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Dr. Mario Hoppema

Topic Editor

Ocean Science Discussion

Dear Dr. Hoppema,

Here we present the revised version of the manuscript “***Seiche excitation in a highly stratified fjord of southern Chile: the Reloncaví fjord***” (MS). Below you find out, in red your comments and in green our answer. We include the number of the line where the changes were made which are marked in yellow into the marked manuscript (attached after the Answer to the reviewers).

We hope that you find this manuscript is now suitable for publication in Ocean Sciences,

Sincerely,

Dr. Manuel I. Castillo (MIC)

on behalf of myself and my coauthors

Referee #1

2) Line 9, p4: avoid repetition of the word “forcing”

Your Answer: The word was deleted on line 93.

MH: This was not implemented in the revised manuscript. Please do.

Ans.

The paragraph was changed on line 93.

Referee#1

3) Line 23, p8: You refer to a mean wave speed, but Equ. (1) defines a time.

Can you clarify?

Your Answer:

The eq. 1, define the fundamental period of oscillation of the basin which is a better way to estimate the oscillation period of a basin. The phase speed is related with the period based on the linear theory. The scope of the manuscript is based on the period of oscillation of the fjord because appear a marked spectral peak on one characteristic frequency (period) band, the three days. That is based on effective phase speed which take into account the changes of depth and lengths of every sub-basin you must notice that the period is related with the phase velocity (c) in the form showed on the eq. 1. Thus imply that, there is an effective period for the entire basin. We incorporated the terms effective phase speed in the MS on lines 234-237.

MH: I understand your explanation, but this does not answer the comment by the referee. The sentence starting in line 231 mentions the internal phase velocity and equation (1) in line 234, which should show that velocity but gives a time instead. Please explain and correct.

Ans.

We re-arranged the eq. 1 (line 233) to be consistent with the entire paragraph. Now the effective period (T) it is defined on lines 235-236.

3) Differences in the spectral peaks at ~12h (fig 4) suggest that there is a significant internal tidal response as has been observed in other fjords (e.g. Allen and Simpson, Winant 2010). You could isolate this component either by projecting on to the modes or by cross-spectral analysis of flow in the upper and lower layers.

Your Answer:

Thanks for the suggestion, in fact the internal tides dynamics is the main topic of the ongoing manuscript from the same authors which take results not only from the Reloncavi fjord also to another fjord of the southern Patagonia. We think that the tidal variability is a different topic and out of the scopes of the manuscript. In the case of the internal tides, recently on the southern Patagonian fjords Ross et al (2014, 2015) showed the relatively importance of the internal tides in the high frequency dynamic of the fjords, indeed in the manuscripts they shows to different ways of forcing for the internal waves: GLOFS and low-frequency changes of barometric pressure. As part of a new project, the group involves in this manuscript is worried about the forcing for one hand tides inducing internal tides due to the pycnocline interaction with the bathymetry for example, and for other hand winds could perturb the pycnocline

inducing natural oscillations of the basin. We want to maintain the manuscript scope on the 3 days oscillation which clearly is due to the natural internal oscillation of the Reloncavi fjord, this finding is extremely relevant for the region because it is the first time that the process is described for the southern Patagonian fjords.

MH: Your suggestion to tackle this in a different publication is fine. However, it would be good if you could at least mention the internal tide response in the manuscript and point to the future work.

Ans.

We incorporate a paragraph to indicate the importance of the semi-diurnal signal in the region, and in other studies. We also indicate that it is necessary to develop internal-tides studies on the entire Patagonian region on lines 482-491.

4) The paper emphasizes the consistency of the density structure but it does vary somewhat (~20%) and it would be useful to relate this variation to the changes in stratification due to variations in freshwater input and surface heating/cooling. Presumably salinity is the main control on density but surface heat exchange may also be playing a role?

Your answer:

We think that the surface heat exchange may play a role in the upper column, in fact on the brackish water layer, where temperature could be more important to the density instead of salinity. We consider including a description of the relevance of the heating/cooling of the upper layer which has a marked seasonal cycle. You must notice that rivers on the region are colder in winter producing a clear thermal inversion (Castillo et al., 2016) while in summer the surface waters could reach until 18°C probably by heat gained by the solar radiation. But the development of the pycnocline along the seasons is consistent with the freshwater input suggesting that the variability of the density in the upper layer is dominated by the freshwater input instead of the surface heating/cooling.

MH: It is not clear to me whether you actually made any changes to the manuscript addressing this issue. Please explain and show where in the manuscript this has been added.

Ans.

We incorporate a similar explanation that above in the manuscript on lines 446-452.

1. It would be useful if the principles around fjord seiches is described in more detail, preferable with a conceptual cartoon. It would also be good if the theoretical calculation of expected oscillations were coupled to the cartoon.

Your Answer:

Thanks for the comment but the seiche (external and internal) are well known mechanisms. We will work on a scheme of the dynamics but the manuscripts already have several figures and we still don't be sure whether or not the scheme will be helpful to understand the dynamics involved.

MH: I agree with the referee that it would be useful to provide a short description of the theory of seiches whether or not with cartoon.

Ans.

We add a brief but concise explanation of the seiche basic dynamics on lines 497-506.

Below are my comments after editor review:

Please use following format for references in the text: (Watson, 1904) (Smith et al., 2004) (comma after name or after et al.)

Ans.

The format of the references in the text was checked and corrected accordingly with the examples along the entire document, but the changes were not marked because were too much marks.

In the Methods section 3.1 please provide precisions of the different measurements.

Ans.

The precision of the measurements is already included on supporting Table S2, we indicate that on lines 151.

L24-25 I suggest: We describe a seiche process based on current, temperature and sea level data obtained from the Reloncavi fjord (41.6° S, 72.5° W) in southern Chile.

Ans.

The sentence was changed on lines 24-26.

L26 define ADCP here (used for the first time)

Ans.

Now we define Acoustic Doppler Currentmeter Profiler (ADCP) on L26.

L53 For better understanding I think this should be changed to: It is possible to find resonant basin modes, but only ...

Ans.

The sentence was changed on L53-L54.

L61 Shouldn't this be: "... IN the pycnocline"

Ans.

We sentence was changed on L61

L64 amplitude

Ans.

We sentence was changed on L64

L97-99 To avoid questions at this point, change to: "The objective of this study was to address how these oscillations affect the temporal and spatial dynamics of currents and temperature, and how these oscillations are forced."

Ans.

We sentence was changed on L97-L98

L103 the northernmost fjord

Ans.

Changed L102

L137 Current (instead of: Currentmeter)?

Ans.

We delete the sentence because ADCP was defined previously

L140 upward looking (instead of: upper-looking)?

Ans.

Changed L139

L184 stabilized (not: stabilization)

Ans.

Changed L182

L202-204 “To focus the study on these perturbations, we used a cosine-Lanczos band-pass filter with half amplitudes at 60 h and 100 h (see results for the justification of the selected band).” You do not just use a filter. With what did you use this filter? I think with the time series data. Please also mention this in the sentence.

Ans.

We indicate in a way explicit that the time series of currents and temperature were band-passed on L200-L201.

L204-205 “As part of the results, the band-passed time series of the current and temperature data are shown (COPAS-SUR Austral, 2012).” I do not understand this. Where are they shown? Or do you mean something different?

Ans.

Thanks for the comment that was a mistake, now we refer to Fig. 6 and Fig. 9, which showed the band-passed time series change was made on L203.

L228 “... for each sub-basin, and season” or “... for all sub-basins, and seasons”

Ans.

Changed L227

L273 ... generally directed out of the fjord ... (insert: directed)?

Ans.

Changed L273

L369-371 “In addition, the density structure showed a condition of continuous stratification in the upper layer along the seasons (Fig. 5).” This is repeated info. Exactly the same is written at the beginning of this paragraph. Please delete one or the other.

Ans.

The entire sentence was deleted on L369.

L378 delete comma

Ans.

Deleted.

L379-380 If I understand correctly, change to: "Mode 1 was highly baroclinic, changing sign at nearly 10 m (sub-basin I) and 15 m (sub-basin IV)." (Please note that this is not easily visible at Fig.5)

Ans.

Changed on L377

L381-382 This was strange. Please change to: "For depths > 30 m (not shown in Fig. 5) the internal modes do not show significant variability."

Ans.

Changed on L380

L387 Change to: Like the internal speeds (c) ...

Ans.

Changed on L386

L399-401 I suggest to slightly change this to: "The vertical patterns at the three locations show inflow-outflow intermittence along the whole time series; also most of these along-fjord structures seem to develop an inclination which indicates the baroclinic nature of this pattern."

Ans.

The suggested changes were implemented on L398-L400

L404 depth

Ans.

Changed

L405 decide (instead of: confirm)

Ans.

