Diatom-inferred $\delta^{18}O$ of a Bolivian paleolake during the last deglaciation (18.6-11.7 ka):
Impact of paleolake evaporation and water recycling on the isotopic composition of Andean glaciers

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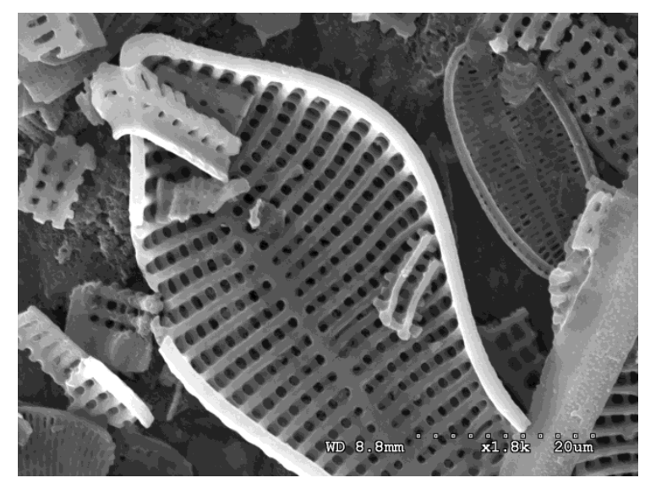
1-Motivation

During the last deglaciation, on the Bolivian Altiplano spread the wide lake Tauca which reached its maximum highstand between 16.5 and 15 ka and covered at least an area of ~51,000 km² (100 m-deep). Overlooking this paleolake, an ice-core record from the Sajama ice-cap that covered the last 25,000 years evidenced an oxygen 18 isotopic excursion of +7‰ matching with the end of the Tauca phase and exhibiting a more pronounced increase of about +5‰ compared with the neighboring ice-core records from the tropical Andes.

Andean paleoclimate and interpretation of continental archives are key challenges. Here we examine to what extent the Tauca lake disappearance could have contributed to moisture source for precipitation on Sajama summit (see Andean signals in Figure 1). To elucidate this question, we used the oxygen isotopic composition of diatoms ($\delta^{18}O_{diatoms}$), complemented by $\delta^{18}O_{ostracods}$, in order to reconstruct the $\delta^{18}O$ variations of the paleolake ($\delta^{18}O_{lake}$ or δ_{lake}).

2-Material and Methods

> Ostracod L.inopinata (EWK 10)



Diatom < (EWK 14)

