Environmental drivers determined by remote sensing and *in-situ* measurements during a spring phytoplankton bloom event in the fjords and channels of southern Chile

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Abstract

Over the past few decades, harmful algal blooms (HABs) have become increasingly frequent in the fjords and channels of southern Chile. However, knowledge of the environmental factors that trigger them remains limited in remote areas. This study uses a combination of *in-situ* observations and satellite remote sensing (Sentinel-3A/B) to analyse the physical, chemical and biological conditions during a phytoplankton bloom in spring (November–December 2021) in the Magellan region. Fourteen stations were sampled during the EXOFAN cruise to evaluate the hydrographic structure, nutrient availability and phytoplankton composition, paying particular attention to potentially harmful species such as *Phaeocystis* spp. and the *Pseudonitzschia cf. pseudodelicatissima* complex. The results revealed spatial heterogeneity in the distributions of salinity, temperature and nutrients, with freshwater inputs and solar heating generating stratified water masses in interior fjords. High cell densities of the target taxa were found in these stable environments, which may act as retention zones favouring bloom persistence. Satellite-derived Sea Surface Temperature and Chlorophyll-a data corroborated the *in-situ* findings, revealing seasonal warming and productivity hotspots despite frequent cloud cover. This study highlights the importance of combining traditional oceanographic methods with remote sensing to understand and monitor bloom dynamics in complex subpolar coastal systems. The observed patterns offer valuable insights into the ecological conditions that drive HAB development. This information is crucial for the development of future prediction models, early warning systems and sustainable aquaculture management strategies, particularly in the face of ongoing climate-driven changes.

1. Introduction

Over the last five decades, there has been an apparent worldwide increase in the frequency, duration and intensity of Harmful Algal Blooms (HABs) events, as well as an increase in their geographical distribution (Hallegraeff, 2010). This increase is attributed to two main factors: i) natural processes such as marine circulation, vertical advection and stratification; and ii) anthropogenic activities, including aquaculture, ballast water, global warming (Trainer et al., 2020; Hallegraeff et al., 2021). In general, harmful microalgae are classified as high biomass producers and toxin producers. The former mainly cause damage by depleting oxygen and nutrients from the water (Smayda, 1997; Reguera et al., 2012), while the latter contaminate filter-feeding shellfish with toxins when the shellfish ingest toxic dinoflagellates (Bricelj & Shumway, 1998).

HABs are becoming increasingly frequent in the coastal waters of southern Patagonia, particularly in the fjord and channel system (Iriarte et al., 2023). Along Chile`s diverse coastline, several species of microalgae that produce marine toxins have been identified. Interestingly, these species are not evenly spread; some are restricted to the southern regions while others are widely dispersed. The former group includes Paralytic Shellfish Toxins (PSTs), Okadaic Acid (OA), Dinophysistoxin-1 (DTX-1) and Pinnatoxin (PnTXs) (Ugarte et al., 2022; Díaz et al., 2022; Möller et al., 2022). In contrast, toxins primarily associated with the southern species include Domoic Acid (DA), Azaspiracids, (AZA), Pectenotoxin-2 (PTX-2), Yessotoxins (YTXs), Spirolids (SPXs) and Gymnodimines (GYMs) (Trefault et al., 2011; Díaz et al., 2019; 2022; Krock et al., 2009, 2018).

Historically, our research into the occurrence and detection of these phenomena in the southern region has been strongly influenced by increased observation efforts in the inland seas of Patagonia (PROFAN and EXOFAN oceanographic cruises, Frangopulos et al., 2023; Iriarte et al., 2023). Although the Magellan region was where the microalgae *Alexandrium catenella,* a PST producer, was first detected in Chile (Guzmán et al., 1975), there is little information on HABs, due to remote or difficult-to-access areas. These areas include ocean areas, channels exposed to the ocean, the turbulent central areas of channels and the interior of glacial fjords, where access by regular monitoring programmes is not possible by small boat.

In light of the intensity and extent of the HABs phenomenon in recent years, the potential expansion of aquaculture activity in the Magellan region and the coexistence of simultaneous harmful blooms of different groups across a large part of the southern coast, as well as the anticipated effects of global warming on plankton dynamics, particularly in sub-Antarctic coastal regions, and the growing efforts to ensure the safe and successful exploitation of fishery and aquaculture resources, there is an urgent need to assess the risk posed by toxic microalgae and, underlying bloom dynamics. This will assist in the development of enhanced management, prediction and mitigation of HABs and their effects on the ecosystems. However, understanding the consequences of these changes and their effects on adjacent regions propose a considerable challenge to local researchers, given that the mechanisms of HABs development necessitate an understanding of the ecological and oceanographic factors controlling the distribution and dynamics of populations of marine toxin-producing species remains quite limited in this area. Consequently, the construction of future scenarios for HABs with the information currently available remains inadequate.

