Summer stratification of Andean lakes of Patagonia and Tierra del Fuego. Global warming or ENSO effects?

Estratificación de verano de los lagos andinos en la Patagonia y Tierra del Fuego: ¿Calentamiento global o efectos del ENOS?

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Abstract

Lakes are traps of water and sediment. As such, they can record past times climate changes. High-latitude Andean piedmont lakes only give information of the interglacial periods – ice-free periods. Climatic studies should be based on analogies with current lakes. In this sense, we must corroborate if varves respond to annual changes (summer-winter seasonality) or if they represent cycles in a longer temporal scale (interannual). Sedimentary records can stand for trends (glacial advances, retreats or captures), local effects (vulcanism, gravity-dominated phenomena) or episodes (*jokulhaups, scablands*). Depending on their dynamics, glacial lakes stratified differently during summer time (monomic, dimictic or polimictic lakes). According to some models, global warming is supposed to give rise to significant changes in the vertical structure of lakes. There are some experiments that indicate these variations (Lydersen et al. 2007). We found that Patagonian and Fueguian lakes stratified at depths between 10 and 22 m during summertime between 2001 and 2007. These thermoclines' depths were shallower than those recorded in summer 1984. On the other side, the lakes from the volcanic district (Neuquén in Argentina and Chilean IX- Region) are recording increases in their temperature with depth. In some lakes, turbidity plumes were recognized as conditioning sedimentation rates and therefore the sedimentary record.

Key words: glacial lakes – thermocline – Patagonia – Tierra del Fuego – ciclicity

Resumen

Los lagos son trampas de agua y sedimento y por lo tanto registran las variaciones climáticas del pasado. Los lagos pedemontanos andinos de altas latitudes guardan información de épocas libres de hielos (interglaciales). Estudios climáticos deben basarse en su analogía con los lagos actuales. En este sentido, debe confirmarse si los varves responden a cambios anuales (estacionalidad verano-invierno) o si los ciclos representan una escala temporal mayor (ciclos interanuales). Los registros sedimentarios pueden representar tendencias (avances glaciales, retrocesos, capturas), efectos locales (vulcanismo, fenómenos dominados por gravedad) o episódicos (*jokulhaups, scablands*). De acuerdo a su dinámica, los lagos glaciales se estratifican de diferente modo durante el verano (lagos monomícticos, dimícticos y polimícticos). Se supone que el calentamiento global provocaría significativos cambios en su estructura vertical de acuerdo a algunos modelos propuestos. Los lagos de Patagonia y Tierra del Fuego se han estratificado entre profundidades de 10 y 22 m entre los años 2001 y 2007. Estas profundidades de las termoclinas fueron menores que las registradas en el verano de 1984. Los lagos del distrito volcánico (Neuquén en Argentina y IX Región de Chile), por otro lado, aumentan su temperatura en profundidad. En algunos lagos se han registrado plumas de turbidez que seguramente condicionan el registro sedimentario.

Palabras clave: lagos glaciales, termoclina, Patagonia, Tierra del Fuego, ciclicidad

Introduction

Lakes are considered particularly sensitive to climatic, hydrologic and geological variations. Their sediments record cycles (called varves) in response to annual and interannual variations. Global programs are interested in South American lakes trying to study past changes in their sedimentary records (*Global Lake Drilling program* GLAD800) or analyzing human impacts on these relatively-closed ecosystems (*Human Impacts on Lake Ecosystems*, LIMPACS; Battarbee, 2000). Although some international programs are oriented to the sedimentary record, they assumed that lake dynamics is similar to other lakes, considering comparisons to other lakes of America (PEP I), Africa (PEP III) or Europe (*European Lake Drilling Programme*). These paleolimnological studies also assume that these lakes have a regular behaviour, although recent studies stated that ENSO events are episodically critic in South America, with significant impacts in their dynamics and the annual hydrologic balances (Depetris and Pasquini, 2001; Villarrosa *et al.*, 2002, Ariztegui et al. 2007).

