Universidad de Concepción

Facultad de Ciencias Ambientales

Programa de Doctorado en Ciencias Ambientales mención Sistemas Acuáticas Continentales

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La Tesis de Doctorado en Ciencias Ambientales con mención de Sistemas Acuáticos Continentales titulada "Reconstrucción de precipitaciones entre la Patagonia septentrional y zona central de Chile: ¿Hay diferencias entre periodos de sequía y mayor precipitación?", de Patricia Alejandra Jana Pinninghoff, realizada en la Facultad de Ciencias Ambientales de la Universidad de Concepción, ha sido aprobada por la siguiente comisión de evaluación:

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Concepción-Chile
2021

FACULTAD DE CIENCIAS AMBIENTALES

Universidad de Concepción

Doctorado en Ciencias Ambientales
Mención en Sistemas Acuáticos Continentales

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Jana, P., Torrejón, F., Araneda, A. and Stehr A. (2018) 'Drought periods during 18th century in central Chile (33_S): A historical reconstruction perspective revisiting Vicuña Mackenna's work', International Journal of Climatology: 39(3), pp 1748-1755. Doi: 10.1002/joc.5884.

Jana, P., Araneda, A., Tejos, E., Fagel, N., Álvarez, D., Schmidt S., Urrutia R., Contreras S. (Enviado a STOTEN) 'Sedimentary leaf wax abundance and δ2H values from two Northern Patagonian lakes: evaluating its sensitivity to reconstruct precipitation changes during the last millennium'.

PUBLICACIONES NO RELACIONADAS CON EL PROYECTO DE DOCTORADO

Fagel, N., Alvarez, D., Namur, O., Devidal, J.-L., Nuttin, L., Schmidt, S., Jana, P., Torrejon, F., Bertrand, S., Araneda, A. and Urrutia, R. (2017) 'Lacustrine record of Holocene eruptions in Northern Chilean Patagonia (45-47°S)', The Holocene: 27(8) pp: 1227-1251. Doi: 10.1177/0959683616687380.

Fagel, N., Pedreros, P., Álvarez, D., Tylmann, W., Namur, O., Da Silva., C., Jana, P., Araneda, A., Billy, I., Schmidt, S., Urrutia, R. (2021) 'Last millennium climate variability of the varved Lake Jeinimeni geochemical record from NE Chilean Patagonia'. Quaternary Science Reviews: 269, Doi: https://doi.org/10.1016/j.quascirev.2021.107134.

EVENTOS CIENCTÍFICOS (CONGRESOS)

N°	Fecha	Evento	País	Título del trabajo	Oral/ Póster
1	Enero/2016	Southern Conection	Chile	Effects of historical fires on lacustrine ecosystems associated with the northern Patagonia settlement process	Póster
2	Mayo/2017	PAGEs	España	Reconstruction of precipitation regimes sicen 1600 AD in Santiago de Chile (33º S) using documentary records as proxy	Póster
3	Diciembre/ 2018	AGU	Estados Unidos	Finding the expression of MCA and LIA along a sediment core from northern Patagonia using fatty acids from leaf waxes (preliminary results)	Póster

ESTANCIAS ACADÉMICAS (PASANTÍAS)

N°	País	Universidad	Escuela/Facultad	Fechas
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A mi primo Pablo

*La **CIENCIA** solo es real cuando se **COMPARTE***

(Adaptado de Emile Hirch/Christopher Mccandless)

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RESUMEN

El Cambio Climático es un problema ambiental de gran interés en los últimos años, el cual se debe al aumento de las emisiones de dióxido de carbono (CO_2) generadas por la acción humana. Por esta razón es importante estableser el comportamiento climático previo a la intervención humana en las emisiones de CO_2. En Chile, existe un gradiente latitudinal de precipitaciones (<1 a >4000 mm/año), en el cuál aumenta de norte a sur. Este cambio se produce debido a la interacción entre el anticiclón subtropical del Pacífico sur (ACP) y la Deriva de los vientos del Oeste (DVO). Además, en la Patagonia chilena, la DVO es la principal responsable por las precipitaciones en esta área y al chocar con el continente, se produce un abrupto gradiente de precipitación que adisminuye de oesta a este. De esta forma, definir la zona más sensible frente a cambios en la intensidad de la DVO es de suma importancia, puesto que se espera que esta zona será capaz de amplificar la señal climática. Así, el objetivo de este trabajo fue reconstruir las precipitaciones entre la zona central de Chile y la Patagonia septentrional chilena para determinar diferencias o similitudes entre periodos de sequía o de mayor precipitación. Para esto se definieron dos zonas de importancia para realizar el estudio, la zona central de Chile (ciudad de Santiago; 33ºS) y los 46º S en la Patagonia Chilena. En la zona central se realizó una reconstrucción climática utilizando registros históricos generados por Benjamín Vicuña Mackenna, quien

plasma la gran mayoría de los registros climáticos existentes de la ciudad de Santiago desde la llegada de los españoles en 1535 DC hasta su publicación en 1877 DC. De esta forma, cuando Vicuña Mackenna relataba un año o periodo de mayor precipitación/sequía, se le asignó un valor de +1/-1. Para realizar la reconstrucción climática en la Patagonia (46º S) se utilizaron registros sedimentarios de los lagos Oscuro y Tranquilo, ubicados dentro del gradiente de precipitaciones que va de oeste a este en esta zona. Se analizaron los indicadores geoquímicos, físicos y sedimentológicos, como materia orgánica, susceptibilidad magnética y granulometría; e indicadores biogeoquímicos como ácidos grasos provenientes de ceras de hoja y δ^2H en el carbón-28 de estos ácidos grasos. En la zona central de Chile (33º S, Santiago) se observaron dos periodos de sequía extrema entre los años 1705 y 1718 AD; y entre los años 1770 y 1797 AD, los cuales podrían estar relacionado con eventos climáticos tipo La Niña. En la Patagonia chilena (46º S), se realizó una reconstrucción de precipitaciones de los últimos 2000 años y las principales conclusiones de esta reconstrucción fue que se encontró un periodo seco , sincrónico con la anomalía climática medieval (ACM; ~800 a 1350 DC) y un periodo húmedo, sincrónico con la pequeña edad del hielo (PEH; ~1400 a 1750 DC y ~1800 a 1900 DC). De las dos áreas evaluadas en la Patagonia (46ºS) para realizar reconstrucciones climáticas, la zona de ecotono bosque-estepa, fue la que mejor representaba la evolución climática del lugar. Finalmente, se realizó la comparación de los registros climáticos, determinando una relación entre la interacción de el ACM y de la DVO en la que, durante la ACM, debido a que se marcan claramente diferentes periodos de aumento y disminución de precipitación, en la cuál la DVO se debilita y disminuyen las precipitaciones.

ABSTRACT

Climate change is an issue that has been in the spotlight during the last years, which has been provoked by the emission of carbon dioxide (CO_2) due to human activities. Therefore, it is important to assess the behavior of climate before human intervention. In Chile, there is an increasisng latitudinal gradient of precipitation from north to south (<1 a >4000 mm/yr), which increases from north to south. This change is produced by the interaction of the South Pacific subtropical high (SPSH) and the Southern Hemisphere westerly wind belt (SHWW). The SHWW is the main responsible for precipitation in Chilean Patagonia. When the SHWW crashes with the continent, all the humidity precipitates on the west side of Patagonia and produces an abrupt gradient. Then, to assess the more sensitive area for changes in precipitation it is important, this area would amplify the climatic signal. The main goal of this work was to made a reconstruction of precipitation between central Chile and north Chilean Patagonia to find differences or similarities in periods of higher and lower precipitation. Two zones were defined to evaluate the changes in precipitation: central chile (Santiago city, 33º S) and the 46º S in the Chilean Patagonia. The climatic reconstruction made in central chile was made using historical records register by Benjamin Vicuña Mackenna, who recorded most of the climatological evidence from Santiago from 1535 AD (Spanish colonization) to the publication of the book

in 1877 AD. Therefore, when Vicuña Mackenna recorded a wet/dry year, a value of +1/-1 was assigned. The climatic reconstruction in Chilean Patagonia (46º S) was made using sedimentary records of lakes Oscuro and Tranquilo, located within the precipitation gradient at 46ºS in west-east direction. Geochemical, physical and sedimentological proxies (e.g. organic matter, magnetic susceptibility, and grain size) and biogeochemical proxies (e.g. fatty acids from leaves waxes and δ^2H in carbon-28 from the fatty acids) were analyzed to determine precipitation differences. Two periods of extreme drought were found in central Chile (33º S), which could be related to La Niña-type events. The precipitation reconstruction in the Chilean Patagonia (46º S), was from the last 2000 years and it was found a dry period synchronous to the medieval climate anomaly (MCA; ~800 a 1350 AD) and a wet period synchronous to the little ice age (LIA; ~1400 a 1750 AD and ~1800 a 1900 AD). From the two sites evaluate in Patagonia, the more sensitive to perform climatic reconstructions were the ecotone forest-steppe. Finally, comparing the two climatic records, from central Chile and Patagonia, we could assess the relationship between the MCA and the SHWW in which, during the MCA there are two periods of increasing and decreasing of precipitation, in which the SHWW is weaker and precipitation decreases.

CAPÍTULO 1: INTRODUCCIÓN, HIPÓTESIS Y OBJETIVOS

1 INTRODUCCIÓN

1.1 Problema Ambiental

El Cambio climático es un problema ambiental de gran interés en los últimos años. Este cambio climático se debe al aumento de las emisiones de dióxido de carbono (CO_2) generadas por la quema de combustibles fósiles y el sistema de economía y consumo humano desarrollado durante el último siglo (IPCC, 2021). El aumento de CO_2 altera el balance radiativo de la atmósfera, pudiendo provocar así un aumento en la temperatura global promedio (Neukom et al., 2014a) y alterando los regímenes de precipitación global (Andres y Peltier, 2016; IPCC, 2021) por sobre la variabilidad natural de estos parámetros climáticos. Los valores de CO_2 han aumentado en un 47% desde 1750 (IPCC, 2021), alcanzando su valor más alto de los últimos 2 mil años en 2019. Además, en 2019, las concentraciones de otros gases de efecto invernadero como CH_4 y N_2O han sido mayores que en los últimos 800 mil años (IPCC, 2021). El (IPCC, 2021) declara en su último reporte que la influencia humana ha aumentado la temperatura global a una tasa sin precedentes de, al menos los últimos 2 mil años. Por otro lado, (Steffen et al., 2015) han determinado que el cambio climático ha sobrepasado la capacidad de carga del sistema terrestre, lo cual traería graves consecuencias tanto económicas como sociales (Cowie, 2007; IPCC, 2014; Vörösmarty et al., 2013).

El cambio climático inducido por los seres humanos, ya está teniendo efectos, provocando eventos metrológicos extremos a nivel global (IPCC, 2021). En el sexto reporte sobre cambio climático (AR6) del Panel Intergubernamental de Cambio Climático (IPCC), ha aumentado la evidencia desde el reporte anterior, de que cambios climáticos extremos como el aumento de: olas de calor, alta precipitación en el área intertropical, sequías en las regiones subtropicales, y ciclones tropicales son atribuidas a la influencia humana. Sin ir más lejos, Chile está viviendo actualmente una sequía en la zona central sin precedentes durante el último milenio (Garreaud et al., 2019). El AR6 (IPCC, 2021), proyecta una disminución de hasta un 25% en las precipitaciones al año 2100 en el sector oeste del sur de América del Sur (área correspondiente a Chile; IPCC 2021). Esta disminuciòn del 25% en las precipitaciones (Garreaud et al., 2019; IPCC, 2021) se proyecta utilizando el modelo CIMP6 con utilizando el escenario de emisión RCP8.5 y un aumento de 2 ºC en la temperatura global y utilizando como base de comparación el periodo pre-industrial entre 1850 y 1900 (IPCC, 2021).

Los modelos utilizados para realizar las proyecciones de cambio climático de los reportes del IPCC, como el CIMP6, están basados en datos obtenidos por reconstrucciones climáticas (IPCC, 2021). Las reconstrucciones climáticas son de suma importancia para determinar las condiciones de precipitación y temperatura previas a las emisiones de CO_2 y otros gases de efecto invernadero que comenzaron con la revolución industrial en ~1750.

Lo antes expuesto es de especial interés para el país, puesto que su zona centro concentra la economía en la actividad agrícola, lo cuál podría causar una caída en la producción de cultivos y, por ende su exportación (IPCC, 2021). En la Patagonia Chilena también es preocupante esta proyección hídrica, debido a que es el escenario natural donde se encuentran los Campos de Hielo Norte y Sur, una de las mayores reservas de agua a nivel mundial (Aniya et al., 1997). Por lo tanto, proyecciones robustas de cambio climático son cada vez más necesarias. En la actualidad, los registros instrumentales en zonas remotas de Chile, como el centro-sur de Chile, son escasos y por ende de baja resolución espacial, los cuales no siempre contienen un registro continuo de los últimos 30 años para obtener su climatología (Contreras et al., 2018). Es por esto la importancia de levantar información climática especialmente en zonas como la Patagonia Chilena.

1.2 Clima actual en Chile

El Desierto de Atacama comienza en la zona sur del Perú y en Chile abarca todo el norte, desde Arica (18º 24’ S) hasta La Serena (29º 55’ S; Figura 1 del Capítulo 4). Este desierto es el más árido en todo el mundo, habiendo lugares en los cuales no se registra precipitación (climatologia.meteochile.gob.cl/; Figura 1). Este fenómeno se da debido a varios factores, entre ellos: (i) La cordillera de Los Andes es de gran altura (sobre los 5000 m.s.n.m.), actúa como barrera de los vientos alisios que provienen del este y puedan entregar humedad al desierto (Garreaud et al., 2009). (ii) Esta zona es la subsidencia de la Celda de Hadley, formándose el anticiclón del Pacifico, lo que genera altas presiones en la costa y no permite el paso de humedad (Flores-Aqueveque et al., 2020; Garreaud et al., 2009). El anticiclón del Pacífico (Figura 2) influencia a todo el norte de Chile y Chile central, se extiende desde los ~5º S hasta los ~30º S durante invierno y durante el verano se expande (Garreaud et al., 2009) hasta los ~40º S en su límite sur, latitud que marca el inicio de la Patagonia Chilena.

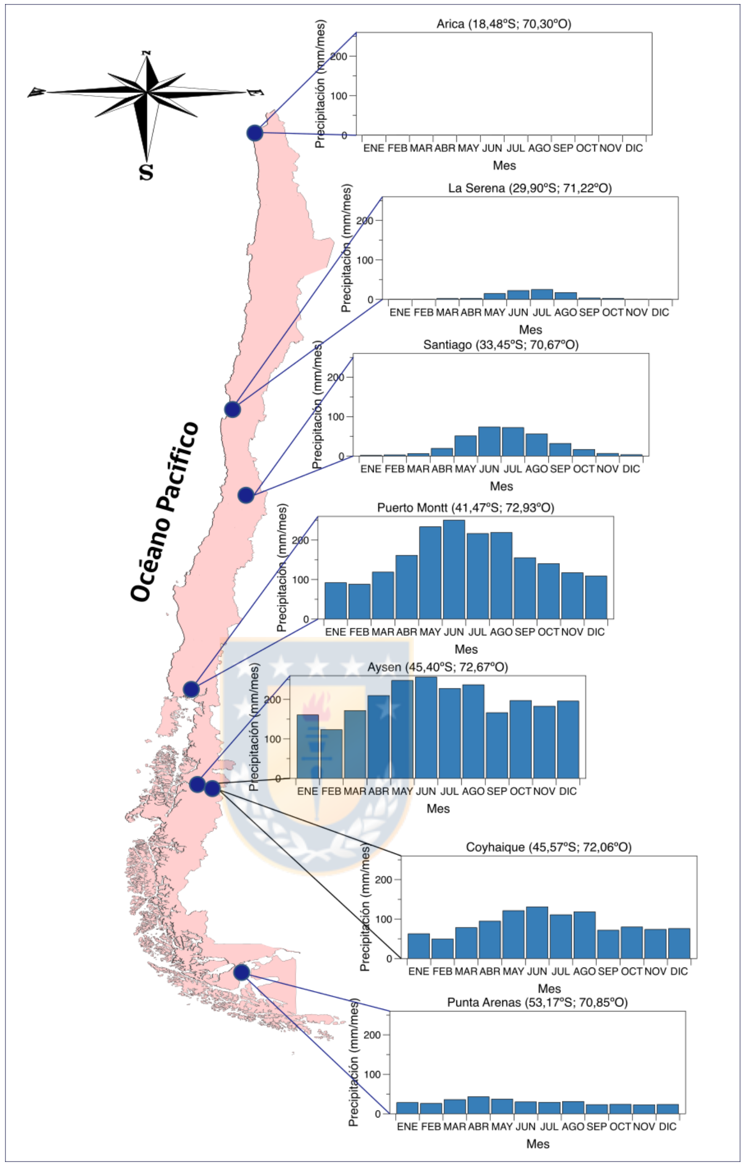

Figura 1: Precipitación mensual promedio entre 1979 y 2018 en siete ciudades de Chile. Fuente: Datos reanalizados de Centro de Ciencias del Clima y la Resilencia (CR2), desde 1979 a 2018.

La precipitación en Chile central, entre los ~30º S y ~40º S, es principalmente de origen orográfica. La precipitación en estas latitudes es mayor durante los meses de invierno y, durante el verano disminuye drásticamente. Así mismo, existe un gradiente latitudinal, en el cuál la precipitación anual es menor en el norte (<1 mm/año en Arica; Figura 1) aumenta hacia el sur (>2500 mm/año en Puerto Aysén; Figura 1) (Contreras et al., 2018). Este cambio se produce debido a la interacción entre el anticiclón del Pacífico y la Deriva de los vientos del Oeste (DVO; **¡Error! No se encuentra el origen de la referencia.**). La interacción entre la DVO y el anticiclón del Pacífico determina esta área como zona de transición entre el desierto de Atacama y la Patagonia chilena.

La Deriva de los Vientos del Oeste (DVO), que giran alrededor de la Antártica, son simétricos debido a la poca masa continental. Como consecuencia, la DVO choca en su totalidad con el continente Sudamericano en la Patagonia (Figura 3). Al sur del los ~40º S, los DVO prevalecen todo el año. Durante el verano sus vientos tienen el periodo de mayor velocidad, con un máximo entre los 45º S y 55º S. En el invierno, la DVO se mueve hacia el norte hasta los 30º S, por lo que a la altura de los 50º S (su núcleo) se debilitan. Por lo tanto la precipitación durante el invierno se concentra desde los 30º S hasta los 50ºS y durante el verano se concentra entre los 40º S y 55º S. El choque del DVO con el continente provoca uno de los gradientes de precipitación más abruptos del planeta. Mientras que en el lado Oeste se pueden registrar precipitaciones de más de

4000 mm/año, en el lado Este la precipitación puede llegar a menos de 300 mm/año (Garreaud et al., 2013).

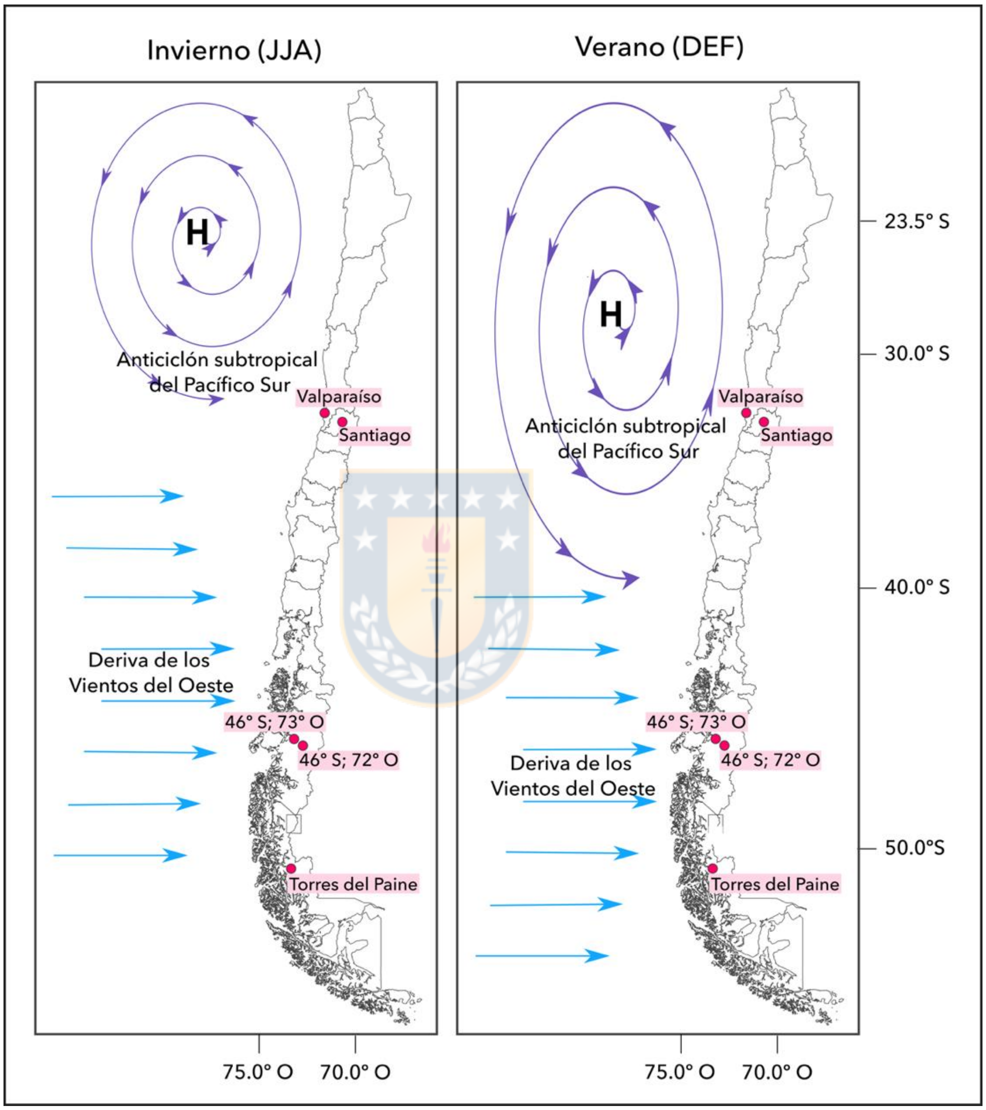

Figura 2: Representación gráfica de la influencia del anticiclón del Pacífico y la deriva de los vientos del oeste (DVO) a lo largo de Chile durante el invierno (figura izquierda) y durante el verano (figura derecha), desde el océano Pacífico (este) hacia el continente (oeste) y lugares claves en los cuales se registran datos de precipitación. Adaptación de Garreaud et al. (2009)

El cambio abrupto de precipitación generado por el choque de la DVO con el continente modela la composición de la vegetación de esta zona desde el oeste hacia el este (Figure 1 del Capítulo 3; Martinic 2005). En la zona cercana al océano pacífico, dominan estructuras de Matorral siempreverde y Turberas y matorral siempreverde de pantano (Gajardo 1994). En dirección al este, la cordillera aumenta su altitud hasta 1500 m.s.n.m., las precipitaciones sobrepasan los 4000 mm/año y el Bosque siempreverde de Aysén y Bosque siempreverde de Puyuhuapi (Gajardo 1994) son las estructuras vegetacionales dominantes. Una vez pasadas las cumbres de la cordillera de los Andes, en dirección hacia el oeste, la precipitación disminuye (~1500 mm/año) y la composición boscosa dominante pasa a ser el Bosque caducifolio de Aysén (Gajardo 1994). Este bosque es una zona de transición entre el bosque siempreverde y la estepa patagónica, es decir, un ecotono de bosque a estepa (Martinic 2005). Finalmente, en el flanco este de la Patagonia chilena (alrededor del límite entre Chile y Argentina) la composición vegetacional dominante es la Estepa Patagónica de Aysén (Gajardo 1993), debido a la baja de precipitación en esta zona (<300 mm/año).

En cuanto a los factores que controlan la precipitación en la Patagonia, la velocidad del viento (de la DVO) es el principal factor. Así, (R. D. Garreaud et al., 2013) evidencian una alta correlación entre la precipitación y la velocidad del viento ($r(P, U_{850})$; ~0.8) en el flanco oeste de la Patagonia. Por lo tanto, al aumentar la velocidad del viento, la precipitación aumenta en este sector (Figura 3). Además, (R. D. Garreaud et al., 2013) evidencia que, a medida que la masa de aire avanza por el continente hacia el este, se pierde la correlación entre la velocidad del viento y la precipitación. En este sentido, los estudios (e.g. Mayr et al., 2013; Oehlerich et al., 2015; Bertrand et al., 2012; Elbert et al., 2011; Fletcher y Moreno, 2012; Holz et al., 2012; Jara y Moreno, 2012; Moreno et al., 2010, 2009; Moy et al., 2008; Villa-Martínez y Moreno, 2007) que se han realizado para la reconstrucción de la DVO en la Patagonia abarcan todas las zonas climáticas de la Patagonia, pero aún no hay consenso sobre cuál es, efectivamente, el área más sensible frente a cambios en la intensidad de la DVO.

Mientras que Moreno et al. (2010), Villamartinez y Moreno (2007); Jara y Moreno (2012); retratan un aumento de las precipitaciones al encontrar un aumento de polen de *Nothofagus* en la zona del ecotono, a través de un índice *Nothofagus*/Poaceae. Estos autores encuentran que la zona más sensible para realizar estudios climáticos sería el ecotono, por ser una zona de transición, debido a que es posible observar una expansión o retroceso en el bosque. Por otro lado, Mayr et al. (2013), Oehlerich et al. (2015) y Zolitschka et al. (2019); señalan que el sector más sensible para realizar estudios climáticos es el flanco este de la Patagonia, puesto que la evaporación aumentaría con la velocidad del viento, amplificando así señales climáticas de baja magnitud.