Changed

L409-410 I am not sure what you mean with Figure 7. I think you mean to show the agreement between the currents, correct? Then please change this sentence to: "The agreement between the 3 days band-pass and the projected along-fjord currents at the mouth is shown in Fig. 7."

Ans.

Thanks for the suggested change which was insert on L408-L409.

L410-412 "Using only the first three modes, it was possible to explain more than 70% of the band-pass variability; changes in the outflow and inflow were highly consistent and the intensifications at the surface were clearly shown by the projected modes."

Ans.

Thanks for the suggested change which was insert on L409-411.

L418-420 Please modify this sentence to: “The vertically averaged KE obtained with 3 days band-pass was higher than that generated with the other the components (modes 1-3); the maximum was observed in the period 9-18 August (Fig. 7), which is consistent with the wind-stress intensification shown in Fig. 3a.”

Ans.

Thanks for the suggested change which was insert on L417-419.

L420-422 “During that period, the modal KE was about one third of the 3 days band-pass kinetic energy; this ratio was higher (i.e. ca. 50%) during September.”

Ans.

Thanks for the suggested change which was insert on L420-421.

L423 delete: relatively (I think this is unnecessary here)

Ans.

Changed

L423 ... was estimated by summing up the ...

Ans.

Changed on L422

L428-429 To describe the temporal variability of this high coherence, ...

Ans.

Changed on L426

L431 (only referred to as coherence hereafter)

Ans.

Changed on L429

L431 spectra

Ans.

Changed on L429

L435 It is not clear to me what opposite winds are here. Please clarify.

Ans.

We refer to the period with down-fjord (to the mouth) winds, we delete “opposite” and explain that on L433.

L444-445 up-fjord wind

L446 down-fjord winds

Ans.

Both were Changed on L442-444

L449 delete: here

Ans.

The entire paragraph was changed to incorporate the observation about the heat/cooling effect on the surface column density on L446-452.

L453-454 I do not understand this sentence: "This change reached depths consistent with the pycnocline (Fig. 2)" Do you mean: "This change reached depths down to the pycnocline (Fig. 2)"

Ans.

Thanks for the suggested change which was insert on L456.

L463 implies

Ans.

Changed on L465

L464 velocity patterns

Ans.

Changed on L466

L469 Change to: We used data collected in one of the most extensive studies ever conducted ...

Ans.

Changed on L471

L476 major (instead of: key)

Ans.

Changed on L478

L487 interaction

Ans.

Changed

L488 (not a peak)

Ans.

Changed on L510

L608 ... (Fig. 10); then the maximum

Ans.

Changed on L630

L609 $KE = 7 \times 10^{-3} \text{ m}^2 \text{ s}^{-2}$, meaning that a great part of this energy might ...

Ans.

Changed on L631

L610-612 This sentence belongs to the Conclusions section.

Ans.

Changed on L659-661

L617 shows (instead of: presents)

Ans.

Changed on L637

L626 local wind stress

Ans.

Changed on L646

L629 with a phase close to 0° , ...

Ans.

Changed on L649

L630 seiche (typo)

Ans.

Changed on L650

L632 strong (instead of: high)

Ans.

Changed on L652

L635 ... winds, which permitted the estimation ...

Ans.

Changed on L655

L636 ... seiche being 9 days; otherwise ...

Ans.

Changed on L656

L680 J. Geophys. Res.

L686-687 Prog. Oceanogr.

L689 Change the journal name to: Deep-Sea Research Part A

L702 Prog. Oceanogr.

L751 Prog. Oceanogr.

L754 Prog. Oceanogr.

Ans.

All the upper issues on the References section was changed, and additionally we checked along the entire section

L797, 799, 802, 803, 820 panel, panels (instead of: inserts)

Ans.

Changed on all the captions

L808-811 I suggest to change the caption slightly to: a) Along-fjord wind stress, positive up to the fjord, (b) sea level, (c) Puelo river discharge, where the straight line represents the long-term mean. Contours of along-fjord currents at (d) Cochamo, (e) Puelo and (f) the mouth; in the filled contours, the blue (red) colors indicate a net outflow (inflow).

Ans.

Changed on L833-836

L813-818 Please change according to: Spectra of along-fjord currents (top) at (a) the mouth, (b) Puelo and (c) Cochamo. Here the black lines indicate the averaged spectra for the upper layer (depths $\leq h_1$) whereas the gray lines show spectra for currents at depths $> h_1$. (d) sea level spectra at the mouth (black line) and at Cochamo (gray). (e) wind stress spectra for their along-fjord (black) and cross-fjord (gray) components. At the bottom of each panel the 95% of confidence intervals for 48, 24 817 and 12 degrees of freedom are shown.

Ans.

Changed on L838-843

Figure 7. Please add a, b and c to the panels and use these in the caption. The caption is not clear about what is actually shown. Please describe in the caption exactly what we see in the figure.

Ans.

We completely change the caption to explain each panel showed on the figure on L853-856.

L833-837 (Caption of Fig. 8) Please modify to include:

Coherence and phase wavelet spectra. (a) Time series of along-fjord wind stress, and (b, c, d, e) coherence and phase wavelet spectra, for the relation mouth-Puelo (b, c) and Puelo-Cochamo (d, e). In the contours, the thick black line indicates squared coherence ≥ 0.6 , only the associated phases were present on the phase wavelet. The thick black curve is the influence cone for the wavelet estimations.

Ans.

Changed on L858-862.

L841 ... and (c) moderate $W \sim 1$

Ans.

Changed on L866

L846 Change to: Damping signal in currents during a period of weak ...

Ans.

Changed on L871

L847 ... at 3m depth ...

Ans.

Changed on L872

L859 Characteristics

Ans.

Changed on L884

1 **Seiche excitation in a highly stratified fjord of southern**
2 **Chile: the Reloncaví fjord.**

3

4

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21

22 **Abstract**

23

24 We describe a seiche process based on current, temperature and sea level data obtained from
25 the Reloncavi fjord (41.6° S, 72.5° W) in southern Chile. We combined four months of
26 Acoustic Doppler Current Profiler (ADCP) data with sealevel, temperature and wind time
27 series to analyze the dynamics of low-frequency (periods > 1 day) internal oscillations in the
28 fjord. Additionally, seasonal CTD data from 19 along-fjord stations were used to
29 characterize the seasonality of the density field. The density profiles were used to estimate
30 the internal long-wave phase speed (c) using two approximations: (1) a simple reduced
31 gravity model (RGM) and (2) a continuously stratified model (CSM). No major seasonal
32 changes in c were observed using either approximation (e.g., the CSM yielded $0.73 < c <$
33 0.87 m s^{-1} for mode 1). The natural internal periods (T_N) were estimated using Merians's
34 formula for a simple fjord-like basin and the above phase speeds. Estimated values of T_N
35 varied between 2.9 and 3.5 days and were highly consistent with spectral peaks observed in
36 the along-fjord currents and temperature time series. We conclude that these oscillations
37 were forced by the wind stress, despite the moderate wind energy. Wind conditions at the
38 end of winter gave us an excellent opportunity to explore the damping process. The observed
39 damping time (T_d) was relatively long ($T_d = 9.1$ days).

40

41 **1 Introduction**

42

43 Internal seiche oscillation has long been known in closed basin geometries (e.g. Watson,
44 1904; Wedderburn, 1907; Wedderburn and Young, 1915). The first detailed description
45 thereof was presented by Mortimer (1952). In these systems, wind is the main force affecting
46 the surface and isotherms (Wiegand and Chamberlain, 1987), which produces a set of
47 periodic oscillations and circulation cells throughout the water column that may contribute to
48 internal mixing of the basin (Thorpe, 1974; Monismith, 1985; Wiegand and Chamberlain,
49 1987; Munnich et al., 1992; Mans et al., 2011; Simpson et al., 2011).

50

51 Although external (barotropic) seiches are ubiquitous in closed basin geometries (Munnich et
52 al., 1992), it is not theoretically evident that there are internal seiches (baroclinic) in a
53 linearly stratified fluid (Maas and Lam, 1995). It is possible to find resonant basin modes,

54 **but only** in well-behaved geometries (Arneborg and Liljebladh, 2001a). However, studies of
55 lakes have yielded good results using layered models (e.g. Lemmin, 1987), normal-mode
56 approximations (e.g. Wiegand and Chamberlain 1987; Münnich et al., 1992) or numerical
57 model simulations (e.g. Goudsmit et al., 2002). In fact, internal seiches have been observed
58 in semi-enclosed systems such as fjords (e.g. Djurfeldt, 1987; Pasmara and Stigebrandt, 1997;
59 Arneborg and Liljebladh, 2001a) with complex geometries and where linear stratification is
60 rarely observed, and thus the only way to maintain consistency with the theory is that the
61 oscillation **in** the pycnocline dominates the internal seiche oscillation (Arneborg and
62 Liljebladh, 2001a). Early in the development of a seiche, its amplitude is related to the
63 forcing intensity, and the standing oscillation then becomes free and requires no additional
64 forcing. The frequencies are retained, but **the amplitude decays** (damping) exponentially due
65 to friction until the system comes to rest (Rabinovich, 2010). The development of seiche
66 oscillations depends of the forcing and damping mechanisms; with large damping, it is
67 impossible to observe a seiche, whereas small damping of a seiche allows for several
68 oscillations (Arneborg and Liljebladh, 2001a).