The use of satellite images and their post-processing represent an optimal tool for monitoring marine environments. The frequency at which satellites orbit, allows the systematic collection of various observations over large areas of the coast and adjacent waters (often inaccessible), in different periods of time. Oceanographic products derived from these observations include estimates of surface winds, water surface temperature, sea level and chlorophyll concentration (Miller et al., 2005). Given the diversity of sensors, techniques and platforms used, satellite observations vary in their temporal, spatial and spectral characteristics. The sampling range of today's satellites ranges from hours to years and from meters to global scales. Therefore, the use of remote sensing as a tool for the early detection and tracking of HABs events has been successfully demonstrated in a wide range of environments (Torres et al., 2019; Spyrakos et al., 2020). However, remote sensing products are not always completely accurate in local areas or in highly dynamic systems such as the fjords and channels of southern Chile. Coastal waters are typically characterised by significant variability in the vertical distribution of phytoplankton and in their optical properties (Spyrakos et al., 2020). These downsides can be assessed utilizing an increased number of acquisitions and afterwards performing binning or averaging.

It is evident that the present study was motivated by the necessity to ascertain the environmental drivers. To this end, the study employed a range of approaches, including in-situ measurements and remote sensing data, during the bloom period in spring 2021 in the Beagle Channel and the Strait of Magellan (southern Chile). The rationale behind this choice is that high abundances of the potentially toxic microalgae, the haptophyte *Phaeocystis* spp. and the diatom *Pseudo-nitzschia pseudodelicatissima* complex were detected in these locations.

Study Area

Sampling for the present study was conducted during the austral spring (from November 27 to December 5, 2021) in the fjord and channel system of the Magallanes and Chilean Antarctic Region, as part of the EXOFAN oceanographic cruise aboard the Chilean Navy's AGS-61 Cabo de Hornos research vessel. To integrate synoptic in situ measurements with satellite remote sensing data, a total of 10 sampling stations were selected for the purpose of assessing the role of islands and protected areas as local retention zones that may favour the growth and persistence of microalgae, including toxic species (Fig. 1).

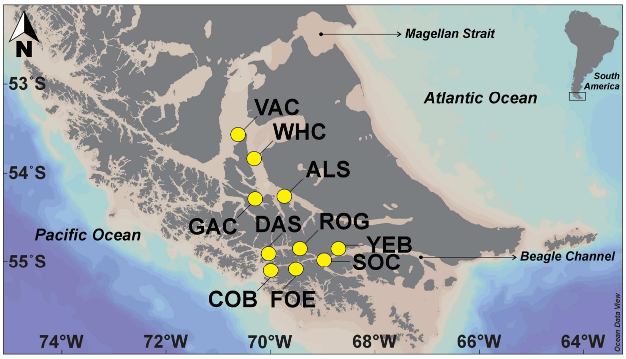

Figure 1. Map of the study area during the EXOFAN cruise in the Magellan and Chilean Antarctic region.

2. Material and Methods

To characterize the phytoplankton community structure, qualitative samples for taxonomic identification of microalgae were collected using vertical hauls with a plankton net of 20 µm mesh size. In parallel, quantitative samples were obtained at discrete depths (0, 5, 10, and 25 m) using Niskin bottles. Cell counts and taxonomic identification were performed in the laboratory using inverted light microscopy, following the sedimentation method described by Utermöhl (1958).

To characterize the physical and chemical hydrographic structure (temperature and salinity) and its influence on phytoplankton communities, a Sea-Bird SBE 21 Seacat thermosalinograph was used during the navigation routes. Meteorological conditions were recorded using a Vaisala weather station located atop the navigation bridge. Data acquisition and analysis were performed using Ocean Data View v5.2.0 (ODV) (Schlitzer, 2021).