Patagonian Andean lakes occupy former piedmont glaciers spanning from 38 to 55 degrees south (**Fig. 1**). Pleistocene glaciers excavated U-shaped valleys leaving terminal moraines that blocked extended lakes when glaciers receded. This simple scheme could not be applied to all lakes as there are differences assigned to geology, weather and dynamics (of the glacier, of the river or of the lake). Some lakes (Caviahue, Aluminé, Villarrica) occupying volcanic districts are assumed to be affected by hydrothermal processes, and subject to episodic tectonic activity (Bertrand et al. 2008). In regard to the geologic composition of their watersheds, plutonic areas are more resistant to weathering than volcanic or sedimentary watersheds. As the Andes Cordillera is an obstacle to water vapour transported from the Pacific Ocean, some watersheds (Chilean) are more rainy than others. Some lakes are very narrow (fetch limited) while other extend in the direction of the dominant westerly winds (Lácar). Some lakes are very oligotrophic comprising watersheds almost exclusively subject to conservation rules; others are being severely affected by urban outfalls (Villarrica, Lácar). Some are smaller and close to the mountains; others are very irregular with significant differences between each arm (Nahuel Huapi). Dealing with lake dynamics, there are processes that are not quite known; for example, acid lakes from the volcanic district (Caviahue or Agrio) have a chemical conditioning (Gammons et al. 2005). Lakes subject to strong winds differ in relation to their extensions: if they are narrow and limited by steep slopes wind-induced currents may dominate. If they are wide, wind may induce stationary waves or seiches. The summer thermocline is a good indicator of their dynamics as it is subject to seasonal variations, and changes that vary from year to year. At the same time, thermocline regulates chemical and biological activity (Quirós and Drago, 1985; Lemmin and Mortimer, 1985; Wotton 1995).

Figure 1. Location map.

Source: Authors.

ENSO positive climatic phases cause significant interannual changes in Western South America. Fluvial watersheds flowing from the Andes are directly affected by these phenomena (Bello et al 2004; Compagnucci and Araneo 2007). Even estuaries of Atlantic watersheds are significantly affected during the strong ENSOs of 192-83 and 1997-98 (Camilloni 2005; Isla 2008). The ENSO of 1997-98 triggered changes in climatic variables and fauna distribution to latitudes up to 62º S in Bransfield Strait (Aguayo-Lobo et al. 1998). These cycles strike in Patagonian piedmont lakes although their impacts in depth have been matter of little concern.

The present paper describes and compares the morphological and dynamical characteristics of some piedmont lakes of Northern Patagonia and Tierra del Fuego, Argentina and Chile (**Fig. 1**). These lakes are located from 38 to 55° S and their summer vertical variations (temperature, pH, turbidity and oxygen dissolved) are here describe in order to interpret their response to climatic impacts.

Lake classification and description

In regard to primary production, there are lakes of low (oligotrophic < 30 g C /m^2/year; Secchi depth > 5 m), intermediate (mesotrophic; 25-60 g C /m^2/year; SD 3-6 m), high (eutrophic: 40-200 g C /m^2/year; SD 1-4 m) and very high productivity (hypertrophic: 130-600 g C /m^2/year ; SD 0-2 m; Hakanson and Jansson, 1995). In this sense, the majority of the Andean lakes of Patagonia and Tierra del Fuego are oligotrophic, although a few are mesotrophic with eutrophic areas close to urban outfalls. In regard to temperature, they are dimictic (stratified during summer and inversely during winter). The metalimnion not only varies seasonally but in response to wind stress. Several parameters vary in depth depending of certain morphometric characteristics lakes and their watersheds (**Table 1**).

Table 1. Morphological characteristics of studied lakes (modified from Quirós et al 1983; Quirós 1985, and Quirós and Drago 1988; Díaz et al. 2007).

	Lat	Alt	Area	Vol	Zmax	Zmed	P	R	WA	Type	Date
CAV	37	1650	9.22	570	95	51	22			V	5FEB02
ALU	38	1125	57	3956	165	69				V	23JAN07
VIL	39	220	185	20967	165	120	53			V	25JAN01
LAC	40	625	49	8134	277	166	58	5.8	1048	G	21JAN01
GUT	41	750	16.4	1307	111	80	25			G	1FEB02
PUE	42	150	44	4902	180	111	57	1	3040	G	19JAN03
EPU	42	250	17.4	1608	148	92	33	3.6	506	G	18JAN04
FUT	43	518	44.6	4510	168	101	72	0.94	2920	G	18JAN03
FAG	54	22	580	46806	200	81	230	24-25		G/T	19FEB03
ROC	55	4	5.5				30			G/T	6MAR02

Lat (degrees); Alt (m over MSL); Area (km2); Volume (hm3); Maximum depth (m); meand depth (m); Perimeter (km); Residence (years); Area of watershed (km2), type (v: volcanic; G: glacial; T: Tectonic)

Source: Authors

Caviahue Lake (37°52’ S, 71°03’ W)

