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A 1500 yr warm-season temperature record from varved Lago Plomo, Northern Patagonia (47° S) and implications for the Pacific Decadal Oscillation (PDO)

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Abstract

High-resolution records of calibrated proxy data for the past 2000 yr are fundamental to place current changes into the context of pre-industrial natural forced and unforced variability. Although the need for regional spatially explicit comprehensive reconstructions is widely recognized, the proxy data sources are still scarce, particularly for the Southern Hemisphere and South America.

We provide a 1500 yr long warm season temperature record from varved Lago Plomo, a proglacial lake of the Northern Patagonian Ice field in southern Chile (46°59′ S, 72°52′ W, 203 m). The thickness of the bright summer sediment layer relative to the dark winter layer (measured as total brightness; % reflectance 400–730 nm) is calibrated against warm season SONDJF temperature (1900–2009; $r = 0.58$, $p_{(aut)} = 0.056$, RE = 0.52; CE = 0.15, RMSEP = 0.28 °C; five-year triangular filtered data). In Lago Plomo, warm summer temperatures lead to enhanced glacier melt and suspended sediment transport, which results in a thicker light summer layer and to brighter sediments (% total brightness). Although Patagonia shows pronounced regional differences in decadal temperature trends and variability, the 1500 yr temperature reconstruction from Lago Plomo compares favourably with other regional/continental temperature records but also emphasizes significant regional differences for which no data and information existed so far. The reconstruction shows pronounced sub-decadal–multi-decadal variability with cold phases in the 5th, 7th and 9th centuries, during parts of the Little Ice Age chronozone (16th and 18th centuries) and in the beginning of the 20th century. The most prominent warm phase is the 19th century which is as warm as the second half of the 20th century, emphasizing a delayed recent global warming in the Southern Hemisphere.

The comparison between winter precipitation and summer temperature (inter-seasonal coupling) from Lago Plomo reveals alternating phases with parallel and contrasting decadal trends of winter precipitation and summer temperature and positive and negative running correlations$_{(winterPP;summerTT)}$. In the 20th century the trend of this

correlation changes at 1920, 1945 and 1975 AD, and the phases with positive (negative) correlations inferred from the lake sediments are also found as a regional robust pattern in reanalysis data, and coincide with the changes of the instrumental PDO index. Enhanced circumpolar flow around 60° S is proposed for positive phases of PDO which leads to the reversed coupling and contrasting decadal trends of winter precipitation and summer temperature during PDO positive phases. Our reconstruction of the inter-seasonal coupling back to 1530 AD reproduces many features of existing PDO reconstructions from the Pacific suggesting that Lago Plomo provides a record for the regional expression of the PDO in Patagonia.

1 Introduction

Quantitative, highly resolved (annual – subdecadal) season-specific and spatially explicit climate reconstructions for the past two millennia are very important to place current changes into the context of long-term natural climate variability, and to discriminate the fingerprint of current anthropogenic forcing (Hegerl et al., 2006). In combination, individual high-quality paleoclimate records provide the basis for multi-site multi-proxy reconstructions of sub-continental climate fields (Trachsel et al., 2012), spatially-explicit seasonally-resolved regional climate reconstructions (Luterbacher et al., 2004), multivariate reconstructions of climate modes and indices (e.g. ENSO and PDO, MacDonald and Case, 2005; Mann et al., 2009; McGregor et al., 2010) and, ultimately combined regionally resolved reconstructions with global coverage (PAGES 2k Consortium, 2013).

In this context, the Southern Hemisphere and in particular South America play an important role. In general, the Southern Hemisphere mid- and high latitudes offer much better opportunities to detect the anthropogenic signal of climate change (Shindell and Schmidt, 2004; Fyfe et al., 2012). Moreover, the Westerly zonal winds in the mid- and high latitudes are important drivers for regional rainfall as well as stratification and upwelling in the southern oceans, which plays a demonstrated role in the global heat and carbon fluxes (Le Quéré et al., 2009). Although a growing body of literature highlights

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the variability of the southern Westerly winds and their relation to large-scale climate modes and indices such as the Southern Annual Mode SAM and the Pacific Decadal Oscillation (PDO; Pezza et al., 2007 and references therein; Fogt et al., 2009) very little is known about the decadal-scale variability of the circum-hemispheric Westerlies in the past centuries to millennia. Among the few studies, Saunders et al. (2012, 2013) have pointed to the teleconnection between the strength of the zonal winds in Tasmania and Patagonia over the past 500 yr. Moreover, Villalba et al. (2012) used a tree ring network from South America, Tasmania and New Zealand to reconstruct SAM for the past 600 yr, and Goosse et al. (2012) assimilated proxy-data from South America, Tasmania, New Zealand and Antarctica to climate model simulations of the past millennium and thus placed the proxy data from different areas into a physically consistent dynamical framework of the southern Westerlies.

Southern South America is the only landmass that extends continuously as far south as 55° S. Hence it has been in the focus of paleoclimate research for decades. In a recent effort, high-quality paleoclimate archives were complied (Villalba et al., 2009) and comprehensive multi-proxy summer and winter surface air temperature field and precipitation reconstructions back to 900 and 1498 AD (Neukom et al., 2010, 2011) were completed.

Nevertheless, the data base for Patagonia (40–55° S) is extremely scarce. In the absence of regional proxy data, the reconstruction by Neukom et al. (2011) used statistical relationships with proxy data from the central Andes and the tropics to infer the climate reconstruction for Patagonia prior to c. 1600 AD. Moreover, in that part of the world, climate field reconstructions are considerably complicated by the pronounced spatial heterogeneity of precipitation and temperature variability and trends (Garreaud et al., 2009, 2013). The influences of the variable ocean currents in the Pacific and Atlantic and the orographic effects of the Andes are poorly understood. Nevertheless, there is evidence from tree rings and lake sediment records, that this spatial heterogeneity persisted also in the past (Villalba, 1994) and the question about the spatial representation of paleoclimate records arises.

