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Climatology of the Sea Temperature from Long-Term In Situ Observations: Northern Chilean Patagonia

Cécile Pujol[1], Alexander Barth[1], Iván Pérez-Santos[2,3], Pamela Linford[3], Aida Alvera-Azcárate[1]

[1]GeoHydrodynamics and Environment Research, University of Liège, Liège, Belgium
[2]Centro de investigación i~mar, Universidad de Los Lagos, Puerto Montt, Chile
[3]Centro de Investigación Oceanográfica en el Pacífico Sur-Oriental COPAS COASTAL, Departamento de Oceanografía, Universidad de Concepción, Chile

Correspondence to: Cécile Pujol (cecile.pujol@uliege.be)

Abstract. Ocean climatologies are essential for understanding the mean state and variability of marine systems, providing reference conditions for detecting anomalies, assessing ecosystem functioning and identifying long-term trends. In this study, we present the first high-resolution, four-dimensional temperature climatology for Northern Chilean Patagonia, a region characterised by the presence of a complex network of fjords and channels. The climatology was generated from approximately three million in situ observations collected over the past 75 years from multiple datasets. Using the Data Interpolating Variational Analysis (DIVAnd) tool, temperature fields were reconstructed with a horizontal resolution of about 900 m and over 32 vertical levels, producing monthly fields from the surface to 400 m depth. The resulting climatology accurately reproduces the main spatial and seasonal temperature patterns reported in previous studies. Surface temperatures show strong summer gradients between the open Pacific and Northern Patagonia, while enclosed regions such as Reloncaví Sound, Comau and Puyuhuapi Fjords exhibit pronounced seasonal amplitude compared with the more stable Corcovado Gulf. Below surface, temperature gradients become smoother and the thermocline deepens in summer, typically ranging between 10 and 50 m. At 100 m depth, temperatures are relatively constant throughout the year, but spatial variations are still observed, with Ancud Gulf and Reloncaví Sound being slightly warmer. This climatology provides a refined and physically consistent representation of the oceanographic structure of Northern Patagonia, offering an essential baseline for future modelling, monitoring and climate-change assessments in a region where satellite observations are limited by persistent cloud cover and complex topography. All climatologies generated in this study are freely available online.

1 Introduction

Ocean climatologies are fundamental tools for understanding and characterising the mean state of the ocean and its long-term variability. They provide reference conditions from a given period that enable the calculation of anomalies, the assessment of ecosystem functioning and the detection of trends associated with climate change (Cheng and Zhu, 2015; Goebeler et al., 2022; Shahzadi et al., 2021b). By offering a consistent baseline against which current or future observations can be compared, climatologies allow scientists to identify whether current or future conditions are normal, anomalous or changing over time (e.g. L. Cheng & Zhu, 2015; Flaounas et al., 2022; Hobday et al., 2016; Martínez-Moreno et al., 2022).

https://doi.org/10.5194/essd-2026-42
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Climatological products derived from a wide range of physical and biogeochemical parameters are also essential for calibrating and validating numerical models, as well as for supporting the sustainable management of marine resources (Barnier et al., 1995; Bianchi et al., 2021; Brodie et al., 2023; Senay et al., 2023). These products are typically constructed over multi-decadal periods to represent the mean conditions of a specified reference period. In oceanographic and atmospheric sciences, a minimum of 30 years of data is generally recommended to ensure that climatologies capture the influence of long-term climate variability, including large-scale processes such as the El Niño Southern Oscillation (WMO, 2023).

Ocean climatological products can be generated from satellite observations, numerical models, in situ measurements obtained from ship-based profiles, moorings and autonomous platforms, or from reanalysis products that combine these diverse data sources (Embury et al., 2023; European Union-Copernicus Marine Service, 2018; Huang et al., 2021; Simoncelli et al., 2020). Each approach offers distinct advantages: the increasing availability of high-resolution satellite data has substantially improved the spatial and temporal coverage of coastal observations, however in situ measurements remain indispensable for subsurface characterisation of the ocean state and for model and satellite data calibration and validation (Dickey et al., 2006; Legler et al., 2015; Minnett et al., 2019).

Chilean Patagonia, located in the southern part of Chile (41-56°S), is a highly complex and dynamic oceanographic region. It is characterised by an extensive network of fjords and channels, strong freshwater inputs from rivers and glaciers that generate sharp salinity gradients and highly variable bathymetry (Narváez et al., 2019; Strub et al., 2019; Vásquez et al., 2021). These systems are strongly influenced by both oceanic processes from the Pacific Ocean and terrestrial freshwater discharge, resulting in marked spatial heterogeneity (Narváez et al., 2019; Saldías et al., 2021; Strub et al., 2019). In recent decades, Northern Patagonia (41-47°S) has received growing scientific attention, partly driven by the rapid expansion of aquaculture and its ecological implications (FAO, 2024; Subsecretaría del Trabajo, Gobierno de Chile and Observatorio Laboral de la Región de Aysén, 2024). This region is particularly narrow, averaging about 50 km wide, and characterised by the presence of fjords which most of them have a wide inferior to 5 km, numerous islands and intricate channels, restricting the water exchanges with the Pacific Ocean and shielding the Inner Sea (Sievers and Silva, 2008). This complex geography in addition to persistent cloud cover and heavy rainfall present considerable challenges for observation and analysis (Díaz et al., 2025; Lara et al., 2017; Pantoja et al., 2011). Standard satellite products and global models, often limited by coarse spatial resolution, typically fail to resolve fjords and channels, and cannot capture the finer scale processes occurring in the most confined areas. Although high-resolution satellite products do resolve most of the fjords and channels, their temporal coverage and temporal resolution is not sufficient to calculate a long-term baseline, which should be based on at least 30 years data according to WMO (2023) recommendations.

Despite its economic and environmental relevance, systematic temperature climatologies remain scarce in the region and mostly based on satellite data (Narváez et al., 2019; Saldías et al., 2021; Vásquez et al., 2021), although regional and local climatologies have been derived from in situ datasets (Linford et al., 2023; Saldías et al., 2019). In complex regions such as Chilean Patagonia, in situ measurements are often the only reliable source for constructing consistent long-term climatologies. Over the last few decades, several oceanographic campaigns in the Northern Patagonian Seas have collected valuable physical and biogeochemical data across the region. However, these datasets are spatially and temporally irregular, making it challenging to generate consistent climatological fields. To date, no study has compiled these observations into a comprehensive, spatially resolved temperature climatology for Northern Patagonia.

To address this gap, this study employs the Data Interpolating Variational Analysis tool (DIVAnd, Barth et al., 2014; Troupin et al., 2012) to construct a temperature climatology for Northern Chilean Patagonia based on historical in situ records that has a final resolution of about 900 m, effectively capturing all the fjords and narrow channels of Northern Patagonia. DIVAnd applies a variational interpolation approach that integrates data uncertainties, spatial correlation scales and topographic constraints making it particularly suitable for complex coastal environments. The objectives of this work are to describe the methodology used to generate the temperature climatology from historical observations, synthetize fragmented datasets into a coherent representation, evaluate its performance and discuss its potential for broader oceanographic applications in data-sparse regions.

2 Material and Method

2.1 Study area

Northern Chilean Patagonia is located in the south of Chile and represents the northernmost part of Chilean Patagonia (41°-56° S). It spans from 41.4° S to 46.7°S and from 72°W to 74°W (Fig. 1). It is delimited to the east by the continent, to the north-west by the Island of Chiloé, and to the south-west by the Chonos Archipelago composed of more than a thousand islands and playing a crucial role in reducing the wind stress and mitigating the waves intensity before they reach the mainland (Pinilla et al., 2019a). To the west of the sea, the continental shelf drops sharply, with depths increasing rapidly to over 2000 m due to the presence of the Peru-Chile Trench. The Northern Patagonian Fjords encompasses diverse basins, channels and fjords. From north to south, the key areas include the large semi-enclosed gulf Reloncaví Sound and the Reloncaví Fjord, which flows into the sound. To the south of Reloncaví Sound, lies the Ancud Gulf and the Corcovado Gulf, separated by the Desertores Islands, forming a natural barrier separating the deeper waters of the Reloncaví Sound and Ancud Gulf from the shallower Corcovado Gulf. Ancud and Corcovado Gulf are regions more influenced by oceanic waters entering through the Guafo Mouth (Calvete and Sobarzo, 2011; Pérez-Santos et al., 2014; Linford et al., 2023), with some fjords extending eastward into the continent. South of the Corcovado Gulf, lies the narrow canal of Moraleda, which transitions into the Elefantes Channel, forming an extensive and complex network of channels and fjords (Soto-Riquelme et al., 2023; Linford et al., 2024). This particular geography makes it considered as a semi-enclosed sea, with the main connections through the ocean passing between Chiloé Island and Chonos Archipelago, a path called Guafo Mouth (Sievers and Silva, 2008). The bathymetry in the Northern Patagonian Fjords is very complex due to its numerous microbasins and islands. Although the bathymetry is mainly lower than 400m, certain microbasins can be exceptionally deep, reaching for example the Jacaf channel with 600m depth (Schneider et al., 2014; Pinilla et al., 2020).