Also called Agrio Lake, it is located at the foot of the Copahue volcano of very modern activity: 1750, 1789, 1867, 1937, 1961 and 1962 (Pereyra, 2001). The region comprises a forest dominated by Araucarias (*Araucaria araucana)*. As it occupies the depression of the caldera Caviahue-Copahue, basaltic rocks dominate in the surroundings. Two levels producing thermal water are located at 800-1000 and 1400 m below ground (Panarello, 2002). Although the area was assumed as glaciated twice, new interpretations assure that there was a unique Pleistocene glaciation without evidences of glaciolacustrine deposits (González Díaz, 2003). Acid water dominates the surroundings, and sulphate-reducing bacteria and methanogenic bacteria were sampled from the bottom (Gammons et al. 2005, 2008) preventing therefore fish communities. The sampling site was located in front of the Caviahue village.

Villarrica Lake (39°17’ S, 72°13’ W)

This lake, also called Mallolaufquen, is also located within a region dominated by volcanic rocks, North of the Villarrica volcano. This volcano has been very active in the last years: 1552, 1640, 1806, 1860, 1869, 1874, 1883, 1893, 1908, 1910, 1920, 1948, 1960, 1963, 1972, 1984 and 1985. The lake is limited to the north by the Quehue Range, receiving water from the rivers Pucón, Claro, Turbio, Quilque and Estero Suizo, and draining towards the Pacific Ocean via the Toltén River. The lake is also very affected by urban activities to the east (Pucón village) and to the west (Villarrica village). Pucón receives more than 70,000 tourists per year. The sampling point was located towards the Villarrica village. Lakes Villarrica and Calafquén have been subject to geophysical surveys that confirmed slides triggered by volcanic activity and sediment volcanoes at their bottom (Moernaut et al. 2009).

Lacar Lake (40°14’ S, 71°30’ W)

This lake is located within the Lanín National Park in a watershed between ranges of 1600 to 1900 m above MSL. Although its maximum area is in the argentinian territory, the lake is draining to the Pacific Ocean via the Huahum River. It is a narrow lake of 27.4 x 3.2 km. Granites and diorites (Huechulafquen formation; Carboniferous; González Díaz and Nullo, 1980), and volcanic and piroclastic rocks (Andesitic Series, Nahuel Huapi Group), dominate the watershed, that was glaciated during Pleistocene. The watershed is practically without population despite the eastern coastline where the city of San Martín de los Andes concentrates 20,000 stable inhabitants. In the neighbourhoods the gymnosperm *Libocedro chilensis* dominates. The lake was considered as template monomictic, and ultraoligotrphic, but the sampled embayment of San Martín de los Andes is oligomesotrphic (Cordini, 1964; Pedrozo *et al.*, 1993; Díaz et al. 1998).

Gutierrez Lake (41°12’ S, 71°26’ W).

It is located 12 km from the city of San Carlos de Bariloche, within the Nahuel Huapi National Park, comprising a complex lake that occupies wide glacial valleys. Particularly, Gutierrez Lake is between the Mascardi and Nahuel Huapi lakes, close to the boundary between the Atlantic and Pacific watersheds. At the region, metamorphic (Cushamen formation), granites, tonalites and granodiorites (Los Machis formation; González Díaz and Nullo, 1980), and volcanic and piroclastic (Andesitic series) rocks are outcropping. Dealing about the forests, *coihue* (*Nothofagus dombeyii*), *lenga*

(*N. pumilio*), and *ciprés* (*Austrocedrus chilensis*) dominate; subordinated, there are *ñire* (*N. antarctica*), *retamo* (*Diostea juncea*), *palo piche* (*Fabiana imbricata*), *maitén* (*Maytenus boaria*) and *bambú* (*Chusquea* sp.; Bailey Willis, 1918). The basin is within a cold and humid region, with mean temperatures below 10° C, and rains below 1000 mm/year. The lake is presently oligotrophic. It was sampled at its southwestern extreme.

Puelo Lake (42º10’ S, 71º40’ W).