69

70 In fjords with shallow sills, the interaction between the sill and the barotropic tide generates
71 internal tides that are more energetic than other internal oscillations and are the focus of most
72 studies regarding mixing and internal oscillations based on internal tides (e.g. Stigebrandt,
73 1980; Stigebrandt and Aure, 1989; Inall and Rippeth, 2002; Ross et al., 2014). In the case of
74 fjords with a deep sill and low tidal energy, the breaking of the internal seiche oscillations at
75 the boundaries could be an important contributor to the internal mixing, promoting the
76 spreading of properties within the fjord, particularly in deep waters (Stigebrandt and Aure,
77 1989; Münnich et al., 1992; Arneborg and Liljebladh, 2001b). Additionally, there are
78 evidences that vertical isopycnal displacements in fjords could be generated by similar
79 displacements outside the fjord (e.g. Svensen, 1980; Djurfeldt, 1987). These remotely
80 generated oscillations could enhance the mixing and ventilation in deep fjords.

81

82 There is still only limited understanding of the main oceanographic processes occurring in
83 the fjord region of southern Chile, although there has been local research during the previous
84 few decades. Since early studies of the hydrography by Pickard (1971), a systematic

85 measurement program in the fjord region has been maintained since 1995 (Palma and Silva,
86 2008; Pantoja et al., 2011; Iriarte et al., 2014), although only a small number of studies have
87 focused on the physical dynamics. Most studies have been conducted over short time spans
88 (e.g. Cáceres et al., 2004; Valle-Levinson et al., 2007), and only a few studies have been
89 based on more than one month of data (e.g. Valle-Levinson and Blanco, 2007; Letelier et al.,
90 2011; Castillo et al., 2012; Schneider et al., 2014), thereby limiting our understanding of sub-
91 inertial variability. In the Reloncavi fjord, time series of approximately 4 months have shown
92 evidence that 3-day oscillations of currents could be produced by internal seiche oscillations
93 (Castillo et al., 2012) but **lack to** describe the forcing mechanism and the seasonal
94 modulation.

95

96 This study presents the first evidence of internal seiche oscillations in a fjord in southern
97 Chile. **The objective of this study was to address how these oscillations affect the temporal
98 and spatial dynamics of currents and temperature, and how these oscillations are forced**

99

100 **2 Study area**

101

102 The Reloncavi fjord (41.5°S, 72.5°W) is the **northernmost fjord** on the coast of Chile (Fig. 1).
103 This "J" shaped fjord is 55 km long and has a width that varies from 3 km near the mouth to
104 1 km near the head. There is a deep sill (~ 200 m depth) located 15 km inland although it
105 does not appear to be a barrier to the exchange of properties between the adjacent basins.
106 Based on bathymetric features and the coastline morphology, this fjord can be separated into
107 four sub-basins displaying the characteristics presented in Table 1 and figure 2.

108

109 The main river discharge is provided by the Puelo River (at the middle of the fjord), which
110 produces a mean annual discharge of $650 \text{ m}^3 \text{ s}^{-1}$. The Petrohue River (at the head of the fjord)
111 has an mean annual discharge of $255 \text{ m}^3 \text{ s}^{-1}$, and there are additional freshwater inputs of
112 minor importance compared with the Cochamo river (mean annual discharge of $20 \text{ m}^3 \text{ s}^{-1}$)
113 and Canutillar hydroelectrical plant (mean annual discharge $75.5 \text{ m}^3 \text{ s}^{-1}$) (Niemeyer and
114 Cereceda, 1984). The freshwater input to the fjord due to direct precipitation is only
115 approximately 2% of the main river discharge (León-Muñoz, 2013), and its contribution may

116 be in balance with evaporation (Castillo et al., 2016). The freshwater input creates a marked
117 along-fjord pycnocline that is deeper at the head (~8 m) and shallower at the mouth (~3 m)
118 (Fig. 2).

119
120 During the winter, the mean wind stress (τ) is low due to calms winds ($< 10^{-3} \text{ N m}^{-2}$). During
121 storm events in winter, τ can reach values as high as 0.4 N m^{-2} (winds of $> 10 \text{ m s}^{-1}$), and the
122 wind tends to blow out of the fjord, thereby reinforcing the upper outflow of brackish water.
123 In contrast, during the spring/summer, the winds exhibit a marked diurnal cycle, and τ can
124 reach values as high as those observed in the winter, whereas the wind blows landward, i.e.,
125 toward the fjord's head and against the upper flow. Tides in the Reloncavi fjord are
126 predominantly semi-diurnal, and during spring tidal range never exceed 6 m, whereas the
127 neap tidal range is about 2 m. The tidal current is relatively weak in the upper layer, which is
128 dominated by gravitational circulation (Valle-Levinson et al., 2007; Montero et al., 2011;
129 Castillo et al., 2012).

130

131 **3 Data and Methods**

132

133 **3.1 Field Observations**

134

135 Current measurements were obtained using Teledyne RD Instruments ADCPs in three
136 subsurface mooring systems. These subsurface systems were located near the fjord mouth,
137 near the Puelo River and between the Cochamo and Petrohue Rivers (Fig. 1). The longest
138 time series spanned the period of August through November 2008 (Fig. 1 and Table 1). At
139 the mouth, two upward looking ADCPs were positioned at nominal depths of 10 m (300
140 kHz) and 450 m (75 kHz). The Puelo mooring held two ADCPs, one facing-up at a depth of
141 30 m (600 kHz) and one facing downward at a depth of 35 m (300 kHz). The Cochamo
142 mooring held one facing-up ADCP at a depth of 11 m (300 kHz). Note that due to the large
143 tidal range, the depths of the ADCPs significantly changed with the tides. These effects —
144 along with small vertical deviations of the ADCPs related to the line movements — were
145 corrected using the ADCPs pressure sensors, and all of the bin depths were referenced to the
146 water surface level. The mooring systems were designed to obtain the best vertical resolution
147 available with emphasis on the upper layer. The ADCP cell sizes were 0.5 m (600 kHz), 1 m

148 (300 kHz) and 4 m (75 kHz), and the data-acquisition time intervals were 10 minutes in most
149 of the ADCPs, with the exception of the deepest ADCP, which was set to acquire data at an
150 interval of 20 minutes. All the ADCPs configurations maintain a standard deviation $< 2 \text{ cm s}^{-1}$
151 ¹ (details in supporting information S2).

152

153 The morphology of the fjord exhibits a sharp bend in the middle, and thus the x and y -
154 components of the currents were rotated to the local orientation of the along-fjord axis (Fig.
155 1 and Table 1). A right-handed coordinate system with a positive-up z -axis and an along-
156 fjord y -axis (positive toward the fjord head) was used. Consequently, the cross-fjord x -
157 component was positive toward the south (east) near the fjord mouth (head). To assess the
158 contribution of the tides to the currents, the amplitudes and phases of several tidal
159 components were calculated at all of the moored ADCPs using a standard harmonic analysis
160 from Pawlowicz et al. (2002).

161

162 The vertical structure of the temperature was obtained from Onset HOBO-U22 temperature
163 sensors installed in three mooring systems along the fjord (Fig. 1). These moorings held
164 surface buoys supporting the thermistor chains with an anchor located at a 25 m depth to
165 maintain their nominal depths (0, 1, 2, 3, 4, 5, 7, 9, 11, 13, 15 and 20 m) from the surface
166 independent of tidal fluctuations. Temperature data were collected every 10 minutes at all
167 locations.

168

169 A Davis Vantage Pro2 meteorological station was installed south of the Puelo River (see Fig.
170 1). This station held sensors for measuring the wind direction and velocity, solar radiation,
171 rain, and air temperature. The wind magnitude and direction sensors were installed 10 m
172 above sealevel and were set to collect data every 10 minutes from 12 June 2008 to 30 March
173 2011. Gaps in the time series represented only 0.04% of the total data. The wind stress (τ)
174 was calculated using a drag coefficient dependent on the magnitude (see Large and Pond,
175 1981) and a constant air density of 1.2 kgm^{-3} .

