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RESEARCH ARTICLE

Influence of hydrological regime of an Andean river on salinity, temperature and oxygen in a Patagonia fjord, Chile

J León-Muñoz[a,b], R Marcé[c] and JL Iriarte[d]*

[a]*Departamento de Economía Ambiental, Ministerio del Medio Ambiente, Santiago, Chile;* [b]*Fundación Centro de los Bosques Nativos FORECOS, Valdivia, Chile;* [c]*Catalan Institute for Water Research, Girona, Spain;* [d]*Instituto de Acuicultura, Universidad Austral de Chile, Puerto Montt. Centro de Investigación en Ecosistemas de la Patagonia (CIEP), Coyhaique, Centro COPAS-Sur Austral, Universidad de Concepción, Concepción, Chile*

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Patagonian fjord ecosystems might experience new scenarios due to climate variability (decreasing annual precipitation and glacier melting) in the short term. Herein, we studied the seasonal variability of the Puelo River regime (North Patagonia, 1944–2007, mean streamflow: 650 m^3/s) and analyses its influence on surface salinity, temperature and dissolved oxygen in the well-stratified Reloncaví Fjord (41.5°S). Our results show a decreasing trend in the Puelo River streamflow since the late 1970s that is frequently associated with regimes lacking a defined interannual pattern. During the study period, years with prolonged periods of low streamflows in autumn and winter were common. On a scale of hydrological years, the influence of the Puelo River on the surface layer of the Reloncaví Fjord varied strongly in function of both the river's streamflow level and regimes. Years with markedly mixed regimes (rainfall/snowmelt), high autumn and spring streamflows ($Q > 1000$ m^3/s) resulted in significantly cooler, fresher conditions in the fjord. These temporal patterns, in turn, determined high, constant saturations (100%) and concentrations (10 mg/l) of surface dissolved oxygen. By contrast, the discharge pattern of 2007 led to stable, low streamflows in autumn and winter ($Q = 250$ m^3/s) that did not influence temperature or salinity. A significant association was found between the temporal variability of the salinity (increasing from 6 to 28 psu) and low dissolved oxygen saturation (<50%) and concentration (<5 mg/l), largely dominated by wind events.

Keywords: hydrological regime; Puelo streamflows; wind influence; hypoxic events; Patagonian fjord

Introduction

Along high-latitude marine coasts, freshwater inputs and sources vary in importance according to their spatial scales. In open coastal areas, direct precipitation over the water surface provides the most important contribution, whereas in semi-closed systems, this comes from the largest tributary rivers (Matthäus & Schinke 1999). Rivers with high streamflows (Q) that empty into coastal and estuarine zones significantly influence circulation patterns (Liu et al. 2007), biogeochemical processes (Malej et al. 1995; Morey et al. 2009) and the transfer of energy to higher trophic levels such as local fisheries (Le Pape et al. 2003; Lloret et al. 2004; Frame & Lessard 2009). The southern region of the eastern South Pacific, specifically Patagonia, has several relevant features: (1) a complex interaction between the atmosphere, land and ocean (strong poleward winds, the poleward Cape Horn Current) (Strub et al. 1998); (2) heavy input of freshwater and terrestrial organic matter from rivers, melting ice and rainfall (Pickard 1971, 1973); (3) vertical stratification

*Corresponding author. Email: jiriarte@uach.cl

due to freshwater input (Dávila et al. 2002; Calvete & Sobarzo 2011); and (4) an enhanced terrigenous sediment supply (Silva et al. 2011).

The Patagonian region is a complex interconnected set of austral fjords and channels—one of the largest interior seas on the planet—and its oceanographic characteristics are significantly associated with high freshwater contributions from direct precipitation (33.5×10^3 m^3/s) and continental run-off (27.8×10^3 m^3/s) (Schmitt 1995; Dávila et al. 2002). The high input of freshwater from tributary rivers generates important variations in salinity that characterise the distinct water masses present in this channel and fjord region (Pickard 1973), resulting in a stratified water column (two to three layers; Cáceres et al. 2002; Valle-Levinson et al. 2002) with strong spatial salinity gradients in the surface fraction (<30 m; Acha et al. 2004; González et al. 2010).

The oceanographic research carried out in these semi-closed systems has typically assumed that the influence of tributary rivers is associated with markedly mixed hydrological regimes in which pluvial and snowmelt peaks are determined by the strong influence of the Andes Mountains (screen effect, meltwater contribution) and the combinations of geomorphologic (exposure, shape) and biogeographic (land cover and land use) attributes of the drainage basins (Niemeyer & Cereceda 1984). However, time-series and dendrochronological studies have shown that, regionally (35–46°S), over the last few decades, precipitation and tributary river streamflows have tended to decrease and show high interannual variability (Lara et al. 2005, 2008). At present, the repercussions of this temporal trend on the freshwater streamflow regimes and, therefore, on the oceanographic processes and their consequences for the North Patagonian fjords and channels (41–46°S) remain unknown.

The present study analyses the influence of the Puelo River hydrological regime on the Reloncaví Fjord (41°S) over two time scales. The Puelo River–Reloncaví Fjord system was chosen for the following reasons: (1) the Reloncaví Fjord is the gateway to the North Patagonian fjords and channels; (2) the Puelo River is the fjord's main tributary ($Q = 650$ m^3/s) and heavily influences its oceanographic characteristics (Bastén & Clement 1999; Valle-Levinson et al. 2007; González et al. 2010); and (3) the Puelo River streamflow has shown a decreasing interannual trend that is representative of the streamflow regimes of other southern rivers that empty along the north and central Patagonian coast (41–48°S; Lara et al. 2008). Finally, the Reloncaví Fjord is also intensely used for salmon farming an activity that has presented an increased fish mortality during some of the last autumn periods caused by higher salinity levels and lower dissolved oxygen concentrations in the surface layer (Bastén & Clement 1999).

Herein, we hypothesise that the interannual decrease in the Puelo River streamflow determines: (1) that the freshwater contributions to Reloncaví Fjord present intra-annual input patterns different from the mixed regime and (2) that in anomalous periods of low streamflow, the temporal variability (on hourly and daily scales) of the surface layer of the fjord is largely influenced by external factors (e.g. wind) and not by the main tributary river. The main objectives of the present study were (1) to establish the effect of the interannual decline of the Puelo River streamflow on the river's hydrological regime, and (2) to analyse, under contrasting hydrological conditions, the influence of the Puelo River streamflow on the surface salinity, temperature and dissolved oxygen of the Reloncaví Fjord. Our results could have important implications regarding ongoing changes in freshwater inputs to fjord ecosystems of southern Chile caused by climate change and how these alterations affect the physical stability of the near surface water column, nutrient advection to the surface and ultimately the magnitude and fate of the primary productivity of fjord ecosystems in southern Patagonia.

