for producing and providing the General Maritime Directorate (Dimar) with the scientific knowledge inputs of the Pacific coast necessary for it to exercise its authority, as well as to coordinate and control maritime activities (Navas *et al*., 2017).

The development of maritime activities involves, among other things, establishing navigable waterways, and signaling and identifying hazards to ensure safe navigation. To achieve this, it is necessary to know the geomorphology of the seabed, for which hydrographic survey campaigns are carried out using single-beam and/or multibeam echosounders, whose functioning is based on the emission and reception of acoustic signals that make it possible to determine the depths and relief of the seabed.

The propagation of acoustic waves is distorted due to fluctuations in temperature, salinity and pressure due to spatial and seasonal variations (Ali, Sakira and Radhika, 2011). Temperature varies with depth, time, location and meteorological conditions (Remiro and Pérez, 2019), while salinity varies as a consequence of tides and volumes of freshwater contributed by precipitation in the coastal area and discharges from river mouths (Reina *et al*., 2013).

According to Peyton, Beaudoin and Lamplugh (2009), sounding throughout the water column to establish the speed of sound is an important component in determining the total propagated uncertainty (TPU), specifically in multibeam surveys, as a result of corrections of refraction; if variations in the speed of sound propagation are significant, sounding readings can be altered by several meters.

The accuracy of bathymetric surveys can be greatly improved by using sound velocity profile data (Jin *et al*., 2015). Lack of knowledge about the sound speed in the water column makes it difficult to determine water depths correctly, resulting in concave or convex distortions of the seabed surface (Mohammadloo *et al*., 2019).

Considering the above, the present work studies the behavior of the sound speed in Tumaco Bay (department of Nariño, Colombia), with the aim of knowing the horizontal and vertical variation of the sound speed in shallow waters.

Study Area

The study area comprises the area delimited by nautical chart COL 770 "Puerto de Tumaco", between the geographical coordinates 1°48'6.3174'' and 1°52'0.2676'' North, and 78°42'1.656'' and 78°46'46.185'' West, inside Tumaco Bay, on the Pacific coast of the department of Nariño. According to the Köppen climate model classification, the region is characterized by a tropical rainy climate (Pabón, Eslava and Gómez, 2001).

A grid with an approximate spatial resolution of 500 m was designed, in which 184 water column profiles were assigned for May 2019 and 165 for April 2021. The distribution of the points where the profiles were obtained in the bay on each date are shown in Figure 1.

Methodology

In May 2019, field measurements were made using a Digibar S profiler, an instrument that uses a 2 MHz acoustic transducer and a time-of-flight technique to emit sound at a known distance and measure the sound speed directly. Simultaneously, it provides temperature and pressure data in the water column; measurements that are stored internally and then downloaded via a USB port (TELEDYNE, 2022)In April 2021, pressure, temperature and salinity measurements were made with a CTD (Conductivity, Temperature, Depth) profiler, from which the sound speed was derived. The CTD is a high-resolution, dynamically accurate instrument that supports numerous auxiliary sensors, an internal-field conductivity cell that minimizes salinity spiking, a pressure-

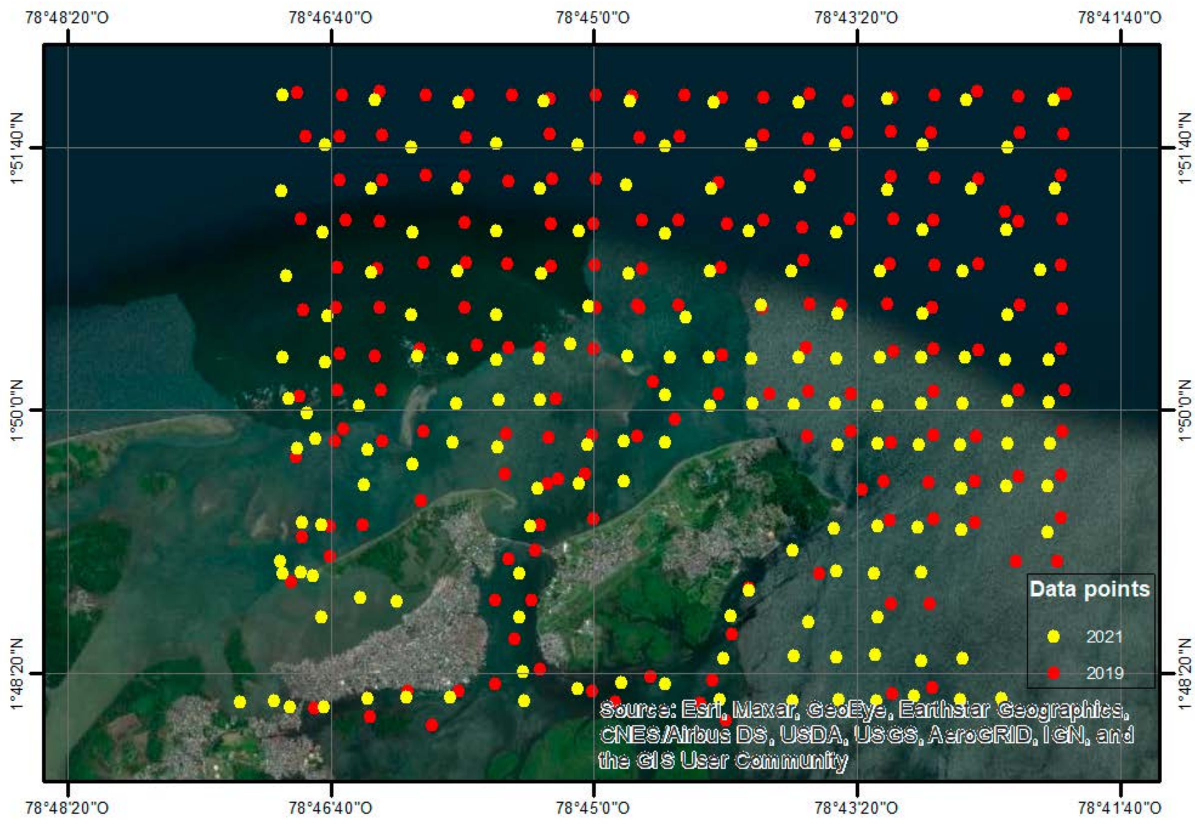


Figure 1. Area of study.