176

177 The salinity and temperature profiles were obtained seasonally using a CTD SeaBird SBE 25
178 at 19 stations in the along-fjord transect shown on Figure 1. The data were processed

179 following the standard protocol suggested by the manufacturer and were averaged in vertical
180 intervals of 0.5 m. Due to large salinity changes in the upper layer, the instrument pump was
181 set to a time interval of 1 minute. After the start of the pumping, the instrument was
182 maintained near the surface until the sensors **stabilized**. Then, the CTD was lowered to the
183 maximum depth of the station (Table 2). The along-fjord transects typically required 12 to 24
184 hours to complete, depending on local weather conditions. Due to technical limitations, the
185 winter transect was performed to a maximum depth of 50 m.

186

187 The sealevel was recorded every 10 minutes using two pressure sensors moored over the
188 seabed. At Cochamo, the pressure sensor was an Onset HOBO-U20, whereas a SeaBird
189 wave-tide gauge SBE-26 was installed near the fjord's mouth (Fig. 1). Subsurface pressure
190 data were corrected for air pressure and converted to an adjusted sealevel.

191

192 Discharge data were provided by Dirección General de Aguas, Chile (2016). These data are
193 regularly collected at a station located 12 km upstream of the Puelo River's mouth (Fig. 1).
194 The time series extended from January 2003 to December 2011, and data gaps represented
195 only 2% of the total.

196

197 **3.2 Time series analysis**

198

199 Previous findings (Castillo et al., 2012) have shown an important oscillation with a period of
200 approximately 3 days (72 h). To focus the study on these perturbations, **the time series of**
201 **currents and temperature were band-pass filtered using** a cosine-Lanczos with half
202 amplitudes at 60 h and 100 h (see results for the justification of the selected band). As part of
203 the results, the band-passed time series of the current **(Fig. 6) and temperature (Fig. 9)** data
204 are **shown**.

205

206 Spectral analyses of the current, wind stress, sealevel and temperature time series were
207 performed using Welch's modified average periodograms (Emery and Thomson, 1998). To
208 achieve statistical reliability of the spectral estimations, each time series was divided into
209 non-overlapping segments to generate spectral estimates. In the case of the current time
210 series, the spectra were (additionally) averaged among depth layers to obtain 12, 24 and 48

211 degrees of freedom, depending on the frequency (see Fig. 3). In addition, to evaluate the
212 consistency of the periodicity between the time series, we calculate a Morlet cross-wavelet
213 analysis following wavelet methods explained by (Torrence and Compo, 1998) and (Grinsted
214 et al., 2004).

215

216 The phase velocity (c) was estimated using two models that took into account the fjord
217 stratification: (1) a simple reduced-gravity model (RGM) and (2) a continuously stratified
218 model (CSM).

219

220 The reduced-gravity model was developed using the typical density profiles in each sub-
221 basin. Here, the base of the upper layer was estimated from the pycnocline depth (Fig. 2),
222 which in the Reloncavi fjord is well represented by the depth of the 24 isohaline (h_1)
223 (Castillo et al., 2016), considering that h_1 is the pycnocline depth and H is the deepest CTD
224 cast (mostly near to the sub-basins maximum depths). The mean density of the upper layer (ρ_1)
225 was estimated from depths between the surface to h_1 , whereas the mean density for the
226 deep layer (ρ_2) was estimated for depths between h_1 and H . These estimations were made
227 for all sub-basins, and seasons (Table 2).

228

229 Using both densities, ρ_1 and ρ_2 , the reduced gravity ($g' = g(\rho_2 - \rho_1) / \rho_2$) was obtained,
230 here g is the acceleration of gravity. The internal phase velocity of each sub-basin,

231 $c_i = (g' h_{1i})^{1/2}$, where $i = 1$ to 4 and h_{1i} represents the mean depth of the upper layer in the

232 sub-basin “ i ” was used to estimate the effective phase speed in the entire fjord (eq. 1),

$$233 \quad c = L \sum_{i=1}^n \frac{c_i}{L_i} \quad (1)$$

234 where L_i is the i sub-basin length and L is the fjord length. This takes into account the
235 changes of depth and lengths of fjord’s sub-basins. Similarly, the effective period (T) was

236 obtained by $T = c L^{-1}$.

237

238 The continuously stratified model (CSM) was developed using the normal mode analysis,
 239 which introduced the stratification as $N^2 = -(g / \rho)(\partial\rho / \partial z)$, which is the buoyancy
 240 frequency, in the Sturm-Liouville expression

$$241 \quad \frac{d}{dz} \left(\frac{1}{N^2} \frac{d\psi_n}{dz} \right) + \frac{1}{c_n^2} \psi_n = 0 \quad (2)$$

242 where $\psi_n(z)$ is the vertical structure of the horizontal velocity for the mode n . Here c_n
 243 represents the n mode speed (see Gill, 1982) and differs significantly from phase speed if
 244 rotation plays a role (van der Lee and Umlauf, 2011).

245

246 Independent of the model used to obtain the phase speed (RGM or CSM), the natural
 247 oscillation period (T_N) was determined using Merian's formula for a semi-enclosed basin, as
 248 suggested by Ravinovich (2010), $T_N = 4 T$.

249

250 The modal decomposition was used to obtain the contribution of each mode in the currents
 251 variability (e.g. Emery and Thomson, 1998; Gill, 1982; van der Lee and Umlauf, 2011). The
 252 along- and cross-fjord band-pass currents $[u_{bp}, v_{bp}]$ could be described by the vertical modes
 253 by (3),

$$254 \quad [u_{bp}, v_{bp}](z, t) = \sum_{n=1}^{\infty} [u_{pj}, v_{pj}](t) \psi_n(z) \quad (3)$$

255

256 The along- and cross-fjord currents projected (u_{pj}, v_{pj}) on the vertical modal structure (ψ_n)
 was obtained by eq. (4),

$$257 \quad [u_{pj}, v_{pj}](t) = \frac{1}{H} \int_{-H}^0 [u_{bp}, v_{bp}](z, t) \psi_n(z) dz \quad (4)$$

258

259 **4. Results**

260

261 **4.1 Density structure**

262 As a result of abundant freshwater input to the fjord, there were marked differences in
263 density between the upper and lower layers along the fjord and small changes in stratification
264 among seasons, particularly near the mouth of the fjord (Fig. 2). One important characteristic
265 of the upper layer is its high and persistent stratification from the surface to the base of the
266 pycnocline (Fig. 2). Along the fjord, the pycnocline depth exhibited clear deepening from 2.3
267 ± 0.1 m at the mouth to 6.1 ± 0.3 m near the head. The pycnocline depth exhibited greater
268 seasonal variability near the head of the fjord (Fig. 2).

269

270 **4.2 Winds, sealevel and freshwater discharge**

271

272 The along-fjord wind stress (τ) displayed two patterns during the transition from winter to
273 spring. During the winter, τ was generally **directed** out of the fjord ($-0.4 \pm 3 \times 10^{-2}$ N m⁻²) and
274 displayed oscillations with a period longer than 1 day. There were also strong events (> 0.2
275 N m⁻²) during the first half of August 2008 that could be associated with the end of winter
276 storms in the region. This winter pattern drastically changed during the early spring (first
277 week of September 2008) and was maintained throughout the rest of the season. Changes
278 were evident in a marked daily cycle and in switches from down- to up-fjord (average of 1.6
279 $\pm 3 \times 10^{-2}$ N m⁻²), against the upper layer outflow (Fig. 3a).

280

281 The sealevel was measured at the mouth and near Cochamo (Fig. 1). At both stations, the
282 form factor was 0.12, which indicates that semi-diurnal tides dominate in the region. In fact,
283 the M₂ amplitude was 1.89 ± 0.06 m at the mouth and 1.91 ± 0.06 m near Cochamo. The
284 mouth-to-head phase difference in this harmonic was negative (-2.4°), indicating propagation
285 toward the head with a lag of approximately 5 minutes. The maximum tidal range during
286 spring tides was approximately 6 m and less than 1 m during neap tides (Fig. 3b). Similar
287 ranges have been observed outside the fjord in the Reloncavi sound (Aiken, 2008).

288

289 Discharge was greatest (approximately $1413 \text{ m}^3 \text{ s}^{-1}$) at the end of August 2008 (winter) and
290 lowers (approximately $459 \text{ m}^3 \text{ s}^{-1}$) at the end of October (spring). In the winter, the historical
291 mean of $650 \text{ m}^3 \text{ s}^{-1}$ (Niemeyer and Cereceda, 1984; Leon et al., 2013) was exceeded 86% of
292 the time, whereas during the spring, this exceedance occurred only 18% of the time. In fact,
293 only a small variability around the mean was observed during the spring (Fig. 3c).

