



# Hydrographic and Biological Impacts of a Glacial Lake Outburst Flood (GLOF) in a Patagonian Fjord

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## Abstract

Glacial lake outburst floods (GLOFs) in Northern Patagonian Ice Field affecting the Baker River basin have increased their frequency in recent years. To evaluate the impact of a GLOF in the hydrography and biological components of the plankton in the Baker Fjord, we assessed the relative contributions of terrigenous versus marine plankton carbon sources to the particulate organic matter (POM) in the fjord before and after a GLOF in the austral summer 2014. We also evaluated whether terrestrial carbon brought into the fjord by the river may reach higher trophic levels via a deposit-feeding organism the juvenile pelagic *Munida gregaria*. Over a 10-day period, hydrographic profiles, water samples for POM, and zooplankton samples were collected daily from three stations and two depths along the fjord's inner section. Samples of suspended POM and tissue from *M. gregaria* were analyzed for stable-isotope composition of carbon ( $\delta^{13}\text{C}$ ) and nitrogen ( $\delta^{15}\text{N}$ ). The GLOF arrival produced a thermal front in the fjord, followed by an oscillation of the pycnocline; an abrupt increase in the total organic carbon content of POM, which was attributed to terrestrial input; and a concurrent peak in the abundance of *M. gregaria*, suggesting an aggregation response to the GLOF. Understanding GLOF effects on local hydrography, productivity, and food web structure provides valuable insight on the potential responses of fjord ecosystems in general to climate change-induced variability. Given present climatic trends in high-latitude zones, more frequent GLOFs might be expected in Patagonian fjords and channels as well as in other high-latitude basins.

**Keywords** GLOF · Fjord · Mixing · Squat lobster · Stable isotope

## Introduction

Fjords are estuaries of glacial origin, associated to high latitudes and characterized by an elongated and deep channel

with a sill (Valle-Levinson 2010). Mixing processes are central to the gravitational circulation in fjords because they modify density gradients that establish the flow (Farmer and Freeland 1983). Fjords and channels from Chilean Patagonia (41.5° S to 55.9° S) receive freshwater discharges from rivers of glacial origin, together with surface runoff and groundwater flows fed by rainfall (100–700 cm year<sup>-1</sup>, MOP-DGA 1987), as well as directly from glacier melting (Moffat et al. 2018). One of the major rivers in this region is the Baker River, which discharges water from glacial lakes and glacier melting into the large fjord basin known as the Baker-Martinez fjord complex, situated between the Northern and Southern Patagonian ice fields, the largest ice fields in South America. The Baker River is the largest in the South American temperate forest biome (Rozzi et al. 2012) with a mean annual outflow of 1133 m<sup>3</sup> s<sup>-1</sup> (DGA); it flows from Lake Bertrand, which receives inflow from Lake General Carrera and flows ca. 370 km along the eastern side of the Northern Patagonian Ice Field, to finally meet the fjord at the NE corner of the Martinez Channel (Baker Fjord complex), near the town of Caleta Tortel (Fig. 1). The region encompassing this river is

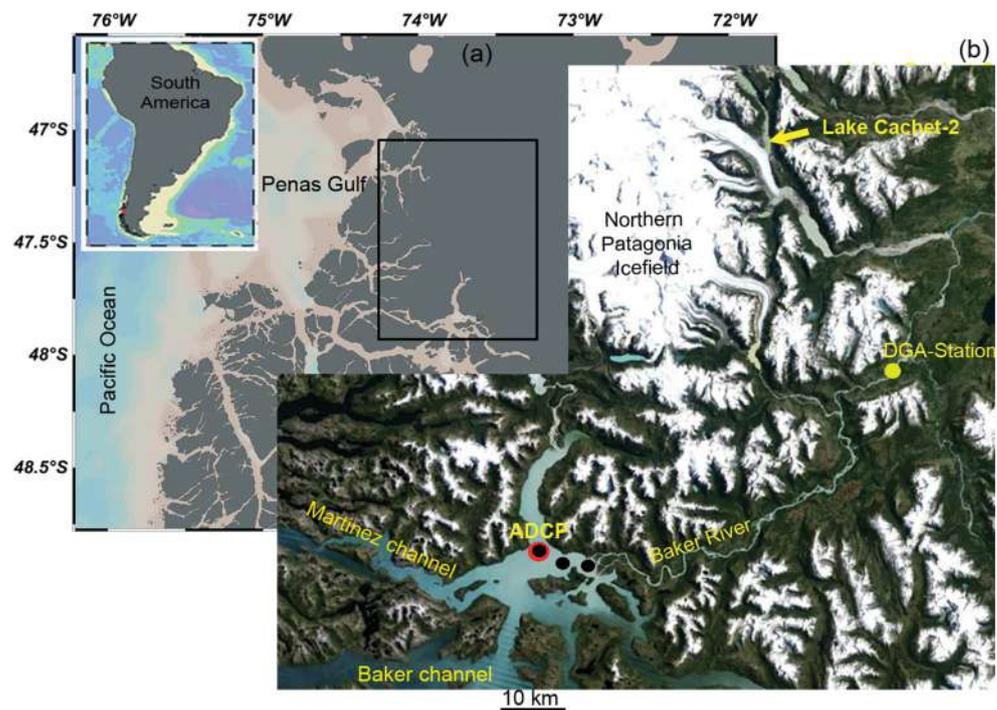
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**Fig. 1** Study area. The sampling stations in the Martinez Channel in the Baker Fjord complex are shown (from left to right: Steffen, center, and Baker stations)



subject to climate change impacts, with an increased contribution of Patagonian Ice fields to sea-level rise over the twentieth century (Glasser et al. 2011). More direct sources of anthropogenic impacts in the near future are the persistent interest in damming the Baker River for hydroelectric power purposes (Vince 2010; Sanchez et al. 2012) and for the establishment of salmon farms in the fjord.

Glacier lake outburst floods (GLOFs) are caused by the rapid drainage of naturally dammed lakes located on or at the margin of glaciers. GLOFs are not a new phenomenon, but with the worldwide trends in glacier retreat and rising temperatures, the probability of their occurrences has risen in many mountain ranges (UNDP 2012). Current rapid retreat of glaciers and ice sheets constitutes one of the most prominent signs of climate change (IPCC 2007, 2013). Together with a sudden increase in river outflow, outburst floods may produce very rapid sediment deposition. For example, a deposition rate of  $0.1 \text{ cm day}^{-1}$  was reported by Jaeger and Nittrouer (1999) for the Bering Glacier in Alaska. Additionally, GLOFs affect the hydrography of fjords; for instance, during drainages of a lake in Greenland, Kjeldsen et al. (2014) reported that large amounts of relatively warm and saline intermediate water were brought to the near-surface layers by entrainment processes near the glacier front. In addition to its effect on the temperature and salinity structure of the water column, this GLOF-induced upwelling of nutrient-rich intermediate water has the potential to impact the entire fjord ecosystem.