protected thermistor that provides stability, and a temperature-compensated pressure sensor. Data are downloaded using SEA-CAT software (SEA-BIRD SCIENTIFIC, 2022).

A C-Nav3050 GPS designed to easily integrate with the hydrographic survey software (HYPACK, 2019) was used to provide the geographic location of the sampling points, allowing positioning with a sub-meter margin of error. Measurements were taken aboard the CCCP Soundermax boat, a vessel with a length of 9.1 m and a maximum draft of 1 m.

Currently, computer tools that process sound velocity profiles in the water column show the distribution in the vertical for a single point. Therefore, to show the horizontal plane and spatial distribution, a free software tool called SS GRAPHIC (developed in Python) was created.

SS GRAPHIC is a powerful tool with a user-friendly interface that allows the user to load sound velocity profile files with different formats along with a file giving the position of the profiles, and purges and processes the information to generate two files from which two- and three-dimensional plots of these variables are generated.

With the information collected in the field trips and using the SS GRAPHIC application, it was possible to analyze the behavior of the sound speed with respect to the measurements of depth, temperature and salinity available for each date.

Results and Discussion

Based on the information obtained in 2019 and 2021, an approximate sketch of the spatial distribution of the measurements was made, showing the maximum depth for each sampling point (Figure 2). Following Orozco-Villegas (2020), we characterized the surface mixing layer, where there is a constant transfer of energy, mass and momentum between the atmosphere and the ocean.

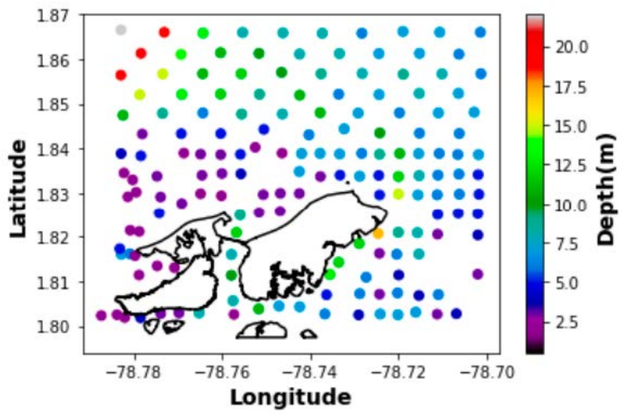


Figure 2. Maximum depth at the sampling points in 2021.

The spatial variability of the thermohaline characteristics is observed in the Temperature-Salinity (T-S) diagram, which considers the T-S relationship of the entire record (Figure 3a) and demonstrates the greater dispersion of the data in the shallowest zones (points with depths less than 5 m). However, in the records with depths greater than 5 m (Figure 3b), a linear behavior can be seen in accordance with the identification and classification of water masses for the Tropical Pacific Ocean, as is the case of Tropical Surface Water (TSW) (16°C<T<29°C and 29.5<S<34.6), documented by Millán and Bejarano (1989).

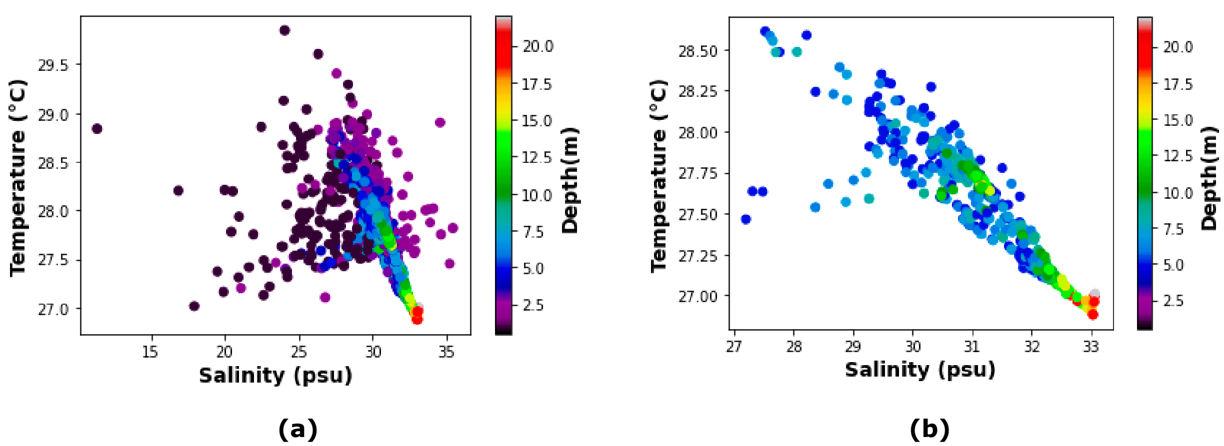
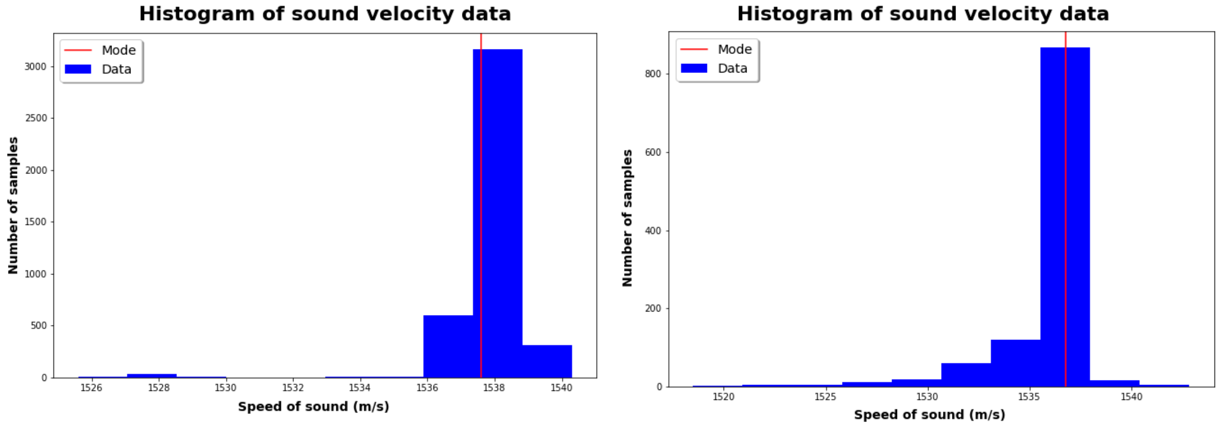


