Cross-canyon variability in zooplankton backscattering strength in a river-influenced upwelling area

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Abstract. Zooplankton are a key component of food webs in upwelling systems. Their distribution is ~~affected~~ influenced not only by mesoscale and climate dynamics ~~,~~ but also by topography and local currents. Submarine canyons that ~~cut~~ incise the continental shelf can act as conduits~~that transport deep~~, transporting deep, nutrient-rich waters to shallower ~~areas,~~ regions and promoting coastal biological productivity. Consequently, these canyons facilitate the advection and accumulation of zooplankton. We aimed to describe the spatio-temporal variability in zooplankton distribution (~~from~~ using net samples and acoustic data) and their association with local currents ~~,~~ in a long~~and~~, narrow submarine canyon located in the highly productive continental shelf ~~of~~ off central Chile. The backscattering strength (Sv), a proxy for zooplankton biomass, was highly variable ~~at a~~ on both diurnal and spatial ~~scale~~scales. Higher Sv and abundances were found ~~during nighttime~~at night, following the classic diel vertical migration pattern. Zooplankton ~~was~~ were not uniformly distributed within the canyon. In the surface and mid-depth layers, the canyon walls accumulated more zooplankton than the center~~of it, especially during the night~~, particularly during nighttime. Within the canyon, the currents were asymmetrical and frequently ~~changed~~ reversed direction. When the positive along-canyon current was ~~more intense in the northern than in the southern~~ stronger on the northern slope, Sv was also higher ~~to the north~~on that wall. This pattern was ~~clearer~~ especially evident in the section closer to the canyon head. We show that ~~submarine canyons are highly dynamic environments where~~ the Biobio canyon is a highly dynamic environment where oceanographic conditions can rapidly ~~change and currents revert~~shift. Our findings suggest a ~~possible~~ feasible mechanism for zooplankton retention ~~based on the asymmetry of canyon currents and the changes in horizontal zooplankton distribution~~driven mainly by along-canyon flow asymmetry and vertical migrations.

1 Introduction

In the Humboldt Current System (HCS), wind-driven upwelling is the main mechanism behind the high primary productivity levels that fuel primary mechanism responsible for the high levels of primary productivity that support abundant zooplankton communities (Brink, 1983; Escribano et al., 2012; Medellín-Mora et al., 2016), even at mesoscale or larger spatial scales along the coast (Landaeta and Castro, 2002; Yannicelli et al., 2006a; Riquelme-Bugueño et al., 2012; Díaz-Astudillo et al., 2022). Other relevant mesoscale and regional drivers of zooplankton abundance and distribution in this ecosystem are coastal upwelling dynamics (Landaeta and Castro, 2002; Yannicelli et al., 2006a; Riquelme-Bugueño et al., 2012; Díaz-Astudillo et al., 2022), mesoscale eddies and fronts (Morales et al., 2007, 2010; Pavez et al., 2010; Riquelme-Bugueño et al., 2015), changes in water-mass distribution (Aronés et al., 2009), and remote low-frequency oscillations (Díaz-Astudillo et al., 2024). Although the influence of these processes on zooplankton dynamics is relatively well knownunderstood, sub-mesoscale mechanisms structuring zooplankton distribution, such as the effect interaction of coastal currents interacting with topography (Prairie et al., 2012), have been less studiedthoroughly investigated.

Abrupt changes in topography (e.g., seamounts, headlands, valleys, and submarine canyons) can lead to the retention or transport of zooplankton and micronekton through different physical mechanisms related to flows over the topography (Genin, 2004) . Submarine various physical mechanisms associated with flows interacting with topographic features (Genin, 2004). Most submarine canyons are V-shaped topographic features that interrupt the continuity of the continental shelf and/or slope for a few to hundreds of kilometers, and can be found on the continental margins of all continents in continental margins worldwide (Harris and Whiteway, 2011). They modify the geostrophic flow that normally follows the direction of the bathymetric contours. The flow flows that typically follow isobaths. Flows over submarine canyons is are dominated by advective and ageostrophic forces, particularly over the head of the canyon (Saldías and Allen, 2020), leading to the generation of baroclinic tides, internal waves, and horizontal and vertical flows that enable the exchange of surface and deep waters through mixing and advection processes (Allen and Durrieu De Madron, 2009). Generally, the presence of submarine canyons in an eastern boundary a continental margin significantly increases the transport of subsurface water from the slope to the inner shelf, promoting water exchange exchanges along the cross-shore axis on a relatively small spatial scale near the canyon (Allen and Durrieu De Madron, 2009; Connolly and Hickey, 2014)(Allen and Durrieu De Madron, 2009; Connolly and Hickey, 2014) .

Usually, negative along-slope flows (i.e. equatorward in eastern boundaries) generate upwelling in the downstream wall of the canyon, while positive flows cause downwelling (Allen and Durrieu De Madron, 2009). In central Chile, episodes of extreme upwelling have been observed at the head of the Biobío Biobio Canyon, decoupled from the wind forcing. These episodes , evidenced by the shoaling of the 10°C isotherm, occurred under weak wind conditions, with currents over the canyon in a northeast direction and negative sea level anomalies , suggesting occurred with northward flows over the head of the canyon and negative sea-level anomalies nearshore, which was coherent with the passage of coastal trapped waves (Sobarzo et al., 2016). These low-frequency waves intensify the topographic upwelling that occurs in submarine canyons (Sobarzo et al., 2016; Saldías et al., 2021)(Sobarzo et al., 2016; Saldías et al., 2021). This and other studies prove that

~~topographically induced~~ topographically-induced upwelling and downwelling respond to both wind forcing and sea level anomalies (Wang et al., 2022).

Through the upwelling of dense deep water into shallower depths, some canyons can provide ~~a similar nutrient input than~~ nutrient inputs comparable to those provided by local wind-driven upwelling (Connolly and Hickey, 2014). If ~~the~~ this deep, nutrient-rich water reaches the photic layer for a period long enough to ~~promote~~ stimulate primary productivity, canyons can become local hotspots of biological productivity and pelagic and benthic diversity (Genin, 2004; Fernandez-Arcaya et al., 2017; Santora et al., 2018). ~~Additionally~~ In addition to enhanced upwelling, increased vorticity generates surface recirculation ~~dynamics~~ patterns and asymmetric currents~~that can lead~~ , potentially leading to the formation of cyclonic eddies near the canyon rim (Connolly and Hickey, 2014)~~, which~~ . These eddies can concentrate particles or organisms~~. This mechanism of aggregation~~ , an aggregation mechanism that has been observed in a relatively shallow submarine canyon ~~in~~ on the Western Antarctic Peninsula, ~~which concentrates krill near the head of the canyon (?)~~where krill accumulate near the canyon head (Hudson et al., 2022b).

Particle transport through canyon-mediated currents can result in the concentration of potential prey in shallower waters, thus supporting trophic interactions and high predator aggregations (Genin, 2004). ~~Zooplankton is an essential component of the food webs of upwelling systems (González et al., 2004; Miller et al., 2010; Thompson et al., 2012; Ekau et al., 2018). Most zooplankton groups perform diel vertical migrations (DVM) within a 24 h period to avoid predation, swimming to deeper waters during daylight hours and returning to the surface at dusk (Bandara et al., 2021). Their vertical movements can interact with coastal wind-driven or tidal currents to match or avoid offshore advection (Castro et al., 1993; Miller and Shanks, 2004; Yannicelli et al., 20 . Because of the intensified cross-shore currents within submarine canyons , they~~ Thus, canyons are thought to be areas where accumulation of zooplankton is high and their advection is low (Vindeirinho, 1998). ~~Thus,~~ Therefore submarine canyons usually serve as foraging sites for several pelagic predators, such as whales (Schoenherr, 1991; Croll et al., 2005; Moors-Murphy, 2014; Salgado Kent et al., 2021; Amano et al., 2023; Buchan et al., 2023), penguins ~~(Clarke et al., 2006; Santora and Reiss, 2011; Schofield~~ (Clarke et al., 2006; Santora and Reiss, 2011; Schofield et al., 2013; Hudson et al., 2022b), and fish (De Leo et al., 2012; Saunders et al., 2021), among others. ~~Submarine canyons are also feeding, nursery and refuge sites for vulnerable ecosystems, as well as essential habitats for fish and invertebrate resources (Yoklavich et al., 2000; Sink et al., 2006; Cartes et al., 2010; Sigler et al., 2015; . Therefore, interest in studying and protecting these coastal habitats has grown.~~

The ~~exploration and~~ study of submarine canyons ~~in~~ along the eastern South Pacific ~~continental margin has mainly focused on their~~ margin has primarily focused on geological and physical ~~dynamics, with only few studies indirectly evaluating their role in biological processes~~ processes, with limited attention to their biological impacts (Silva and Araújo, 2021). The ~~Biobío Canyon (BBC~~Biobio Canyon (BbC) is a long canyon located in the upwelling-influenced continental shelf off central Chile (Sobarzo et al., 2016; Vergara et al., 2024). The area surrounding the ~~BBC~~ BbC provides important ecosystem services (Soto et al., 2022) ~~, and is known for having~~ and hosts abundant aggregations of zooplankton ~~(Yannicelli et al., 2006b; Landaeta et al., 2008)~~ (Yannicelli et al., 2006b; Landaeta et al., 2008) and zooplankton predators ~~(e.g. whales , Cisterna-Concha et al. (2023))~~such as whales (Cisterna-Concha et al., 2023). However, the mechanisms driving ~~its~~ enhanced biological productivity in this canyon remain largely unknown. ~~Hence, the goals of this study are~~ Thus, this study aims to (1) ~~to describe the~~ describe intra-diurnal

~~changes~~ variations in zooplankton abundance and backscattering strength over the ~~BBC after~~ BbC following an upwelling event ~~,~~ and (2) to ~~explore the~~ examine canyon-driven physical processes ~~underlaying zooplankton dynamics~~influencing zooplankton variability.