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Here we provide a new quantitative high-resolution record of warm-season SONDJF surface air temperature from varved lake sediments in proglacial Lago Plomo, Patagonia (45° S/73° W) back to 500 AD. Previous work in Lago Plomo has demonstrated that the sediment laminae couplets (dark and white layers) are seasonal deposits and that the total annual Mass Accumulation Rate (MAR) is a proxy for winter precipitation and snow melt (Elbert et al., 2012). In this work we show that the thickness of the white summer layer and admixtures of white minerals in the dark winter layer, measured as total brightness (TB) of the sediment (% of reflected light between 400–730 nm) is a proxy for summer temperature and suspended sediment transported in glacier melt water from the Northern Patagonian Ice field.

The simultaneous presence of a proxy for winter precipitation and a different proxy for summer temperature in the same archive offers the possibility to study inter-seasonal coupling of precipitation and temperature. Our lake sediment data and 20th century reanalysis data show that the positive and negative seasonal coupling and trends between temperature and precipitation in that area correlate with the PDO index and we suggest that this seasonal coupling as inferred from the lake sediment data might be a regional expression of the PDO index for the past 470 yr.

2 Study site

Lago Plomo (46°59′ S, 72°52′ W, 203 m a.s.l., Fig. 1) is a proglacial, oligotrophic, deep (> 200 m) exorheic lake, located on the eastern side of the Northern Patagonian Icefield (NPI). It is partly dammed by a cross-valley moraine (11 ± 0.5 ka, Glasser et al., 2012) and drains through an isthmus into Lago Bertrand. Both lakes are polymictic to warm monomictic (stratified in January 2009) and belong to the Rio Baker system which drains into the Pacific.

The catchment extends westwards with deep valleys and steep slopes to the glaciers and snowfields of the NPI and northwards to the Cordón Contreras. The geology in the catchment area is mostly composed of Devonian carboniferous sandstone and phyllite,

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and Jurassic crystalline intrusiva (SERNAGEOMIN, 2003). During the Early Holocene (at 11.0–11.7 ka) glacier Soler was about 30 km advanced from its current position, covered the area of Lago Plomo and formed a distal moraine (Glasser et al., 2012). In consequence, the catchment consists of glacially scoured bedrock and extensive sandar deposits on the major ice discharge routes from the NPI.

Melt water from glacier Soler drains through river Soler into Lago Plomo and transports fluvioglacial sediments into the lake. The sediments of Lago Plomo are rhythmically laminated and alternate between a light, silty summer layer and a dark clay-rich winter layer (Elbert et al., 2012). The annual nature of the laminae was confirmed by independent age determination with radionuclide measurements. It was suggest that undercurrents are active during snowmelt in spring and summer, and transport coarse, bright minerals (rich in feldspar) to the distal part of the lake. Fine, darker material is deposited during calmer, less windy conditions in winter. In windy summer, the fine clay-size material remains suspended in the lake water, which leads to very limited light transparency of the water (Secchi-disc depth = 0.5 m) (Elbert et al., 2012).

Patagonia has a temperate climate with average annual temperatures for Lago Plomo of 5–6 °C and annual precipitation of c. 900 mm (calculated from CRU TS 3.1, Mitchell and Jones, 2005; 47.0° S 72.5° W, 1901–2009 AD). The correlation field analysis (Fig. 1 inset) shows that SONDJF-Temperature at Lago Plomo is positively correlated with SONDJF-Temperature in southern South America (37–55° S) except for the area 44–49° S in western Argentinean Patagonia, which is uncorrelated with the Andean domain at the same latitude.

Across Patagonia there are very strong temperature and precipitation gradients from north to south, modified by the Andes (West/East gradients) and the seasonal temperature contrast between the oceans and the continent (Garreaud et al., 2013 and references therein). The position and strength of the Westerly winds, modulated by the SAM and PDO also control up-welling of cold water, cloud cover and rain along the western side of the Andes (Garreaud et al., 2009). It is noteworthy that glacier fluctuations respond mainly to changing circulation patterns and latitudinal shifts in the moisture-bearing southern Westerlies (Glasser et al., 2012).

Decadal-scale changes of precipitation and temperature in the Pacific domain but also in the Southern Hemisphere mid-latitudes are influenced by the PDO (Pezza et al., 2007 and references therein). Well-documented is the significant "climate shift" 1976/1977 when the PDO changes from the cold phase into the warm phase.

3 Materials, data and methods

A 3 m long UWITEC piston core (PLO-11, January 2011) was retrieved from the distal part of Lago Plomo at a water depth of 31 m (Fig. 1). The sediment cores were kept dark and cool until analysis. We split the core lengthwise, cleaned the surface, photographed and described the sediment lithologically.

Immediately after core opening we scanned the clean sediment surface with non-destructive reflectance spectrometry (VIS-RS 380–730 nm) at 2 mm resolution using a Gretag McBeth spectrophotometer (Rein and Sirocko, 2002; Trachsel et al., 2010). Here, we used total brightness (% reflected light) as calculated from the average reflectance 400–730 nm (Rein et al., 2005) and use this index as a proxy for the relative proportions of the bright summer layer to the dark winter layer in the varves and admixtures of white 'summer-layer' minerals in the winter layer (Elbert et al., 2012).

Varve counting was performed on polished resin-embedded sediment blocks. Samples were cut from the fresh sediment using aluminum U trays (18 cm long × 2 cm wide × 0.5 cm deep) keeping an overlap of > 5 cm. After sampling the sediment blocks were flash frozen with liquid nitrogen, freeze-dried, impregnated with epoxy resin (58 % NSA, 23 % VCD, 18 % DER and 1 % DMAE) under vacuum and polished (6 µm). The polished blocks were scanned (flat-bed) at 1200 dpi. Number and thickness of varves were measured semi-automatically using the WinGeol Lamination tool of the Terramath program WinGeol (http://www.terramath.com) three times by two analysts, along different lines on the scanned images of the resin-embedded sediment blocks. Varve

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thickness was converted into annual mass accumulation rates (MAR) after Niessen et al. (1992).