Several GLOFs have been recorded in Northern Patagonian Ice Field over the last decades (Dussailant et al. 2010). Recently, GLOFs in the Baker River basin have

increased their frequency due to the recurrent drainage of Lake Cachet II, on the eastern margin of Northern Patagonian Ice Field (Casassa et al. 2010). In the Southern Patagonian Ice Field, the formation or enlargement of glacial lakes also highlights the potential hazards associated to GLOFs (Loriaux and Casassa 2013).

In the Baker Fjord area, Ross et al. (2014) described episodes of intense internal wave activity, which are correlated with periods of high freshwater outflow from the Baker River. Later, Ross et al. (2015) reported the internal motion of the pycnocline with a periodicity that is consistent with the Southern Hemisphere's baroclinic annular mode (BAM). From an ecological point of view, the internal waves may increase the vertical mixing of nutrients towards the surface (Munk and Wunsch 1998); produce short-term increases in light availability (Cuyper et al. 2011), which, in spring-summer months, is severely limited by the high load of suspended glacial silt in the top low-salinity layer; consequently trigger changes in the composition or biomass of phytoplankton (Evans et al. 2008; Pannard et al. 2011); and eventually affect the zooplankton community.

In recent years, the use of carbon isotopes has become a common approach to study food webs in aquatic ecosystems. Because different energy sources may have distinct  $\delta^{13}\text{C}$  values, carbon  $\delta^{13}\text{C}$  may be used to trace the original carbon source at the base of the web (Sackett and Thomson 1963; Parker 1964; Vander Zanden and Rasmussen 1999, 2001; Overman and Parrish 2001). Marked changes in freshwater input to the coastal zone due to rainfall and river flow can

modify the sources of organic carbon incorporated to the pelagic trophic web in coastal areas as well as the bottom sediments (i.e., allochthonous carbon, from terrestrial sources; autochthonous carbon, from marine phytoplankton production). Recent analyses of stable isotope composition in Patagonia show that sediments at the inner sections of fjords and channels differ in  $\delta^{13}\text{C}$  content from those in ocean-influenced zones (Silva et al. 2011). Along the Baker-Martinez fjord system, variations in  $\delta^{13}\text{C}$  in the sediments and benthic organisms revealed a seasonally fluctuating influence of riverine organic matter versus marine organic matter (Quiroga et al. 2016). Differences in  $\delta^{13}\text{C}$  content among juveniles and adults of pelagic fish from Northern Patagonia point to an ontogenetic change in feeding preferences (Montecinos et al. 2016). All these studies support the hypothesis that changes in freshwater input due to ice melting and rain might influence carbon fluxes in fjords and the pelagic trophic web and eventually reach the benthic environment through processes such as particulate matter sedimentation, fecal pellet sinking, and settlement of meroplanktonic organisms. Thus, changes in the organic carbon flux induced by the more recurrently occurring GLOFs in Patagonia due to global climate change might affect feeding of key planktonic and pelagic species in fjords, the structure and carbon cycling in the pelagic food web, and eventually, the input of carbon to benthic habitats.

In Patagonian trophic webs, the squat lobster *Munida gregaria* is considered a key species (Romero 2003, 2004; Varisco and Vinuesa 2007) being preyed upon by numerous species of fish, marine mammals, and birds. In their adult benthic phase, *M. gregaria* may reach high abundances in the fjords and become an important component of the food web through its role both as deposit feeder and as prey for demersal predators (Vinuesa and Varisco 2007; Pérez-Barros et al. 2010). The postlarval stage of *M. gregaria* is pelagic, and it frequently forms large aggregations prior to settling on the bottom and beginning the adult benthic phase (Zeldis 1985). In southern South America, the records of juvenile aggregations are scarce and restricted to the continental shelf from Argentina (Matthews 1932; Rayner 1935; Varisco and Vinuesa 2010) with only one published record for the Chilean Patagonia in the Gulf of Penas, at the end of the Baker Fjord, in the Pacific Ocean (Tabeta and Kanamaru 1970).

In this context, the objective of this study was to evaluate the impacts of a GLOF in the Baker Fjord hydrography as well as in the biological components of the planktonic system. The aim of the work was to evaluate the GLOF change in water temperature, salinity, and mixing in the Baker Fjord near the Baker River mouth. In addition to this, we intended to assess if there was a change in the relative contributions of allochthonous (i.e., terrigenous) versus autochthonous (i.e., marine plankton) carbon sources to the particulate organic matter (POM) pool in the fjord during a GLOF and also whether this

potential change might be transferred to higher-trophic level organisms such as to the juvenile pelagic squat lobster, *M. gregaria*, which aggregates near the Baker River mouth during its juvenile phase and in months with maximum river outflow (Meerhoff et al. 2013).

## Materials and Methods

### Study Area and Data Collection

Hydrographic profiles, POM, and zooplankton were obtained from the eastern most section of the Martinez Channel in the Baker Fjord complex, which is flanked by the Baker River mouth on the east and by the Steffen Fjord on the west (Fig. 1). This particular survey was part of a larger sampling program conducted by COPAS Sur-Austral Center at the fjord since 2009 that included an almost monthly (1–2-day) hydrographic and zooplankton sampling at three stations until 2015 and process-oriented (1–2-week) seasonal cruises (in some years) until present.

Three stations located at ca. 1 km (*Baker station*, 47° 47.78' S, 73° 35.77' W, 37 m depth), 4 km (*center station*, 47° 47.11' S, 73° 38.97' W, 228 m depth), and 6 km from the Baker River mouth (*Steffen station*, 47° 47.25' S, 73° 40.20' W, 270 m depth) were sampled daily between the 28th of January and the 4th of February 2014. Hydrographic profiles were obtained with XR-620 RBR conductivity temperature depth (CTD) sensors (RBR, Canada) equipped with dissolved oxygen, fluorescence, and turbidity sensors. Samples of seawater (2 L) for POM analyses were collected from the three stations with Niskin bottles at 3 m and 15 m depths. The particulate material was retained on glass fiber filters of 0.7  $\mu\text{m}$  pore diameter of 47 mm, previously combusted at 550 °C. All filters were frozen for later isotopic analyses. At each station, stratified zooplankton samples were collected through oblique tows (from 25 m to the base of the pycnocline and from the pycnocline to sea surface), at a nominal speed of 2 knots, using a Bongo net of 60 cm mouth diameter and 300  $\mu\text{m}$  mesh equipped with a mechanical flowmeter and a closing mechanism. Juvenile *M. gregaria* caught in the zooplankton samples were immediately frozen at  $-20$  °C until processing in the laboratory.