294

295 **4.3 Along-fjord currents**

296

297 The along-fjord currents were one order of magnitude larger than the cross-fjord currents (in
298 this study we focused on the along-fjord component). At the three measurements sites at
299 Cochamo (Fig. 3d), Puelo (Fig. 3e) and the mouth (Fig. 3f), the along-fjord currents
300 displayed certain common features: (1) semi-diurnal oscillations attributed to tidal effect, (2)
301 a two layered structure with persistent outflow above the pycnocline and an intermittent
302 lower inflow layer beneath, and (3) several low-frequency (period > 1 day) oscillations were
303 present in the time series.

304

305 Currents in the upper outflow layer displayed a mean velocity of 66 cm s^{-1} at the mouth and
306 45 cm s^{-1} at Cochamo, indicating that the outflow increased through the mouth. Additionally,
307 the upper layer was deeper at Cochamo (Fig. 3d) than at the mouth (Fig. 3f), which is
308 consistent with the along-fjord pycnocline depth (Fig. 2). Below the upper layer, a sub-
309 surface layer displayed intermittent inflow (see Fig. 3d, 3e and 3f) with a maximum ($> 20 \text{ cm}$
310 s^{-1}) centered at the $\sim 6 \text{ m}$ depth.

311

312 This two-layered pattern was clearly observed in the upper 10-15 m and is consistent with a
313 gravitational circulation due to the along-fjord pressure gradient. This pressure gradient is
314 also consistent with the observed along-fjord pycnocline tilt (Fig. 2). At depths $> 20 \text{ m}$, the
315 along-fjord currents at Puelo and at the mouth exhibited an important influence ($> 40\%$ of
316 the variability) of a semi-diurnal component of the tide. In addition, in this layer, low-
317 frequency (periods > 7 days) oscillations suggest a bottom-to-surface propagation that was
318 more intense from the end of August to the beginning of September during a period of high

319 discharge ($> 650 \text{ m}^3 \text{ s}^{-1}$). This layer on average exhibited a weak outflow ($\sim 1 \text{ cm s}^{-1}$) at the
320 mouth, which in turn implies a 3-layer pattern of the residual flow near the mouth.

321

322 **4.4 Spectral characteristics of currents, temperature, sealevel and winds**

323

324 To obtain better statistic reliability, the spectra of the along-fjord currents were depth-
325 averaged. The upper layer was defined until the pycnocline depth ($z \leq h_l$), whereas the deep
326 layer contains $z > h_l$ (Fig. 4).

327

328 All of the spectra displayed an energetic peak at the semi-diurnal frequency (M_2), and this
329 peak was greater in the deep layer (Fig. 4). In the diurnal band, the spectra at Puelo and at the
330 mouth presented a clear (and highly energetic) peak in the surface layers. This diurnal peak
331 is likely due to the influence of wind stress (see Fig. S1), which displayed a marked diurnal
332 cycle during the late winter (end of August) and spring (Fig. 3a). An important peak (10^4 cm^2
333 $\text{s}^{-2} \text{ cph}^{-1}$) was observed only at Cochamo in the 6 hour band (M_4), suggesting an increase in
334 the importance of non-linear interaction between M_2 and the bathymetry in this sub-basin.
335 The spectra in the upper layer displayed an important accumulation of energy in the band
336 centered on the 3days period. The band was wider (between 2 and 7 days) at the mouth and
337 Puelo and narrower (between 1.5 and 4 days) at Cochamo. At the mouth, the maximum
338 spectral density was in the 3 days band ($> 10^5 \text{ cm}^2 \text{ s}^{-2} \text{ cph}^{-1}$) and was one order greater than
339 the maximum spectral density observed at Cochamo ($\sim 10^4 \text{ cm}^2 \text{ s}^{-2} \text{ cph}^{-1}$). Another important
340 accumulation of energy in the along-fjord currents was centered on the 15 days period. One
341 characteristic of the 15 days band is the influence on the entire water column at Puelo and the
342 mouth (Fig. 4).

343

344 The sealevels at Cochamo (η_c) and at the mouth (η_m) were similar at frequencies less than
345 0.165 cph (periods longer than 6 h). The spectra displayed an important accumulation in the
346 synoptic band (10 days). Both locations exhibited the same energy at the diurnal (K_1)
347 semidiurnal (M_2) frequencies, although M_2 was clearly the dominant harmonic in the fjord.
348 The spectral energy was one order of magnitude higher than the diurnal (K_1) harmonics and
349 three orders of magnitude higher than the quarter-diurnal (M_4) harmonics. The spectra

350 exhibited no accumulation of energy in the 3days band, although at high frequencies (> 0.5
351 cph), an important accumulation of energy was observed in the 1.3h band (between 1.16 h
352 and 1.56 h) at η_C (Fig. 4).

353

354 The wind stress (τ) indicated that the along-fjord wind stress was significantly higher than
355 the cross-fjord component. The spectra displayed a marked peak (particularly in the along-
356 fjord component) in the diurnal band, which is likely due to the sea-breeze phenomenon.

357 Another interesting feature of the spectrum was the peak in the semi-diurnal frequency,
358 which was observed in both components. At longer periods (> 1 day), the along-fjord wind
359 stress displayed an important but not statistically significant peak at 2.8 days, which is highly
360 consistent with the currents (Fig. 4).

361

362 **4.5 Seasonality of the internal oscillations**

363

364 The density structure on the fjord does not show an upper mixing layer along the seasons;
365 indeed a continuously stratified upper layer is present along the seasons (Fig. 5). The along-
366 fjord mean of the pycnocline depth (h_I), which was estimated based on salinity/density
367 gradient, was used to estimate the internal phase velocity (c) and the internal period (T_N).
368 Seasonally, h_I does not change significantly during winter, spring and summer (between 4.6
369 and 4.8 m) but was shallower during autumn (~ 4.1 m) (Table 2).

370

371 In the case of the RGM approximation, internal phase velocities (c) were highest during
372 spring and summer (> 0.83 m s⁻¹) whereas in winter and autumn the intensities were < 0.76
373 m s⁻¹, thus we obtain internal periods between 2.9 and 3.4 days (70 and 82 hours) (Table 2).

374

375 The horizontal velocity structure (ψ_n) profile of the first 3 internal modes obtained from the
376 CSM showed high consistency along the fjord (in each sub-basin) and through the seasons
377 (Fig 5). The mode 1 was highly baroclinic, changing sign at nearly of 10 m (sub-basin I) and
378 15 m (sub-basin IV). In the case of mode 2 and 3, relatively high variability along the
379 seasons was observed specially at the sub-basins I and IV above of 20 m depth. For depths $>$
380 30 m (not shown in Fig. 5) the internal modes do not show significant variability (Fig. 5).

381 The modal speeds for the first 3 modes described above were relatively high during spring
382 and summer (c_I was $> 0.84 \text{ m s}^{-1}$) and lower during winter and autumn (here c_I was $< 0.77 \text{ m}$
383 s^{-1}). These results were highly consistent with the internal speeds obtained by RGM (Table
384 2).

385

386 Like the internal speeds (c), the natural internal period (T_N) obtained by RGM with the mode
387 1 of CSM were highly consistent. For comparison, we take into account T_N obtained from the
388 mode 1 of the CSM which ranged between 2.9 days (spring) and 3.5 days (winter). The
389 estimations of T_N with RGM showed speeds between 2.9 days (spring) and 3.4 days (winter
390 and autumn), indicating that oscillations between these periods are dominated by mode 1
391 internal seiche oscillation.

392

393 To focus on these internal seiche oscillations, we filtered the along-fjord currents with a 70h
394 to 90h cosine-Lanczos band-pass filter. Additionally, mode 1 of the internal seiche was
395 associated with the pycnocline depth, which is restricted to the upper 8 m (Fig. 2). Therefore,
396 we describe the along-fjord currents in the upper 10 m (Fig. 6).

397

398 The vertical pattern at the three locations shows inflow/outflow intermittence along the
399 whole time series; also most of these along-fjord structures seem to develop an inclination
400 which indicates the baroclinic nature of this pattern. The band-pass along-fjord currents were
401 intense at the mouth ($> 15 \text{ cm s}^{-1}$) but diminish toward the head. Intense perturbations
402 oscillations were observed near the surface between 10 and 20 August 2008 at the mouth and
403 Cochamo, internal intensification (between 4 m and 10 m depth) of the inflow/outflow
404 pattern was clear at Puelo and Cochamo at the ends of September. To decide whether the
405 nature of the along-fjord currents pattern was baroclinic or barotropic we used $\psi_n(z)$ to
406 project the band-pass currents (eq. 3 and 4), similar to van der Lee and Umlauf (2011).

407

408 The agreement between the 3 days band-pass and the projected along-fjord currents at the
409 mouth is shown in Fig. 7. Using only the first three modes, it was possible to explain more
410 than 70% of the band-pass variability, changes in the outflow/inflow were highly consistent
411 and the intensifications at the surface were clearly shown by the projected modes. In

412 addition, the vertical structures of the outflow/inflow were well defined by the projections.
413 To make an approximation of the relative importance of the currents variability we estimated
414 kinetic energy ($K_E = (u^2 + v^2) / 2$) of i) the projected modes 1-3, ii) the 3 days band-pass
415 and iii) the semi-diurnal (12h) + diurnal band pass (1d) along-fjord currents at the mouth.