Terrestrial plant macrofossils were AMS radiocarbon dated at Beta Analytic Inc and calibrated using the ShCal04 calibration curve (McCormac et al., 2004). The dates were used to verify the varve chronology in the upper part of the core and to constrain the floating varve chronology below an unlaminated sedimentary unit in the core at 180 cm with an anchor point.

The piston coring system does not preserve the top c. 15 cm of sediment (which are important for the proxy-climate calibration). Therefore we combined the piston core with a 120 cm long UWITEC gravity core from an adjacent coring site (PLO-09). Both cores were stratigraphically correlated with diagnostic marker-varves to a composite core of 281 cm length. Because both cores have slightly different mean color (brightness) and varve thickness we used an overlapping period of 240 varve yr (varves 1701–1940 AD) to homogenize both time series with linear regression. Pearson's product moment correlation coefficient r and p values corrected for serial autocorrelation ($p_{(aut)}$, Dawdy and Matalas, 1964) reveal for total brightness in the overlapping period a significant correlation ($r = 0.67$, $p_{(aut)} = 0.025$). Leave-one-out cross-validation (jack knifing) was carried out on the entire overlapping period (1700–1940 AD) to calculate the RMSEP (RMSEP = 0.4 % reflectance, i.e. approximately 10 % of the amplitude of the brightness values). While the decadal scale variability in the overlapping period is very well reproduced in both cores, errors are larger at the annual (varve) scale. This limitation arises due to the relatively large sensor field for VIS-RS (2 mm) in relation to the varve thickness (1–3 mm), implying that our data are suitable for the sub-decadal scale but should not be used as annual values (although one data point corresponds roughly to 1 yr).

We used the homogenized series with the varves 1900–1939 AD from the composite core and the varves 1940–2009 AD from the gravity core for the proxy – climate calibration. The total brightness – summer temperature calibration (linear inverse regression), the calibration statistics (RE, CE, RMSEP), the verification and reconstruction, follow the procedure applied previously in Lago Plomo for the MAR – winter precipitation calibration (Elbert et al., 2012; von Gunten et al., 2009, 2012 and references therein). For validation we used the split period approach with a calibration period (1952–2007 AD) and a validation period (1903–1951 AD). In addition to the calibration model, we test with the validation period also the quality of data homogenization in the period 1903–1939. Leave-one-out cross-validation was carried out on the entire calibration period (1903–2007 AD) to calculate the RMSEP. According to von Gunten et al. (2012) we use five-year triangular filtered data to account for maximum varve counting uncertainties in the calibration period and measurement errors (VIS-RS resolution relative to the varve thickness). In order to (i) remove potential long-term non-temperature-related effects on MAR in proglacial clastic sediments (Blass et al., 2007) and (ii) to make our temperature record from Lago Plomo consistent with the precipitation record from the same lake (Elbert et al., 2012) we applied locally weighted polynomial regression (LOESS span = 0.85; Cleveland and Devlin, 1988) on the total brightness data. In summary, our data series is designed to investigate sub-decadal- to centennial-scale variability and should not be used to infer multi-centennial and lower frequency variability.

Because local meteorological time series are short and discontinuous for this area, we used seasonal and annual reanalysis data from the CRU TS 3.1 data set (Mitchell and Jones, 2005; grid cell 46.5–47.0° S and 72.5–73.0° W, period 1900–2009 AD) for the comparison with the measured lake sediment proxy (total brightness). The CRU TS data perform well in this area and are correlated with the nearest regional weather station in Puerto Aysén (JJA – Precipitation: $r = 0.91$, $p_{(aut)} < 0.001$, 1931–1992; SONDJF-Temperature: $r = 0.64$, $p_{(aut)} < 0.001$,1952–1981).

4 Results and interpretation

The 281 cm long composite sediment core consists of regular clastic varves ranging from 0.2 to 4.5 mm in thickness. Throughout the core, the varves are composed of a dark fine-grained winter layer and a light coarse-grained summer layer. At

180–184 cm sediment depth, a The 4 cm thick unit shows massive un-laminated parts and sediment packs with very fine distorted varves that are not in situ, we interpret this unit as a slump.

Figure 2 shows the chronology of the composite core. The segment from 1391 AD onwards above the sediment slump is based on continuous varve counts with a maximum varve counting error of ±22 yr. Below the slump, the sediment segment 184–281 cm contains 775 continuous but floating varves with a maximum counting error of ±37 yr. The floating chronology is anchored through the age mid-point of a ^{14}C AMS-dated twig fragment (1270±30 ^{14}C yr BP, cal 752–891 AD, midpoint 854 AD; Beta-301562). Hence the lower varved segment ranges between 468 and 1242 AD, and the slump encompasses 148 varve yr (c. 1243 to 1390 AD).

The overall sedimentation rate is very homogenous with c. 30 cm per century from 1391–1900 AD and c. 20 cm per century between c. 700 and 1242 AD, and in the 20th century. Very small sedimentation rates were found in the 5th and 6th centuries.

The proxy data total brightness (TB), MAR and Water Content are shown in Fig. 2. Both MAR and TB show considerable variability in the interannual, decadal and centennial frequency domains. MAR values are generally high (i.e. $>0.3\,\mathrm{mg\,cm^{-2}\,yr^{-1}}$) between 140 and 50 cm sediment depth and brighter sediments are found between 50–140 cm and between 280–200 cm.

The correlation matrix (TB versus monthly, seasonal and annual temperature and precipitation) with annual, 3- and 5 yr triangular filtered data revealed the strongest correlation between TB and austral warm–season September–February temperatures (CRU TS 3.1 data). The calibration statistics for the calibration period 1900–2009 AD for 5 yr triangular filtered data yielded a correlation coefficient of $r = 0.58$, a significance level corrected for serial autocorrelation of $p_{(aut)} = 0.056$, positive values for Reduction of Error (RE = 0.52) and Coefficient of Efficiency (CE = 0.15), and a Root Mean Square Error of Prediction (RMSEP = 0.28 °C), that is approximately 15–20 % of the mean amplitude of multi-decadal temperature variation in the reconstruction.