To characterize the dominant flow during our survey, we used data from an acoustic Doppler current profiler (WorkHorse Sentinel ADCP, 307.7 kHz) moored close to the Steffen fjord mouth (Steffen station, Fig. 1) for a period spanning the austral summer of 2014 through the following summer season. The ADCP was installed at  $\sim 100$  m depth pointing upward, collecting data with hourly temporal resolution, and set up to produce 250 pings per ensemble, with a bin size of 1 m; these settings yielded data with an estimated velocity standard deviation of  $0.86 \text{ cm s}^{-1}$ .

Concurrently, and to characterize the main source of hydrographic forcing at the time of our survey, outflow data for the Baker River were obtained from a hydrological station located approximately at 56 km upstream from the river mouth (station Ñadis), operated by the Dirección General de Aguas (<http://www.dga.cl>).

### Laboratory Analysis

At the laboratory, a small piece of *M. gregaria* muscle was removed from the abdomen of each specimen. Tissue samples were then dried in a drying oven for 24 h at 60 °C, weighed up to 1.5 mg of muscle tissue, and then packed in tin capsules.

The POM samples obtained in the filters were also dried for 24 h at 60 °C. Samples of *M. gregaria* (muscle) and POM samples were used to analyze the isotopic signal during the sampling period. Total carbon and nitrogen, and stable isotope ratios of carbon ( $\delta^{13}\text{C}$ ) and nitrogen ( $\delta^{15}\text{N}$ ) were measured at the University of California, Davis, USA, by continuous flow isotope ratio mass spectrometry (20-20 mass spectrometer, PDZ Europa).

### Stable Isotope Analysis

Stable isotope ratios are expressed in delta ( $\delta$ ) notation, defined as the deviation in parts per thousand (‰) from a standard material (Pee Dee Belemnite for  $\delta^{13}\text{C}$  and atmospheric nitrogen for  $\delta^{15}\text{N}$ ), according to the formula

$$\delta X = \left[ \frac{(R_{\text{sample}})}{(R_{\text{standard}})} - 1 \right] \times 1000$$

where  $X = {}^{13}\text{C}$  or  ${}^{15}\text{N}$  and  $R = {}^{13}\text{C}/{}^{12}\text{C}$  or  ${}^{15}\text{N}/{}^{14}\text{N}$  (Peterson and Fry 1987).

For *M. gregaria* isotopic composition, we made a lipid correction following McConnaughey and McRoy (1979). For the estimation of trophic position, we considered the particulate organic matter at the base of the food web as the first trophic level. The trophic position was computed according to the equation

$$\text{TP}_{\text{consumer}} = 2 + (\delta^{15}\text{N}_{\text{consumer}} - \delta^{15}\text{N}_{\text{base}}) / 3.4$$

where  $\text{TP}_{\text{consumer}}$  is the estimate of the trophic position for the consumer and  $\delta^{15}\text{N}_{\text{consumer}}$  is the measured  $\delta^{15}\text{N}$  value in the analyzed specimen. The  $\delta^{15}\text{N}$  value of POM was attributed to primary producers and thus represents the reference value at the base of the food web ( $\delta^{15}\text{N}_{\text{base}}$ ). Many works use POM as the base of the food web for isotope analysis (for example, in fjords (Montecinos et al. 2016)); in particular in this study area, the autochthonous POM is phytoplankton-based POM (Vargas et al. 2011). The 3.4‰ denominator is the enrichment in  $\delta^{15}\text{N}$  per trophic level (Post 2002). We

calculated the relative importance of terrestrial organic matter in the diet of *M. gregaria*, applying a two-source mixing model (Bianchi 2007)

$$\% \text{POC}_{\text{terr}} = (\delta^{13}\text{C}_{\text{sample}} - \delta^{13}\text{C}_{\text{marine}}) / (\delta^{13}\text{C}_{\text{terrestrial}} - \delta^{13}\text{C}_{\text{marine}})$$

where  $\delta^{13}\text{C}_{\text{sample}}$  is the isotopic composition of a sample,  $\delta^{13}\text{C}_{\text{marine}}$  is the marine endmember from more oceanic stations, and  $\delta^{13}\text{C}_{\text{terrestrial}}$  is the riverine/lake endmember values for POC. Particulate organic matter has been used as the endmember in other trophic studies (Post 2002; Benstead et al. 2006; Vargas et al. 2011). The values used for the endmember were reported by Vargas et al. (2011) for this study area and correspond to  $\delta^{13}\text{C} - 27.4\text{‰}$  (reported for Lake General Carrera) and  $-20.1\text{‰}$  for the marine endmember (this oceanic station was located at 80 km west and approximately 160 km south from the stations of this study). The isotopic signal of the sample was the mean value of *M. gregaria* tissues in both strata.