416
417 The vertically averaged K_E obtained with 3 days band-pass was higher than that generated
418 with the other components (modes 1-3), the maximum was observed in the period 9 - 18
419 August (Fig. 7), which is consistent with the wind-stress intensification shown in Fig. 3a.
420 During that period, the modal K_E was about one third of the 3 days band-pass kinetic energy,
421 this ratio was higher (i. e. ca. 50%) during September. The importance of the tides at the
422 mouth was estimated by summing up the K_E of the diurnal and semi-diurnal currents. In
423 terms of energy, the K_E contribution of tides was similar to the modal currents (Fig. 7).

424
425 Along-currents were highly coherent at 3 days band which is the period of the first mode of
426 the internal seiche (Table 2). To describe the temporal variability of this high coherence,
427 along the time, we selected 3 m depth ADCP bins (on the upper layer) from the mouth, Puelo
428 and Cochamo to make a Morlet cross-wavelet analysis and to estimate the squared coherence
429 (only referred to as coherence hereafter) and phase spectra for the relations mouth/Puelo
430 (MP) (Fig. 8b, 8c) and Puelo/Cochamo (PC) (Fig. 8d, 8e). Both relations showed high
431 coherence in the semi-diurnal and diurnal band especially during spring-tides.

432
433 A low coherence (< 0.6) was observed during the down-fjord winds (Fig. 8a and 8b).
434 Similarly, the coherence for the PC relation was high along the 3 days band except during the
435 change of the wind direction described above (Fig. 8d). The associated phase spectra (only
436 the significant coherence) at the 3 days band was $\sim 0^\circ$ indicating that the oscillation is in
437 phase along the fjord (Fig. 8c and 8e).

438
439 At the beginning of the time series, intense fluctuations were observed at Cochamo and at the
440 mouth (Fig. 6). To explore their relationship with the wind forcing, a detailed view of the
441 period between 8 and 31 August 2008, is presented in Fig. 9. During this period, the along-
442 fjord wind stress (not filtered) displayed three different states: (a) strong ($> 0.2 \text{ N m}^{-2}$) up-

443 fjord winds, (b) weak ($< 0.1 \text{ N m}^{-2}$) or nearly calm winds and (c) moderate ($\sim - 0.1 \text{ N m}^{-2}$)
444 down-fjord winds. During (c), the winds displayed an apparent diurnal cycle (e.g., Fig. 3a).
445

446 Although density is dominated by salinity, changes in the surface heat exchange may play a
447 seasonality role in the upper column. The rivers on the region are colder in winter producing
448 a clear thermal inversion (Castillo et al., 2016) while in summer the surface waters reach
449 18°C by the heat gained by solar radiation. But the persistent pycnocline depth along the
450 seasons is consistent with the freshwater input suggesting that the variability of the density in
451 the upper layer is dominated by the freshwater input instead of the surface heating/cooling
452 variability. We used temperature moorings to emphasize that the internal oscillation reported
453 here had an expression in other properties of the water within the fjord. In addition, the band-
454 pass temperature time series and the along-fjord currents shows consistent oscillations
455 pattern (Fig. 9). During (a), the upper outflows weakened due to the opposing winds at the
456 surface. This change reached depths down to the pycnocline (Fig. 2), causing a disruption
457 and subsequently forcing of the internal oscillations observed in the currents and temperature
458 fields (Fig. 9). Here, intense perturbations were observed that weakened the surface outflow
459 and introduced the colder water of the upper layer to depths $> 2 \text{ m}$ at Cochamo and Puelo.
460 During (b), the upper outflow displayed minimum perturbations in both the currents and
461 temperature. In (c), perturbations in the currents and temperature were evident at Cochamo
462 and at the mouth with no major oscillations at Puelo (Fig. 9). In addition, 3 days band-pass
463 vertical velocities (w) were included as arrows on the contours of the along-fjord currents in
464 Fig. 9. The maximum w were 1 cm s^{-1} at the mouth, outflow (inflow) was related with
465 downward (upward) circulation in the entire fjord. This implies that the oscillation observed
466 on the along-fjord currents also was consistent with the vertical velocities patterns.

467

468

469 **5 Discussion**

470

471 We used data collected in one of the most extensive studies ever conducted in a Chilean
472 fjord. The data included currents (ADCPs) and temperatures from moored instruments,

473 seasonal CTD information and times series of winds and sealevel to study the dynamics of
474 the internal seiche oscillations in the Reloncavi fjord.

475

476 In fjords with shallow sills such as the Gullmar fjord in Sweden (Arneborg and Liljebladh,
477 2001a), the Knight Inlet in Canada (Farmer and Freeland, 1983) and the Aysen fjord in Chile
478 (Cáceres et al., 2002), internal tide oscillations may play **major** role in the internal mixing
479 (e.g. Stigebrandt, 1976; Farmer and Smith, 1980). In lakes, large internal seiche oscillations
480 significantly contribute to the mixing of the entire basin (Cossu and Wells, 2013), and these
481 oscillations could also be important in fjords where the relative importance of internal tides
482 may be less than the internal seiche oscillations (Arneborg and Liljebladh, 2001b). **The semi-**
483 **diurnal signal in the spectra of the along-fjord currents (Fig. 4) suggests the relative**
484 **importance of internal tides on the region which is similar to other fjordal regions (e.g.**
485 **Stigebrandt, 1976; Allen and Simpson, 1998; Valle-Levinson et al., 2007). The tidal**
486 **interaction with the bathymetry is not the only mechanism to produce internal oscillations.**
487 **Recently Ross et al (2014, 2015) shows the forcing by glacier lake outburst floods (GLOFs)**
488 **and by low-frequency changes of barometric pressure. The relative importance of the**
489 **internal-tides on the southern Patagonian fjords is unknown and studies focused on**
490 **determine its contribution to the dynamics of currents and mixing must be done on future**
491 **studies.**

492

493 In this study, we demonstrate the presence (and persistence) of seiches in a Chilean fjord
494 based on the sealevel slope (barotropic seiche), currents and temperatures (internal seiche).
495 We also studied the main processes forcing the natural oscillation of the pycnocline.

496

497 **In the basic dynamic of a barotropic seiche into the fjord winds tilt the along-fjord surface**
498 **and piled water at the head of the fjord. The entire fjord basin begins to oscillate after the**
499 **wind stop. The maximum amplitude of the seiche is located at the head whereas a node (zero**
500 **amplitude) is located at the mouth of the fjord (Dyer, 1997; Rabinovich, 2010). In the**
501 **baroclinic seiche winds events which perturb the pycnocline to induce its oscillation in a**
502 **period accordingly with the fjord stratification (Djurfeldt, 1987). The horizontal structure of**
503 **currents associated with the seiche dynamics is related with the standing wave nature of the**

504 seiche oscillation where the maximum currents occur in a node (the mouth) and minimum
505 currents are present in an anti-node (the head) in both closed and semi-closed basins (Dyer,
506 1997; Rabinovich, 2010).

507

508 At high frequencies, the tidal spectrum (Fig. 4) displayed a clear accumulation of energy
509 centered at a period of 1.3 h. This frequency is not related to any tidal harmonic interaction
510 (Pawlowicz et al., 2002), and the shape of the spectrum (not a peak) suggests resonance in
511 this frequency band. We explored the effect of the natural oscillation of the basin in this
512 pattern using the barotropic phase velocity (c) for a shallow water wave $c = (gh)^{1/2}$, where h
513 is the mean depth of the fjord. If one assumes a mean fjord depth of $h = 250$ m (Table 1),
514 then $c = 49.5$ m s⁻¹, and the natural period $T_N = 4L c^{-1} = 1.24$ h. This period is lower than the
515 observed period in Fig. 5 (1.3 h) because the mean depth takes into account the entire fjord
516 bottom profile (Fig. 1), and thus the effective depth (up to Cochamo) was 233 m and it is
517 closer to the 226 m necessary to obtain the observed period in Fig. 5. Winds in the region are
518 moderate (see Fig. 3), but their intensity is sufficient to tilt the surface slope at Cochamo
519 (Castillo et al., 2012), and thus the surface of the fjord oscillates with the natural period of
520 the basin. Further evidence of this pattern is provided by the clear differences in amplitude of
521 the sealevel spectrum at Cochamo (near the fjord's head) and at the mouth. This association
522 is attributed to the dynamics of seiches in fjords, which tend to produce a node at the mouth
523 and an anti-node at the head (Dyer, 1997). At the node, the sealevel amplitude must be zero,
524 whereas near the head, it must be a maximum. This pattern is highly consistent with the
525 observed spectra at 1.3 h (Fig. 5). Based on all of these results, we suggest that oscillations
526 close to 1.3 h will resonate with the natural period along the fjord.