It occupies a glaciofluvial depression 180 m depth, draining towards the west, to the Pacific Ocean. It receives water from the Turbio, Azul and Epuyén rivers, the latter bringing water from the Epuyén Lake. The watershed comprises plutonic, volcaniclastic (Ventana formation), metamorphic and sedimentary rocks (Piltriquitrón formation). Rains reduce from 3000 mm at the international border to 500 mm to the east. *Austrocedrus chilensis* and *Nothofagus* (lenga, coihue and ñire) forests dominate, although the area has suffered severe impacts due to fire woods. El Bolsón, Lago Puelo and El Hoyo concentrate a stable population of 22,000 inhabitants that receives 20,000 tourists during the summer. The lake is within the Lago Puelo National Park. Although the urban growth of El Bolsón and Lago Puelo has increased their sewage inputs, the photic zone extends to depths of 25 m. Oligotrophic conditions persist even in the north shore where the sampling was conducted (Azul River inlet).

Epuyen Lake (42°11’ S, 71°30’ W)

Epuyén Lake delivers water towards the Puelo. Today, this watershed has no glaciers but the ice eroded these glacial during the Pleistocene. Plutonic (Tonalita del Platero formation; Cazau 1980) and vulcaniclastic rocks extend to the ranges. Glaciolacustrine deposits have been described at the eastern boundary (Caldenius 1932; Isla and Espinosa 2008). The lake was found ultraoligotrophic in the samplings conducted in 1984 (Quirós, 1988) and 1991 (Pizzolon, 1991). The Secchi disc can be distinguish at the depths lower than 20 m. Fishing logs and industries related to the wood are the only activities in its shore. Several samplings were conducted at different parts of the lake.

Futalaufquen Lake (42°49’ S, 71°43’ W))

It is located in the middle of a complex of lakes of glacial origin. The Arrayanes River collects water from the Rivadavia and Menendez lakes,and It flows to the Kruger Lake. Coihues and cypress forests, and metamorphic (Cushamen formation; Esquistos de Esquel) and plutonic rocks dominate in the surroundings. Two thirds of this watershed is under the Los Alerces National Park administration. 2,000 inhabitants are stable although in summer 18,000 tourists visit the lake. There is an incipient cattle (cows and sheeps) activity. The lake is oligotrophic and nitrogen conditions primary productivity during the summer. Secchi depths can be distinguished to depths of 12-18 m, reaching lower depths during winter (Quirós 1988). Pleistocene lakes have been recognized in the region (Caldenius 1932) pointing to ancient levels of 735 m over MSL. The site of measurements was located towards the south of the lake.

Fagnano Lake (54º 35’ S, 68º 00’ W)

Also called Cami Lake, it is located in the centre of the Grande Island of Fueguian Archipielago. Elongated with an east-west orientation, it is flowing towards the western Magellan Strait by the short Azopardo River. The watershed is covered by ñire forests to the north, and lenga and guindo dominating to the southern slope of the ranges. The lake receives several rivers (Claro, Milna, Tuerto, Valdés and Turbio). It is stratified during most of the summer, and behaves as a close lake to the headlands as the area is of the same order of magnitude of the drainage area (Quirós 2002). It is located in the boundary between Southamerican and Scotia plates. Low-grade metamorphic and Cretaceous sedimentary rocks dominate in this region (Yahgan and Alvear formations, respectively; Caminos 1980). Glaciolacustrine deposits overtopped by peat bogs dominate the basin. The lake is considered ultraoligotrophic due to high transparency, low chlorophyll and nutrient contents (Mariazzi *et al.*, 1987). An ancient paleolake has been described as reaching levels 18-21 m over present Fagnano Lake (Caldenius, 1932; Bujalesky *et al.*, 1992, 1997). Sampling was conducted in the middle of the lake in front the settlement of the coastguards.

Roca Lake (54º 48' S, 68º36 'W)

This small lake is positioned at only 4 m over MSL between the ranges of Valdivieso and de las Pirámides. It receives water from the Lapataia and Rojas rivers (both in Chile) and flows to Lapataia Bay (Beagle Channel) within the Tierra del Fuego National Park. High-grade metamorphic rocks (Lapataia formation; Borrello 1969) dominate at the inlet, but the watershed also comprises the sedimentary rocks of the Yahgan formation. Peat bogs composed mainly of *Sphagnum* occupy the depressions between forests of lenga and coihue. The input of suspended sediment provided by glaciers caused low transparency (Mariazzi et al.1987). The lake has been described as a fjord: glaciers met the Beagle Channel before the maximum Holocene highstand melted them. Sampling was conducted at the SE extreme, close to the outlet towards the Beagle Channel.