El poder identificar la zona más sensible frente a cambios en la intensidad de la DVO (Figura 3), para poder identificar eventos climáticos de baja magnitud es de suma importancia para los últimos mil años. Dos periodos de baja magnitud (cambios en la temperatura de entre 0.5º y 1.5º C) se han identificado durante el último milenio en la Patagonia: la Anomalía Climática Medieval (ACM) y la Pequeña Edad del Hielo (PEH). La ACM se manifestó como un periodo cálido y seco durante los años ~800–1350 AD (Neukom et al., 2014b; R. Neukom et al., 2011) y la PEH se manifiesta como periodos fríos y húmedos durante los años ~1400–1750 AD y 1800–1900 AD (Neukom et al., 2014b; R. Neukom et al., 2011). Entonces, se plantea la siguiente pregunta: ¿Cuál de es la zona bioclimática más sensible a los cambios climáticos y ambientales? **…..…………………………………………………………...……………………………..(1)**

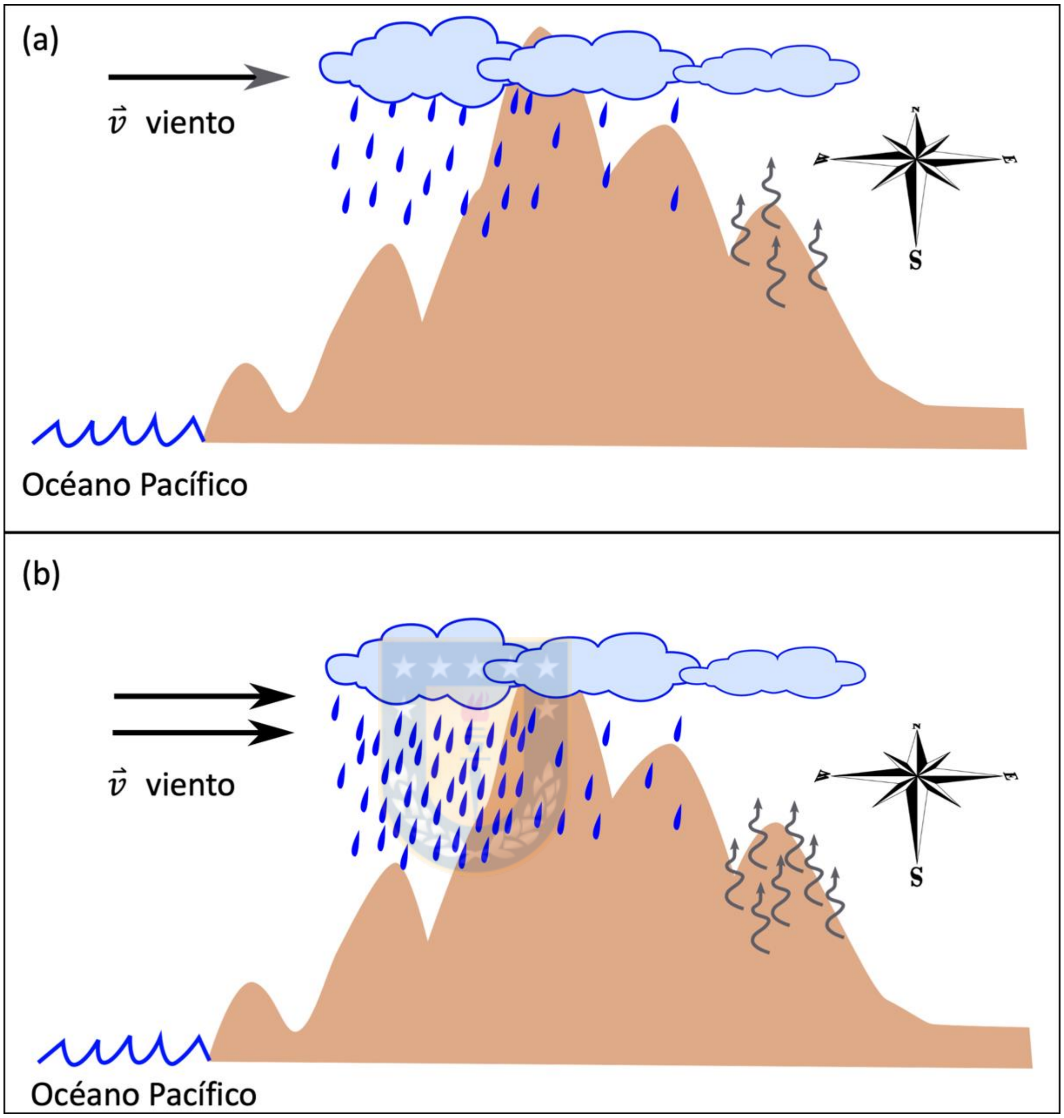

Figura 3: Representación esquemática sobre la relación de cambios en la velocidad del viento y el efecto que este tendría sobre las tasas de evaporación y precipitación en los flancos oeste y este de la Cordillera de los Andes. (a) escenario de menor precipitación; (b) escenario de mayor precipitación.

1.2.1 Variabilidad interanual e interdecadal

A lo largo de Chile existen tres anomalías climáticas de variabilidad interna, interanual e interdecadal, las que regulan la variabilidad climática en el país: (i) El Niño Oscilación Sur (ENOS); (ii) Oscilación Decadal del Pacífico (ODP); y (iii) Oscilación Antártica (OAA) o Modo Anular Sur (MAS). ENOS es una anomalía climática que tiene su raíz en el Pacífico tropical y fluctúa entre periodos de aumento en la temperatura oceánica superficial (El Niño o fase positiva) y disminución de esta (La Niña o fase negativa). (Garreaud et al., 2009) correlacionó el Índice Multivariado de ENOS (IME) con un aumento en las precipitaciones en Chile central y un aumento en las temperaturas durante la fase positiva de IME. En su fase negativa se encontró una correlación opuesta en el mismo territorio. Además estos autores determinaron que los meses de mayor influencia del ENOS en Chile central es durante los meses de invierno (Garreaud et al., 2009).

La ODP es una oscilación decadal de precipitaciones y temperaturas tipo ENOS, pero con mayor amplitud. Esta oscilación está relacionada con ENOS en cuanto a su influencia espacial, por lo tanto la ODP sería un modulador de ENOS. Así un ENOS positivo sería aún más fuerte durante una fase positiva de ODP y viceversa.

El MAS es el patrón líder de la circulación troposférica al sur de los 20º S. Se caracteriza por tener anomalías de presión de un signo centradas en la Antártica y de signo contrario en una banda circumglobal entre los 40º y 50º S. Al parecer este fenómeno viene de la interacción entre los vientos zonales y ciclones de baja intensidad. Un MAS positivo conlleva a una baja de la presión superficial y, por lo tanto se produce una disminución de las alturas geopotenciales en la Antártica y lo contrario sucede en latitudes medias (centro-Chile). Es así como se formaría una especie de balancín de precipitaciones entre latitudes altas y latitudes medias (Figura 4). Por lo tanto, durante un periodo de MAS positivo, disminuyen las presiones y alturas geopotenciales en la Antártica, se desplaza la DVO hacia el sur y expande el anticiclón del Pacífico, cambiando el régimen de precipitación a lo largo de Chile (Flores-Aqueveque et al., 2020; Garreaud et al., 2009). Esta condición ha prevalecido durante los últimos 30 años (R. Garreaud et al., 2013; Garreaud et al., 2009). De hecho, (Garreaud et al., 2009), observaron que existe un fenómeno tipo-MAS que regula el movimiento anual de la DVO.

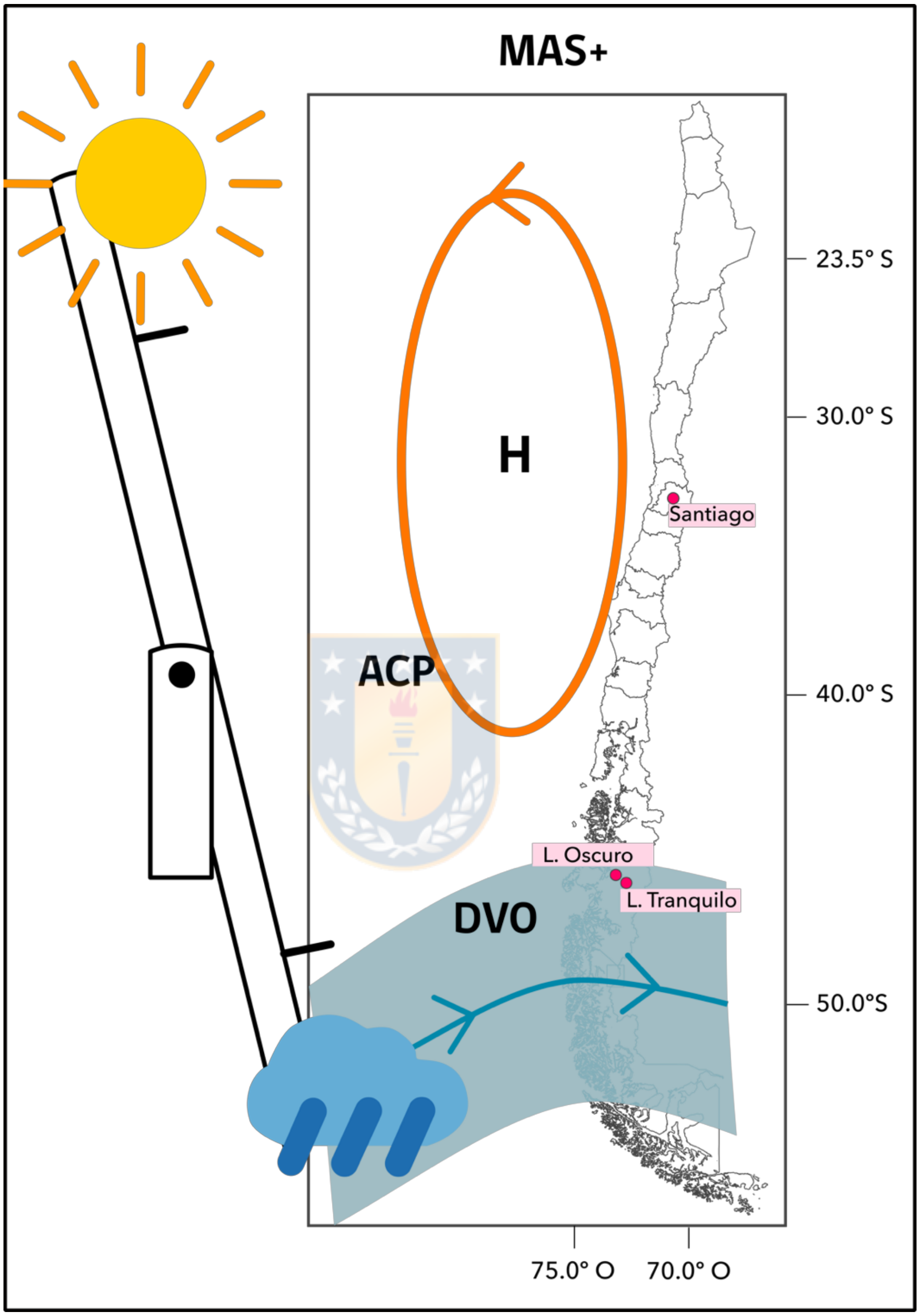

Figura 4: Esquema representando el balancín que provoca un MAS positivo. Así, al subir las temperaturas al sur de los 60ºS, la DVO se mueve hacia el polo y el ACP se intensifica. Las precipitaciones aumentan en el sector donde se mueve el centro de la DVO y disminuye en los extremos. Además como el ACP se intensifican, se produce sequía en Chile central

Para ver el comportamiento actual de las precipitaciones, se estableció una correlación simple para la precipitación en diferentes latitudes de nuestro país, utilizando la serie de de precipitación mensual (1979 a 2018) de los datos reanalizados desarrollados por el Centro de Ciencias del Clima y Residencia (CR2; www.cr2.cl/datos-productos-grillados/; Figura 5.a). Esta correlación fue de -0.62 ($p<0.001$) entre la precipitación acumulada de los tres meses de invierno (junio, julio y agosto) Chile central (33º S; Figura 3) y Patagonia sur (51º S; Figuras 3.b). También existe una correlación negativa de -0.5 entre Chile central y la Patagonia norte (46º S; Figura 5.b), lo cual explicaría una migración de la DVO hacia el norte durante el invierno, provocando así una disminución de las precipitaciones en el límite sur de la DVO y aumentándolas en el límite norte. Pero, ¿Qué pasa en el pasado? ....**(2)**

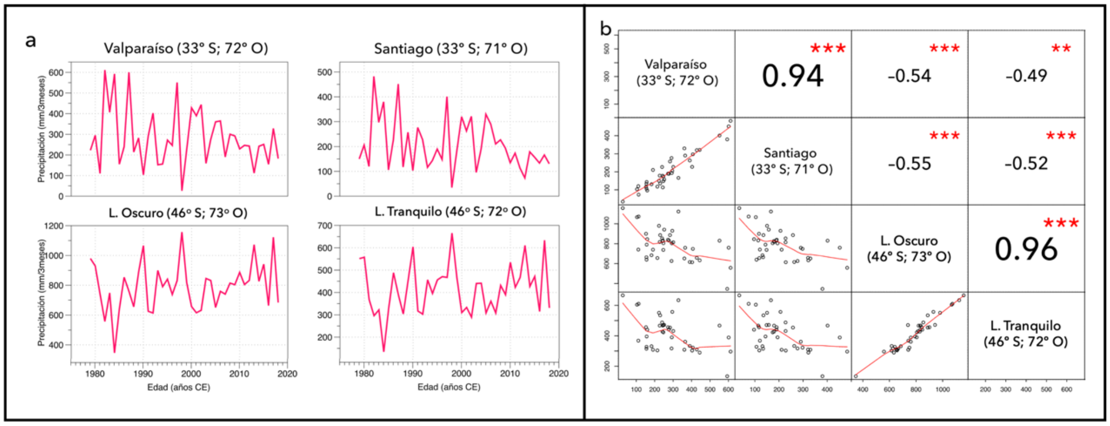

Figura 5: a) Serie de tiempo de precipitaciones durante los meses de invierno (junio, julio y agosto) obtenidas desde los datos reanalizados de Centro de Ciencias del Clima y la Resilencia (CR2), desde 1979 a 2018. b) Matríz de correlación entre las diferentes series de tiempo. En la parte superior se indica la correlación (R^2) y su grado de significancia (*** indica valores de p menores a 0.001 y ** indica valores de p entre 0.001 y 0.01). en la parte inferior se puede observar la gráfica y tendencia de estas correlaciones.

1.3 Determinación de condiciones pasadas

Determinar la variabilidad climática es de gran importancia para mejorar las predicciones de cambios en el futuro (Neukom et al., 2014a), especialmente dentro del último milenio, periodo en que la variabilidad climática no estuvo afectada por el hombre (Álvarez et al., 2015; Andres y Peltier, 2016; Moy et al., 2008). Variados estudios (e.g. Christie et al., 2011; Elbert et al., 2011; Garreaud et al., 2009; Gunten et al., 2009b; le Quesne et al., 2006; Mann et al., 2008;

Martel-Cea et al., 2016; Muñoz et al., 2016; R Neukom et al., 2011) han realizado proyecciones de cambio de las variables climáticas, utilizando menos de 100 años de datos registrados de precipitación, debido a la falta de estos en periodos más antiguos.

Estudiar la variabilidad climática durante el último milenio permite establecer una línea de base del comportamiento de las variables climáticas sin la influencia del hombre, en cuanto a su explosión demográfica y previo a la revolución industrial, y con oscilaciones cercanas a las actuales. En este contexto, los estudios históricos y paleolimnológicos toman una mayor relevancia (Brázdil et al., 2010, 2005; Lamy et al., 2010; Larocque et al., 2001; Neukom et al., 2014a; Prieto y Herrera, 2009), especialmente en las zonas donde los registros instrumentales son muy escasos o no existen, como es el caso de América del Sur (Neukom et al., 2014a) y, en especial la Patagonia Chilena (Contreras et al., 2018), en donde se tiene por objetivo aumentar el rango de registro, disminuir la incertidumbre de las reconstrucciones (Gagen et al., 2006).

En este sentido, Lamy et al. (2010) realizó una reconstrucción tomando todo el periodo del Holoceno y utilizando la climatología actual para realizar una interpretación de sus resultados. Los autores observaron que durante el Holoceno temprano (~10 ka BP), la precipitación era sustancialmente menor en Chile central (33º S) que en la Patagonia sur (53º S), donde realizaron su estudio.

Al contrario, durante el Holoceno medio (~5.5 ka BP), ellos observaron que mientras en Chile central disminuían las precipitaciones, en la Patagonia sur aumentaban. Lamy et al. (2010) asociaron este cambio de precipitación a escala milenial a patrones de movimiento de la DVO similares a los descritos durante invierno y verano (Garreaud et al., 2009; Lamy et al., 2010). Los movimientos de la DVO estacionales se refiere a que, durante el invierno/verano austral la DVO emigra hacia el norte/sur, por una condición negativa/positiva del MAS y una disminución/aumento en la intencidad del ACP. Sin embargo, ¿será posible describir este fenómeno a menor escala i.e. centenial y/o decadal?**..(3)**

1.3.1 Documentos históricos para reconstrucciones climáticas

Entre los archivos utilizados para realizar reconstrucciones pasadas del clima, los registros documentales son los más precisos. Los registros históricos pueden representar con fechas precisas y directamente condiciones climáticas adversas que pudieran originar cambios en la organización social de un lugar determinado (Brázdil et al., 2005; Prieto y Herrera, 2009). Además estos registros tienen alta resolución temporal, permitiendo distinguir entre diferentes eventos que se produjeron en un corto periodo de tiempo (Brázdil et al., 2005). Algunas desventajas son, en algunos casos la falta de datos continuos y la influencia en la percepción de quién o quienes registraron estos eventos. En Chile los registros históricos comenzaron con la llegada de los Españoles, puesto que los indígenas pertenecientes al territorio Chileno, no contaban con escritura, solo con relato oral (Prieto y Herrera, 2009). Como una forma de complementar los registros históricos como archivos temporales, es posible utilizar sedimentos lacustres.

1.3.2 Sedimentos lacustres como archivador temporal

Otra forma de estudiar la variabilidad climática pasada, es mediante el uso de los sedimentos lacustres, ya que estos actúan como archivos del pasado, puesto que registran una mezcla de señales ambientales y climáticas (Håkanson y Jansson, 1983; Smol, 2008). El registro ambiental y climático proviene de dos fuentes: autóctonas y alóctonas. El componente autóctono corresponde, a restos biológicos originados en el mismo sistema lacustre y que han sido depositados en los sedimentos luego de cumplir con su ciclo de vida. Algunos ejemplos de estos organismos son diatomeas, crisofíceas y quironómidos (Battarbee y Bennion, 2011; Smol, 2008). En cuanto al material alóctono, originado fuera del sistema lacustre y que puede llegar a él en diferentes manera: (i) a través de la escorrentía, donde los componentes orgánicos e inorgánicos del suelo llegan al lago; (ii) A través de la atmósfera, desde donde partículas como polen, radionucleídos radioactivos (^{210}Pb, ^{137}Cs, ^{14}C), ceniza volcánica, entre otros, llegan al lago por transporte físico y a través de la precipitación, depositándose por gravedad en el sedimento; (iii) a través de acuíferos, incorporando nutrientes y minerales (Håkanson y Jansson, 1983; Smol, 2008).

La ventaja de utilizar sedimentos lacustres como archivos ambientales es que estos registran señales ambientales de toda la cuenca y sus alrededores, tales como cambios de uso de suelo, erupciones volcánicas y variabilidad climática (Álvarez et al., 2015; Neukom et al., 2014a). Tanto las partículas autóctonas y alóctonas son depositadas en el sedimento lacustre de forma laminar, obedeciendo a la ley de superposición (Smol, 2008), la cual, generalmente establece que los depósitos más profundos son los más antiguos y los más nuevos se superponen progresivamente. Así, el análisis de indicadores, tanto biológicos como geoquímicos, permite establecer series de tiempo y reconstruir condiciones ambientales y climáticas pasadas.

1.3.2.1 Indicadores geoquímicos

Los indicadores geoquímicos se utilizan para determinar cambios en la composición del sedimento, que pudieran ser producidos por cambios geográficos, ambientales y/o climáticos. Los indicadores más utilizados son el carbón orgánico total, nitrógeno total, isótopos estables ($\delta^{13}C$), susceptibilidad magnética y granulometría. En cuanto a los indicadores orgánicos en el sedimento, se ha determinado su origen (autóctono o alóctono) utilizando la proporción de carbón orgánico y nitrógeno total (C/N) (Meyers y Teranes, 2001). Las algas tienen un valor de C/N cercano a 6.6, debido a que su compoción es alta en nitrógeno (Bertrand et al., 2012). El valor de C/N de las algas, por lo tanto, el material orgánico que es producido en el lago tiende a tener valores de C/N menores a 10. Así cuando el C/N se acerca a valores menores a diez, se asocia a un aumento en la productividad primaria. Por el contrario, el material proveniente de la cuenca, el cuál es altamente influenciado por plantas terrestres, los valores suelen ser sobre 20 (Meyers y Teranes, 2001; Smol, 2008), debido a que su principal componente es la lignina, teniendo así un mayor porcentaje de carbono (Bertrand et al. 2012).

La susceptibilidad magnética y tamaño de grano del sedimento son parámetros básicos informativos de la historia ambiental y climática de la cuenca. En conjunto, es posible asociar un aumento de ambos parámetros con el aumento de precipitación (Gilli et al., 2005). Osea, por ejemplo, al aumentar la precipitación, aumenta la escorrentía, por ende aumenta el material terrígeno, orgánico con un alto contenido en fierro (elemento más abundante en el suelo), lo cuál aumentaría el porcentaje de carbono orgánico total, con un C/N sobre 20, incremento de susceptibilidad magnética y un aumento del tamaño del grano producto del aumento de la energía cinética provocada por la precipitación. Por ejemplo,

Bertrand et al. (2014), realizó un reconstrucción de las precipitaciones del fiordo Quitralco, a través de cambios en la granulometría del sedimento, debido a que el río Pelu arrastraba material de mayor tamaño, debido al aumento de energía en la precipitación en la cuenca de este río.

1.3.2.2 *Indicadores biogeoquímicos*

Indicadores biogeoquímicos, más específicos que los geoquímicos, como los isótopos estables del hidrógeno (δ^2H) presente en las ceras de hojas de plantas terrestres (e.g. cadenas largas de alcanos, ácidos grasos, etc.), son utilizados en reconstrucciones climáticas. Específicamente, los ácidos grasos son ácidos carboxílicos con cadenas alifáticas que son producidos por múltiples organismos y el tamaño de la cadena alifática varía según su origen (Bataglion et al., 2016). En cuanto a los ácidos grasos provenientes de materia vegetal, estos se pueden clasificar según la cantidad de carbonos que contienen de la siguiente manera (Bataglion et al., 2016; Castañeda y Schouten, 2011; Ficken et al., 2000; Norström et al., 2018): (i) Cadenas entre 4 y 14 carbones (C_{4-14}): ácidos grasos provenientes de material acuático como microalgas, zooplancton o bacterias. (ii)

Cadenas entre 20 y 24 carbones (C_{20-24}): ácidos grasos provenientes de macrófitas tanto semi-sumergidas como sumergidas. (iii) Cadenas entre 26 y 32 carbones (C_{26-32}): ácidos grasos provenientes de plantas vasculares terrestres.

Por lo tanto, determinando el largo de la cadena alifática, se puede determinar si su fuente en el sedimento lacustre es de origen terrígeno o acuático. Ácidos grasos provenientes de ceras de hojas (C_{26-32}), son componentes de la cutícula de las hojas de plantas terrestres (Eglinton y Hamilton, 1967; Liu et al., 2015). Estos son fácilmente transportados, a través de restos de hojas, desde los ecosistemas terrestres a los acuáticos a través de la escorrentia y la erosión eólica (Castañeda y Schouten, 2011; Feakins y Sessions, 2010; Liu et al., 2015).

Algunas características de los ácidos grasos que los hace excelentes indicadores biogeoquímicos son: se depositan continuamente por lo que habría un registro continuo de ellos en el sedimento; como son saturados no se oxidan y consecuentemente perduran en el tiempo; resistentes a la degradación biológica; son susceptibles a movimientos por escorrentías por lo que llegan con facilidad a los cuerpos de agua; su extracción y purificación es de alta precisión, así como su capacidad de indicar cambios en las condiciones climáticas a través de la razón de isótopos estables de hidrógeno (δ^2H) (Castañeda y Schouten, 2011; Reiffarth et al., 2016).

Los isótopos estables provenientes del agua ($\delta^{18}O$ y $\delta^{2}H$) son también utilizados para determinar condiciones climáticas pasadas debido a su precisión en registrar estos cambios climáticos en el pasado (Norström et al., 2018). Por lo tanto, el uso de $\delta^{2}H$ en compuestos específicos como ceras de hojas, abre la puerta para su uso en estudios paleoclimáticos, ya que en lagos pequeños y poco profundos la señal isotópica retenida en estos compuestos tiene una alta probabilidad de que quede intacta (Norström et al., 2018; Sachse et al., 2012). Si bien el $\delta^{2}H$ proveniente de las ceras de hoja sufre de fraccionamiento isotópico durante la biosíntesis, es representativo de la señal de $\delta^{2}H$ de la precipitación del lugar donde se formó (Feakins y Sessions, 2010; Norström et al., 2018). Combinar esta información con isotopología del agua, adquiere aún más relevancia.

2 HIPÓTESIS Y OBJETIVOS

De acuerdo con lo expuesto en los puntos (1), (2), y (3), se formulan las siguientes hipótesis para esta investigación:

2.1 Hipótesis 1

Si existe una conexión a escalas interdecadales y/o centeniales entre el anticiclón subtropical del Pacífico sur (ACP) y la deriva de los vientos del oeste (DVO), entonces deberíamos observar patrones de precipitación similares a la interacción interanual actual descrita anteriormente (Capítulos 2 y 3).

2.2 Hipótesis 2

Si los lagos en el flanco oeste de la Patagonia chilena están sometidos a altas precipitaciones (> 3500 mm/año), entonces los lagos que se encuentren en zonas de menor precipitación (<1500 mm/año), ubicados en el ecotono bosque-estepa, serán más sensibles a cambios en la intensidad de la DVO, o sea, a cambios en la precipitación que los lagos que ubicados en el flanco oeste de los Andes (bosque denso y altas precipitaciones). (Capítulo 3)

2.3 Objetivos

2.3.1 Objetivo general

Evaluar el cambio de precipitaciones, entre la Patagonia septentrional y zona centrel de Chile, generado por la interacción entre el anticiclón subtropical del Pacífico sur y la deriva de los vientos del oeste a escala interdecadal/centenial dentro del último milenio.

2.3.2 Objetivo específicos

1. Identificar las variaciones de precipitaciones de los últimos 500 años en la zona central de Chile utilizando registros históricos.

2. Determinar variabilidad de precipitaciones de los últimos 1000 años en la Patagonia utilizando registros sedimentarios.

3. Evaluar la zona más adecuada para realizar una reconstrucción de precipitaciones en la Patagonia (entre el lado este y oeste).

4. Estimar la ocurrencia de eventos climáticos del último milenio en ambas zonas (Patagonia y Chile central) y buscar similitudes/diferencias entre los determinantes climáticos de cada zona.

CAPÍTULO 2: DROUGHT PERIODS DURING 18TH CENTURY IN CENTRAL CHILE (33^{o}S): A HISTORICAL RECONSTRUCTION PERSPECTIVE REVISITING VICUÑA MACKENNA'S WORK

DROUGHT PERIODS DURING THE 18TH CENTURY IN CENTRAL CHILE (33°S): A HISTORICAL RECONSTRUCTION PERSPECTIVE THROUGH OF THE REVISIT TO THE BENJAMIN VICUÑA MACKENNA WORK.

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Key words: Historical Reconstruction, Drought, Documentary Records, Precipitation, Mid-Latitudes, Climate, Chile.

ABSTRACT

Understanding past climate variability is important for obtaining better predictions of future changes. Documentary records are high temporal resolution proxies that can be used to reconstruct aspects of the climate, such as precipitation. Vicuña Mackenna developed a compilation of historical climatic events between the 16th and 19th centuries using chronicles from Spanish colonizers and town council records. The objective of this work was to classify dry and wet periods beginning in the 16th century using records from Vicuña Mackenna by generating a precipitation index based on events in the documentary evidence (e.g., epidemics, “pro pluvia” rogations, and infrastructural damage) into a simple annual precipitation index on an ordinal scale. The index used a three-term classification scale, with 0 representing normal years, 1 representing wet years, and -1 representing dry years. The documentary records were not substantial enough to identify wet/dry periods during the 16th and 17th centuries. However, it was possible to identify dry and wet years described by conquerors and settlers that first arrived in the study area. During the 18th century, two long periods of drought were identified: 1705 to 1718 and 1770 to 1797. During these droughts, people organized rogations to the *Virgen* and different saints in desperation due

to the lack of water. Finally, during the 19th century, technological improvements in measuring precipitation made it possible to identify intermittent dry and wet periods with higher resolution and precision, and these events could be related to the El Niño Southern Oscillation (ENSO).

1 INTRODUCTION

Determining past climate variability is important for obtaining improved predictions of future climate changes (Neukom et al., 2014). Such records are especially relevant during the last millennia, which is the last period that was not affected by anthropogenic factors (Andres and Peltier, 2016; Alvarez et al., 2015; Moy et al., 2008). Among the different proxies that can be used to reconstruct past climate, documentary records are one of the most precise. These records can directly represent adverse climatic conditions that originate from problems and changes in the roles and organization of societies (Brázdil et al., 2005; Prieto and García Herrera, 2009). Documentary records are accurate and have high temporal resolutions, which allow them to distinguish between different climatic events, such as changes in precipitation and temperature (Brázdil et al., 2005). Several disadvantages are the lack of continuous time series and bias due to societal perception (Brázdil et al., 2005). Although there are disadvantages, documentary records are an accurate and trusted source of climatic information (Brázdil et al., 2010).