2 Data and Methods

~~The BBC~~

2.1 Study area and field cruise

The BbC is a river-influenced, shelf-incising submarine canyon located ~~in~~ on the continental shelf off central Chile ~~, to the north of the Gulf of Arauco~~ (Fig. 1). The canyon ~~is born~~ originates near the mouth of the ~~Biobío river , and it then zigzags for~~ Biobio river and extends ∼40 km ~~in~~ west–east in a zigzag pattern until reaching the shelf break. Beyond this point, it shifts to a northwest orientation to connect with the ~~W-E direction until it reaches the continental break. From then on, it takes a SE-NW orientation and extends into the~~ submarine trench and the abyssal plain, ~~adding up to~~ with a total length of 134 km (Rodrigo, 2010). Its width ~~fluctuates between~~ ranges from 3 and 9 km, and its depth ~~between~~ from 20 and ∼1200 m.

~~From July 27 to July 28, 2023, we conducted a 26 h experiment over the BBC during which we collected data on horizontal currents, acoustic backscatter, and hydrographic structure onboard the L/C Kay Kay II. Two transects were sampled 8 times each over the course of 26 h. The ship was constantly navigating from the eastern transect (ET in Fig. 1) to the western transect (WT in Fig. 1), which was located 2.1 km to the west of the ET.~~

~~On a seasonal scale, surface temperature in this area is mostly~~ In general, hydrographic conditions over the shelf north of the canyon are mainly controlled by the seasonal heat flux cycle ~~, while surface salinity is controlled by the annual cycle of the Biobío river , which outflows directly to the head of the BBC (Sobarzo et al., 2007). The Biobío river has the highest average annual discharge of all rivers in central Chile~~and the seasonal variability of the Biobio and Itata river discharges (Sobarzo et al., 2007). The Biobio River outflow, being the largest freshwater source along central Chile (Rojas et al., 2023), directly influences the hydrographic structure over the canyon head (Vergara et al., 2024), and its plume can influence a large extension of the Gulf of Arauco (Saldías et al., 2016; Vergara et al., 2024). Its annual cycle is mainly controlled by precipitation, resulting in higher discharges during the winter months ~~(Masotti et al., 2018)~~(Saldías et al., 2012). Consequently, the river plume and riverine nutrient export is higher during the rainy season (June to September~~, austral winter~~) (Masotti et al., 2018). In the region, winds are mainly driven by the Pacific anticyclone with a seasonality marked by southwestern (SW) winds during austral spring-summer and northeastern (NE) winds during autumn-winter ~~(Sobarzo et al., 2007; Ancapichún and Garcés-Vargas, 2015)~~ (Sobarzo et al., 2007; Ancapichún and Garcés-Vargas, 2015).

From July 27 to July 28, 2023, we conducted a 26-hour experiment over the BbC, during which we collected data on horizontal currents, acoustic backscatter, and hydrographic structure onboard the RV Kay Kay II. Two cross-canyon transects (eastern and western transects; Fig. 1b,c), separated by 2.1 km, were sampled 8 times each during the 26-hour cycle.

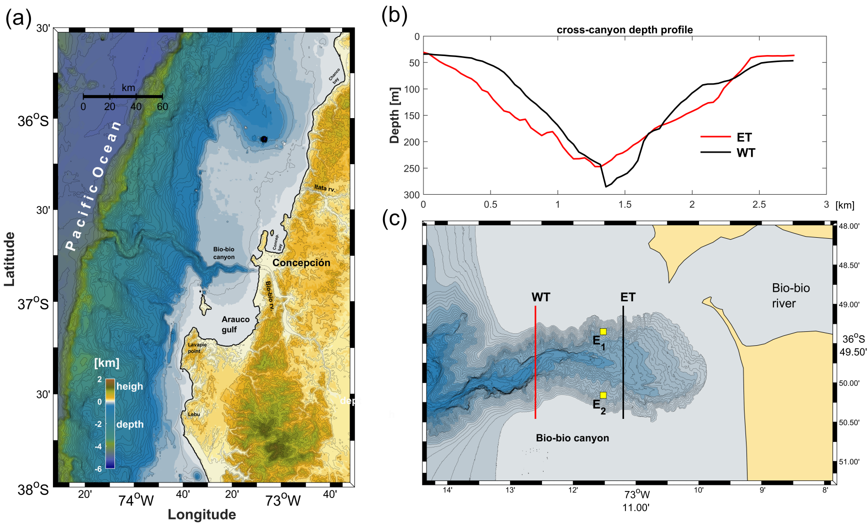

Figure 1. (a) Location of the ~~Biobío~~ Biobio Canyon ~~in~~ on the continental shelf and slope ~~of~~ off central Chile. ~~The~~ (b) Bathymetric profiles of the western transect (WT) ~~is portrayed in red,~~ and ~~the~~ eastern transect (ET), are shown in red and black, respectively. ~~The bathymetric profile~~ (c) Zoomed-in view of ~~both transects is shown in~~ the ~~upper panel. Zooplankton samples were taken at~~ area around the canyon head, showing the positions of WT and ET, as well as the locations of stations E1 and E2 where zooplankton samples were collected.

2.2 Hydrographic conditions

Temperature, salinity and chlorophyll-a (chl-a) profiles were obtained with a rapid-response ~~towel~~ towed CTD (Teledyne Valeport ~~Rapidpro~~ RapidPro CTD) equipped with a fluorescence sensor. The CTD was deployed ~~at each navigation along the transects~~ during each pass along WT and ET (Fig. 1)~~with a total of~~ , completing 14 transects for the entire sampling period ~~. Each downward profile was obtained by releasing the instrument at free fall constant speed, and the subsequent upward profile was retrieved by the help of a winch system. Measurements comprise~~ (Supplementary Table 1). Measurements extended from the surface ~~down to~~ to a depth of 100 m ~~depth~~ in the canyon~~area, or up to near the bottom in the area~~ , or to near-bottom depths outside the canyon, with ~~a temporal resolution~~ all sensors recording at a frequency of 4 Hz ~~for all sensors~~. The transects were ~~surveyed with a maximum of~~ conducted at intervals of no more than 2 hours~~between each one and then~~ , and were interpolated using the Barnes objective analysis scheme (Barnes, 1994).

2.3 Winds, tides and river discharge

Hourly ~~reanalysis wind data were downloaded~~ wind reanalysis data were obtained from ERA5 product (https://cds.climate.copernicus.eu/)~~which is the fifth generation ECMWF for the~~ , the fifth-generation global climate and weather ~~. The ERA5 data are gridded in a~~ dataset from ECMWF (Hersbach et al., 2020), at a spatial resolution of 0.25~~ºx0.25~~º ~~(e.a.~~ × 0.25º (31 ~~x~~ × 31 km)~~spatial resolution. The nearest pixel of the grid to the location was selected to download the u (east-west) and~~

v(north-south) components (. Wind components (u and v, at 10 m above the surface) of the wind product (more details (Hersbach et al., 2020)). The tide data from Concepcion Bayheight) were extracted from the grid point nearest to the study site. Tide data for Concepción Bay, recorded at 1-minute intervals, were downloaded from the Sea Level Monitoring Facility (https://www.ioc-sealevelmonitoring.org/list.php) , which were recorded every 1 minute. This tide gauge is part of the Chilean monitoring network from Servicio Hidrografico y Oceanografico and provided by the Chilean Navy Hydrographic and Oceanographic Service (SHOA)of the Chilean Navy (). The discharge data of the Biobío river were downloaded from Direccion . Daily discharge data for the Biobio River, near its mouth, were obtained from the Dirección General de Aguas (DGA; https://snia.mop.gob.cl/dgasat/pages/dgasat_main/dgasat_main.htm) which maintains a network of discharge monitoring stations in Chile. Daily discharge values measured close to to quantify freshwater input into the Biobío river mouth were used to characterize the freshwater input of the region.

2.4 Currents

Underway currents Velocity and acoustic backscatter profiles were measured during the navigation track using a downward looking collected along ET and WT using a downward-looking 153 kHz Quartermaster Teledyne RDI Acoustic Doppler Current Profiler (ADCP). The ADCP was , mounted on a stainless steel arm on the side of the ship and fixed to have the transducers with transducers about 1 m below the surface. Real-time measurements were recorded acquired in bottom-track mode with a maximum ship at a maximum vessel speed of 2 knots (2.5 $m^3\ s^{-1}$). The ADCP configuration considered to acquire currents profiles using was configured to collect data in 120 cells of vertical cells (3 m bin sizewith) at a 1 s pings and recorded every ping rate, with a sampling time interval of 4 s. The first bin was located centered at 4.31 m from the ADCPand the maximum range was , with a profiling range up to 350 m. Currents were recorded as earth components u (zonal (u; east-west) and v(meridional (v; north-south) . This coordinate reference was maintained along the entire analysis. components.

The quality Quality control of the current profiles considered the elimination of obviously involved removing erroneous data from each circuit, a standard criteria of goodness over goodness-of-fit criterion greater than 50%, flows < excluding flow speeds exceeding 10 $m\ s^{-1}$, and error less than ensuring velocity errors below 0.008 $m\ s^{-1}$. Additionally, we only considered the profiles whose difference between the ADCP bottom track recorded speed and the GPS speed were only profiles for which the difference between ADCP bottom-track speed and GPS-derived speed was less than 0.30 $m\ s^{-1}$ (e.g. Lwiza et al. (1991); Cáceres et al. (2006); Castillo et al. (2012)). The second criteria considered the correction of the directionDirectional correction was also applied, since the ADCP's magnetic compass can be influenced by the vessel's magnetic field and by local magnetic compass is affected by the magnetic fields generated by the displacement of the vesseland by the local magnetic deviation (Joyce, 1989; Pollard and Read, 1989; Trump and Marmorino, 1997). The residual anomalies (Joyce, 1989; Pollard and Read, 1989; Trump and Marmorino, 1997). Residual currents were estimated for each component (u and v) for using least-squares harmonic fitting for the principal tidal components K1 (23.93 h) and M2 (12.42 h) by the least-square fitting analysis following the procedure suggested by following Lwiza et al. (1991). The results of the harmonic analysis and the residual circulation revealed that the tidal currents were (weak, with amplitudes $< 0.05\ m\ s^{-1}$).