https://doi.org/10.5194/essd-2026-42
Preprint. Discussion started: 18 February 2026

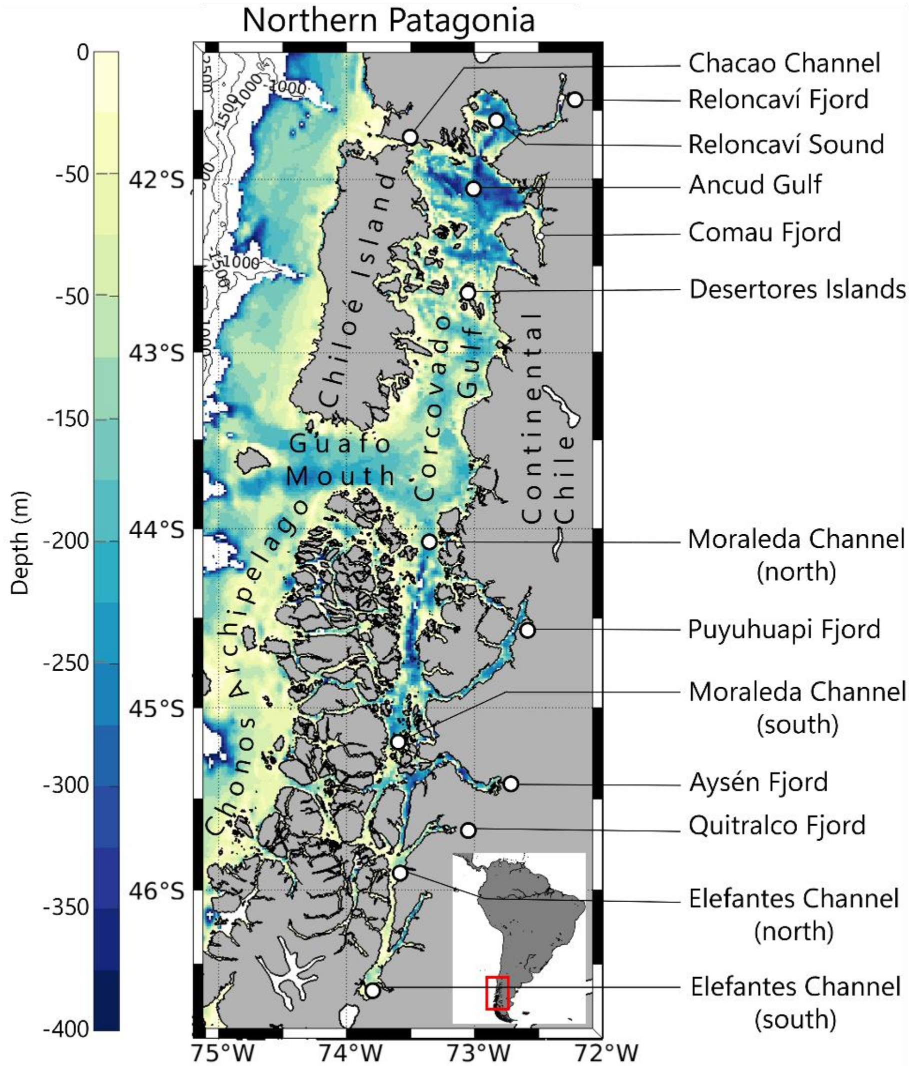

Figure 1: Map of the study area with depth. The level lines are indicating the depth every 500m, and bathymetry above -400 m is indicated by the colorbar.

2.2 Datasets

To construct the climatology, we gathered all available in situ temperature data to obtain a comprehensive dataset that best represents the region both spatially and temporally. The data come from various online repositories and direct field measurements, and were acquired using a range of sampling techniques, including CTD casts, drifting buoys or anchored moorings. Further details on data provenance are provided in Table 1 and in the supplementary material. Only samples located within the study area (-75.1°E, -72.0°E and -41.4°N, -46.7°N) were retained, encompassing both surface and depth observations. All datasets were homogenised prior to merging, and variables were standardised to consistent units (°C for

https://doi.org/10.5194/essd-2026-42
Preprint. Discussion started: 18 February 2026

temperature and metres for depth). Data selection involved retaining only values flagged as valid when quality indicators were available, and excluding "obviously" wrong data (such as temperatures superior to 30°C). In addition, for each major basin, the mean and standard deviation of temperature were calculated from the in situ samples, and any observation lying outside the range of mean +/- 5*standard deviation were discarded. This relatively wide tolerance was chosen to preserve realistic extreme values while removing measurements that were physically implausible or likely to result from sensor errors (Garcia et al., 2024; Hoteit et al., 2009). Duplicate or near-duplicate observations were eliminated when the following criteria were simultaneously met: a horizontal distance of less than 0.01° (about 1 km), a vertical distance of less than 0.1 m, a sampling time difference of less than one day (given that many datasets have daily rather than hourly precision), and a temperature difference smaller than +/- 0.1°C.

Table 1: Origin of the in situ data used for the construction of the climatology and information on the platform type, the institute that conducted the campaigns (if available), and the spatial and temporal extent of the samples. References are available in the supplementary files.

Source/ Provider	Platform type	Institute	Temporal extent	Spatial extend	References
CMEMS	Drifters	/	1950-01-01 to 2021-12-31	All study area	Szekely et al., 2023[1]
	CTD				
Pangaea	Shallow water monitoring stations	Wagner institute Huinay Scientific Field Station	2009-04-07 to 2014-02-11	Fjord Comau	[2] to [54]
				Fjord Renihue	
				Fjord Piti Palena	
				Repollal Islands	
EMODnet	Drifting buoys	/	2016-09-20 to 2021-05-31	All study area	[55] to [59]
World Ocean Database (WOD)	CTD (conductivity temperature depth)	/	1948-11-23 to 2020-05-12	Open Ocean, West of the Chiloé Island	Boyer et al., 2018[60]
	OSD (ocean station data)				
	XBT (expandable bathythermograph)				
	MBT (Mechanical Bathythermograph)				
	APB (Autonomous Pinniped Bathythermographs)				
	PFL (Profiling Floats)				

https://doi.org/10.5194/essd-2026-42
Preprint. Discussion started: 18 February 2026

Centro de datos oceanográficos y meteorológicos (CDOM)	Anchored buoy	COPAS Sur-Austral	2013-03-09 to 2014-06-19	Reloncaví Fjord (Cochamo) -72.31E, -41.52N	http://cdom.cl/
			2010-07-01 to 2018-04-06	Puyuhuapi Fjord -72.72E, -44.58N	
Centro de investigaciónes i~mar	Anchored buoy	Centro de investigaciones i~mar	2017-04-28 to 2023-09-01	Reloncaví Sound -72.8345E, -41.6364N	http://cdom.cl/
		COPAS Sur-Austral			
Centro de investigaciónes i~mar	CTD	Centro de Instrucción y Capacitación Maritima (CIMAR)	1970-03-20 to 2022-09-01	Northern Patagonia	/
	Microprofiler (VMP-250)	Centro de investigaciones i~mar			
		Instituto de Fomento Pesquero (IFOP)			

In total, 3.3 million data samples were used for the construction of the climatology, representing 5880 unique stations (Fig. 2A). The complete dataset spans the period from 1948 to September 2023, although spatial, vertical and temporal coverage are uneven (Fig. 2). Vertically, the measurements extend from surface to 400 m. Given that the climatology forms the core of our analysis, it was essential to use a reliable and representative dataset. The extensive spatial and temporal distribution of in situ measurements makes them well-suited for this purpose.

The inherently heterogeneous nature of in situ data results in variable sampling density through time and space. In particular, the Comau Fjord was disproportionately sampled due to the long-term monitoring efforts of the Huinay Scientific Centre, which accounts for approximately 76% of the total samples (Table 2). However, the other fjords and regions have also been relatively well sampled, though they represent a much smaller proportion of the total dataset (Table 2). Additionally, three anchored buoys were deployed in Reloncaví Fjord, Reloncaví Sound and Puyuhuapi Fjord from 2010 onwards (Table 1), contributing significantly to the increased number of observations during the last decade in these basins. As a result, the temporal distribution of observations is strongly skewed toward recent decades: 99% of the measurements were collected after 1990 and 55% after 2010 (if considering only non-mooring data). Nevertheless, pre-1990 observations, though fewer in number, remain valuable as they include more than 1000 unique measurements that extend the time span of the

https://doi.org/10.5194/essd-2026-42
Preprint. Discussion started: 18 February 2026