Historically documented climate began in Chile with the Spanish settlers, specifically with the foundation of Santiago de Chile in 1541 (Prieto and García

Herrera, 2009). Although indigenous people inhabited this territory before the arrival of Spanish conquerors, they did not maintain written records. The earliest climatic records in Chile are those from the Santiago area, which were first compiled by Vicuña Mackenna (1877). Vicuña Mackenna used chronicles and town council (*Cabildo*) records to document climatic events (Prieto and García Herrera, 2009; Ortlieb, 1994). There are only two more recent historical compilations of climatic events, Taulis (1934) and Urrutia and Lanza (1993), but it was not possible to verify this information due to the lack of references in their studies (Prieto and García Herrera, 2009; Ortlieb, 1994). Vicuña Mackenna (1877) has been the only work in Chile which has compiled climatic events. Ortlieb (1994) analysed Vicuña Mackenna's work to reconstruct El Niño Southern Oscilation (ENSO) years, focusing only in wet periods. Therefore, the compilation of Vicuña Mackenna is the only reliable source for inferring climatic events because its sources have been verified. Hence, the objective of this work is to classify dry and wet periods since the 16th century using the Vicuña Mackenna (1877) records by generating a precipitation index based on ancient chronicles or other written records from people who lived in the Santiago region (Figure 1a).

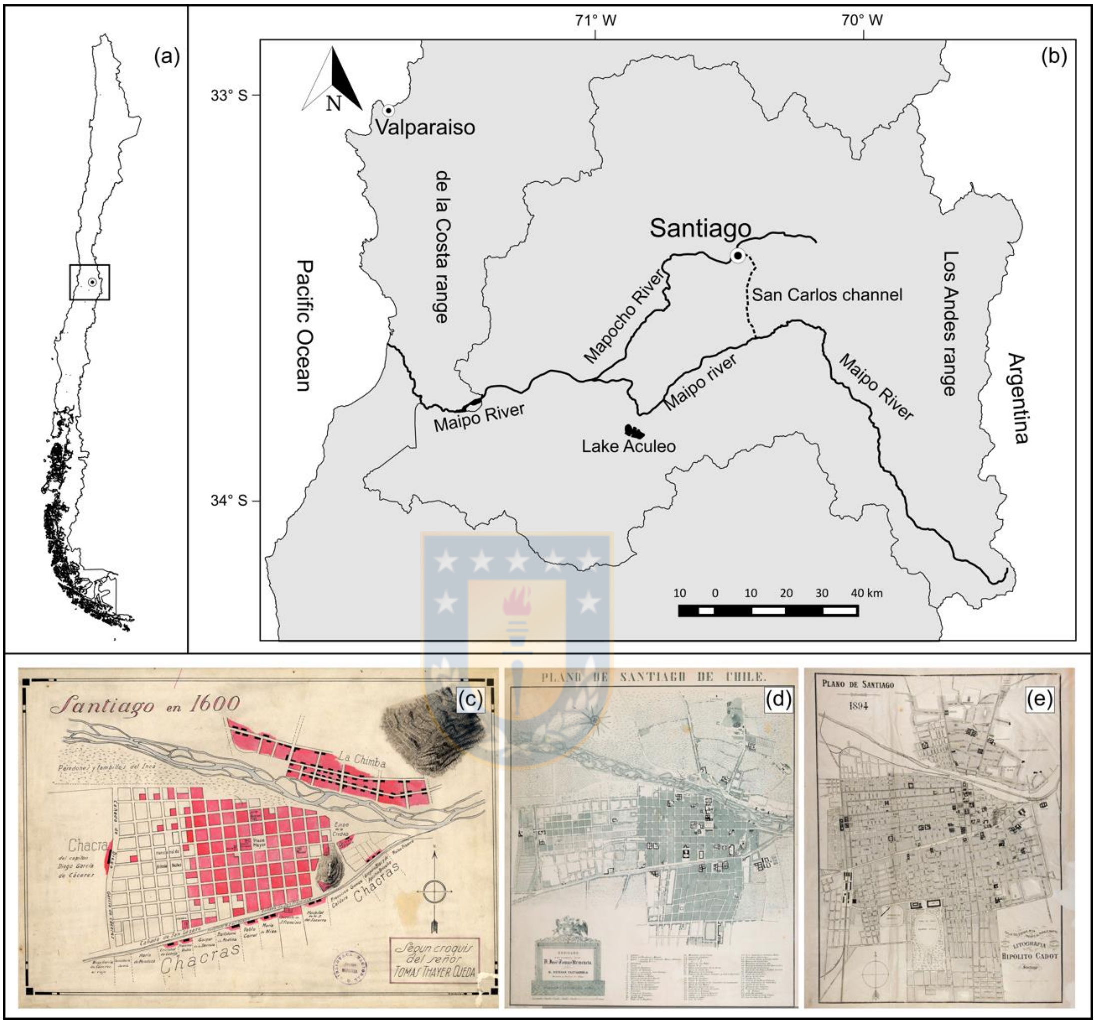

Figure 1: (a) Map of Chile showing the location of Santiago. (b) Map of the Metropolitan Region and its main features. (c) Map of Santiago in 1600 (from the Biblioteca Nacional de Chile, 2017a). (d) Map of Santiago during the 18th century (from the Memoria Chilena, 2017). (e) Map of Santiago in 1984 (from the Biblioteca Nacional de Chile, 2017b).

Santiago is located in the central valley between the Andes and the coastal range in central Chile (Figure 1b). Central Chile has a Mediterranean climate; most precipitation occurs between May and October, with a maximum in July (Figure 2b). Interannual variability is driven by the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Garreaud et al., 2009). Santiago is the most populated city in the country; the population in the metropolitan surrounding areas is approximately 7 million (Censo, 2017). Since its foundation, Santiago has obtained the majority of the country's population; however, during the 16th century, the population likely did not exceed 2000 inhabitants (Vicuña Mackena, 1924; Figure 1c). During the 17th century, but especially through the 18th century, a noticeable increase brought the estimated population to approximately 64,000 inhabitants (Archivo Nacional, 1953; Figure 1d, e).

Population growth generates an increase in the resources needed for survival, which are provided by either governmental or religious services. Therefore, any climatological or environmental pressures on the lifestyles of the inhabitants are likely to be recorded, either by local writers or governmental or religious authorities (e.g., the number of precipitation-induced rogations registered by the Catholic church).

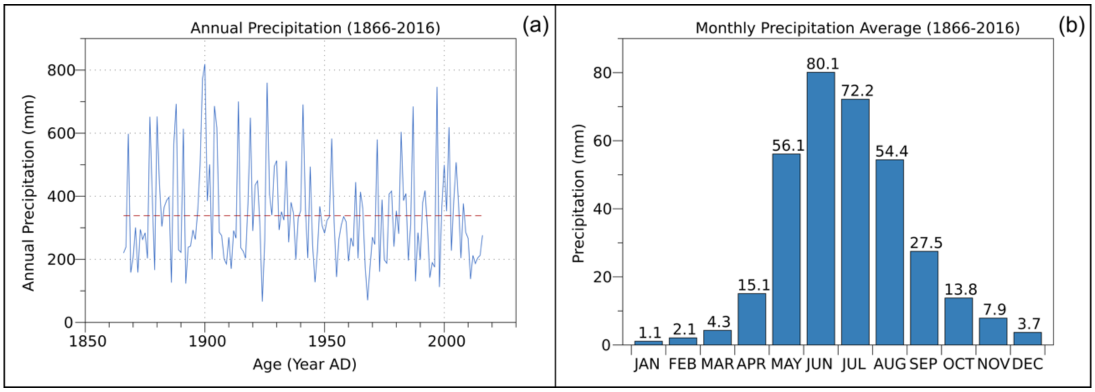

Figure 2: (a) Annual precipitation in Santiago (33°26’35”S; 70°38’40”W) between 1866 and 2016 (blue line) and the average precipitation during this period (red dotted line). (b) Monthly average precipitation from 1866 to 2016 (the data from 1866 to 1960 are from Ramirez, 1971; the data from 1961 until 2016 are from the Terraza Oficinas Centrales DGA meteorological station; 33°26’35”S; 70°38’40”W; DGA, 2017).

2 METHODS

A precipitation index was developed according to (Pfister, 1999a), where values based on documentary evidence were obtained by transforming basic documentary data into a simple annual precipitation index on an ordinal scale. The documentary evidence was obtained from (Vicuña Mackenna, 1877): "Ensayo Histórico sobre el Clima de Chile". Vicuña Mackenna (1877) registered climatic evidence from first-hand records of Spanish chronicles, administrative documents, manuscripts, and epistolary evidence during the Colonial period. For this study, climatic indicators related to droughts and high precipitation events were analysed. The selected indicators for droughts were as follows: i) variations in agricultural production, ii) epidemics (Brázdil et al., 2005) associated to lack of hygiene, due to no water available (Stanke et al., 2013), and iii) "pro pluvia" rogations, which are important in Catholic culture (Barriendos, 1997). Indicators of high precipitation events were i) floods, ii) infrastructural damages, iii) mouse plagues (Brázdil et al., 2005), and iv) "pro serenitate" rogations (Barriendos, 1997). Finally, the index used a three-term classification scale, with 0 representing normal years, 1 representing wet years, and -1 representing dry years.

3 RESULTS AND DISCUSSION

A precipitation index was developed with the information from Vicuña Mackenna (1877) using the classifications described in the Methods section. The climatic record used from Vicuña Mackenna (1877) goes from 1541 until 1877, going through different politic-administrative periods of Chilean history. Starting with the Spanish colonization and domain, from middle of the 16^{th} century until beginning of the 19^{th} century, when the Independent starts. The final period is the consolidation of the republic during the decade of 1820. Overall, during the 16^{th} and 17^{th} centuries, there was limited information regarding climatic conditions; thus, it was not possible to identify important wet or dry periods. During the 18^{th} century, two periods of droughts were identified: 1705 to 1718 and 1770 to 1797 (Figure 3a). Finally, there were intermittent wet and dry periods during the 19^{th} century (Figure 3a), which could be related to ENSO (Ortlieb, 1994). In the following sections, a detailed description of the climatic conditions mentioned by Vicuña Mackenna (1877; as shown in Table S1) is presented, and the dry and wet periods are presented in chronological order.

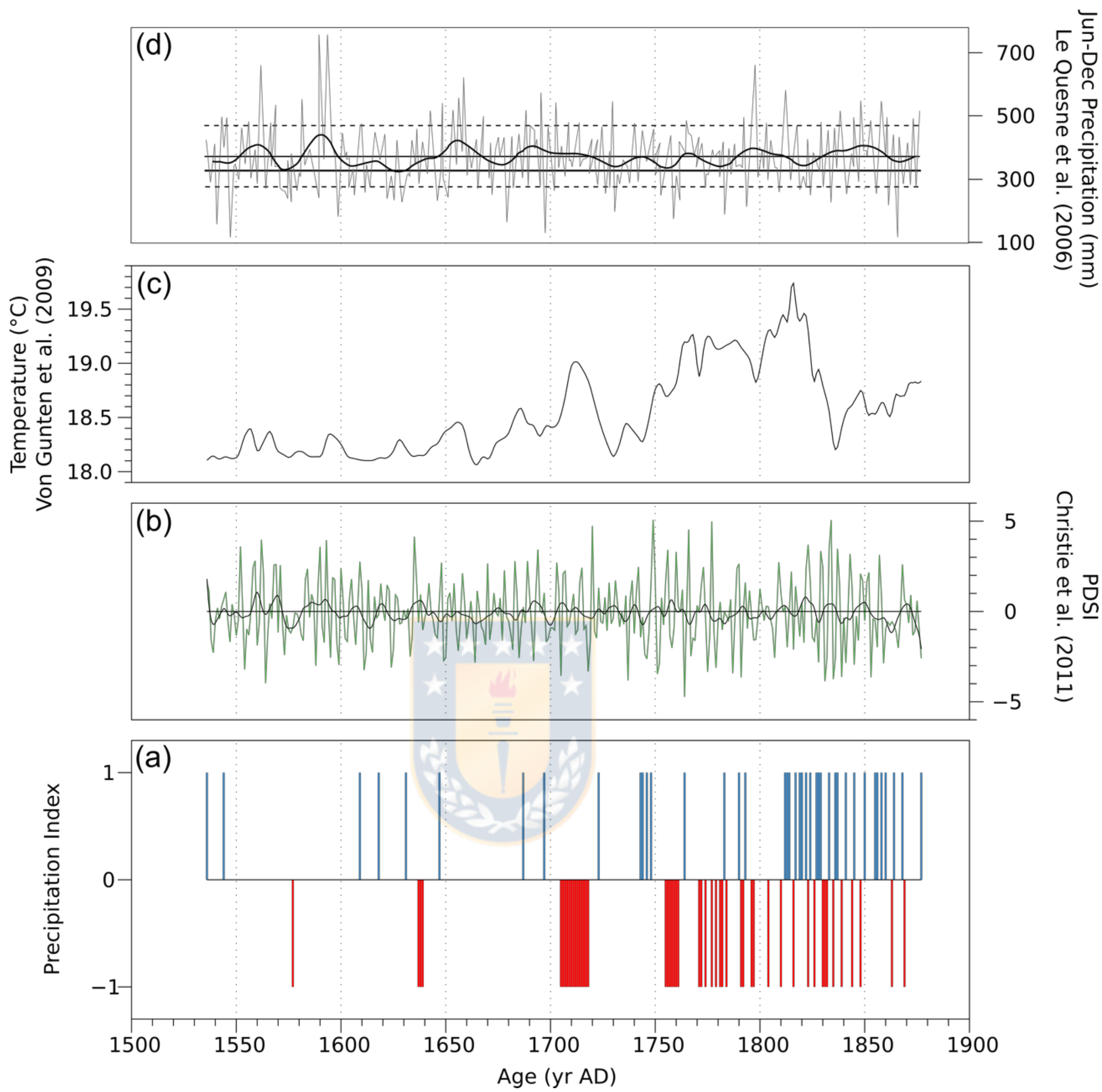

Figure 3: (a) Precipitation index developed from Vicuña Mackenna (1877), where 1 represents wet years, 0 represents normal years, and -1 represents dry years. (b) Palmer Severity Drought Index (PDSI) reconstruction from late spring to early summer using *Austrocedrus chilensis* tree rings in south-central Chile (Christie et al., 2011). (c) Austral summer temperature reconstruction in Lake Aculeo (33°S) using pigments from lake sediments (von Gunten et al., 2009). (d) June to December precipitation reconstruction using *Austrocedrus chilensis* tree rings (Le Quesne et al., 2006).

3.1 Climate during the 16th and 17th centuries

The climate of central Chile was described by Vicuña Mackenna (1877) as mild during the 16th and 17th centuries, although there were a few droughts and wet periods. The first individuals to record climatic conditions in Chile were Spanish colonizers, who documented climatic phenomena that caught their attention, and these records were later compiled by Vicuña Mackenna (1877). The first year recorded was 1536 AD, when the Spanish colonizers experienced "deluges" that discouraged them from continuing exploration (page 18). The winter of 1544 AD was described as outrageous due to the high amount of precipitation (page 20), and Vicuña Mackenna (1877) indicated in his book that the indigenous people had never experienced this type of event (page 21). The first drought that was documented occurred in 1577 AD, when the Mapocho River water level diminished so severely that it generated problems in the water supply needed by Spanish settlers for irrigation (pages 7-8). Another extreme "deluge" occurred in 1609 AD, which destroyed several crops and farms and generated a massive rat plague, which induced a religious rogation and procession (page 28). Rat plagues are indicators of extreme rainfall events (Grivenville et al., 2013) because rodents look for shelter in populated areas (Grivenville et al., 2013). The year 1631 AD was also rainy, which provoked another rat plague. This rat plague was of such concern that the women of Santiago were invited to a procession (page 141), despite their usual lack of participation in such events. The second drought occurred between 1637 and 1639 AD; this made inquisitional debt-collectors unable to charge taxes during this time due to the drought, which abruptly diminished harvests (page 48). In 1647 AD, the winter was harsh, and there were three days of snowfall, which generated considerable livestock fatalities (page 36). The year 1697 AD was also characterized by wet conditions due to a great flood in the area of Santiago, where several cattle and horses died (page 38).

Vicuña Mackenna (1877) recorded several years of drought and floods during the 16th and 17th centuries, but there were not enough documentary records to develop a robust reconstruction. The lack of records during the 16th century could be because the Chilean territory was in a conquest process. Therefore Spanish settlers were in a war with the indigenous and did not documented prevailing climatic conditions during this time. Several authors (Christie et al., 2011; Le Quesne et al., 2009; Muñoz et al., 2016) have developed precipitation reconstructions from tree rings in south-central Chile. Christie et al. (2011) found a multidecadal drought period that occurred at approximately 1585 AD (Figure 3b), and the first record of drought documented by Vicuña Mackenna (1877) occurred in 1577 AD. Le Quesne et al. (2009) showed a drought between 1570 and 1635, and Muñoz et al. (2016) found that the driest year during the last four centuries in central Chile occurred in 1680 AD. Droughts in historical records are characterized by religious “pro pluvia” rogations in Catholic culture (Barriendos, 1997). These rogations occurred when the diminished harvest caused people to despair, which consequently meant there was a lack of food. At that time, the population surrounding Santiago's jurisdiction was small; as a consequence, the agricultural production would have been enough to feed the local population, and public rogations were not needed, which could explain why Vicuña Mackenna (1877) did not fully record these periods.

3.2 Climate during the 18th century

The 18th century started with a long period of drought between 1705 AD and 1718 AD (Figure 3a). The *Cabildo* of Santiago ordered a rogation due to the lack of rainfall on August 7th, 1705 AD (page 52; this event occurred during austral winter, which is important when considering that precipitation begins in May; Figure 2). Twelve years later, the situation did not change, and the *Cabildo* still instructed a rogation due to a long period of drought. The Mapocho River reached its lowest water level during the drought of 1717 AD (pages 52-53), which caused the municipality to establish attentive laws to avoid water robbery. The vigilance towards water was expensive for the municipality, which inspired the idea to transfer water from Maipo to the Mapocho River (page 59; Figure 1). The following year, Santiago had problems with the maintenance of ditch channels due to the lack of water, and, therefore, the *Cabildo* ordered a novena for the *Virgen del*

Socorro in 1718 (page 54). The decade starting in 1740 was characterized as wetter than the previous decades. In 1743 AD, the *Cabildo* requested a procession for the *Virgen del Socorro*, but this was not executed because it started to rain (pages 65-67). 1746 AD was a rainy year, which caused the harvests to be more abundant than those in other years (pages 68-69). Santiago was flooded in 1748 AD by a deluge, comparable with the deluge that occurred in 1609 AD, which destroyed the cutwater of the Mapocho River and the *Puente de los Siete Arcos* bridge (page 69).

The second half of the 18th century was even drier than the first half; generally, after a period of drought, a rainy year occurred. According to Orlieb (1994), the intermittent dry and wet periods described by Vicuña Mackenna were likely related with ENSO. The first drought documented during this period occurred under the government of Governor Manuel de Amat between 1755 and 1761 AD (pages 72-73). This government was denoted as a time of *skinny cows* because the lack of water provoked an economic shortage; however, this period was followed by a flood in 1764 AD (page 74). Vicuña Mackenna (1877) established a 30-year period of drought between 1770 and 1797 AD, during which the following were the driest years: 1770, 1771, 1773, 1774, 1777, 1781, 1782, 1784, 1791, and 1797 AD (Figure 3a). The total amount of rainfall during 1770 was equivalent to five consecutive days of rain (page 76). The following year, the *Cabildo* ordered a rogation to the *Virgen del Socorro* (page 78), but it did not rain, and the fields were sterile (page 79). As a consequence, another rogation was organized in September to the *Nuestra Madre Señora de las Mercedes* (pages 80-81). By the year 1772 AD, the drought was so severe that there was a threat of famine (pages 83-84). The following year, mules did not have enough food because of the drought, which delayed fish deliveries in Santiago during Lent (page 84). Therefore, the mayor of Santiago asked for permission to eat meat four days a week during this period (page 85). The year 1774 AD was the driest of the century, and it was mentioned that the following years were not more or less humid (page 86). Farmers rejected the saints in 1777 AD because it had not rained during the last decade; therefore, they began to pray to *Señor de la Agonía* (pages 86-87). The situation changed noticeably in 1779 AD, when several floods destroyed the bridge *de Cal y Canto*, which was under construction (pages 74, 90). The high precipitation events during this year also generated a disease called *Malesito*, which symptoms were similar to Yellow Fever (page 90) and it was mentioned that the floods and electrical storms seemed like atmospheric earthquakes. After the flood of 1779, drought continued between 1781 and 1782 AD (pages 92-93; Figure 3a). As an example, Catholic mass could not be performed in Renca (near Santiago) because there was no water for the vinegar bottles (page 94). The lack of water provoked a sanitary problem during the austral summer of 1784 AD because there was no water for people to clean their houses (page 126). As a result, people began the rogations to the saints in 1791 AD because the soil was catastrophically infertile. That year, there were several reports of plague because there was not enough water to clean the sumps in the houses; there were also substantial livestock fatalities. Consequentially, the *Cabildo* request a rogation to the *Nuestra Señora del Rosario*, *la Grande* (pages 128-129). As before, a rainy year followed the drought, and in 1793 AD, the water level of the Mapocho River was substantially higher (page 140). Finally, 1797 AD was very dry, and precipitation events occurred after June 7th; as a consequence, the fields were sterile, and the livestock was extremely thin. Therefore, people organized a rogation to *San Isidro*, who is the saint patron of rain (page 135).

Regarding other climatic records in the area, von Gunten et al. (2009) developed a temperature reconstruction (Figure 3c) from Lake Aculeo (Figure 1), where a cold period between the 16th and 18th centuries was identified, which was synchronous with the Little Ice Age (LIA). After this cold period, there was an increase in temperature between 1700 and 1720 AD (von Gunten et al., 2009; Figure 3c). The warm period described by von Gunten et al. (2009), coincided with the droughts between 1705 and 1718 AD, which were identified in this study as the longest drought during the second half of the 18th century. Furthermore, Martel-Cea et al. (2016) produced a precipitation reconstruction using pollen and diatoms as proxies in Lake Chepical (32°S), and they found a dry period during the 18th century. However, due to low resolutions, they could not identify the events with precision during those years. Le Quesne et al. (2006) used tree rings as a proxy and found a dry period between 1771 and 1785 AD (Figure 3d), which is the same period that Vicuña Mackenna (1877) describes as "the driest year of the century". Currently, Garreaud et al. (2017) reconstruct precipitation during the last 1000 years in central Chile using tree rings records. They found that the longest period of drought has been 2010-2015 AD and they did not describe the droughts of the 18th century. On the other hand, Bird et al. (2011) reconstructed annual precipitation associated with the South American Summer Monsoon (SASM) using $\delta^{18}O$ contain in calcite from lake Pumacocha (10°S) sediments. They found drier periods during LIA at the beginning and ending of the 18th century. Morales et al. (2012) also found a tendency to drought at the end of the 18th century in the *Altiplano* region (17°-22°S) in a reconstruction of SASM precipitation. The changes in SASM precipitation are modulated by ENSO, which caused latitudinal changes in the Inter Tropical Convergence Zone (ITCZ; Bird et al., 2011; Morales et al., 2015). A northern change of ITCZ would decrease precipitation related with SASM. Then, the dry period described by Vicuña Mackenna (1877) could be associated with a northern change in the ITCZ provoked by ENSO phenomenon. The explanation of why the drought periods found in Vicuña Mackenna (1877) records, could be the perception of droughts by people. Consequently, the perception of drought and the demand of resources for sustenance were higher than those during the 17th century. Moreover, prolonged and moderate droughts (similar to those in the 18th century) could cause negative effects in water availability. Water supply decreased each year due to severe droughts (Barbet et al., 2014), which caused problems with agriculture.

3.3 Climate during the 19th century

The 19th century was characterized by the implementation of technological improvements, which made quantitative measurements of precipitation possible. Therefore, a longer record of dry and wet years could be achieved (Figure 3a). The measurement of precipitation started in 1824 AD, when precipitation was only measured by the number of rain days annually. The first precipitation records began in 1850 AD, and the records were in millimetres per year. The lack of data before 1824 AD can be explained by the independence process, where the focus is the record of combats and political facts. Vicuña Mackenna (1877) described the first half of the 19th century as wet. From 1827 to 1829 AD, several floods occurred, which destroyed multiple bridges in Santiago (pages 214, 215, 340). In contrast, the period from 1830 to 1832 AD was very dry, and 1832 AD was the driest year from 1824 to 1850 AD (page 287). From the same series, the wettest year was 1833 AD (page 340), which was followed by another dry year in 1835 AD (page 77). The years 1836 and 1837 AD were both wet, followed by a dry year in 1839 AD (page 77). A seven-year wet period began in 1841 and ended in 1848, which disturbed the period of drought (pages 340, 299). Finally, 1850 AD was described as one of the roughest winters in Chile due to high precipitation events (page 218). During the second half of the 19^{th} century, precipitation began to be measured in millimetres, which made them comparable with current measurements. The years 1858 and 1860 AD were considered wet, with precipitation totals of 622 and 513 mm/year, respectively (page 308), while 1863 AD was dry and calamitous due to a drought (only 114 mm/year; page 326). The years 1864 and 1868 AD were very wet, with precipitation totals of 732 and 875 mm/year, respectively (pages 327, 328). Similar to past patterns, the following year (1869 AD) was very dry, and the precipitation total was only 149 mm/year (page 260). Finally, 1877 AD was termed the year of Great Floods; these floods were comparable with those in 1856 and 1858 AD pages 98, 272, 319). Unfortunately, this was when the book by Vicuña Mackenna (1877) was written, so we do not have information regarding the amount of precipitation that fell.

Muñoz et al. (2016) observed an extreme drought between 1818 and 1822 AD in the Maule River, which is when Vicuña Mackenna (1877) described a wet period. Nevertheless, Prieto and García Herrera (2009) described an increase of snowfall in the chilean-argentinian pass (32° S) between 1810 and 1830 by using historical records. Christie et al. (2011) observed that 1849 AD was one of the most humid years during the 19^{th} century (Figure 3b), and Vicuña Mackenna (1877) described 1850 AD as the roughest winter in Chile. The aforementioned study also found that severe to moderate droughts occurred during 1860 (Christie et al., 2011; Figure 3b), which matches with the description of calamitous drought by Vicuña Mackenna (1877) at approximately 1863 AD. In general, the record during the 19th century was more complete than that during the previous centuries due to the technological advances in precipitation measurement that were implemented. For the same reason, this record was quantitative, especially after 1850 AD, when the measurements were recorded in millimetres.

4 CONCLUSIONS

The historical data contained in the record of Vicuña Mackenna allowed for the identification of dry and wet periods since the 18th century with a high resolution. Although Vicuña Mackenna did not fully record the 16th and 17th centuries, he was able to identify several dry and wet years but with a very low resolution. The intense droughts identified during the 18th century were not fully documented by natural proxies; these different drought records could be attributed to perception and a more intensive use of land for agriculture. Finally, during the 19th century, the quantitative measurement of precipitation began. This study identified a pattern throughout the record in which, following a drought, a distinct period of intense rain occurred, which could be associated with ENSO. For future studies, it is necessary to complement the record of Vicuña Mackenna with other documental proxies, such as newspapers, and archives as the *Biblioteca Nacional de Chile* and the *Archivo General de Indias*, to improve the climatic reconstruction.