To increase the amount of information on the study area, several products from remote sensors (satellite) were calculated, the platform selected for this purpose is Sentinel 3A and Sentinel 3B. These satellites can obtain several marine products using 21 bands covering a wavelength from 400 nm to 1020 nm with a resolution of 300 m. In this work we produced Sea Surface Temperature (SST) and Chlorophyll-a Concentration (Chl) starting from L1 products, seeking to improve the cloudy conditions of this region monthly averages were produced from November and December 2021. All calculations were performed by Sentinel SNAP software (European Space Agency) and finally exported into QGIS for map generation.

4. Results

4.1. Atmospheric and hydrographic conditions

In the atmospheric system, relative humidity remained predominantly high (>80%) along most of the transect, particularly in coastal areas and within fjords, reflecting the strong oceanic influence and orographic moisture retention. Lower humidity values (<60%) were observed in more sheltered or inland areas, likely associated with local subsidence or reduced advection of moist air masses (Fig. 2a). On the other hand, the atmospheric pressure showed a clear barometric gradient, with higher values (>1005 hPa) in the northwest and central sectors, and a low-pressure zone (<990 hPa) in the southeast, suggesting the presence of a cyclonic system associated with unstable weather and strong winds (Fig. 2b).

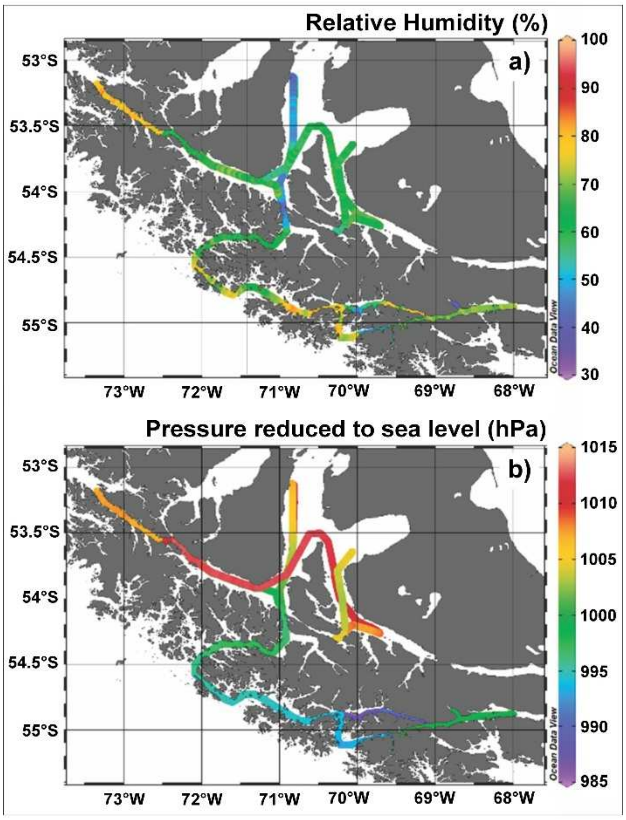

Figure 2. Atmospheric variables of relative humidity (a) and pressure reduced to sea level (b) measured during the EXOFAN oceanographic cruise in the Magellan and Chilean Antarctic region.

Meanwhile, the zonal wind component (Fig. 3a) exhibited significant spatial variability, with westerly winds reaching up to 50 knots in exposed areas and easterly flows in more enclosed sectors, likely shaped by the complex fjord topography. Similarly, the meridional component (Fig. 3b) revealed strong northerly winds (down to –40 knots) in several areas, while moderate southerly winds (up to 10 knots) were recorded elsewhere, possibly reflecting post-frontal conditions.

Surface salinity and temperature (at 3 m depth) exhibited clear spatial gradients across the fjord and channel system. Salinity decreased from oceanic sectors in the west (>31.5 PSU) toward more sheltered interior fjords (~29 PSU), reflecting significant freshwater input from continental runoff and glacial melt (Fig. 4a). Concurrently, surface temperature was higher (>9 °C) in northern and central fjords and lower (<8 °C) in the more open southern areas, likely due to reduced mixing and increased solar heating in confined zones (Fig. 4b). The combination of low salinity and elevated temperature suggests the presence of stable, stratified water masses in interior fjords, potentially favouring phytoplankton accumulation and bloom development (Fig. 4).

