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Ship-of-Opportunity Monitoring of the Chilean Fjords Using the Pocket FerryBox

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ABSTRACT

Results from two field campaigns in the Chilean fjords region are presented to demonstrate the benefits and limitations of the “pocket FerryBox” for monitoring from ships of opportunity. The October 2009 (spring) campaign covered the region of the Chilean coast between 41.5° and 46.7°S, and that in March 2010 (autumn) covered the region between 41.5° and 51.8°S. In the campaigns the pocket FerryBox—a portable flow-through system for underway multiparametric monitoring—was installed temporarily on board the vessel *M/V Ro-Ro Evangelistas*. The taking of water samples allowed posterior calibration of the sensors and analyses for nutrients and plankton. The pocket FerryBox may be configured with multiple sensors [in this case temperature, salinity, dissolved oxygen, chlorophyll-*a* fluorescence, pH, turbidity, and colored dissolved organic matter (CDOM)] and includes the hardware and software for data acquisition and real-time presentation. In the Chilean campaigns multiple transects of up to 1700 km in length were obtained, which provided a unique and highly valuable dataset at a very low cost. The data uncovered a number of previously unreported results, including a tidally driven low dissolved oxygen zone in the Corcovado Gulf, a high level of spatial and temporal variability of, and a complex relationship between, dissolved oxygen and chlorophyll-*a* fluorescence, and the detection of high concentrations of CDOM in the vicinity of the Laguna San Rafael. The campaigns confirm that the pocket FerryBox may be easily installed on board ships of opportunity to obtain rapid, low-cost, and spatially extensive surveys of highly relevant surface water properties.

1. Introduction

The high cost of acquiring in situ data at sea is commonly a severe limitation on our ability to investigate the marine environment. The problem is most relevant in the developing world where science funding is necessarily low and access to research platforms is restricted, and is exacerbated when the marine territories to be studied are extensive. Such is the case for Chile's vast and sparsely populated fjords region that stretches between 40° and 54°S along the eastern boundary of the South Pacific

(Fig. 1). A handful of dedicated scientific expeditions to the area performed over the past decades have provided an overview of its water properties and general circulation patterns (e.g., Sievers et al. 2001; Silva 2008), but there remains very little information regarding natural variability in the system at any scale, from synoptic to interannual. The scarcity of observations remains the principal limitation for improving our understanding of the often complex physical, chemical, and biological process that occur in the region. As a result, the low costs and high spatial coverage that can be provided by ships of opportunity (SOO) makes them extremely convenient platforms from which to observe such an extensive area. With this in mind, the pilot observational network Ferries Observando los Canales Australes (FOCA) was established in 2007 to provide continuous monitoring of surface water

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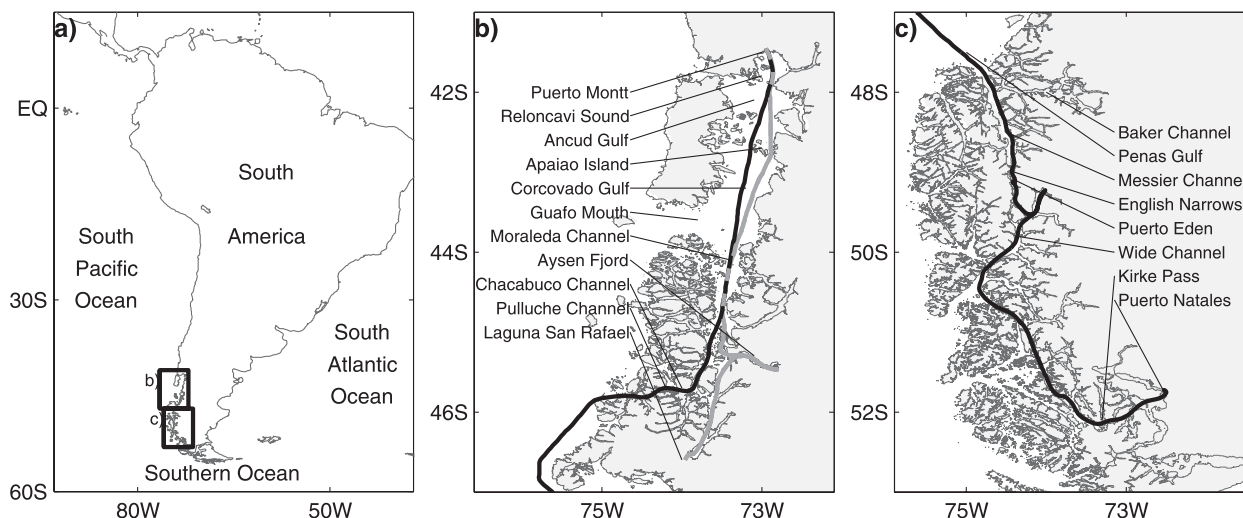


FIG. 1. (a) Geographical setting of the study area, and maps of the (b) northern and (c) southern sections of the Chilean fjords. The locations of geographical features mentioned in the text are indicated, together with the routes covered during the spring (gray line) and autumn (black line) field campaigns.

properties in the Chilean fjords. To assess the best way to extend the FOCA network, a series of field campaigns using the pocket FerryBox (pFB)—a portable self-contained flow-through multiparametric monitoring system—were undertaken. In the following we provide an overview of the pFB and demonstrate its utility as a tool for providing rapid surveys of extensive regions with reference to the measurements taken in the Chilean fjords.

The regionally integrated ocean-observing systems being developed in many parts of the world [e.g., Coastal Observation System for Northern and Arctic Seas (COSYNA), information at <http://www.cosyna.de>; Integrated Marine Observing System (IMOS), information at <http://www.imos.org.au>; etc.] commonly include the use of SOO. Flow-through sensors may be installed on board SOO to autonomously monitor a range of physical, chemical, and biological parameters. Typically, these systems involve pumping seawater from a hull-mounted sea chest through the sensor circuit housed in the ship's engine room. Because vessels typically provide a favorable environment for sensor operation (e.g., abundant power supply, protection from damage and theft, low pressure, and possibility for regular maintenance), such installations can provide extremely reliable continuous observations of surface properties (Petersen et al. 2003, 2007). The development of standardized self-contained automated flow-through systems, known as FerryBoxes, has greatly facilitated the implementation and massification of this observational technique, and a number of manufacturers have now commercialized such systems, such as 4H Jena GmbH (Germany), Chelsea Technologies Group (United Kingdom), and SubCTech GmbH

(Germany). In addition to housing the flow-through circuit, these systems typically include sophisticated data management and telemetry capacities and implement strategies to cope with biological and chemical fouling (Petersen et al. 2006).

The FerryBox concept began with the Baltic Sea Algaline Project (Rantajärvi 2003), and was expanded to cover a large fraction of European waters through the European Commission Fifth Framework Programme (FP5) FerryBox Project, led by the Gesellschaft zur Förderung der Kernenergie in Schiffbau und Schiffstechnik (GKSS) Research Center (Germany; Petersen et al. 2006). In addition to the considerable amount of scientific knowledge produced, both directly and through the dissemination of data to other researchers, the project has driven technological advances in the system and promoted its operational use (Petersen et al. 2006). FerryBoxes are now used operationally on over 10 vessels operating in European waters (<http://www.ferrybox.org>).