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The calibration and the reconstruction of warm-season temperature from Lago Plomo back to 468 AD is shown in Fig. 3a (LOESS detrended, span = 0.85). The reconstruction gap between 1243 and 1390 AD corresponds to the sediment section with the slump (Fig. 2). The reconstruction shows pronounced sub-decadal – multi-decadal variability with cold phases in the 5th, 7th and 9th centuries, during parts of the Little Ice Age chronozone (16th and 18th centuries) and in the beginning of the 20th century. The most prominent warm phase in the 19th century is as warm as the second half of the 20th century.

The comparison between winter precipitation (data from Elbert et al., 2012) and summer temperature from Lago Plomo in the 20th century (Fig. 4a and b) reveals alternating phases of the 20 yr running correlation$_{(\text{winterPP;summerTT})}$ (5 yr triangular filtered lake sediment data; Fig. 4c, note inverse y-axis). The sign and trends of this running correlation change between positive and negative values at a frequency of 20–30 yr. Negative correlations (high JJA precipitation–low SONDJF temperatures and low JJA precipitation–high SONDJF temperatures, respectively) are found from 1980 AD onwards, positive correlations (high JJA precipitation–high SONDJF temperatures and low JJA precipitation–low SONDJF temperatures, respectively) in the 1960s and early 1970s, again negative correlations in the 1930s and 1940s and again positive values at the beginning of the century. The most prominent changes in the multi-decadal correlation trends are found around 1920, 1945 and 1975 AD.

Figure 4c and d shows that the sign changes and the trend changes of the intra-seasonal precipitation and temperature correlation inferred from the sediments are in phase with changes in the PDO Index from predominantly positive (warm PDO phase, 1920–1948 AD) to negative (cool PDO phase until 1976 AD) and again positive values (1977–2000 AD) in the 20th century.

Figure 5a–c extends the intra-seasonal precipitation and temperature coupling as inferred from the sediments of Lago Plomo back to the year 1530 AD. The running 20 yr correlation$_{(\text{winterPP;summerTT})}$ shows a trend from negative values 1530 AD to positive values 1610 AD (note reversed scale), generally increasing amplitudes of variability from

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1650 AD onwards, and predominantly positive values between 1650–1860 AD (generally the Little Ice Age chronozone) particularly during several decades centered around 1600, 1800, 1850, 1920 and 1960 AD. The decades with pronounced negative correlations are observed around 1630, 1890, 1930 AD and 1980s.

5 Discussion

First we discuss the data quality. Then we put the warm season temperature reconstruction of the past 1500 yr from Lago Plomo into the context of regional paleoclimate data sets. Then we discuss to which extent the inter-seasonal coupling between winter precipitation and warm season temperature can be used as a proxy for the PDO index since 1530 AD. Finally, we use composites of PDO positive and PDO negative years to provide a dynamic explanation for the winter precipitation and warm season temperature coupling and its relation to PDO.

5.1 Sedimentation processes and chronology

In general, the sediments of the composite core are very similar to the sediments of the past 470 yr (Elbert et al., 2012) and represent annual clastic varves. Also the sedimentation processes seem to be the same: the light coarse grained Fe-rich summer layers are interpreted to be related to strong undercurrents and oxygenation of the bottom waters during snow and glacier melt in the warm season. The dark very fine grained winter layers were formed during calm conditions with weaker winds and reduced river influx.

In order to get a continuous undisturbed sediment series we combined a short gravity corer for the surface sediments and a piston core for the deeper sections. Both cores were stratigraphically correlated for a section with 240 varve years overlap (varves from 1701–1940 AD). The homogenization model and the reproducibility of the MAR

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and brightness values in the overlap section make the chronology and the proxy time series in the composite core robust.

Multiple varve counting yields a reliable highly accurate and precise chronology back to 1391 AD (above the sediment slump). The varve counting error of ±22 yr for the this part is at the smaller end of typical values (Ojala et al., 2012). The section with the slump prior to 1391 AD represents a chronological discontinuity of c. 148 yr. Hence, the absolute ages and related uncertainties of the sediments below the slump are on the order of typical ^{14}C ages ($\pm 1\sigma = 140$ yr) while the relative sediment ages (floating varve chronology) are much smaller (±37 yr). In summary, the chronology is much better in the part above the slump (since 1391 AD ± 22 yr) as compared with the lower part (before 1243 AD up to ±139 yr).

The correlation matrix between the sediment proxies and the climate data revealed the best values for the relationship between sediment brightness and summer temperatures. The relationship between sediment flux, glacier melt and summer temperature in proglacial lakes is well documented around the world (e.g. Leonard, 1997; Blass et al., 2007 and references therein, Trachsel et al., 2010; Nussbaumer et al., 2011). However, Blass et al. (2007) showed that the positive relation between summer temperature and MAR (mediated through glacier melt water) is only valid for interannual to multi-decadal time scales while, at centennial and longer time scales, this relationship is actually negative because the MAR is dominated by glacier length variations and prolonged cool and rainy climate (MAR mediated through glacial abrasion). Although this effect has not yet been directly documented in the Southern Hemisphere or in the Patagonian Andes, the MAR data of Lago Plomo (Fig. 2) also suggest a strong relation to centennial-scale glacier length variations: greatest MAR between 1500 and 1900 AD coincided with significant maximum glacier advances in that part of the world (Masiokas et al., 2009). This is the reasoning, why we have deliberately removed the low frequency variability (multi-centennial and longer) from the sediment-inferred temperature reconstruction. The low frequency variability of sediment brightness may have a non-temperature component which is very difficult to assess. Thus LOESS filtering

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was applied to be on the conservative side. This implies that our temperature reconstruction has best skill in the sub-decadal to multi-decadal domain of variability and should not be used to infer phenomena that operate at the multi-centennial and longer time-scales.