Materials and methods

Study area

This fjord is approximately 55 km long and 3 km wide, with maximum depths of 450 m at the mouth and 100 m at the head (Fig. 1). It has a three-layer circulation pattern in which the surface (less dense, <20 m) and deepest (>80 m) layers tend to move toward the mouth, whereas the intermediate layer (<20 to 80 m) moves towards the head of the fjord (Valle-Levinson et al. 2007). In this area, the marine ecosystem corresponds to a positive estuarine system, with high salinity (>31 psu) and high nutrient loads entering the fjord area below a surface layer of

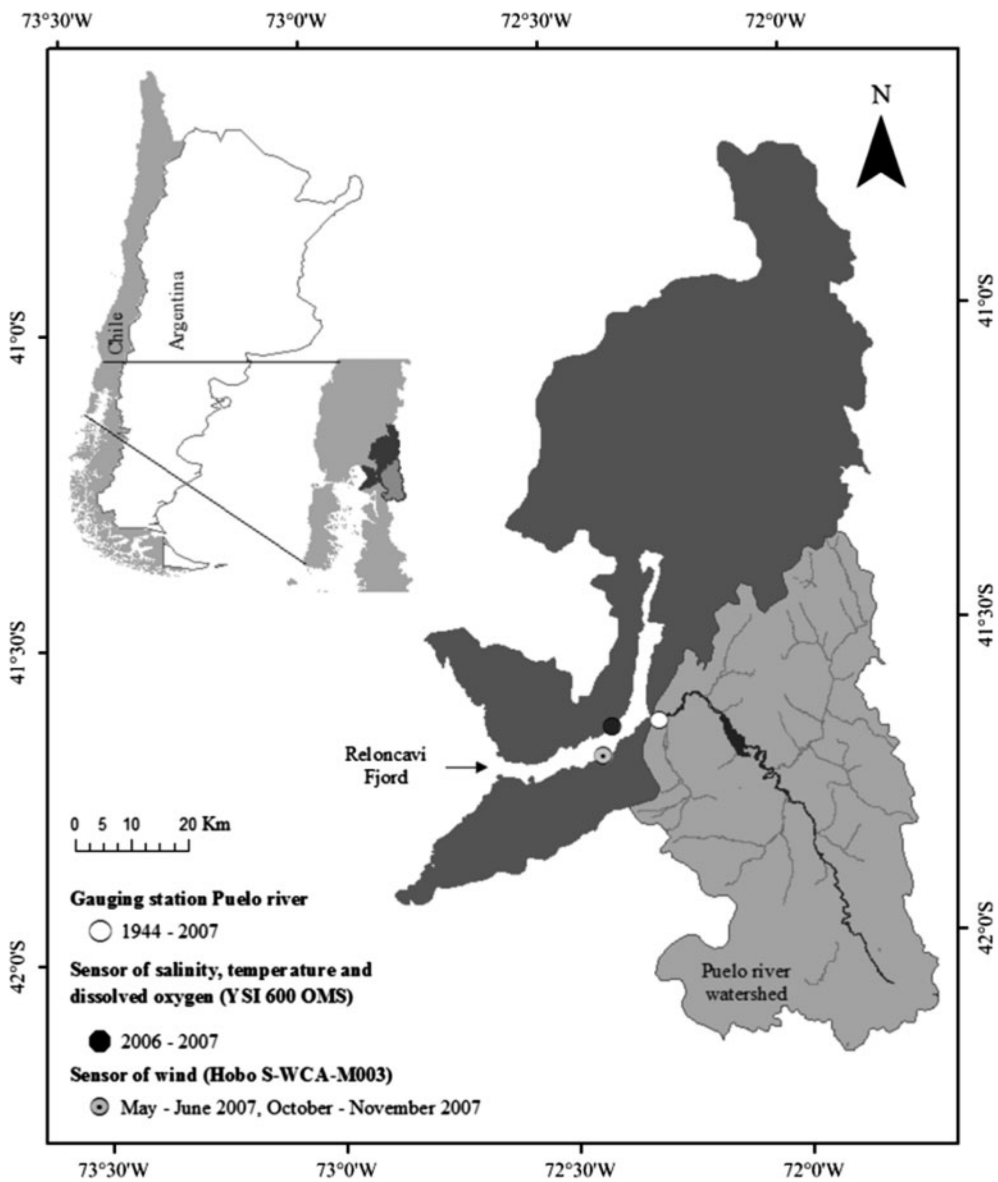

Figure 1 Reloncaví Fjord in the context of southern Chile; the light grey area shows the Puelo River drainage basin. The circles indicate the sites used to measure streamflow, wind direction and speed in the Puelo River, and surface temperature, salinity and dissolved oxygen in the fjord.

fresher (2–25 psu) estuarine water. In terms of dissolved oxygen concentrations, the fjord has haline stratification and high biological activity resulting in a marked oxycline (7–4 mg/l) at 10 m (head) and at 20 m (mouth). Below this oxycline, the dissolved oxygen concentration drops to around 3 mg/l (González et al. 2010).

The estuarine condition of the Reloncaví Fjord is closely tied to high freshwater contributions from the drainage basin, particularly from the Puelo River (Fig. 1). This river begins in Argentina (Lake Puelo, 250 m a.s.l.) and covers 84 km before reaching its mouth in the middle of the fjord (Fig. 1). The incidental precipitation in the drainage basin of the Puelo River and Reloncaví Fjord is dominated by seasonal variations of the eastern South Pacific anticyclone off the Chilean coast (Aceituno et al. 1993). Specifically, precipitation in the Puelo River drainage basin (8817 km^2) is 2800 mm/year on the Chilean side and 700 mm/year on the Argentinean side (Lara et al. 2008). The mean monthly streamflow of the Puelo River fluctuates widely, averaging ~650 m^3/s ($Q = 150$–$2350\ m^3/s$), and its hydrological year lasts from April of one year to March of the next. The river has a mixed hydrological regime characterised by greater pluvial concentrations in winter and a higher influence from snowmelts (nival regime) in spring (Niemeyer & Cereceda 1984) (Fig. 2). The temporal streamflow pattern from the Puelo River is significantly related ($r^2 = 0.9$, $P < 0.05$) to the other two main tributary rivers that empty into the middle sector (Cochamó River $Q = 100\ m^3/s$) and head (Petrohué River $Q = 350\ m^3/s$) of the Reloncaví Fjord.

Time-series of the Puelo River streamflow

Streamflow information was obtained from the hydrological station Carrera Basilio (41.6°S, 72.2°W) of the Dirección General de Aguas de Chile (General Water Office of Chile, DGA). This database consists of the daily streamflows between the hydrological years 1944 and 2007 (1 April 1944 and 31 March 2008). This gauging station is the closest to the mouth of the Puelo River in the Reloncaví Fjord and offers a representative view of the total contributions from this river's drainage basin (Fig. 1). The seasonal trend of the streamflow series was analysed through the non-parametric Mann–Kendall trend test and the regression of the Sen slope (Gilbert 1987; Helsel & Hirsch 1992). These statistical methods have been used to analyse seasonal data without a normal distribution (Molnár & Ramírez 2001; Zhang et al. 2001; Birsan et al. 2005; Pellicciotti et al.