### Statistical Analysis

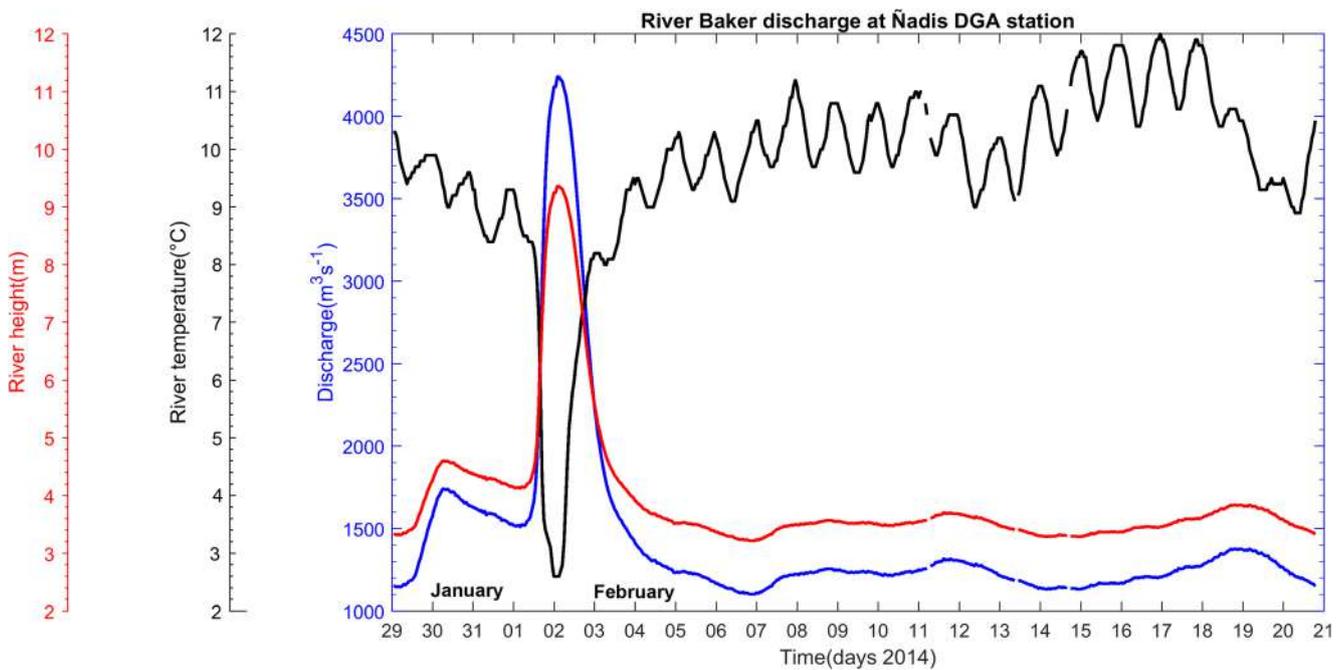
The data were examined for normality and homogeneity of variance using the Shapiro-Wilk and Bartlett tests, respectively. The Mann-Whitney  $U$  test was used for the analysis for non-parametric data.

## Results

### Hydrographic Variability During the Sampling Period

During the sampling period, a GLOF event occurred on the 2nd of February that appeared as an almost threefold increase the Baker River outflow (Fig. 2). This increase to  $> 4000 \text{ m}^3 \text{ s}^{-1}$  in the Baker River outflow measured at the Ñadis hydrological station reflected the sudden draining of Lake Cachet II. Following this increase in river outflow, the Baker River height increased twofold, and water temperature dropped by ca. 6 °C. The increase in Baker River discharge from  $\sim 1000 \text{ m}^3 \text{ s}^{-1}$  to a maximum of  $4240 \text{ m}^3 \text{ s}^{-1}$  took place within 4 days.

A drop in water temperature throughout the near-surface layer (0–10 m) was detected in the Baker Fjord at a time that was consistent with the increase of Baker River outflow, thus evidencing the GLOF's arrival to the Baker Fjord (Fig. 3a, g). The arrival of GLOF water to the fjord produced a thermal front, with a temperature drop of 4 °C. In this cold layer, salinity was extremely low, with freshwater (FW) occupying the top 5–10 m (Fig. 3b). Below the surface layer (depth  $> 10$  m), warmer and salty water revealed the presence of the estuarine salty water (ESW, 21–31) as well as sub-Antarctic modified water (MSAAW, 31–33) below 25 m depth (Fig. 3b).



**Fig. 2** Baker River outflow, height, and water temperature at the Nadis river flow-recording station during the sampling period

The GLOF also caused a deepening of the pycnocline (see, for example, the 4–20 isohalines in Fig. 3c). As a consequence of the increased freshwater input during the GLOF, superimposed on the seasonal increase in river outflow, a strong and persistent stratification was observed at 8 m depth (Fig. 3d). In addition, the GLOF produced an oscillation of fluorescence at the pycnocline (Fig. 3e) and a clear increase in turbidity within the surface layer in the Baker station, at the Baker River mouth, on the day of the GLOF (Fig. 3l).

Prior to the GLOF's arrival to the Baker Fjord, currents within the top 25 m of the water column were predominantly oriented along a NW-SE axis, which is roughly aligned with the Martinez Channel at the mooring site (Fig. 1), with residual velocities of up to  $15 \text{ cm s}^{-1}$ . Upon the GLOF's arrival, a surface layer with more intense flow in the along-channel axis became apparent during at least 2 days, whereas the change in flow structure along the across-channel axis was shorter lived (Fig. 4a, c). The absolute maxima of along-channel and across-channel velocities were  $16.4 \text{ cm s}^{-1}$  and  $23.8 \text{ cm s}^{-1}$  with standard deviations of  $2.4 \text{ cm s}^{-1}$  and  $\pm 2.9 \text{ cm s}^{-1}$ , respectively. The time series for currents at 15 m depth indicated a drop in current velocities upon the GLOF's arrival to the fjord. The low-pass-filtered time series for currents at 15 m depth indicated that residual flow was initially south-eastwards, north-eastwards, and eastwards in general, representing inflow of subsurface water from the ocean. With the exception of the 30th of January, the dominant direction was north-westwards. Also, the magnitude of residual velocities was low ( $\sim 1 \text{ cm s}^{-1}$ ) on the day of the GLOF, which is consistent with previous records for the area, but then increased to  $\sim 3 \text{ cm s}^{-1}$  (Fig. 4e).