5.2 1500 yr SONDJF temperature reconstruction

The proxy-climate calibration statistics are comparable with other calibrations of sedimentological proxies using the Calibration-in-Time approach (von Gunten et al., 2012, and references therein). It should be noted that the calibration is made with reanalysis data. This is not ideal but this is the best data available and the quality of the reanalysis data has been verified with regional station data. Since the calibration/verification period is relatively short and the temperature range of the 20th century variability is limited, the typical caveats for reconstructions apply: (i) reconstructions are only valid within the temperature range covered by the calibration period, and (ii) the assumption of stability of the statistical proxy-climate relationship is made (Juggins, 2013).

Figure 3 shows the comparison of the summer temperature reconstruction from Lago Plomo with regional paleoclimate data sets. The only available record from the transition zone between Northern and Southern Patagonia (44–48° S) is the reconstruction of mean annual temperature from Laguna Escondida (45°31′ S, 71°49′ W, Elbert et al., 2013). 5 yr filtered reanalysis data for SONDJF temperatures from Lago Plomo and annual temperatures from Laguna Escondida are correlated with $r = 0.57$ ($p_{(aut)} = 0.069$). Although it is not clear from observations, reanalysis data (Garreaud et al., 2013) and regional paleoclimate data sets (Neukom et al., 2011), whether or not comparable decadal signals in annual, winter and summer temperatures are expected, both records (Lago Plomo: summer temperature and Laguna Escondida: annual temperature) show good agreement in the decadal to centennial temperature variability for most parts of the reconstruction. Both records show warming in the 6th and 7th centuries, relatively cool conditions 650–700 AD, two warm peaks around 710 and 800 AD, a cool 9th century, and intermediate to warm conditions in the 10–12th centuries with

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four warm peaks. The 16th century was cool in both records with a pronounced warm decade around 1550 AD. The 18th century was consistently cool. Major disagreements (warm summers but cool years) are observed 1400–1450 AD, around 1600 AD and from 1800–1910 AD, whereas the opposite (cooler summers but warm years) was found between 1650–1700 AD.

The regional warming in the 19th century is surprising in comparison to hemispherical or global data compilations (Wanner et al., 2011; PAGES 2k Consortium, 2013) but seems to be significant in some parts of South America. Exceptionally warm summers around 1800 AD were also found in Laguna Escondida (Elbert et al., 2013), in tree rings from the Northern Patagonian Andes (Villalba, 1994), in Tierra del Fuego (Boninsegna et al., 1989) and in lake sediments from Central Chile (von Gunten et al., 2009), whereas tree rings from the Southern Patagonian Andes do not show a temperature anomaly during that time (Villalba, 1994). Warmth in the beginning of the 19th century is also supported by glacier recession in the northern Patagonian Andes (42° S) started after the maximum expansion from 1600–1800 AD (Ruiz et al., 2012).

Also the multi-decadal long warm periods in Lago Plomo around 1080 AD and 1200 AD were found in Laguna Escondida and the comprehensive regional reconstruction (Neukom et al., 2011). This is actually surprising since the Neukom et al. (2011) reconstruction does not have any local proxy data set as a predictor for Patagonia prior to the 17th century and temperatures further back are reconstructed with proxies from the central Andes or the tropics.

Because of the sediment hiatus in Lago Plomo (13–14th centuries), our record is not conclusive with regard to summer temperatures during the Medieval Climate Anomaly with reported warmth 1200–1350 AD (Neukom et al., 2011).

5.3 Pacific decadal oscillation

It is exceptional in paleoclimate archives that two different climate variables (temperature and precipitation) for two different seasons (winter and summer) can be reconstructed at near-annual resolution in the same archive. We have shown in Fig. 4 that the inter-seasonal coupling between winter precipitation and summer temperature as reconstructed from the Lago Plomo varved sediments changes the sign of its correlation with a frequency of 20–30 yr. Moreover, positive correlations and negative decadal trends of these correlations are in phase with negative phases of the PDO index and vice versa. The three most prominent changes in the sediment proxies are observed around 1920, 1945 and 1975 AD. These years closely match the index changes of the PDO index (Fig. 5d; Mantua et al., 1997, updated version).

Hence the question arises whether the observations from Lago Plomo are significant and reproduced in regional reanalysis data and a dynamic explanation can be found for their relation with PDO. Figure 6a–c shows the spatial correlation maps (JJA-PP and SONDJF-TT) of 20 yr long composites for PDO positive phases (1925–1944, and 1980–1999 AD) and a PDO negative phase (1950–1969; UDel, version 2.01, 1901–2008, Legates et al., 1990a,b, data 5 yr filtered like lake sediment data). The inter-seasonal coupling found in the sediments of Lago Plomo is reproduced in regional reanalysis data and the pattern is spatially robust. CRU TS 3.1 data yield the same results (data not shown).

Due to its location, the climate of western Patagonia is strongly controlled by low-level zonal wind fluctuations (Garreaud et al., 2013). Precipitation variability at daily and annual timescales is all year round positively (negatively) correlated with zonal wind at 850 hPa at the western (eastern) flank of the Andes. In contrast, the temperature effect of zonal wind advection from the cool Pacific onto the continent differs with the season (cooling in spring, summer and autumn but warming in winter) over major parts of southern South America (Garreaud et al., 2013).

In order to investigate the inter-seasonal temperature-precipitation coupling, we apply an objective cluster analysis on all pairs of data (SONDJF temperature and JJA precipitation) covering 1901–2006, previously normalized with respect to the whole period. From a total of four clusters, we selected two clusters which depict different annual regimes (dominance of either SONDJF temperature or JJA precipitation). Cluster C1 encompasses years with relatively warm spring and summer seasons and small winter

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precipitation departures from the 20th century mean (1913, 1915, 1917, 1922, 1945, 1962, 1980, 1986, 1987, 1989, 1990, 1993, 1998, 1999, 2001, 2003, 2004, 2005 AD). In contrast, cluster C2 is formed by years with relatively wet winters and relatively less variation in temperature during summer (1901, 1904, 1910, 1933, 1937, 1939, 1953, 1957, 1958, 1963, 1965 AD). While C1 years agglomerate during the PDO positive phases (especially after late-1970s), the majority of the C2 events are found during the PDO negative phase and none during the last PDO positive phase. These groups do not vary much when the clustering procedure is applied on detrended normalized series.