Figure 3. T-S diagram in 2021: **(a)** T-S correlation for all depths **(b)** Correlation for depths greater than 5 m

The pressure data, directly related to the depth values, are used as a reference for position in the water column and to generate the horizontal planes. From the information provided by the 184 profiles taken in May 2019, an average sound velocity value of 1537.44 m/s was obtained, with a variation from 1526.6 m/s to 1540.3 m/s, for depths from 1 m to 26 m, although the predominant depths, for 88% of the study area, are of the order of 6 m.

The sound velocity data record, obtained vertically and horizontally, shows that 97.8% of them are in the interval between 1534 m/s and 1541 m/s, while 2.2% are between 1525 m/s and 1533 m/s (Figure 4a).

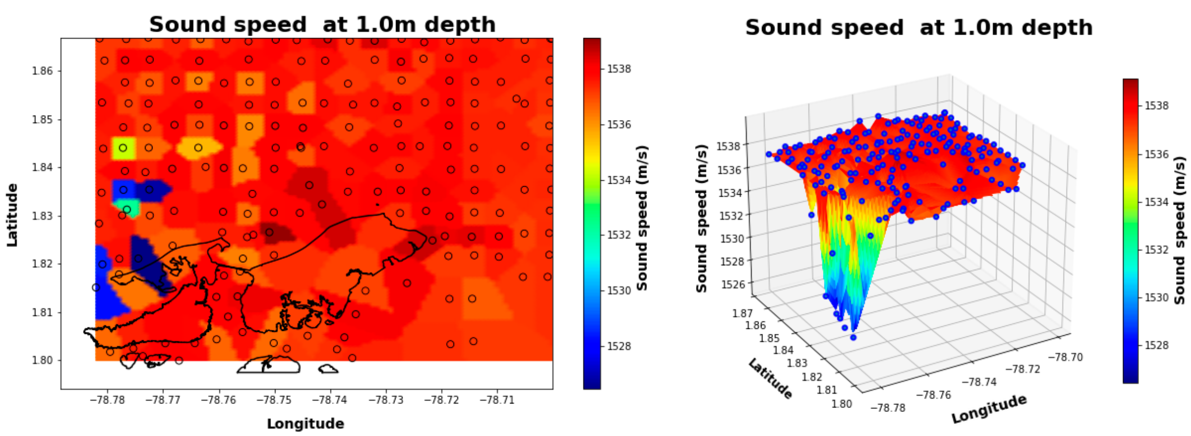


(a) **(b)**

Figure 4. Histogram of sound velocity data in **(a)** May 2019 and **(b)** April 2021

For their part, the information available from the 165 profiles recorded in April 2021 gave an average sound speed of 1536.75 m/s and a variation from 1518.51 m/s to 1542.82 m/s at depths from 1 m to 22 m. The sound velocity data log consolidates the values obtained vertically and horizontally, and the histogram indicates that 95.3% of the recorded data were within the range of 1534 m/s to 1543 m/s and 4.7% are between 1518 m/s to 1533 m/s (Figure 4b).

The predominant sound velocity values remained between 1536 m/s and 1539 m/s (Figure 5). The mean value obtained for the two dates differs by only 0.69 m/s. After obtaining the values for each date, the horizontal sound velocity mapping was created, showing all the values measured at the same depth.