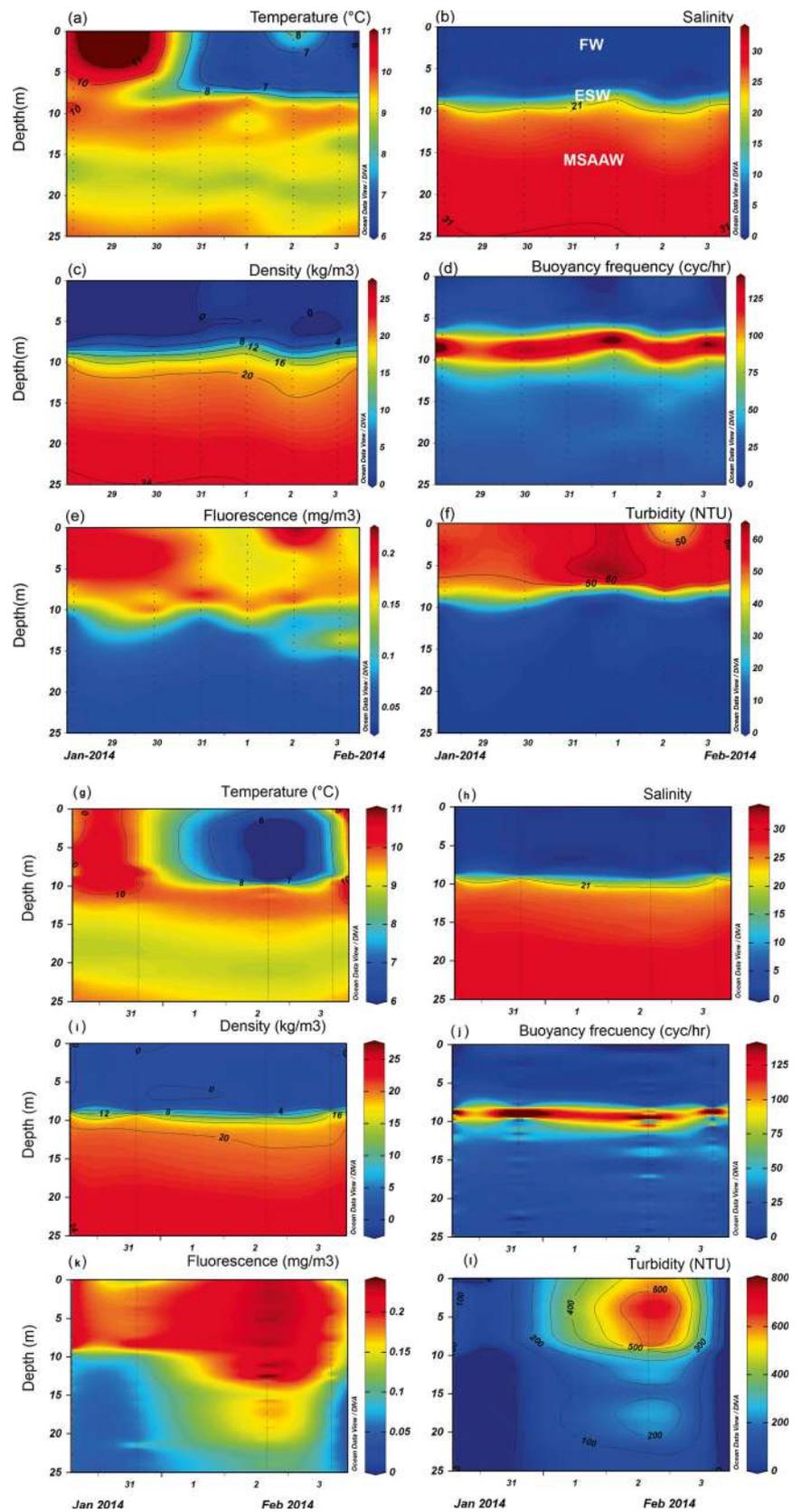
### Characterization of the POM

Considering the three stations, throughout the sampling period, the amount of total organic carbon in POM was significantly higher at the surface (mean  $212 \mu\text{g L}^{-1}$ ) than at the subsurface (mean  $120 \mu\text{g L}^{-1}$ ,  $F = 12.7$ ,  $p < 0.05$ ). On the day of the GLOF, there was an increase in the organic carbon content of POM ( $600 \mu\text{g L}^{-1}$ ), which was particularly apparent at the Baker station (Fig. 5). The total content of organic nitrogen showed a similar pattern, with higher values at the surface throughout the sampling period (surface mean =  $30.3 \mu\text{g L}^{-1}$ , subsurface mean =  $15.9 \mu\text{g L}^{-1}$ ,  $F = 11.5$ ,  $p < 0.05$ ) and increasing also in the surface at the Baker station on the 2nd of February (Fig. 5).

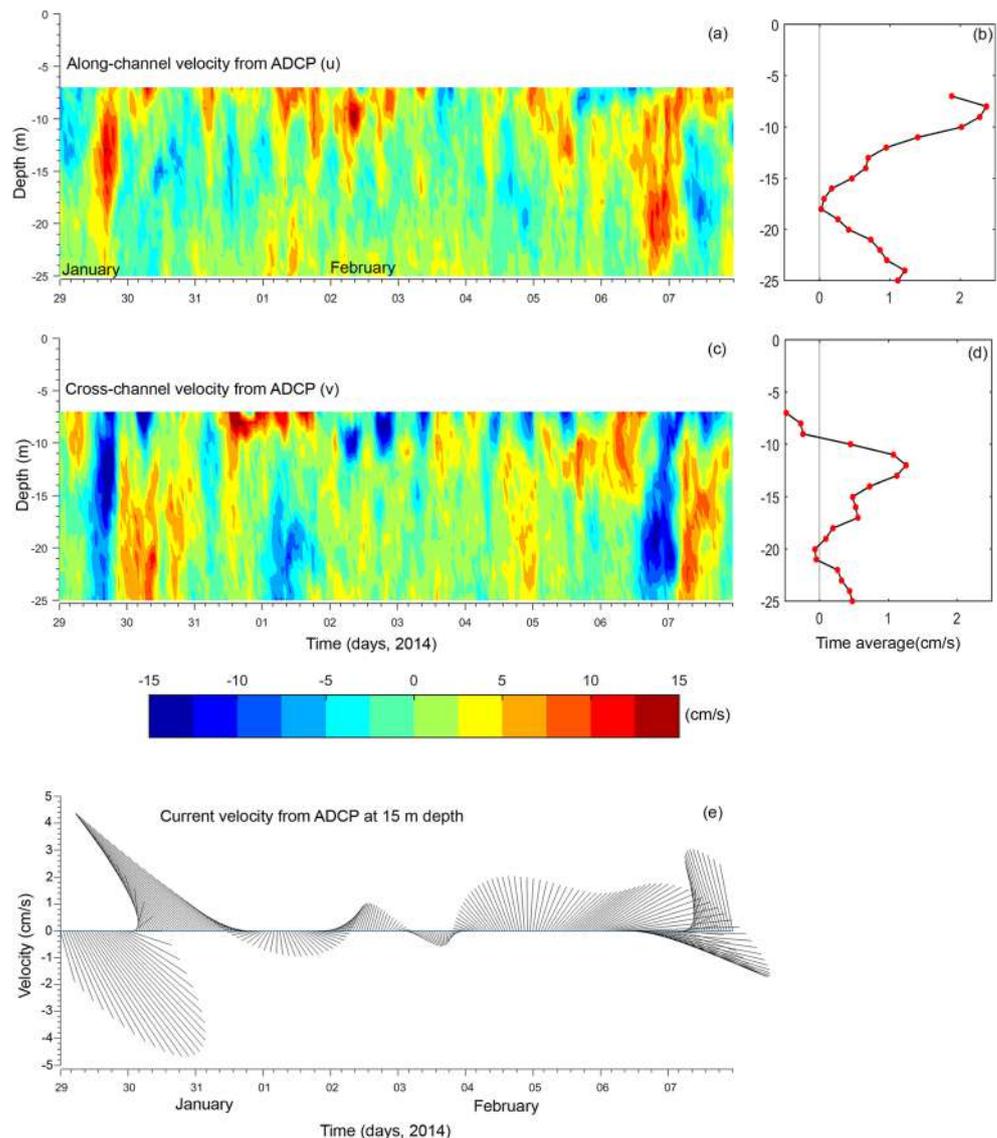
On the day of the GLOF (February 2), an increase in the C/N ratio of POM was observed at the Steffen station at depths of 3 m and 15 m (Fig. 6). At the center and Baker stations, there was a lag between the change in the C/N ratio at the surface (3 m) and subsurface (15 m), with an increase of the C/N ratio detected first at 15 m depth and 1 day later at the surface (Table 1).