527

528 Daily winds were highly coherent with surface along-fjord currents, especially on the
529 brackish water layer (S1). During the spring, daily periodicity of winds was strong (Castillo
530 et al., 2016) with intensities capable of perturbing the pycnocline and to induce the internal
531 seiching process.

532

533 The surface slope indicates that the sealevel at Cochamo was 0.07 m higher than at the
534 mouth, and this value can be taken as the amplitude of the surface seiche. According to the

535 RGM, the pycnocline deviation (η_l) is related to the surface elevation (η_0) in the form
536 $\eta_l = -(\rho / \Delta\rho) \eta_0$, which implies that for a mean surface perturbation of 0.07 m and a typical
537 $\Delta\rho$ of 15 kg m^{-3} , we obtain a mean η_l of -4.8 m. This finding indicates that the water piles
538 up at the head of the fjord, likely due to the predominant into the fjord winds in the region
539 (Fig. 3a) and produces a pycnocline deepening of about 5 m (Fig. 2).

540

541 At low frequencies (periods > 1 day), the along-fjord currents spectra displayed a marked
542 peak in energy centered at 3 days. To explore the origin of this variability, we analyzed the
543 density profiles along the fjord (Fig. 2) and applied two methods, the RGM and CSM. The
544 internal phase velocities (c) obtained from both methods were similar, and ranged between
545 0.73 m s^{-1} and 0.87 m s^{-1} (taking into account the mode 1 of CSM for comparison). The high
546 c value was obtained during the spring (November 2008), when the upper layer presented the
547 lowest densities of the seasons, likely due to high discharge ($> 1000 \text{ m}^3 \text{ s}^{-1}$). Remarkably, the
548 stratification is linked to the freshwater input despite no major observed changes in c (Fig.
549 6e-h). The high consistency between the CSM (mode 1) modal speeds and the phase speed
550 obtained by RGM suggest that rotation do not play a significant role on the along-fjord
551 dynamics of these oscillations (van der Lee and Umlauf, 2011). But cross-fjord, the
552 dynamics has been nearly geostrophic, especially at the fjord's mouth (Castillo et al., 2012).

553

554 For longer periods (> 10 days), there are evidences of baroclinic oscillations clearly observed
555 on the along-fjord time series (Fig. 3) and in the averaged spectra (Fig. 4). Recently, Ross et
556 al., (2015), described a similar periodicity on currents of a southern Patagonian fjord of Chile
557 associated to Baroclinic Annular variability, a regional feature on the air-pressure in the
558 region. This mechanism of generation for the 10 days oscillations on the Reloncavi fjord
559 needs to be verified on future studies.

560

561 The internal T_N of the entire fjord displayed periods between 2.9 and 3.5 days. These results
562 suggest that the accumulation of energy observed in the along-fjord currents are due to the
563 first mode of an internal seiche oscillation in the fjord. This result could be explained by the
564 presence of a node at the mouth, where the sealevel amplitude is minimum (Fig. 5) but the
565 currents are maxima (Figs. 3 and 6). This difference was also observed in the projected

566 currents (u_{pj} , v_{pj}) supporting the idea of the presence stationary wave along the fjord.
567 Additionally, the currents were highly coherent and in phase (Fig. 8) as we expected from a
568 basin-scale seiche wave like. As a way to estimate the contribution of the internal seiche to
569 the internal mixing the K_E was enhanced during the into the fjord winds (Figs. 3 and 7),
570 which were periods when the internal seiche band (3 days) was highly coherent along the
571 fjord (Fig. 8).

572

573 The winds exhibited high coherence with the along-fjord currents until the pycnocline
574 depths, at frequencies centered at 1 and 3 days (see Fig. S1). To study the extent to which the
575 wind stress perturbs the pycnocline, we used the Wedderburn number, which is given by the
576 equation $W = (h_1 / L) Ri$ (Thompson and Imberger, 1980; Monismith, 1986), where
577 $Ri = g'(h_1 / u_*^2)$ represents the bulk Richardson number, an index of the stability of the upper
578 layer (h_1). The frictional velocity (u_*) is obtained from the surface wind stress using the
579 equation $u_*^2 = \tau / \rho_0$, which results in the equation,

$$580 \quad W = \frac{h_1^2 \Delta \rho g}{L \tau} \quad (5)$$

581

582 According to Thompson and Imberger (1980), this value indicates the effect of the wind
583 stress on local upwelling in a stratified fluid (i.e., perturbing the pycnocline). Under weak τ
584 conditions ($W \gg 1$), the wind energy is insufficient to tilt the interface. Under strong τ
585 conditions ($W \ll 1$), however, upwelling conditions dominate, there by tilting the interface,
586 which produces conditions favorable to forcing of the internal seiche. The critical conditions
587 ($W \sim 1$) indicate the beginning of upwelling (Thompson and Imberger, 1980; Stevens and
588 Imberger, 1996), although the ideal transition point occurs at $W = 0.5$ (Monismith, 1986). All
589 of these conditions were observed during the period of August 2008, as it is shown on Fig. 9.
590 During strong τ ($\sim 0.3 \text{ N m}^{-2}$) conditions, $W = 0.27$ produced intense perturbation of the
591 pycnocline (Fig. 9a). In contrast, during weak τ ($\sim 0.01 \text{ N m}^{-2}$) conditions, a value of $W = 8$
592 indicates that the wind was too weak to perturb the pycnocline, favoring a seiche damping
593 process (Fig. 9b). Transition conditions occurred when $\tau \sim 0.1 \text{ N m}^{-2}$ and $W = 0.8$, indicating

594 that the winds were strong enough to perturb the pycnocline and stop the damping process
595 (Fig. 9c).

596

597 **5.1 Internal seiche damping**

598

599 The wind stress changed from a state where τ was strong enough to actively disturb the
600 pycnocline ($W < 1$) to a period of nearly calm winds ($W > 1$) between the 16 and 24 August
601 2008 (Fig. 9). During this period, both the along-fjord currents and temperatures tended to
602 decay, which is clearly evident in the isolines of these properties at the three sites (Fig. 9).

603

604 To study the damping process in detail, we selected the time series of the along-fjord
605 currents at a depth of 3 m at Cochamo during the above period in August to span the period
606 of forcing, damping and re-enforcing of the internal oscillation.

607

608 Typically, any real oscillations undergo damping, which is given by the equation,

$$609 \quad x(t) = A e^{(-k t)} \cos(\omega t + \phi) \quad (7)$$

610 where t is time and A is the initial amplitude, k is the damping coefficient which has units of
611 [s^{-1}], $\omega = 2\pi/T_N$ and ϕ is the phase. In the case studied here, $\phi = 0$, $A = 8 \text{ cms}^{-1}$, and $T_N = 2.5$
612 days, which was the internal period at Cochamo (Fig. 4). The best fit occurred when $k = 1/3$
613 (Fig. 10).

614

615 The time for the initial amplitude A to decay to $A \sim 0$ is the damping time (T_d). There was a
616 good fit (Fig. 10) between the observed current and the curve adjusted with the damping
617 effect. Here, $T_d = 9.1$ days, which is more than 3 times longer than the natural oscillation
618 (T_N); more precisely, $T_d = 3.6 T_N$ at this site. The observed internal oscillations of the
619 currents were not completely damped because the winds increased from nearly calm ($W > 1$)
620 to moderate conditions, which disturbed the pycnocline ($W \sim 1$) and induced the intense
621 oscillations during the spring (Fig. 6). In the spring, the winds displayed a marked diurnal
622 cycle that remained during the spring and summer (Castillo et al., 2012). This finding
623 suggests that the internal seiche (mode 1) process is active without damping because it is

624 forced daily (Fig. 3). Our findings indicated that the internal seiche process is an active
625 contributor for the mixing in the Reloncavi fjord, the magnitude of this contribution might be
626 similar as the tidal forcing. The maximum amplitude of the tidal currents on the Reloncavi
627 fjord is 10 cm s^{-1} (Valle-Levinson et al., 2007; Castillo et al., 2012), using the K_E to estimate
628 the maximum contribution of the tide obtain $5 \times 10^{-3} \text{ m}^2 \text{ s}^{-2}$ which is similar to the observed
629 K_E at the mouth (Fig. 7). One example of the dissipation of the energy through this process
630 was observed previous to 19 August 2008 (Fig. 10), then the maximum currents were 0.7 m
631 s^{-1} and through eq. 7, we obtain $K_E = 7 \times 10^{-3} \text{ m}^2 \text{ s}^{-2}$, meaning that a great part of this energy
632 might be dissipated within the Reloncavi fjord on 9 days.