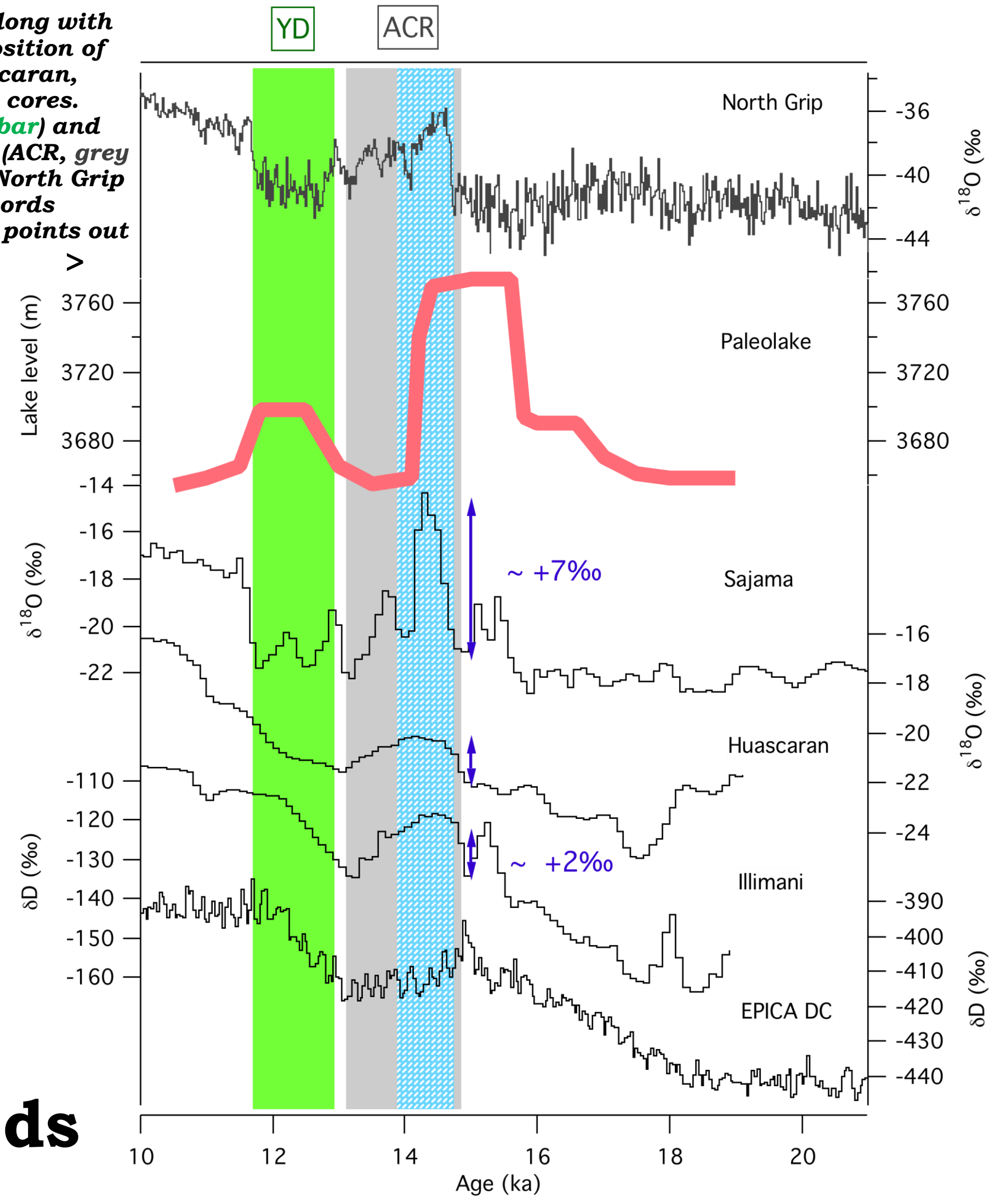
Materials

21 bulk samples rich in diatoms, collected in sediment sections outcropping around the Salars of Coipasa and Uyuni were selected for $\delta^{18}O_{diatom}$ analysis. These samples were described in a previous study dedicated to the lake level chronology coupled with the characterization of the paleoenvironments (Sylvestre et al., 1999).

4 ostracod samples (n=60 by sample) were only found in samples EWK1, 2, 3 and 10. Unfortunately, they are absent from the others samples. Studies sites are displayed in Figure 2. Most of the specimen observed was *Lymnocythere* and we keep a single specie *L. inopinata* from which its vital effect is estimated of δ_{ev}= 0.78±0.20‰, calculated with calcite-water equation of Friedman and O'Neil (1977).

Each section (e.g. EWK, CB, PJ, BT) was ^{14}C dated and the ages of studied samples were calculated by linear interpolation. Each sample age was calibrated using IntCal09. These sedimentary sections cover the lake Tauca phase between ~18.6 and 14.1 ka as well as the lake Coipasa oscillation between ~12.6 and 11.7 ka.

Figure 1 **:** ***Lake level (m) along with the oxygen isotopic composition of North Grip, Sajama, Huascaran, Illimani and EPICA DC ice cores. Younger Dryas (YD, green bar) and Antarctical Cold Reversal (ACR, grey bar) are defined with the North Grip and EPICA DC isotopic records respectively. The blue bar points out the end of Tauca phase*** >