SUPPORTING INFORMATION

Table S1 contains the records from Vicuña Mackenna (1778) used in this study to develop the precipitation index. These records are given in textual form and in their original language.

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CAPÍTULO 3: SEDIMENTARY LEAF WAX ABUNDANCE AND δ^2H VALUES FROM TWO NORTHERN PATAGONIAN LAKES: EVALUATING ITS SENSITIVITY TO RECONSTRUCT PRECIPITATION CHANGES DURING THE LAST MILLENNIUM

SEDIMENTARY LEAF WAX ABUNDANCE AND $\delta^{2}H$ VALUES FROM TWO NORTHERN PATAGONIAN LAKES: EVALUATING ITS SENSITIVITY TO RECONSTRUCT PRECIPITATION CHANGES DURING THE LAST MILLENNIUM

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Key words

Precipitation changes, lake sediments, δ^2H in leaf waxes, Patagonia

Highlights

- There is a lack of hydrological studies from the last millennia in Patagonia.
- Sensitiveness and coherency regarding climate changes, for the last millennia, in two sites of Patagonia
- Changes in precipitation by examine a suite of geochemical and biogeochemical proxies (e.g. $\delta^{13}C$ FAMEs, δ^2H) from lake sediments
- Our records of δ^2H from the ecotone site, is according to the general climatic trends in Patagonia.
- The best place to do precipitation reconstruction using biogeochemical proxies in Patagonia would be the ecotone

ABSTRACT

The climatic variability on studies that include the last millennia in Patagonia shows low sensitivity to changes in hydrological patterns at lower magnitudes such as the Little Ice Age (LIA) and Medieval Climatic Anomaly (MCA). This study will inquire into the behavior of geochemical (total organic carbon, $\delta^{13}C$, grain size and magnetic susceptibility) and biogeochemical proxies, such as leaf wax abundance and distribution as well as hydrogen isotopes ($\delta^{2}H$) contained in leaf waxes extracted from sediments cores of two lakes separated by only 45 km of distance but one located in a high precipitation area (Lake Oscuro) and another in a medium precipitation range area (Lake Tranquilo). The sedimentological and biogeochemichal proxies are different in both lakes. While lake Oscuro is more organic rich, lake Tranquilo has less organic content in them sediments, thicker material, most probably because differences in climate and, thus, the vegetational structure around both lakes. Lake Oscuro, located 15 km from Exploradores glacier, giving origin to the Exploradores river, has an abrupt change in sedimentological proxies, probably by an glacier lake outburst flood. Biogeochemical proxies also are different in both lakes, where lake Oscuro has three orders of magnitude higher amount of leaf waxes most probably related to high precipitation and terrigenous input into the basin of Oscuro. $\delta^{2}H$ is around 10‰ of difference between cores, which is less negative in Lake Oscuro. Although

our δ^2H values resolve a low resolution with very discrete data, it is possible to observe changes in the hydrological cycle that the other proxies do not record. More exhaustive studies are needed to ensure that these changes in the hydrological cycle are represented specifically by the δ^2H in leaf waxes. In conclusion, there is a potential use of δ^2H from leaf waxes to assess changes in the hydrological cycle of Chilean Patagonia.

1 INTRODUCTION

Changes in projected water balance based on climate change would affect water availability worldwide (Andres and Peltier, 2016; IPCC, 2021). The southern part of South America is not an exception. According to Brêda et al., (2020), relevant changes are expected in the water availability in South America. The model simulations from CMIP5, using an RCP8.5 scenario, show a decrease in precipitation (ca. 25%) in southern Chile for the next 20 years, mainly due to climate change (Brêda et al., 2020). Therefore, it is important to understand how precipitation has changed before industrial times to better understand natural climate variability and assess the impact of climate change on the hydrological cycle. Many studies have elevated the importance of studying precipitation trends in Patagonia (Bertrand et al., 2014; Elbert et al., 2011; Fletcher and Moreno, 2012; Zolitschka et al., 2019) which is the only landmass that intercepts the Southern Hemisphere westerly winds (SWW) belt south of 55º S.

The SWW are the most critical variable in climate modulation south of 40º S of South America (Garreaud et al., 2013, 2009). In annual variations, SWW are stronger during summer between 45º S and 55º S, and during winter, the jetstream moves northward, reaching 30º S (Garreaud et al., 2009). Therefore, precipitation is stronger during summer between 45º and 55º S. In addition, another geographic feature that controls precipitation in a west-east gradient is the Andes range. The SWW intercept the Andes range, which provokes one of the steepest precipitation gradients in the world (Garreaud et al., 2013, 2009). While the maximum precipitation at the west side is over 4000 mm yr^{-1}, at about 60 km east, the precipitation does not reach 300 mm yr^{-1} (Garreaud et al., 2013). The west-to-east precipitation gradient (Fugure 1) provoked an abrupt change in vegetation in three major bioclimatic zones: evergreen forest at the west, steppe at the east, and deciduous forest between the evergreen forest and steppe.

Several researchers have focused on understanding the behaviour of SWW at different time and space scales, from the last glacial maximum to the early Holocene and from 40 to 55 ºS. The proxies used to reconstruct precipitation for the last thousand years in Patagonia are mainly pollen, charcoal (Fletcher and Moreno, 2012; Zolitschka et al., 2019), diatom (Zolitschka et al., 2019), tree rings (Roig and Villalba, 2008) and geochemical records in ocean sediments (Sepúlveda et al., 2009). Nevertheless, all these proxies do not record the changes of climatic anomalies described by (R Neukom et al., 2011) during the last millennium, such as the Little Ice Age (LIA) and the Medieval Climatic Anomaly (MCA). (R Neukom et al., 2011) found changes of less than 0.5 ºC for the period between 1150 and 1350 CE (MCA) and anomalies of more than -1 ºC between 1400 and 1650 CE and between 1800 and 1900 CE in northern Patagonia. Therefore, based on (R Neukom et al., 2011) record the proxies studied in Patagonia show low sensitivity to changes in hydrological patterns of lower millenical scale variability.

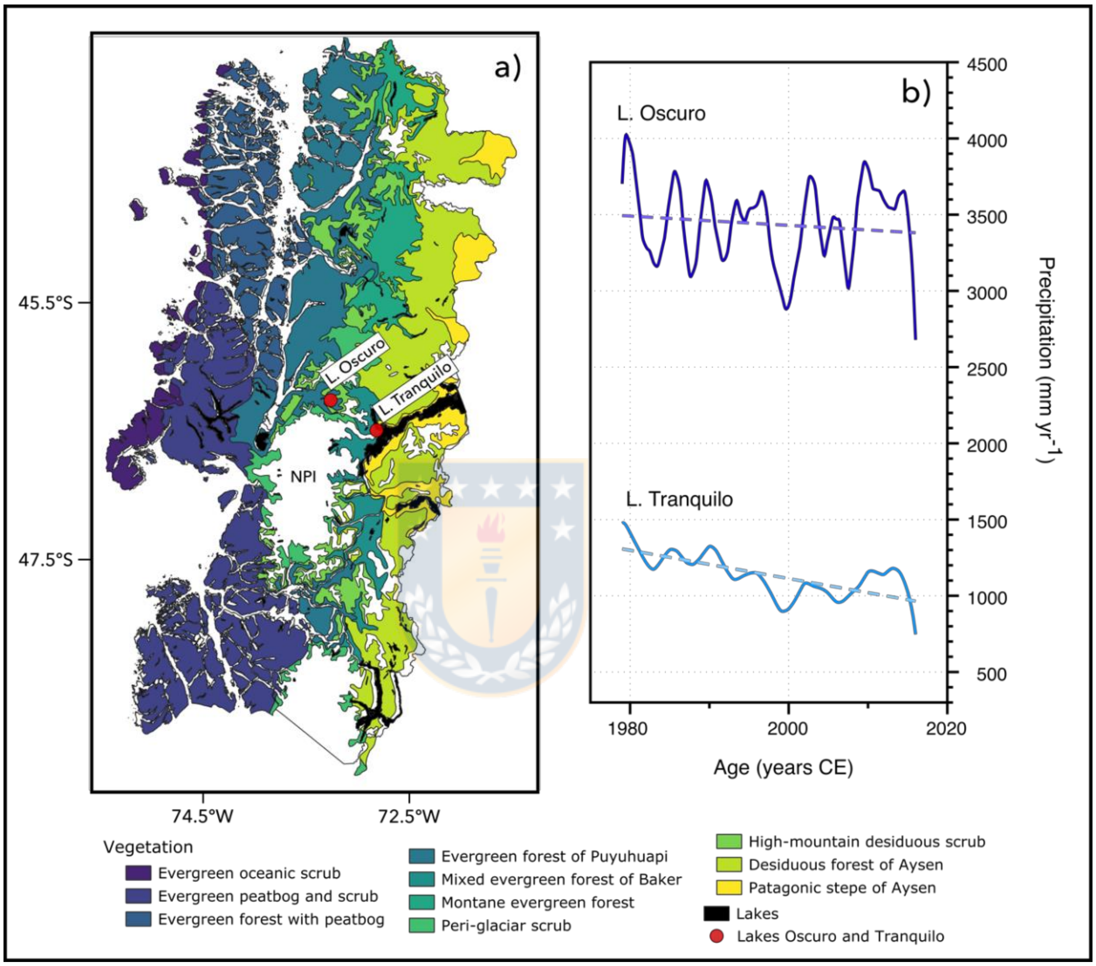

Figure. 1: a) Spatial average of annual precipitation between 1979 and 2016 in the Aysen region with the location of L. Oscuro and L. Tranquilo (NPI = North Patagonian Icefield); b) annual average of precipitation from lakes Oscuro and Tranquilo (Source: http://www.cr2.cl).

Lake sediment profiles preserve information in the sedimentary organic matter that helps to reconstruct environmental and climatic conditions in the past (Smol, 2008). The behaviour of proxies like sedimentary total organic carbon (TOC), C/N ratio, and $\delta^{13}C$ have been used in core top lake surface sediments along the western side of South America to assess latitudinal and elevation changes (Contreras et al., 2018). Hydrogen stable isotopes ($\delta^{2}H$) in specific compounds, such as leaf wax fatty acids, are used to assess precipitation changes (Bataglion et al., 2016). The fatty acids from leaf waxes are aliphatic chains of even carbons, measured as fatty acid methyl esters (FAMEs), and form part of the cuticle of the leaves of terrestrial plants. These fatty acid leaf waxes are transported from a terrestrial ecosystem to lakes through runoff and winds (Castañeda et al., 2009; Liu et al., 2015; Sachse et al., 2012) and are sensitive to changes in climatic conditions (Castañeda and Schouten, 2011; Norström et al., 2018; Reiffarth et al., 2016). Nevertheless, $\delta^{2}H$ fractionates in the leaf via biosynthesis, and the values of $\delta^{2}H$ are representative of the precipitation (Norström et al., 2018; Sachse et al., 2012). Recent studies propose that fatty acids from leaf waxes are sensitive proxies to small changes in precipitation (Feakins and Sessions, 2010; Sachse et al., 2009).

This study examines how a suite of organic proxies (TOC, C/N, $\delta^{13}C$) behaves downcore in two different sites separated by 45 km of distance, considering that one is located in a high precipitation area (over 4000 $mm yr^{-1}$) and another in a medium precipitation range area (average of 1500 $mm yr^{-1}$), to see how sensitive and coherent the suite is regarding recent and past climate changes, such as the

MCA and LIA. This study will also inquire into the behaviour of sedimentary biogeochemical proxies, such as leaf wax abundance and distribution as well as hydrogen isotopes (δ^2H) contained in leaf waxes from sediments, to see trends, matches, mismatches, and differences downcore in each site and between sites. Some questions to be addressed in this research: (i) Are there differences in proxies among sites and downcore? (ii) Are the proxies sensitive to regional precipitation? (iii) Which site is most suitable for climatic reconstructions?

2 METHODS

2.1 Study area

The two lakes under study, Lakes Oscuro and Tranquilo (Figure 1), are within a precipitation gradient that forms different vegetation structures. Lake Oscuro is located in the "evergreen forest of Puyuhuapi" (Figure 1) area, with rainfall of 3438 mm yr^{-1}. The "evergreen forest of Puyuhuapi" extends in the low slopes and western valleys of the Andes range as well as the fjords and archipelagos of Patagonia (Gajardo, 1993). The main species are *Nothofagus betuloides*, *Nothofagus nitida*, *Podocarpus nubigena*, and *Pilgerodendron uvifera* (Gajardo, 1993). Lake Tranquilo is in the "mixed evergreen forest of El Baker" (Figure 1), with rainfall of 1136 mm yr^{-1}, which is a transition from evergreen to deciduous forest (Gajardo, 1993). The representative species of this type of forest are *Nothofagus betuloides*, *Nothofagus pumilio*, *Nothofagus antartica*, *Berberis serrato-dentata*, and *Pernettya mucronate* (Gajardo, 1993).

2.2 Geochronology

The sediment cores from Lakes Oscuro (2014) and Tranquilo (2013) were retrieved with an Uwitec® hammer gravity corer with 116 cm and 146 cm long recovery, respectively. The cores were kept in a cold chamber at 4° C until analysis. The age-depth model was made using Clam package (Blaauw, 2010) in Oscuro and Bacon package (Blaauw and Christen, 2011) in Tranquilo. The data included ^{210}Pb and ^{137}Cs for the last 150 years with AMS radiocarbon dates for deeper sediments. The ^{210}Pb and ^{137}Cs analyses were made at the Environnements et Paléoenvironnements Océaniques et Continentaux, University of Bordeaux, France using non-destructive low-background, high-efficiency gamma spectrometry with a germanium detector, equipped of a cryo cycle. Dates were estimated with the constant flux-constant sedimentation (CF:CS) model for Lakes Oscuro and the constant rate supply (CRS) model for lake Tranquilo. The AMS radiocarbon dates were sent to Direct AMS (Oscuro, 117 cm; Tranquillo, 115 and 131 cm), Gadam, Silesia University of Technology, and Beta Analytic (Oscuro, 72 cm).

2.3 Geochemical proxies

The sediment was decarbonated with HCl vapour for TOC and $\delta^{13}C$ analysis. They were measured in a FISONS NA 1500 NC elemental coupled to a mass spectrometer (IR-MS) in the Laboratory of Oceanology and Laboratory of Animal Systematics and Diversity, University of Liege. The C/N ratio was calculated using the atomic ratio according to (Meyers and Teranes, 2002). The most recent $\delta^{13}C$ values were corrected by the Suess effect, according to (Verburg, 2007).

2.4 Biogeochemistry

We used 1.5 to 5.0 g of freeze-dry sediment to extract the total lipids. The total lipid extraction (TLE) was obtained using microwave-assisted extraction (MAE) in a microwave Milestone Ethos Easy using 10 mL of CH_2Cl_2: MeOH (9:1) at 100° C for 15 minutes, extracted 2 times. The TLE was separated in an amino-propyl bond elute column (Clean Up®), eluting the fatty acid fraction with 10 mL of glacial acetic acid: diethyl-ether 1:24. Then the fatty acid fraction was methylated with boron trifluoride diethyl etherate to produce fatty acid methyl esters (FAMEs). The sample was dissolved with 25 (or 50) µL of ethyl acetate, and 25 (or 50) µL of androstane (1000 ng/µL) was used to quantify the samples. Finally, 1 µL of this FAMEs fraction was injected into an Agilent GC-FID with an HP-5 GC column of

30 m length and 0.25 µm of internal diameter. The average chain length (ACL) index was calculated as the weighted average of the chain concentration between C_{26} and C_{30} as follows:

$ACL = \frac{\sum[C_i] \times i}{\sum C_i}$, where "$C_i$" is the concentration of each chain, and "i" is the chain number.

The hydrogen isotope composition of FAMEs was analysed using an Elementar isoprime visION HTGC-P-IRMS (Elementar UK Ltd., Cheadle, UK) in the Organic Geochemistry Laboratory (OG Lab) at University of Colorado Boulder. The instrument comprised an Agilent 7890B GC fitted with an on-column injector, linked to a GC5 interface (maintained at 380 °C) and a hollow ceramic reactor, enabling pyrolysis at 1450 °C. Ferrules used to connect the ceramic furnace and GC-column, as well as the sample line He used as an additional carrier in the GC-IRMS system, were 100% graphite. Ion beams at m/z 2 and 3 were monitored via an isoprime visION mass spectrometer. The H^{3+} factor was determined daily or at least every 4 runs. Compounds were separated in the GC on a Zebron ZB-5HT analytical column (7 m × 0.25 mm × 0.1 µm) with high-temperature resistant polyimide coating, which was fitted to a transfer line and an exhaust to allow diversion of the solvent peak to waste via a glass Y-splitter fixed with high temperature resin (Phenomenex Ltd., Aschaffenburg, Germany). He was used as a carrier gas at a flow rate of 2.2 ml min^{-1} and the oven was programmed as follows: 1 min hold at 70 °C, increase by 10 °C min^{-1} to 350 °C, followed by an increase at 3 °C min^{-1} o 400 °C (10 min hold) Results were calibrated using a mixture of n-alkanes (B3, A. Schimmelmann, Indiana University, Bloomington, IN, USA) according to (Sessions et al., 2002, 1999), which was injected at least every four analyses, and analysed using a He flow of 1 ml min^{-1}, with a different temperature program (injection at 50 °C held for 1 min followed by an increase of 10°C min^{-1} to 300 °C and a 10 min hold). The calculation of δ^2H was made using The isoreader package for R (Kopf et al., 2021). Sixty samples were run, of which 28 where in a trustworthy range to display the results.

3 RESULTS

3.1 Chronology

The chronological model of the sediment cores Os2014B from Lake Oscuro in Figure 2 was constructed using the non-Bayesian interpolated, age-depth model from R package Clam (Blaauw, 2010). The chronological model of the sediment core Tr2013C from Lake Tranquilo (Figure 2) was constructed using a Bayesian model from the R package Bacon (Blaauw and Christen, 2011). The Clam package was used for Lake Oscuro because Bacon does not consider the slump to cut the age model. For Lake Oscuro, the accumulation rate from 0 to 36 cm is 0. 0.56 cm yr^{-1} average; from 36 to 50 cm, it is 0.06 cm yr^{-1}; from 50 to 100 cm, it is 8.33 cm yr^{-1}, and from 100 to 117 cm, it is 0.08 cm yr^{-1} average, and the total age of the core is 581 yr. For Lake Tranquilo, the accumulation rate from 0 to 30 cm is 0.26 cm yr^{-1} average, and from 30 to 131 cm, it is 0.05 cm yr^{-1} average, with a total age of 2110 yr.

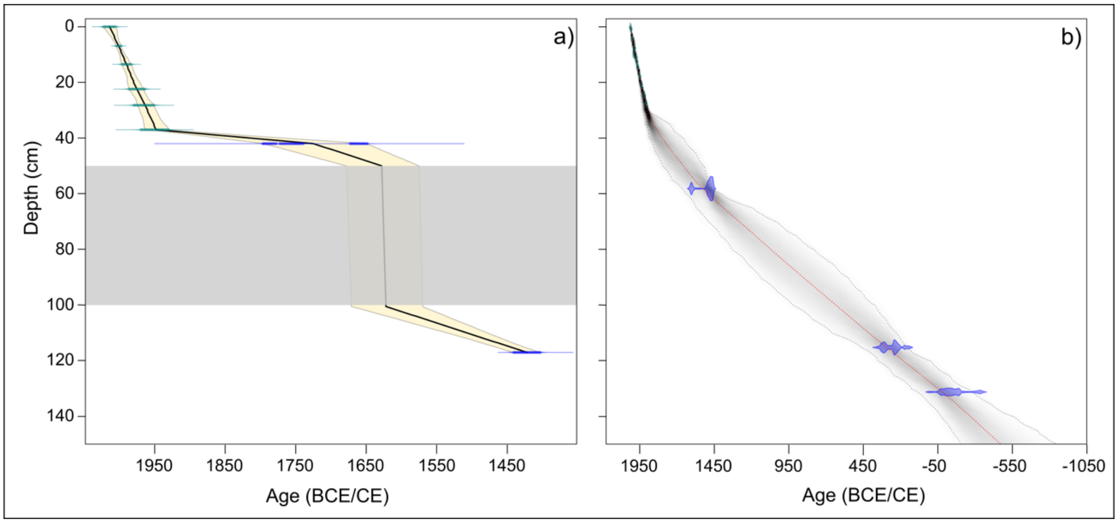

Figure. 2: Age models of lakes a) Oscuro, made in Clam considering a gray layer of 50 centimeters. The green measures are from the ^{210}Pb model and blue from ^{14}C; b) Tranquilo, made in Bacon. The upper green ages come from the ^{210}Pb model, and the blue is from ^{14}C.

3.2 Geochemical proxies

3.2.1 Lake Oscuro

The geochemical proxy values in Lake Oscuro are very stable, from 116 to 100 cm. TOC is around 4%, C/N values are just over 20, $\delta^{13}C$ is around -28.5‰, and grain size is about 6 phi. Only the magnetic susceptibility shows a decreasing trend from 135.2 to 47.6 x 10^{-8} SI up to 90 cm. Above 100 cm, all these parameters except grain size change abruptly. TOC drops to values near 1%, with a slight decreasing trend from 1% to 0.5%, and C/N drops abruptly to 17, decreasing up to 12. The $\delta^{13}C$ increases abruptly up to -26.7‰, reaching values up to -25.4‰. Magnetic susceptibility increases up to 211.8 x 10^{-8} SI with grain size showing some variability but stable around 6.5 phi. Magnetic susceptibility decreases abruptly at around 70 cm without big changes in grain size where the biogeochemical proxies start to change and recover more stable values as below 100 cm, with an increasing TOC trend up to 40 cm where it reaches values of 6%, two units higher than the average value before 100 cm. The C/N and $\delta^{13}C$ recover stable values faster than TOC, right above 70 cm, with values around 23 and -28.9‰, respectively, and slightly higher than the average before 100 cm. After 70 cm and an abrupt decrease, the magnetic susceptibility holds similar values as before to decrease and reach more stable values of 87 x 10^{-8} SI at around 50 cm. Grain size increases, reaching a maximum size around 50 cm to then reach stable values around 40 cm as TOC. Above 40 cm, all records reach stable values except for a slight decrease in grain size and an increase of 2‰ in $\delta^{13}C$ towards the surface of the sediment core of Lake Oscuro. After 70 cm, it recovers to -28.2‰. Between 50 cm and the bottom, the TOC reaches 6% at 40 cm and then stays constant with a peak of 7% at 20 cm, and the C/N is around 25. $\delta^{13}C$ increases from -28.2‰ to -26.6‰; magnetic susceptibility is around 80 x 10^{-8} SI, and from 7 cm, it decreases to 6.9 x 10^{-8} SI. The grain size stays constant at around 6 phi (Figure 3a).

3.2.2 Lake Tranquilo

The sediment core of lake Tranquilo has four clear zones where the parameters change. The first is between 146 cm and 122 cm, where the TOC, C/N, and $\delta^{13}C$ have high variability. The TOC oscillates between 0.2% and 3.7%, the C/N between 7.1 and ·30.8, and $\delta^{13}C$ between -29.4 and -27.6. Magnetic susceptibility increases from 37.7 to 82.1x10^{-8} SI, and grain size varies from 4.5 to 6.3 phi. The second zone is between 122 cm and 80 cm. The organic geochemistry parameters tend to be steady in this zone. The TOC is around 1.6%, the C/N is around 12.5, $\delta^{13}C$ increases from -28.5‰ to -27.8‰, the magnetic susceptibility (MS) is lower and oscillates between the values of 8.6 and 94.9x10^{-8} SI, and the grain size is around 5.8 phi. The third zone is between 80 cm and 40 cm. The TOC stays constant at around 1.5%, the C/N decreases from 13.2 to 12.2, $\delta^{13}C$ remains around -27.7‰, the MS values are around 55x10^{-8} SI, and the grain size varies between 4.2 and 6.6 phi. The fourth zone is between 20 cm and 0 cm. The TOC and C/N decrease from 1.5% to 1.1% and from 11.9 to 10.2, respectively. $\delta^{13}C$ decreases from -27.7‰ to -29.0‰; the MS at 22 cm increases from 40 to 60x10^{-8} SI, and the grain size is around 5.6 phi. Within this zone, there is a valley (or peak) at 12 cm for all the sedimentological proxies. The TOC, C/N, $\delta^{13}C$, MS, and grain size values are 0.1%, 5.2, -26.7‰, 291.8x10^{-8} SI, and 5.8 phi, respectively (Figure 3b).

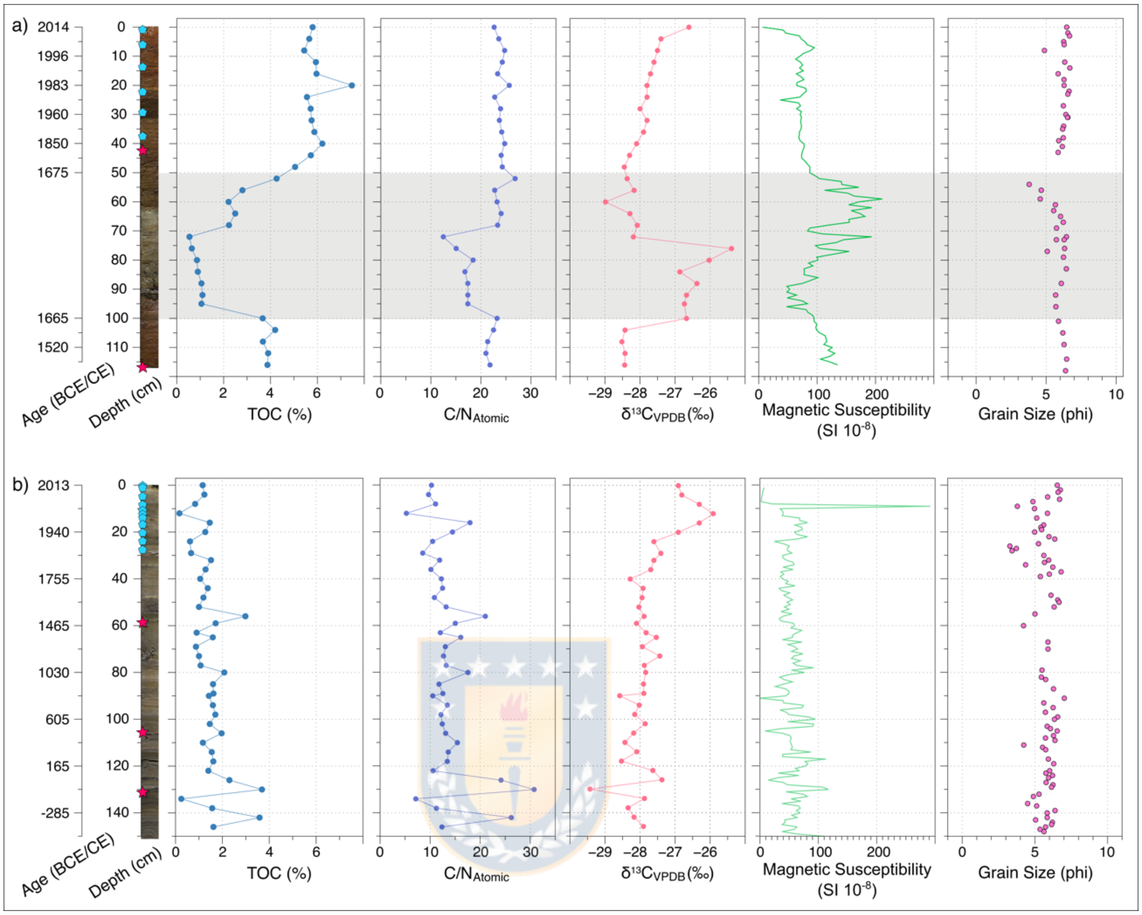

Figure. 3: Sedimentological parameters for lakes a) Oscuro, considering a gray layer of 50 centimeters; and b) Tranquilo. ($\delta^{13}C$ from both lakes were corrected for the Suess according to Verburg (2007). Blue dots are the ^{210}Pb dates and red start are the ^{14}C dates.