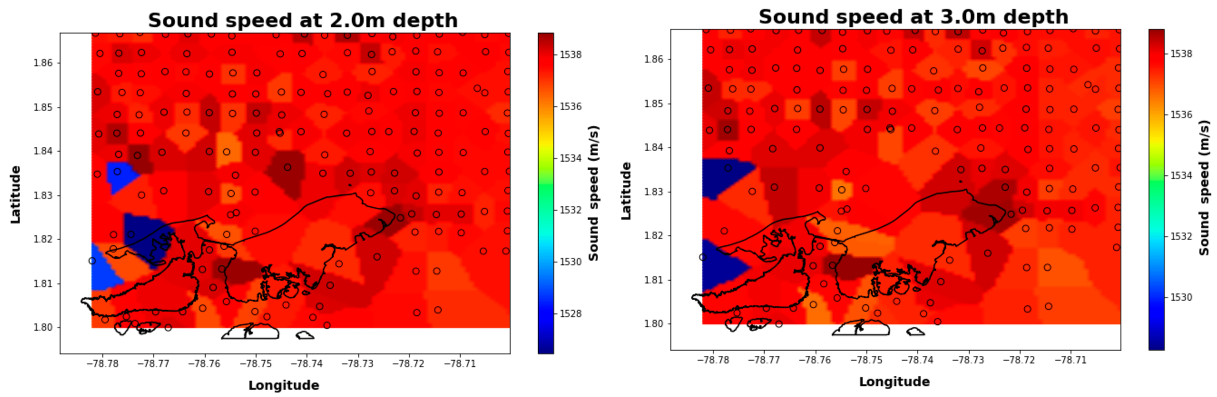


(a) **(b)**

Figure 5. Sound speed at 1 m depth in 2019: (a) 2D representation (b) 3D representation

In May 2019, the sound velocity gradient had a range of 13.7 m/s and much of the study area for the 1 m layer exhibited little difference with respect to the mean value obtained. A significant change can be seen in the southwest of Tumaco Bay, where the minimum value obtained for the sound speed was found (1,526.6 m/s).

The maximum depth found for this zone was 4 m. For this reason, to analyze if the decrease in the speed of sound was maintained at other depths, the horizontal maps from 1 m to 4 m were checked (Figures 6 and 7).



(a) **(b)**

Figure 6. Sound speed measured in 2019: **(a)** at 2 m depth **(b)** at 3 m depth.

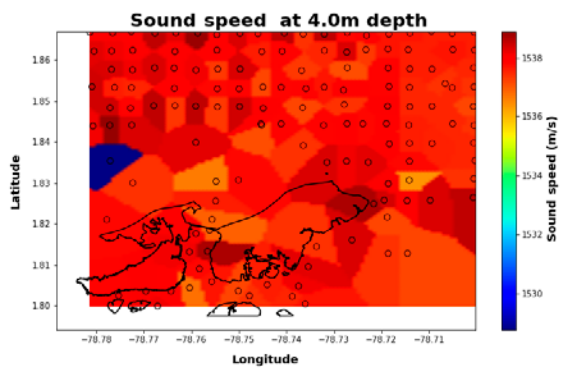


Figure 7. Sound speed measured in 2019 at 4 m depth.

In the above figures, it can be observed that the horizontal sound velocity gradient at the different depths maintained the trend with lower values in the same zone, and the widest variation was in the shallowest layer at 1 m.

Additionally, the temperature mapping for the same date was analyzed. The temperature values varied between 25.75ºC and 29.21ºC at 1 m depth (Figure 8a). The widest range of temperature variation was obtained in this layer; however, no correspondence with the decrease in sound speed was evident. Temperature variation is associated with factors such as the speed and direction of currents, air temperature, dominant climate type, latitude of the site and underwater topography, the most important of which is the absorption of energy emitted by the sun (Reyna *et al*., 2013).

When reviewing the different layers, it was observed that the variance does not exceed 2°C, indicating a more homogeneous behavior in the horizontal in this variable. At a depth of 4 m (Figure 8b), the temperature ranges from 28.2°C to 28.9°C, a variance of less than 1°C. The temperature layers have no observable correspondence with the variation in sound velocity.

With no further information available on this date for the variables measured, a geographical review of the area was made, in which some of the mouths of the Mira River that flow into the study area were identified (Figure 9). This review allowed us to consider an alteration in salinity, since the influence or contributions of river water to the ocean decreases the salt concentration, which in turn probably generates a decrease in the sound velocity values in this particular area.

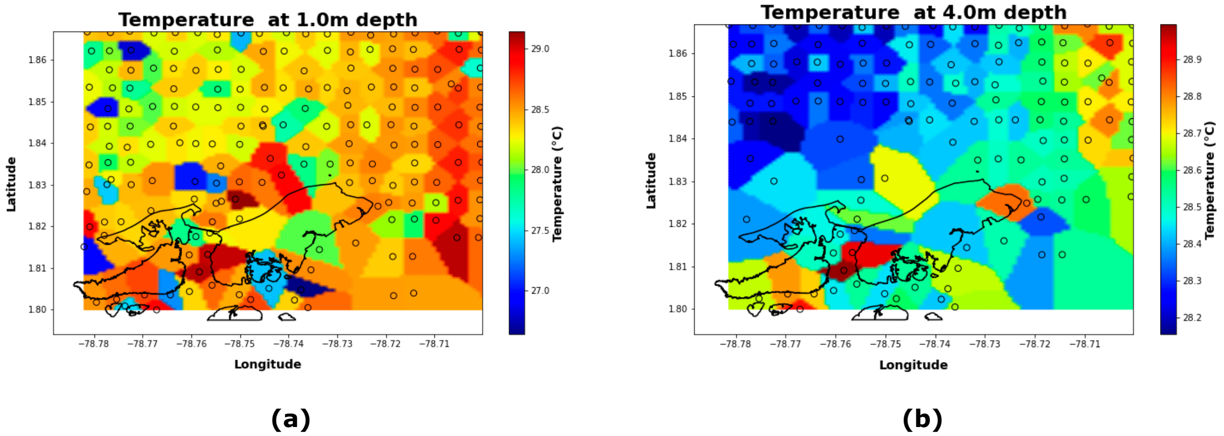


Figure 8. Temperature in 2019: **(a)** 1 m depth **(b)** 4 m depth.

Therefore, for the following field trip, equipment was used to provide the same variables as before, plus salinity.