2.5 Zooplankton backscattering strength

To ~~study high resolution changes~~ investigate high-resolution variations in zooplankton abundance over the ~~BBC~~BbC, we converted the ADCP ~~'s echo counts to~~ echo intensity into mean volume backscattering strength (MVBS)~~. The MVBS (hereafter called Sv,~~ , denoted as Sv (dB re 1 m^{-1})~~is often used to observe~~ . MVBS is widely used to asses zooplankton distribution and behavior~~as it gives high resolution~~ , offering high-resolution data collected passively and ~~simultaneously with current data~~ concurrently with current measurements (Fielding et al., 2004; Dwinovantyo et al., 2019; Cisewski et al., 2021). Sv was ~~computed~~ calculated for each depth cell ~~following~~ using the sonar equation originally proposed by Deines (1999) and modified by Mullison (2017):

$$Sv = C + 10log_{10}[(Tx + 273.16)R^2] - 10log_{10}L - P_{DBW} + 2\alpha R + 10log_{10}(10^{K_c(E-E_r)/10}) - 1 \quad (1)$$

~~In this equation C~~ where C is a sonar-configuration scaling factor (-161.01 dB) that is specific to the RDI Workhorse ~~QuarterMaster~~ ADCP, *Tx* is the temperature at the transducer (°C), *L* is the transmit-pulse length (2.85 m), *PDBW* is the 10log10 of the output power (15.72 W), α is the depth-variable sound absorption coefficient (dB m^{-1}), *E* is the recorded automatic gain control (AGC or "echo counts"), and *Er* is the echo reference, determined as the minimum AGC recorded for each beam in the absence of any acoustic signal (40 counts). ~~*Kc*~~ Kc is a beam-specific sensitivity coefficient used to convert the raw echo data into dB, and it was calculated following Bozzano et al. (2013) as:

$$Kc = \frac{127.3}{Tx + 273.16} \quad (2)$$

Finally, ~~R~~ R is the slant range to the sample bin (m), which uses ~~the~~ depth as a correction (Lee et al., 2004)~~. Therefore, R~~ , and it is expressed as:

$$R = \frac{B + \frac{L+d}{2} + ((n-1)d) + \frac{d}{4}}{(cos\theta)} \frac{C^-}{C_I} \quad (3)$$

where ~~B~~ B is the blanking distance (3.23 m), ~~d~~ d is the depth cell size (3 m), ~~n~~ n is the depth cell number of the particular scattering layer being measured, θ is the beam angle (20°), C^- is the average sound speed from the transducer to the depth cell (1453 m s^{-1}) and C_I is the nominal sound speed used by the instrument (1454 m s^{-1}). According to the ~~the~~ ADCP's ~~manufacturers~~ manufacturer manual, the maximum range of acceptable data (Rmax) is defined by:

$$R_{max} = H\cos\theta \quad (4)$$

where ~~H~~ H is the distance between the instrument and the bottom. ~~All~~ To minimize potential seafloor interference, all data below Rmax ~~was eliminated, which contributed to reducing any potential seafloor noise~~were excluded. A minimum ~~correlation~~

beam correlation threshold of 25% among beams was used. If was applied to ensure data quality. Bins where the Sv of a given single beam exceeded the mean Sv of the other 3 beams by three beams by more than 5 dB , the bin was discarded. This process assures echo count consistency among the beams and eliminates were discarded, a procedure that enhances consistency among beams and helps eliminate signals from large scatterers (Jiang et al., 2007). The 4 Subsequently, data from the four beams were averaged, and a median filter was applied to smooth the signal. The final Sv was then gridded at a horizontal spatial resolution of 40 mSubsequently, data from the four beams were averaged, and a median filter was applied to smooth the signal. Finally, all Sv values exceeding -40 (dB m^{-1}) were removed to further reduce the influence of large scatterers (e.g. fish with swim bladders) on the total volume backscattering strength.

After carefully analyzing the vertical distribution of the scatterers, 3 acoustic scatterers, three distinct layers were identified based on their average Sv and diurnal behavior: a surface layer extending from the surface to 25 m deepdepth, a mid-depth layer from 25 to 100 mdeep, and a deep layer from 100 m to the bottom. These layers were later seafloor. The delineated layers were subsequently used to compare the Sv and horizontal flows between transects and slopes. geometric-mean Sv values and horizontal flow dynamics across different transects and slope regions. The geometric-mean allows to compare relative changes in Sv while considering that the MVBS is a logarithmic measure of backscattering cross-section per unit volume.

2.6 Zooplankton sampling

Stratified A total of eight stratified zooplankton samples were taken at 2 stations (collected at stations E1 and E2 in Fig. 1(Fig. 1c) during both daytime and nighttime. To avoid interfering with the continuous hydrographic and acoustic sampling that took place conducted between 8 PM on July 27 and 10 PM on July 28 (local time), the zooplankton sampling was conducted before (performed before and after the experiment (see details in Supplementary Table 2PM on July 27) and after (1 AM on July 29) the experiment). A Tucker Trawl net (with a 1 m^2 of mouth area and 300 μm of mesh size) mesh size, equipped with a General Oceanics flowmeter, was deployed to a depth of 100 m depth and then obliquely towed and then towed obliquely to the surfaceto obtain 2 , obtaining two stratified samples from 100-50 m and 50-0 m. The sample was Samples were fixed with 5% buffered formaldehyde for subsequent taxonomic analyses. In the laboratory, zooplankton groups were identified and quantified, and the abundance was with abundances standardized to individuals per 1000 m^3.

3 Results

3.1 Oceanographic conditions

To put the observations in the context of the environmental conditions for the region, the time series of the wind vector, Biobío river discharge and Concepcion Bay tides were obtained for July-August 2023 (Fig. 2). During July-August, the winds were mainly from the south with intensities below 12 m s^{-1}, and the northern winds were weak (c.a. 5 m s^{-1}). An event of strong upwelling-favorable winds took place right before the sampling . During the ADCP measurements, winds were weak and mainly from the north. The tidal cycle was in late ebb with a range of 1 m and a river discharge of ~1600 m^3 s^{-1}.

~~Time series of wind vectors, Biobío river discharge, and tidal cycles during the study period (in gray).~~

~~The~~ occurred prior to sampling (Fig. S1). The water column was highly stratified ~~due to the Biobío river input . The first~~ primarily due to freshwater input from the Biobio River. The upper 20 m ~~of the water column had lower salinity , lower temperature and higher~~ were characterized by lower salinity and temperature, along with elevated chl-a ~~concentration than the rest of the water column~~ concentrations (Fig. ~~3~~ 2 and Figs. ~~S1 to S4~~S2 to S5). In ~~the upper 20 m, the ET had relatively higher chl-a and lower temperature and salinity than the WT due to its closer position to the Biobío river~~ this surface layer, the eastern transect (ET), located closer to the river mouth, displayed higher chlorophyll-a levels and lower salinity and temperature than the western transect (WT) (Fig. ~~3 A and B~~2a,b). Below 20 m~~deep, the~~, temperature and salinity ~~diagrams show~~ profiles indicated the presence of ~~the~~ Equatorial Subsurface Water ~~, which is typical for the area and intrudes in the coast~~ (ESSW), a water mass typical of the region that intrudes onto the shelf during upwelling conditions (Sobarzo et al., 2007). ~~Below 20 m the WT and ET were similar in their hydrographic structure~~At these depths, both transects exhibited similar hydrographic structures, with the ~~greatest change~~ most notable changes occurring around the 1025.6 kg m^3 isopycnal. The WT had a slightly higher proportion of ~~data~~ measurements within the 33.4 to 34 salinity range, which ~~presented the highest chl-a values within~~ corresponded to the highest chlorophyll-a values observed at that depth (Fig. ~~3 C and D~~2c,d).

The pycnocline~~was defined as~~, defined by the 1025.6 kg m^3 ~~density contour. Its depth fluctuated through time and~~ isopycnal, exhibited temporal and spatial variability along the cross-canyon axis (Fig. ~~4). In general, the pycnocline~~ 3). Generally, it was shallower in the ~~ET, shifting~~ WT, ranging between 15 and 35 m depth~~. In the WT, its depth varied between~~, while in the ET, it varied from 12 ~~and~~ to 30 ~~m~~meters. In the WT, the pycnocline was ~~∼~~approximately 10 ~~m~~ meters deeper on the southern slope (SS) of the canyon~~, while~~. Conversely, in the ET~~the pycnocline had~~, it maintained a similar depth on both ~~walls, although~~ slopes, though it was slightly shallower on the northern slope ~~during the first~~ (NS) during the initial 18 ~~h of the study~~hours of observation. In both transects~~the pycnocline got deeper through timeand reached~~, the pycnocline deepened over time, reaching its maximum depth by the end of the study period.

3.2 Horizontal flows over the canyon

The mean flow ~~in both the WT and ET is~~ patterns in both transects are shown in Fig. ~~5~~4. In both ~~transects,~~ sections, the zonal (u) component exhibited a mean offshore (i.e., negative) flow ~~was observed~~ from the surface ~~to~~ down to approximately 50 m~~deep in the u component. From~~. Between 50 m ~~to~~ and ∼200 m the mean flow in the WT ~~was~~ became positive and centered ~~in~~ within the canyon (Fig. ~~5 A), and positive and tilted to the northern slope~~ 4a), while in the ET it was also positive but inclined toward the NS (Fig. ~~5 B). From~~ 4b). Below 200 m~~to the bottom the flow became negative again, although the standard deviation of the flow was high at~~, the flow turned negative again. However, flow variability increased considerably, as indicated by the large standard deviations in both transects (Fig. ~~5 C and D~~4c,d). The ~~v~~ meridional (v) component showed a positive ~~flow in the surface layer it~~ (i.e., northward) surface flow in both transects, ~~although velocities were slightly higher~~ with slightly higher velocities in the WT (Fig. ~~5 E and F). The northward direction of the surface flow suggests that it possibly is a~~ 4e,f), suggesting the influence of wind-driven ~~flow. From~~ forcing. Below 50 m~~to the bottom, the flow was negative and had a high standard deviation~~, the meridional flow reversed and remained highly variable down to the bottom (Fig. ~~4 G and H). The rise in the~~