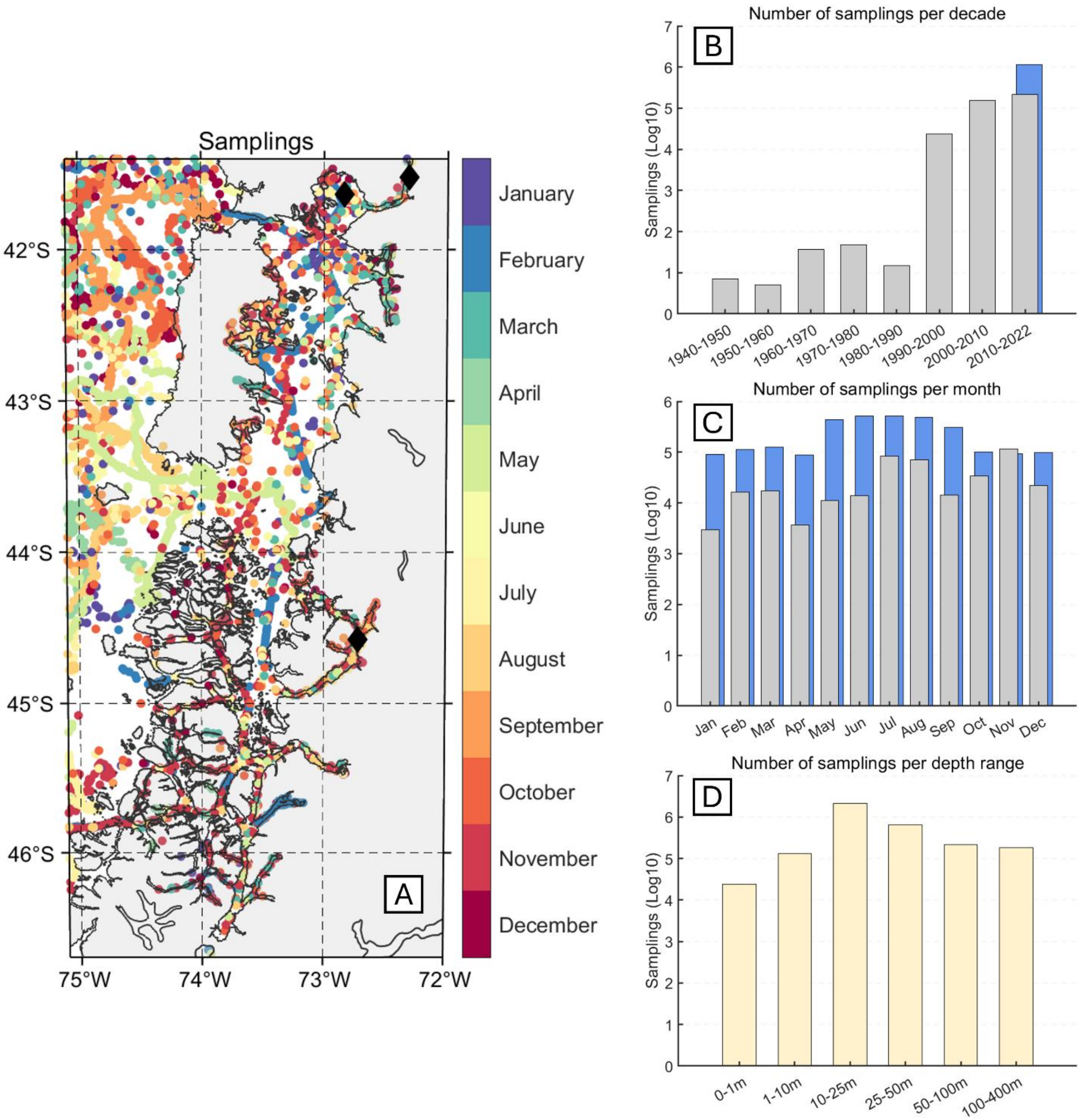

Figure 2: Spatial distribution of in situ observations (0-400m depth), and the month during which it has been collected (A). The three black rhombus in Reloncaví Sound, Reloncaví Fjord and Puyuhuapi Fjord represent the localisation of the three moorings. Temporal distribution (B-C) of the in situ observation over decades (B) and over months (C). Vertical distribution (D) over certain depth ranges is shown. For (B) and (C), grey bars represent the non-mooring data, while blue bars represent the mooring data, and for (D) both mooring and non-mooring data are merged.

https://doi.org/10.5194/essd-2026-42
Preprint. Discussion started: 18 February 2026

climatological record back to 1948. Importantly, despite this temporal heterogeneity largely driven by a few intensively monitored sites, the overall spatial coverage remains extensive across the region (Fig. 3). Vertically, sampling is also heterogeneous, with approximately 70% of all observations located within the upper 25m of the water column (Fig. 2D).

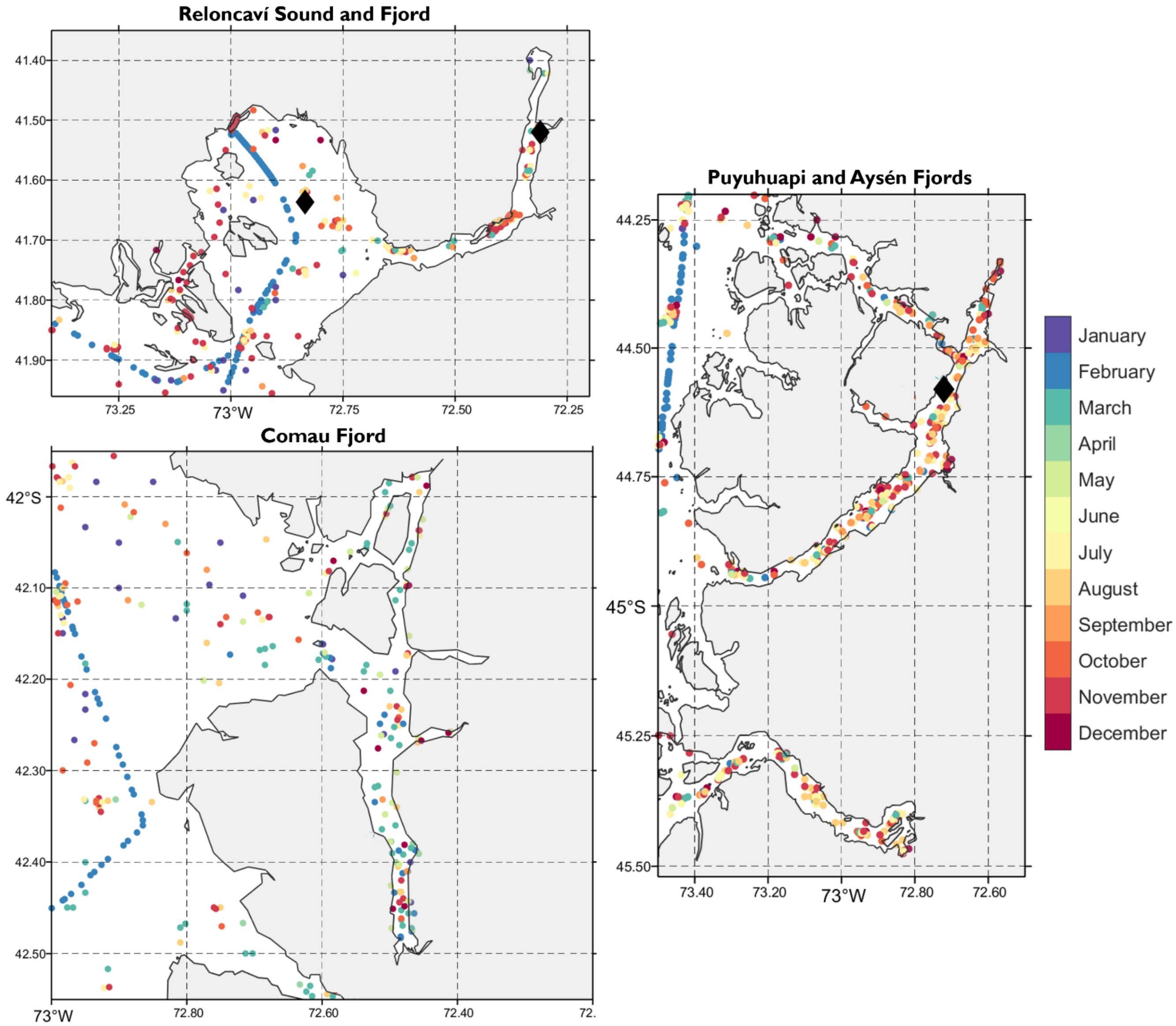

Figure 3: Spatial distribution of in situ observations (0-400m depth), and the month during which it has been collected in specific regions. Black diamond indicate the location of anchored buoys.

Table 2: Spatial repartition of samplings (at all depths) in different regions of the study area. The second column indicates the total number of samplings in an area, while the third one shows which proportion those samplings represent among the entire study domain.