The various commercially available FerryBoxes, however, are designed for permanent installation, and their size and weight mean that a significant effort is required in the initial installation. It was recognized there was a need for a system that was sufficiently small and light to allow for easy transport and temporary use on smaller vessels, leading to the development of the pFB. In the following we provide a technical description of the pFB, present results from two campaigns carried out in the Chilean fjords, and discuss the utility and limitations of the pFB as a tool for monitoring the ocean state. It will be shown that the use of pFB on SOO enables rapid surveys of surface properties of the ocean to be obtained

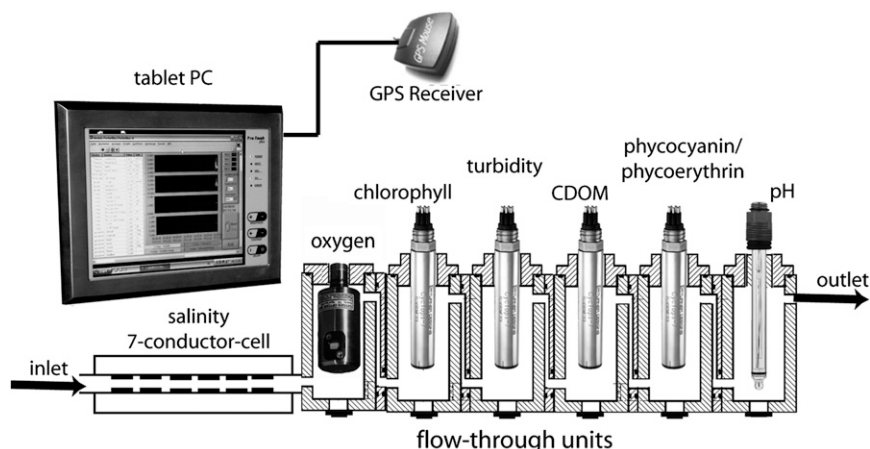


FIG. 2. Schematic of the configuration of the pocket FerryBox used in the two field campaigns. The temperature sensor is integrated into the salinity cell.

at extremely low cost, and hence represents a powerful new tool for spatially extensive oceanographic monitoring.

2. Materials and methods

a. Technical summary of the pocket FerryBox

The basic operating principle of the pFB follows that of the FerryBox manufactured by 4H Jena (Germany; Petersen et al. 2006, 2011). In designing the pFB the main considerations were that the flow-through unit should be altered to optimize size, that small but reliable sensors should be favored, that the housing should be water resistant for use on open decks in small boats, that the software interface should be simplified for use under trying weather conditions, and that, in the absence of a 220-V power supply, the system should be able to operate for 6–8 h from a single standard 12-V car battery.

A schematic of the pFB is given in Fig. 2. Up to six identical flow-through cells are connected together within the housing, with one sensor installed in each cell. To minimize dead volume, water circulates vertically through each cell, entering at the bottom and leaving at the top. At the bottom a sealable inspection hole allows sensors to be cleaned in situ, obviating the need for their regular removal. A large variety of standard commercial sensors may be readily mounted in the flow cells, allowing substantial freedom to configure the system appropriately for the chosen application. The sensors used during the campaigns measured temperature and salinity [seven-conductor cell from Sea&Sun (Germany) in the October 2009 campaign and Excell from Falmouth Scientific, Inc. (United States) in the March 2010 campaign]; dissolved oxygen [Optode, Aanderra Data Instruments AS (Norway)]; pH (Meinsberger, Germany);

and turbidity, chlorophyll fluorescence, colored dissolved organic matter (CDOM), and the algal pigments phycocyanine and phycoerythrin, which aid detection of cyanobacteria and certain phytoplankton types [six Cyclops sensors (Turner Designs, United States)]. An external GPS receiver connected to the pFB provides positioning data. In this case a Garmin 17× HVS receiver was lashed to an external pole on the deck. All data are recorded on a waterproof tablet PC with a purpose-built data acquisition program written in LabView (National Instruments, United States) and run under standard Windows XP (Microsoft, United States). The pFB may record multiple external data streams in Recommended Standard (RS)-232 format. To simplify its operation during unfavorable sea conditions, additional hardware switches for “start measuring,” “suspend measuring,” and “stop measuring” are provided. All data are displayed on the screen in alphanumeric form in real time, while graphically represented time series of six selected parameters are constantly updated. The whole system (excluding the battery) is installed within a stainless steel housing to protect against rain, sea spray, and physical shock. The system fits within a shockproof and waterproof suitcase appropriate for air transport. The complete pFB system weighs about 32 kg, including the housing, and thus can be transported as normal luggage on an airplane. When more than six parameters are required additional sensors may be installed externally to the pFB on the same water circuit, and the sensor output may be added to the pFB data stream via additional RS-232 ports. In the Chilean field campaigns a second sensor for chlorophyll-a fluorescence and turbidity [Self-Contained Underwater Fluorescence Apparatus (SCUFA)-II, Turner Designs, United States] in addition to a flowmeter and a UV nitrate detector (ProPS, TriOS, Germany) for optical detection of nitrate

TABLE 1. List of sensors used in the pocket FerryBox during the two campaigns.

Parameter	Instrument	Manufacturer (location)	Campaign
Temperature	PT100	Sea & Sun (Germany)	Oct 2009
Temperature	Excell	Falmouth Scientific, Inc. (United States)	Mar 2010
Salinity	Seven-conductor cell	Sea & Sun (Germany)	Oct 2009
Salinity	Excell	Falmouth Scientific, Inc. (United States)	Mar 2010
Dissolved oxygen	Oxygen Optode	Aanderaa Data Instruments As (Norway)	Both
pH	EGA 140 SMEK-X	Meinsberger (Germany)	Both
Turbidity	Cyclops	Turner Designs (United States)	Both
Chlorophyll-a	Cyclops	Turner Designs (United States)	Both
CDOM	Cyclops	Turner Designs (United States)	Both
Phycocyanine	Cyclops	Turner Designs (United States)	Both
Phycocerythrin	Cyclops	Turner Designs (United States)	Both
Chlorophyll-a	SCUFA-II	Turner Designs (United States)	Mar 2010
Nitrate	ProPS	TRIOS (Germany)	Mar 2010

were used externally, with the latter two sensors only used in the March 2010 campaign. All parameters were recorded at a frequency of once per minute. A list of sensors used on both campaigns is summarized in Table 1.

b. Field campaign in the Chilean fjords

The pFB was installed on board the vessel *Evangelistas*, a 123-m roll on-roll off passenger and goods ferry that is operated by Navimag Ferries (<http://www.navimag.com>). The two campaigns were performed from 3 to 10 October 2009 and from 26 March to 9 April 2010, corresponding to spring and autumn conditions, respectively. The route covered by the *Evangelistas* is from Puerto Montt (41.5°S) to either the Laguna San Rafael (46.7°S) or Puerto Natales (51.8°S), depending on the time of year. Observations from the spring campaign were taken on the former and shorter route, and from the autumn campaign on the latter. Both routes cover the section within the Chilean inland sea between Puerto Montt and the entrance to Aysén Fjord.