Figure 6d–i shows composites of the C1-C2 difference ("PDO positive" – "PDO negative") fields for wind at 850 hPa (Fig. 6d and g; 20CRv2, 1871–2008, Compo et al., 2011), temperature (Fig. 6e and h) and precipitation (Fig. 6f and i). During austral winter (JJA), we observe stronger Westerlies to the south of 45° S, which strengthen the northerly warm advection in northern Patagonia. Consequently, positive temperature anomalies of up to 1 °C are observed for this composite difference in the area of Lago Plomo. Due to the southward-shifted storm-track, less (more) precipitation is observed to the north (south) of Lago Plomo. During spring and summer (SONDJF), we recognize a similar wind difference field as in the previous case, although the positive westerly anomaly is weaker and displaced more to the south in comparison with the winter season. Thus, less cold advection reaches southern South America, which is at least partly causing the warm anomaly (plus 1 °C) around Lago Plomo. A similar effect (but weaker, note the different scales) in winter precipitation is observed. Enhanced circumpolar flow, in particular over the Drake Passage, was proposed for the surface wind anomalies during the positive phase of the ENSO-like inter-decadal mode of Southern Hemisphere circulation (Garreaud and Battisti, 1999). This phenomenon seems to be, at least partially, responsible for the reversed seasonal coupling of precipitation and temperature during opposite phases of the PDO.

Multi-century long PDO reconstructions exist from a comprehensive multi-proxy network from the tropical Pacific back to 1650 AD (McGregor et al., 2010) and from tree

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ring networks in North America (MacDonald and Case, 2005; Mann et al., 2009 and references therein). Similar to our data from Lago Plomo (Fig. 5c), Mann et al. (2009) propose a negative PDO trend from 1530–1610 AD, relatively positive PDO around 1630 AD, during several short intervals in the 18th century and in the 2nd half of the 19th century. Pronounced negative anomalies are found around 1610, 1830 and 1910 AD. Noteworthy is also the generally increasing trend in the amplitude of variability from 1650 AD onwards (McGregor et al., 2010) which is also found in the Lago Plomo data. There are a number of similar features jointly found in various independent data sets.

However, in all the records there is very strong sub-decadal and decadal variability and it is very difficult to identify a coherent PDO pattern throughout the Pacific for the past centuries. Moreover it is very difficult to test the robustness of our PDO reconstruction from Patagonia. This is attributable to three challenges: (i) despite the very good varve chronology of the past 470 yr, dating uncertainties exist (±20 yr). This dating uncertainty is small for lake sediments, but very large and maybe even fatal if the phenomenon under consideration requires an accuracy of a few years only; (ii) reconstruction of large-scale climate fields and modes is in general very challenging (McGregor et al., 2010), but particularly difficult or even not recommendable from single site reconstructions (Schmutz et al., 2000), and (iii) there is increasing evidence for non-stationarity of teleconnections and the spatial representation of modes (Wilmes et al., 2012), which questions fundamentally the basic assumptions for the reconstruction of modes from individual sites or regional networks.

6 Conclusions

In this work we presented a 1500 yr long austral summer temperature reconstruction from varved sediments of proglacial Lago Plomo in Patagonia (46° S), southern South America. The structure of the varves, Mass Accumulation Rates MAR and sediment brightness values in the analyzed sediment core are very similar to the sediments

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documented in previous work. The varve counting chronology is highly precise and accurate (±22 yr) in the upper part of the sediment from 1391 AD onwards and within ^{14}C dating uncertainty (140 yr) in the section 1243 to 500 AD, i.e. below an un-laminated slump that encompasses 148 yr.

In this lake we used total sediment brightness (% reflectance in the range of 400–730 nm) as a proxy for warm season temperature. The significant correlation between the proxy (total brightness as a measure for the thickness of the light summer sediment layer) and reanalysis data in the 20th calibration period proved to be robust and revealed good calibration and validation statistics (positive RE and CE values, small RMSEP). Moreover, our physical explanation for the proxy-climate relationship (more glacial melt water and suspended sediment transport in a warmer summer) has been well documented elsewhere in the world. We conclude that the proxy-climate relationship and the calibration are robust.

For the reconstruction back to 500 AD, the general caveats to the calibration-reconstruction assumptions apply. For these reasons we applied a LOESS filter cutting off the > 100 yr variability implying that our reconstruction has best skills in the sub-decadal to multi-decadal frequency bands.

The reconstruction shows pronounced cold phases in the 5th, 7th, 9th and 18th centuries and in the beginning of the 16th and 20th century. Warm phases are found in the 6th, 8th, 15th and 19th century. Our reconstruction compares favorably with independent regional and sub-continental temperature records but shows also specific discrepancies. Thus we conclude that the Lago Plomo record provides a robust temperature series for southern South America for the past 1500 yr and helps further resolving regional climate differences.

The comparison between the lake sediment-inferred winter precipitation and summer temperature from Lago Plomo provides insight into the inter-seasonal coupling of both variables and shows phases with positive and negative correlations and trends in the frequency band of 20–30 yr. The phases with positive and negative running correlations (parallel and contrasting decadal trends) between winter precipitation and

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summer temperature are spatially robust and coincide with trends in the PDO index. We conclude from composites with PDO+ and PDO− years that enhanced circumpolar flow in the south (60° S over the Drake Passage) in PDO+ years with associated changes in the vectors of wind anomalies further north (in the area of Lago Plomo 46° S) provides a dynamic explanation for the different inter-seasonal coupling in this area.

Our PDO reconstruction back to 1530 AD reproduces some of the features proposed in two existing PDO reconstructions from the northern and tropical Pacific. However, overall the three PDO reconstructions available cannot be considered as consistent. Possible reasons for the inconsistencies are changes in the teleconnections and spatial fields in the domain of PDO which is difficult to assess.

Therefore, at the current state of research we conclude that (i) the inter-seasonal coupling in the proxies of Lago Plomo in the 20th century is reproduced in the reanalysis data and regionally consistent, (ii) the positive (negative) coupling is highly consistent with negative (positive) phases of the PDO, (iii) there is a dynamic explanation for the positive (negative) seasonal coupling that is consistent with composites for positive (negative) PDO phases, and (iv) there is – at least – partial consistency with PDO reconstructions from the tropical Pacific and North America.