Region	Samplings	Proportion of samplings (%)
Reloncaví Sound	76206	2.26
Reloncaví Fjord	35158	1.04
Ancud Gulf	53604	1.59
Comau Fjord	2587816	76.83
West of Chiloé Island	25221	0.75
Corcovado Gulf	299623	8.89
Guafo Mouth	10937	0.32
Moraleda Channel	52668	1.56
Chonos Archipelago	31879	0.95
Puyuhuapi Fjord	110604	3.28
Elefantes Channel	10637	0.32
West of Chonos Archipelago	5615	0.22

2.3 Construction of the temperature climatology

To create a continuous field of the climatology of the temperature in Northern Patagonia from sparse in situ data, we employed DIVAnd (Data-Interpolating Variational Analysis in n dimensions). DIVAnd is a spatio-temporal interpolation tool for geophysical variables that utilises scattered, spatially and temporally irregularly distributed data to create a continuous field via variational interpolation, taking the bathymetry into account (Troupin et al., 2010; Barth et al., 2014). DIVAnd is an extension of DIVA (Data Interpolating Variational Analysis) for more than 2 dimensions field (Beckers et al., 2014; Brasseur and Haus, 1991; Troupin et al., 2012). This tool has been widely used for climatologies construction of many oceanic variables from sparse data to continuous fields (Barth et al., 2021; Shahzadi et al., 2021a, b; Simoncelli et al., 2020). It is particularly well-suited for our study area since it can handle both spatial, temporal and vertical dimensions, allowing for the interpolation of data across 2D (longitude x latitude), 3D (time or depth) or 4D (time and depth). The method is based on a variational inverse approach that minimises a cost function balancing two objectives: the analyse field should remain close to the available observations and it should exhibit a degree of spatial smoothness (Brasseur and Haus, 1991). Unlike a pure interpolation, DIVAnd does not force the resulting field to pass exactly through each observation, as measurements can be subject to errors and may not fully represent the environmental conditions (Janjić et al., 2018). The cost function is detailed below in Eq. (1):

$$J(\varphi) = \sum_{j=1}^{Nd} \mu_j \left[d_j - \varphi(x_j)\right]^2 + \|\varphi - \varphi_b\|^2 \qquad (1)$$

https://doi.org/10.5194/essd-2026-42
Preprint. Discussion started: 18 February 2026

where φ is a scalar ocean field defined (in our case, the temperature) and d_j are the Nd measurements of the field φ at the location x_j for a given time, with their associated weight μ_j. φ_b is a background estimate of the field, representing a first guess of the field to interpolate. The norm $\|.\|^2$ also involves spatial/temporal derivatives of the field to penalise abrupt variations. The computation was realised using DIVAnd v2.7.12 available as a package in Julia programming language and in conjunction with Jupyter Notebooks (https://github.com/gher-uliege/DIVAnd.jl). The variable to interpolate in this study was the temperature, with the objective to build a 4D climatology. The input to provide is a table of potentially irregularly distributed data with associated coordinates (longitude and latitude), depth and date.

To generate a fine-scale spatio-temporal climatology from in situ surface and subsurface data, we first computed a background field, which is a first guess representation of the temperature distribution that served as the basis for the subsequent monthly climatology (Barth et al., 2021). This background field was produced at a seasonal temporal resolution by grouping months into four standard seasons: January-February-March (austral summer), April-May-June (autumn), July-August-September (winter), October-November-December (spring). For each season, only the in situ observations corresponding to the relevant months were used. This approach mitigates the uneven temporal coverage and spatial gaps in the dataset, particularly in regions and periods with limited sampling, and provides a representative mean seasonal state of the temperature field. The result is an averaged representation of the study area over the time period 1948-2023 with seasonal temporal resolution.

The monthly climatology was then derived by refining background fields. For each month, the corresponding seasonal grid was used as the background field, and all available in situ observations from that month were incorporated to enhance spatial and temporal detail. This two-steps approach ensured that the monthly climatology remained dynamically and statistically consistent with broader seasonal patterns while resolving finer-scale monthly variability. The outcome is a set of twelve fields, corresponding to a monthly climatology (monthly temporal resolution), each representing the mean temperature state for every grid cell of the study area for the period 1948-2023. Both the seasonal background and the monthly climatology share identical vertical and horizontal resolutions and were processes following the same methodological framework.

For both products (background and climatology), the configuration of DIVAnd was designed to balance data fidelity and spatial smoothness, ensuring a robust and physically consistent representation of the temperature field. To reduce the influence of spatially clustered measurements, the DIVAnd weighting function was applied with a 0.1° (~10 km) threshold for cluster identification. The interpolation smoothness was tuned using correlation length scales of 50 km horizontally and 50 m vertically, which define the spatial influence of the observations. The observations error variance, representing the uncertainties associated with each measurement, was set to 0.01 and scaled by the previously assigned weights. Parameter values were selected to optimise performance metrics obtained from independent validation tests. The final gridded fields were produced with a 0.008° (approximately 900 m) horizontal resolution, reaching our computational limits, representing a horizontal grid of size 357x751, covering the Northern Chilean Patagonian fjords between -75,1°E to -72°E and -47°N to -41°N. Bathymetric constraints were derived from GEBCO dataset which has a spatial resolution of 30 arcseconds (https://www.gebco.net/data_and_products/gridded_bathymetry_data/). As approximately 70% of the samples were

https://doi.org/10.5194/essd-2026-42
Preprint. Discussion started: 18 February 2026

collected within the upper 25m, climatologies were computed on a non-uniform vertical grid to reduce near-surface bias. Temperature was interpolated onto 32 unevenly spaced depth levels ranging from the surface to 400 m, with finer spacing near the surface (0m, 2.5m, 5m, 7.5m, 10m, 12.5m, 15m, 17.5m, 20m, 25m, 30m, 35m, 40m, 45m, 50m, 60m, 70m, 80m, 90m, 100m, 125m, 150m, 175m, 200m, 225m, 250m, 275m, 300m, 325m, 350m, 375m, 400m). The DIVA interpolation resulted in a monthly climatology at 32 different depths with a resolution of approximately 900 m, effectively resolving all fjords and channels from the northern Patagonia.

To assess the performance of the monthly climatology and validate it, 5% of the in situ observations were put aside from the reconstruction process as an independent validation dataset (see Table XX for details). Most of this subset was selected randomly across space and time to ensure representative coverage of the study area. However, for the anchored moorings, random temporal sequences of varying lengths were withheld instead of isolated points, in order to provide a more robust validation of the reconstructed temporal variability. Validation was performed separately for each monthly field by comparing the reconstructed and observed temperatures. Statistical performance was quantified using the correlation, the bias, the root mean square error (RMSE), the centred root mean squared error (CRMSE), and the standard deviation. Together these metrics evaluate both the strength of the relationship and the magnitude of residual errors between observations and the climatology.

Table 3: Total number of samples collected at the sea surface (0-1m depth), separated into mooring and non-mooring sources, along with the 5% of each group set aside for validation.

Month	Total samples	Mooring samples	Mooring validation	Non-mooring samples	Non-mooring validation
Jan	8792	8693	435	99	5
Fev	14680	13685	684	995	50
Mar	13921	13711	686	210	11
Apr	8534	8373	419	161	8
May	10081	9478	474	603	30
Jun	9409	9077	454	332	17
Jul	9825	9331	467	494	25
Aug	9022	8557	428	465	23
Sep	10289	9540	477	749	37
Oct	9659	9174	459	485	24
Nov	8712	7701	385	1011	51
Dec	9238	9020	451	218	11

https://doi.org/10.5194/essd-2026-42
Preprint. Discussion started: 18 February 2026

Many oceanographic and ecological applications require daily climatologies to capture short-term physical or biological variability more accurately (e.g. Hemming et al., 2020; Hobday et al., 2016). We therefore derived a daily climatology from the monthly fields described in the previous section. To convert the monthly climatology into a daily time-scale product, each monthly field was expanded over the corresponding number of days in that month (for instance, the January field was repeated 31 times, February 29 times, March 31 times, etc.) This produced a continuous sequence of 366 daily fields with the same spatial characteristics as for the monthly fields. To smooth the resulting daily time series and ensure a physically realistic and gradual transition between months, a 90-day centred moving average was then applied to each grid cell. This temporal filter mitigates abrupt discontinuities at month boundaries and yields a continuous, smoothed representation of the annual temperature cycle. The choice of a 90-day window balances temporal smoothness and the preservation of the seasonal signal, consistent with similar approaches in construction high-frequency climatologies.

The resulting dataset (later referred as "daily-derived climatology" in the manuscript) provides one representative value per day of the year for each grid cell, ensuring internal consistency with the monthly product while allowing finer temporal analyses and comparison with daily observational or model data. This approach preserves the large-scale seasonal and monthly variability of the original climatology, without attempting to reproduce intra-monthly variability that is not resolved by the available in situ data in most of the basins.

3 Results

3.1 Validation of the climatology

To validate the monthly climatology, 5% of the total in situ data was set aside and excluded from the reconstruction process (see Methods). This independent subset was then used to evaluate the accuracy of the monthly climatology through statistical comparisons. Overall, the results indicate that the monthly climatology reproduces the spatial and seasonal variability of surface temperature with reasonable accuracy (Table 4).

Biases between the interpolated field and the observations are small throughout the year (ranging from -0.139°C to 0.214°C) and RMSE values rarely exceed 1°C, suggesting a robust representation of the mean state. Correlation coefficients exceed 0.7 during the austral winter (May-September), when surface waters show less spatial variation, while lower correlations and higher errors are found in summer months, reflecting stronger small-scale variability and stratification. January and April display the lowest correlations, consistent with the limited number of available in situ samples (99 and 161 respectively, compared to an average of 485 per month). The CRMSE is close to the RMSE for all months, indicating that most of the errors arise from spatial variability rather than a systematic bias. The standard deviation of the climatology is consistently smaller than the in situ data's one, meaning that the reconstructed fields are smoother than the original observation, which is an expected feature for a climatological product.