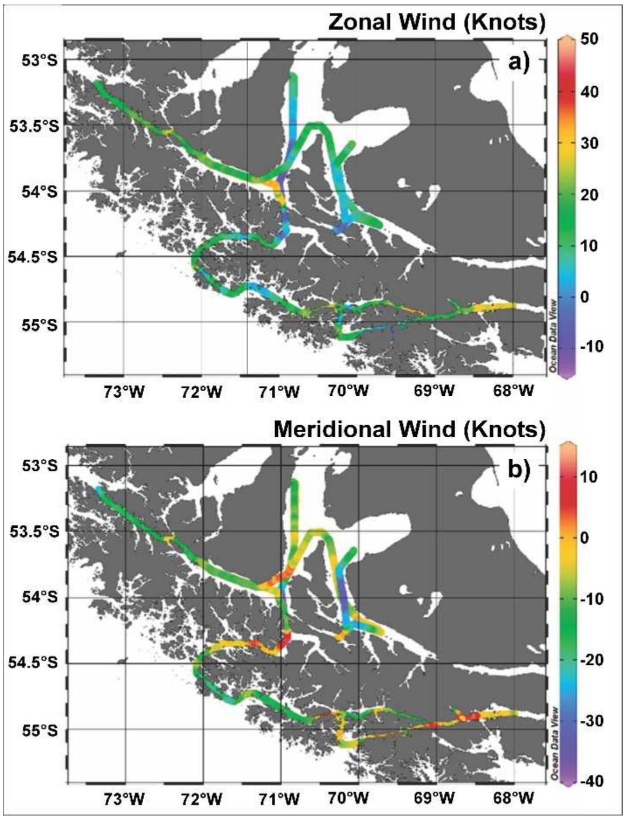

Figure 3. Atmospheric variables of zonal wind (a) and meridional wind (b) measured during the EXOFAN oceanographic cruise in the Magellan and Chilean Antarctic region.

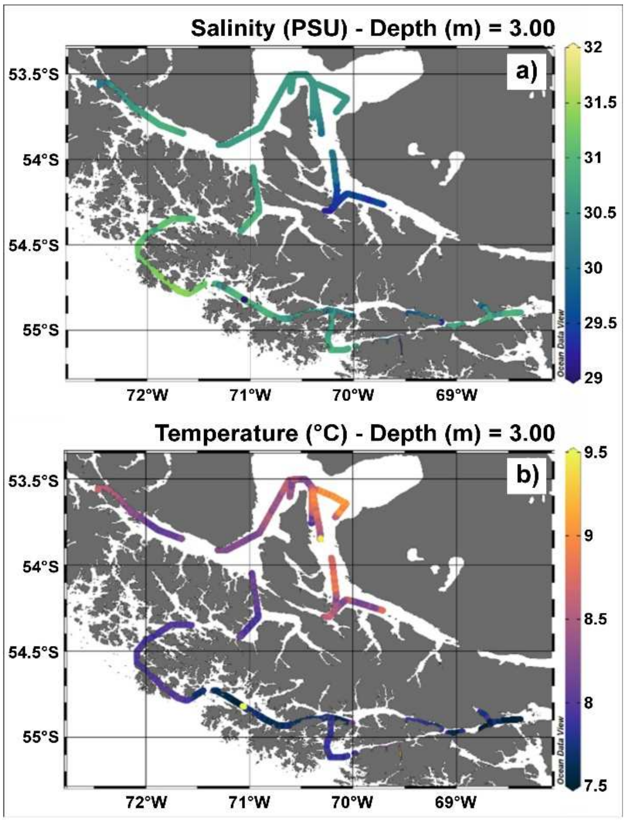

Figure 4. Oceanographic variables of salinity (a) and temperature (b) recorded at a depth of 3 meters by the thermosalinograph during the EXOFAN oceanographic cruise in the Magellan and Chilean Antarctic region.

4.2. Distribution of inorganic nutrients

The concentrations of nutrient exhibited significant variability among the sampled sites (Fig. 5). Nitrate showed the most pronounced differences, with the highest concentrations (3.1 µM) recorded at VAC, ROG, and SOC, whereas the lowest values (<0.2 µM) were observed at ALS and GAC. The Phosphate levels exhibited relative homogeneity across the stations, with a range from 0.4 to 0.9 µM, and the maximum concentration recorded was 0.9 µM at YEB. Nitrite levels remained consistently low (i.e. below 0.2 µM) at all sites, with a slight increase recorded at WHC (0.2 µM). In the case of silicic acid, concentrations ranged from 0.6 to 3.6 µM, with the highest values detected at DAS (3.6 µM) and the lowest at ALS (0.6 µM).