The unit was placed within the CO₂ cooling room, located on the upper deck at approximately 10 m above the waterline and connected to a permanent seawater circuit used exclusively for cooling the CO₂ tank. In normal ship operation seawater is constantly pumped from the sea chest, located at approximately 4 m below the surface, directly up to the CO₂ room. Being able to use the water from this circuit was greatly advantageous, because this obviated the need for an independent intake and pump to be installed, and problems with the pump and circuit were attended to immediately by the ship's crew as part of their normal duties. For example, although the CO₂ room pump was fouled by krill on a number of occasions during the spring campaign, circuit downtime was generally less than 15 min each time. Because the time taken for seawater to transit from the sea chest and the pFB was relatively brief, the observations are representative of

near-surface conditions with an insignificant time delay. The only parameter for which significant differences are expected to occur relative to the in situ value is temperature. Heat transfer along the approximately 20-m length of the circuit between the sea chest and pFB, plus a small effect resulting from passage through the pump, tended to cause a significant but relatively stable increase in the measured temperature. Measurements taken concurrently at the pFB and adjacent to the sea chest indicated that the pFB temperature exceeded the real temperature by <0.5°C. The flow of seawater through the pFB was regulated to be, on average, 7 L s⁻¹. Under normal conditions the *Evangelistas* sails at approximately 12 kt.

The calibration of the salinity sensor was checked against reference water samples before and after the campaign. The pH sensor was calibrated with pH standards using the National Bureau of Standards (NBS) scale. Samples were taken along the route in order to perform posterior analysis for dissolved nutrients (nitrate, nitrite, phosphate, silicate, and ammonia) and plankton (chlorophyll-a, cell count, and biomass). For nutrient analysis water samples of 50 mL were filtered with a glass microfiber filter (Whatman, 0.7-μm pore size) and maintained at -18°C in the ship's freezer. The nutrients were analyzed in the laboratory according to Grasshoff et al. (1999) with an autoanalyzer (AutoAnalyzer II, Bran + Luebbe GmbH, Germany). For chlorophyll-a filtering, the handling of the filters and high-performance liquid chromatography (HPLC) analysis were done according to the procedure described by Wiltshire et al. (1998) and were also kept frozen in the ship's freezer. The continuously measured chlorophyll-a fluorescence data were recalibrated against the HPLC measurements. The correlation coefficient between chlorophyll-a fluorescence and an HPLC of 0.77 suggests that the fluorometer provides a good proxy for chlorophyll-a concentration (Fig. 3). Both the nutrient samples and the chlorophyll filters were

transported frozen to Germany and analyzed at GKSS. Although the HPLC samples were transported at a temperature significantly above -70°C , as commonly recommended, the relatively good correlation between HPLC and chlorophyll-a fluorescence indicates that pigment deterioration is likely to have been minor. The uncertainty introduced is certainly less than that resulting from the dependence of fluorescence yields upon species, physiological state, and light conditions. We note that throughout both campaigns phycocyanine and phycoerythrin fluorescence were, in general, either close to or below the limit of detection and hence are not presented. For algal counting, samples were stored in 200-mL glass bottles fixed with 15 drops of Lugol (5% I_2 , 10% KI) and were kept in the dark. Plankton identification was performed with a Leica DMIL inverted microscope following the method of Utermöhl (1958) and was carried out at the Faculty of Marine Science of the University of Valparaíso, in Viña del Mar, Chile.

3. Observations of the Chilean fjords using the pFB

In this section we present a number of pertinent results from the field campaigns that serve to illustrate the benefits and limitations of the pFB and its use from SOO.

a. Spring campaign

A segment of the multiparameter dataset gathered with the pFB during the first transect of the spring 2009 campaign is illustrated in Fig. 4. A strong correlation may be appreciated between a number of the parameters, although it is noteworthy that the degree and sign of the correlation varies spatially. Within the Ancud Gulf (42°S) a series of patches of relatively warm and fresh water were crossed, corresponding to the plumes of the Petrohué and Reñihue Rivers. The fresh plumes tend to be associated with higher temperature, dissolved oxygen, pH, turbidity, and lower chlorophyll-a. Ancud Gulf is the only section in which significant spatial variability was observed in temperature. Upon passing the Apiao Islands (42.5°S) the chlorophyll-a, dissolved oxygen, pH, turbidity, and CDOM decreased rapidly and remained at these lower levels throughout the Corcovado Gulf. Although a number of substantial continental rivers drain into Corcovado Gulf, it contains the saltiest water of the transect due to it being freely connected to the open ocean via the Guafo Mouth (43.5°S) and subject to strong tidal and wind-driven vertical mixing. Variability in all parameters except temperature increased again once the fresher waters from the Moraleda Channel (43.6°S) were entered. Although high spatial variability was seen in both the Ancud Gulf and Moraleda Channel, the relationships between the various parameters

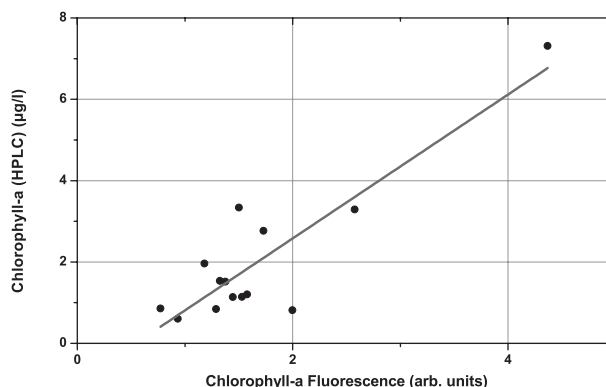


FIG. 3. Correlation between HPLC and chlorophyll-a fluorescence as recorded with the SCUFA fluorometer during the March 2010 campaign.

differ between the sections. While within Moraleda Channel chlorophyll-a, dissolved oxygen, pH, and turbidity are strongly correlated, with correlation coefficients $r > 0.9$ and $p < 0.0001$, in Ancud Gulf the correlation of chlorophyll-a with dissolved oxygen is weak ($r = 0.27$, and $p = 0.0007$), and the correlation with pH is not statistically significant ($p = 0.13$).

Thus, three distinct zones can be identified based upon the properties of the surface waters and the relationship between them. In particular, the relationship between chlorophyll-a fluorescence and dissolved oxygen levels in the surface waters differed substantially either side of the Corcovado Gulf, indicating a possible difference in the oxygen dynamics between the northern and southern sections of the inland sea.