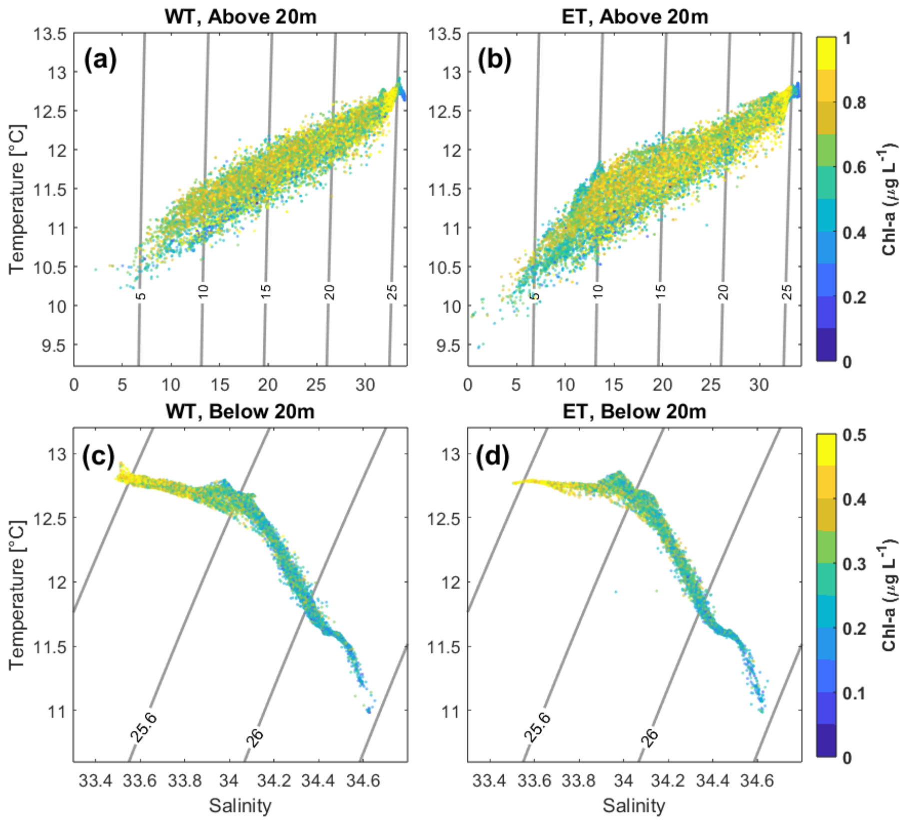

Figure 2. ~~Temperature and salinity~~ Temperature-salinity plots ~~showing~~ for all sections along the ~~western~~ WT (~~A~~ a and ~~C~~c) and ~~eastern~~ ET (~~B~~ b and ~~D~~d)~~transects together~~. ~~The colors of~~ Panels (a) and (b) show the ~~dots represent chlorophyll-a concentrations. The~~ upper 20 m of the water column~~(~~, while panels ~~A and B) are plotted separately than the rest of the water column~~ (~~panels C~~ c) and ~~D~~(d) represent the deeper layers. Colors indicate chlorophyll-a concentrations.

~~standard deviation~~ 3g,h). Notably, the increased standard deviations (> 0.1 m s^{-1}) in both ~~the~~ cross- and along-shore ~~currents in the deeper area of the canyon suggests that the flow is highly variable~~ components indicates enhanced flow variability near the canyon floor.

Spearman rank correlations between the ~~flow in~~ currents on the NS and SS revealed differences in the ~~behavior of the current~~ flow variability between the ET and the WT, ~~and~~ as well as between the cross- and along-shore flow. In the ET, ~~none of the layers had correlated u-velocities~~ no significant correlations were found in the zonal velocities between the northern and southern slopes. ~~Only~~ In contrast, only the deep layer of the WT ~~had~~ exhibited a positive correlation between the cross-shore flow ~~in the NS and the SS~~ between the two slopes (Fig. ~~6 a, b and c~~5a-c). On the other hand, the along-shore velocities ~~in~~ between the NS and SS were highly correlated ~~in the~~ across all 3 ~~analyzed~~ layers of the ET. In the surface layer, this suggests that the northward flow ~~of~~ associated with the river plume equally affected ~~the northern and southern sections~~ both sides of the canyon. In the WT, ~~only the mid-depth layer had correlated~~ a significant correlation in v-velocities ~~in the northern and~~

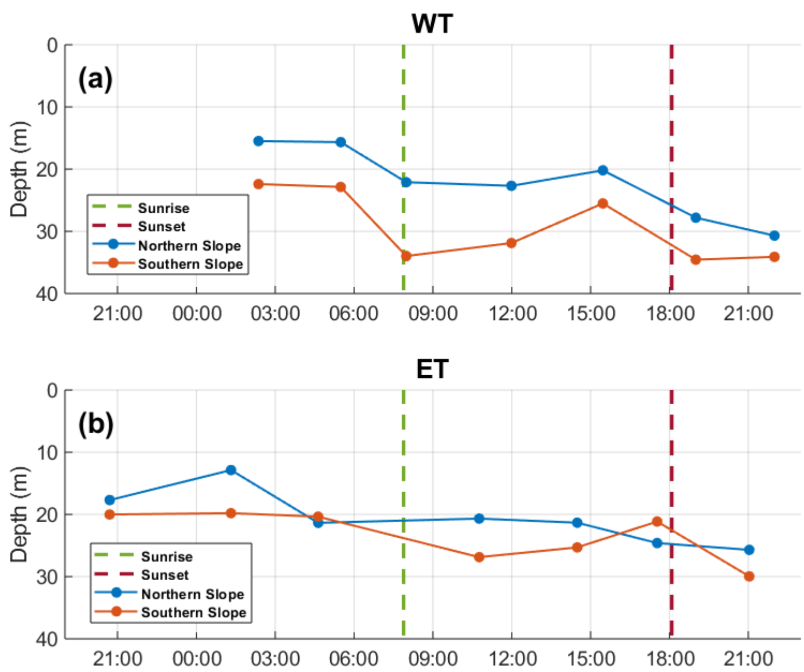

Figure 3. Evolution of ~~the depth of the~~ pycnocline ~~through~~ depth over time in the ~~WT~~ (~~upper panel~~a) WT and ~~ET~~ (~~lower panel~~b) ET. The blue line ~~represent~~ represents the NS, and the red line ~~,~~ represents the SS.

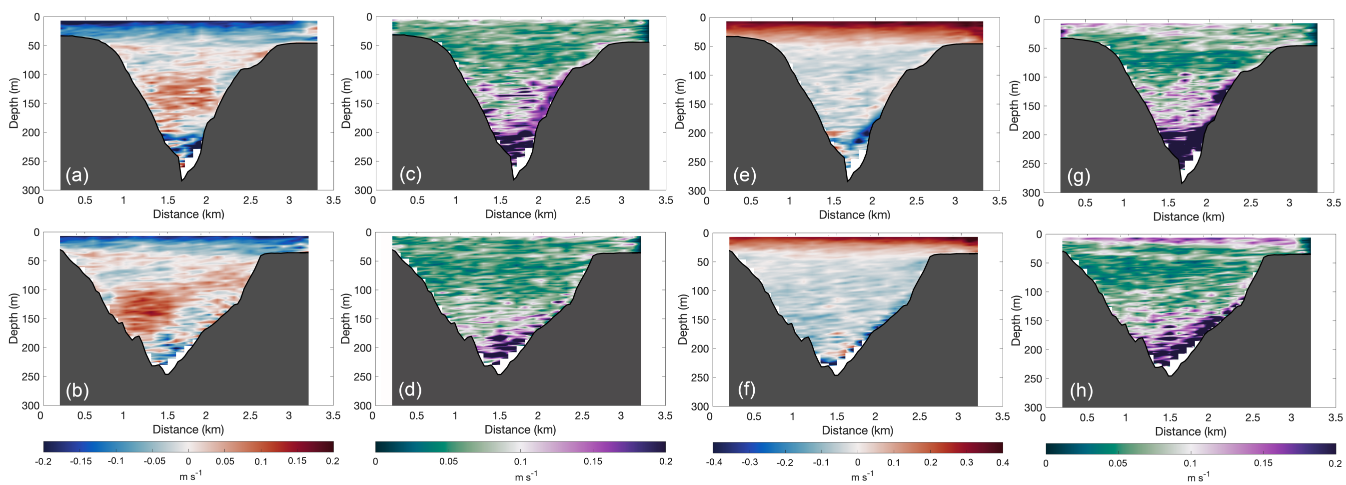

Figure 4. Mean cross-shore velocities in the ~~WT~~ (~~A~~a) WT and ~~ET~~ (~~B~~b) ~~and~~ ET with their respective standard deviations shown in (~~C~~ c) and ~~D~~(d), and mean along-shore velocities in the ~~WT~~ (~~E~~e) WT and ~~ET~~ (~~F~~f) ~~and~~ ET with their respective standard deviations in (~~G~~ g) and ~~H~~(h). Positive cross-shore velocities indicate onshore flow, while positive alongshore velocities indicate equatorward flows.