When comparing the interpolation errors with the natural variability of the system, RMSE values are generally smaller than the standard deviation of the in situ data during the austral summer, indicating that the climatology successfully captures the large-scale temperature patterns. In contrast, during winter months, RMSE slightly exceeds the standard deviation of the observations, showing that even small absolute errors can represent a significant fraction of the reduced thermal variability typical of this period. Since RMSE quantifies the difference between the monthly climatology and instantaneous in situ measurement, it also encompasses sub-seasonal and interannual variability. Consequently, even a perfect climatology derived from an unlimited number of observations would not achieve a zero RMSE or a correlation of one. Overall, the validation confirms that the generated climatology is consistent with the available observations, performs best during the winter months, and provides a reliable baseline for representing surface temperature variability in Northern Chilean Patagonia. The complete climatology (both monthly and daily-derived) is freely available at https://doi.org/10.5281/zenodo.18255999 (Pujol et al., 2026).

Table 4: Statistic metrics for the validation of the monthly climatology at the surface level only (between 0 and 1m) for every month: Correlation, Bias (°C), Root mean square error (RMSE, °C), Centred root mean square error (CRMS, °C), the average Standard deviation (SD, °C) across the entire study area for the climatology, the average Standard deviation (°C) across the entire study area for the entire in situ dataset.

Month	Correlation	Bias (°C)	RMSE (°C)	CRMS (°C)	SD climatology	SD in situ data
Jan	0,159	0,214	1,847	1,834	1,160	1,974
Feb	0,709	0,039	1,433	1,433	1,274	2,054
Mar	0,320	0,112	1,141	1,135	1,019	1,685
Apr	0,171	-0,068	1,006	1,004	0,910	0,830
May	0,558	-0,082	0,783	0,779	0,937	0,774
Jun	0,810	-0,083	0,709	0,705	1,002	0,458
Jul	0,806	0,062	0,872	0,870	0,811	0,594
Aug	0,821	-0,139	0,707	0,693	0,536	0,580
Sep	0,748	0,010	0,731	0,731	0,608	0,511
Oct	0,396	0,202	0,952	0,930	0,672	0,817
Nov	0,410	0,086	1,232	1,229	0,738	1,234
Dec	0,446	0,105	1,421	1,417	1,081	2,184

3.2 Description of the climatology

3.2.1 Surface temperature patterns

Before examining the monthly fields, the seasonal background climatology provides an overview of the large-scale thermal structure of Northern Chilean Patagonia (Fig. 4). These background fields, computed as the first step of the DIVA interpolation and over all 32 depth levels (0-400 m) following the same vertical structure as the monthly climatology, summarise the dominant spatial patterns for summer, autumn, winter and spring. At the surface, they clearly highlight a

https://doi.org/10.5194/essd-2026-42
Preprint. Discussion started: 18 February 2026

strong temperature gradient during summer in the Pacific Ocean, and warm regions in the inner sea, such as Reloncaví Sound and Fjord, and Puyuhuapi Fjord. Autumn shows a progressive cooling of the region, with a north-south gradient, relatively uniform temperature in winter, and warming in spring. The seasonal backgrounds reveal the persistent west-east gradient in summer, and the marked cooling of the southern fjords in winter, particularly Aysén Fjord. These backgrounds were used for the subsequent monthly DIVA analyses, ensuring that the interpolation respects the main seasonal structure while allowing finer monthly features to emerge.

The DIVA-interpolated monthly climatology captures the mean thermal structure and seasonal variability of Northern Chilean Patagonia, based on in situ observations. The product spans 32 depth levels, from the surface to 400 m, and reveals consistent spatial and vertical temperature patterns across the region (Fig. 5, 6, 7, 8).

At the surface (Fig. 5), the climatology reveals marked seasonal and spatial variations. During summer (Jan-Feb-Mar), strong west-east temperature gradients are observed in both the open Pacific and Northern Patagonia, particularly in Reloncaví Sound and Ancud Gulf. Most of the study area records temperatures between 12°C and 14°C, with local maxima in February reaching approximately 18°C in Puyuhuapi Fjord, 17°C in Reloncaví Sound and Fjord and in the north-western open ocean, and 16°C in Comau Fjord. Despite being located only 50 km south of Puyuhuapi Fjord, Aysén Fjord reaches only 13°C in February, highlighting its cooler conditions. The Chacao Channel and the area south of Desertores Islands stand out as particularly cold regions throughout the summer.

During autumn (Apr-May-Jun), surface temperatures gradually decrease, though a weaker west-east gradient persists. By June, a clear north-south gradient becomes apparent in Northern Patagonia with values ranging from 10-11°C in Reloncaví Sound to about 8°C in the southernmost part of the domain.

Winter (Jul-Aug-Sep) is characterised by uniform surface temperatures and minimal spatial variability. Most areas remain around 10°C, with the lowest values of about 8°C in Puyuhuapi Fjord and 7°C found in Elefantes Channel and Aysén Fjord. A slightly warmer patch southwest of Chiloé Island in July can be observed, but likely results from an anomalous measurement or uneven temporal sampling.

In spring (Oct-Nov-Dec), gradual warming resumes with the development of the west-east gradient and pre-summer conditions established by December. Temperatures reach 15°C to 17°C in Puyuhuapi Fjord and Reloncaví sound, while colder waters (below 11°C, locally down to 9°C) persist in southern Northern Patagonia and west of the Chonos Archipelago.

These spatial patterns are associated with marked seasonal contrasts, with temperature amplitudes varying significantly between open and enclosed basins. Indeed, temperature fluctuations are stronger in enclosed fjords and sounds. Reloncaví Sound varies between 10°C in winter and 17°C in summer. Puyuhuapi Fjord ranges from 8°C at its head in winter to 18°C in summer (9-16°C in its central part), and Aysén Fjord exhibits a seasonal range of 6 to 13°C at its head and 9 to 13°C near its mouth. In contrast, open basins show smaller seasonal amplitudes: Corcovado Gulf (10-13°C), Moraleda Channel (9-13°C) and Ancud Gulf (11-14°C). The open Pacific west of Chiloé Island experiences a wider range (10-17°C), whereas west of the Chonos Archipelago, seasonal variability is more moderate (9-13°C).

https://doi.org/10.5194/essd-2026-42
Preprint. Discussion started: 18 February 2026

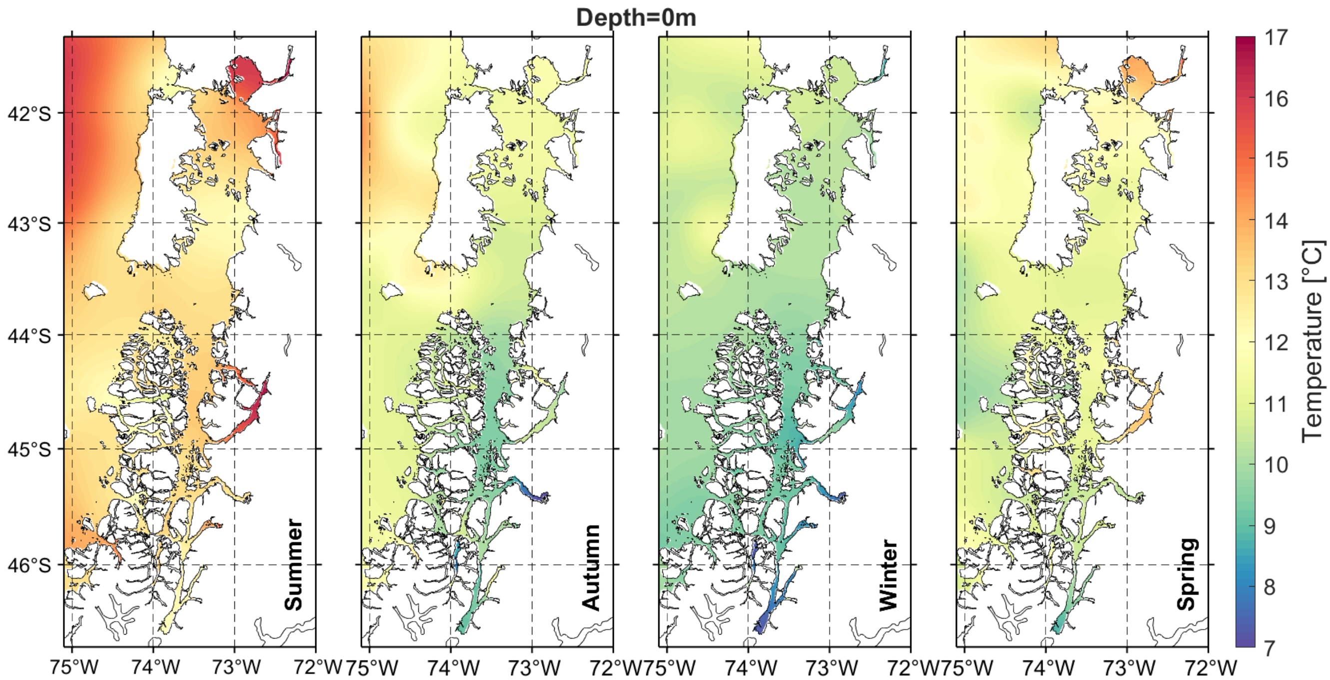

Figure 4: Background seasonal fields of the interpolation for surface.