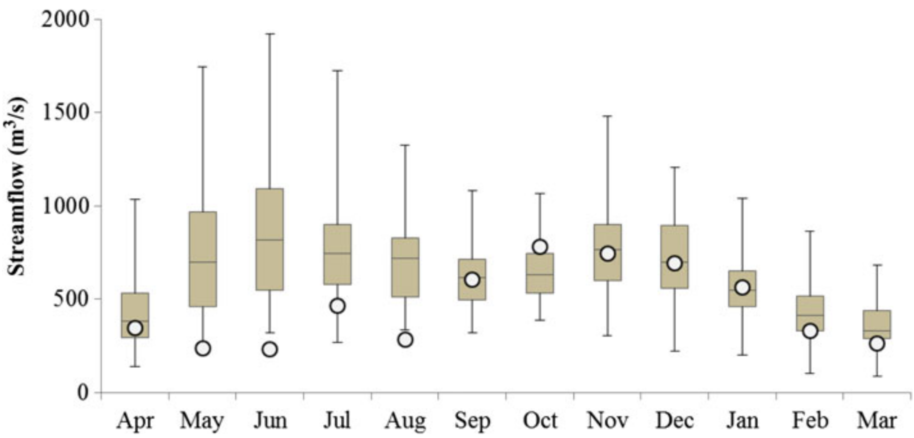

Figure 2 Hydrological regime of the Puelo River corresponding to the time-series between 1944 and 2011. The box (grey rectangle) corresponds to the 25th and 75th percentiles; horizontal line = median; error bars = minimum and maximum values; grey circles = monthly mean of hydrological year 2007.

2010). The data were processed in the MAKESENS application (Salmi et al. 2002) and analysed at the level of three seasonal scales: (1) hydrological years, (2) months and (3) ratios between months.

The interannual variability of the Puelo River regime was analysed by classifying each hydrological year (1944–2007) in terms of its type of streamflow regime (mixed: rainfall and snowmelt peaks, or nival: spring peak by snowmelt). The hydrological regimes were classified according to the mixed regime of the Puelo River (Niemeyer & Cereceda 1984) and the nival regime of the Baker River (47.8°S, $Q = 870$ m^3/s). The classification criteria used were the Spearman rank correlation coefficient ($P < 0.05$) and graphic analyses between the hydrological years of the Puelo River and the type of streamflow regime (mixed or nival). The years that did not agree with either of the two streamflow trends used ($P > 0.05$) were classified as irregular regimes.

River and fjord environment measurements (2006–2007)

To analyse the freshwater influence of the Puelo River on Reloncaví Fjord, we compiled a database consisting of streamflows (m^3/s) and the surface values of salinity (psu), temperature (°C) and dissolved oxygen (saturation % and concentration mg/l) collected at a depth of 1.5 m. The sensors were fixed to a surface anchored platform that followed the near surface motions (i.e. tidal-wave conditions). Thus, the absolute measurement depth was always 1.5 m below the surface. The streamflow was obtained from the hydrological station Carrera Basilio (DGA), and the surface data of the fjord were taken from a multiparameter sensor (YSI 600 OMS) installed opposite the mouth of the Puelo River (Fig. 1). This information was recorded by the sensor every 2 h between August 2006 and December 2007. To determine the effect of the wind, a meteorological station (H21-002) was installed at a height of 10 m and an anemometer (Hobo S-WCA-M003) in the middle section of the fjord (Fig. 1). The wind data (direction and speed) were gathered in winter (May–June) and spring (October–November) 2007, and were processed considering the orientation of the fjord axis in the section used for measurements (65° with respect to the north).

The information was analysed based on (1) two different temporal scales between August 2006 and December 2007 (streamflow vs temperature, salinity, dissolved oxygen) and (2) in two contrasting periods of streamflow in 2007 (May–June and October–November; wind vs temperature, salinity, dissolved oxygen). In both cases, we applied analyses of continuous wavelet transform (CWT) and cross wavelet transform (XWT) (Grinsted et al. 2004; Cazelles et al. 2008). This approach evaluates the associations (time–frequency) between variables at the seasonal level (Labat et al. 2004, 2005; Marcé et al. 2010). The identification of regions in the time–frequency space with significant and consistent phase relationship between series is interesting because it suggests potential causal mechanisms linking the time series (Grinsted et al. 2004). Specifically, the application of XWT allows determination of the common power of two CWT decompositions, identifying when two series oscillate in a common frequency, be it in phase (e.g. simultaneous maxima and minima) or in anti-phase (e.g. maxima of one signal aligned with the minima of the other). The areas of significance in the wavelet graphs were estimated using Monte Carlo techniques (Grinsted et al. 2004; Maraun & Kurths 2004). The CWT and XWT analyses were developed using software provided by Aslak Grinsted (http://www.pol.ac.uk/home/research/waveletcoherence/).

Results

Puelo River streamflow variability and mixing regimes

Between 1944 and 2007, the Puelo River streamflow showed high interannual variability and a significant decline (year 1945 = 885 m^3/s, year 1998 = 347 m^3/s), both strongly associated with the decreasing tendencies of the summer (January, February, March) and autumn (May) streamflows (Fig. 3A, B). This seasonal pattern was associated with lower precipitation (e.g. February, May), decreasing the capacity of the drainage basin to reload and slowing the usual pluvial increase of streamflows. Specifically, the month of May presented a significant drop in the streamflow compared with the previous winter (June, July, August; $P < 0.05$) and spring (October; $P < 0.01$) months (Fig. 3B). By contrast, October was the only month with an increasing pattern, which was, moreover, significant in relation to the streamflows of November, January and February ($P < 0.01$). As a whole, these variations were associated with an extension of the period of lower streamflows towards the end of autumn (May) and an advance of the greater springtime (October) streamflows (Figs. 2 and 3C) associated to early contributions