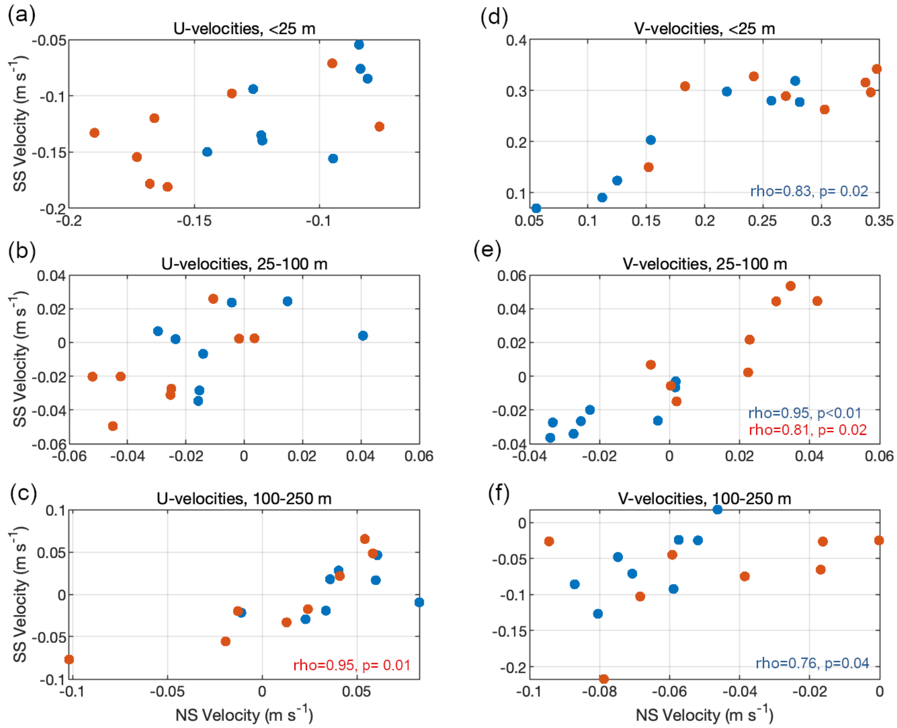

Figure 5. Correlations between the mean flow in the northern slope (NS) and southern slope (SS) for both the WT (red dots) and ~~the~~ ET (blue dots), shown by layer. When significant, the correlation coefficient and ~~p-values~~ p-value are ~~shown~~indicated.

~~southern slopes~~ was observed only at mid-depth (Fig. ~~6). The~~ 5). These differences in the ~~response of the flow between the NS and the SS~~ flow over the slopes suggest that the cross-shore flow is ~~much more prone to vary~~ more variable inside the canyon ~~that~~ compared to the along-shore flow. Consequently, we further ~~looked into~~ investigated the variability of the cross-shore (i.e. along-canyon) ~~flow~~component.

We identified the section of the canyon where ~~bottom depth was >~~the bottom depth ranged between 60 and ~~<~~120 m~~deep. We then averaged the~~ , and computed the time-depth evolution of the cross-shore velocity ~~to see its evolution through time and by depth,~~ at each slope. In both the NS and SS of the WT, the first 40 m of the water column ~~had negative~~ exhibited negative (offshore) velocities throughout the study period. ~~From~~ Between 40 ~~to~~ and 120 m the velocities were predominantly positive (onshore) in the NS, except during the first 3 hours and at the end of the experiment, when the ~~velocities shifted~~ flow reversed and became strongly negative ~~in the NS~~ (Fig. ~~7 A~~6a). In ~~the SS~~contrast, velocities in the ~~40-120 m deep section~~ 40–120 m layer of the SS remained variable, alternating between ~~periods of~~ positive and negative velocities (Fig. ~~7 B~~6b). Consequently, the ~~difference in the velocity magnitude between both slopes also alternated between periods of positive and negative differences~~velocity difference between the two slopes also fluctuated over time, indicating a stronger ~~current in the southern slope~~ flow on the SS at the end of the experiment (Fig. ~~7 C~~6c). The ET also ~~had mostly~~ exhibited predominantly negative velocities in the upper 40 m ~~of the water column, both in~~ at both the NS and SS. ~~In the NS, the rest of the water~~

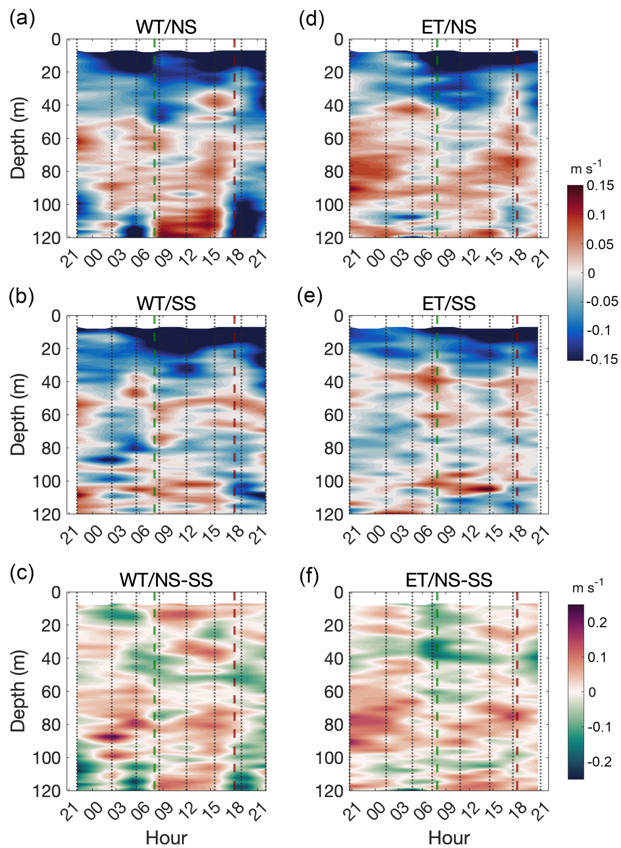

Figure 6. Mean cross-shore currents by depth and time ~~,~~ in a section of the canyon walls where bottom depth ~~was 60-120~~ ranged from 60 to 120 m~~deep~~. ~~The currents~~ Currents over the northern slope (NS, upper panels) and southern slope (SS, middle panels) are shown of both the WT (~~left panels~~a, ~~A and B~~b) and ET (~~right panels~~d, ~~D and E~~e)~~are shown~~. The difference in ~~the~~ current magnitude between the NS and SS is shown in panels ~~C~~ c (WT) and ~~F~~ f (ET). ~~The~~ Vertical gray dotted lines ~~overlaying~~ indicate the ~~plots represent the~~ time of each transect; the green dashed line marks the sunrise, and the burgundy dashed line marks the sunset.

~~column had mostly~~ Below this layer, the NS displayed mainly positive velocities throughout the experiment (Fig. ~~7 D), while the SS presented mainly~~ 6d), whereas the SS exhibited predominantly negative velocities (Fig. ~~7 E~~6e). The ~~differences between both~~ velocity difference between the slopes was variable in the upper 40 m~~of the water column, and mostly~~ , but consistently positive in the deeper section, indicating stronger (and onshore) along-canyon currents in the ~~northern slope~~ NS (Fig. ~~7 F~~6f).

3.3 Zooplankton spatial and temporal variability

~~The Sv~~Mean volume backscattering strength (Sv) over the canyon ~~had high~~ exhibited pronounced temporal, vertical~~and spatial (~~, and spatial variability, both between transects and ~~slopes) variability~~between the NS and SS. Some of the ~~changes observed in the Sv were also observed in the zooplankton samples. The more evident pattern present~~ patterns observed in Sv corresponded

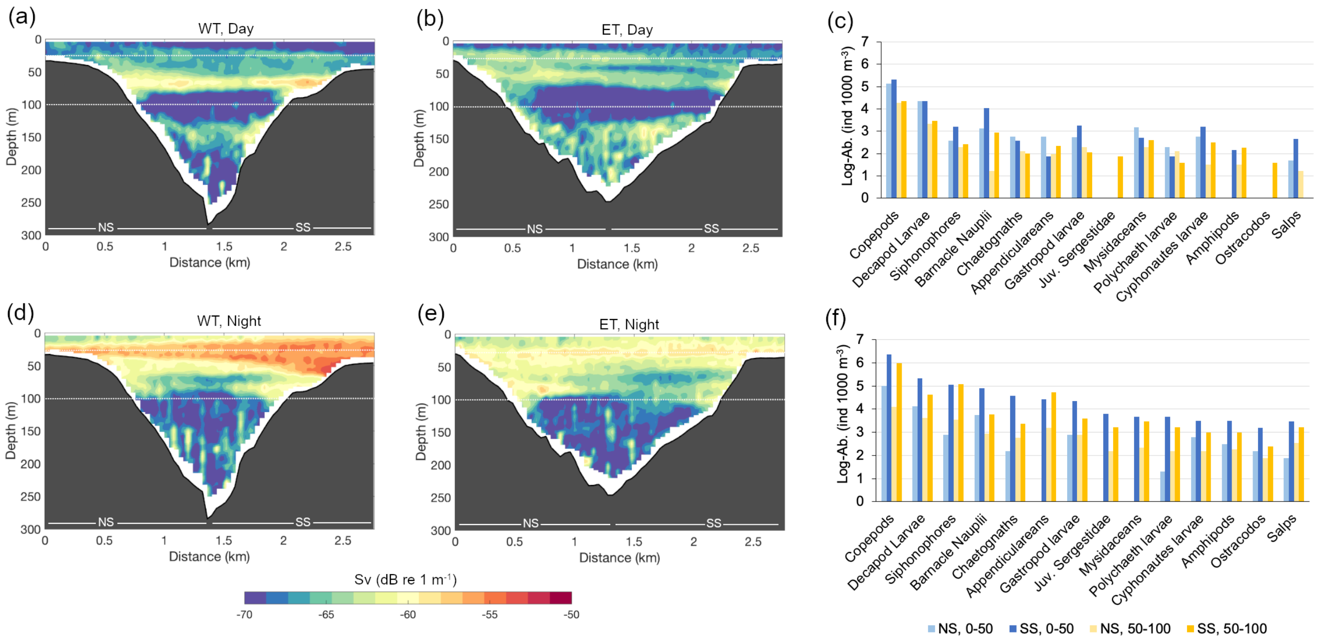

Figure 7. Selected Sv sections ~~over~~ along the western transect (WT) and eastern transect (ET). ~~A: first~~ First diurnal section along the WT ~~;~~ ~~B: first diurnal~~ (a) and ET (b). ~~D: last~~ Last night section along the WT ~~. E: last night~~ (d) and ET (e). Standardized zooplankton abundances by group (~~collected in~~ from stations E1 and E2 ~~close to the~~ near ET) ~~are shown in panel C~~ for samples collected during the day prior to the ~~beginning of the~~ experiment (daytime~~)~~, c) and ~~in panel F for samples collected~~ after the end of the experiment (nighttime, f). Labels NS ~~:~~ ~~northern slope,~~ and SS ~~:~~ in panels (a,b,d,e) indicate the locations of northern and southern ~~slope~~slopes, respectively. Horizontal dotted lines indicate the boundaries of the 3 layers used for layer analyses.

with zooplankton abundance estimates from net tows. The most evident feature in the Sv sections was the ~~higher observed Sv in the night transects, both at~~ consistent increase in Sv during nighttime hours in both the WT and ET (~~Fig. 8 and S5). The biological samples taken near ET showed that most of the zooplankton groups also exhibited higher abundances during the night (Fig. 8). The cross-canyon Sv sections also showed differences~~ Figures 7 and S6). Zooplankton samples collected near the ET also showed higher nighttime abundances across most taxonomic groups (Figure 7). Differences in Sv between the ~~northern and southern slopes, which changed with time. Zooplankton samplesalso showed this pattern. By~~ NS and SS closely mirrored cross-canyon differences in zooplankton abundance from net samples. For instance, toward the end of the experiment, ~~higher abundances were found on the southern slope, and Sv was also significantly higher in the southern wall (Fig. 8~~standardized zooplankton abundances were higher on the SS (Figure 7f), corresponding with significantly elevated Sv values on the same slope (Figure 7d). These ~~results validate the use of the acoustic data~~ matching patterns support the reliability of acoustic measurements as a proxy for zooplankton ~~abundance~~distribution in the BbC.