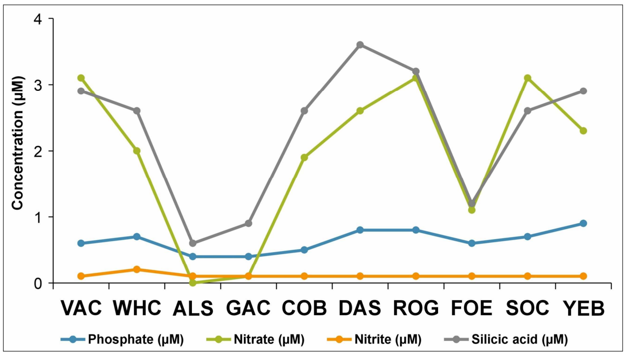

Figure 5. Surface nutrient concentrations at the study sites during the EXOFAN oceanographic cruise in the Magellan and Chilean Antarctic region.

4.3. Phytoplankton composition based on light microscopy

In the phytoplankton assemblages, 115 taxa were identified, distributed across six phyla and eight classes; Bacillariophyta (59 spp.) and Dinophyta (50 spp.) were the most prevalent. A significant degree of spatial variability was observed among phytoplanktonic assemblages along the Magellan and Chilean Antarctic region, regarding taxonomic composition and cell density. While some taxa were found to be geographically constrained, with most exhibiting a wide distribution with variable abundances, further research is required to ascertain the full extent of this phenomenon. It is evident that several species are responsible for the production of lipophilic toxins, including *Dinophysis acuta*, *D. acuminata*, *Lingulodinium polyedra* and *Protoceratium reticulatum.* In addition to these, hydrophilic toxins are also produced by various species, such as *Alexandrium catenella*, *A. ostenfeldii, Pseudo-nitzschia* cf. *australis* and *P.* cf. *pseudo-delicatissima complexes*.

The high cell density of the Haptophyta *Phaeocystis* spp. showed spatial variability between sampling sites, with maximum values observed in SOC (13.979 cel mL^{-1}) and DAS (11.549 cel mL^{-1}), and lower values in YEB (9.754 cel mL^{-1}) and FOE (9.870 cel mL^{-1}) (Fig. 6a). The cell density of *Pseudo-nitzschia* cf. *pseudo-delicatissima* complex showed marked spatial variability among the study sites (Fig. 6b). VAC exhibited by far the highest recorded density (>23.000 cel mL^{-1}). In contrast, the other sites, WHC, ALS, and GAC showed considerably lower values (<8.000 cel mL^{-1}) (Fig. 6b). The high prevalence of *P.* cf. *pseudo-delicatissima* complex at a specific site may have ecological and public health implications, given the toxigenic potential of the genus founded in the fjords and channels of the Magellan region (Pinto-Torres et al., 2023).

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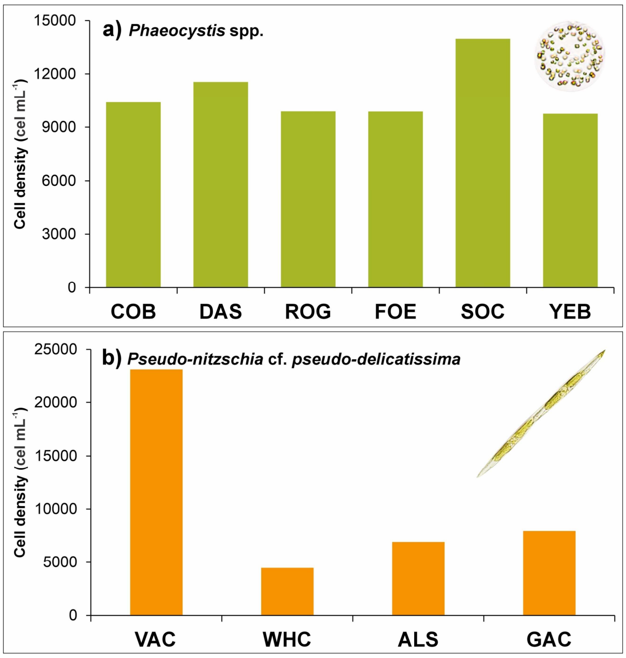

Figure 6. Cell density (cel mL^{-1}) of the (a) *Phaeocystis* spp. and (b) *Pseudo-nitzschia* cf. *pseudo-delicatissima* complex in the Magellan and Chilean Antarctic region.