In April 2021 and using the data obtained with the CTD, mappings were made at the same depths as for 2019. For the layer at 1m, there was a decrease in the sound speed in the sector previously identified in 2019. The range of values at 1m was 24.32m/s, wider than that at the same depth in 2019. There was a coincidence in that the minimum value for the sound speed (1518.51 m/s) was in the same layer as in 2019 (Figure 10).

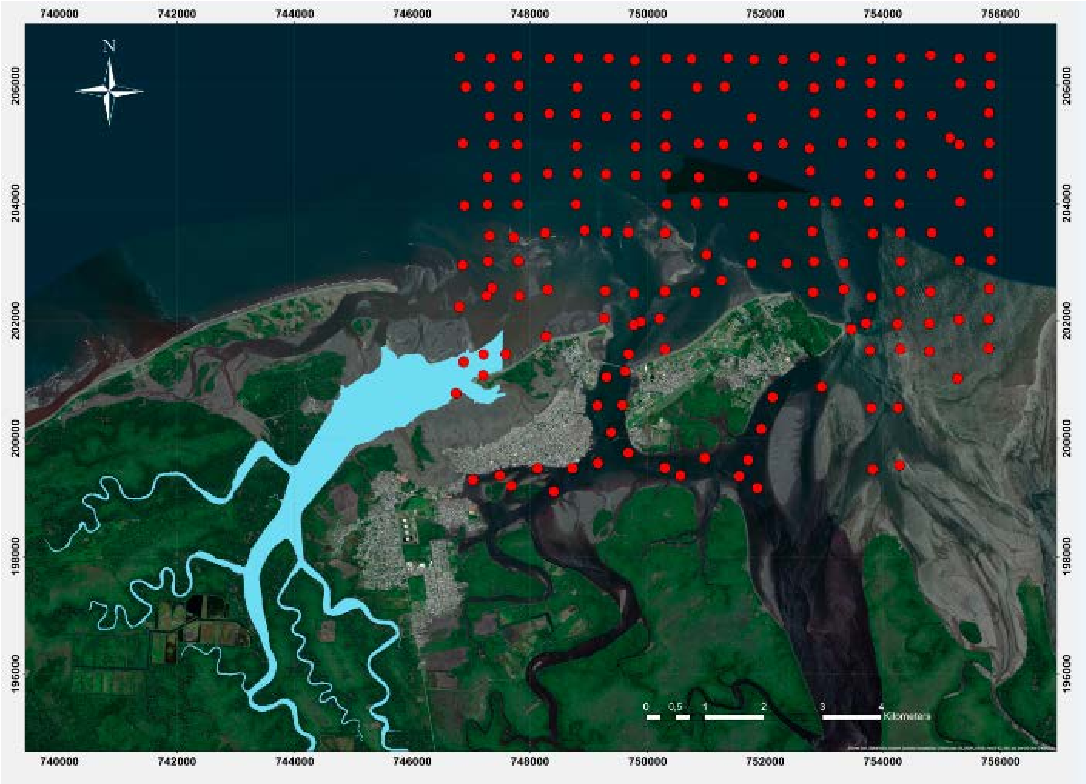


Figure 9. Mouth of the River Mira in Tumaco Bay.

In the sound velocity mapping for depths of 2 m, 3 m and 4 m, the lowest sound velocity values were found in the same area (Figures 11 and 12). When comparing the sound velocity behavior for 2019 and 2021 in the same layers, a similar trend was observed, in that the lowest velocities correspond to the same sector.

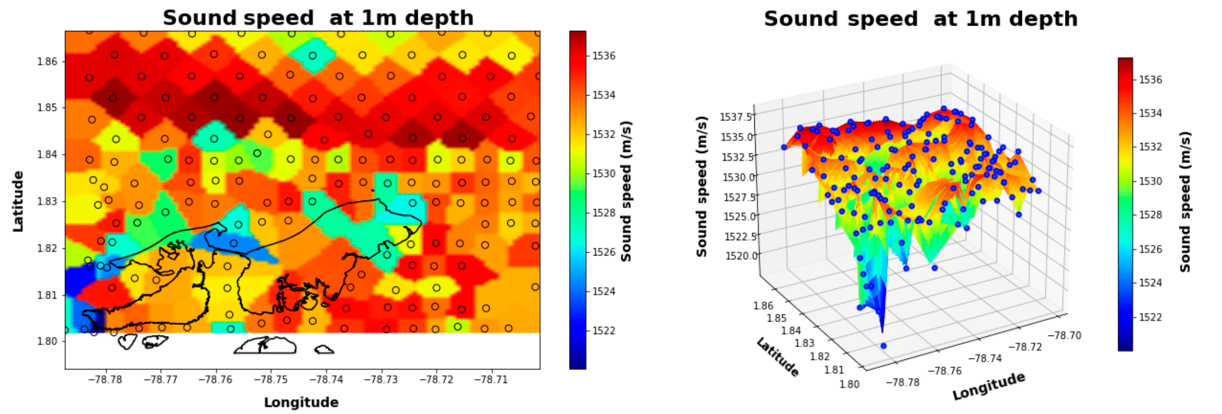
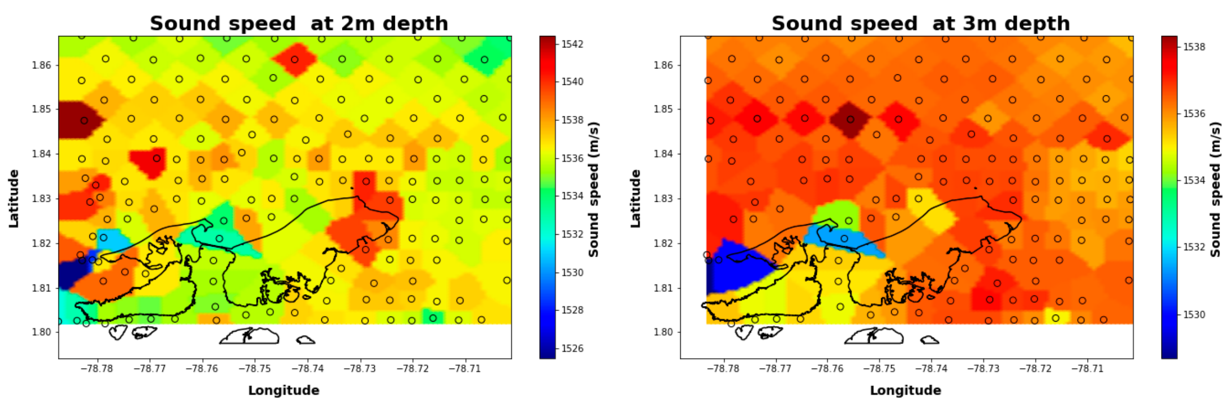