Throughout the sampling period, there was a consistent difference in the  $\delta^{13}\text{C}$  of POM from the surface versus subsurface layer, with more negative values of  $\delta^{13}\text{C}$  at the surface layer (Fig. 6). Values in the subsurface layer were slightly less negative and exhibited a positive trend (i.e., towards less negative values) at center station (Fig. 6). A marked increase in  $\delta^{13}\text{C}$  of POM was observed for both strata at the Steffen station on the day after the GLOF (from  $-22$  at the subsurface and  $-26$  at the surface to  $-14$ ). At the center station, the  $\delta^{13}\text{C}$  of POM changed from a mix from

**Fig. 3** Hydrographic, turbidity, and fluorescence sections at the Steffen station (a–f) and Baker station (g–l, vertical lines show cast times)



**Fig. 4** **a** Along-channel and **c** cross-channel velocities from ADCP 307.7 kHz moored in the Baker Fjord during January–February 2014. (Positive velocities are oriented landward, and negative velocities are oriented seaward for the along channel component; positive velocities are oriented towards the north, and negative velocities are oriented towards the south for the cross channel component). **b, d** Time average from along- and cross-channel velocities. **e** Velocity and direction of the current at 15 m depth from ADCP (data were filtered with Lanczos cosine of 40 hs to eliminate the tide effects)



terrestrial and marine influence on the days prior to the GLOF ( $-23.33 \pm 1.5$  between January 28 and February 2) to a stronger marine signal ( $-20.54 \pm 1.6$  from February 3 onwards) at 15 m depth. This shift was not observed near the river mouth at the Baker station, where the  $\delta^{13}\text{C}$  signal in POM remained terrestrial throughout the sampling period.

### Abundance and Isotopic Composition of *Munida gregaria*

Concurrently with the GLOF, there was a peak in abundance of juvenile *Munida gregaria* at the center and Baker stations, with numbers as high as  $13 \text{ ind m}^{-3}$  on the 2nd of February (Fig. 7).

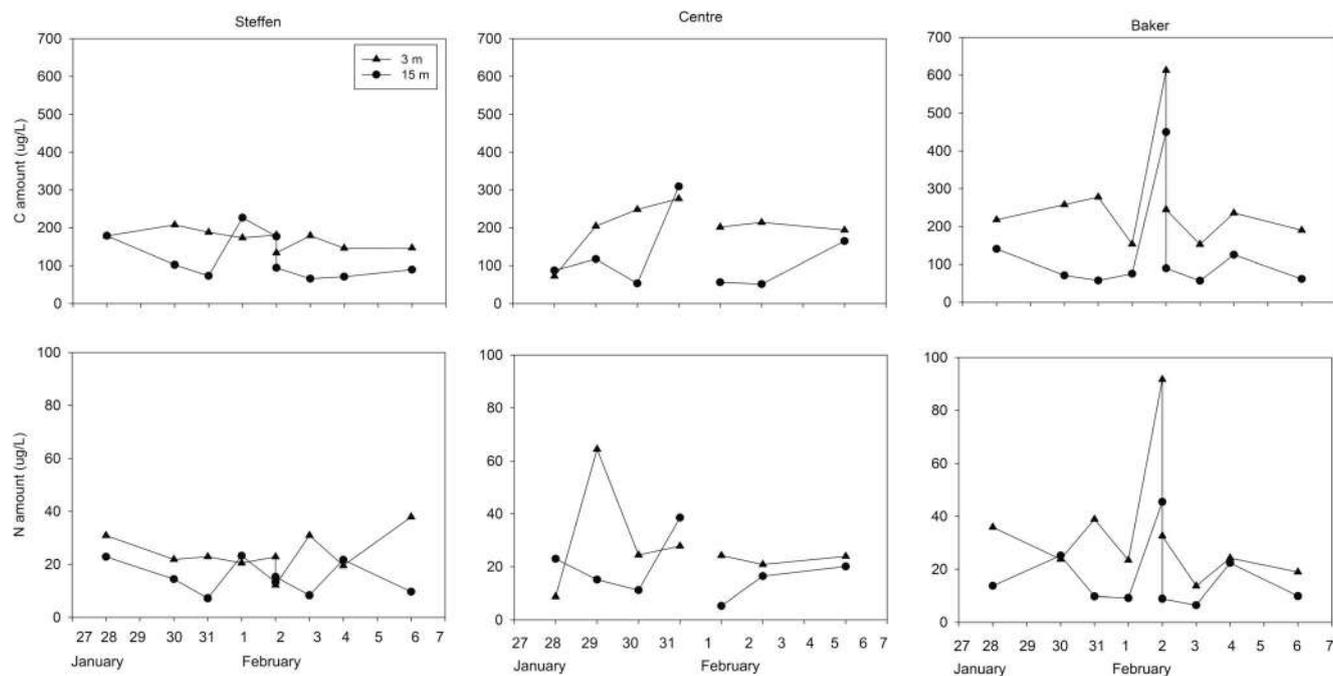
The  $\delta^{13}\text{C}$  signature in muscle tissue obtained from *M. gregaria* was marine for both surface and subsurface, with

values ranging between  $-19$  and  $-21$  over the entire sampled period (Fig. 8). The  $\delta^{15}\text{N}$  signature of muscle tissue, on the other hand, ranged between values 12 and 10 for both depths (Fig. 8).

From the two-source mixing model, we estimated the contribution of terrestrial organic carbon to the diet of *M. gregaria* equal to 8%.