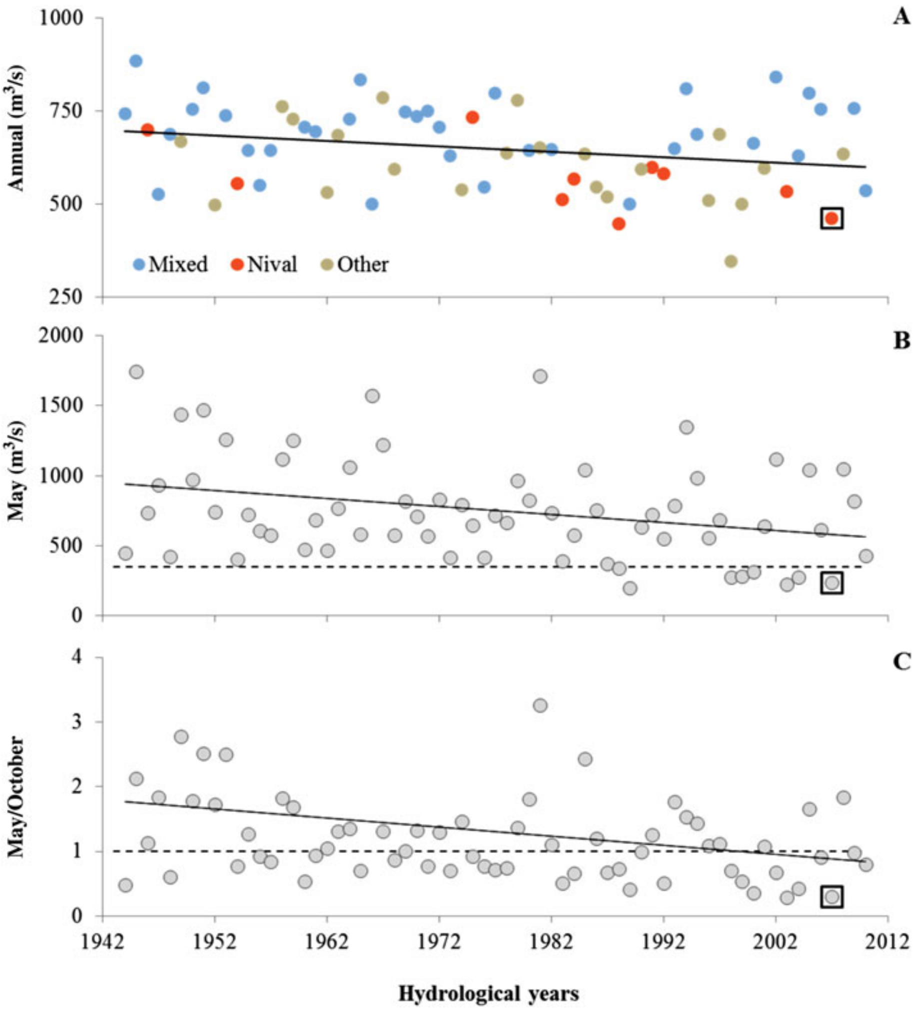

Figure 3 Trend of the Puelo River streamflow between 1944 and 2007: **A,** average annual streamflow and hydrological regimes; **B,** average streamflow for month May; **C,** ratio between the average streamflows for May–October period. The dashed lines indicate the level of 350 m^3/s (B) and the ratio of May/October equal to 1 (C). The black squares highlights the hydrological year 2007.

of meltwater from increased temperatures. At the level of the hydrological regime, two highly contrasting stages were distinguished in the 64 years analysed (Figs. 2 and 3A). Thus, until the end of the 1970s, the mixed regime was the most frequent discharge pattern (23 of 36 years), with a generally stable ratio (1:1) between the maximum streamflows in winter (May–July: $Q = 815$ m^3/s, pluvial contribution) and spring (October–December: $Q = 750$ m^3/s, including meltwater) (Figs. 2 and 3C). On the other hand, the hydrological years from 1980 on showed regimes other than mixed (Figs. 2 and 3C). Therefore, in this period, it was common to record irregular streamflow patterns with prolonged periods of low streamflows (e.g. year 1998: $Q = 347$ m^3/s) and nival regimes. This last anomalous streamflow pattern (e.g. hydrological year 2007) was characterised by low, constant streamflows in autumn and winter (May–June) (Figs. 2 and 3A, B, C).

Relationships between streamflow and oceanographic variables

Between August 2006 and December 2007, the Puelo River presented highly contrasting flow periods, recording typical ranges in spring (September–December, mean = 730, SD = 270 m^3/s) and strongly anomalous ranges between February and August 2007 (mean = 310, SD = 30 m^3/s) (Fig. 2). In the surface fraction of the Reloncaví Fjord, the temperature revealed a marked difference between the periods of summer (17°C) and winter (9°C), salinity increased continuously until the end of winter (December 2006 = 5 psu, August 2007 = 19.5 psu), and the dissolved oxygen showed a strong decline in its mean concentrations and saturation levels during the months of May and June 2007 (May–June = 50, SD = 20%; mean = 5, SD = 2.2 mg/l) (Fig. 4).

The XWT analysis identified oscillations in temperature and in salinity coherent with those in streamflow (Fig. 4). These associations were stronger and longer in the spring months of both years. During these stages, we recorded significant couplings at different periods (1, 1–5,

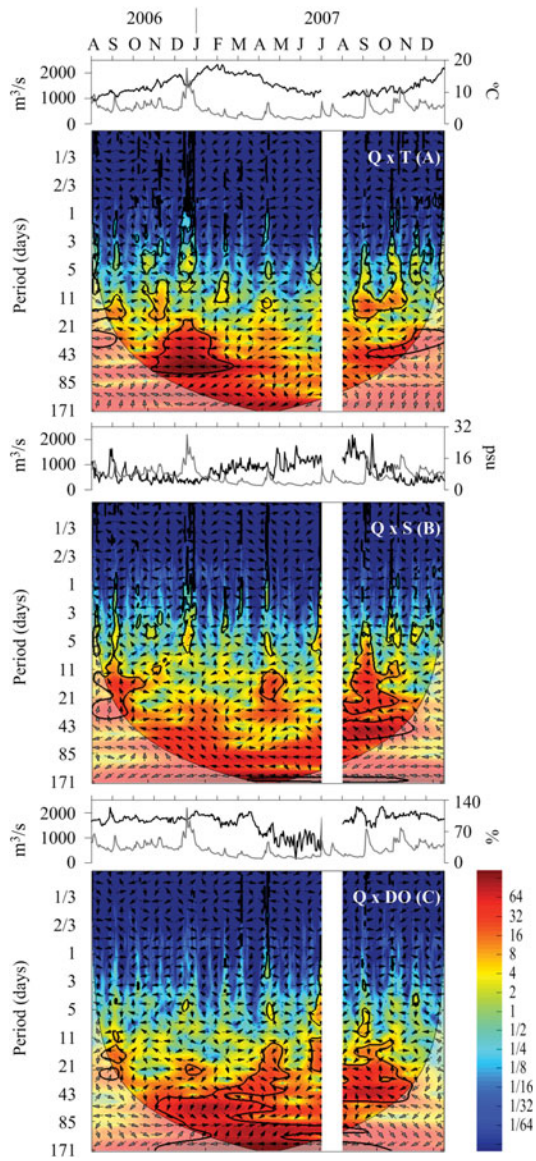

Figure 4 Spectral cross-wavelet power between the Puelo River flow (Q, m^3/s, grey line) and surface temperature (T, °C), salinity (S, psu), and dissolved oxygen (DO, %) of the Reloncaví Fjord (1.5 m). The black contour lines indicate coherent oscillations at significance level of $P < 0.05$, and the arrows indicate the relative phase relationship between series in a portion of the time domain (right = phase; left = anti-phase; down = first series leads the second by 90°). The white area indicates the absence of temperature data during the month of July 2007.