3.3 Biogeochemistry

3.3.1 Lake Oscuro

Fatty acid methyl esters (C_{26}+C_{28}+C_{30}) ($FAMEs_{C26+C28+C30}$) are constant through the sediment at around 250 µg/g, with five peaks at 102, 82, 62, 52, and 32 cm of 1254, 2184, 1853, 879, and 91305 µg/g. The $ACL_{C26–C30}$ varies between 26.9 to 27.8 from the bottom of the core up to 30 cm from the top. From 30 cm to the top, the $ACL_{C26–C30}$ trends towards increasing with low variability from 27.2 to 27.7. Finally, the δ^2H trends towards increasing (less negative values) from -185.2‰ to -165.4‰; the only part that does not follow this trend is within the grey layer (Figure 4a).

3.3.2 Lake Tranquilo

The $FAMEs_{C26+C28+C30}$ have high variability between 1 and 15 µg/g from the bottom until 50 cm. From 50 cm until the top, FAMEs tend to decrease. The $ACL_{C26–C30}$ display a general trend to increase along the core upwards from 27 to 27.5. The only intervals that deviate from this general trend are 142–130 cm, 110–100 cm, and 80–60 cm. Finally, the δ^2H increases rapidly (more positive values) in the first part of the sediment core, from 130 to 100 cm. Also, between 81 and

68 cm, values have high variation between -191.2‰ and -174.7‰. The measurements at 68 cm upwards display a trend to be less negative (Figure 4b).

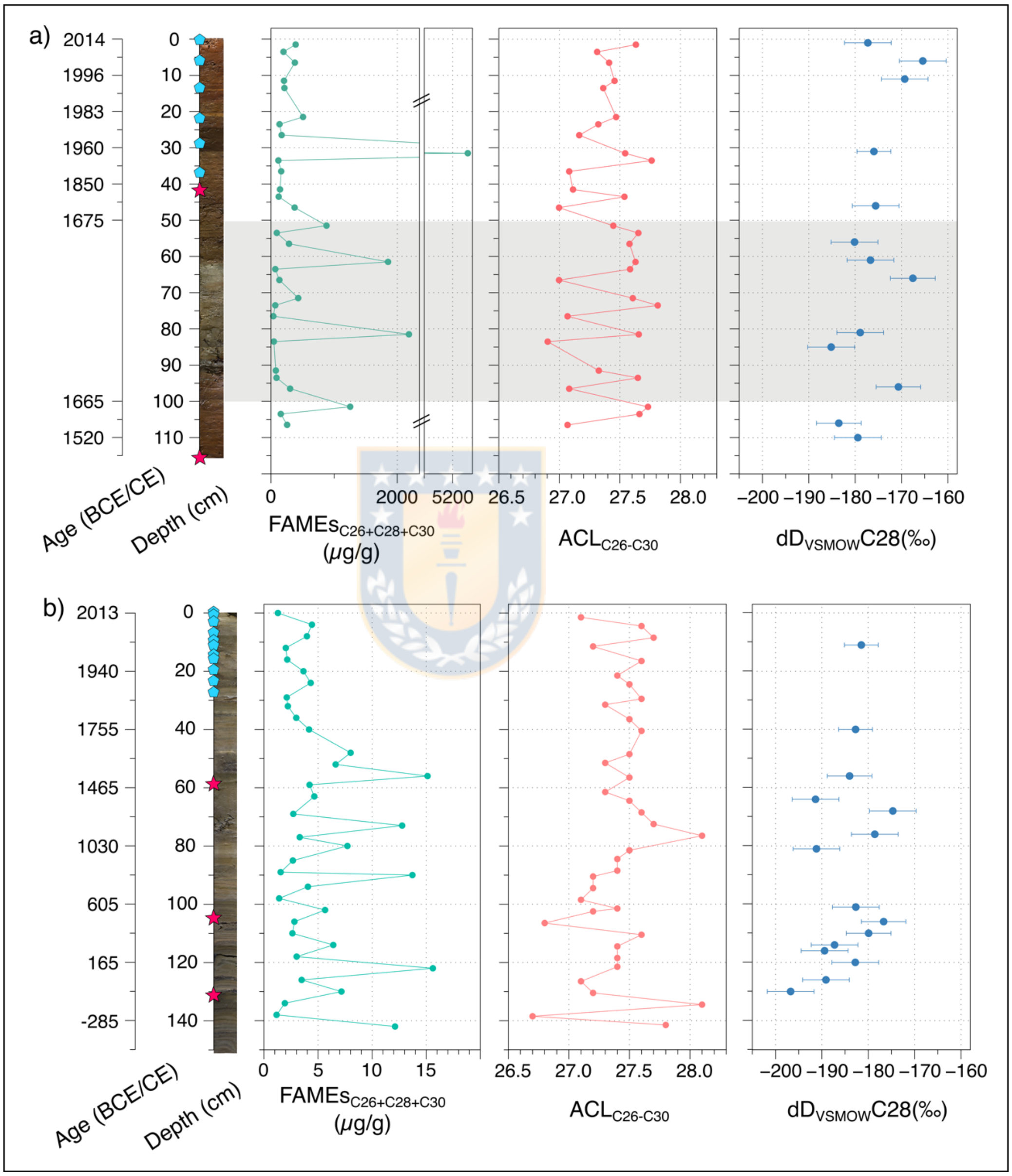

Figure. 4: Biogeochemical parameters for lakes a) Oscuro considering a gray layer of 50 centimeters; and b) Tranquilo. Blue dots are the ^{210}Pb dates and red start are the ^{14}C dates.

4 DISCUSSION

4.1 Interpretation of sedimentological proxies

Magnetic susceptibility (MS) measured in sediments varies with magnetic minerals as very common iron-bearing materials; hence, it can determine the mineralogical contribution of sediments (Zolitschka et al., 2002) due to runoff, rock weathering, or volcanic eruptions. Grain size can indicate increased runoff due to precipitation changes (Bertrand et al., 2014). The proportion of TOC and total C/N ratio distinguished the characteristics of algae and vascular plants accumulated in sediments. If the sedimentary C/N values are higher than 20, the TOC is associated with a higher proportion of allochthonous sources (vascular plants); values lower than 10 indicate autochthonous sources like algae (Meyers and Teranes, 2001). The $\delta^{13}C$ composition from TOC reflects the productivity of the lake (Bertrand et al., 2005; Fiers et al., 2019), where sedimentary organic matter from more productive and eutrophicated lakes has more positive values of $\delta^{13}C$ due to an increase in organic matter from algae (Meyers and Teranes, 2001) that use ^{12}C preferentially, increasing the $\delta^{13}C$ produced in the lakes (Meyers, 2003).

The sedimentological proxies are different in both lakes. The TOC in Lake Oscuro sediments is three times higher than in Lake Tranquilo and holds C/N values higher than 20, while in Lake Tranquilo, the values are between 10 and 20. Therefore, Lake Oscuro has a higher input of allochthonous organic matter, which is expected due to the very different precipitation amount associated with each lake (Figure 1b). The $\delta^{13}C$ has similar values in both lakes, although Lake Oscuro has an abrupt change between 100 and 70 cm, with an increase at the surface, and Lake Tranquilo has less negative values of $\delta^{13}C$ between 20 and 4 cm. The values of MS are lower on average in Lake Tranquilo. Lake Tranquilo also has a thicker material input, probably because of the difference in climate and, thus, the vegetational structure of both lakes (Figure 1).

The TOC, C/N, $\delta^{13}C$ and MS change abruptly in Lake Oscuro between 100 and 70 cm (around 1620 CE; Figure 3a). At 100 cm, there is a decrease in TOC and C/N ratio and an increase in $\delta^{13}C$ and MS (decades of the 1660s/1670s; Figure 3a). Lake Oscuro is located 15 km from Exploradores glacier, giving origin to the Exploradores river (Figure 5). Glacier floods have been described recently in the Exploradores river (Bañales-Seguel et al., 2020), in Martinez Channel and Steffen Fjord (Vandekerkhove et al., 2020a), and in the reconstruction in the basin of the Baker River (Vandekerkhove et al., 2020b). Hence, a decrease in C/N would indicate an increase of nitrogen, likely from the glacier sediment, which comes from the rock weathering of the glacier. In this area, rocks are granitic

(SERNAGEOMIN, 2003), and the proportion of nitrogen will be more abundant (lower C/N). The Exploradores glacier that flows into the Exploradores river, which passes next to Lake Oscuro, is the most suitable candidate to explain the sedimentological changes (Figure 5). Besides, the Exploradores river has a $\delta^{13}C$ value of around -26‰ (Bertrand unpublished data), which could explain the increase of $\delta^{13}C$ on the lake sediments (Figure 3a). Therefore, together with an increment of SM, it would indicate an input of glacier sediments.

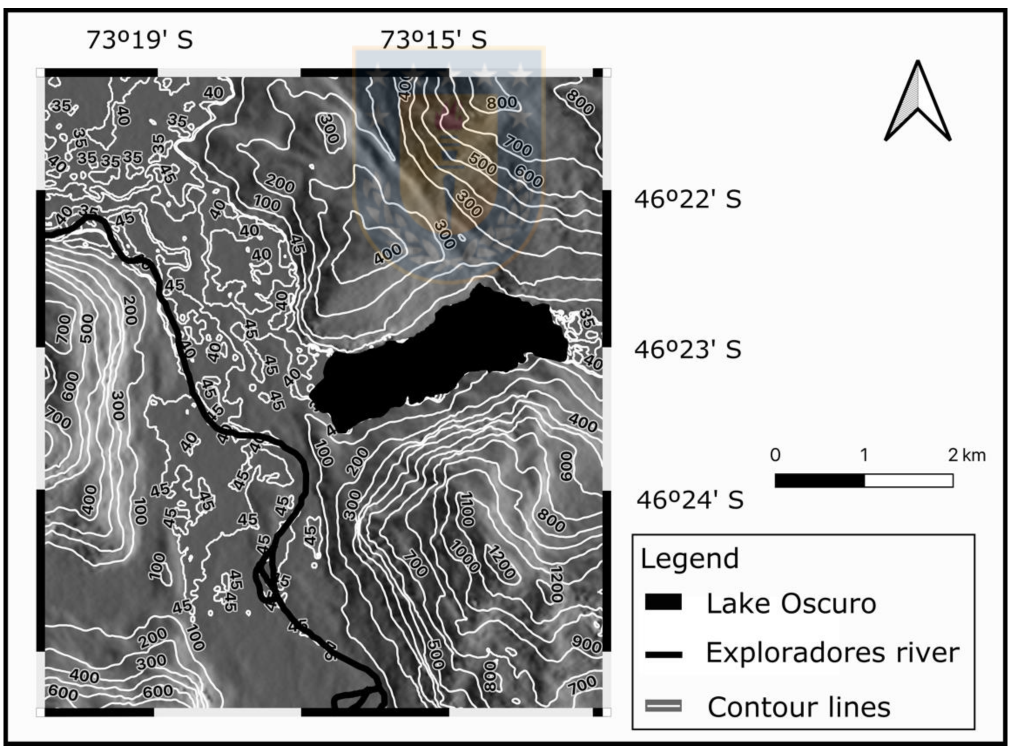

Figure. 5: Digital Elevation Model (DEM) for Exploradores river and lake Oscuro.

The Exploradores river would have been flooded during the 1660s or 1670s, resulting in the arrival of floodwater to Lake Oscuro because there is just a 5 m level difference between the river and the lake (Figure 5). This flood brought approximately 40 cm of sediment, which could eventually be a glacial lake outburst flood (GLOF). Between 70 and 50 cm, the sedimentological parameters (Figure 4a) recovered from the perturbation, but they were still influenced by it. Magnetic susceptibility and grain size increased during this time. This could be due to a rise in precipitation, maybe in a liquid state, which increases runoff.

The TOC has its higher values (6%); C/N is higher than 20, and $\delta^{13}C$ increases steadily from 1850 until 2013 (Figure 3a). Therefore, there is an increase of organic matter probably related to the exploitation of Fitzroya cupressoides in the Aysén archipelagos (Torrejón et al., 2013) together with the settling period at the beginning of the 20th century (Martinic, 2005; Torrejón et al., 2013).

The Lake Tranquilo sediment’s core has a high variability of TOC and C/N between 445 BCE and 25 CE (Figure 3b), which could be related to vegetational changes in the lake watershed. Between 25 and 1030 CE, these proxies do not record important changes (Figure 3b). The TOC, CN, $\delta^{13}C$, and grain size tend to increment between 1890 and 2013 CE. At the same time, MS has a peak at 1990 CE, and TOC drops in this year (Figure 3b). This can be the effect of the 1991 Hudson eruption (Naranjo and Stern, 1998), and it was used as a temporal marker to correct the model in five years. After the eruption, TOC recovered, and $\delta^{13}C$ increased until 1940 while C/N decreased. Then, $\delta^{13}C$ decreased until the top of the core (Figure 3b). The increase in TOC and $\delta^{13}C$ and the decrease in C/N could be related to the fires provoked by the settlers at the beginning of the 19th century, which caused the input of nutrients to the lake through erosion. Therefore, the lake could increase productivity during this period.

4.2 Interpretation of geochemical proxies

FAMEs are carboxylic acid with aliphatic chains produced by many organisms (Bataglion et al., 2016), and according to their size, they can indicate the origin of organic matter. Smaller carbon chains ($x < 18C$) come from algae organisms, whereas medium-length carbon chains ($20 < x < 24$) are from aquatic plant origins, and long carbon chains ($26 < x < 32$) have vascular plant origins (Bataglion et al., 2016; Liu et al., 2015). The ACL from vascular plants could indicate warm and/or dry conditions (Wang et al., 2016). When there is a dry and/or warm period, plants produce lipids of bigger carbon chains to avoid evaporation (Ling et al., 2017; Schefuß et al., 2003). The ACL can also be a proxy of changes in the forest structure, depending on the species of vascular plants that dominate the vegetational structure (i.e., forest or grassland). The δ^2H from leaf waxes is also used in paleoclimatic studies because it does not have fractionation within the sediment (Norström et al., 2018; Sachse et al., 2012). Hence, the biologic fractionation during biosynthesis in the plants is representative of δ^2H from precipitation (Feakins and Sessions, 2010; Norström et al., 2018). There are two main environmental factors that could affect fractionation of δ^2H (Sachse et al., 2012): (i) Continental effect, means that when air masses advance through the continent and loose moisture, the δ^2H values are lower further inland. (ii) The variation of the amount of precipitation in one place, where there is a depletion/enrichment of deuterium at higher/lower precipitation (Sachse et al., 2012). Therefore, more negative/positive values of δ^2H represent higher/lower precipitation within the same core.

FAMEs differ in both lakes. Lake Oscuro has values of three orders of magnitude higher, probably because higher precipitation in the basin of Oscuro drags more material from vascular plants (Castañeda and Schouten, 2011). In contrast, ACL values are similar, and δ^2H is around 10‰ of difference, which is less negative in Lake Oscuro. This difference could be due to as lake Oscuro is located in the west side, it precipitates first and the rain it is more reach in δ^2H. While the cloud past from west to east, the rain becomes lighter and values of δ^2H are more negative.

FAMEs in Lake Oscuro are high (over 500 μg/g) in the sediment core, especially around 1950 CE, where the concentration is over 5200 μg/g (Figure 4a). This peak could be related to an increment of runoff during the settlement period in this area because the settlement implied forest clearance by fires, leaving unprotected soil exposed to precipitation (Araneda et al., 2013; Martinic, 2005). The high variability of ACL throughout the core reflects the high precipitation variability of the place, which could vary from 3000 to 4500 mm yr^{-1} (Figure 1b). Aside from more negative values of δ^2H within the $16^{th}/17^{th}$ centuries (Figure 4a), this could be related to higher precipitation. In contrast, more positive values from the 19^{th} century to the current time could be related to lower precipitation rates.

The Lake Tranquilo record has a high variability of ACL and δ^2H between 445 BCE and 25 CE (Figure 4a). This change in ACL could be related to changes in vegetation or a disturbance in the landscape, such as a forest fire. Fire reconstructions in Patagonia evidence a prevalence of regional fires during the late Holocene period (Porras et al., 2012). More specifically, Pesce and Moreno (2014) found a high occurrence of fires during 950 BCE and 1150 CE at 43º S. The δ^2H has an increment (less negative values) of 10‰ (Figure 4a), which could be interpreted as a decrease in precipitation. Between 1030 and 1890 CE, ACL also tends to follow δ^2H (Figure 4a); therefore, the most likely explanation is drier conditions. Although the sedimentological variables are also stable during this period, grain size increases at around 1460 CE (Figure 4a), which matches a peak in TOC and C/N. The peak of C/N indicates an increase in allochthonous material, which could be dragged to the lake by higher energy (higher runoff), probably provoked by an increment in precipitation during that time. ACL changes during the 19th century could be due to a change in vegetation from forest to grassland provoked by the fires induced by the first settlers in Patagonia (Araneda et al., 2013; Martinic, 2005). As there is only one value in δ^2H, we can interpret the year 1975 CE as having a climate similar to that of the previous period.

4.3 Climatic interpretation of proxies

Our data records show a decrease in precipitation between 25 and 1030 CE and very low precipitation between 1030 and 1465. This dry period is followed by an increase in precipitation between 1460 CE and 1600 CE and a decrease in humidity between 1850 and the current time. The increases and decreases in precipitation fit in with other reconstructions obtained in Patagonia (Figure 6).

Sepúlveda et al., (2009) estimated with alkenones that before 1050 CE, it was 1 degree Celsius warmer than today at Jacaf fiord (44º S). Bertrand et al., (2017) found warmer periods due to a significant meltwater event increasing grain size and leading to concomitant decreases in organic carbon of marine origins between -50 and 750 CE at Altamirantazgo fiord (54º S). Fletcher and Moreno, (2012) found a warmer period between 950 and 1225 CE due to increased fire activity, plus rapid bulk dry sediment accumulation because of the low growing season's moisture and increased fire activity at Laguna San Pedro, Lonquimay

(38º S). Zolitschka et al., (2019) attribute the dry period between 760 and 1450 CE to more eutrophication corresponding to lower lake levels at Laguna Azul (52º S). Bertrand et al., (2014) found interphase towards drier conditions between 1200 and 1500 CE due to an increase of Fe/Al and Ti/Al (Figure 6). Although the period between 600 and 1030 CE is described as humid and cold in Chilean Patagonia (Bertrand et al., 2014; Fletcher and Moreno, 2012; Zolitschka et al., 2019), we do not have enough data to make this interpretation.

Fletcher and Moreno, (2012) attribute the cold and wet period between 225 and 1829 CE to low fire activity and slow bulk sedimentation. Sepúlveda et al., (2009) found that it was one degree Celsius colder than today between 1500 and 1700 CE at Jacaf Fjord (44º S) using alkenones-based SST; they also found that there was higher runoff from the continent using plant-derived biomarkers. Zolitschka et al., (2019) evidenced the moister and less windy conditions between 1550 and 1850 CE using a multi-proxy approach (XRF, diatoms, pollen, dissolved inorganic carbon) at Laguna Azul (52º S). Elbert et al., (2011) described wetter conditions from 1630 to 1690 CE around Lago El Plomo (47º S; Figure 6). Araneda et al., (2007) show a retreat of the San Rafael Glacier (46º S) using historical records at around 1675 CE, which were interpreted as cold and probably wetter during the period between 1766 and 1898 CE due to an advance of the San Rafael Glacier (46º S) by doing historical reconstruction. They also found that around 1675 CE, conditions were prevailingly warm.

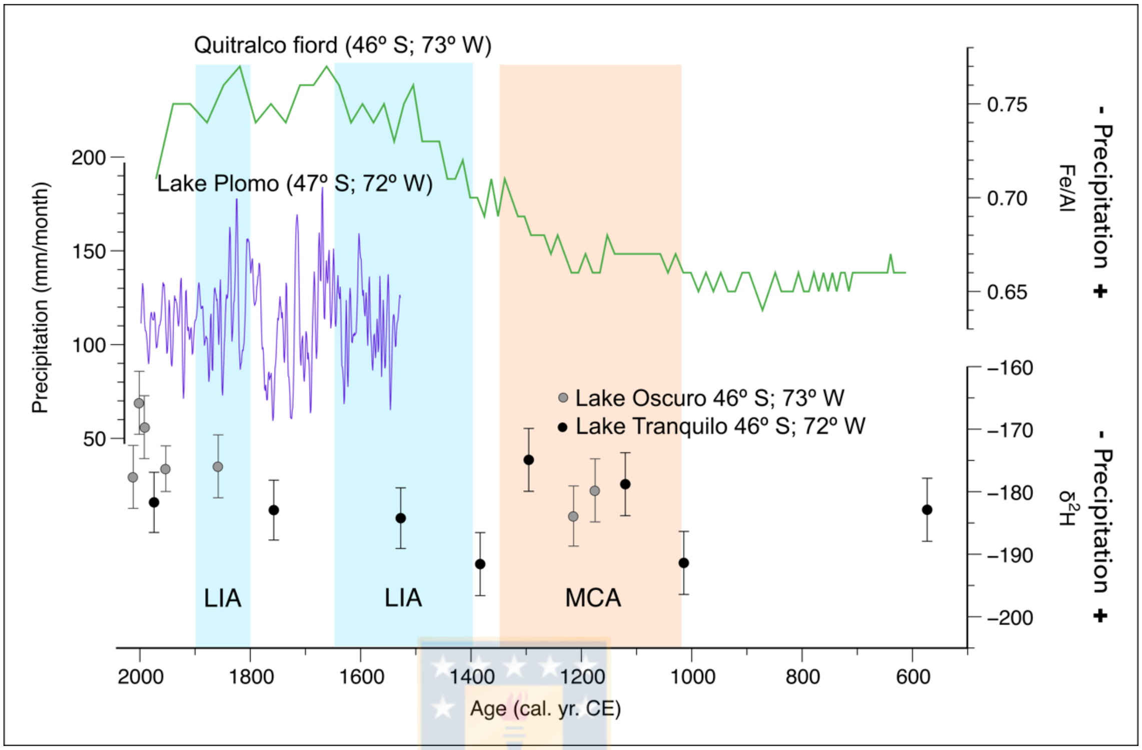

Figure. 6: Precipitation reconstructions near the study area: a) Quitralco fiord (46º S; 73º W) from (Bertrand et al., 2014) ; b) Lake Plomo (47º S; 72º W) from Elbert et al. (2011); c) Lakes Oscuro and Tranquilo.

Zolitschka et al., (2019) described the period of the second half of the 20th century as warm because of the decrease in the lake level at Laguna Azul (52º S). The 20th century was when the first settlers arrived in Patagonia, changing the landscape completely from forest to grassland. To convert the forest into open grassland, the settlers set fire to the existing vegetation. The strong wind conditions, in combination with the forest characteristics, provoked a prevailing fire condition between 1920 and 1950 CE in the area of the ecotone (Araneda et al., 2013; Martinic, 2005). Thus, the variation of the proxies within this timeframe would be influenced by the change in land use and the consequences of these fires.

Neukom et al., (2014) did a temperature reconstruction of the Southern Hemisphere using more than 300 records and found the evidence of climatic anomalies during the last millennium, referred to as the Medieval Climatic Anomaly (MCA; 1000–1200 CE) and the Little Ice Age (LIA; 1570–1722 CE). Our data record a dry period synchronous to the MCA described by Neukom et al., (2014) and a wet period synchronous to the LIA.

4.4 Differences between lakes

The differences between the locations of both lakes – Oscuro, located in a high precipitation area, and Tranquilo, located in a drier zone – are described next. Lake Oscuro has a high local influence of glaciers from Campo de Hielo Norte and a low response to precipitation changes. This is because the precipitation is so high that changes are not completely visible. On the other hand, Lake Tranquilo has a regional climatical representativity. Since the 1500s, it is possible to observe a difference of ~10‰ between the δ^2H of lakes Tranquilo and Oscuro. This difference can be explained by the fact that precipitation occurs on the western side first, in the form of rain more enriched with δ^2H; then, it becomes lighter as the front advances to the east.

Although our δ^2H values are very discrete, it is possible to observe changes in the hydrological cycle that the other proxies do not record. However, more exhaustive studies are needed to ensure that these changes in the hydrological cycle are represented specifically by the δ^2H in leaf waxes. In conclusion, there is a potential use of δ^2H from leaf waxes to assess changes in the hydrological cycle of Chilean Patagonia.

5 CONCLUSIONS

With the work done in this research, we can conclude the following:

- The precipitation in Lake Oscuro, during the last 800 yr, is more than two times higher than in Lake Tranquilo. Consequently, the TOC amount in the sediment core of Lake Oscuro is higher and with a dominant allochthonous input. The dominant allochthonous input is also confirmed with higher input of FAMEs from leave waxes on Lake Oscuro. Therefore, the precipitation is the primary driver in the organic input of the two lakes studied.
- The values of δ^2H, in both lakes and at the same period (after 1500 CE), have a difference of 10‰. These could be due to a depletion of δ^2H while the precipitation advances from west to east.
- A GLOF happened in 1670, provoking an increase of at least 5 m in the level of the Exploradores river. This flood carriage is inorganic material to Lake Oscuro, which affects half of the sediment core.
- Values of $\delta^{13}C$ and TOC in both sediment cores show a tendency of eutrophication during the last century, which could be provoked by the settlers, which provoked drastic changes in the landscape. They changed the vegetation cover through several fires during the first half of the 20th century.

- Nevertheless, we have discrete samples of δ^2H; it is possible to conclude that our data records of δ^2H from lake Tranquilo seem to fit with the general climatic trends in Patagonia. We found a decrease in precipitation between 25 and 1030 CE and meager precipitation between 1030 and 1465. Between 1460 CE and the 17th century were increased precipitation, followed by a decrease in humidity between 1850 to the current time. On the other hand, lake Oscuro influences the surrounding glaciers, overshadowing the δ^2H signal.
- For future work, the best place to do a climatological study using δ^2H derived from FAMEs from leave waxes would be the ecotone, which has enough amount of organic matter to perform a δ^2H, has the climatic signal of Patagonia, and it does not have a local influence like glaciers.

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CAPITULO 4: DISCUSIÓN Y CONCLUSIONES GENERALES

6 DISCUSIÓN

Chile continental es un país que abarca más de 4 mil kilómetros de largo, desde los ~18º S hasta los ~55º S. De esta forma, abarca varias regiones climáticas, pasando del desierto más seco del planeta, hasta los climas de la Patagonia que se caracterizan por sus altas precipitaciones (Capitulo 1; Figura 4). Como se expuso en el Capítulo 1, las diferentes condiciones climáticas son generadas debido a la geografía del país, combinada con diferentes circulaciones atmosféricas (Figura 2 del capítulo 1). Si bien existen reconstrucciones climáticas a lo largo de todo Chile, no existe un trabajo que realice una relación entre las diferentes zonas climáticas a nivel centenial y/o interdecadal con el objetivo de establecer posibles diferencias o similitudes en los fenómenos climáticos sincrónicos. Evaluar esta interacción es de interés debido a que, como se relata en el Capítulo 1, existe una relación entre la deriva de los vientos del oeste (DVO) y el anticiclón subtropical del Pacífico sur (ACP) influenciada por variabilidad climática interanual, tales como el modo anular sur (MAS) y el niño oscilación sur (ENOS).

Los movimientos de la DVO estacionales se refiere a que, durante el invierno/verano austral la DVO emigra hacia el norte/sur, por una condición negativa/positiva del MAS y una disminución/aumento en la intencidad del ACP.

A continuación se describen periodos sincrónicos realizados en el transcurso de esta tesis para describir fenómenos climáticos en la zona central de Chile (33º S) y en la Patagonia Chilena (46º S).