During the spring 2009 campaign the *Evangelistas* traversed the Aysén Fjord on six occasions over the space of 1 week, providing approximately daily transects of each parameter along the axis of the fjord. The evolution of a number of the parameters, starting with the transect from 4 October, is shown in Fig. 5. It may be seen that there is substantial variability in each parameter over the course of the week and along the length of the fjord. The freshening seen until the transect of 7 October can be related to an episode of heavy rain on 4 October and a resulting increased discharge from the Aysén River thereafter. Of particular note is the relationship, or lack thereof, between chlorophyll-a, dissolved oxygen, and pH within the surface waters of the fjord. An algal bloom located close to the Cinco Hermanas Reserve (73.25°W) on the afternoon of 4 October and the early morning of 5 October, as inferred by a relatively high chlorophyll-a fluorescence, was not accompanied by a coincident and concurrent increase in oxygenation and pH, as would be expected in the absence of other processes. On the contrary, dissolved

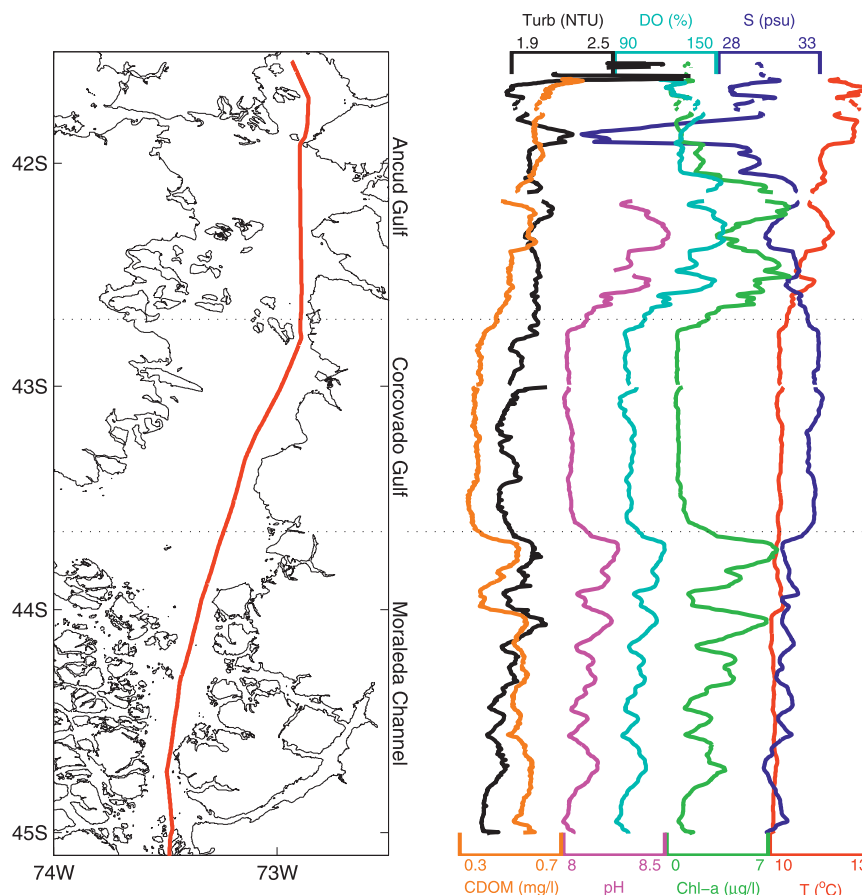


FIG. 4. (left) The ship route section is shown. (right) An example of the multivariate data obtained with the pocket FerryBox on 3 Oct 2009.

oxygen levels only became supersaturated after the evening of 5 October when the bloom was already in decline, and were most intense westward of the site of the bloom. The increase in pH also lagged chlorophyll-*a* by 1 day, but was located eastward of the peak in chlorophyll-*a*, toward the fjord head. This suggests a complex dynamic of the oxygen budget in the surface layers of Aysén Fjord that the surface measurements of the pFB were unable to resolve. Posterior plankton analysis identified the diatom *Skeletonema costatum* as the dominant bloom species. The potentially harmful species *Pseudo-nitzschia australis* was also identified at low levels in Aysén Fjord and throughout the survey area.

Figure 6 displays the observed distribution of CDOM, turbidity, salinity, and temperature between Puerto Chacabuco and Laguna San Rafael on 5 October 2009. The relatively high concentrations of CDOM found within Aysén Fjord and Elefantes Channel are consistent with a terrestrial/pluvial source. The small peak of CDOM midway along the Aysén Fjord is located at the mouth of the Cuervo River. The presence of high concentrations

of CDOM following the period of heavy rain is likely to derive from the leaching of organic matter from the mature forests and grasslands that cover the adjacent land area, much of which is protected within nature reserves and/or is pristine. Significant CDOM levels have also been observed in New Zealand fjords (Gonsior et al. 2008) and Arctic rivers (Retamal et al. 2007), with similar characteristics to this region of Chile, but have not been previously reported within the Laguna San Rafael area. Because the estuarine water in this region tends to have high turbidity, either due to high concentrations of suspended fine particulate matter of glacial origin (rock flour) close to Laguna San Rafael or sediment from the Aysén River, salinity is strongly anticorrelated with turbidity and CDOM in this section. This suggests that the CDOM distribution is explained by conservative mixing, possibly because insufficient time had elapsed since the strong rain event for significant degradation or transformation of the CDOM. The fact that this correlation does not hold in the estuarine waters of the northern and far southern sections, where

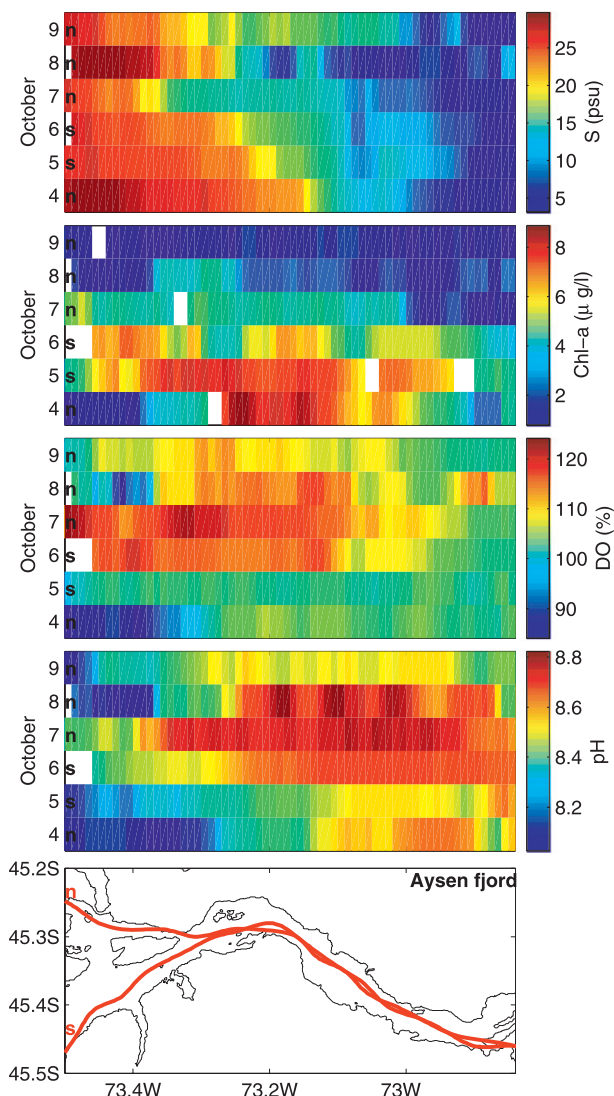


FIG. 5. (top) Evolution of surface salinity, chlorophyll-a, dissolved oxygen, and pH within Aysén Fjord over the period from 4 to 9 Oct 2009. (bottom) The ship route section is shown. The northern and southern variations of the route are indicated by “n” and “s”, respectively.

low salinity and high turbidity were observed to occur with significantly lower CDOM concentrations, may be due to the differences in the adjacent watersheds or the simple fact that measurements were not taken immediately following rain.

b. Autumn campaign

The autumn campaign, held over the period from 26 March to 9 April 2010, provided four consecutive transects of the route between Puerto Montt and Puerto Natales within the space of 2 weeks. Substantial variations were seen between consecutive journeys, in particular, in

the northern fjords section north of 46°S. The observed dissolved oxygen and chlorophyll-a from the second and fourth (northbound) transects, separated in time by 1 week, are shown in Fig. 7. The zone of low dissolved oxygen located in the northern Corcovado Gulf at $\approx 43^\circ\text{S}$ in the first panel was observed to be present during each of the first three transects, and only on the fourth transect was it observed to have moderated toward normal saturated conditions. Dissolved oxygen is typically positively correlated with chlorophyll-a, such as occurs with the strong bloom at 45°S during the fourth transect. However, primary productivity, as inferred by the chlorophyll-a concentration, does not appear to have controlled dissolved oxygen in the low oxygen zone. In fact, a weak bloom was observed within the low oxygen zone during the first transect, with negligible effect upon dissolved oxygen. As a result, although zooplankton grazing is a potential mechanism for a postbloom reduction in dissolved oxygen, it cannot explain the degree or persistence of deoxygenation seen here.