4.4. Improving understanding of blooms through remote sensing

The Sea Surface Temperature (SST) results coming from remote sensing analysis are presented in the Figure 7, is possible to verify that due to cloud cover some stations could not be calculated, but these represents just a small fraction of our data. Chlorophyll-a data results can be observed in the Figure 8. Both results were filtered from clouds and masked from poor or ambiguous calculations. The specific results from all available stations are summarized at Table 1.

Satellite analyses of Chlorophyll-a (Chla) and Sea Surface Temperature (SST) revealed patterns consistent with the occurrence of blooms of *Phaeocystis* spp. and *Pseudo-nitzschia* cf. *pseudo-delicatissima* in the fjord and channel system of the Magallanes and Chilean Antarctic Region. In the case of *Phaeocystis* spp., cell densities were found to be high and relatively homogeneous at most stations in the Beagle Channel (COB, DAS, ROG, FOE, and YEB), with a maximum recorded at SOC (Fig. 6a). These areas coincided spatially with patches of higher phytoplankton biomass (0.6–1.2 mg m^{-3} of Chla) (Fig. 7), detected mainly in sectors of enclosed inner channels influenced by glacial discharges. In addition, stations exhibiting the highest abundance of *Phaeocystis* spp. were found to be associated with cold water masses (~6–9 °C) (Fig. 8), which is consistent with the documented affinity of these organisms for sub-Antarctic environments characterised by optimal nutrient conditions. In contrast, *P.* cf. *pseudo-delicatissima* exhibited an intense and localised bloom in VAC within the Strait of Magellan, with densities reaching approximately 23,000 cells mL^{-1}, a value significantly higher than that recorded at the other stations (Fig. 6b). This event coincided with a period of elevated chlorophyll (≥ 1 mg m^{-3}) and relatively warmer waters (~10–12 °C), conditions conducive to the proliferation of diatoms of this genus (Fig. 7 and 8). It was also observed that other sites with moderate abundances (ALS and GAC) exhibited correspondence with patches of intermediate chlorophyll (0.4–0.6 mg m^{-3}) (Fig. 7), although with reduced intensity compared to that observed in VAC. The findings of this study demonstrate that spatial gradients in phytoplankton biomass and temperature, as derived from remote sensing methodologies, provide a substantial explanation for the differential dynamics observed between the two assemblages within sub-Antarctic fjords and channels.

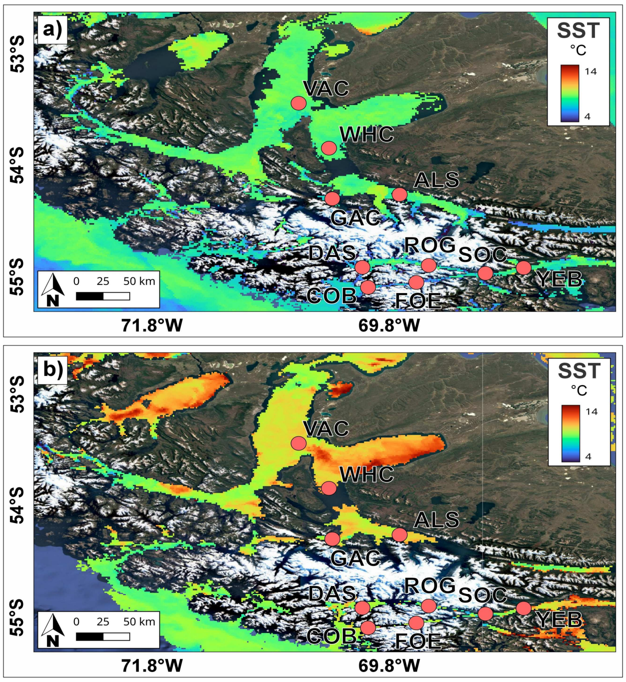

Figure 7. Sea Surface Temperature from Sentinel-3 data, (a) November 2021, (b) December 2021. As background a Google Earth image.

Table 1. Sea Surface Temperature and Chlorophyll-a values from satellite data at all available stations in the Magellan and Chilean Antarctic region. N.D = No Data.