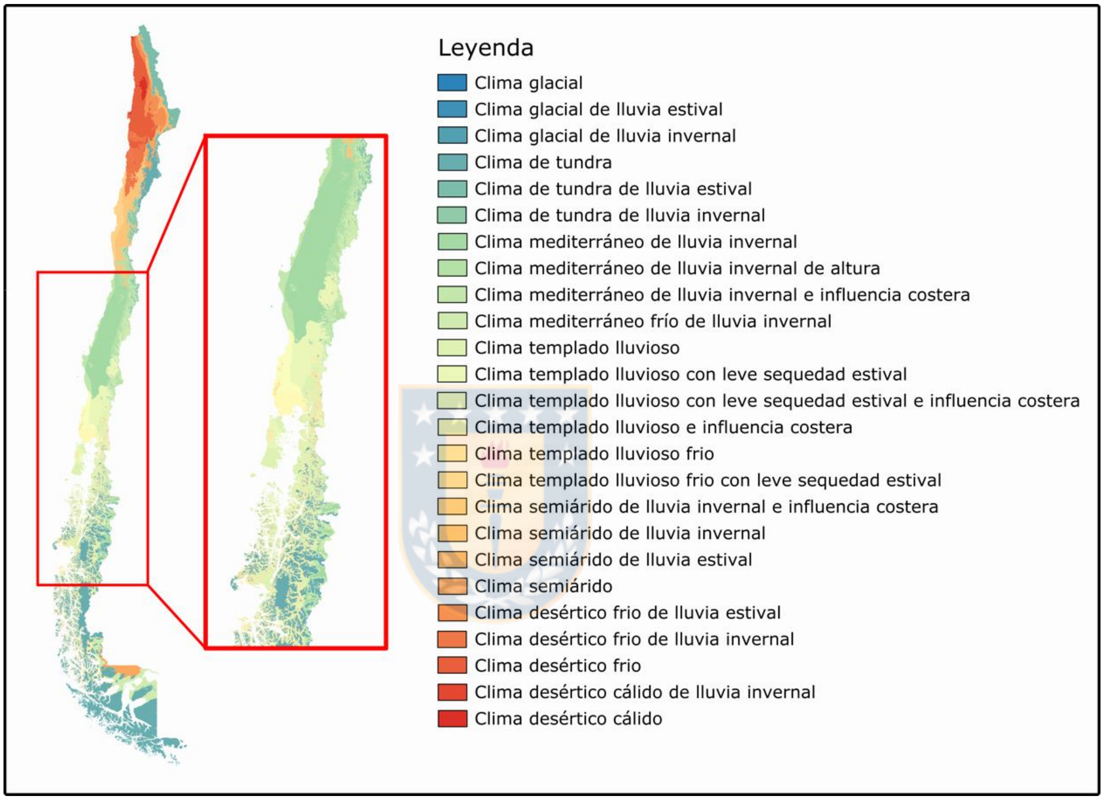

Figura. 1: Mapa de Chile con las regiones climáticas según clasificación de Köppen-Geiger. En el rectángulo rojo se enmarca la zona de interés de este estudio (fuente: www.ide.cl).

6.1 Reconstrucción climática en la zona central (33º S)

En el Capítulo 2 se realizó la reconstrucción climática en la zona central utilizando registros históricos de Vicuña Mackenna. La metodología utilizada en este paper estuvo basada en Pfister (1999b), que consiste en asignar un valor positivo en la descripción de mayor precipitación y asignarle un valor negativo a periodos de menor precipitación (Jana et al., 2019). Durante el siglo XVIII se registraron dos grandes periodos de sequías. El primer periodo entre entre los años 1705 y 1718 DC, y el segundo periodo entre 1770 y 1797. Estas sequías fueron de tal magnitud que hubo riesgos de hambrunas y problemas de higiene debido a la falta de agua (Jana et al., 2019). Probablemente esta sequía fue debido a condiciones negativas persistente de la El Niño Oscilación Sur (ENOS).

ENOS es la modulación de variabilidad climática interanual más importante en la cuenca del pacífico (Garreaud et al., 2009; Timmermann et al., 2018). Un ENOS positivo (El Niño), ocurre debido a que una serie de tormentas con dirección oeste en el pacífico ecuatorial oriental, hacen que las ondas Kelvin, ondas de circulación oceánica, se sumerjan (Timmermann et al., 2018). Esto disminuye la surgencia en el Pacífico oriental, lo cuál causa un calentamiento de la superficie en el Pacífico este/central (Timmermann et al., 2018). El calentamiento en la superficie oceánica causa que cambie la convección de la circulación atmosférica, la cuál se traslada desde el Pacífico Oeste al Pacífico central, reduciendo los vientos alisios ecuatoriales (Timmermann et al., 2018). Esto tiene como consecuencia cambios en las precipitaciones en la cuenca del Pacífico (Garreaud et al., 2009; Timmermann et al., 2018), incluido Chile central, lugar en que las precipitaciones de primavera aumentan durante un ENOS positivo (Garreaud et al., 2009).

En Chile central, ENOS tiene una influencia sobre el anticiclón subtropical del Pacífico sur (ACP), así, cuando se presenta un ENOS positivo/negativo, aumenta/disminuye el paso de tormentas debido a un debilitamiento/intensificación del ACP (Montecinos y Aceituno, 2003; Oertel et al., 2020). Cabe destacar, que un ENOS negativo se manifiesta con cielos más despejados y por ende, una mayor probabilidad de sequía, acompañada por una disminución en la acumulación de nieve en la cordillera y menor escorrentía de primavera (Oertel et al., 2020). En la zona norte de Chile central, el ACP prevalece durante todo el año, por ende, solo es afectado por ENOS cuando es fuerte (Montecinos y Aceituno, 2003; Oertel et al., 2020). Un ENOS fuerte se refiere a que, los cambios de precipitación (aumento o disminución) son más pronunciados. En la zona sur de Chile central (al rededor de los 36º S) ENOS tiene una gran influencia en las precipitaciones de primavera, es decir, que en un ENOS positivo/negativo, ingresa un mayor/menor número de tormentas al continente (Montecinos y Aceituno, 2003; Oertel et al., 2020; Timmermann et al., 2018). Por lo antes expuesto, los largos periodos de sequía registrados durante el siglo XVIII, probablemente estén asociados a condiciones prevalentes de ENOS negativo.

6.2 Reconstrucción climática en la Patagonia (46º S)

En el capítulo 3 se realizó la reconstrucción climática en la Patagonia Chilena norte (46º S) utilizando registros sedimentarios del Lago Oscuro (46.4º S; 73.2º O) y Lago Tranquilo (46.6º S; 72.8º O). Esto con el objetivo de establecer el mejor lugar para realizar una reconstrucción de precipitación, considerando el abrupto gradiente de precipitación, que en 60 km pasa de 4000 mm/año a 500 mm/año (Garreaud et al., 2013; Garreaud et al., 2009). Para realizar estos estudios se tomaron dos núcleos de sedimento, uno de cada lago, realizandose análisis de carbono orgánico total (COT), $\delta^{13}C$ en el sedimento, susceptibilidad magnética, granulometría, ácidos grasos provenientes de ceras de hojas (FAMEs), y $\delta^{2}H$ en C28 proveniente de las ceras de hojas. Estos indicadores están descritos con mayor detalle en los capítulos 1 y 2.

En este trabajo se pudo concluir que, debido a las diferencias en precipitación de ambos lagos, hay diferencias en el ingreso de COT. En lago Oscuro el ingreso es mayor y con una fuente externa dominante, además los FAMEs tuvieron un ingreso mucho mayor, que en el lago Tranquilo. Al tener el lago Oscuro una mayor precipitación, sería éste el principal factor de ingreso de materia orgánica (Figuras 4 y 5 del Capítulo 3). Con los indicadores estudiados en Lago Oscuro y Lago Tranquilo se puede concluir que el mejor lugar para realizar un estudio de precipitaciones es el Lago Tranquilo, debido a que se encuentra en una zona de transición (ecotono bosque-estepa), siendo mayores aún las diferencias en las precipitaciones en este lugar. A pesar de que las muestras de δ^2H fueron discretas, es posible concluir que los registros de este indicador en lago Tranquilo están relacionados con las tendencias climáticas en la Patagonia, como por ejemplo en los trabajos de: (Bertrand et al., 2014; Elbert et al., 2011; Fletcher y Moreno, 2012; Zolitschka et al., 2019).

En el Capítulo 3, se identificaron diferentes periodos de precipitación. Entre 25 y 1030 CE hubo una disminución en las precipitaciones y, entre 1030 y 1465 la precipitación fue escasa. Entre 1465 y durante el siglo de 1600 la precipitación incrementó, mientras que a partir de 1850 hasta la actualidad, la precipitación ha estado disminuyendo. Esta información concuerda con el estudio de Neukom et al. (2014a), en el cuál se identifican la anomalía climática medieval (ACM) y la pequeña edad del hielo (PEH), entre 1000 a 1200 CE y entre 1570 y 1722 CE, respectivamente. Por lo tanto, en los registros de este estudio, se observa un periodo seco sincrónico a la ACM y un periodo húmedo sincrónico a la PEH (Figura 6 del Capítulo 3).

6.3 Comparación registros Chile Central vs. Patagonia Norte

El primer gran periodo seco descrito en Jana et al. (2019; Capítulo 2), entre 1705 y 1718 (Figura 5) coincide con un aumento en la temperatura de la zona central de Chile (Gunten et al., 2009a; Jana et al., 2019). Durante este periodo, no existen registros de δ^2H ni en lago Oscuro, ni en lago Tranquilo (Figura 2), debido a que, como fue descrito en el Capítulo 3, hubo muestras que no se pudieron medir. Por esta razón este periodo seco descrito en la zona central, se compara con la reconstrucción de precipitaciones realizada por Elbert et al. (2011). En este estudio se realizó una reconstrucción de precipitaciones de invierno (junio, julio y agosto) utilizando la tasa de sedimentación del Lago Plomo (47º S; 73º O), en una resolución anual (Figura 2). Entre los años 1705 y 1718 CE, Elbert et al. (2011) registran un periodo en que la precipitación va en incremento, desde los 83±16 a los 149±34 mm/mes respectivamente. Entre los años 1770 y 1797, Elbert et al. (2011) también evidencia un incremento de las precipitaciones a lo largo de este periodo, desde 79±18 mm/mes en 1970, hasta llegar a 130±17 mm/mes en 1797. Por lo tanto, esto podría significar condiciones de un Modo Anular Sur (MAS) positivo según lo descrito en la Capítulo 1.

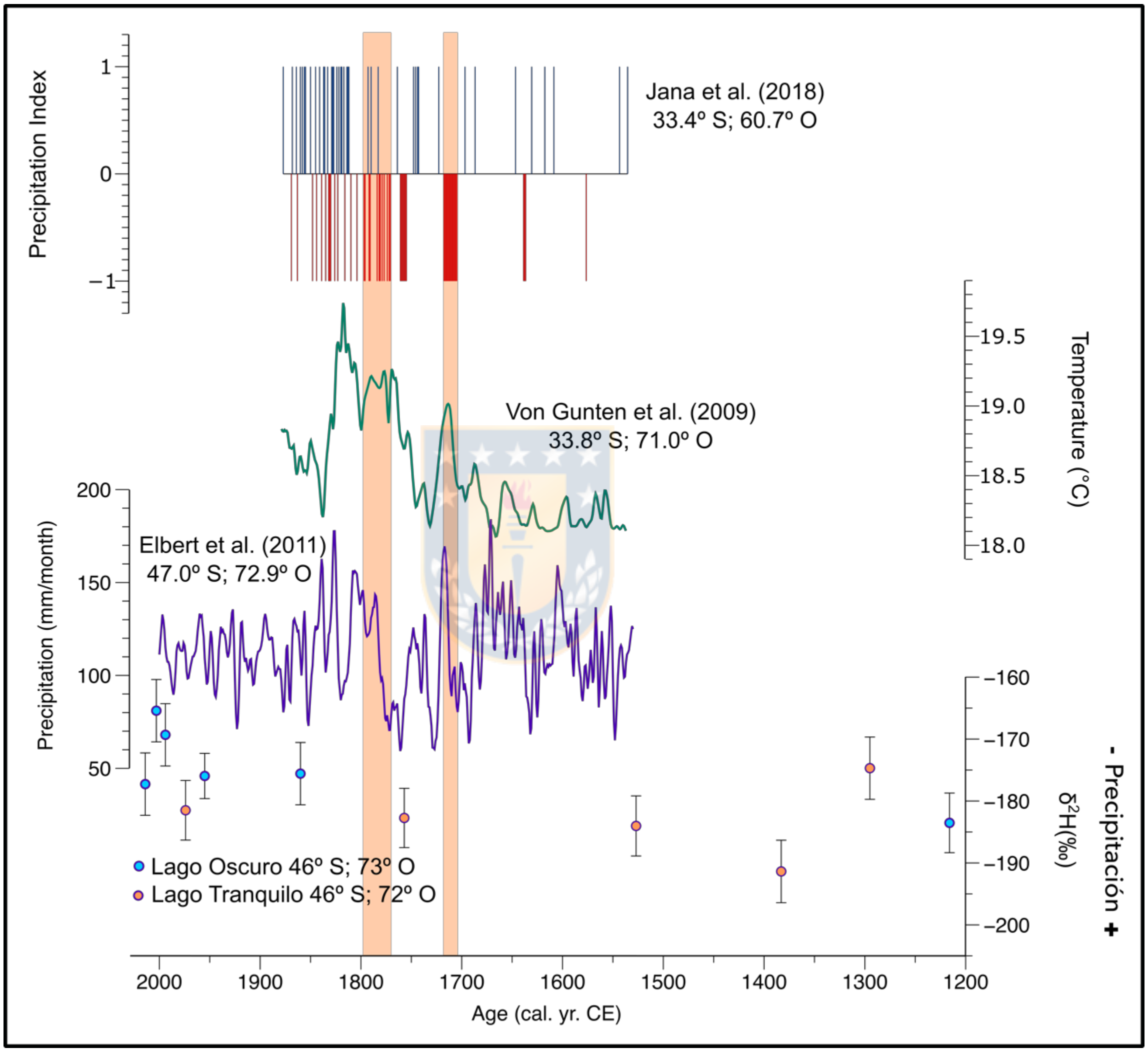

Figura. 2: Comparación de precipitaciones para los últimos 800 años en Chile central (Jana et al. 2018), temperatura en Chile central (von Gunten et al. 2009), y precipitaciones en la Patagonia (Elbert et al. 2011; Jana et al. en revisión).

Cómo fue descrito en el Capítulo 1, los principales componentes climáticos que actúan en Chile son el Anticiclón del Pacífico (ACP) y la Deriva de los Vientos del Oeste (DVO). Mientras que el ACP, en las costas de Chile, tiene una fuerte componente meridional del viento en dirección sur; la DVO tienen una fuerte componente zonal en dirección oeste. Así, cuando hay una intensificación del ACP, los vientos meridionales del sur, se intensifican, evitando que ingresen frentes de baja presión al continente en la zona central de Chile, y el proceso contrario sucede cuando el ACP se debilita (Flores-Aqueveque et al., 2020; Garreaud et al., 2009). En complemento, cuando existe una intensificación de la DVO, también se intensifica su componente zonal, lo cual es asociado a un aumento en las precipitaciones en la Patagonia chilena.

Flores-Aqueveque et al. (2020) determinan que durante tiempos en que prevalecen condiciones cálidas, como el actual calentamiento de la segunda mitad del siglo XX, el ACP se intensifica al sur de los 35ºS, pudiendo llegar hasta los 45º S en verano, disminuyendo así las precipitaciones en el centro-sur de Chile. Una intensificación del ACP estaría relacionado con un movimiento hacia el sur de la DVO. Además este movimiento está fuertemente influenciado por MAS y ENOS descritas en el Capítulo 1 (Collins et al., 2019; Dätwyler et al., 2020; Flores-Aqueveque et al., 2020; Garreaud et al., 2009).

En los periodos descritos en Jana et al. (2019; Capítulo 2) entre 1705 y 1718, y 1770 y 1797, en los que se identificó dos grandes periodos de sequías, también se registran altas temperaturas (von Gunten et al. 2009; Figure 2), por lo que probablemente se registre una intensificación del ACP, evitando así la entrada de sistemas frontales y provocando los periodos de sequía descritos. En la Patagonia Elbert et al. (2011; Figura 2) registra que la precipitación va en incremento durante ambos periodos de sequía. Como fue descrito en el Capítulo 1, el área de mayor velocidad de la DVO se encuentra entre los 55º y 45º S, lugar donde las precipitaciones son más altas. Por lo que, probablemente al inicio de estas sequía, al intensificarse el ACP, la DVO se traslada hacia el sur, trasladando así su núcleo y disminuyendo las precipitaciones en la zona de los 46/47º S. Luego, la DVO podría volver a su posición más hacia el norte durante este periodo de sequía. Así, al menos al inicio de los periodos de sequía, podría darse una condición de MAS positivo. En relación a esto, Dätwyler et al. (2020) encuentra que durante el siglo XVIII MAS y ENSO eran del mismo signo, probablemente asociado a una Oscilación Interdecadal del Pacífico (OIP) negativa, oscilación que dura 80 años aproximadamente; o sea condiciones similares a La Niña.

7 CONCLUSIONES GENERALES

En la zona central de Chile (33º S, Santiago) fue posible realizar una reconstrucción climática semi-cuantitativa utilizando registros históricos a partir del siglo XVIII. Esto debido a que anterior a este periodo, los registros históricos eran muy escasos. En esta reconstrucción se observaron dos periodos de sequía extrema, a diferencia que durante el siglo XIX, en el cuál, Mackenna habla de periodos alternados entre mayor y menor precipitación. Los periodos de sequía durante el siglo XVIII coinciden con otras reconstrucciones realizadas hacia el norte de Santiago, por lo que este periodo podría estar relacionado con eventos climáticos tipo ENOS. Para realizar estudios con registros históricos más precisos es necesario complementar la información de Vicuña Mackenna con otros registros de la época y/o con otros archivos, como registros sedimentarios.

En la Patagonia chilena (46º S), se realizó una reconstrucción de precipitaciones de los últimos 2000 años en la Patagonia utilizando δ^2H, Ácidos grasos provenientes de ceras de hojas, e indicadores geoquímicos como indicadores de precipitación en registros sedimentarios. Las principales conclusiones de esta reconstrucción fue que los registros de precipitación coincidían con otros estudios realizados en la Patagonia, encontrando un periodo seco, sincrónico con la ACM y un periodo húmedo, sincrónico con la PEH. De las dos áreas evaluadas en la

Patagonia para realizar reconstrucciones climáticas, la zona de ecotono bosque-estepa, fue la que mejor representaba la evolución climática del lugar. Finalmente, se realizó la comparación de los registros climáticos, determinando una relación entre la interacción de el ACM y de la DVO en la que, durante la ACM, debido a que se marcan claramente diferentes periodos de aumento y disminución de precipitación, en la cuál la DVO se debilita y disminuyen las precipitaciones.

En relación a la primera hipótesis de trabajo, es posible concluir que existe una conexión entre el ACP y la DVO. Al intensificarse el ACP las sequías aumentan en la zona central del país y la DVO se traslada hacia el sur. Al trasladarse hacia el sur, cambia su núcleo, área de mayor velocidad de viento, por lo que la precipitación en esta área es mayor. Al trasladarse su núcleo hacia el sur, cambia la zona de en la cual se incrementa la precipitación y esta disminuye en los extremos de la DVO. Por lo tanto, la interacción interanual entre la DVO y el ACP es posible encontrarlo a escalas decadales. No obstante aún existen contradicciones sobre la sincronía de periodos a estas escalas, por lo que es necesario seguir estudiando y comprendiendo estos fenómenos.

La segunda hipótesis se responde a través del capítulo 3. Tras realizar un análisis de Multi-indicador en los lagos Oscuro (zona de alta precipitación y bosque denso) y Tranquilo (zona de precipitación media y bosque caducifolio mixto) es posible concluir que la mejor zona para realizar una reconstrucción climática es la zona del lago Tranquilo. Esto debido a que, los indicadores son más sensibles a los cambios de precipitación al haber una menor precipitación anual (1500 mm/año). A diferencia del lago Oscuro en que las precipitaciones son mayores a 3500 mm/año, por lo que los indicadores no son mayormente sensibles a sus cambios. Con respecto a la reconstrucción de precipitaciones a través de δ^2H, el registro resultó muy discreto debido a problemas con el análisis de muestras descritos en el capítulo 3. Aún así, fue posible encontrar influencia de un periodo de menor precipitación asociado con el periodo de altas temperaturas sincrónico con la Anomalía Climática Medieval descrita por varios autores en la zona sur de América del Sur, además se encontró una relación con las reconstrucciones climáticas realizadas en la zona.

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ANEXO 1: PAPER PUBLICADO

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SHORT COMMUNICATION

Drought periods during 18th century in central Chile (33°S): A historical reconstruction perspective revisiting Vicuña Mackenna's work

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Understanding past climate variability is important for obtaining better predictions of future changes. Documentary records are high temporal resolution proxies that can be used to reconstruct aspects of the climate, such as precipitation. Vicuña Mackenna developed a compilation of historical climatic events between the 16th and 19th centuries using chronicles from Spanish colonizers and town council records. The objective of this work was to classify dry and wet periods beginning in the 16th century using records from Vicuña Mackenna by generating a precipitation index based on events in the documentary evidence (e.g., epidemics, "pro pluvia" rogations, and infrastructural damage) into a simple annual precipitation index on an ordinal scale. The index used a three-term classification scale, with 0 representing normal years, 1 representing wet years, and −1 representing dry years. The documentary records were not substantial enough to identify wet/dry periods during the 16th and 17th centuries. However, it was possible to identify dry and wet years described by conquerors and settlers that first arrived in the study area. During the 18th century, two long periods of drought were identified: 1705 to 1718 and 1770 to 1797. During these droughts, people organized rogations to the *Virgen* and different saints in desperation due to the lack of water. Finally, during the 19th century, technological improvements in measuring precipitation made it possible to identify intermittent dry and wet periods with higher resolution and precision, and these events could be related to the El Niño–Southern Oscillation (ENSO).

KEYWORDS
Chile, climate, documentary records, drought, historical reconstruction, mid-latitudes, precipitation

1 | INTRODUCTION

Determining past climate variability is important for obtaining improved predictions of future climate changes (Neukom *et al*., 2014). Such records are especially relevant during the last millennia, which is the last period that was not affected by anthropogenic factors (Moy *et al*., 2008; Alvarez *et al*., 2015; Andres and Peltier, 2016). Among the different proxies that can be used to reconstruct past climate, documentary records are one of the most precise. These records can directly represent adverse climatic conditions that originate from problems and changes in the roles and organization of societies (Brázdil *et al*., 2005; Prieto and García Herrera, 2009). Documentary records are accurate and have high temporal resolutions, which allow them to distinguish between different climatic events, such as changes in precipitation and temperature (Brázdil *et al*., 2005). Several disadvantages are the lack of continuous time series and bias due to societal perception (Brázdil *et al*., 2005). Although there are disadvantages, documentary records are an accurate and trusted source of climatic information (Brázdil *et al*., 2010).

Historically documented climate began in Chile with the Spanish settlers, specifically with the foundation of Santiago de Chile in 1541 (Prieto and García Herrera, 2009). Although indigenous people inhabited this territory before the arrival of Spanish conquerors, they did not maintain written records. The earliest climatic records in Chile are those from the Santiago area, which were first compiled by Mackenna (1877). Vicuña Mackenna used chronicles and town council (*Cabildo*) records to document climatic events (Ortlieb, 1994; Prieto and García Herrera, 2009). There are only two more recent historical compilations of climatic events, Taulis (1934) and Urrutia de Hazbún and Lanza Lazcano (1993), but it was not possible to verify this information due to the lack of references in their studies (Ortlieb, 1994; Prieto and García Herrera, 2009). Mackenna (1877) has been the only work in Chile which has compiled climatic events. Ortlieb (1994) analysed Vicuña Mackenna's work to reconstruct El Niño–Southern Oscillation (ENSO) years, focusing only in wet periods. Therefore, the compilation of Vicuña Mackenna is the only reliable source for inferring climatic events because its sources have been verified. Hence, the objective of this work is to classify dry and wet periods since the 16th century using the Mackenna (1877) records by generating a precipitation index based on ancient chronicles or other written records from people who lived in the Santiago region (Figure 1a).

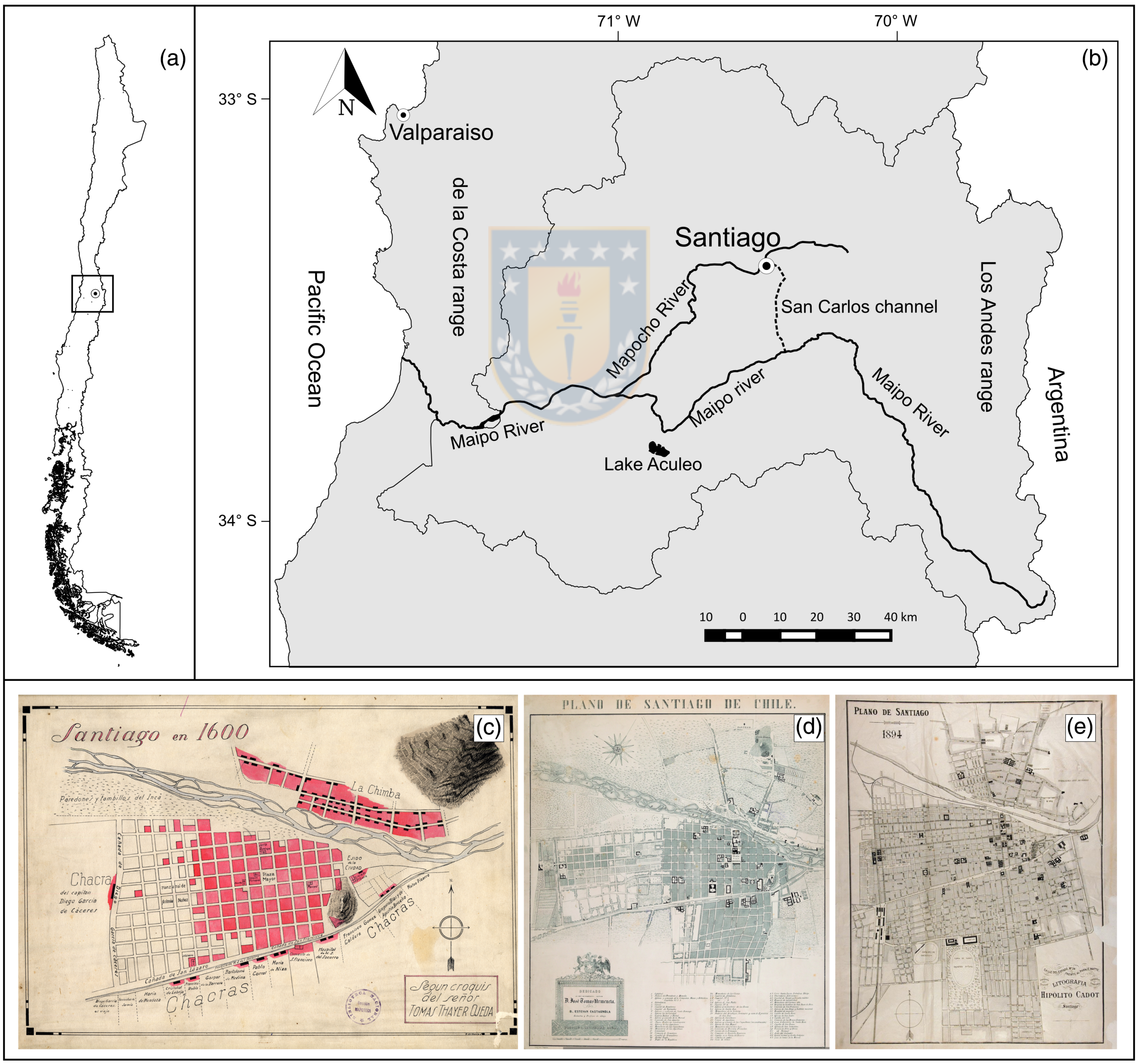

FIGURE 1 (a) Map of Chile showing the location of Santiago. (b) Map of the Metropolitan Region and its main features. (c) Map of Santiago in 1600 (from the Biblioteca Nacional de Chile, 2017a). (d) Map of Santiago during the 18th century (from the Memoria Chilena, 2017). (e) Map of Santiago in 1984 (from the Biblioteca Nacional de Chile, 2017b) [Colour figure can be viewed at wileyonlinelibrary.com]

Santiago is located in the central valley between the Andes and the coastal range in central Chile (Figure 1b). Central Chile has a Mediterranean climate; most precipitation occurs between May and October, with a maximum in July (Figure 2b). Inter-annual variability is driven by the ENSO and the Pacific Decadal Oscillation (PDO; Garreaud *et al*., 2009). Santiago is the most populated city in the country; the population in the metropolitan surrounding areas is approximately 7 million (Censo, 2017). Since its foundation, Santiago has obtained the majority of the country's population; however, during the 16th century, the population likely did not exceed 2,000 inhabitants (Mackenna, 1924) (Figure 1c). During the 17th century, but especially through the 18th century, a noticeable increase brought the estimated population to approximately 64,000 inhabitants (Archivo Nacional, 1953) (Figure 1d,e).