633

634 **6 Conclusions**

635

636 The along-fjord seasonal density structure of the Reloncavi fjord showed small changes in
637 the stratification. The upper layer shows a persistent stratification from the surface to the
638 pycnocline base, the latter of which has a mean depth of 2 m near the mouth and 6 m near the
639 head of the fjord.

640

641 The along-fjord sealevel signal showed a 1.3 h energetic peak not related with any tidal
642 harmonics, additionally at this period the sealevel amplitude at the mouth was significantly
643 higher than the sealevel at the head of the fjord. This pattern was consistent with the presence
644 of a barotropic seiche on the Reloncavi fjord.

645

646 Local winds stress was able to perturb the along-fjord pycnocline and produce internal seiche
647 oscillations. The period centered on 3 days was consistent with the first baroclinic oscillation
648 mode. This mode explained 44% of the variability of the 3 days band. The oscillation was
649 highly coherent along the fjord and with a phase close to 0° , consistent with a standing wave,
650 like an internal seiche, within the Reloncavi fjord.

651

652 The internal seiche could be strong contributor to the internal mixing within the fjord, in fact
653 the kinetic energy (K_E) associated to the internal seiche was similar to the maximum
654 contribution of the tides in the along-fjord currents. During winter, the internal oscillations

655 were present a relatively long period of time with nearly calm winds, which permitted the
656 estimation of the damping time of the internal seiche being 9 days, otherwise during the
657 spring daily winds continuously forced the pycnocline.

658

659 Future studies should focus on evaluating more precisely the available energy for the mixing
660 process within the fjord and their effects on other water properties such as the salinity,
661 oxygen or nutrients.

662

663

664 **Data availability**

665

666 The installation of the moorings for measuring the current, temperature and sealevel in the
667 region was approved by the Chilean Navy through permit DS711. No specific permits were
668 required to install the meteorological station because the location is a publicly controlled site.
669 This study also did not involve any endangerment to species in the region. The authors
670 indicated that all data are available to download from a COPAS-SUR Austral (2012) website
671 (<http://www.reloncavi.udec.cl/>, last access 6 June 2016). The discharge data from the rivers
672 of Chile are available from the Dirección General del Aguas de Chile website
673 (<http://dgasatel.mop.cl/>, last access 1 July 2016). Also, all data sets can be requested from the
674 corresponding author (Manuel I. Castillo).

675

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684

685

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687

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822

823 **Figure captions**

824 **Figure 1:** Study region and location of the measuring stations. Left panel shows the area of
825 the Reloncavi fjord (A). The location of the Reloncavi sound (B) is also shown. The right
826 panel shows the study area (close-up view of A) and the positions of all measurements.
827 Numbers are CTD stations.

828

829 **Figure 2:** Seasonal profiles of density and bathymetry of the region. The upper inserts show
830 the seasonal mean density profiles in each sub-basin of the fjord (a-d). In the panel below
831 (e.), the along-fjord bathymetry and sub-basin nomenclature are shown. The black line
832 represents the mean pycnocline depth, and corresponding standard deviations are represented
833 by the gray shading.

834

835 **Figure 3:** a) Along-fjord wind stress, positive up to the fjord, (b) sea level, (c) Puelo river
836 discharge, where the straight line represents the long-term mean. Contours of along-fjord
837 currents at (d) Cochamo, (e) Puelo and (f) the mouth; in the filled contours, the blue (red)
838 colors indicate a net outflow (inflow).

839

840 **Figure 4:** Spectra of along-fjord currents (top) at (a) the mouth, (b) Puelo and (c) Cochamo.
841 Here the black lines indicate the averaged spectra for the upper layer (depths $\leq h_1$) whereas
842 the gray lines show spectra for currents at depths $> h_1$. (d) sea level spectra at the mouth
843 (black line) and at Cochamo (gray). (e) wind stress spectra for their along-fjord (black) and
844 cross-fjord (gray) components. At the bottom of each panel the 95% of confidence intervals
845 for 48, 24 817 and 12 degrees of freedom are shown.

846

847 **Figure 5:** The left panel shows mean density (σ_t) within the sub-basins. The panels to the
848 right of these show the first 3 baroclinic $\psi_n(z)$ modes and modal speeds obtained from the
849 CSM analysis (normalized). Note that phase velocity is in [m s⁻¹].

850

851 **Figure 6.** Band-passed along-fjord currents. Contours of band-passed (70-90 h) along-fjord
852 currents. Negative (positive) currents in blue (in red) imply an outflow (inflow). Note the
853 dotted square at the middle of August it is zooming on figure 9.

854

855 **Figure 7.** (a) Reconstruction of the along-fjord band-passed currents at the mouth using the
856 modes 1-3, (b) Band-passed along-fjord currents at the mouth, (c) Kinetic energy (K_E)
857 estimated using reconstructed currents (black), the 3 days band-pass currents (red), and the
858 diurnal and semi-diurnal band-pass currents (blue).

859

860 **Figure 8.** Coherence and phase wavelet spectra. (a) Time series of along-fjord wind stress,
861 and (b, c, d, e) coherence and phase wavelet spectra, for the relation mouth-Puelo (b, c) and
862 Puelo-Cochamo (d, e). In the contours, the thick black line indicates squared coherence \geq
863 0.6, only the associated phases were present on the phase wavelet. The thick black curve is
864 the influence cone for the wavelet estimations.

865

866 **Figure 9.** Time-series of along-fjord wind stress (τ) and contours of along-fjord Currents and
867 Temperatures at Cochamo, Puelo and the mouth. There are three states of wind stress based
868 on the Wedderburn number (W) with (a) strong $W < 1$, (b) weak $W > 1$ and (c) moderate $W \sim 1$
869 winds. Note that contours of the Currents and Temperature for a given location are plotted
870 together. The arrows represent the 3 days band-pass vertical velocities where the maximum
871 was 1 cm s^{-1} .

872

873 **Figure 10.** Damping signal in currents during a period of weak winds ($W > 1$) at Cochamo (16
874 to 24 August 2008). The band-pass currents at 3 m depth (black line) was compared with a
875 damping oscillatory curve $x(t) = A e^{(-kt)} \cos(\omega t + \phi)$ (gray line). The damping time (T_d) was
876 3.6 times longer than the fundamental internal period (T_N).

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884 **Table titles**

885

886 **Table 1:** Characteristics of Reloncavi fjord. The name, mean depth (H) and length (L) of
887 each sub-basin and for the entire fjord are presented.

888

889 **Table 2:** Seasonal statistics of the descriptive parameters of the fjord. Here we present the
890 mean depth of the upper layer (h_1), and densities of the upper (ρ_1) and deep layers (ρ_2). In
891 addition, the phase and modal velocities (c) and theirs periods (T) estimated using the
892 Reduced Gravity and Continuously Stratified models are shown.

893

894 **Table 1.**

Sub-basin	Description	H [m]	L [km]
I	mouth–Marimeli	440	14.0
II	Marimeli – Puelo	250	13.0
III	Puelo–Cochamo	200	17.5
IV	Cochamo–head	82	10.5
Total	mouth -head	250	55

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1 **Table 2.**

2

Reduced Gravity Model (RGM)					
	h_1 [m]	ρ_1 [kg m ⁻³]	ρ_2 [kg m ⁻³]	c [m s ⁻¹]	T [days]
Winter	4.60 ± 0.60	1009.72± 4.32	1024.62 ± 0.74	0.76 ± 0.01	3.37 ± 0.03
Spring	4.79 ± 0.53	1007.63± 5.32	1024.78 ± 0.62	0.87 ± 0.02	2.92 ± 0.03
Summer	4.68 ± 0.26	1008.77± 3.26	1024.78 ± 0.63	0.83 ± 0.01	3.07 ± 0.02
Autumn	4.05 ± 0.41	1009.90± 3.92	1024.95 ± 0.48	0.75 ± 0.01	3.38 ± 0.03

Continuous Stratified Model (CSM)						
	c_1 [m s ⁻¹]	c_2 [m s ⁻¹]	c_3 [m s ⁻¹]	T_1 [days]	T_2 [days]	T_3 [days]
Winter	0.73 ± 0.11	1.46 ± 0.21	2.18 ± 0.32	3.50 ± 0.25	1.75 ± 0.13	1.17 ± 0.08
Spring	0.87 ± 0.10	1.73 ± 0.21	2.59 ± 0.31	2.94 ± 0.18	1.47 ± 0.09	0.98 ± 0.06
Summer	0.84 ± 0.07	1.68 ± 0.13	2.52 ± 0.20	3.03 ± 0.12	1.51 ± 0.06	1.01 ± 0.04
Autumn	0.77 ± 0.08	1.54 ± 0.15	2.32 ± 0.23	3.30 ± 0.16	1.65 ± 0.08	1.10 ± 0.05

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