The explanation is more likely to be related to the strong vertical mixing present at some locations in the inland sea during spring tides. Because of the fact that the Chilean inland sea is close to resonant under semi-diurnal forcing, tidal ranges within Reloncaví Sound and along the eastern coast of Chiloé Island can exceed 9 m, and tidal velocities in the channels have been observed to exceed 4 m s^{-1} (Cáceres et al. 2003). Tidal amplitudes differed greatly between the first three transects and the final, with the tidal range at Puerto Montt reaching $\approx 7 \text{ m}$ on 30 March but less than 2 m on 6 April. Tidal currents are strongest both within the Corcovado Gulf and the constricted channels between adjacent basins and leading to the open ocean (Aiken 2008). Strong vertical mixing is likely to occur during spring tides in these areas, especially where stratification is weak, which may allow deeper, less oxygenated waters to be brought to the surface. This hypothesis is supported by the fact that a decrease and recovery in oxygen levels that was synchronized with that in the northern Corcovado Gulf at approximately 43°S was observed in a number of distant locations known to be tidally active, such as the Chacabuco and Pulluche Channels that connect Moraleda Channel to the open ocean at $\approx 46^\circ\text{S}$, the English Narrows at $\approx 49^\circ\text{S}$, and Kirke Pass at $\approx 52^\circ\text{S}$. Relatively low surface dissolved oxygen associated with destratification and vertical mixing is evident in these channels in the results of the Cimar Fiordo 1 expedition (Silva et al. 1997).

Figure 7 also reveals a section of relatively high chlorophyll-a fluorescence in the Wide Channel south of Puerto Eden between 49° and 50°S . This section showed above-average surface chlorophyll-a over the

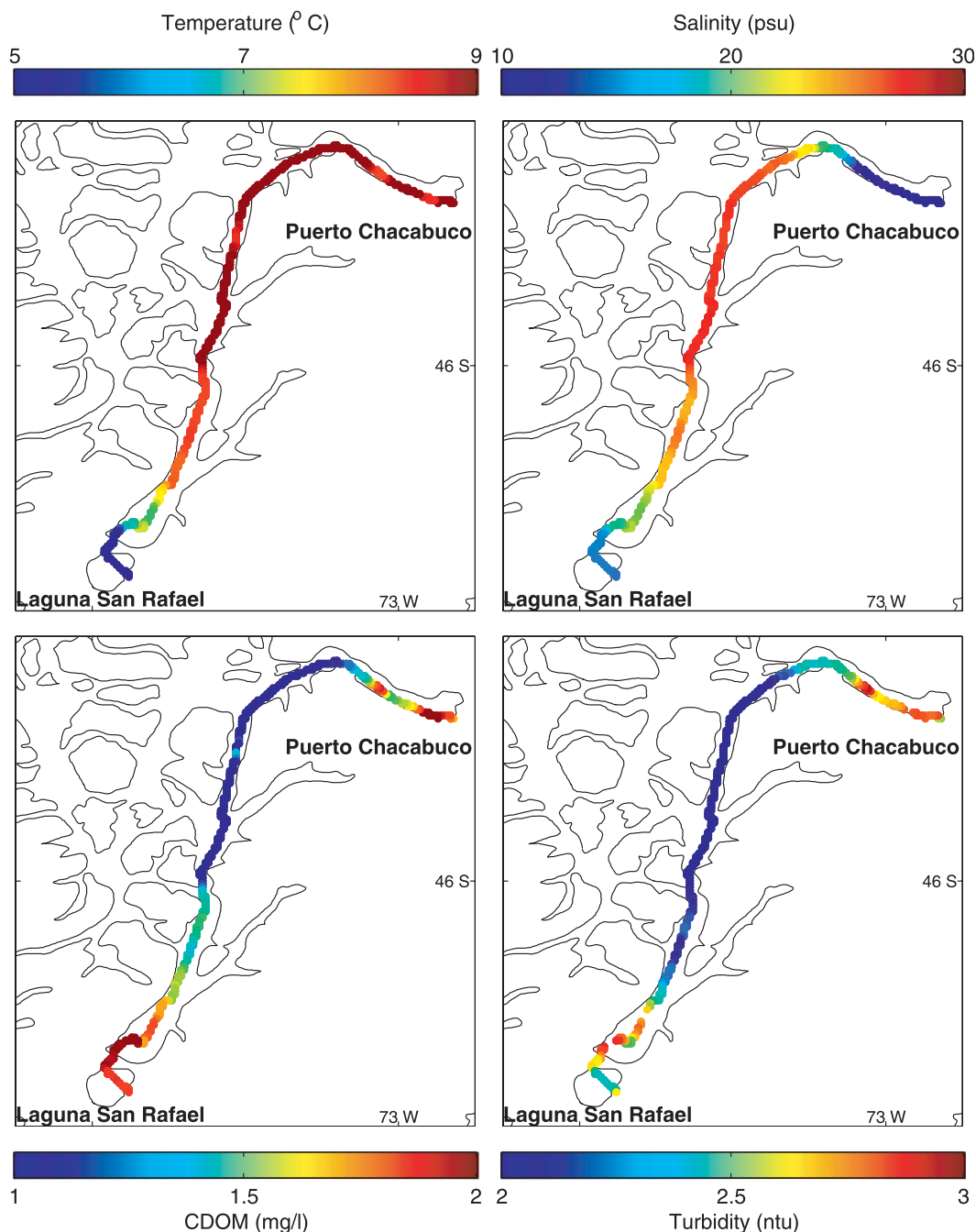


FIG. 6. Distribution of surface temperature, salinity, CDOM, and turbidity on the 5 Oct 2009 transect from Puerto Chacabuco to Laguna San Rafael. In general, the temperature measured at the pFB was consistently greater than that at the sea surface by $<0.5^{\circ}$.

entire 2-week period spanned by the March 2010 campaign, in contrast to the rest of the southern fjords region where very little phytoplankton growth was observed. The fact that this location appears to sustain stronger primary productivity than the surrounding waters may be linked to nutrient availability, as discussed in continuation.