Figure 10. Sound speed at 1 m depth in 2021: **(a)** 2D representation **(b)** 3D representation.



(a) **(b)**

Figure 11. Sound speed measured in 2021: **(a)** at 2 m depth **(b)** at 3 m depth.

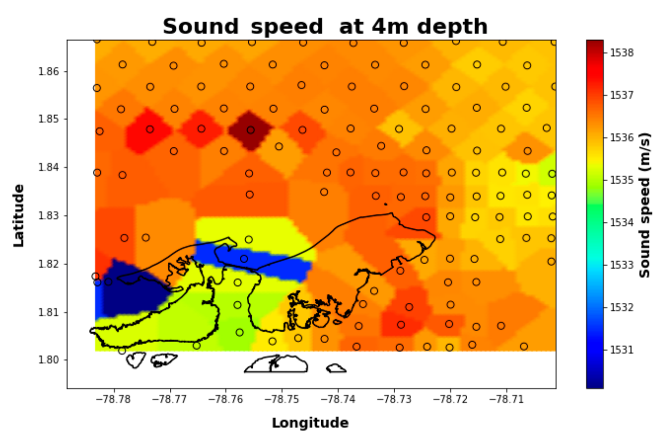
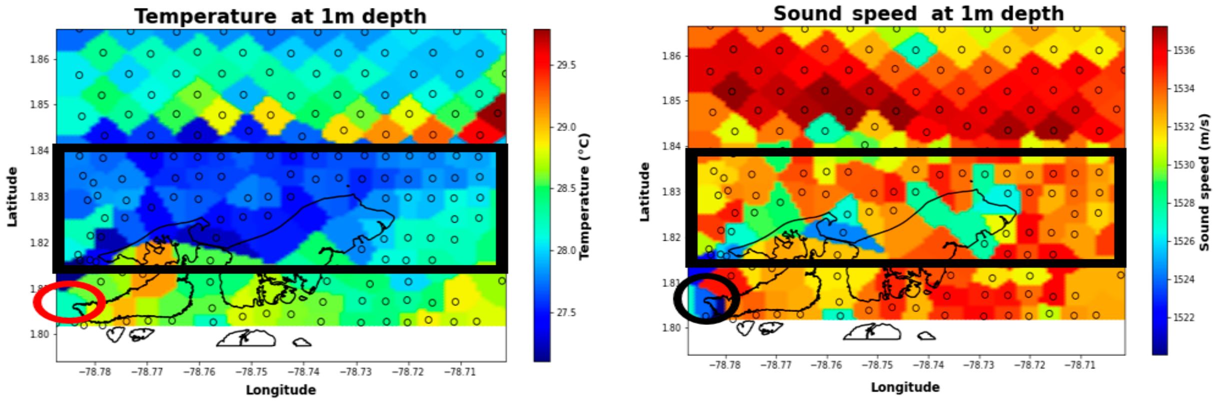


Figure 12. Sound speed measured in 2021 at 4 m depth.

When comparing the available variables, the temperature values for 2021 ranged from 26.88ºC to 29.84ºC. For the layer at 1 m depth, a homogeneous water layer was observed in the central zone with lower temperature values compared to the average for the study area (Figure 13); when observing the sound speed in the same layer, a decrease was also found in this central zone. It was also found that there were low temperatures in the same zone that was identified in 2019 (red circle in Figure 13): this time, minimum values of temperature and sound velocity are preserved at every level within the zone, a relationship not identified in 2019; however, the range of sound velocities is much wider than the temperature gap.



(a) (b)

Figure 13. Temperature **(a)** and sound speed **(b)** at 1 m depth in 2021.

Continuing with the observation for depths of 2 m, 3 m and 4 m (Figure 14), it was found that the decrease in the sound speed coincides with the decrease in temperature in the identified zone, but there is no correspondence for the whole study area.

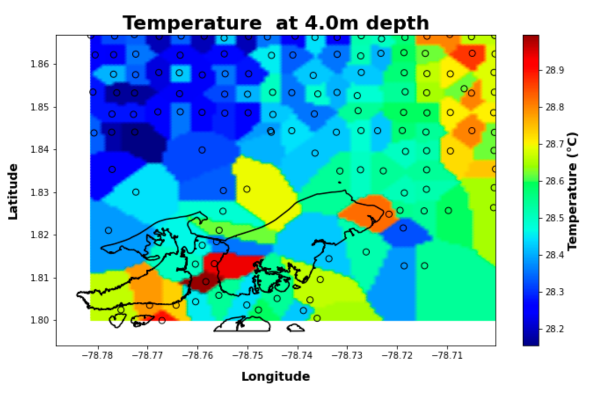


Figure 14. Temperature in 2021 at 4 m depth.