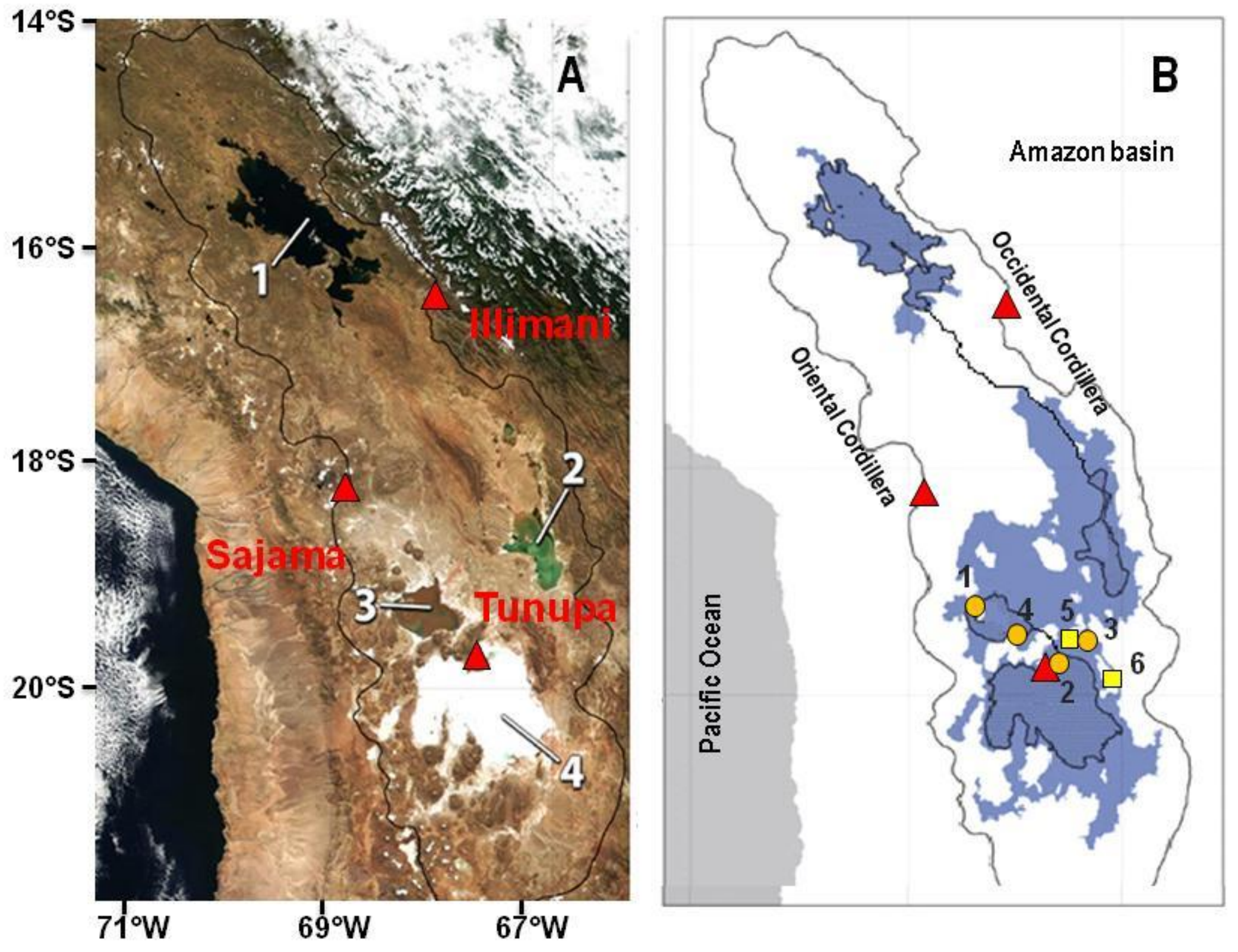


Figure 2 : ***Location of studied sites (1) Estancia Willa Khollu [EWK samples] (2) Churacari Bajo CB [C samples] (3) Pakollo Jahuira PJ [J0 samples] (4) Tauca [BT samples] (common with Blard et al. 2011) and sites (5) Jahuila, (6) Nueva Esperanza from Blard et al. (2011) . Triangles indicate some regional noticeable summits.***

Methods

(1) Dissolution of carbonates and oxidation of organic matter with $HClO_4$ (70%) and HNO_3 (65%) heated at 50°C for ~30 min
(2) Oxidation of organic matter performed using H_2O_2 (33%). Steps 1 and 2 were repeated followed each time by
(3) Rinsing with distilled water.
(4) Clay removal by decanting in settling columns is repeated until a clear suspension is reached. The final purification was achieved by physical extraction using
(5) Laminar flux separation with SPLITT cell system and/or
(6) Densimetric separation using $ZnBr_2$ at a density of 2.3.
(7) Once the **purity of samples > 95%** of diatoms is reached (XRF checking).