The concentrations of NO_x (nitrate plus nitrite), orthophosphate, silicate, and ammonia derived from the analysis of water samples at 39 locations along the first transect from Puerto Montt to Puerto Natales are presented, together with the concurrent salinity, chlorophyll-a, dissolved oxygen (oxygen saturation),

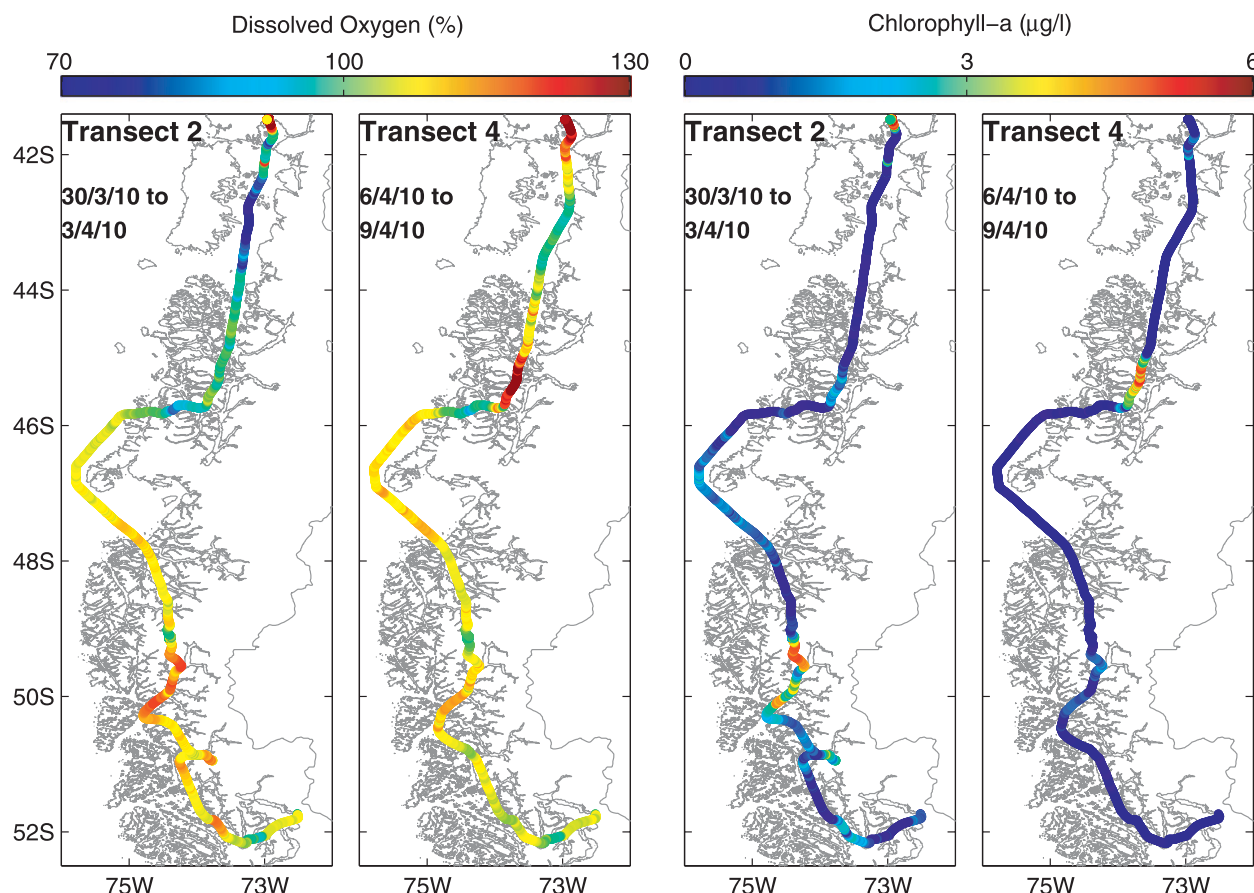


FIG. 7. Surface dissolved (left) oxygen and (right) chlorophyll-a as observed on the two northbound transects from Puerto Natales to Puerto Montt that started on 30 Mar and 6 Apr 2010, respectively.

and pH measurements taken with the pFB in Fig. 8. A general trend may be appreciated for the nutrient concentrations to decrease toward the south, with relatively high concentrations of nitrate (up to $18 \mu\text{M}$) and phosphate (up to $2.5 \mu\text{M}$) in the Ancud and Corcovado Gulfs (42° – 44°S), dropping to the limit of detection in the far southern channels. The high nutrient concentrations in the Ancud Gulf coincide with an intense but spatially contained phytoplankton bloom, which is also evident in dissolved oxygen and pH. A broader and less intense bloom located at approximately 45°S is associated with sharp minima in all nutrients, indicative of a mature bloom that had consumed all of the available nutrients. Similar planktonic consumption of nutrients is also apparent in the open ocean at approximately 46.5°S and in the Messier Channel slightly north of 50°S .

A significant exception to the generally oligotrophic nature of the surface waters in the southern channels is the very high concentration of silicate ($13 \mu\text{M}$) at approximately 48°S . The corresponding low salinities of around 10 psu identify the silicate to have a pluvial origin.

Relatively high CDOM concentrations (not shown) were also found in the region of low salinity. The Baker and Pascua Rivers, with a combined annual mean discharge of approximately $1600 \text{ m}^3 \text{ s}^{-1}$, drain the Patagonian ice fields and are extremely silicate rich (from 40 to $150 \mu\text{M}$) as a result, resulting from the load of suspended glacial silt (rock flour), but poor in all other nutrients (Silva 2008). Discharge from both rivers empties to the ocean through the southeastern corner of the Penas Gulf, with a pronounced late summer maximum (Prado-Fiedler 2008).

Iriarte and González (2008) note the vulnerability of the fjord ecosystem in this region and how the Redfield N:P (nitrogen to phosphorous) ratio affects primary productivity, and in turn fisheries production. The calculated N:P ratio of the dissolved nutrients along the whole transect is in most cases within the 8–10 range, below the theoretical Redfield ratio of 16. These data are in agreement with observed N:P values in previous studies in the inland sea region (Calvete 1997; Iriarte et al. 2010). The extremely low phosphorus concentrations in the Messier Channel (48° – 49.5°S), however, yield N:P ratios that are