Population growth generates an increase in the resources needed for survival, which are provided by either governmental or religious services. Therefore, any climatological or environmental pressures on the lifestyles of the inhabitants are likely to be recorded, either by local writers or governmental or religious authorities (e.g., the number of precipitation-induced rogations registered by the Catholic church).

2 | METHODS

A precipitation index was developed according to Pfister (1999), where values based on documentary evidence were obtained by transforming basic documentary data into a simple annual precipitation index on an ordinal scale. The documentary evidence was obtained from Mackenna (1877): "Ensayo Histórico sobre el Clima de Chile." Mackenna (1877) registered climatic evidence from first-hand records of Spanish chronicles, administrative documents, manuscripts, and epistolary evidence during the Colonial period. For this study, climatic indicators related to droughts and high-precipitation events were analysed. The selected indicators for droughts were as follows: (a) variations in agricultural production, (b) epidemics (Brázdil *et al*., 2005) associated to lack of hygiene, due to no water available (Stanke *et al*., 2013), and (c) "pro pluvia" rogations, which are important in Catholic culture (Barriendos, 1997). Indicators of high-precipitation events were (a) floods, (b) infrastructural damages, (c) mouse plagues (Brázdil *et al*., 2005), and (d) "pro serenitate" rogations (Barriendos, 1997). Finally, the index used a three-term classification scale, with 0 representing normal years, 1 representing wet years, and −1 representing dry years.

3 | RESULTS AND DISCUSSION

A precipitation index was developed with the information from Mackenna (1877) using the classifications described in section 2. The climatic record used from Mackenna (1877) goes from 1541 until 1877, going through different politic-administrative periods of Chilean history. Starting with the Spanish colonization and domain, from middle of the 16th century until beginning of the 19th century, when the Independent starts. The final period is the consolidation of the republic during the decade of 1820. Overall, during the 16th and 17th centuries, there was limited information regarding climatic conditions; thus, it was not possible to identify important wet or dry periods. During the 18th century, two periods of droughts were identified: 1705 to 1718 and 1770 to 1797 (Figure 3a). Finally, there were intermittent wet and dry periods during the 19th century (Figure 3a), which could be related to ENSO (Ortlieb, 1994). In the following sections, a detailed description of the climatic conditions mentioned by Mackenna (1877) as shown in Table S1,

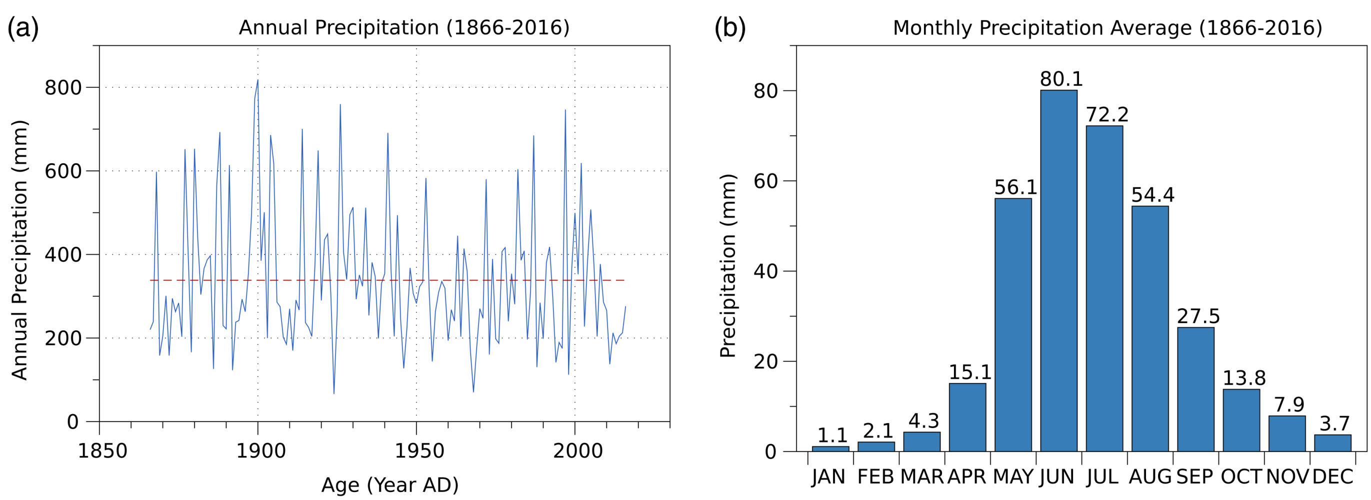

FIGURE 2 (a) Annual precipitation in Santiago (33°26′35″S; 70°38′40″W) between 1866 and 2016 (continuous line) and the average precipitation during this period (dotted line). (b) Monthly average precipitation from 1866 to 2016 (the data from 1866 to 1960 are from Ramirez, 1971; the data from 1961 until 2016 are from the Terraza Oficinas Centrales DGA meteorological station; 33°26′35″S; 70°38′40″W; Dirección General de Aguas, 2017) [Colour figure can be viewed at wileyonlinelibrary.com]

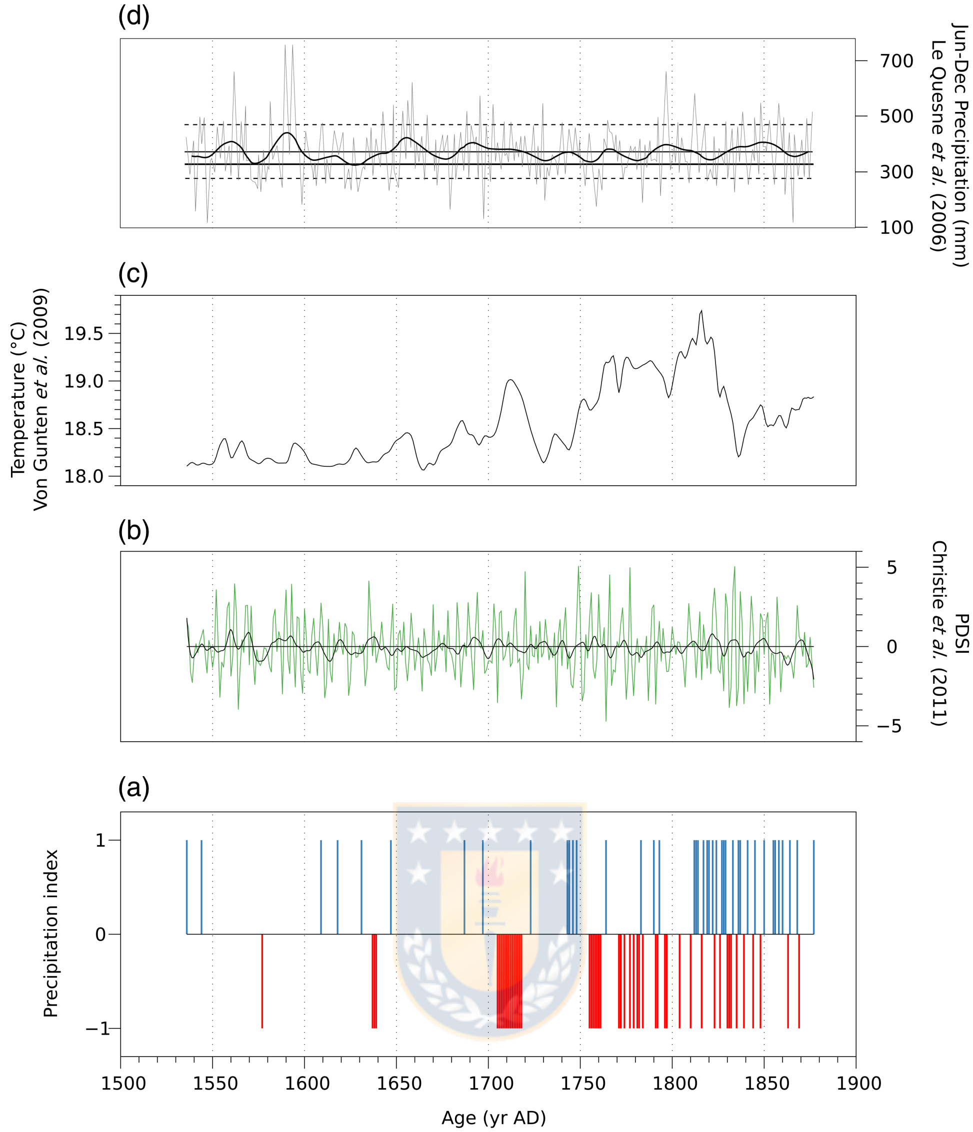

FIGURE 3 (a) Precipitation index developed from Mackenna (1877), where 1 represents wet years, 0 represents normal years, and −1 represents dry years. (b) Palmer severity drought index (PDSI) reconstruction from late spring to early summer using *Austrocedrus chilensis* tree rings in south-central Chile (Christie *et al*., 2011). (c) Austral summer temperature reconstruction in Lake Aculeo (33°S) using pigments from lake sediments (von Gunten *et al*., 2009). (d) June to December precipitation reconstruction using *A. chilensis* tree rings (Le Quesne *et al*., 2006; ©American Meteorological Society. Used with permission) [Colour figure can be viewed at wileyonlinelibrary.com]

Supporting Information is presented, and the dry and wet periods are presented in chronological order.

3.1 | Climate during the 16th and 17th centuries

The climate of central Chile was described by Mackenna (1877) as mild during the 16th and 17th centuries, although there were a few droughts and wet periods. The first individuals to record climatic conditions in Chile were Spanish colonizers, who documented climatic phenomena that caught their attention, and these records were later compiled by Mackenna (1877). The first year recorded was 1536 AD, when the Spanish colonizers experienced "deluges" that discouraged them from continuing exploration (p. 18). The winter of 1544 AD was described as outrageous due to the high amount of precipitation (p. 20), and Mackenna (1877) indicated in his book that the indigenous people had never experienced this type of event (p. 21). The first drought that was documented occurred in 1577 AD, when the Mapocho River water level diminished so severely that it generated problems in the water supply needed by Spanish settlers for irrigation (pp. 7–8). Another extreme "deluge" occurred in 1609 AD, which destroyed several crops and farms and generated a massive rat plague, which induced a religious rogation and procession (p. 28). Rat plagues are indicators of extreme rainfall events (Greenville *et al*., 2013) because rodents look for shelter in populated areas (Greenville *et al*., 2013). The year 1631 AD was also rainy, which provoked another rat plague. This rat plague was of such concern that the women of Santiago were invited to a procession (p. 141), despite their usual lack of participation in such events. The second drought occurred between 1637 and

1639 AD; this made inquisitional debt-collectors unable to charge taxes during this time due to the drought, which abruptly diminished harvests (p. 48). In 1647 AD, the winter was harsh, and there were 3 days of snowfall, which generated considerable livestock fatalities (p. 36). The year 1697 AD was also characterized by wet conditions due to a great flood in the area of Santiago, where several cattle and horses died (p. 38).

Mackenna (1877) recorded several years of drought and floods during the 16th and 17th centuries, but there were not enough documentary records to develop a robust reconstruction. The lack of records during the 16th century could be because the Chilean territory was in a conquest process. Therefore Spanish settlers were in a war with the indigenous and did not documented prevailing climatic conditions during this time. Several authors (Le Quesne *et al*., 2009; Christie *et al*., 2011; Muñoz *et al*., 2016) have developed precipitation reconstructions from tree rings in south-central Chile. Christie *et al*. (2011) found a multi-decadal drought period that occurred at approximately 1585 AD (Figure 3b), and the first record of drought documented by Mackenna (1877) occurred in 1577 AD. Le Quesne *et al*. (2009) showed a drought between 1570 and 1635, and Muñoz *et al*. (2016) found that the driest year during the last four centuries in central Chile occurred in 1680 AD. Droughts in historical records are characterized by religious "pro pluvia" rogations in Catholic culture (Barriendos, 1997). These rogations occurred when the diminished harvest caused people to despair, which consequently meant there was a lack of food. At that time, the population surrounding Santiago's jurisdiction was small; as a consequence, the agricultural production would have been enough to feed the local population, and public rogations were not needed, which could explain why Mackenna (1877) did not fully record these periods.

3.2 | Climate during the 18th century

The 18th century started with a long period of drought between 1705 and 1718 AD (Figure 3a). The *Cabildo* of Santiago ordered a rogation due to the lack of rainfall on August 7, 1705 AD (p. 52; this event occurred during austral winter, which is important when considering that precipitation begins in May; Figure 2). Twelve years later, the situation did not change, and the *Cabildo* still instructed a rogation due to a long period of drought. The Mapocho River reached its lowest water level during the drought of 1717 AD (pp. 52–53), which caused the municipality to establish attentive laws to avoid water robbery. The vigilance towards water was expensive for the municipality, which inspired the idea to transfer water from Maipo to the Mapocho River (p. 59; Figure 1). The following year, Santiago had problems with the maintenance of ditch channels due to the lack of water, and, therefore, the *Cabildo* ordered a novena for the *Virgen del Socorro* in 1718 (p. 54). The decade starting in 1740 was characterized as wetter than the previous decades. In 1743 AD, the *Cabildo* requested a procession for the *Virgen del Socorro*, but this was not executed because it started to rain (pp. 65–67). 1746 AD was a rainy year, which caused the harvests to be more abundant than those in other years (pp. 68–69). Santiago was flooded in 1748 AD by a deluge, comparable with the deluge that occurred in 1609 AD, which destroyed the cutwater of the Mapocho River and the *Puente de los Siete Arcos* bridge (p. 69).

The second half of the 18th century was even drier than the first half; generally, after a period of drought, a rainy year occurred. According to Ortlieb (1994), the intermittent dry and wet periods described by Vicuña Mackenna were likely related with ENSO. The first drought documented during this period occurred under the government of Governor Manuel de Amat between 1755 and 1761 AD (pp. 72–73). This government was denoted as a time of *skinny cows* because the lack of water provoked an economic shortage; however, this period was followed by a flood in 1764 AD (p. 74). Mackenna (1877) established a 30-year period of drought between 1770 and 1797 AD, during which the following were the driest years: 1770, 1771, 1773, 1774, 1777, 1781, 1782, 1784, 1791, and 1797 AD (Figure 3a). The total amount of rainfall during 1770 was equivalent to five consecutive days of rain (p. 76). The following year, the *Cabildo* ordered a rogation to the *Virgen del Socorro* (p. 78), but it did not rain, and the fields were sterile (p. 79). As a consequence, another rogation was organized in September to the *Nuestra Madre Señora de las Mercedes* (pp. 80–81). By the year 1772 AD, the drought was so severe that there was a threat of famine (pp. 83–84). The following year, mules did not have enough food because of the drought, which delayed fish deliveries in Santiago during Lent (p. 84). Therefore, the mayor of Santiago asked for permission to eat meat 4 days a week during this period (p. 85). The year 1774 AD was the driest of the century, and it was mentioned that the following years were not more or less humid (p. 86). Farmers rejected the saints in 1777 AD because it had not rained during the last decade; therefore, they began to pray to *Señor de la Agonía* (pp. 86–87). The situation changed noticeably in 1779 AD, when several floods destroyed the bridge *de Cal y Canto*, which was under construction (p. 74, 90). The high-precipitation events during this year also generated a disease called *Malesito*, which symptoms were similar to Yellow Fever (p. 90) and it was mentioned that the floods and electrical storms seemed like atmospheric earthquakes. After the flood of 1779, drought continued between 1781 and 1782 AD (pp. 92–93; Figure 3a). As an example, Catholic mass could not be performed in Renca (near Santiago) because there was no water for the vinegar bottles (p. 94). The lack of water provoked a sanitary problem during the austral summer of 1784 AD because there was no water for people to clean their houses (p. 126). As a result, people began the rogations to the saints in 1791 AD because the soil was catastrophically infertile. That year, there were several reports of plague because there was not enough water to clean the sumps in the houses; there were also substantial livestock fatalities. Consequentially, the *Cabildo* request a rogation to the *Nuestra Señora del Rosario*, *la Grande* (pp. 128–129). As before, a rainy year followed the drought, and in 1793 AD, the water level of the Mapocho River was substantially higher (p. 140). Finally, 1797 AD was very dry, and precipitation events occurred after June 7th; as a consequence, the fields were sterile, and the livestock was extremely thin. Therefore, people organized a rogation to *San Isidro*, who is the saint patron of rain (p. 135).

Regarding other climatic records in the area, von Gunten *et al*. (2009) developed a temperature reconstruction (Figure 3c) from Lake Aculeo (Figure 1), where a cold period between the 16th and 18th centuries was identified, which was synchronous with the Little Ice Age (LIA). After this cold period, there was an increase in temperature between 1700 and 1720 AD (von Gunten *et al*., 2009) (Figure 3c). The warm period described by von Gunten *et al.* (2009), coincided with the droughts between 1705 and 1718 AD, which were identified in this study as the longest drought during the second half of the 18th century. Furthermore, Martel-Cea *et al*. (2016) produced a precipitation reconstruction using pollen and diatoms as proxies in Lake Chepical (32°S), and they found a dry period during the 18th century. However, due to low resolutions, they could not identify the events with precision during those years. Le Quesne *et al*. (2006) used tree rings as a proxy and found a dry period between 1771 and 1785 AD (Figure 3d), which is the same period that Mackenna (1877) describes as "the driest year of the century." Currently, Garreaud *et al*. (2017) reconstruct precipitation during the last 1,000 years in central Chile using tree rings records. They found that the longest period of drought has been 2010–2015 AD and they did not describe the droughts of the 18th century. On the other hand, Bird *et al*. (2011) reconstructed annual precipitation associated with the South American summer monsoon (SASM) using δ^{18}O contain in calcite from lake Pumacocha (10°S) sediments. They found drier periods during LIA at the beginning and ending of the 18th century. Morales *et al.* (2012) also found a tendency to drought at the end of the 18th century in the *Altiplano* region (17°–22°S) in a reconstruction of SASM precipitation. The changes in SASM precipitation are modulated by ENSO, which caused latitudinal changes in the Intertropical Convergence Zone (ITCZ; Bird *et al*., 2011; Morales *et al*., 2015). A northern change of ITCZ would decrease precipitation related with SASM. Then, the dry period described by Mackenna (1877) could be associated with a northern change in the ITCZ provoked by ENSO phenomenon. The explanation of why the drought periods found in Mackenna (1877) records could be the perception of droughts by people. Consequently, the perception of drought and the demand of resources for sustenance were higher than those during the 17th century. Moreover, prolonged and moderate droughts (similar to those in the 18th century) could cause negative effects in water availability. Water supply decreased each year due to severe droughts (Barbeta *et al*., 2015), which caused problems with agriculture.

3.3 | Climate during the 19th century

The 19th century was characterized by the implementation of technological improvements, which made quantitative measurements of precipitation possible. Therefore, a longer record of dry and wet years could be achieved (Figure 3a). The measurement of precipitation started in 1824 AD, when precipitation was only measured by the number of rain days annually. The first precipitation records began in 1850 AD, and the records were in millimetres per year. The lack of data before 1824 AD can be explained by the independence process, where the focus is the record of combats and political facts. Mackenna (1877) described the first half of the 19th century as wet. From 1827 to 1829 AD, several floods occurred, which destroyed multiple bridges in Santiago (pp. 214, 215, 340). In contrast, the period from 1830 to 1832 AD was very dry, and 1832 AD was the driest year from 1824 to 1850 AD (p. 287). From the same series, the wettest year was 1833 AD (p. 340), which was followed by another dry year in 1835 AD (p. 77). The years 1836 and 1837 AD were both wet, followed by a dry year in 1839 AD (p. 77). A 7-year wet period began in 1841 and ended in 1848, which disturbed the period of drought (p. 340, 299). Finally, 1850 AD was described as one of the roughest winters in Chile due to high precipitation events (p. 218). During the second half of the 19th century, precipitation began to be measured in millimetres, which made them comparable with current measurements. The years 1858 and 1860 AD were considered wet, with precipitation totals of 622 and 513 mm/year, respectively (p. 308), while 1863 AD was dry and calamitous due to a drought (only 114 mm/year; p. 326). The years 1864 and 1868 AD were very wet, with precipitation totals of 732 and 875 mm/year, respectively (p. 327, 328). Similar to past patterns, the following year (1869 AD) was very dry, and the precipitation total was only 149 mm/year (p. 260). Finally, 1877 AD was termed the year of Great Floods; these floods were comparable with those in 1856 and 1858 AD, p. 98, 272, 319). Unfortunately, this was when the book by Mackenna (1877) was written, so we do not have information regarding the amount of precipitation that fell.

Muñoz *et al.* (2016) observed an extreme drought between 1818 and 1822 AD in the Maule River, which is when Mackenna (1877) described a wet period. Nevertheless, Prieto and García Herrera (2009) described an increase of snowfall in the chilean-argentinian pass (32°S) between 1810 and 1830 by using historical records. Christie *et al.*

(2011) observed that 1849 AD was one of the most humid years during the 19th century (Figure 3b), and Mackenna (1877) described 1850 AD as the roughest winter in Chile. The aforementioned study also found that severe to moderate droughts occurred during 1860 (Christie *et al.*, 2011) (Figure 3b), which matches with the description of calamitous drought by Mackenna (1877) at approximately 1863 AD. In general, the record during the 19th century was more complete than that during the previous centuries due to the technological advances in precipitation measurement that were implemented. For the same reason, this record was quantitative, especially after 1850 AD, when the measurements were recorded in millimetres.

4 | CONCLUSIONS

The historical data contained in the record of Vicuña Mackenna allowed for the identification of dry and wet periods since the 18th century with a high resolution. Although Vicuña Mackenna did not fully record the 16th and 17th centuries, he was able to identify several dry and wet years but with a very low resolution. The intense droughts identified during the 18th century were not fully documented by natural proxies; these different drought records could be attributed to perception and a more intensive use of land for agriculture. Finally, during the 19th century, the quantitative measurement of precipitation began. This study identified a pattern throughout the record in which, following a drought, a distinct period of intense rain occurred, which could be associated with ENSO. For future studies, it is necessary to complement the record of Vicuña Mackenna with other documental proxies, such as newspapers, and archives as the *Biblioteca Nacional de Chile* and the *Archivo General de Indias*, to improve the climatic reconstruction.

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CONFLICT OF INTERESTS

The authors declare no potential conflict of interests.

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SUPPORTING INFORMATION

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Table S1: Data extracted from Vicuña Mackenna (1877) and used to developed the precipitation index.

Year	Extracts from Vicuña Mackenna (1877)	Source in Vicuña Mackenna (1877)
1536	"los terribles padecimientos que esperimentó la columna descubridora de Almagro, al atravesar los Andes, viniendo del Cuzco, via de Jujui i Catamarca, por los pasos de Copiapó, en el mes de junio de 1536. Los historiadores hablan de millares de indios helados en las punas, i de negros que el frio convertía en estatuas de sal." (p. 18). "Pero un historiador famoso, cuyas crónicas han visto recientemente la luz pública i que fué amigo personal de Almagro, nos ha conservado testimonio de que si fué dura la intemperie invernal de las cordilleras del norte, jeneralmente templadas, los primeros descubridores de Chile esperimentaron en el resto de esa estación recios temporales i lluvias tan copiosas i continuas que al fin los desalentaron en su empresa." (p. 18) "Consta también que en ese año [1536] el mas antiguo de que haya memoria fija en nuestros anales, Almagro esperimentó una gruesa nevazón, a la altura del valle de Lúa (Ligua), lo que pone de manifiesto la crudeza estraordinaria de aquel invierno excepcional." (p. 19)	History of Chile (books in general) Juan Gomez de Alvarado (letters) Juan Gomez de Alvarado (letters)

1544	"En junio adelante (cuenta Pedro de Valdivia del año de 1544), que es el riñon del invierno, le hizo tan grande i desaforado de lluvias i tempestades, que fué cosa monstruosa, i como es toda esta tierra llana, pensamos de nos ahogar." (p. 20) "I dicen los indios […] que nunca tal han visto, pero que oyeron a sus padres que en tiempo de sus abuelos hizo así otro año." (p. 21) "Pone también de manifiesto la revelacion que los indíjenas hicieran al conquistador, el hecho de que las lluvias de 1544 fueron con mucho esceso mayores que las que habían acobardado a los castellanos de Almagro en el primer año del descubrimiento." (p. 21)	
1577	"Arqueábase el Mapocho en esos años no por regadores sino por bateas, de las que el 5 de junio de 1577 tenia, medidas por adarmes, 1453, según una acta inédita del cabildo. I aun así, i por razón misma de su escasez irremediable, su reparto era cuestión de litijios, de turnos i de hurtos, como hoi en los mas empobrecidos valles de nuestra zona del norte." (pp. 7-8)	
1609	"Hállanse contestes los viejos cronistas, i especialmente el bien informado Rosales, sobre que el año de 1609 presentó los fenómenos de un verdadero diluvio como el de 1544. —Fué aquel invierno, dice el último historiador, mui lluvioso i de la humedad hubo tan gran multitud de ratones que parecía la plaga de Ejipto." (p. 25) "Para esterminar a aquellos enjambres de roedores se ocurrió a una rogativa, pública i se celebró una procesion por las calles de Santiago" (p. 25) "Es de creerse que en el año mencionado de 1609 hubo furiosos aluviones en todos nuestros rios, porque el Mapocho salió una o dos veces dé madre, por abril i junio" (p. 26)	

	"Fueron tan serios los daños que acarreó la avenida de 1609, precursora de los ratones, destruyendo las mieses i las chácaras de mantenimiento, que el belicoso presidente García Ramón hubo de abandonar sus precisadas faenas de la guerra en la frontera para poner en ejecución las de alarife en el Mapocho." (p. 28)	
1631	"La segunda plaga de ratones de que haya llegado noticia cierta hasta nosotros tuvo lugar en pleno verano i nada menos que el 1.° de enero de 1631, i ocurrió en ella la particularidad de que a la procesión de su esterminio se invitó especialmente a las mujeres [...] En este dia, dice en efecto el acuerdo inédito del dia referido, se acordó se pregone que todos los vecinos i moradores de esta ciudad í las mujeres acudan a la procesión que se hace el domingo que viene en la tarde para pedir a Dios el remedio del daño que hacen los ratones, i que se pida limosna para la cera." (p. 141)	
1637-1639	En estos tres años (1637, 38 i 39) [...] no se ha cobrado blanca por las secas." (p. 48) “Denominada la seca de Juan de Mañosca.” (p. 48)	
1647	"Como la avenida grande, mas de un siglo posterior, ha conservado una época de inolvidable calamidad en la memoria de nuestro pueblo." (p. 35) “Cítase solo con mas particularidad la salida de madre del Tinguiririca en ese propio invierno, cuyas aguas arrastraron mas de cincuenta mil cabezas de ganado, probablemente de lana i lina en su mayor número.” (p. 36) “Fué aquel invierno en estremo rigoroso, porque a las lluvias se sucedieron las pestes (fiebres pútridas llamadas chavalongos) i	

	volvieron los campos i las ciudades a despoblarse de su, mejor jente de trabajo. Tuvo también lugar en ese invierno una nevazón de tres días." (p. 36) "Parece tambien que con el motivo de aquellos aluviones vínose al suelo el puente de suspensión del Maipo, i el cabildo solicitó del rei permiso para vender su estancia de la Dehesa con el objeto de reconstruirlo" (p. 37) "Desde Cauquenes a Coquimbo se malograron todas las trojes derribadas i mojadas, i en seguida los granos que guardaban." (p. 251)	
1697	"… Jines de Lillo, i otros hablan también de una inundación general en el país, que tuvo lugar en 1697 i en la que perecieron muchos ganados i especialmente caballos." (p. 38)	
1705-1717	"En días tan avanzados del invierno como el siete de julio de 1705, tratóse en efecto en el cabildo de Santiago de hacer una rogativa pública por la esterilidad de las lluvias, i doce años mas tarde encontramos todavía un acuerdo análogo" (p. 52) "Tratábase de poner remedio a una prolongada sequía" (p. 52)	
1717	"Por falta de agua que se espera por la sequedad del tiempo, los dichos señores mandaron que el alcalde de aguas distribuyese por marco, a los hacendados, la que correspondiese a las tierras que poseyeren, imponiéndoles las penas correspondientes" Así se cuidaban mediante vigilancia las bateas." (p. 52) "Hé aquí el escaso Mapocho puesto en pleno invierno a turno de bateas entre los chacareros, i esto talvez por la centésima vez desde que las bateas i los turnos fueron establecidos juntos con el primer cabildo i con la primera chácara, en tiempo de Don Pedro de Valdivia." (pp. 52-53) "Surjió en 1717 la primera idea de traer al valle del Mapocho las	

	aguas fertilizantes del vecino rio, empresa que tardaría un siglo cabal en su trabajosa ejecución” (p. 59)	
1743	“Esta ciudad i sus contornos esperimentando el azote de la Divina Justicia en una terrible seca i falta de lluvia, con una consiguiente peste en sus habitadores de dolores de costado, tabardillos i otros males tan inconocidos por los médicos que moria muha jente […] El Ilustre Cavildo, Justicia i Rejimiento de esta dicha ciudad […], acordó hacer a su costa una rogativa de nueve dias a Dios Nuestro Señor, por la intercesión i amparo de Nuestra Señora del Socorro […] I al salir de la Iglesia estaba el cielo tan entoldado de nubes densas, que discurrimos nos sucediese lo que en otra ocasión pasada se esperimentó por la misma intercesión, que no permitió salir de sus claustros la procesión por la mucho agua que descendió.” (pp. 65-67)	
1746	“Consta en efecto del libro de actas del cabildo de Quillota, que orijinal hemos visto, la circunstancia de haber sido tan sumamente copioso en lluvias el año de 1746 (tres años posterior al del milagro) que aun por el mes de octubre no se habia terminado las faenas de las siembras.” (pp. 68-69)	
1748	“Pero aquella, que no pasó de ser una riada del Mapocho, embravecido con las creces invernales, fue sobrepujada en gran manera por el terrible aluvion ocurrido en el otoño de 1748, como el de Pentecostés de 1609. […] fueron tan impetuosas sus embestidas contra los muros de defensa que no solo postraron por el suelo los tajamares […], sino que se llevó por delante como una leve pluma el único puente de siete arcos de sólida mampostería” (p. 69).	