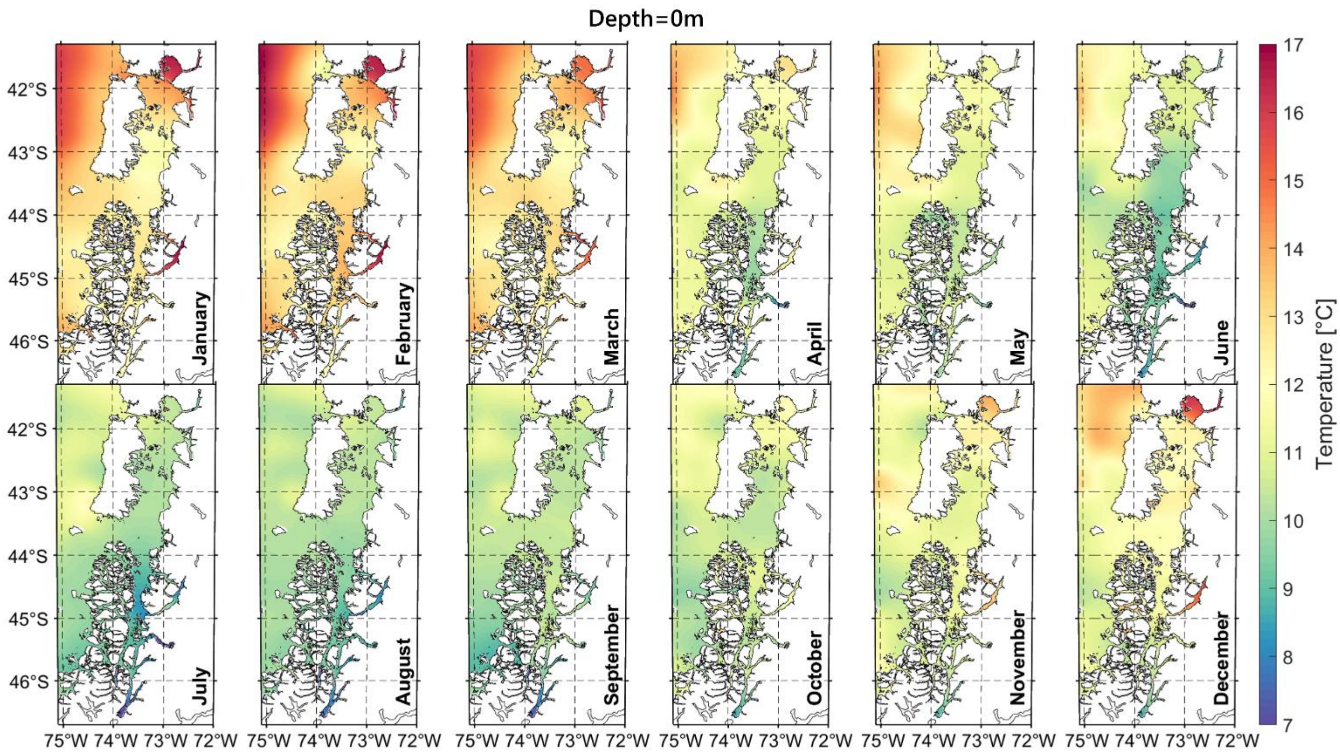

Figure 5: Monthly climatology of the sea temperature at the surface.

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Preprint. Discussion started: 18 February 2026

3.2.2 Subsurface structure

Below the surface, temperatures decrease with depth and horizontal gradients weaken, especially during summer. At 30 m depth, the field becomes nearly homogeneous in winter, whereas in summer it varies from 14°C west of Chiloé Island to 10°C in the south (Fig. 6). At 100 m depth (Fig. 7), temperatures remain relatively stable throughout the year around 10°C, with slightly warmer conditions (about 11°C in winter and 12°C in summer) in Ancud Gulf and Reloncaví Sound and their associated fjords. At 200 m depth, these northern basins remain slightly warmer (10-11°C) than the rest of the region (8-9°C). At 400 m, temperatures stabilise near 7°C across the entire domain year-round, except in Aysén Fjord, where values oscillate between 10°C (July-December) and 8.5°C (January-June). This seasonal pattern aligns with in situ measurements collected over multiple years, suggesting relatively slow temperature adjustment in this fjord.

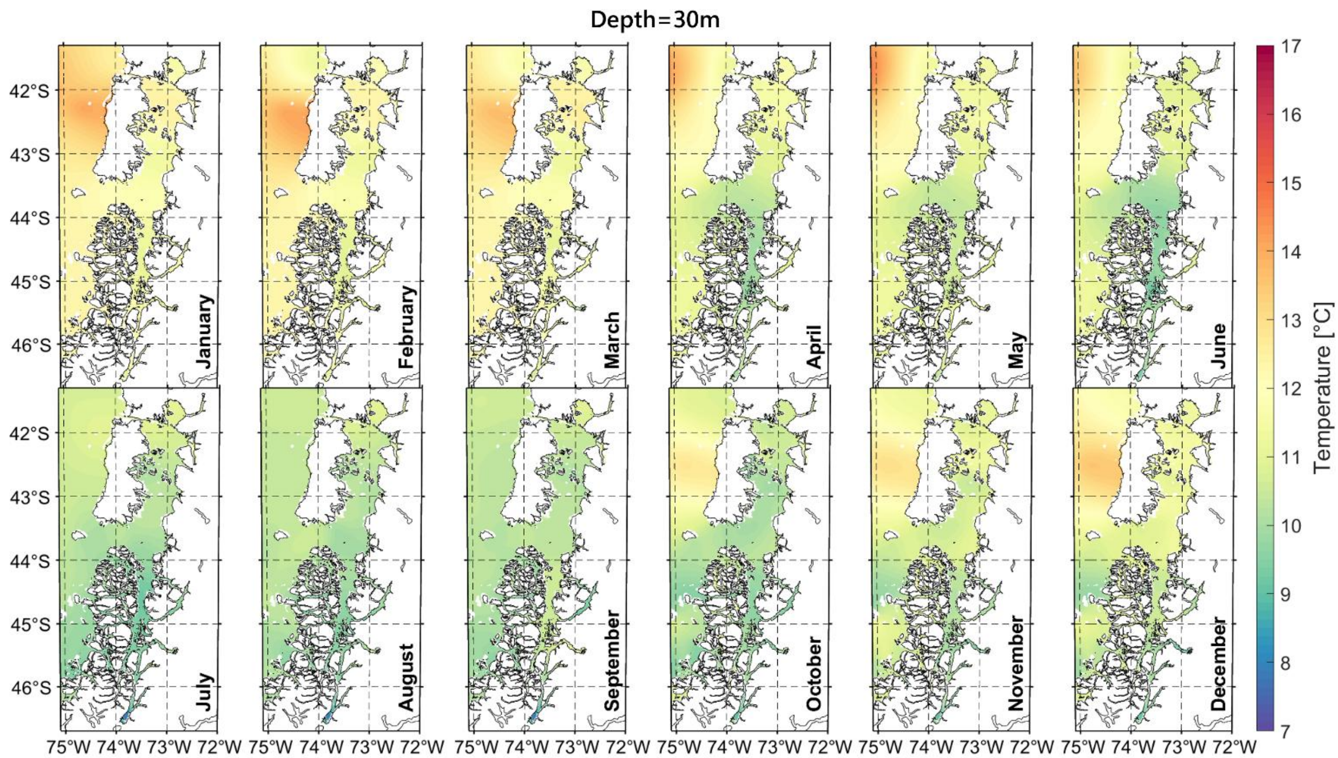

Figure 6: Monthly climatology of the sea temperature at 30m depth.

The vertical temperature distribution highlights a strong seasonal variation of stratification in Northern Patagonia (Fig. 8). Four regions are described, and the comparison between the original observational vertical profiles and the climatology's results are available in Fig. 8. In most basins, the thermocline typically lies between the surface and 20 m depth and strengthens during summer, as illustrated for Reloncaví Sound (Fig. 8A, B). It can deepen to 50 m west of Chiloé Island or within Aysén and Puyuhuapi Fjords (Fig. 8G, H), and even extend down to 100 m in Guafo Mouth and Corcovado Gulf (Fig.

8E, F). In winter, the entire water column is nearly homogeneous, especially around Chacao Channel, the northern half of Corcovado Gulf and Ancud Gulf (Fig. 8C, D). The surface mixed layer is generally shallow in summer (less than 10 m) with pronounced surface stratification in fjords and semi-enclosed basins.