Methods

Field works comprise vertical profiles conducted during mid-summer (January-February) by the mean of a Horiba U-10 quality checker. Windy days were avoided to conduct measurements. By the mean of IGM charts, hydrographic basins and lake morphometry (following Hakanson 1981 and Hakanson and Jansson 1995) were estimated. Data was collected every 2 m to a maximum depth of about 30 m. PH, conductivity and salinity were corrected by temperature (Horiba 1991). Oxygen is measured through a permeable membrane (Tabla 2). Dissolved Oxygen (DO) is also corrected according to salinity. The nephelometer approximated turbidity (0-800 nephelometric turbidity units) in response to the attenuation of an infrared light.

Table 2: Instruments used, ranges and accuracies.

Parameter	Range	Precission	Units
pH	0-14	0,01	Adimensional
Conductivity	0-1	0,001	MS/cm
Turbidity	0-800	1	NTU
Dissolved oxygen	0-19,9	0,1	Mg/l
Temperature	0-50	0,1	º C
Salinity	0-4	0,1	%

Source: Authors

Results

Lakes profiles were coherent although measurements were collected in different years. However, there are some differences that were related to their different emplacement, dynamics and sizes.

CAVIAHUE (CAV)

In February 2002, this lake was stratified at 12 m depth, between 16 and 13 ºC **(Fig. 2).** Similar results were obtained in 2000 with cold temperatures of about 5 ºC below 40 m (Geller et al 2006). At surface, pH was 5.3 indicating acid waters related to the Copahue volcano at the surroundings. Turbidity plumes (interflows) were identified below 18 m depth. DO was lower than 1 mg/l preventing the colonisation of many species.

VILLARRICA (VIL)

This Chilean lake was stratified at only 6 m. Surface temperatures were around 18 º C changing to 16 º C below this depth. However, below the 20 m depth temperature increased to 18 º C at 26 m depth. This behaviour was assigned to hydrothermal activity related to the Villarrica Volcano. PH is also probing these volcanic effects (pH 7.8) although at surface pH water was 9 **(Fig. 3).** DO presented high levels (between 10 and 12 mg/l).

LACAR (LAC)

Lácar is an oligotrophic lake that stratifies at 18 m depth during the summer at the centre of the bay of San Martín de los Andes. Temperature drops in depth from 17 º C at surface to 13º C below the thermocline. PH maintained stable between 8.5 and 9, and no turbidity plumes were recorded **(Fig. 4)**. Dissolved Oxygen increased with depth from 8 to 11 mg/l.

GUTIERREZ (GUT)

In February 2002, the southern sector of the Gutiérrez Lake was stratified with a thermocline at depths of 16-18 m. PH was also stable between 10 and 10.5. A turbidity plume was detected between 9 and 13 m depth. DO was also uniform with levels approaching 4 mg/l **(Fig. 5)**.

PUELO (PUE)

A profile was measured at the vicinities of the inlet of the Azul River in the lake. Temperature was uniform about 15-16º C **(Fig. 2)**. PH was stable betwen 10 and 11. A turbidity plume was detected between 21 and 26 m assigned to the effects of the river inlet. DO was stable around 6 mg/l.

EPUYEN (EPU)

Epuyén Lake was tested stratified at 12 m depth; 18º C were measured at surface and 13º C about 26 m depth. PH was stable around 8.3 **(Fig. 3).** Water was clear from surface to a depth of 12 m, since then it was progressively increasing to maximum turbidity of 200 NTU below 16 m depth (**Fig. 4**).

FUTALAUQUEN (FUT)

At the upper 26 m this lake was uniform with a temperature of 15º C. PH increased with depth from 9.5 to 10 at 17 m depth. As this lake is rather deep and receiving water from other lakes, no turbidity plumes were detected **(Fig. 4)**. DO was only 4 mg/l at surface, diminishing to 2 mg/l in depth.

FAGNANO (FAG)

At this large lake of Tierra del Fuego, temperature is uniform in depth between 10 and 11º C. PH is also uniform at 8. No turbidity plumes were recorded. DO reduced from 5.6 to 4.6 mg/l in depth **(Fig. 5).**

ROCA (ROC)

It has a uniform temperature of 10º C **(Fig. 2)**. PH fluctuates around 10 but with a slight decrease to 14 m depth. Several turbidity plumes were detected at 10, 14 and 20 m depth; below 22 m depth it is transparent again. DO diminished in depth from 4 to 2.6 mg/l.