	"La ciudad fue completamente inundada por sus tres causes secos, esto es, por la Cañada, la Cañadilla i por las calles de las Ramadas, de San Pablo y de las Rosas." (p. 70)	
1755-1761	"Durante el gobierno del duro presidente Amat, entre 1755 y 1761, que fueron las siete vacas flacas de Chile, estableciόse por aquel autoritario gobernante lo que se llamó entonces i mas tarde la tasa de Amat, para la venta del pan al pormenor. […] las panaderías de hornos de adobon, no tenia tasa, es decir que se vendía o se regalaba el pan por canas tas i petacas, con afrecho i todo." [because the scare of rain]. (pp. 72-73)	
1764	"Agregaremos ahora, respecto de la zona de humedad que se enseñoreó sobre el pais en el segundo tercio del siglo XVIII […] ocurrió el aluvión llamado de Gonzaga porque tuvo lugar durante el gobierno del presidente de ese nombre (1764)." (p. 74)	
1770-1781	"Por esto nos limitaremos a agregar que la gran seca que habia comenzado para nuestros abuelos en 1770 sé prolongaba todavía con todos sus rigores en 1781." (p. 93)	
1770	"Desde 1770 no llovia en el valle de Santiago sino a razon de 112 horas en cada invierno, hecho del cual hai pocos ejemplos del presente siglo [siglo XIX], porque en realidad apénas equivalia a cinco dias escasos de lluvia continuada" (p. 76)	

1771	"1771 [...] por cabildo estraordinario, acordaron que en atencion a lo seco que se esperimentaba el año presente, de que resulta no solo la escasez que se prepara en los frutos, sino tambien que se pueda recelar prudentemente, como en otras ocaciones, alguna epidemia en la salud o algun temblor grande i para implorar la piedad de Dios nuestro Señor, se ponga por intercesora a su Santísima Madre, venerada en esta ciudad en su milagrosa imájen del Socorro, patrona ella en la iglesia del convento grande del señor San Francisco, habiendo correspondido siempre el suceso a la confianza de este cabildo, lográndose, mediante la novena i procesion hecha a tan sagrada imájen, la deseada lluvia" (p. 78) "El invierno de 1771 habia sido por consiguiente de completa esterilidad. No habian llovido ni las 112 horas calamitosas del historiador hacendado." (p79) "Desairados en efecto por nuestra señora del Socorro en sus preces, los santiaguinos ocurrieron a nuestra señora de las Mercedes [...] mes de Setiembre de 1771 años, los señores de este Ilustre Cabildo […] siendo notoria la consternacion en que se halla esta ciudad por la *seca* i esterilidad que esperimenta en sus campos, de que resultan pestes i enfermedades que ya se están igualmente sintiendo, era conveniente ocurrir a la proteccion i amparo de Nuestra. Madre i Señora de Mercedes, Patrona jurada por esta dicha ciudad i Abogada de las pestes i terremotos, sacándola en devota procesion i rogativa por las calles, con la esperanza cierta de que por la intercesion de esta soberana Reyna se ha de conseguir el alivio i socorro en las urjencias que nos aflijen i la fertilidad de los campos." (pp. 80-81)	
1772	"la sequedad que habia comenzado [...] inmediatamente despues del aluvion de 1768, arreció en 1772 hasta el punto de amenazar con hambre a la poblacion." (pp. 83-84)	

1773	“Pero volviendo al tiempo que pasó, es lo cierto que por la escasez de los pastos sospecharon los ediles de Santiago que iban a verse obligados a quebrantar el santo ayuno, i por el siguiente acuerdo pidieron solemnemente licencia al Ordinario para que el vecindario pudiese no ciertamente promiscuar (nefando crímen cuando se adoraba la bula como sacramento) sino para comer carne cuatro días de los siete de cada semana cuaresmal.” (p. 84) “se halla este ilustre cabildo en intelijencia de la mucha escasez de los necesarios elementos para cumplir en el todo el ayuno de la santa quaresma presente, pues siendo tan contingente la conducción del pescado fresco asi por la casualidad de su pesca como porque aquella, no habiendo pastos para las mulas, se hace en mas largo tiempo del regular i la de el pescado seco que viene de Coquimbo” (p. 85)	
1774	"Pasó a su turno el año de 1774 i fué uno de los mas secos del siglo, i no fueron mas húmedos ni mas benignos los subsiguientes, hasta que desesperados los estancieros i labradores, i desairados por todos los santos i santas de la corte celestial, se confiaron a los brazos enclavados de la cruz del Señor de la Agonia en 1777.–El iracundo rostro del Señor de mayo hacíase dulce por aquella agonía de sed que duraba ya una larga década de rigorosos años." (p. 86)	
1777	"hasta que desesperados los estancieros i labradores, i desairados por todos los santos i santas de la corte celestial, se confiaron a los brazos enclavados de la cruz del Señor de la Agonía en 1777.— El iracundo rostro del Señor de mayo hacíase dulce por aquella agonía de sed que duraba ya una larga década de rigorosos años." (p. 86) "Acordaron (dice en efecto de los ediles el acta del 25 de junio de 1777) que con motivo de la escasez de agua que se esperimenta por falta de lluvias, por lo que se esperaba esterilidad de los campos en el presente año i la conocida pérdida de ganados que	

	se están muriendo con grave perjucio del público i así́ del Reyno, que se haga Rogativa en la forma acostumbrada en otra necesidad al Señor de la agonía del convento del Señor San Agustín; que asi mismo, siendo tan pública la escasez de arbitrios de todo el vecindario del barrio de la Chimba por cuya causa no pueden hacerse otras rogativas a Nuestra Señora del Rosario, intitulada de la Viña, que para este fin se le den cincuenta pesos al padre superior de aquel convento, para que a un tiempo se hagan las dos i salgan en un mismo dia las divinas imájenes por las calles, i de este acuerdo se le dé testimonio al señor Procurador Jeneral para que con él se presente a esta Real Audiencia para su aprobacion, i así lo acordaron i firmaron dichos señores, de que doi fe." (pp. 86-87)	
1779	"Aquella, del 13 de mayo […] de 1779. Esta última riada, ocurrida en entradas de invierno, inundó la parte baja de la ciudad i atacó las colosales rampas del puente de cal i canto." (p. 74) "En esta ocasion apiadáronse las nubes del clamor del pueblo i ocurrió durante este preciso año de 1779 el aluvion que dejamos recordado i que puso en peligro las estremidades del puente cal i canto, aún inconcluso." (p. 90). "Pero fué aquel remedio excesivo en su dósis para la enfermedad de sed que padecia el pueblo i los campos, porque desarrollóse en aquella primavera la rara enfermedad que se llamó el *malsito*, especie de fiebre amarilla en su forma mas benigna i que postró millares de infelices en improvisados lazaretos." (p. 90) "Los aluviones parecen solo fenómenos electricos, como los temblores verdaderos terremotos de la atmósfera, si la figura permitida, pero que ejercen en la mutacion de los elementos constitutivos del clima una influencia ménos poderosa que los sacudimientos puramente terráqueos del globo en que como equilibristas, mas que como parásitos vivimos" (p. 91). "Reuniéndose el cabildo, i sus consejales dijeron que respecto de estar esperimentando la ciudad i sus campañas *alguna esterilidad por la escasez de lluvias* i las muchas pestes que se ha	

	introducido, provenida de esta misma […] de que se hallan contajiados sus vecinos, a fin de implorar el beneficio de la divina misericordia i evitar todas estas calamidades por medio de la intercesion de su poderosa madre se dedique una rogativa a Nuestra Señora del Socorro." (p. 91)	
1781	"la gran seca que habia comenzado para nuestros abuelos en 1770 se prolongaba todavía con todos sus rigores en 1781." (pp. 92-93)	
1782	"se dejó de decir misa en la iglesia parroquial de Renca *porque no hubo agua para las vinagreras*, es éste un hecho real, positivo e histórico que consta de una acta auténtica del cabildo" (p. 94) "I sin embargo, ese año [1782] fué la víspera de la avenida grande!" (p. 95)	
1784	"A fin de reparar de algun modo, decia el ayuntamiento en su sesión del 27 de febrero de 1784, esto es, al aproximarse a su fin el verano que siguió a la gran crece histórica, a fin de reparar de algun modo los considerables daños i perjuicios que está padeciendo todo este vecindario con la notable escasez de agua necesaria para el aseo de sus habitaciones i cultivos de sus plantíos i heredades, que por esta causa se hallan casi en el todo arruinadas, y, sus habitadores escesivamente pensionados con la fetidez que originan sus estelicidios" (p. 126)	

1791	"volvían otra vez los ojos a los santos en demanda de agua en 1791. En consideracion a lo estéril i calamitoso del presente año [...] a propósito de un dia tan avanzado ya del invierno como el 7 de junio, que por falta de las aguas se están experimentando no solo la ruina de las haciendas de campo por las mortandades crecidas de sus ganados i falta de fruto de que se abastese a este vecindario, sino las muchas enfermedades i muertes que hai al presente, orijinándose todo por la sequedad del tiempo [...] acordaron que al propio fin se saquen en forma de procesión la imájen de Nuestra Señora del Rosario, con el tı́tulo de la grande." (pp. 128–129) "I el síndico del Consulado tenia razón inmediata i buena para lo que escribia al soberano, por que si es cierto que en los años de 1791 i 92 habían sido inusitadamente secos" (p. 140)	
1793	"el agua del río tomó un altor amenazante. Siempre la inmutable proporcionalidad de los años propicios i malignos, siempre las vacas flacas siguiendo las pisadas de las vacas gordas" (p. 140)	
1797	"lo avanzada que se halla ya la estacion del invierno (era el siete de junio) i que los campos están sumamente estériles i sin pasto alguno, que por este motivo los animales se ven mui extenuados, flacos i próximos a morir, sin que hasta ahora haya caido algun aguacero capaz de remediar esta calamidad [...] que echando ya ménos la humedad en sus cuerpos, están padeciendo algunas indisposiciones, que no seria estraño se hiciera, alguna epidemia, para cuyo remedio en otras ocasiones se ha ocurrido a implorar el auxilio divino, como pudiera hacerse ahora [...] una rogativa trayendo en procesión desde su parroquia a esta santa iglesia Catedral al glorioso Señor San Isidro, por cuya intersecion se ha conseguido otras veces lo que ahora tanto se necesita i desea" (p. 135) "[...] del propio acuerdo de 1797 consta que no era esa la primera vez que se hacia con fruto aquel homenaje a San Isidro, lo que	

	pone de manifiesto que habían ocurrido ántes muchas sequías, de las cuales nosotros no hemos tomado nota por falta de suerte o dilijencia." (p. 138)	
1824	"En la larga serie de años antiguos de que se llevó cuenta prolija por un observador entre 1824 i 1850, solo conocemos, en veinte i siete años, once en que hubiese llovido mas que en 1876: 1824 (220 horas); 1827 (302 horas i año de aluviones 1828 (280 horas); 1829 (320 horas); 1833 (404 horas); 1836 (219 horas); 1837 (288 horas); 1841 (313 horas); 1843 (390 horas); 1845 (417 horas), i 1850 (285 horas.))" (pp. 334-335)	
1827	"El puente del presidente Henriquez, sobre los vestijios de cuyos machones se reedificó despues de la avenida de 1827 el puente de palo, habia desaparecido" (p. 101) "De los años de la Patria vieja (1810-1814) no sabemos otra cosa sino que el 10 de octubre de 1812 bajó el único barómetro que existia en la capital al punto que hoi se llama temporal en tercer grado, alcanzando el mismo nivel de depresión que presentó ese mismo instrumento en lo mas crudo del aluvión del 5 de junio de 1827, quince años mas tarde." (p. 160) "En la ciudad de Santiago de Chile, a seis dias del mes de Junio de 1827, reunidos los señores del ayuntamiento en sesión ordinaria, se abrió un oficio del cabildo eclesiástico en que invitaba a la Municipalidad para asistir a la rogativa del Señor San Antonio, abogado jurado para los aluviones del rio Mapocho, i se contestó en la misma noche, archivándose aquella nota." (pp. 173-174)	

	"el año de 1827, el mismo cuyo invierno se cambió en Chile en una serie no interrumpida de aluviones." (p. 214) "Recordar que el año de 1827, en que poníamos término a aquella relación, fué uno de los mas abundantes en lluvias del presente siglo" (p. 284) "Así, sin contar la época anterior a 1827, en que hemos fijado este mismo fenómeno, observamos que ese propio invierno formó una agrupación de tres años húmedos con los de 1828 i 29." (p. 340) "Los años mas marcados como lluviosos [...] del presente siglo [...] 1827, 33, 50, 58, 64, 68 i 77." (p. 470)	
1828	"El año de 1828 fué casi tan lluvioso en Chile como el que le precedió" (p. 215) "Así, sin contar la época anterior a 1827, en que hemos fijado este mismo fenómeno, observamos que ese propio invierno formó una agrupación de tres años húmedos con los de 1828 i 29." (p. 340)	
1829	"Deberemos agregar ahora que [...] 1829 (tres años) fueron para Chile tipos de sus períodos lluviosos" (p. 284) "Así, sin contar la época anterior a 1827, en que hemos fijado este mismo fenómeno, observamos que ese propio invierno formó una agrupación de tres años húmedos con los de 1828 i 29." (p. 340)	
1830	"De estos 50 años (1824-1850) […] solo conocemos cuatro en que lloviera ménos tiempo que el promedio del siglo XVIII —a saber— 1830, ciento diez i seis horas— 1835, ciento diez i ocho—	

	1839, ciento veinte i cinco, i 1844, ciento treinta horas:— -dos horas menos." (p. 77) "En 1830, el año de Lircai, llovió solo ciento dieziseis horas, repartidas en diezisiete dias" (p. 285) "Del período de humedad abundante de 1827-29 pasamos al de una sequedad relativa (1830-32)" (p. 312)	
1831	"En 1831 llovió cuatro días ménos, si bien la proporción de tiempo fue mayor (ciento cincuenta horas), i a este año lastimosamente seco para la salud pública" (p. 285)	
1832	"El de 1832, año de horrores en que llovió 99 horas" (P. 76) "En todos los inviernos observados desde 1824 a 1850, estos dos años [1832 and 1833] seguidos i jemelos, son el uno el mas seco de la serie (1832) i el otro, con una sola escepcion (1833), el mas lluvioso." (p. 287) "Fué una época de plagas i de muertes. Presentóse el invierno tan enjuto, que una epidemia de escarlatina negra, que atacaba especialmente a las señoras de la alta sociedad, introdujo el terror en la capital, en Valparaíso i en otros pueblos mediterráneos. La opinión fué unánime en cargar a la cuenta de la sequedad de la atmósfera aquellos estragos." (p. 285)	
1833	"I ese [1833] ha sido precisamente el año más húmedo en Chile (con escepcion del 45) de la segunda mitad del presente siglo [XIX]" (pp. 222-223) "En todos los inviernos observados desde 1824 a 1850, estos dos años [1832 and 1833] seguidos i jemelos, son el uno el mas seco de la serie (1832) i el otro, con una sola escepcion (1833), el mas lluvioso." (p. 287)	

	"Los años mas marcados como lluviosos [...] del presente siglo [...] 1827, 33, 50, 58, 64, 68 i 77." (p. 470)	
1833-1837	"El de 1833 constituyó un grupo aun mayor con los de 1834, 35, 36 i 37: cinco años húmedos seguidos." (p. 340)	
1835	"solo conocemos cuatro en que lloviera menos tiempo que el promedio del siglo XVIII —a saber— 1830, ciento diez i seis horas— 1835, ciento diez i ocho— 1839, ciento veinte i cinco, 1844, ciento treinta horas:— -dos horas menos." (p. 77)	
1839	"solo conocemos cuatro en que lloviera menos tiempo que el promedio del siglo XVIII —a saber— 1830, ciento diez i seis horas— 1835, ciento diez i ocho— 1839, ciento veinte i cinco, 1844, ciento treinta horas:— -dos horas menos." (p. 77) "el año de 1839, el año de Yungai, debe considerarse como comparativamente seco, según nuestra cuenta, i la verdad fue solo un tanto mas húmedo que el calamitoso de 1832" (pp. 290-291)	
1841	"El período lluvioso que vuelve a comenzar en 1841 se prolonga durante seis años hasta 1847" (p. 340)	
1848	“el 1848, por el contrario, de alarmante sequedad: 111 horas” (p. 299)	
1850	"el invierno que le siguió (1850) pasa por uno de los mas crudos de Chile" (p. 218)	

1851-1852	“No tenemos a la vista los datos de 1851 i 52 i aun creemos que por descuido no existen.” (p. 307)	
1856	"Ofreció el año memorable de 1856, memorable especialmente por su inesperado i ruinoso aluvión del 10 de marzo […] según Pisis cayeron en Chile 550 milímetros" (p. 219)	
1858	“1858: 622 milimetros” (p. 308)	
1860	"Está en la memoria de todos qué este año fue sumamente lluvioso en Chile. Recojiéndose en el observatorio de […] Santiago 513 milímetros" (p. 220) "1860: 513 milímetros" (p. 308)	
1863	"las secas que comenzaron en 1863 i que han durado hasta la víspera de esta fecha." (1877) (p. 92) "1863 habia sido en Chile de una completa i calamitosa esterilidad." (p. 221) "1863, el mas seco año del siglo" (p. 306) "hemos visto sucederse al año desastroso de 1863, en que solo cayeron 4.48 pulgadas (114 milímetros) de agua" (p. 326)	
1864	“1864: 28.81 pulgadas [732 mm]” (p. 327)	
1868	"En 1868 cayeron 875 milímetros de agua, lo que le coloca a la cabeza (con la sola escepcion de 1858) de todos los inviernos que han sido observados científicamente en los últimos veintiocho años". (p. 328)	

1869	"Años comparativamente secos, como el de 1869, en que cayeron solo 149 milímetros de agua." (p. 260)	
1877	"este año de 1877, que se llamará probablemente en plural— "el año de las avenidas grandes" (p. 98) "en 1877,en que amenazo´inundar con sus aguas el pueblo i puerto de Chañaral, situado en su embocadura." (p. 272) "Las nubes de 1877 tienen por tanto que hacer todavía un pujante esfuerzo para llegar al nivel del de los años que, como el de 1856 i 1858 sirvieron de últimos eslabones a la éra de lluvias." (p. 319)	

ANEXO 2: MATERIAL SUPLEMENTARIO TESIS, TABLA RESUMEN PRINCIPALES ESTUDIOS UTILIZADOS EN ESTA TESIS

Tabla resumen principales estudios utilizados en esta tesis

Paper	Titled	Place	Proxy
Sepúlveda et al. 2009	Late Holocene sea-surface temperature and precipitation variability in northern Patagonia, Chile	Jacaf Fiord (44°S)	Alkenone based SST and plant derived biomarkers to asses runoff
Bertrand et al. 2017	Postglacial fluctuation of Cordillera Darwin glaciers (southernmost Patagonia) reconstructed from Almirantazgo fiord sediments	Almirantazgo Fiord (54°S)	Multi-proxy sedimentological and geochemical analysis
Fletcher and Moreno 2012	Vegetation and fire regime changes in the Andean region of southern Chile (38°S) covaried with centenial-scale climate anomalies in the tropical Pacific over last 1500 years	Laguna San Pedro, Lonquimay (38°S)	Polen and charcoal (plus sedimentological proxies)

Paper	Titled	Place	Proxy
Araneda et al. 2007	Historical records of San Rafael glacier advances (North Patagonian Icefield): another clue to "Little Ice Age" timing in southern Chile?	Glacier San Rafael (46°S)	Historical records
Elbert et al. 2011	Quantitative high-resolution winter (JJA) precipitation reconstruction from varved sediments of Lago Plomo 47°S, Patagonian Andes, AD 1530-2002	Lago el Plomo (47°S)	MAR, XRF, VIS-RS; quantitative precipittion reconstruction from MAR
Bertrand et al. 2014	Late Holocene covariability of the southern westerlies and sea surface temperature in northern Chilean Patagonia	Quitralco fiord (46°S)	Fe/Al and Ti/Al and grain size
Zolitschka et al. 2019	Southern Hemispheric Westerlies control sedimentary processes of Laguna Azul (south-eastern Patagonia, Argentina	Laguna Azul (52°S)	multi-proxy aproach (XRF, diatoms, polen, DIC)

Paper	Titled	Place	Proxy
Moreno et al. 2014	Southern Annular Mode-like changes in southwestern Patagonia at centenial timescales over the last three millennia	Lago Cipreses (51°)	pollen, charcoal, temperature reconstruction (Kilian and Lamy)

Paper	Date (period)	Cold	Warm	Humid
Sepúlveda et al. 2009	before 900 cal yr BP **(1050 CE)**		1°C warmer than today (SST)	
	after 700 cal yr BP (750-600) and (450-250) **(1200 - 1150 CE y 1500 - 1700 CE)**	1°C colder than today (SST)		higher runoff from continent
Bertrand et al. 2017	2000-1200 cal yr BP **(-50 - 750 CE)**	---	significant mealt water event increase in grain size and concomitant decreases in OC of marin origins	---
Fletcher and Moreno 2012	1500-1300 cal yr BP **(450-650 CE)** and 1000-725 cal yr BP **(950-1200 CE)**	---	Increase fire activity, plus rapid bulk sediment acumulation (small freezing season) under warmer climate	---
	1300-1000 cal yr BP and **(650 - 950 CE)** 725-121 cal yr BP **(1225 - 1829 CE)**	Low fire activity and slow bulk sedimentation (prolong freezing season) due to colder climate	---	Moist conditions and low fire activity

Paper	Date (period)	cold period	Warm	Humid
Araneda et al. 2007	**1766-1898 CE**	glacier maximum 1876	---	also suggest increase in precipitation
	arround 1675 CE		prevailed of warm conditions	
Elbert et al. 2011	arround **1600 AD; 1630-1690 AD; 1780-1850 AD**	---	---	wetter conditions
	1690-1780 AD	---	---	
Bertrand et al. 2014	**600-1200 CE**	---	---	low values of Fe/Al and Ti/Al, and high gran size, which means increase in seasonal floods
	1200-1500 CE	---	---	---
	1500-1950 CE	---	---	---
Zolitschka et al. 2019	1300 cal yr BP **(650 CE**); 1190±100 cal yr BP **(760 CE +- 100)**	---	---	higher lake level
	1400-500 cal yr BP **(550- 1450 CE) (MCA)**	---	---	---
	1550-1850 AD (LIA)	---	---	moister and less windy conditions
	second half of the 20th century (CWP)	---	---	---

Paper	Date (period)	cold period	Warm	Humid
Moreno et al. 2014	**1890 AD (industrial warming); MCS; Roman late bronce**	---	warm periods	---
	1890-800 AD (LIA); 1100-1800/2100-2700 AD (DACP;Iron age cold)	cold period		hyperhumid and humid fases

Paper	Dry	Some conclusions
Sepúlveda et al. 2009	lower runoff from continent	strong latitudinal sensitivity to changes in SWW
Bertrand et al. 2017	---	---
Fletcher and Moreno 2012	Low growing season moisture and increase fire activity	LIA: cold/wet and MCA: dry/warm; plus ENSO is the main driver of climate
	---	

Paper	Dry	Some conclusions
Araneda et al. 2007	---	---

Elbert et al. 2011	---	JJA precipitation of L. Plomo is representative in southwest from 41°S to 51°S
	prolonged drier period	
Bertrand et al. 2014	---	decrease in seasonal flow is interpreted as an equatorward shift of SWWW, then they were more polward position before 1200 CE and it gradually shifted to and equatorial position between 1200 and 1500 CE and from 1500 to 1950 mantained ist position
	increasing Fe/Al and Ti/Al, which means an interfase towards drier seasons	
	hifh Fe/Al and Ti/Al, decrease Gran Size that means dry conditions	
Zolitschka et al. 2019	---	
	More euthrofication corresponding to lower lake level	
	---	
	decrease lake levels	

Paper	Dry	Some conclusions
Moreno et al. 2014	and dry conditions and intense fire activity	