~~The canyon slope and diurnal differences in backscattering strength changed~~ Diurnal and slope-related differences in Sv varied not only over time ~~,~~ but also with depth. The surface layer ~~had high~~ exhibited pronounced intra-diurnal ~~temporal~~

~~fluctuationsin the Sv values, with evident higher Sv during the night~~fluctuations, with consistently higher Sv values during nighttime. In the WT, the difference ~~in Sv~~ between the lowest daytime and the highest ~~values was ∼~~nighttime Sv reached approximately 12 ~~db re 1 ms~~dB re m^{-1}~~. In~~, whereas in the ET, this difference ~~reached~~ increased to ∼18 dB re ~~1 ms~~m^{-1} (~~Fig. 9 A and B~~Figure 8a,b). In the ET, the mid-depth layer ~~had~~ displayed the highest mean Sv values, while in the WT~~its values were similar than those~~ , mean Sv in the mid-depth layer was comparable to that of the surface layer. In both transects, the ~~U-shape of the lines representing the mean Sv evidenced an effect of the canyon shape on zooplankton abundances (Fig. 9 C and D). This translated in higher abundances over the northern and southern~~ U-shaped profiles of mean Sv values revealed an influence of canyon topography on zooplankton distribution, with higher abundances observed over the slopes than in the central ~~area of the canyon~~ canyon axis (Figure 8c,d). In the mid-depth layer, the diurnal ~~pattern~~ signal in Sv was ~~clear (especially~~ still evident, particularly over the canyon ~~slopes), but less intense~~ walls, though less pronounced than in the surface layer. ~~The~~ In contrast, the deep layer showed ~~little change in Svwith time. The evident diurnal differences found in both the surface~~ minimal temporal variations in Sv. The clear diurnal differences observed in the upper and mid-depth layers were ~~not found in the deeper layer, where the diurnal differences were negligible (Fig. 9 E and F). The~~ largely absent at depth, where Sv remained relatively constant throughout the day (Figure 8e,f). Nevertheless, the topographic effect of the canyon ~~shape was also present in the deeper layer, observed as higher Sv~~ was still apparent in the deep layer, with higher Sv values near the canyon walls ~~, and lower Sv in the central area of the canyon~~compared to its center.

To compare ~~the Sv between the northern and southern canyon slopes, we repeated the method previously done with the u-velocities. The section of the canyon where bottom depth was >60 and <120 m deep was identified to then average the Sv to see its evolution over time on each slope. We also~~ Sv between NS and SS, we applied the same methodology previously used for u-velocity analysis. Additionally, we calculated the Sv difference between the ~~northern and southern sections and correlated that with the horizontal flows in each layer. Several~~ NS and SS and associated it with horizontal current velocities in each depth layer. Distinct differences in the vertical distribution of zooplankton were observed between ~~slopes, at~~ the slopes in both transects. ~~The NS of the WThad high Sv in the 20-80 m water column section during the entire~~ In the WT, the NS consistently exhibited elevated Sv values between 20 and 80 m throughout the study period (~~Fig. ?? A). The SS of the WT consistently showed a layer of~~ Figure 9a). On the SS, a ∼20 m ~~width with high Sv values~~thick high-Sv layer was present, which deepened during ~~the day~~ daylight hours and became shallower and ~~wider during the second night (Fig. ?? B). The intensity of the backscattering strength was higher in~~ thicker (up to ∼100 m thick) during the night (Figure 9b). Backscatter intensity was generally higher on the SS, ~~thus the difference in Sv~~ resulting in predominantly negative Sv differences between the NS and SS ~~was mostly negative throughout the study Fig. ?? C). In~~ throughout the ~~NS of the ET, high Sv values (>~~deployment (Figure 9c).

In the ET, Sv values exceeding 63 dB re ~~1 ms~~m^{-1} ~~) were present in almost the entire~~ were observed across much of the NS water column during the first 12 ~~h of the study (Fig. ?? D~~hours (Figure 9d). Later in the day, Sv ~~decreased and low values were observed within the first~~ values declined in the upper 50 ~~meters of the water column. Surface Sv increased again~~ m, followed by a new increase near 8 PM. ~~In the SSof the ET high~~ On the SS, elevated Sv values were ~~observed only between the 20-50 m layer in the first~~ confined to the 20–50 m layer during the initial 12 h of the study~~. Near 9 AM, that~~ , but this layer deepened

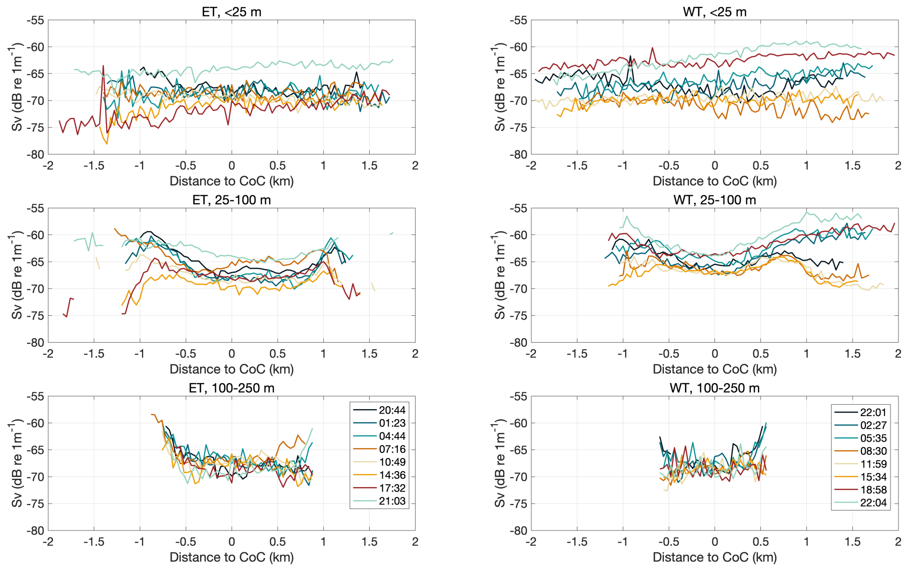

Figure 8. Mean Sv in the surface (upper panels), mid-depth (middle panels) and deep (bottom panels) layers along the WT and ~~ETs~~ET. Each of the 8 ~~tracks~~ transects along the western (left panels) and eastern (right panels) transects ~~are~~ is represented by a different ~~colors~~color. Distance ~~was~~ is referenced to the center of the canyon (CoC), ~~identified~~ defined as ~~the~~ its deepest point ~~of it, in order~~ to facilitate the comparison between the ~~northern~~ NS and ~~southern slopes~~SS. Negative ~~distances represents the northern slope, and~~ (positive) distances correspond to the northern (southern) slope.

and ~~its intensity decreased (Fig. ?? E~~weakened around 9 AM (Figure 9e). The ~~difference in Sv~~ Sv difference between the NS and ~~the~~ SS of the ET ~~was~~ reached ∼10 dB re ~~1~~ m^{-1} ~~between~~ in the 50~~and~~–120 m layer at the beginning of the study, ~~which agreed with strong differences in the~~ coinciding with pronounced differences in along-canyon ~~currents (i.e. higher velocitiesin the northern wall~~ current velocities—specifically, stronger flows on the NS of the ET~~)~~. Although this difference decreased ~~with~~ over time, the NS consistently ~~had~~ exhibited higher Sv within ~~that layer~~ this depth range compared to the SS (~~Fig. ?? F~~Figure 9f).

4 Discussion

The “canyon hypothesis” suggests three main mechanisms by which submarine canyons promote local biological productivity~~(?Genin, 2004)~~. The first ~~is related to~~ involves the fertilization of surface and subsurface layers ~~through~~ via the advection of deeper, nutrient-rich waters to the surface (i.e. “topographic upwelling~~), which should last~~ ”). For this mechanism to support biological productivity, the upwelling must persist long enough to allow phytoplankton and zooplankton populations to ~~reproduce and increase in abundance~~grow and accumulate. The second mechanism involves the generation of a subsurface eddy ~~, which causes isopycnal domingand consequently leads to upward water~~ that induces isopycnal doming, thereby enhancing