10–25, 40–60 days) and mainly in the anti-phase (Fig. 4). By contrast, between February and August 2007, the significant couplings between these variables decreased noticeably and were limited to sporadic events of greater streamflow (16–21 April 2007; $Q = 700$ m^3/s) (Fig. 4). Respect to the streamflow and dissolved oxygen, the XTW analysis registered coherent oscillations (periods >10 days) that were significant and prolonged until mid-autumn 2007 and from August to the end of December 2007 (Fig. 4). By contrast, in May and June 2007, this coherence was practically non-existent in periods shorter than 90 days (Fig. 4). The significant coherence observed at many periods well illustrates the degree of influence that the Puelo River has on the physical and chemical characteristics of the fjord's surface layer, via its control over the thickness of that layer, suppressing to a greater or lesser degree, the upwelling of more saline, less oxygenated water.

Wind influence on the surface layer of the fjord

The autumn (T1 May–June) and spring (T2 October–November) 2007 sampling periods differed highly in terms of freshwater contributions from the Puelo River (T1 mean $= 230$, SD $= 40$ m^3/s vs T2 mean $= 765$, SD $= 245$ m^3/s) (Fig. 2). Although both periods were influenced mostly by winds coming from the southern component (Fig. 5), the maximum wind speeds registered were distinct (Fig. 5). In these contrasting periods, the XWT analysis showed stronger, more significant associations between the wind time-series and the surface oceanographic variables of the fjord in the autumn months (Fig. 6). Specifically, between May and June, the wind speed series presented prolonged significant couplings (periods <1 day, 3–15 days) with respect to salinity and dissolved oxygen (both associations near anti-phase) (Fig. 6). The time-series of temperature and dissolved oxygen also registered coherent oscillations. However, their significant couplings (anti-phase, periods between 3 and 10 days) were more sporadic and less prolonged than those observed with respect to salinity. By contrast, between October and November 2007, the influence of the wind was weaker and tied mainly to significant couplings with respect to the temperature (periods <1 day, 2–3 days), whereas

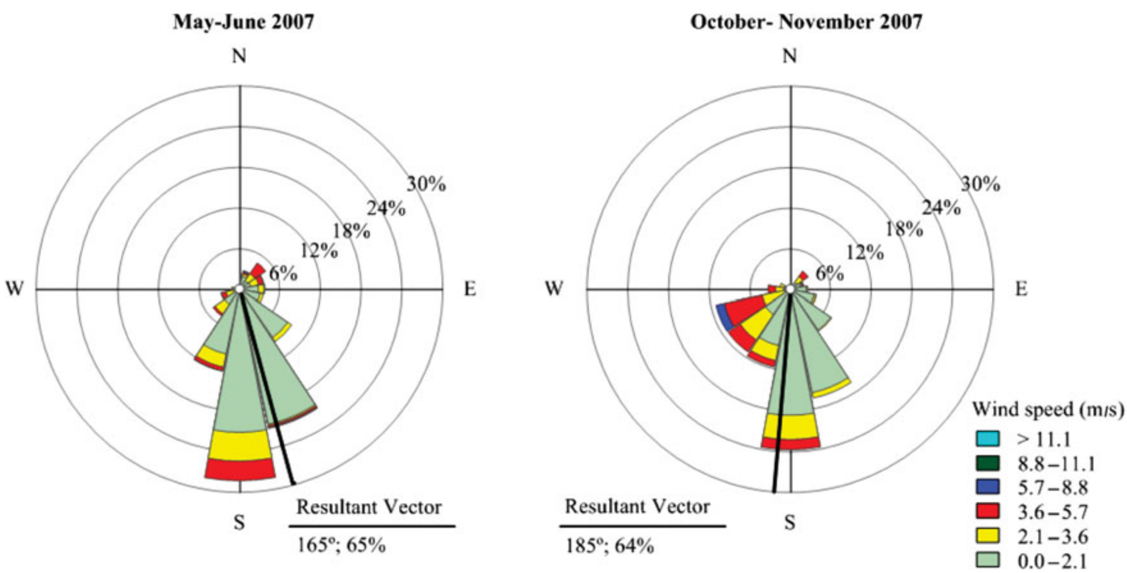

Figure 5 Wind speed and direction measured in the Reloncaví Fjord in autumn (May–June) and spring (October–November) 2007. The direction indicates the wind source.