Controlled Isotopic Exchange (CIE) (Juillet-Leclerc and Labeyrie, 1987) is used to fix the exchangeable oxygen isotopic composition using two waters of known $\delta^{18}O$ values.

Oxygen extractions were then performed using the **IR Laser-Heating Fluorination Technique** (Crespin et al., 2008). The oxygen isotopic composition of the diatoms was measured with the dual inlet mass spectrometer (ThermoQuest Finnigan Delta Plus).

3-Results

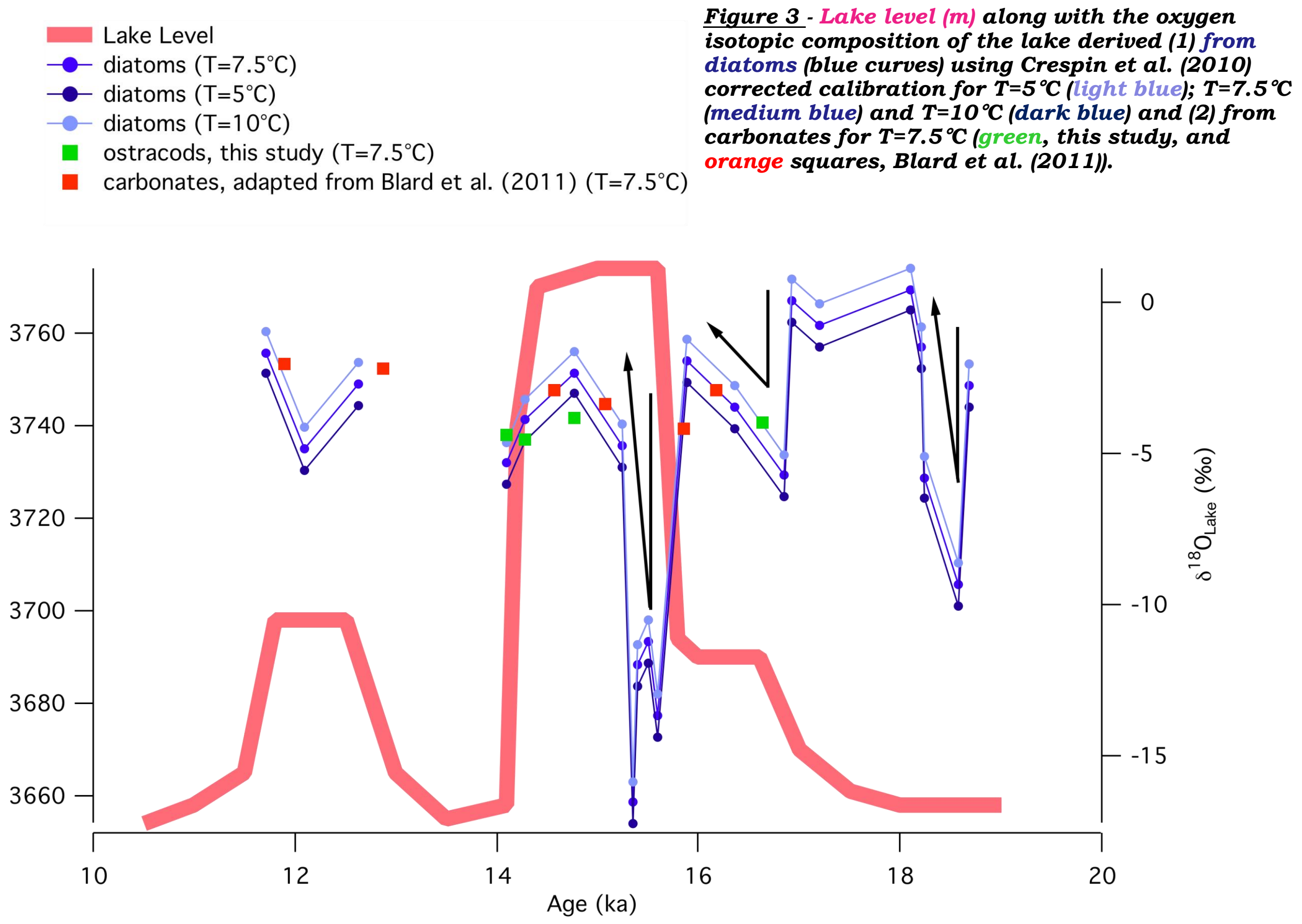


Figure 3 **-** ***Lake level (m) along with the oxygen isotopic composition of the lake derived (1) from diatoms (blue curves) using Crespin et al. (2010) corrected calibration for T=5°C (light blue); T=7.5°C (medium blue) and T=10°C (dark blue) and (2) from carbonates for T=7.5°C (green, this study, and orange squares, Blard et al. (2011)).***