In addition to the temperature data for 2021, salinity records were obtained, and they showed a variation between 11.36 psu and 35.44 psu in the study area, demonstrating significant variance.

Figure 15 shows that, at 1 m depth, salinity had a significant variation in the marked zone with a value of 24.08 psu; in addition, when compared with the sound speed at the same depth (Figure 13), it is clear that lower figures for both indicators were found in the same zone, showing a reciprocal relationship in the maps that makes it possible to suggest salinity as the main responsible for the variation of the sound velocity in the study area. In 2021, lower sound velocities were found compared to 2019 and there was also a coincidence in a temperature layer.

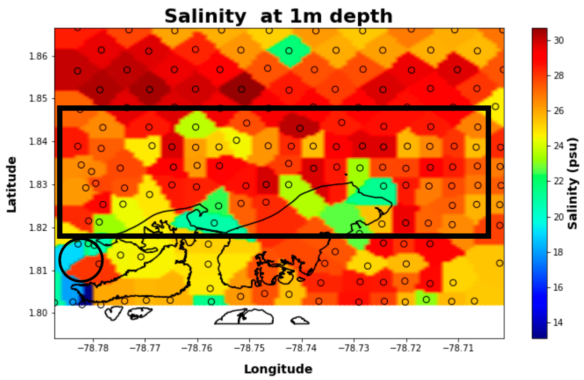


Figure 15. Salinity in 2021 at 1 m depth.

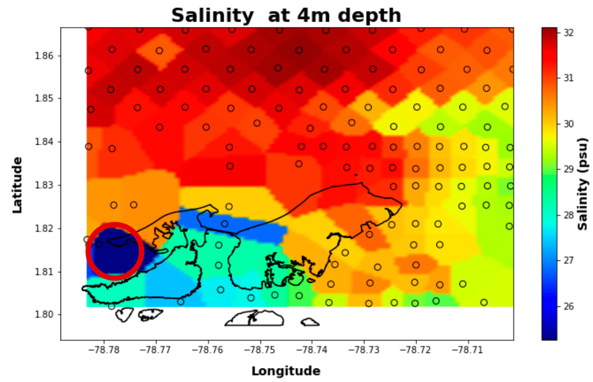


Figure 16. Salinity in 2021 at 4 m depth.

Observing the map, it is clear that the decrease in salinity and speed of sound (Figures 13 and 15) occur at the mouth of the River Mira (Rodriguez, 2011). To verify that the behavior is maintained in relation to the sound speed, we checked the salinity of other layers (Figure 16).

Considering that the salinity and sound velocity maps correspond, Pearson's linear correlation coefficient was calculated to identify the dependence of the two variables. The value obtained was 0.898, which indicates that the data set can be modeled with a linear regression. This gave an r2 value of 0.81, demonstrating the strong association between the change in sound velocity and the salinity gradient in the study area (Figure 17).

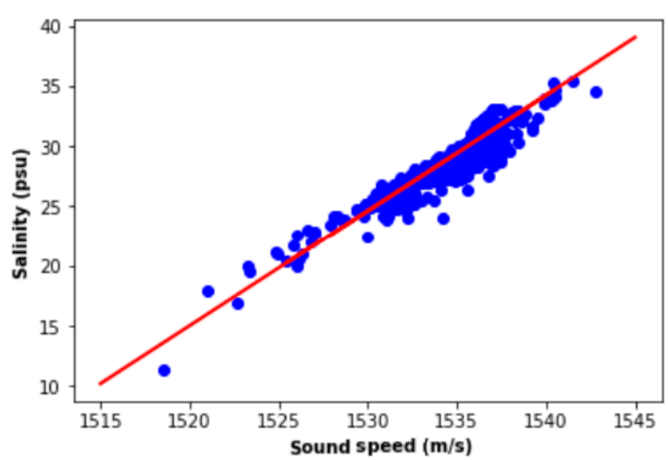


Figure 17. Salinity-sound velocity relationship in 2021.

We also evaluated three water column profiles at the deepest points of the study area using the data from 2021 (Figure 18), from which we observed the direct relationship between the sound speed and salinity. This corroborated that salinity is the variable that has the greatest influence on the behavior of the sound speed in the study area. For its part, the range of variation in temperature was identified as very narrow.

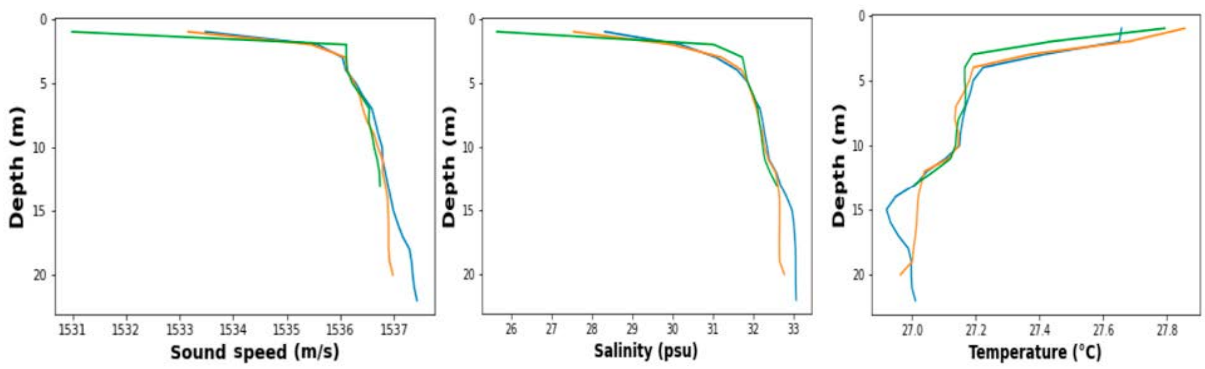


Figure 18. Profiles of sound velocity, salinity and temperature in 2021.