### Discussion

During the GLOF that occurred on the 2nd of February 2014, hydrographic and biological effects were observed in the water column of Martinez Channel, Baker Fjord complex, and near the Baker River mouth. The GLOF caused a deepening of the pycnocline, which coincided with the observed effects of internal waves expected to develop under these outflow



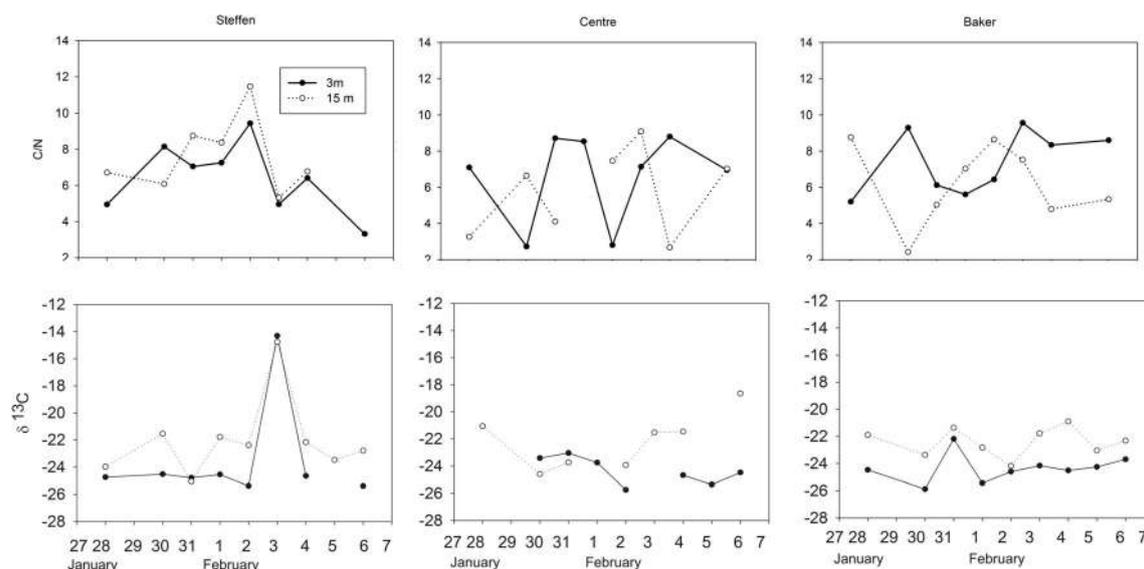
**Fig. 5** Time series of total C and N in POM at the three stations and two depth strata

conditions (Ross et al. 2014). Additionally, there was an increase in the abundance of juvenile *Munida gregaria*, a species that appears to be a key for the fjord's food web.

Because the fjords and channels of Chilean Patagonia are influenced by intrusions of deep oceanic waters with high salinity/nutrients, which interact with surface waters of low salinity/nutrients (Iriarte et al. 2010) and considering that sub-Antarctic waters from below the pycnocline are the source of nutrients (Silva and Neshyba 1979), vertical displacements of the pycnocline forced by events such as GLOFs could be

very important for the incorporation of nutrients into the euphotic zone. At high-latitude fjords, changes in hydrography such as stronger stratification due to climate change will likely lower phytoplankton productivity due to attenuated reintroduction of nutrients to surface waters (Quigg et al. 2013).

On the other hand, in other areas, the increased freshwater input due to climate change will greatly enhance estuarine circulation and the resulting input of nutrients to fjords, which is expected to increase biological productivity (Rysgaard et al. 2003). Given present climate trends and increases in the melting



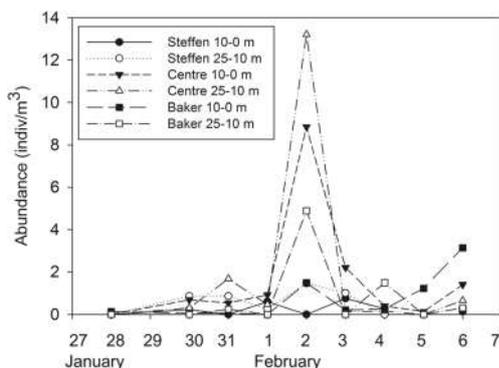
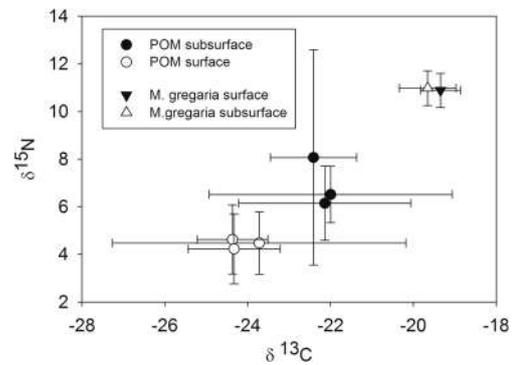
**Fig. 6** Time series of the C/N ratio in POM at the three sampled stations and both strata (upper panels) and time series of  $\delta^{13}\text{C}$  in POM at surface and subsurface strata (lower panels)

**Table 1** Average ( $\pm$  standard deviation values) for POM and *Munida gregaria* at the two sampled strata

	C ( $\mu\text{g}$ )	N ( $\mu\text{g}$ )	C/N	$\delta^{13}\text{C}$
<b>POM</b>				
Surface	113.7 $\pm$ 50.2	11.8 $\pm$ 5.6	16.22 $\pm$ 7	-24.5 $\pm$ 0.8
Subsurface	83.6 $\pm$ 22	16.22 $\pm$ 7	6.6 $\pm$ 2.2	-22.2 $\pm$ 2.1
<b><i>M. gregaria</i></b>				
Surface			3.9 $\pm$ 0.3	-16.7 $\pm$ 6
Subsurface			4 $\pm$ 0.3	-18.9 $\pm$ 3.8

rate and retreat of glaciers from Patagonian ice fields (Glasser et al. 2011; Rivera et al. 2012), changes in the freshwater inputs could strengthen the estuarine circulation because of the increase of along-fjord density gradients at both the surface and subsurface (Aiken 2012; Meerhoff et al. 2014; Moffat et al. 2018). However, it is uncertain how this might affect productivity in the area, given that GLOFs also increase turbidity and light attenuation which might ultimately have a negative effect on primary production (Goebel et al. 2005; Aracena et al. 2011; Jacob et al. 2014). Very little is known about the ecology of turbid glacier-fed aquatic ecosystems and how changes in turbidity and other related environmental parameters influence diversity and community composition, whereas studies on adaptation to these changes have only recently begun (Sommaruga 2015). However, it is known that in lakes, the planktonic food web structure in highly turbid meltwater lakes seems to be truncated and dominated by microbes (Sommaruga 2015).