Parameter *a*	Characterization *b*	Default value *c*	Range of change *d*	Literature constraints *e*	^{18}O increase during level-stable phase *f*
h_{Tauca}	Humidity after t_{Tauca}	0.6	[0.4 ; 0.8]	-	[0.2 ; 8.4] ‰
$P(0)$	Precipitation before Tauca phase	400 mm/yr	[300 ; 500]	-	[4.0 ; 4.3] ‰
P_{Tauca}	Precipitation after Tauca phase	600 mm/yr	[400 ; 800]	(Blard et al, 2009)	[1.8 ; 8.7] ‰
δ_{P0}	^{18}O composition before Tauca phase	-20 ‰	[-15 ; -25]	(Thompson et al., 1998)	4.1 ‰
α_P	Local amount effect	-0.02 ‰/mm.yr	[-0.06 ; 0]	(Vimeux et al., 2005)	[1.8 ; 5.2] ‰
S_{TOT}	Tauca catchment area	138 875 km²	[100 000 ; 170 000]	(Blard et al, 2009); (Condom, 2002)	[2.8 ; 7.6] ‰
t_{Tauca}	Time of Tauca filling phase	100 years	[50 ; 300]	This study ; (Condom, 2002)	[0.7 ; 15.7] ‰

Table 1 **-** ***Sensitivity tests performed on the main parameters of the simple hydro-isotopical model.***

$\delta^{18}O_{lake}$ reconstruction

1) Calculation of $\delta^{18}O_{diatoms}$ with CIE procedure.

2) Calculation of $\delta^{18}O_{lake}$ with i) application of diatom silica-water fractionation coefficient (e.g Matsuhisa et al., 1979 ; Alexandre et al., 2012) and ii) choice of constant lake temperature (7,5°C see Blard et al., 2011).

3) Choice of "best" calibration : $\delta^{18}O$ Carbonates-constraints (n=10) to minimize difference between diatom-reconstructed $\delta^{18}O_{lake}$ and carbonates-reconstructed $\delta^{18}O_{lake}$.

4) Best agreement is obtained (~-0.40±1.22‰ at 7.5°C) with corrected diatoms-water equation from Crespin et al. (2010)**,** privileged in this study (see Figure 3)

- **Filling phases : drop in $\delta^{18}O_{lake}$ (15.9ka) coherent with precipitation increase and "amount effect".**
- **Apparent « steady-state lake level » phases : enrichment in $\delta^{18}O_{lake}$ (15.3 ka)**