Finally, and to evaluate the ranges of variation in the vertical, we analyzed the behavior of the speed of sound in the water column of the stations distributed in the study area. Salinity and temperature have spatial and temporal variations (Ali, Sakira and Radhika, 2011). In the study area, it was observed that the spatial variation corresponds to characteristics of the area already identified in the horizontal mapping (Figures 19 and 20), since the study area is characterized as a coastal area receiving water from short but fast-flowing rivers, which form an area of estuaries and mouths that are subject to an exchange of marine and fluvial currents (Figure 20) (Rodríguez, 2011)

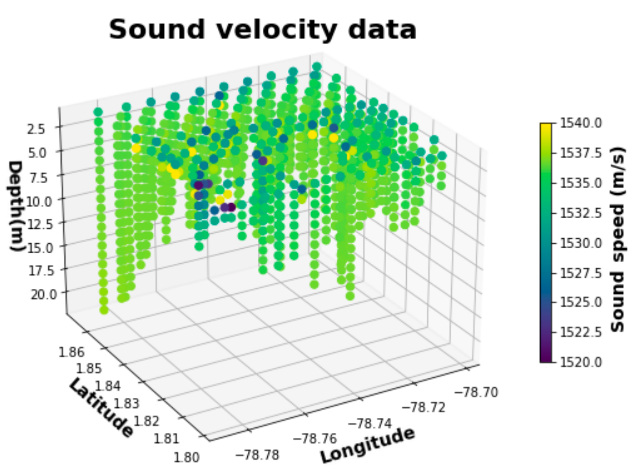


Figure 19. 3-dimensional distribution of the speed of sound in 2019.

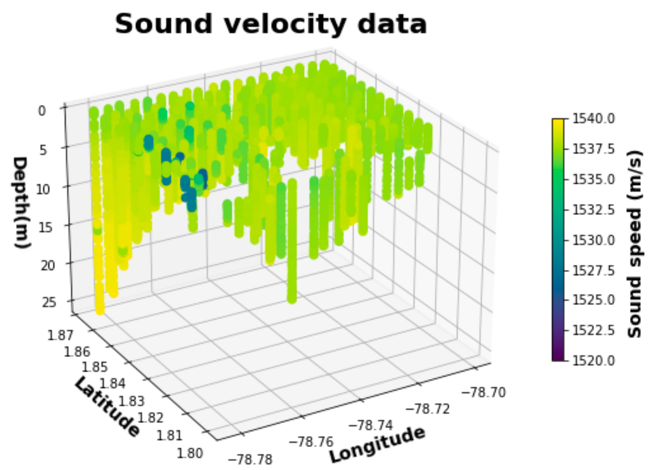


Figure 20. 3-dimensional distribution of the speed of sound in 2021.

In 2021 (Figure 20), for the sector with the greatest depth, a little farther from the coast, it was found that the speed of sound increased, in different proportions, with increases in temperature, salinity and depth (Redondo and Ruiz, 2017).

For 2019, it is observed that the data in the surface layer are less homogeneous than in the 2021 data, so we consider that one of the reasons for this variation could be due to the fact that record temperatures for the month of May were recorded on the days when the field trip was conducted (CCCP, 2019).

For the 2019 and 2021 data, the minimum sound velocity values were found in the area that the River Mira flows into. Rainfall of 313.6 mm was recorded for the month of April 2021, 63.1 mm higher than the data recorded for the month of May 2019 (CCCP, 2021). According to Reyna *et al*. (2013), the increase in precipitation has an influence on the salt concentration where the River Mira flows, which could explain the difference between the minimum sound speed values from one year to another.

Considering the sound velocity gradients in the area enables the collection of more accurate data in hydrographic surveys to map the seafloor geomorphology (Amoroso and Parente, 2021). All the information provided by the two field trips made it possible to describe the behavior of the speed of sound and the relationship with salinity and temperature in Tumaco Bay, which are useful inputs for hydrography, and oceanographic, climatological and biological modeling, among other areas.

Conclusions

The results obtained allow us to identify a representative value for the wet-season speed of sound in the study area of 1537.44 m/s for 2019 and 1536.75 m/s for 2021.

The minimum values of sound speed for 2019 and 2021, 1526.6 m/s and 1518.5 m/s respectively, are located in the 1 m depth layer, and are associated with the inputs from the River Mira, which cause changes in salinity concentration.

Zones with greater sound velocity variability were identified in specific sectors of the study area. This constitutes a relevant and necessary contribution to improve the accuracy of the data provided in hydrographic survey campaigns, which are inputs for national nautical cartography, maritime safety and hydrographic research in the Colombian Pacific. We recognize the importance of continuing with investigations that will allow these results to be verified with double calibrated or inter-calibrated equipment.

The software designed constitutes a potential contribution to hydrography, since it processes, purges and integrates the information of sound velocity profiles and the positions of the points where they were measured and generates 2D and 3D graphic outputs of the variables that influence the vertical and horizontal variation of the sound velocity in the water column.

Recommendations

It is important to carry out this study of Tumaco Bay during the dry season in order to observe and describe the behavior of the speed of sound associated with the seasonal variability of climatic conditions and river flow.

We also recommend creating a database with all the sound velocity profiles from Tumaco Bay obtained to date.

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