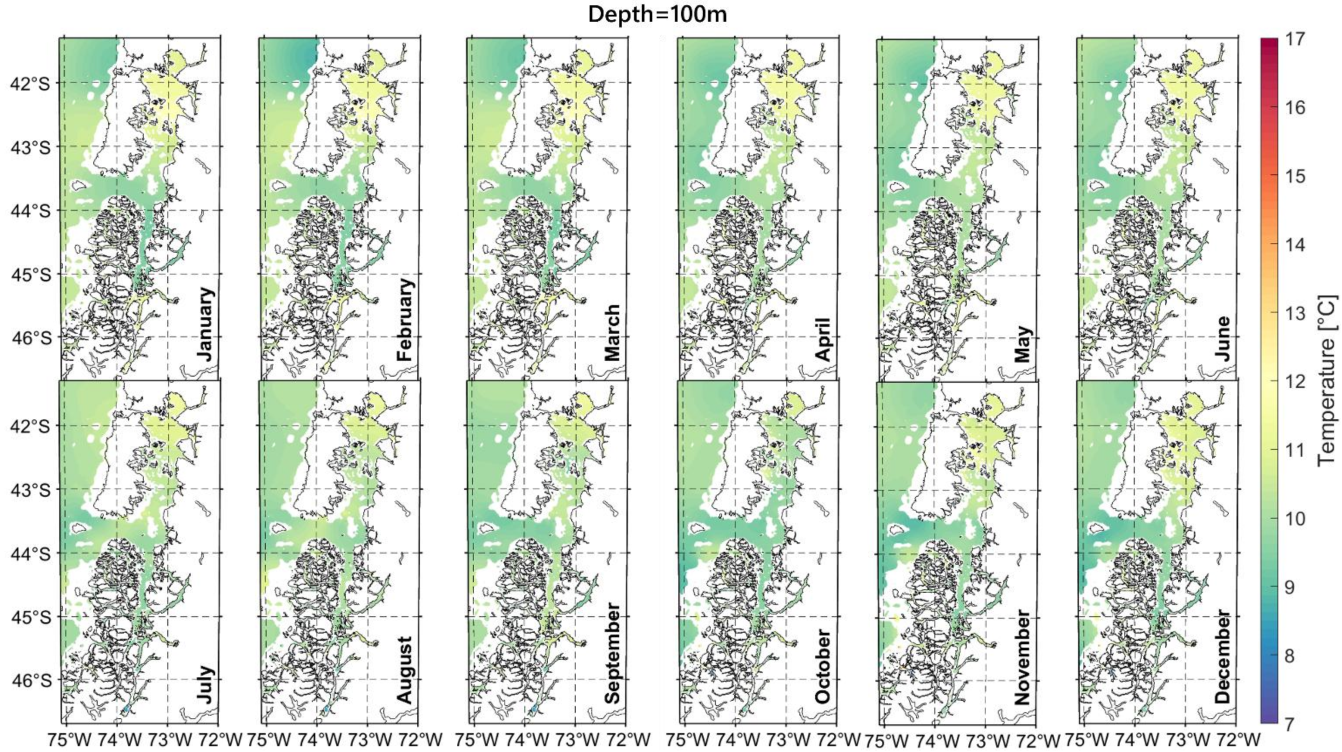

Figure 7: Monthly climatology of the sea temperature at 100m depth.

4 Discussion

In this study, a 4-dimentional climatology was constructed from 75 years of in situ observations in Northern Chilean Patagonia, a region characterised by highly complex bathymetry, strong freshwater inputs, and an intricate network of fjords and channels (Pantoja et al., 2011; Rodrigo, 2008; Strub et al., 2019). With a horizontal resolution of approximately 900 m, the product accurately reproduces the long-term thermal conditions of one of the most sensitive fjord critical zone in the world (Bianchi et al., 2020). To our knowledge, this represents the first high-resolution, multi-decadal in situ-based temperature climatology developed for Northern Patagonia. Previous efforts have provided valuable insights into the regional oceanography through seasonal or annual climatologies derived from shorter time series or satellite products (Saldías et al., 2021; Strub et al., 2019). However, such datasets are generally limited in temporal extent and often too coarse to capture the fine-scale variability inherent to fjord systems. Each subregion of Northern Patagonia responds differently to external forcings such as wind, freshwater discharge, residence time and heat fluxes, all modulated by local topography

https://doi.org/10.5194/essd-2026-42
Preprint. Discussion started: 18 February 2026

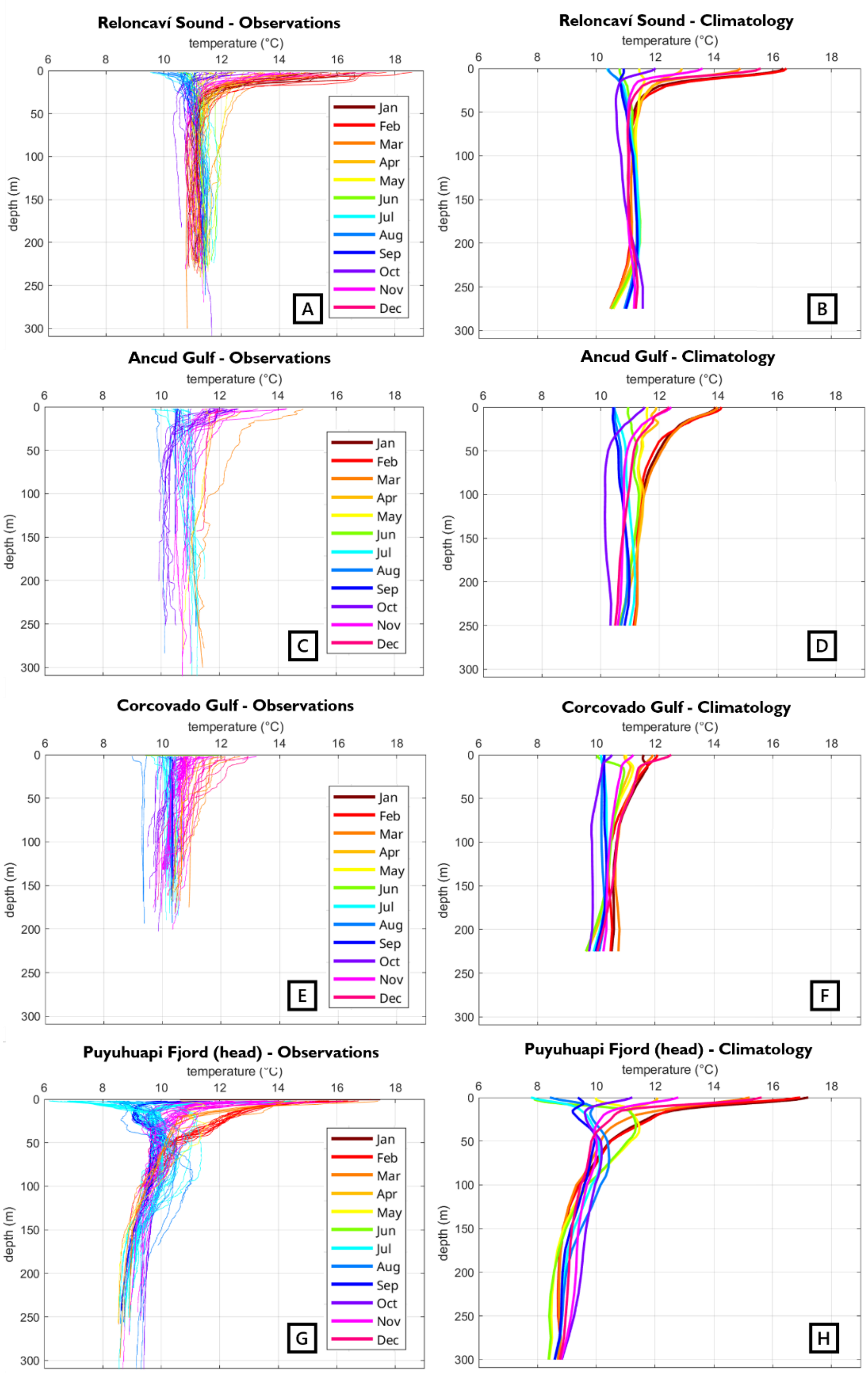

Figure 8: Profile plots of the in situ observations (left) and the monthly climatology in different basins of the study area: A-B: Reloncaví Sound, C-D: Ancud Gulf, E-F: South of the Corcovado Gulf, G-H: the head of Puyuhuapi Fjord. Each colour represents the monthly climatology for a specific month of the year. The profile terminates according to the local bathymetry.

(Kilpeläinen et al., 2011; Pinilla et al., 2019a, 2021; Soto et al., 2019). Accurately resolving these local variations in temperature is therefore essential to characterise the physical dynamics of the region and understanding its sensitivity to environmental change.

Overall, the temperature climatology derived from in situ data in this study shows strong consistency with previous observational and modelling work conducted in Northern Chilean Patagonia. Both the large-scale seasonal cycle and the finer spatial patterns observed at the surface and in subsurface layers closely match those reported in earlier studies (e.g. Castillo et al., 2016; León-Muñoz et al., 2013; Linford et al., 2024; Narváez et al., 2019; Saldías et al., 2021).