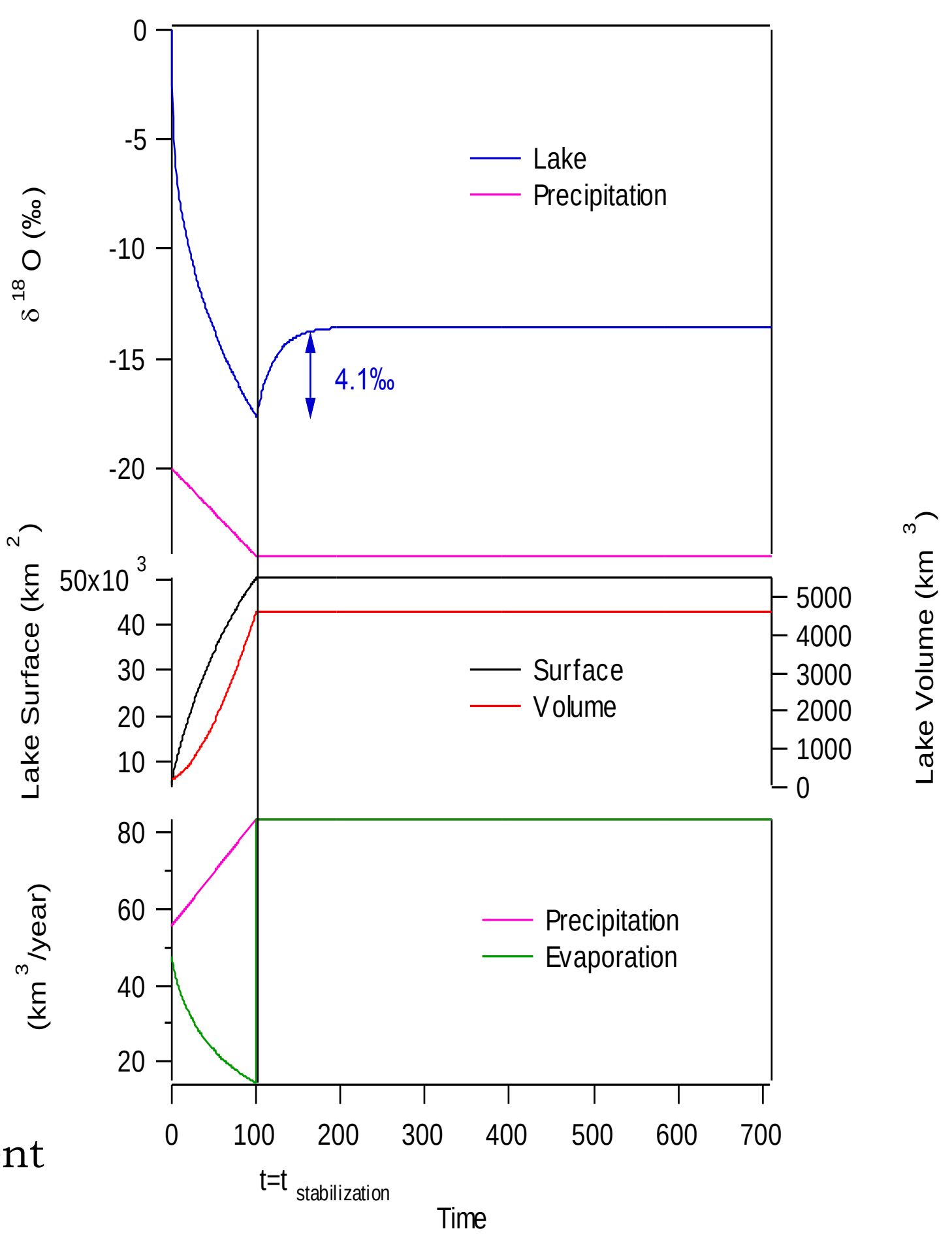
?

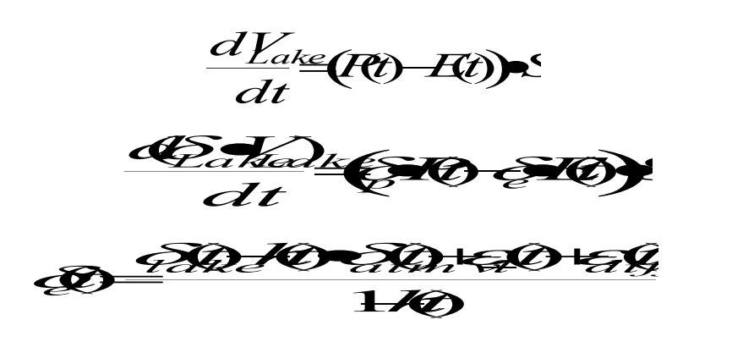
Possible explanations :

- Reduction of high rainfall regime but apparent stable level or Desagauadero depleted input.
- **With stable precipitation regime, can we observe an $\delta^{18}O_{lake}$ enrichment ?** Use of climate inputs constrained by literature (humidity, Precip, Volume(H), Lake elevation H(t), surface S, dV/dt…see Table 1) with basic **hydro-isotopical modelling** (see Figure 4).