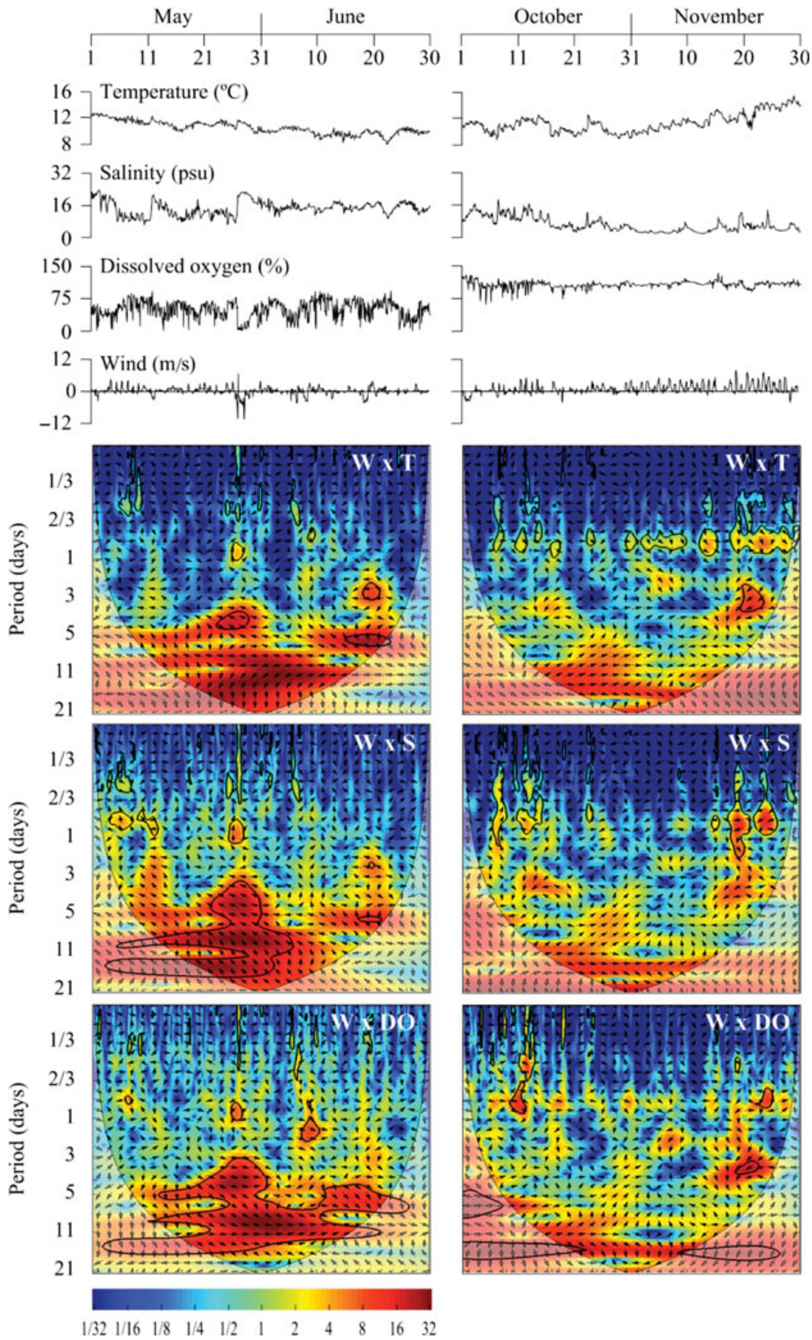

Figure 6 Spectral cross-wavelet power between the wind (*W*, m/s) and the surface salinity (*S*, psu), temperature (*T*, °C) and dissolved oxygen (DO, %) of the Reloncaví Fjord (1.5 m). The black contour lines indicate coherent oscillations at significance level of $P < 0.05$, and the arrows indicate the relative phase relationship between series in a portion of the time domain (right = phase; left = anti-phase; down = first series leads the second by 90°).

in the case of salinity and dissolved oxygen, the coherent oscillations with the wind were limited to the moments of low streamflow and were registered in periods of <1 day (Fig. 6). During spring samplings, the significant couplings of the variables of the surface fraction of the fjord (periods <1 day, 2–5 days and 10–15 days) were in phase, with increases in salinity and mainly temperature associated with increases in the constant and high levels of dissolved oxygen saturation (mean = 100, SD = 7%) and concentration (mean = 10, SD = 1.2 mg/l) (Fig. 7).

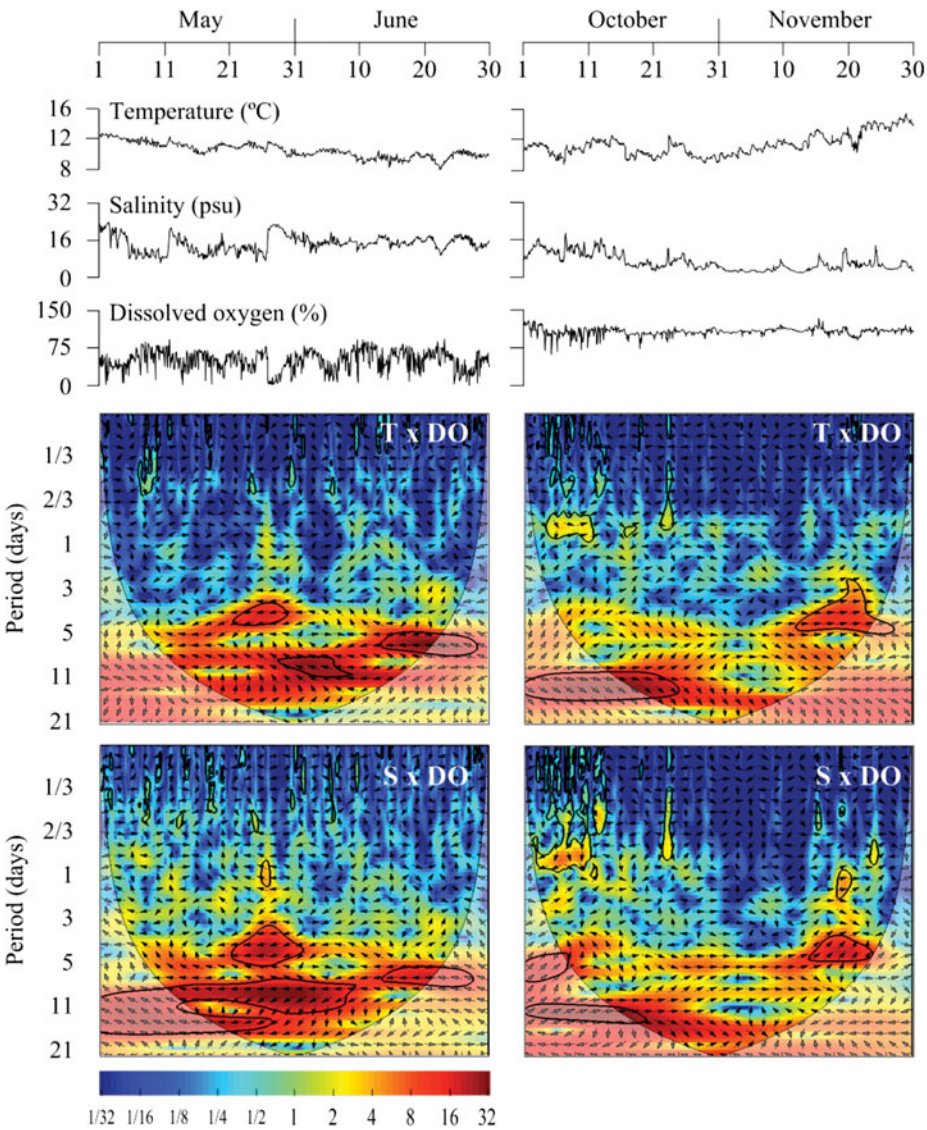

Figure 7 Spectral cross-wavelet power between the surface temperature (T, °C), salinity (S, psu) and dissolved oxygen (DO, %) of the Reloncaví Fjord (1.5 m). The black contour lines indicate coherent oscillations at significance level of $P < 0.05$, and the arrows indicate the relative phase relationship between series in a portion of the time domain (right = phase; left = anti-phase; down = first series leads the second by 90°).