At the surface, the pronounced west-east gradient detected during summer in both the open ocean and the Inner Sea agrees with satellite and model-based observations (Castillo et al., 2016; León-Muñoz et al., 2013; Linford et al., 2024; Saldías et al., 2021). Similarly, the warm conditions recorded in Reloncaví Sound, Comau Fjord and Puyuhuapi Fjord during summer have been consistently reported in those same studies. The marked contrast between the relatively warm Puyuhuapi Fjord and the cooler Aysén Fjord, despite their close proximity is likely driven by stronger freshwater discharge, glacier meltwater and snowmelt input in Aysén (Calvete and Sobarzo, 2011; León-Muñoz et al., 2024; Pinilla et al., 2019b). The colder conditions identified in the Chacao Channel and south of the Desertores Islands are also consistent with (Narváez et al., 2019) who attributed these localised minima to tidal mixing and shorter water residence times. The same study also suggested that the higher temperature amplitudes observed in the Inner Sea of Chiloé may be influenced by variations in tidal forcings, local winds and stratification intensity.

The seasonal evolution of surface temperature follows the pattern described by (Saldías et al., 2021): in their study, they used 17 years of satellite data to show a strong summer gradient that weakens in autumn, a nearly homogeneous winter distribution (9-12°C) and renewed warming in spring. The north-south gradient emerging in austral winter and the relatively cold conditions in Puyuhuapi Fjord (Linford et al., 2024; Pérez-Santos, 2017; Saldías et al., 2021; Schneider et al., 2014) are also captured by the climatology. The higher temperature variability in enclosed fjords such as Reloncaví Sound and the head of Puyuhuapi Fjord agrees with previous findings (Pérez-Santos et al., 2021; Pinilla et al., 2020; Schneider et al., 2014), reflecting the strong influence of freshwater inflows and restricted circulation. Saldías et al. (2021) also illustrate that the sea surface temperature standard deviation is much higher in enclosed fjords than in more exposed basins (as Corcovado Gulfs), confirming that our interpolation reflects known physical processes. Conversely, open basins such as Corcovado Gulf, Moraleda Channel and Ancud Gulf display smaller seasonal amplitudes, with Corcovado Gulf showing the lowest amplitude, as also noted by Buchan et al. (2021). Narváez et al. (2019) further suggested that the enhanced warming in the northern sector may be partly due to the Desertores Islands, which shelter the surface waters from wind and currents, allowing greater local heating.

Below the surface, the temperature gradually decreases and spatial gradients become smoother, in agreement with observations by Pérez-Santos et al. (2021). At 30 m depth, seasonal variations remain visible, while at 100 m depth, the temperature remains nearly constant throughout the year, although some spatial differences are observed, consistent with results of (Pinilla et al., 2021). At 200 m depth, relatively warm conditions persist in the northern basins (Reloncaví Sound

https://doi.org/10.5194/essd-2026-42
Preprint. Discussion started: 18 February 2026

and Ancud Gulf) with temperatures around 10 to 11°C, contrary to other basins showing temperatures around 8-9°C, possibly because the Desertores Islands act as a physical barrier, limiting water renewal and trapping warmer intermediate waters (Linford et al., 2024; Pérez-Santos et al., 2021). At 400 m depth, the temperature stabilises near 7°C across most of the domain, except in Aysén Fjord, where it fluctuates between 8.5°C (July to December) and 10°C (January to June). These seasonal changes likely reflect the long water residence time in this fjord (up to 120 days; Linford et al., 2024) which buffers rapid thermal adjustments.

The vertical structure provided by the climatology also agrees with previous studies. The thermocline typically develops between the surface and 20 m depth during summer and reaching 50 m in fjords such as Puyuhuapi and Aysén, or in the open ocean west of Chiloé Island. In well mixed-areas such as Guafo Mouth and Corcovado Gulf, the thermocline extends even deeper (up to 100 m) reflecting strong regional vertical mixing (Calvete and Sobarzo, 2011). During winter, the entire water column becomes nearly homogeneous, particularly around Chacao Channal, Ancud Gulf and the northern Corcovado Gulf, as also observed by (Pérez-Santos et al., 2021). The shallow summer mixed layer (typically inferior to 10 m) and intense surface stratification in fjords and enclosed basins resemble conditions observed in other high-latitude fjords, such as those in Finland (Merkouriadi and Leppäranta, 2015) and Norway (Skogseth et al., 2020). Stratification tends to be stronger at the fjord heads, where freshwater inputs are higher, a pattern also reported for southern Patagonian fjords (Maturana-Martínez et al., 2021) and Arctic fjord systems (Szeligowska et al., 2020).

The climatology developed in this study has a wide range of potential applications in ecological, oceanographic and management domains. From an ecological perspective, it provides a robust reference for assessing thermal niches, predicting shifts in species distributions under climate warming and evaluating the thermal stability of habitat relevant to larval dispersal, or harmful algal blooms (e.g. Aiken et al., 2007; Moore et al., 2008). In the aquaculture sector, the multi-decadal baseline enables comparison between present-day temperature and historical conditions, helping identify warming hotspots and periods of increased thermal stress for farmed species. By spanning 75 years, the dataset allows the quantification of long-term thermal anomalies and the detection of persistent temperature shifts within individual fjords, supporting risk mapping for temperature-sensitive species and informing spatial planning, including the identification of thermally distinct regions suitable or not for aquaculture expansion. The climatology also offers a valuable tool for environmental monitoring. When combined with near real-time observations from for example moorings, it provides a reference against which anomalies from expected conditions can be rapidly identified, an approach particularly relevant for managing salmon farming risks associated wit harmful algal blooms, oxygen depletion or rapid warming events. Moreover, the monthly and daily-derived fields can serve as an appropriate baseline for marine heatwaves detection and characterisation, following standard definition based on long-term climatology (Hobday et al., 2016). This is especially important in fjord environments, where satellite sea surface temperature products often fail to resolve fine-scale thermal structure. Finally, the climatology can support a wide range of oceanographic applications, including its use for background field for hydrodynamic or biogeochemical models, and as a high-resolution reference for model validation in regions where traditional gridded products perform poorly (Lazure et al., 2009; Ridgwell et al., 2007; Vichi et al., 2003).

https://doi.org/10.5194/essd-2026-42
Preprint. Discussion started: 18 February 2026

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5 Conclusions

In this study, a four-dimensional temperature climatology was constructed from approximately 3 million in situ observations collected over the past 75 years from multiple datasets in Northern Chilean Patagonia, a region characterised by complex bathymetry, strong freshwater inputs and extensive network of fjords and channels. With a horizontal resolution of approximately 900 m and 32 vertical levels, this product accurately reproduces the long-term thermal conditions of the region and represents, to our knowledge, the first high-resolution, multi-decadal, in situ-based temperature climatology developed for Northern Patagonia. By resolving fjord-scale temperature gradients and identifying distinct spatial and vertical thermal regimes, the climatology provides a refined and physically consistent representation of the oceanographic structure of this highly dynamic region. Enclosed basins such as Reloncaví Sound, Comau and Puyuhuapi Fjords display stronger seasonal temperature amplitudes, while more open systems such as Corcovado Gulf exhibit comparatively stable conditions.

This approach demonstrates the value of in situ-based reconstructions in regions where satellite observations remain limited by cloud cover and complex coastal geometry. It establishes a robust foundation for future oceanographic analyses and model validation in Northern Chilean Patagonia. The methodology relies exclusively on in situ data, freely accessible online, most of which were collected through local monitoring campaigns funded by public institutions. However, a substantial quantity of high-quality environmental data is also gathered by private operators, particularly aquaculture companies, which routinely monitor temperature, salinity, oxygen and other parameters at high temporal frequency. Sharing such data would greatly enhance the spatial and temporal coverage of regional datasets. Closer collaboration and data sharing between the private sector and the scientific community would provide substantial mutual benefits advancing public research while also offering private stakeholders improved environmental knowledge, forecasting capacity and long-term sustainability strategies.

All climatological fields generated in this study, monthly and daily at 32 different depth levels, are freely available online (Pujol et al., 2026), providing a valuable resource for future scientific research and applied ocean monitoring in Chilean Patagonia.

Data availability

The monthly and daily-derived climatologies described in Sections 2 and 3 are available on Zenodo under DOI https://doi.org/10.5281/zenodo.18255999 (Pujol et al., 2026) and can be freely used for any purpose.

Figures fully describing the monthly climatology at every depth level are available in the supplementary material.

The list, description and sources/DOIs of all the in situ data used for the construction of the climatologies (Sect. 2.2) are also available in the supplementary material.

Author contribution

C.P. Conceptualization, formal analysis, investigation, methodology, validation, writing (original draft and editing), writing (review and editing).

A.B. Conceptualization, methodology, supervision, validation, writing (original draft and editing), writing (review and editing).

I.P-S. Conceptualization, methodology, resources, supervision, writing (original draft and editing), writing (review and editing).

P.L. Resources, writing (original draft and editing), writing (review and editing).

A.A-A. Conceptualization, methodology, supervision, validation, writing (original draft and editing), writing (review and editing).

Competing interests

The authors declare that they have no conflict of interest.

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