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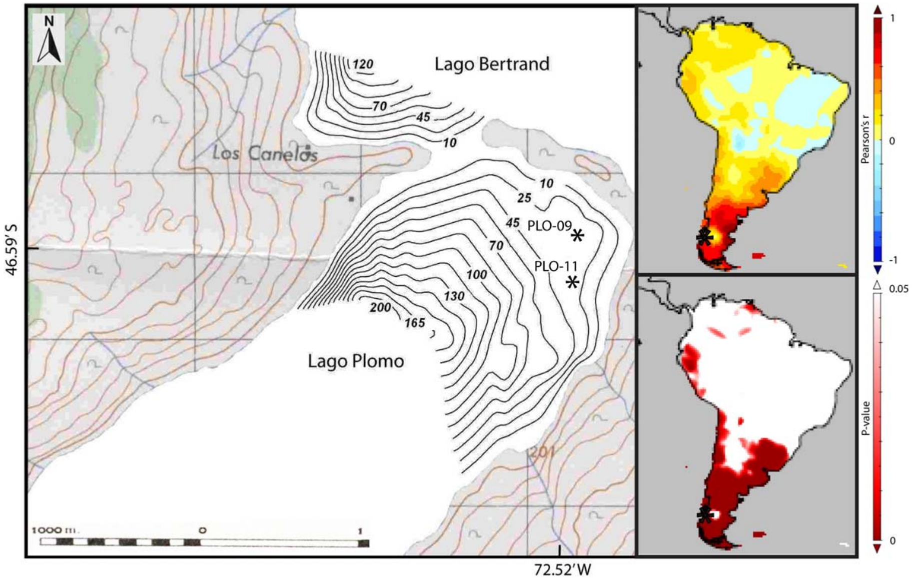

Fig. 1. Showing Lago Plomo, the bathymetric contour map (m water depth) and the coring sites 2009 and 2011. Inset: SONDJF temperature Pearson Correlation map between Lago Plomo (asterisks) and South America (upper map) and the corresponding P values (values < 0.05 in red; lower map). Data: Mitchell and Jones (2005).

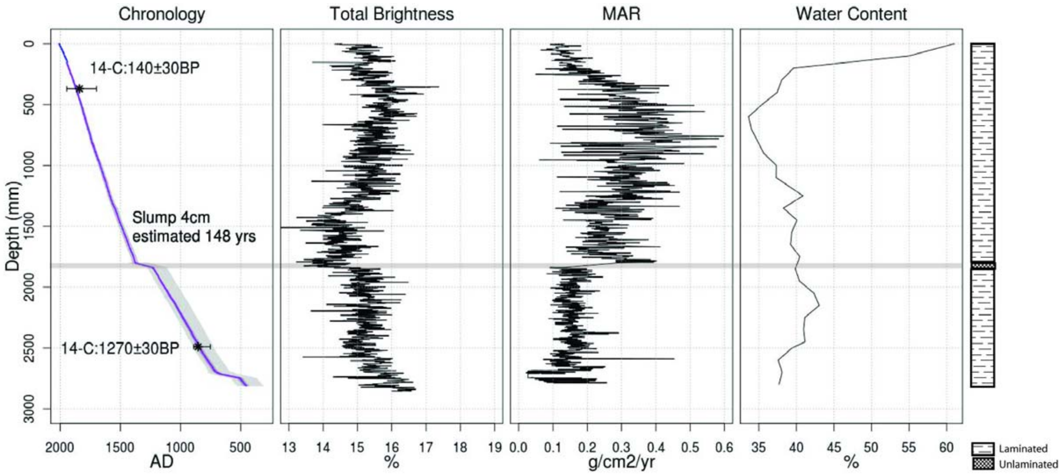

Fig. 2. Varve chronology (midpoint pink line), varve counting errors (above the slump, shaded), cumulative varve counting and ^{14}C errors (below the slump, shaded) and ^{14}C AMS dates for the composite core (Elbert et al., 2012 and this work). Total brightness [% reflected light] derived from VIS-RS 400–730 nm, Mass Accumulation Rates (MAR) and Water Content and bedding description of the composite core.

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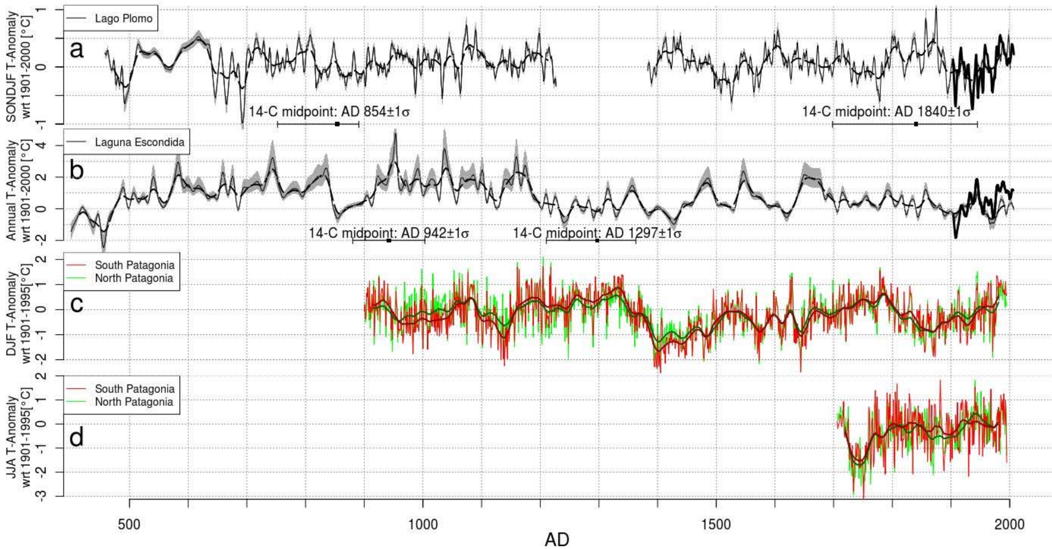

Fig. 3. (a) SONDJF temperature reconstruction from Lago Plomo (black bold line: reanalysis data used for calibration; thin black line with shading: 5 yr triangular filtered data with RMSEP, broken line 30 yr filtered; the time series is LOESS detrended span + 0.85); **(b)** annual temperature from Laguna Escondida (Elbert et al., 2013); lines represent the same as for **(a)**; **(c)** multiproxy summer (900–1995 AD) and **(d)** winter (1706–1995 AD) annual and 30 yr filtered surface air temperature field reconstructions by Neukom et al. (2011) for Northern Patagonia (green) and Southern Patagonia (red).