Discussion

The eastern South Pacific Ocean off austral Chile is characterised by high precipitation due to the strong influence of sub-polar low-pressure systems associated with rainfall (Silva & Neshyba 1979; Dávila et al. 2002; Calvete & Sobarzo 2011). The Andes Mountain Range facilitates the accumulation of water in the form of ice and glaciers, and rivers eventually discharge this water into the sea. In general, the temporal influence of tributary rivers on coastal systems is widely described at the level of physical and biogeochemical processes (Malone et al. 1988; Matthäus & Schinke 1999; Costa et al. 2007; Martinho et al. 2007; Buranapratheprat et al. 2008). Our results highlight the dominance of streamflow patterns other than the typical mixed regime and an increase in nival regimes associated with the trend of lower streamflows registered for the Puelo River since the mid-1970s. Considering these characteristics and that the variability of the Puelo River streamflow is correlated with that of other important rivers in southern Chile (41.5–46°S; Yelcho River = 363 m^3/s, Palena River = 130 m^3/s, Cisnes River = 240 m^3/s, Aysén River = 628 m^3/s; Lara et al. 2008), it can be predicted that, like the Reloncaví Fjord, other North Patagonian channels and fjords are being influenced by freshwater discharges without a defined interannual pattern. Although the oceanographic processes and patterns of the North Patagonian fjords and channels are highly regulated by variations of salinity (Pickard 1973; Valle Levinson et al. 2002, 2007; Iriarte et al. 2007), little information exists regarding the temporal influence of high freshwater inputs from tributary rivers. From our small scale (spatial and temporal) approach using long and short time series, we emphasise the potential coupling of the streamflows of tributary rivers and the physical and biogeochemical variables of the coastal systems into which these rivers empty. Here, oceanographic studies have had to rely on the temporal patterns of hydrological regimes (mixed or nival) described more than 25 years ago (Niemeyer & Cereceda 1984). Although these descriptions may correctly represent the average streamflows of these rivers, the referential use of such times series involves a high degree of uncertainty since: (1) they do not consider the decreasing interannual trend described for precipitation and streamflows from local tributary rivers (Lara et al. 2008), and (2) average streamflows tend to mask heavily contrasting hydrological regimes (e.g. year 2007: nival regime, $Q = 462$ m^3/s; year 1999: pluvial regime, $Q = 499$ m^3/s). Thus, greater efforts are needed and must include the hydrological regimes of major Patagonian tributary rivers (e.g. Puelo River, 41.6°S: $Q = 650$ m^3/s; Baker River, 47.8°S: $Q = 870$ m^3/s) as relevant watersheds modulating the continent–ocean interface.

The analysis of hydrological and oceanographic data on a scale of hydrological years revealed that the Puelo River influence on the surface layer of the Reloncaví Fjord varied as a function of streamflow levels and temporality (hydrological regime). Thus, in autumn and spring of 2006 and 2007, the high streamflows of the Puelo River (e.g. September–December; $Q > 730$ m^3/s) caused a significant decline in the fjord's surface salinity (mean = 7 psu) and allowed high, constant concentrations of surface dissolved oxygen (mean = 10 mg/l). By contrast, the low streamflows in autumn and winter of 2007 (March–June; $Q = 265$ m^3/s) did not influence the temporal patterns of the fjord's surface layer. The same situation has been reported for coastal systems highly influenced by tributary rivers at other latitudes. During periods of low flows, the spatio-temporal variability of salinity and circulation processes is largely dominated by internal waves, tidal cycles and wind events (Schroeder et al. 1990; Dong et al. 2004; Liu et al. 2007; Buranapratheprat et al. 2008). In turn, anomalous hydrological events (e.g. prolonged periods of low flows during nival regimes of the Puelo River) have been associated with the upwelling of a more saline, less oxygenated water mass to the surface layer of the coastal system at the river mouth (e.g. Yin et al. 2004; Melrose et al. 2007; Guo & Valle-Levinson 2008). Recently, in the Reloncavi Fjord, it was hypothesised that low-oxygen and high-salinity deep waters below the pycnocline could get near surface through internal lateral seiches (Valle Levinson et al. 2007). Those authors associated the occurrence of lateral seiches in the Reloncaví Fjord with low autumn streamflows of the Puelo River ($Q < 350$ m^3/s) and high-salinity (> 20 psu), low-oxygen (< 3 mg/l) waters ascended to the surface layer. Our results indicate that, in May and June 2007, the limited influence of the river (230 m^3/s) conditioned the surface layer of the fjord to be more responsive to wind events. In spring of the same year, the presence of strong winds did not generate significant changes in the surface layer, which was heavily influenced by the high streamflows of the Puelo River (October–November 765 m^3/s). Moreover, the relevance of such associations is clear when considering that the summer and autumn streamflows of the Puelo River are expected to decrease in the coming decades due to changes in the circulation of the Southern Hemisphere (Lara et al. 2008) as well as a decrease in precipitation in southern Chile (Quintana & Aceituno 2012). In those scenarios, drastic and sustained reductions in precipitation and river discharges, which are driven by both local and remote processes, may produce strong fluctuations in hydrological regimes and a reduction in the streamflow from the rivers and glaciers that reach the fjord and channel regions of southern Chile.

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References

Aceituno P, Fuenzalida H, Rosenblüth B 1993. Climate along the extratropical coast of South America. In: Mooney H, Fuentes E, Kronberg B eds. Earth systems responses to global change: contrast between North and South America. New York, Academic Press.

Acha EM, Mianzan HW, Guerrero RA, Favero M, Bava J 2004. Marine fronts at the continental shelves of austral South America: physical and ecological processes. Journal of Marine System 44: 83–105.

Bastén J, Clement A 1999. Oceanografía del estuario de Reloncaví, X Región de Chile. Ciencia y Tecnología del Mar 22: 31–46.

Birsan MV, Molnár P, Burlando P, Pfaundler M 2005. Streamflow trends in Switzerland. Journal of Hydrology 314: 312–329.

Buranapratheprat A, Yanagi T, Matsumura S 2008. Seasonal variation in water column conditions in the upper Gulf of Thailand. Continental Shelf Research 28: 2509–2522.

Cáceres M, Valle-Levison A, Sepúlveda H, Holderied K 2002. Transverse variability of flow and density in a Chilean fjord. Continental Shelf Research 22: 1683–1698.

Calvete C, Sobarzo M 2011. Quantification of the surface brackish water layer and frontal zones in southern Chilean fjords between Boca del Guafo (43°S) and Estero Elefantes (46°S). Continental Shelf Research 31: 162–171.

Cazelles B, Chavez M, Berteaux D, Ménard F, Vik JO, Jenouvrier S, et al. 2008. Wavelet analysis of ecological time series. Oecologia 156: 287–304.

Costa MJ, Vasconcelos R, Costa JL, Cabral HN 2007. River flow influence on the fish community of the Tagus estuary (Portugal). Hydrobiologia 587: 113–123.

Dávila PM, Figueroa D, Muller E 2002. Freshwater input into the coastal ocean and its relation with the salinity distribution off austral Chile (35–55° S). Continental Shelf Research 22: 521–534.

Dong L, Su J, Wong L, Cao Z, Chen J 2004. Seasonal variation and dynamics of the Pearl River plume. Continental Shelf Research 24: 1761–1777.

Frame ER, Lessard EJ 2009. Does the Columbia River plume influence phytoplankton community structure along the Washington and Oregon coasts? Journal of Geophysical Research 114: C00B09. doi:10.1029/2008JC004999

Gilbert RO 1987. Statistical methods for environmental pollution monitoring. New York, Van Nostrand Rienhold Company, Inc.

González HH, Calderón MJ, Castro L, Clement A, Cuevas LA, Daneri G, et al. 2010. Primary production and plankton dynamics in the Reloncaví Fjord and the Interior Sea of Chiloé, Northern Patagonia, Chile. Marine Ecology Progress Series 402: 13–30.