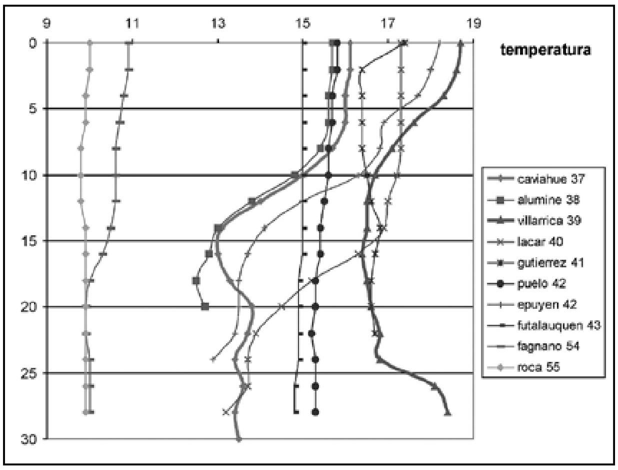


Figure 2. Vertical variations in temperature (°C)

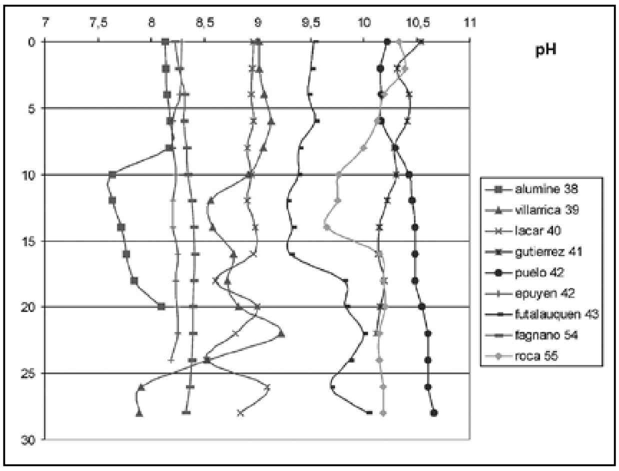


Figure 3. Vertical variations in pH.

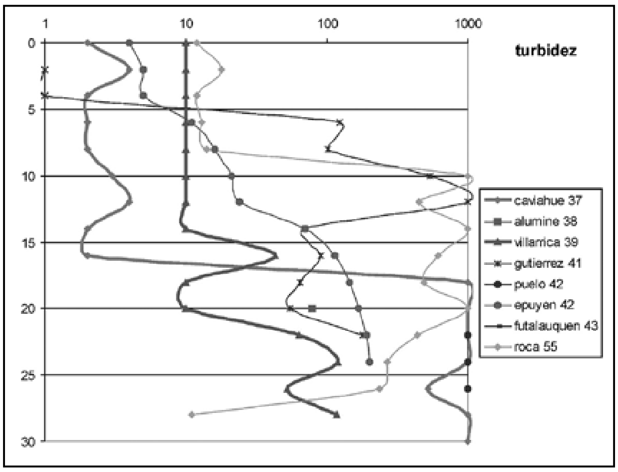


Figure 4. Vertical variations of turbidity (NTU).

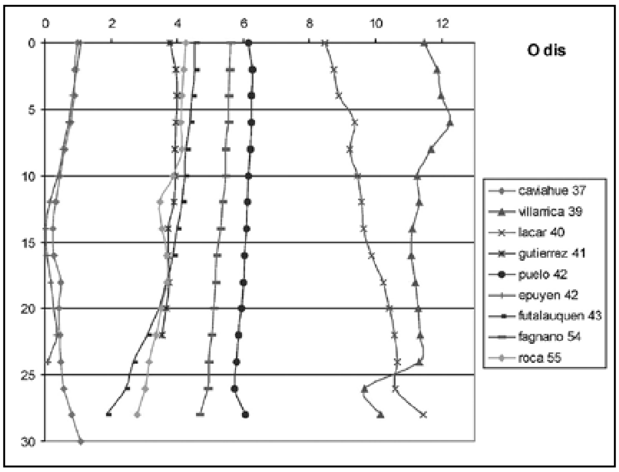


Figure 5. Vertical variations of Dissolved. oxigen (mg/l).

Comparisons between lakes

TEMPERATURE

Lakes from Northern Patagonia, betwen 38 and 40 º S (CAV, VIL, LAC) are subject to a summer stratification between depths of 8 and 12 m due to isolation. South of 40º S, no stratification was recorded. Temperature vertical variations of the Villarrica and Caviahue lakes were explained by hidrothermal processes related to volcanic activity (**Fig. 2**). Thermoclines detected in the lakes between 2001 and 2004 were shallower than those measured in 1980 in the same lakes (CAV, VIL, LAC and GUT; Quirós and Drago, 1985).