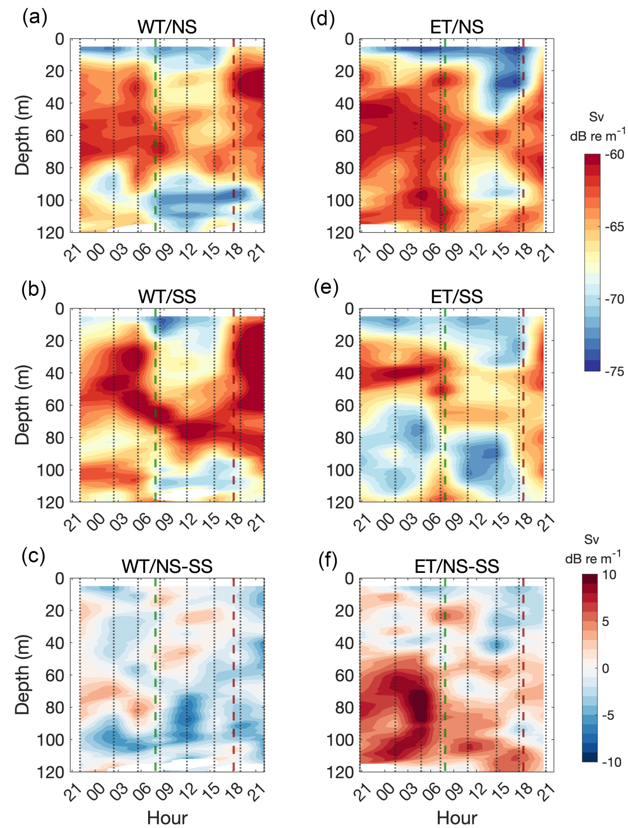

Figure 9. Mean Sv currents by depth and ~~Sv difference~~ time in a section of the canyon walls where bottom depth ~~was 60-120~~ ranged from 60 to 120 m~~deep~~. ~~The~~ Sv over the northern slope (NS, upper panels) and southern slope (SS, middle panels) ~~slopes of~~ are shown for both the WT (~~left panels~~a, ~~A and B~~b) and ET (~~right panels~~d, ~~D and E~~e)~~are shown~~. The difference in Sv between the NS and SS is shown ~~by depth and time~~ in panels ~~C~~ c (WT) and ~~F~~ f (ET). ~~The~~ Vertical gray dotted lines ~~overlaying~~ indicate the ~~plots represent the~~ time of each transect~~.~~; the green dashed line marks the sunrise, and the burgundy dashed line marks the sunset

upward transport and/or ~~enhanced particle retention~~ promoting the retention of particles. The third mechanism involves the physical retention and aggregation of organisms due to the interaction of ~~currents with topography and DVM~~canyon topography with alongshore currents and diel vertical migration (DVM) of planktonic organisms (Hudson et al., 2022b, a; Genin, 2004). Globally, direct observational evidence supporting these mechanisms remains limited. In our study, the short duration of observations precludes confirmation of the first mechanism, and we found no clear evidence of eddy formation within the canyon. ~~Worldwide, there is little direct evidence of these mechanisms because of the challenges of studying the highly dynamic processes that take place in submarine canyons.~~ Nonetheless, we present ~~evidence to prove that the BBC plays an important role in zooplankton distribution variability on a diurnal scale by means~~ strong indications that the BbC plays a significant role in modulating zooplankton distribution on diurnal timescales, likely through a variation of the third ~~and a possible fourth~~ mechanism.

4.1 The interaction of diel vertical migrations with abrupt ~~topographies~~topography

The intra-diurnal changes in Sv within the canyon were ~~mostly linked with zooplankton diel vertical migrations (DVM), while the spatial changes appeared to be associated with the canyon presence and shape~~primarily associated with zooplankton DVM, while spatial variations appeared to reflect the influence of the presence of the canyon and its morphology. The accumulation of organisms near the canyon slopes was evident in the ~~U-shape of the Svlines, as higher Sv was found in both the northern and southern walls~~ U-shaped distribution of Sv, as elevated values were found along both the NS and SS compared to the central ~~region~~ axis of the canyon. This pattern ~~might hint at an~~ suggests the interaction between zooplankton migration behavior and the steep topography ~~. In the general DVM pattern, zooplankton migrates to deeper layers at dawn and swim up~~ of the BbC. Most zooplankton taxa undergo DVM within a 24-h cycle to reduce predation risk, typically descending to deeper waters during daylight and ascending to the surface at dusk ~~(Forward, 1988; Hays, 2003). Shallow topographies might block the descend of zooplankton towards deeper surrounding waters, causing an accumulation of organisms over shallow areas~~(Forward, 1988; Hays, 2003; Bandara et al., 2021). In regions with abrupt or shallow topography, vertical migration may be blocked, resulting in the aggregation of organisms above topographic features, a mechanism called "topographic blocking" often ~~evidenced over seamounts (Aarflot et al., 2019; Mohn et al., 2021). Another type~~ documented over seamounts (Aarflot et al., 2019; Mohn et al., 2021). Another form of topographic blocking ~~is found when horizontal currents transporting organisms encounter a steeply sloping bathymetry~~occurs when horizontally transported zooplankton encounter steep bathymetric gradients, such as shallow banks (Isaacs and Schwartzlose, 1965) or the continental shelf break (Mackas et al., 1997). Submarine canyons have ~~long~~ also been proposed as ~~features prone to generate topographic blocking (Genin, 2004), as bathymetry changes abruptly in the canyon walls.~~ zones where such blocking can occur (Genin, 2004), due to their abrupt changes in depth. In our study, an accumulation of zooplankton was observed on the SS of the WT approximately 30 minutes after sunrise (Fig. SF6, Transect 8 at 08:30). This aggregation persisted throughout the day and was both shallow ($\sim$75 m) and intense ($>$ 60 dB re m^{-1}) compared to the typical daytime Sv values within the canyon. These observations suggest that the daytime distribution of zooplankton in the WT is shaped by topographic blocking of their DVM.

Additionally, zooplankton DVM can interact with alternating vertical currents to promote ~~zooplankton retention. We often found opposite directions in the flow over~~ or avoid retention. For example, some taxa exhibit vertical movements that interact with coastal wind-driven or tidal currents to either facilitate or avoid offshore advection (Castro et al., 1993; Miller and Shanks, 2004; Yann . In our observations, we frequently detected flow reversals with depth (see Fig. ~~5~~4), as well as differences in Sv between vertical layers (see Fig. ~~?? and S5). In coastal environments, alternating flows are usually associated with tidal currents or estuarine circulation (Valle-Levinson et al., 2014; Meerhoff et al., 2015). In this study, we found alternating flows that had little association with the tidal cycle, but were possibly explained and enhanced by the presence of the canyon.~~ 9 and S6). The surface layer consistently exhibited an offshore flow, while currents in the mid-depth layer were predominantly positive, especially in the NS. Such opposing flow patterns could be exploited by zooplankton to promote retention.

The zooplankton community was composed of several ~~groups that are strong migrants~~taxa known for their strong migratory behavior (Mackas et al., 2005; dos Santos et al., 2008; Escribano et al., 2009; Bandara et al., 2021), such as decapod larvae, amphipods and copepods~~(Mackas et al., 2005; dos Santos et al., 2008; Escribano et al., 2009; Bandara et al., 2021)~~. These organisms ~~may exploit the fluctuating vertical flows~~ often utilize fluctuating vertical flow regimes to avoid offshore advection by migrating between layers with ~~opposed~~ contrasting current directions, a well-documented ~~mechanisms~~ mechanism of zooplankton retention in tidal and estuarine systems (Castro et al., 1993; Hill, 1998; Poulin et al., 2002; Emsley et al., 2005; Kimmerer et al., 2014). This mechanism may have been present in the NS of the canyon. A migrating organism inhabiting the upper 30 m of the water column of the NS of the BbC would be subject to offshore transport. By migrating to deeper layers at sunrise, the organism could be transported onshore by the positive currents within the canyon. Upon ascending at dusk, it would again be exposed to offshore-flowing surface currents. Through this cycle, DVM behavior could facilitate retention within the canyon. This hypothesis might explain the elevated Sv values observed in the mid-depth layer of the NS during daytime, whereas topographic blocking may account for the elevated Sv in the SS, particularly within the mid-depth layer of the WT.

4.2 ~~Canyon-mediated~~ Canyon-induced horizontal advection~~and retention~~

~~We also found striking differences~~ Differences in zooplankton abundance between the NS and SS, ~~in both the~~ observed in both acoustic and in situ sampling, ~~which~~ were highly variable and alternating over time. ~~Apparently, these differences were~~ These differences appeared to be associated with the contrasting cross-shore flows on either side of the canyon. Observational and numerical modeling studies have shown that submarine canyons ~~impact~~ can significantly influence and modify coastal circulation ~~(Sobarzo et al., 2016; Saldías and Allen, 2020)~~patterns (Sobarzo et al., 2016; Saldías and Allen, 2020; Figueroa et al., 2025). The presence of a shelf-incising canyon in a western continental margin often generates a flow ~~"dipole" where an along-canyon inshore flow is found in the downstream canyon wall , and an outflow in~~ dipole, characterized by an inshore flow along the downstream wall and an offshore flow along the upstream wall (Allen and Durrieu De Madron, 2009; Vergara et al., 2024). A recent study ~~modeled~~ used high-resolution hydrodynamic simulations to investigate the influence of the ~~BBC~~ BbC on the coastal circulation of the Arauco Gulf during upwelling and downwelling events ~~, using high-resolution hydrodynamic simulations (Vergara et al., 2024). They evidenced the formation of the~~ (Vergara et al., 2024). The results revealed a persistent dipole in the mean cross-shore flow field. ~~The downstream~~ Specifically, the northern side of the canyon ~~(i.e. southern slope) had positive cross-shore velocities, meaning and inflow through the canyon, while the upstream side~~ exhibited an onshore flow, while the southern area showed an offshore flow. Although this dipole pattern was present during both upwelling and downwelling ~~events~~conditions, the inshore flow was stronger ~~when windswere favorable for upwelling. They~~ under upwelling-favorable winds, resulting in a net onshore transport. The simulations also evidenced the advection of dense~~deep water over the shelf under upwellingconditions, which is an indicator of topographic upwelling~~ , deep water onto the shelf during upwelling, consistent with enhanced upwelling at the canyon head. Under downwelling conditions, a similar circulation dipole is formed, with minor differences in the magnitudes of offshore and onshore transports (Klinck, 1996; Spurgin and Allen, 2014; Figueroa et al., 2025) . This dipole structure can trap particles within the canyon, promoting anticyclocnic recirculation and particle retention for several days (Figueroa et al., 2025). Consequently, an upwelling precondition may favor the advection of offshore zooplankton into the canyon, whereas downwelling conditions may promote their retention through recirculation within the canyon.