Site	Nov SST (°C)	Dec SST (°C)	Nov Chl (mg.m^{-3})	Dec Chl (mg.m^{-3})
VAC	7.07	10.75	0.126	0.142
WHS	7.39	10.73	0.457	0.079
ALS	7.10	10.48	0.297	0.128
GAC	6.33	8.50	0.124	0.189
COB	6.45	9.26	0.189	0.268
DAS	6.71	8.76	0.016	0.268
FOE	5.56	7.90	0.298	0.143
ROG	6.86	7.84	0.301	0.173
SOC	6.37	8.41	N.D	0.175
YEB	7.05	9.42	0.188	0.409

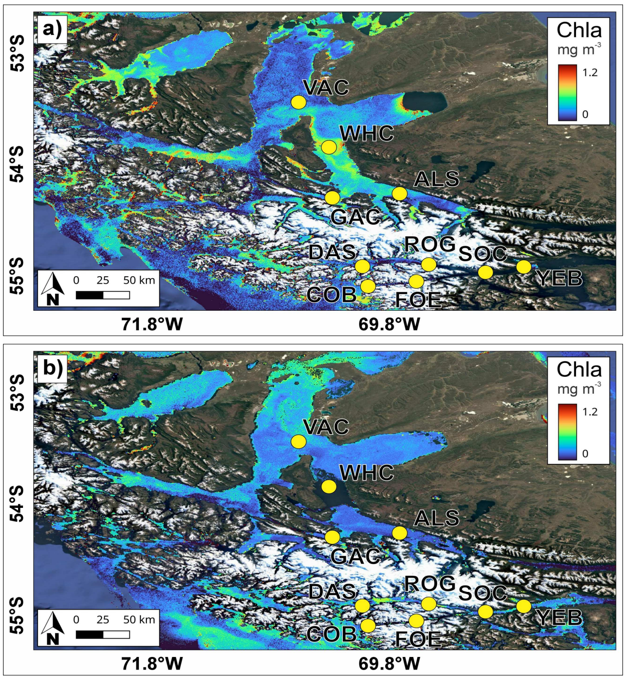

Figure 8. Chlorophyll-a from Sentinel-3 data, (a) November 2021, (b) December 2021. As background a Google Earth image.

3. Conclusions

This study integrated *in situ* observations and satellite remote sensing to characterize the environmental drivers of a spring phytoplankton bloom event in the fjords and channels of southern Chile. The results indicate significant spatial variability in atmospheric, hydrographic, and biological conditions, influenced by the inherent environmental heterogeneity of the Magellan and Chilean Antarctic Region. It was observed that elevated concentrations of *Phaeocystis* spp. and the *Pseudo-nitzschia* cf. *pseudodelicatissima* complex were observed in specific areas. This finding suggests the presence of local retention zones that promote the development and persistence of potentially toxic microalgae under springtime environmental conditions. It was determined that the species *Phaeocystis* spp. and *P.* cf. *Pseudodelicatissima complex* responded strongly to the availability of inorganic nutrients, primarily nitrate. However, as indicated by the data, *P.* cf. *pseudodelicatissima* exhibited an even more pronounced dependence on high concentrations of silicates. This finding is consistent with the specie's strategy of rapid growth under favourable conditions.

The utilisation of Sentinel-3 satellite imagery effectively complemented the *in-situ* data, thereby facilitating the identification of spatiotemporal variations in sea surface temperature and chlorophyll-a concentration. These findings confirm the usefulness of remote sensing as a monitoring tool; moreover, further adjustments to its application in dynamic coastal environments are required to improve the tool's accuracy. The data obtained in this study serve to enhance our comprehension of the mechanisms that regulate harmful algal blooms (HABs) in sub-Antarctic geographic areas. To enhance the predictive and early warning capacities for these events under scenarios of global climate change, it is recommended that additional variables can be incorporated. Such variables may include the concentration of coloured dissolved organic matter (CDOM) or photosynthetically active radiation (PAR).

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Appendix

Table 2. Information on study sites in the Magallanes region and Chilean Antarctica.

Study site	Code	Long (°W)	Lat (°S)
Valentin channel	VAC	-70.6117	-53.6016
Whiteside channel	WHC	-70.3117	-53.8472
Almirantazgo sound	ALS	-69.7161	-54.2643
Gabriel channel	GAC	-70.2831	-54.3014
Cook bay	COB	-69.9823	-55.0928
Darwin sound	DAS	-70.0295	-54.9159
Fouquet estuary	FOE	-69.5754	-55.0491
Romanche glacier	ROG	-69.4707	-54.8988
Sonia cove	SOC	-68.9481	-54.9683
Yendegaia bay	YEB	-68.6708	-54.9198

https://doi.org/10.5194/isprs-annals-X-3-W4-2025-141-2026