PH

Lakes from the Volcanic District (VIL, LAC) are more acid. PH increased to the south to maximum values of 10 (**Fig. 3**).

TURBIDITY

Turbidity plumes were detected at lakes Gutierrez, Puelo and Roca. In Caviahue Lake, turbidity increased significantly below 16 m (**Fig. 4**). In Epuyen Lake, turbidity increased constantly in depth from 12 m.

DISSOLVED OXYGEN

Lakes of Northern Patagonia (Villarrica and Lácar) reported higher values of dissolved oxygen (**Fig. 5**). Wind effects at the Lácar Lake explained this increase in depth. In the acid lake of Caviahue, DO is very low. Lakes without much energy (within tall mountains) that communicate other lakes, and do not receive fluvial supplies have low contents in DO (GUT, FUT and ROC).

Discussion

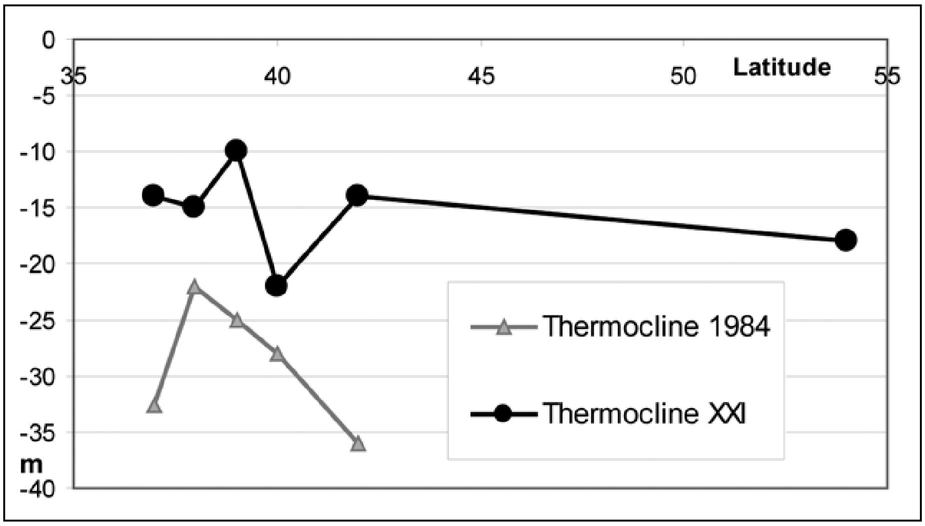
Intra and Inter-hemispheric comparisons

Locations of the summer termocline were significantly shallower than those reported for the summer-autumn (February-April) of 1984 (**Fig. 6**). In those days, the depth of the thermocline was explained in response to the fetch each lake, to the summer wind velocity and in relation to lakes areas (Quirós and Drago, 1985). Considering slight differences in the time of the year of the measurements, the Argentine lakes have lower temperatures than Chilean lakes assumed as subject to colder winters (Quirós and Drago, 1985). However, comparing surface temperatures of 1984 and XXI century there are no significant differences between lakes located north of 42º S.

Lakes respond to the climatic changes that occurred in their watersheds, and those that receive glaciers are reflecting the effects of the ice balance. Considering glaciers draining the South Patagonia Ice Cap, those that were more in contact with lakes (Upsala, Ameghino, O'Higgins, Jorge Montt) receded more rapidly. Those grounded at their outlets (Viedma, Perito Moreno) were more stable in the last years (Lliboutry, 1988).

Norther Andean Patagonian lakes, between 38 and 40° S, are stratified between 14 and 22 m depth. In this sense, they can be compared to alpine lakes from Switzerland that stratified between 12 and 20 m at latitudes of 46-47° N (Lugano, Zurich, Ginebra, Zug, Baldegg, Windermere; Lemmin and Mortimer, 1986). However, some oligotrophic lakes, with a cold monomictic bias, from the southern Patagonia do not stratified, at least in their upper 26 m. These differences can be explained by geomorphologic conditions: northern lakes located to the east of the Andes are protected from westerly winds by the high altitude Cordillera, and are therefore less turbulent in their upper levels; i. e. they have a shallower summer thermocline. Southern lakes are located transverse to the low-relief Cordillera. They are therefore subject to the constant action of the energetic westerlies. A monitoring for seiches (see Hakanson and Jansson, 1995) could explain more about thermocline fluctuations in these lakes. Water-level differences of several decimetres were measured at the Fagnano Lake (J. L. Hormaechea, personal communication).