The average cross-shore current ~~showed~~ revealed an inshore flow ~~of water~~ through the canyon, ~~which was clearly tilted to the northern slope~~ clearly tilted toward the NS in the ET, ~~following~~ consistent with the theoretical dipole pattern. This ~~circulation pattern makes sense considering that the study took place after a short but intense event of~~ flow configuration agrees with the upwelling-favorable ~~winds. During~~ wind conditions that preceded the study. For most of the ~~study period, the~~ sampling period, cross-shore flow in the 40-120 m ~~layer was positive in the northern slope~~ depth layer was predominantly positive (onshore) in the NS of the ET, and negative or alternating in the ~~southern slope. This~~ SS. The difference in the current magnitude and direction ~~of the currents was more evident~~ was more pronounced during the first 6 ~~h~~ hours of the study, ~~matching the shallowest depths of the pycnocline . The highest Sv difference was also found during that periodof time, when Sv was~~ coinciding with the shallowest pycnocline depths. The largest difference in Sv was also observed during this period, with Sv values approximately $\sim$10 dB re m^{-1} higher in the NS ~~of the ET~~ compared to the SS ~~.~~ of the ET.

Thus, the inshore flow over the ~~northern wall~~ NS of the ET ~~agreed~~ was associated with a shallower pycnocline, higher ~~zooplankton backscattering strength, and high zooplankton abundances~~Sv, and increased zooplankton abundance. In the WT, ~~the farthest~~ located farther from the canyon head, the coherence between ~~the~~ cross-shore flow and ~~the acoustic backscatter was less clear~~Sv patterns was less apparent. Nonetheless, ~~there was a strong~~ a marked difference in Sv between the ~~slopes~~ NS and SS of the WT ~~by~~ emerged toward the end of the experiment, which was also ~~evident~~ reflected in the zooplankton samples, ~~as higher abundances were found~~ with higher abundances in the SS. ~~In the same period (the last~~ During the final 6 h of the ~~experiment)~~ study, a strong offshore flow ~~was observed~~ developed in the NS ~~that might explain the decrease in Svon the NS~~of the WT, potentially explaining the concurrent decline in Sv. Overall, the ~~differences in Sv between the northern and southern wall, along with their alternations (Fig. 7 and **??**) during the 24 h~~ alternating Sv patterns and observed differences between the NS and SS across transects (see Figs. 6 and 9) throughout the 24-hour cycle suggest that ~~organisms may use the asymmetrical currents to retard the advection and/or enhance retention~~ zooplankton may be unevenly transported within the canyon ~~. This mechanism acts similar to the interaction of DVM with opposed vertical flows, but in the horizontal axis, and would result in a neutral net flux of zooplankton~~due to asymmetrical cross-shore circulation.

While our findings suggest that ~~canyon currents promote an~~ canyon-induced currents promote asymmetrical advection of zooplankton, ~~more efforts are needed to confirm these findings. The variability in the flows and in Sv was highand the topography adds complexity~~they are based on a short (albeit intensive) observational period. Both flow and Sv variability were high, and the canyon's complex topography adds further challenges to interpretation. In the ET, alongshore flows between the ~~along-shore flows over the~~ NS and ~~the~~ SS were highly correlated~~due to its .~~, likely due to the transect's proximity to the ~~Biobío river~~ Biobio River mouth. In the WT, only the mid-depth layer ~~had correlated along-shore velocities in~~ showed correlated alongshore velocities between the NS and SS. ~~Regarding the~~ For cross-shore velocities, only the deeper layer of the WT ~~showed~~ exhibited a correlation between the ~~flow in the NS and SS. The horizontal currents inside~~ two sides of the canyon. Horizontal currents within the canyon not only differed between ~~walls,~~ its walls but also shifted ~~in direction within a period~~ direction over timescales of less than a day. ~~Hence, longer time series together with simultaneous zooplankton sampling at~~

~~both canyon walls could~~ The BbC is a complex and elongated feature, with a smaller tributary canyon at its midpoint and pronounced changes in curvature from the continental slope to its head. This morphological complexity influences the spatial distribution of cross-shore transport and vertical velocities throughout the canyon (Vergara et al., 2024), potentially modifying the circulation patterns and particle retention mechanisms described in previous idealized numerical studies. These findings highlight the need for continued observational efforts to achieve a comprehensive understanding of the topographic upwelling driven by the canyon and to better resolve the net transport of zooplankton.

4.3 Ecological implications

Some submarine canyons ~~have substantial scientific evidence about~~ are well-documented for their role in ~~the formation of~~ promoting zooplankton aggregations. ~~The Monterey Canyon ,~~ Among the best-studied is Monterey Canyon in the California Current System, ~~is one of the best studied. This canyon is~~ a known foraging ~~cite~~ site for large cetaceans (Schoenherr, 1991) ~~, and is one of the main habitats for krill , in what has been defined as an ecologically critical~~ and a critical krill habitat within an ecologically important canyon network (Santora et al., 2018). ~~Submarine canyons of~~ In contrast, submarine canyons within the HCS have only recently begun to ~~be explored in depth. Earlier~~ receive detailed scientific attention. For example, earlier research on the Itata Canyon~~(a relatively large canyon located~~ , located approximately 60 km north of the ~~BBC) found~~ BbC, reported higher abundances of several crustacean larvae ~~close to the shore in the survey transects conducted over the submarine canyon. Outside of it, larvae were more abundant offshore~~ nearshore over the canyon, while offshore abundances dominated outside of it (Yannicelli et al., 2006a). Although the dynamics ~~inside the canyon were not~~ were not explicitly described, this ~~was an indirect sign of~~ pattern suggested potential inshore transport facilitated by the canyon. ~~New research has suggested that a recently discovered and~~ More recent work has proposed that a newly identified, relatively small canyon ~~might~~ may explain the high concentration of whales and krill in ~~a known and protected marine reserve in~~ northern Chile (Buchan et al., 2023). To our knowledge, this is the first study ~~that attempts to combine~~ combining simultaneous observations of zooplankton aggregations and ~~measurements of~~ canyon-induced currents to ~~elucidate~~ investigate the physical mechanisms ~~driving zooplankton dynamics~~shaping zooplankton distributions.

Our findings ~~highlight the role of the Biobío Canyon as a potential key player~~ suggest that the BbC plays a key role in shaping local zooplankton distributions through mechanisms such as asymmetric advection, topographic blocking, and ~~enhanced particle retention . These processes , driven by complex interactions between~~ particle retention processes influenced by the complex interplay of canyon morphology, hydrography, and circulation~~patterns, emphasize the~~ . These dynamics highlight the ecological importance of submarine canyons ~~as ecological hotspots in the upwelling system of the HCS~~within the Humboldt Current upwelling system. However, ~~given the dynamic nature of canyon processes and the temporal~~ due to the short temporal scale and spatial limitations of our study, ~~longer-term and higher-resolution datasets are neededto fully understand these mechanisms~~which focused primarily on intra-diurnal patterns and discrete sampling, further research is needed. Future efforts ~~aiming to elucidate the variability of flows and organisms distribution over submarine canyons should consider the installation of multiple arrangements to cover the spatial variability existing in canyons. Expanding research efforts on submarine canyons, particularly in under-explored areas with high socio-ecological importance, is crucial for unveiling their ecological significance~~

~~and their role in regional productivity. These insights are essential~~ should incorporate long-term moorings to better capture the spatial and temporal variability of physical and biological processes. Expanding studies in underexplored, high-value regions is critical not only for ~~the advancement of scientific~~ advancing oceanographic knowledge but also for ~~informing~~ guiding conservation and management ~~strategies in these biologically rich and~~ of these ecologically significant habitats.

5 Conclusions

We aimed to describe the spatio-temporal variability in zooplankton distribution and currents ~~within~~ at the head of a long and narrow submarine canyon. ~~We found evidence to prove~~ Our results provide evidence that the canyon influenced zooplankton distribution and abundance ~~, all in a period of less than one~~ within a day. The experiment ~~took place after~~ was conducted following an event of ~~upwelling favorable winds. The water column was highly stratified because of the Biobío river output. The horizontal~~ upwelling-favorable winds, under conditions of strong water column stratification driven by freshwater input from the Biobio River. Horizontal flows within the canyon were highly variable~~and had high standard deviation. The mean currents showed an entrance of water towards the coast through the northern wall of the canyon~~ , with notable differences in flow velocity and direction between vertical layers and between the northern (NS) and southern (SS) slopes. On average, an onshore flow was observed in both the western (WT) and eastern transects (ET), with a tilt toward the NS in the ET. However, ~~currents changed rapidly in~~ along-canyon currents frequently reversed direction at both ~~canyon walls, which resulted in non-correlated current velocities between the two surveyed transects and between the canyonslopes. There were differences in the flow velocity and direction between vertical layers, and also between canyon slopes.~~ slopes, resulting in low correlation between current velocities on either side of the canyon. Zooplankton abundance also ~~changed through time and space~~varied spatially and temporally. At the beginning of the study, net abundances were higher in the ~~northern slope, which reverted~~ NS than in the SS, but this pattern reversed by the end of the ~~study. The same pattern~~ experiment. A similar trend was observed in ~~the Sv~~acoustic backscatter (Sv), which was ~~always~~ consistently higher near the canyon walls than ~~in the centerof the canyon. In general, the SS of the WThad higher Sv than the NS, while the opposite was found~~ at its center. In the WT, Sv was generally higher in the SS, while in the ET, the NS showed higher Sv values. In the ET, ~~the higher Sv in~~ peaks in Sv at the NS coincided in both time and depth with ~~a difference in the current direction, which was positive in the NS and negative in the SS . Thus, the asymmetrical horizontal currents possible caused the horizontal~~ positive (onshore) flow, while the SS exhibited offshore flow, suggesting that asymmetric horizontal currents likely contributed to spatial differences in zooplankton distribution. ~~This~~ We also found evidence of topographic blocking in the WT following sunrise. The interaction between zooplankton and ~~opposed and~~ opposing, alternating canyon flows ~~might promote their retention and aggregation. Our~~ may promote both their advection and retention. Overall, our findings demonstrate that submarine canyons are highly dynamic ~~habitats and highlight the need to study these key ecosystems, specially in areas~~ environments that significantly influence biological patterns at short timescales. These results highlight the importance of further studying submarine canyons, particularly in regions that provide essential ecosystem services.

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Competing interests. The authors declare that they have no conflict of interest.

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