Figure 4

Hydro-isotopical modelling





4-Discussion

- **Partial explanation of reenrichment** in stable phase by reduction of evaporative flux and reequilibration of isotopic fluxes (robust positive reenrichment among coherent parameter values, see *Table 1*)

Important caveats :

1) Assumption of **spatial isotopic homogeneity throughout the lake** (~100 m-deep, maximal extension > 400km), which is improbable. But, reconstruction relies on sample series located at different depths and distance from the lake center, suggesting that a potential spatial heterogeneity is partly captured (Figure 1).
2) **Constant lake temperature** during Tauca and Coipasa phases is obviously erroneous but it has only a small influence on the result (see section 5.2.1). Thus, the isotopic shift of 14‰ between 15.4 and 15 ka is not an artifact due to water lake temperature variation along this period.
3) **Use of corrected diatoms-water equation deduced from a modern calibration** in Lake Annecy-France (Crespin et al., 2010). But variations are rather well reconstructed (constant slope of published calibration factors) and constraints are given by rather high-confidence of ostracod reconstruction.

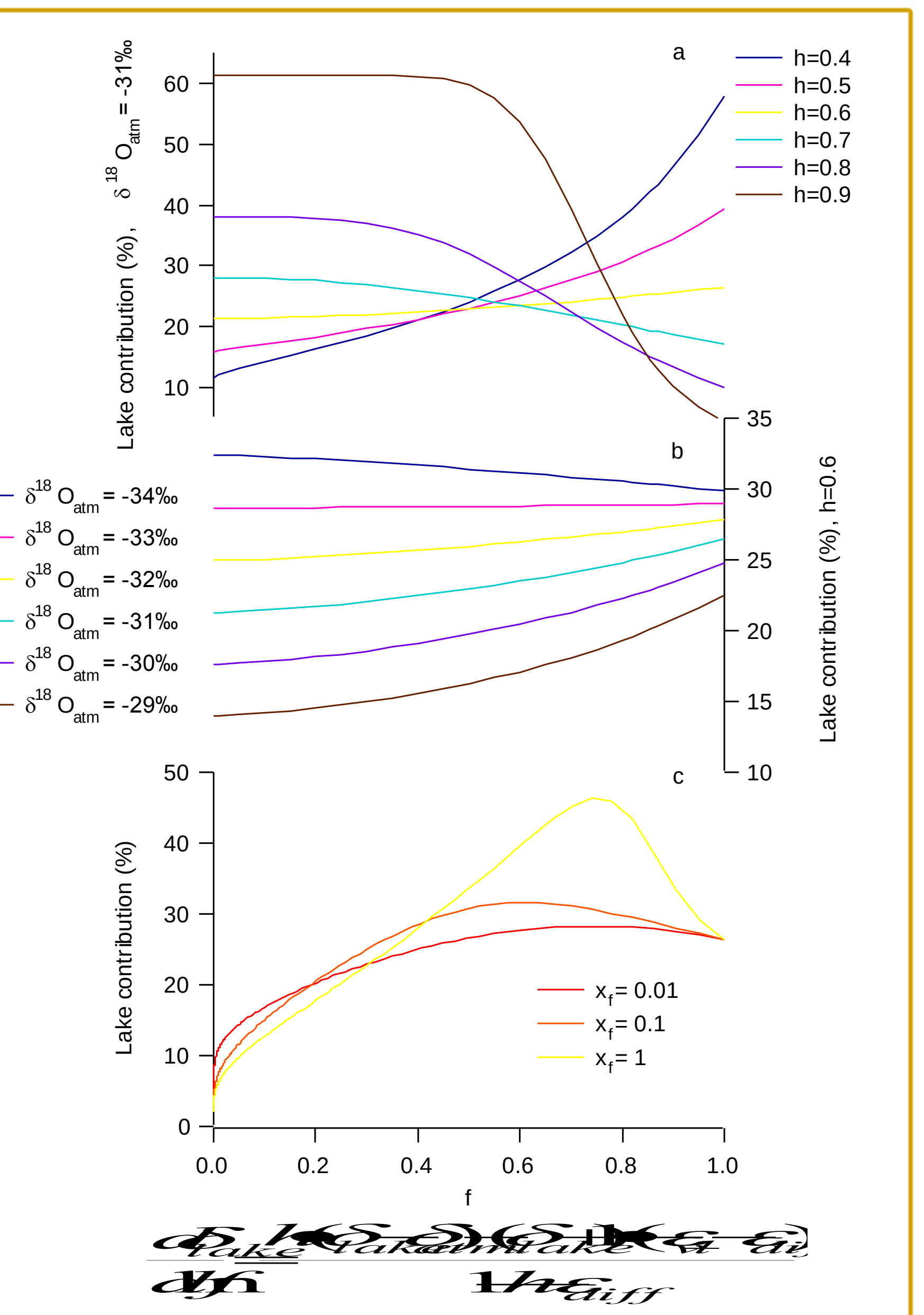


Figure 5 **-** ***Evolution of lake contribution (in %) to Sajama precipitation as a function of the remaining fraction (f) of water in the lake (when lake has disappeared, f=0) for varying h with d18Oatm=-31‰ (isotopic equilibrium at T=2.5°C with d18Op=-20‰) (a); for varying d18Oatm with h=0.6 (b) and for varying d18Oatm and h with for different influence of lake evaporation on the isotopic composition of the atmosphere above the lake (c). Three different relative contribution of advected vapor vs. vapor originating from the lake are displayed (x_f).***