Figure 6. Depth of the thermocline according to latitude in 1984 and those measured during this century.



Source: Authors.

Climatic effects

Significant changes of high-latitude lakes based on the diatom content in sediments have been related to global warming (Rühland and Smol, 2005; Mackay 2007; Soloieva et al. 2008).

Climatic changes have significant variations in Patagonian lakes. For example, Cardiel (49°S, Argentina) lake level rose 120 m between 12,320 and 10,800 years BP (Ariztegui et al. 2008). The Perito Moreno Glacier (Santa Cruz) was reported as affected by ENSO interannual events and therefore impacting on the Argentino Lake (Depetris and Pasquini, 2001). In a similar way, the Tronador Arm of the Mascardi Lake (Río Negro Province) has fluctuations in its sedimentation rate that was also attributed to ENSO effects (Villarosa *et al.*, 2002). Varved lake sediments from Quebrada de Cafayate (Santa María Basin, 25º S, Salta, Argentina) reveals a relationship to strong ENSO positive phase that produced an increase in mudslides (Trauth et al. 2003). Even lakes from New Zealand were reported to contain an ENSO signal related to wet periods (Eden and Pages 1998). In cores from the Lago Frías (41°S, Argentina), ENSO cycles were recorded in sediments of the last 200 years confirming previous references provided from tree rings (Ariztegui et al. 2007, 2008). These are fluctuations in the hydrologic balances condition thermocline depths and therefore related to their sedimentary record. In this sense, varves are not only recording seasonal variations (summer-winter) but also interannual cycles (Isla and Espinosa 2008).

Patagonian lakes are of special interest to analyze past changes due to their particular evolution during the Quaternary that also permitted the preservation of glaciolacustrine sequences. End moraines not only permitted the flooding of piedmont depressions excavated by glaciers, but also produced changes in the watersheds. These glaciated watersheds that drained towards the Atlantic Ocean during Maximum Glaciation (ice-divide), changed abruptly towards the Pacific Ocean when the glaciers receded (water divide; Quensel, 1910; Caldenius, 1932). Patagonian rivers that flew towards the Atlantic Ocean lost their recharge areas (21-24 %) and recharge volumes (33-34%) delivering less water to the Patagonian desert and therefore transformed into misfit valleys (Isla and Cortizo in press). For example, the Lácar Lake began to drain via the Huahum river; The Epuyén-Puelo complex via the Puelo River, the Futaláuquen via the Grande and Futaleufú rivers, and the Fagnano lake via the Azopardo River. These significant changes in the recharge of the watersheds facilitated the preservation of glaciolacustrine deposits corresponding to larger, higher and deeper Pleistocene lakes.

Episodic effects

Lakes from the volcanic district are episodically affected by volcanism and tectonic activity (Ariztegui et al. 2008; Moernaut et al. 2009). In Icalma Lake (39°S, Chile), earthquakes, landslides or sub-lacustrine slides are assumed to trigger seiches that produced chaotic deposits recognized in geophysical surveys (Bertrand et al. 2008). This lake received an ash deposit about 3000 years BP attributed to the Sollipulli Volcano. Seiches triggered by the earthquakes of 1960 were reported from Lake Puyehue (Veyl 1961) and Nahuel Huapi (Villarosa et al. 2007). Southern Patagonia lakes are also assumed to be affected by Holocene volcanic ashfalls (Stern 1990).

Conclusions

1. Andean lakes of Northern Patagonia are stratified during the summer at depths between 10 and 22 m. These values are shallower than those measured in 1984. As there is not a monitoring program scheduled, these differences can be assigned either to a warming trend or to climatic cycles; ENSO cycles being the more probable.
2. At high-latitude lakes, as Fagnano and Roca (Tierra del Fuego), there is no stratification shallower than 26 m depth. They behave as cold monomictic lakes.
3. Anomalous thermal stratifications were recorded within the Volcanic District (lakes Caviahue and Villarrica) showing hydrothermal effects in depth.
4. Turbidity plumes were detected at the lakes Caviahue, Gutiérrez, Puelo, Epuyén and Roca, between 10 and 26m.
5. With the only exception of the acidic Caviahue and Epuyén lakes, dissolved oxygen varies between 4 and 12 mg/l. In mot lakes, pH varies between 7.5 and 10.5.
6. These characteristics of present lakes should be considered when interpreting ancient deposits that could be related to same watersheds.

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