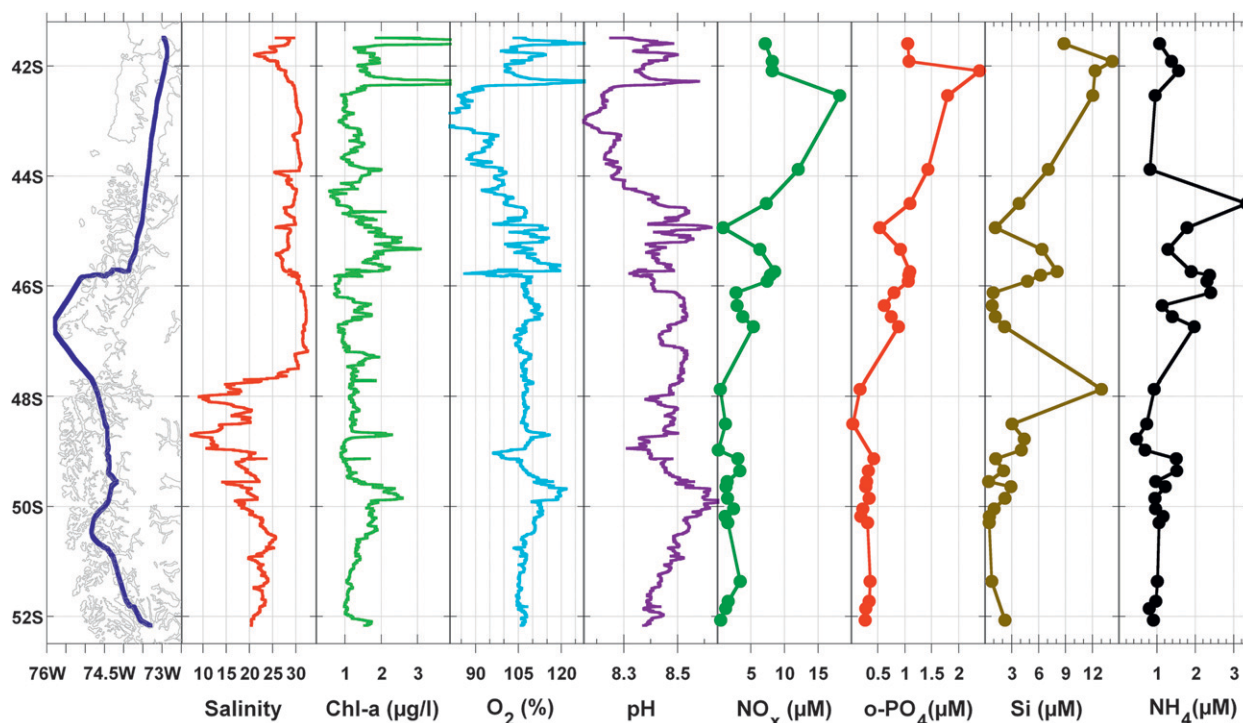


FIG. 8. pFB measurements of salinity, chlorophyll-a, dissolved oxygen, and pH, shown together with the concurrent surface concentrations of nitrate + nitrite (NO_x), ortho-phosphate (o-PO_4), silicate (Si), and ammonia (NH_4) as determined by posterior analysis of water samples taken between Puerto Montt and Puerto Natales over the period from 26 to 29 Mar 2010.

significantly higher than those in the inland sea. This indicates that surface planktonic primary production in Messier Channel may be limited by the availability of phosphorus. A quite generalized phosphorus limitation in the Chilean fjords region has been postulated (Prado-Fiedler 2008), especially at the head of the Baker Channel where sufficient nitrate and high concentrations of silicate occur.

Given the generally pristine nature of much of the Chilean fjords region, the detection of relatively high levels of ammonia was unexpected. The region of high ammonia concentrations in Moraleda Channel at approximately 45°S may relate to nearby intensive aquaculture activity. The local increase in ammonia and nitrate in the vicinity of 49.3°S may have its source from the untreated residual water from the nearby locality Puerto Eden of approximately 500 inhabitants.

c. Comparison of campaigns

The two campaigns allow the conditions of spring 2009 and autumn 2010 to be compared to each other and to previous measurements. Figure 9 demonstrates that surface waters were, on average, significantly fresher throughout the northern fjords region in March 2010 compared to October 2009. In both cases large fresh

plumes from the Petrohué River were observed at $\approx 42^\circ\text{S}$ within the Reloncaví Sound, but the plume of the Palena River at $\approx 44^\circ\text{S}$ was only observed in the March 2010 campaign. The increased salinity in October 2009 relative to March 2010 is consistent with the seasonal averages determined from temperature and salinity data taken in the FOCA project over the periods from September to November 2007 and from February to April 2008, respectively (dashed lines) (C. M. Aiken 2011, unpublished manuscript). While the general surface salinity distributions agree broadly, clearly there are significant differences between the two datasets, which are indicative of significant interannual variability. For example, surface salinity in the Corcovado Gulf section (between approximately 42.5° and 44°S) tended to be 1–2 psu higher during the two campaigns with the pFB relative to that in the FOCA data.

4. Discussion and conclusions

The two field campaigns using the pFB uncovered a series of unique and interesting results concerning the surface water properties within the Chilean fjords region that would have been significantly more difficult and expensive to obtain by any other observational method.

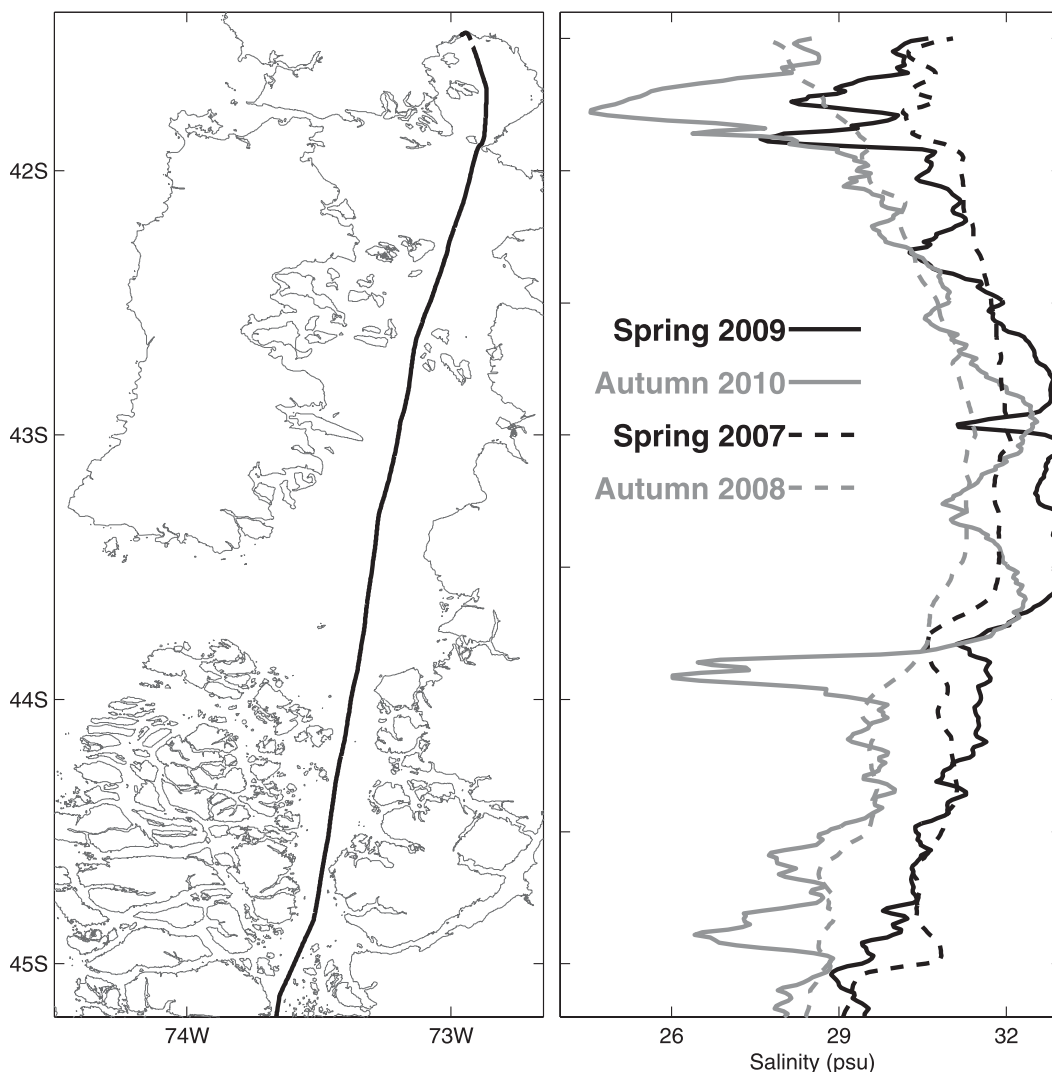


FIG. 9. (left) The ship route section is shown. (right) Mean salinity as a function of position from the spring 2009 (solid black line) and autumn 2010 (solid gray line) campaigns with the pFB, shown together with the means for spring 2007 (dashed black line) and autumn 2008 (dashed gray line) from the FOCA project for the northern fjords region between Puerto Montt and Puerto Aysén.