Grinsted A, Moore JC, Jevrejeva S 2004. Application of the cross wavelet transform and wavelet coherence to geophysical time series. Nonlinear Processes in Geophysics 11: 561–566.

Guo X, Valle-Levinson A 2008. Wind effects on the lateral structure of density-driven circulation in Chesapeake Bay. Continental Shelf Research 28: 2450–2471.

Helsel DR, Hirsch RM 1992. Statistical methods in water resources. New York, Elsevier.

Iriarte JL, González HE, Liu KK, Rivas C, Valenzuela C 2007. Spatial and temporal variability of chlorophyll and primary productivity in surface waters of southern Chile (41.5–43°S). Estuarine, Coastal and Shelf Science 74: 471–480.

Labat D, Goddéris Y, Probst J, Guyo J 2004. Evidence for global runoff increase related to climate warming. Advances in Water Resources 27: 631–642.

Labat D, Ronchail J, Guyot J 2005. Recent advances in wavelet analyses: Part 2 Amazon Parana Orinoco and Congo discharges time scale variability. Journal of Hydrology 314: 289–311.

Lara A, Urrutia R, Villalba R, Luckman B, Soto D, Aravena JC, et al. 2005. The Potential of tree-rings for streamflow and estuary salinity reconstruction in the Valdivian Rainforest Eco-region, Chile. Dendrochronologia 22: 155–161.

Lara A, Villalba R, Urrutia R. 2008. A 400-year tree-ring record of the Puelo River summer-fall streamflow in the Valdivian Rainforest eco-region, Chile. Climatic Change 86: 331–356.

Le Pape O, Chauvet F, Desaunay Y, Guerault D 2003. Relationship between interannual variations of the river plume and the extent of nursery grounds for the common sole (*Solea solea*, L.) in Vilaine Bay. Effects on recruitment variability. Journal of Sea Research 50: 177–185.

Liu W-C, Chen W-B, Cheng RT, Hsu M-H, Kuo AY 2007. Modeling the influence of river discharge on salt intrusion and residual circulation in Danshuei River estuary, Taiwan. Continental Shelf Research 27: 900–921.

Lloret J, Palomera I, Salat J, Solé I 2004. Impact of freshwater input and wind on landings of anchovy (*Engraulis encrasicolus*) and sardine (*Sardine pilchardus*) in shelf waters surrounding the Ebro (Ebro) River delta (north-western Mediterranean). Fisheries Oceanography 13: 102–110.

Malej A, Mozetic P, Malacic V, Terzíc S, Ahel M 1995. Phytoplankton responses to freshwater inputs in a small semi-enclosed gulf (Gulf of Trieste, Adriatic Sea). Marine Ecology Progress Series 120: 111–121.

Malone TC, Crocker LH, Pike SE, Wendler BW 1988. Influences of river flow on the dynamics of phytoplankton production in a partially stratified estuary. Marine Ecology Progress Series 48: 235–249.

Maraun D, Kurths J 2004. Cross wavelet analysis: significance testing and pitfalls. Nonlinear Processes in Geophysics 11: 505–514.

Marcé R, Rodríguez-Arias MA, Gracía JC, Armengol J 2010. El Niño Southern Oscillation and climate trends impact reservoir water quality. Global Change Biology 16: 2857–2865.

Martinho F, Leitao R, Viegas I, Dolbeth M, Neto JM, Cabral HN, et al. 2007. The influence of an extreme drought event in the fish community of a southern Europe temperate estuary. Estuarine, Coastal and Shelf Science 75: 537–546.

Matthäus W, Schinke H 1999. The influence of river runoff on deep water conditions of the Baltic Sea. Hydrobiologia 393: 1–10.

Melrose C, Oviatt C, Berman M 2007. Hypoxic events in Narragansett Bay, Rhode Island, during the summer of 2001. Estuaries and Coasts 30: 47–53.

Molnár P, Ramírez JG. 2001. Recent trends in precipitation and streamflow in the Rio Puerco basin. Journal of Climate 14: 2317–2328.

Morey S, Dukhovskoy D, Bourassa M 2009. Connectivity of the Apalachicola River flow variability and the physical and bio-optical oceanic properties of the northern West Florida Shelf. Continental Shelf Research 29: 1264–1275.

Niemeyer H, Cereceda P 1984. Hidrografía: Colección Geográfica de Chile. Instituto Geográfico Militar, Santiago, Chile.

Pellicciotti F, Bauder A, Parola M 2010. Effect of glaciers on streamflow trends in the Swiss Alps. Water Resources Research 46: W10522.

Pickard G 1971. Some physical oceanographic features of inlets of Chile. Journal of Fisheries Research Board of Canada 28: 1077–1106.

Pickard G 1973. Water structure of Chilean fjords, In Fraser R ed. Oceanography of the South Pacific. Wellington, National Commission for UNESCO.

Quintana JM, Aceituno P 2012. Changes in the rainfall regime along the extratropical west coast of South America (Chile): 30–43°S. Atmósfera 25: 1–22.

Salmi T, Mtt A, Anttila P, Ruoho-Airola T, Amnell T 2002. Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates—the excel template application Makesens. Helsinki, Finish Meteorological Institute.

Schmitt R 1995. The ocean component of the global water cycle. Reviews of Geophysics 33: 1395–1409.

Schroeder WW, Dinnel SP, Wiseman Jr WJ 1990. Salinity stratification in a river-dominated estuary. Estuaries and Coasts 13: 145–154.

Silva N, Neshyba S 1979. On the southernmost extension of the Peru–Chile undercurrent. Deep-Sea Research 26: 1387–1393.

Silva N, Vargas C, Prego R 2011. Land-ocean distribution of allochthonous organic matter in the surface sediments of the Chiloé and Aysen Interior Seas (Chilean Northern Patagonia). Continental Shelf Research 31: 330–339.

Strub PT, Mesias JM, Montecino V, Rutllant J, Salinas S 1998. Coastal ocean circulation off western south America. In Robinson C, Brink T eds. The sea. New York, John Wiley & Sons.

Valle-Levison A, Cáceres M, Sepúlveda H, Holderied K 2002. Patrones de flujo asociados a la boca del seno Aysén. Ciencia y Tecnología del Mar 25: 5–16.

Valle-Levinson A, Sarkar N, Sanay R, Soto D, León J 2007. Spatial structure of hydrography and flow in a Chilean fjord, Estuario Reloncaví. Estuaries and Coasts 30: 113–126.

Yin K, Lin Z, Ke Z 2004. Temporal and spatial distribution of dissolved oxygen in the Pearl River Estuary and adjacent coastal waters. Continental Shelf Research 24: 1935–1948.

Zhang X, Harvey KD, Hogg WD, Yuzyk TR 2001. Trends in Canadian streamflow. Water Resources Research 37: 987–998.