Twentieth-century climate warming is responsible for recent moraine dam failures in mountains throughout the world, forcing glaciers to retreat, prompting ice avalanches, landslides, and GLOFs in many places [i.e., in British Columbia (Clague and Evans 2000) and in East Greenland (Grinsted et al. 2017)]. For other subaerial ice-dammed lakes worldwide, regional warming will also promote higher-impact GLOFs by raising the likelihood of warm weather during their occurrence, unless other factors reduce lake volumes at flood initiation to outweigh this effect (Ng et al. 2007). In areas where

**Fig. 7** Time series of *Munida gregaria* juvenile abundance at three stations in the Baker Fjord**Fig. 8**  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  in POM and juvenile *Munida gregaria* tissue

the GLOFs discharge into fjords, similar impacts in the ecosystem could be observed.

The deepening of the pycnocline caused an effect on the seston. The C/N ratio of the POM revealed a lag between the surface and 15 m depth, showing that terrestrial organic matter became more important in the subsurface layer immediately after the GLOF, which is probably caused by resuspension from the sediments. Rebolledo (personal communication) observed a distinct terrestrial signal ( $\delta^{13}\text{C}$  values  $-27\text{‰}$  to  $-26\text{‰}$ ) in the sediments of Martinez Channel near the Baker River mouth (i.e., our study area). The resuspension produced due to the GLOF's arrival to the fjord can put terrestrial carbon that was deposited in the sediments back in the water column. However, over longer time scales, fjords in Northern Patagonia ( $41\text{--}47^\circ\text{S}$ ) appear to act as  $\text{CO}_2$  sinks, with substantial burial of organic carbon (Sepúlveda et al. 2011). In addition, the terrestrial organic material resuspended during the mixing could be advected towards oceanic areas as is the case of Norwegian and Alaskan fjord systems, where organic matter of terrestrial origin does reach the open ocean (Louchouart et al. 1997; Winkelmann and Knies 2005).

Current results show that during the GLOF, there was an increase of the carbon content in POM ( $600\ \mu\text{g L}^{-1}$ ) from the Baker station. At the Steffen station, the  $\delta^{13}\text{C}$  in POM changed in a direction that suggested a transition from values characteristic of C3 terrestrial plants at the surface and marine signal at the subsurface to C4 plants in the whole water column; C4 plants include most summer grasses, sedges, and a few halophytic shrubs, and average around  $-12 \pm 2\text{‰}$  (Cerling and Quade 1993). The most abundant vascular plants in the Baker and Pascua River basins are in the families Poaceae, Asteraceae, and Cyperaceae (Rodríguez et al. 2008), which, in fact, are C4 plants (Sage et al. 2011). Debris from C4 plants have been reported as an important part of the diet of zooplankton and zooplanktivorous fish in South African estuary (Paterson and Whitfield 1997), whereas debris from C4 plants in salt marshes appear to be important in the diet of the killifish, *Fundulus heteroclitus* (McMahon et al. 2005), as well as in detritivorous benthic organisms in a coastal lagoon of Southern Brazil (Abreu et al. 2006).

Coincidentally with the GLOF, there was a peak in *M. gregaria* juvenile abundances at the center and Baker stations with abundances as high as  $13 \text{ ind m}^{-3}$ . This abundance is 1 order of magnitude higher than the abundances observed in the fjord in summer months (Meerhoff et al. 2013). The isotopic signal of *M. gregaria* was marine like the subsurface POM, thus indicating the subsurface origin of these organisms. Similar isotopic values have been recorded by Quiroga et al. (2016) in this area, who submit that these values are indicative of the incorporation of chemosynthetic biomass.

Adult *M. gregaria* are considered a key component of Patagonian food webs because it connects organic carbon deposited in sediments with higher trophic levels, thus increasing the efficiency of energy transfer from detritus to higher levels. *Munida gregaria* is part of the diet of several top predators such as squids, decapods, fish, marine birds, and whales (Romero 2003; Varisco and Vinuesa 2007), and local fishermen have observed that the stomach of fish collected along the fjord are often full of these squat lobsters (personal communication); the sudden increase in abundance observed near the Baker River mouth after the GLOF could indicate a high capacity to respond rapidly to fluctuations in freshwater inputs to the fjord, thus connecting the dynamics of local food webs with alterations in local and regional hydrology predicted for future climate scenarios.

We do not have information on the diet of juvenile *M. gregaria* in this area, nor do we know whether juveniles may feed also on benthic substrates. However, our results show that the  $\delta^{13}\text{C}$  signature in *M. gregaria* tissue was mainly marine over the entire sampled period, and also that our estimates of the contribution of terrestrial organic carbon to the diet of *M. gregaria* in this summer season was 8%. If sediments near the Baker River mouth show a strong terrestrial signal ( $\delta^{13}\text{C}$  values  $-27$  to  $-26\text{‰}$ ; Rebolledo, personal communication), our results indicate juvenile *M. gregaria* either (i) had been feeding in the water column before the GLOF event or (ii) that the residence time of *Munida* in waters with increased benthic suspended sediment needs a longer period to show up the terrestrial contribution in *Munida* tissues. An alternative hypothesis we cannot rule out at this point is that during the season our sampling took place, sediments may have not had such a large amount of terrestrial sediments as observed in other seasons by Rebolledo (personal communication), a hypothesis which is in agreement with the isotopic carbon signal of POM in the water column.

In conclusion, the GLOF had several effects on the fjord, including a change in the C/N ratio and in the isotopic signal of the POM in surface waters, which represents a change in the origin of the POM from autochthonous to allochthonous. Furthermore, an increase in the abundance of the juvenile pelagic stage of a key species in the ecosystem, the squat lobster *M. gregaria*, was observed during the GLOF, and the tissue sampled from these juvenile lobsters revealed the

isotopic signature of terrestrial organic carbon (8%). The results highlight the importance of GLOFs as a disturbance (sensu Resh et al. 1988), both for the hydrography and circulation of this basin and for the functioning of this fjord ecosystem. If the current trend of more frequent GLOFs in the Baker River basin due to the recurrent drainage of Lake Cachet II (Casassa et al. 2010) is maintained, a more frequent deepening of the pycnocline is expected in the fjord, thus increasing the supply of nutrients and potentially enhancing local productivity in the fjord (see, for example, Montero et al. 2017). Our findings also imply that modifications in the regime of freshwater discharge and organic matter fluxes into the fjord, such as those expected under river-damming scenarios, may impact the productivity, carbon cycling, and food web dynamics of this and other Patagonian fjord ecosystems. Finally, present results could have implications in the ecosystem functioning of other high-latitude glacier-influenced fjords around the world.

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