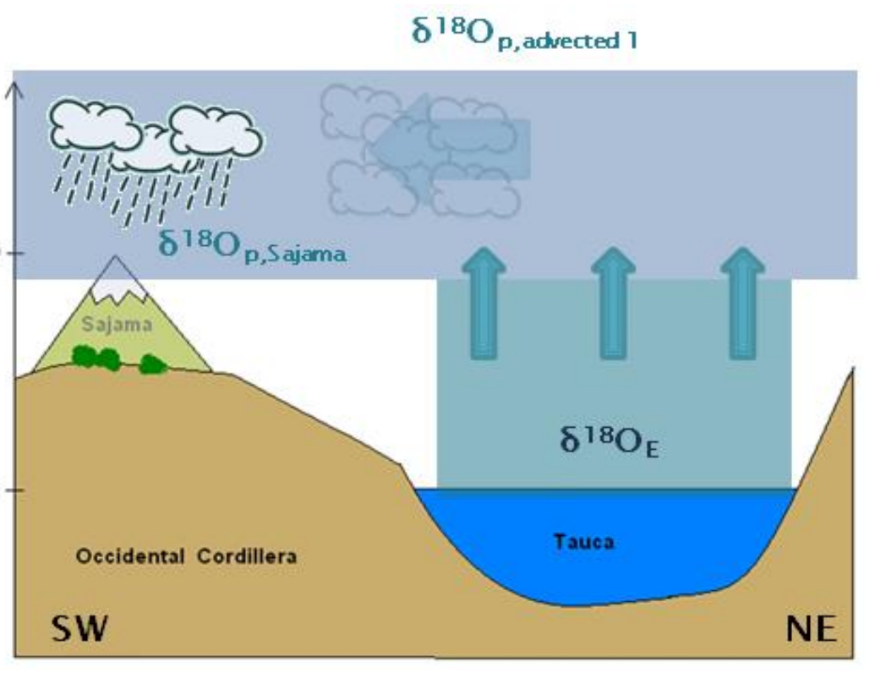


Figure 6 **–** ***Schematic picture of isotopic balance between lake evaporation and advection fluxes.***

- **Extra-enrichment of 5‰ at Sajama can be explained with a water vapor input of lake water varying with a contribution tending to 0 when the lake disappears** (Figure 5).
- **Substantial contribution of lake moisture to regional precipitation with basic considerations :** Lake volume evaporation (~4500 km³) represents ~30-80% of water advection during lake disappearance (Figure 6).

5-Conclusions

- **New and original reconstruction of $\delta^{18}O$ of large Andean paleolake Tauca** and Coipasa water (18.6-11.7 ka) from 21 lacustrine diatom and 4 ostracod samples.
- Strong features appear : 1) **Abrupt depletion of $\delta^{18}O_{lake}$ during lake filling phases** and 2) Enrichment during apparent lake stable phases. ~15.9ka : **Depletion of ~14 per mil concomitant with lake Tauca highstand.**
- Simple hydro-isotopic modelling approach based on literature constraints : Reincrease of $\delta^{18}O_{lake}$ can be partly explained by reduction of evaporative flux during high rainfall regime and consecutive reequilibration of istopic fluxes in steady-state
- **Total or partial (from 5 to 60%) evaporation of the lake during Tauca phase regression could explain the pronounced isotopic excursion at Sajama summit.**

Local hydrological cycle could substantially affect the interpretation of signals from nearby records of isotopic composition of precipitation