Multiple repeat sections and high-resolution along-route observations revealed the variability of, and relationships between, a number of important parameters across an extensive section of the fjords. In general, variability in all of the parameters over short space and time scales was seen to be much greater within the northern section of the fjords, until $\approx 46^{\circ}\text{S}$, than farther south. Within the northern section very low variability was seen within Corcovado Gulf, but in the Ancud Gulf and Moraleda Channel rapid evolution of all parameters in space and time was observed. The relationships between the various parameters were at times complex and differed between the two regions. Of particular note, the distribution of surface-dissolved oxygen was found to not always be

well correlated with chlorophyll-a fluorescence, as would typically be expected. For example, within the Ancud Gulf dissolved oxygen was only weakly correlated with chlorophyll-a, and in the Aysén Fjord no clear relationship was found between chlorophyll-a fluorescence, dissolved oxygen, and pH.

A complete explanation for these results is likely to require consideration of the vertical structure. The extremely strong gradients found within the fjords at the base of the estuarine layer, in particular, within Aysén Fjord, mean that the water properties at the surface monitored by the pFB may be weakly coupled to the values at greater depth. For example, given that plankton species are often confined to a tight salinity range, blooms may occur

within thin lenses that, if not located at the depth of the pFB intake, will not be detected. Because the resulting dissolved oxygen signal may mix away from the source, the detection of oversaturated dissolved oxygen without a concurrent chlorophyll-*a* signal may be due to the bloom being concentrated slightly below the sampling depth. In addition, given that the strong density gradients inhibit mechanical vertical mixing, differential rates of molecular diffusion for different parameters (so-called double diffusion) could result in parameter ratios that differ greatly across the pycnocline.

Zones of relatively low dissolved oxygen, found in the Corcovado Gulf, Chacabuco Channel, and English Narrows, were inferred to be produced through tidal mixing, which breaks down the strong pycnocline and brings deeper, more poorly oxygenated waters to the surface. Despite the fact that intensive salmon farming in the Chilean fjords lends dissolved oxygen an increased economic importance, studies of the spatial and temporal variability in surface dissolved oxygen levels, as presented here, have not previously been reported.

The detection of relatively high concentrations of CDOM close to Laguna San Rafael, while not unexpected based on similar results in equivalent geographical regions, also represents the first time this has been reported. CDOM was observed to occur adjacent to river mouths immediately following a high rainfall event and to be strongly anticorrelated with salinity, consistent with a terrestrial/pluvial origin and conservative mixing.

Nutrient analysis of discrete surface water samples revealed unexpectedly high concentrations at the surface throughout the Ancud and Corcovado Gulfs. The reason for the relatively high surface nutrient concentrations is not completely clear. While the fact that only single water samples were taken and analyzed at each station introduces some uncertainty in the accuracy of the nutrient analysis, the significant and spatially coherent nutrient concentrations are unlikely to have resulted from sampling variability alone. In contrast to our results, the Cimar Fiordo expeditions observed extremely low nutrient concentrations in surface waters throughout the Ancud Gulf (e.g., Silva et al. 1997), indicating that there is considerable variability in these parameters. As a result, given the threat of eutrophication in the Chilean interior waters, the campaigns have uncovered a need to monitor nutrient levels on a regular basis, and have demonstrated an affordable means to achieve this.

The field campaigns provided a number of important points for consideration in the expansion of the FOCA permanent ship-of-opportunity network in the Chilean fjords. The fact that surface dissolved oxygen, pH, and chlorophyll-*a* were often found to be, at best, weakly correlated within the Chilean fjords suggests that there

is no redundancy in measuring all three parameters. In fact, further research may allow such surface correlations to be used to infer vertical structure. The detection of significant concentrations of CDOM confirms that it is likely to be an important component of the local carbon budget, and that a flow-through system is well suited for monitoring it. The case for dissolved oxygen is similar, especially given that the observed extensive undersaturated zones may have relevance for economically important local industries. The campaigns also indicated the level of fouling that is likely to affect permanently deployed sensors. Iron oxide deposits released from the ship's hull and piping represented the major source of fouling, and necessitated the cleaning of optical sensors approximately every 3–4 days.

The spatially extensive repeat sections performed in the field campaigns, sampling lengths of coastline of up to 1700 km for a broad range of parameters, would have been extremely difficult and/or expensive to obtain by any other means. Given the ubiquity of cloud cover and highly complex coastal geometry that is characteristic of the Chilean fjords, the utility of satellite products in this region is diminished. In addition, with a FerryBox it is possible to monitor a wide range of parameters in situ for which no satellite product exists, and to perform automated or manual sampling for posterior calibration and plankton analysis. Considering that the two campaigns sum to over 13 000 km navigated and continuously sampled in a total period of 3 weeks, acquisition of the same dataset from an open-ocean-capable research vessel would have been extremely expensive.

Unlike a traditional FerryBox, the pFB provides great deployment flexibility. Installation of the pFB on board the *Evangelistas* was rapid and trouble free, being completed within a number of hours using only standard tools. In this case the process was greatly facilitated through the assistance of the ship's crew, but this was by no means essential. It should be noted, however, that gaining the necessary permissions from the ship's owner and identifying a suitable location may be a lengthy process. The unit was shipped between Germany and Chile as standard luggage for each campaign. Although not designed for unmanned use, the pFB performed extremely reliably for periods of up to 10 days without any human intervention. These campaigns represent the first time the pFB has been used in unmanned mode.

In summary, the pFB proved to be an excellent tool for easily and inexpensively obtaining a multiparametric overview of a vast region that would otherwise remain unmonitored because of the difficulty and extremely high cost involved. The two field campaigns confirmed the correct function of the pFB in unmanned mode for extended periods on board an SOO, and also demonstrated

that continuously recorded surface observations represent a valuable new source of information in the Chilean fjords region. The campaigns furnished novel results regarding the spatial distribution of various water properties, their variability in space and time, and their interdependence. The high spatial and temporal variability seen in many of the observed parameters would be difficult to detect by other means, as well as prohibitively expensive to undertake as part of a regular monitoring program, and thus represents a significant new data source to complement existing platforms. As a result, the campaigns provided important guidance for the future development of an underway monitoring SOO network in the Chilean fjords. The fact that the pFB is portable makes it ideal to be used for short-term monitoring, in support of field campaigns, or, as in this case, for the planning of permanent monitoring networks.

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