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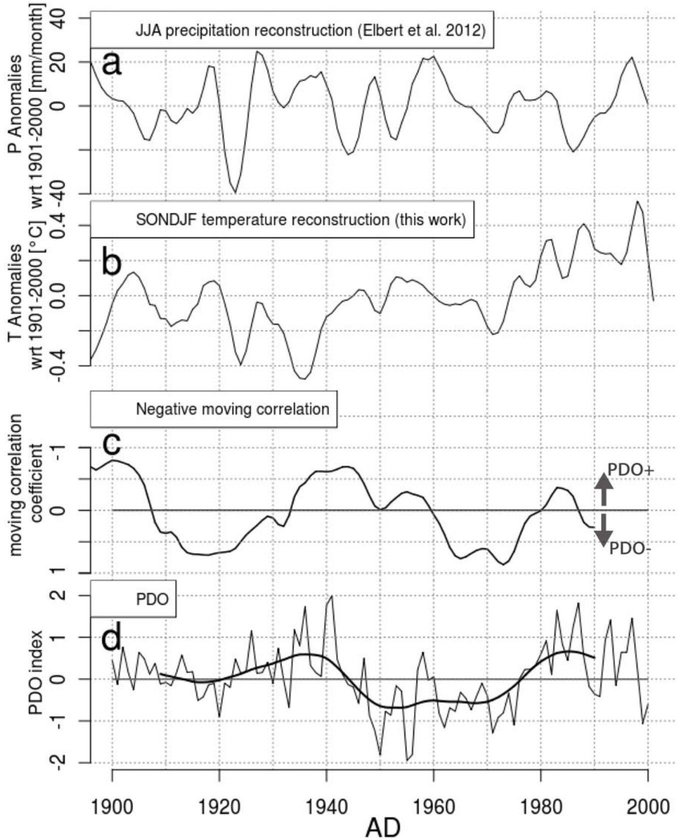

Fig. 4. (a) JJA-precipitation reconstructed from Lago Plomo 1900–2007 AD (Elbert et al., 2012). **(b)** SONDJF-Temperature reconstructed from Lago Plomo (this study). **(c)** Negative running correlation (20 yr) of winter precipitation and summer temperature from Lago Plomo (5 yr filtered version); **(d)** annual and 20 yr filtered PDO index (Mantua et al., 1997, updated version online).

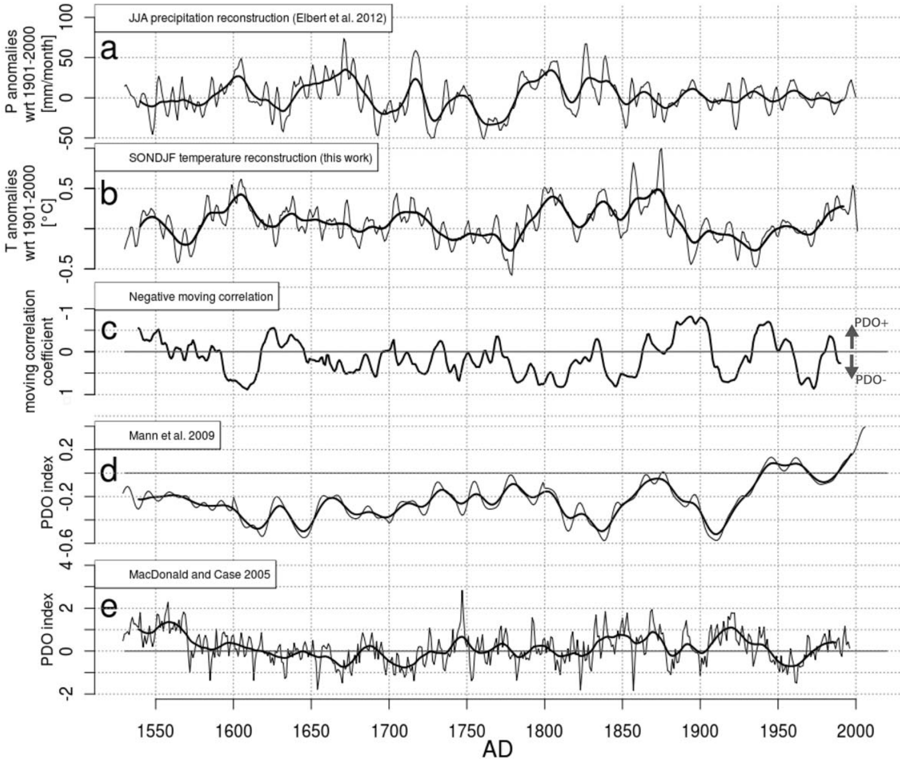

Fig. 5. (a) winter precipitation anomalies from Lago Plomo back to 1530 AD (Elbert et al., 2012, 5 and 20 yr filtered data, LOESS detrended), **(b)** warm season SONDJF temperature reconstruction from Lago Plomo (this work; 5 and 20 yr filtered data, LOESS detrended). **(c)** Negative 20 yr moving correlation between winter precipitation and summer temperature from Lago Plomo (note inverse y-axis). **(d)** PDO reconstruction by Mann et al. (2009, original data and 20 yr filtered) and **(e)** PDO reconstruction by MacDonald and Case (2005; annual and 20 yr filtered data).

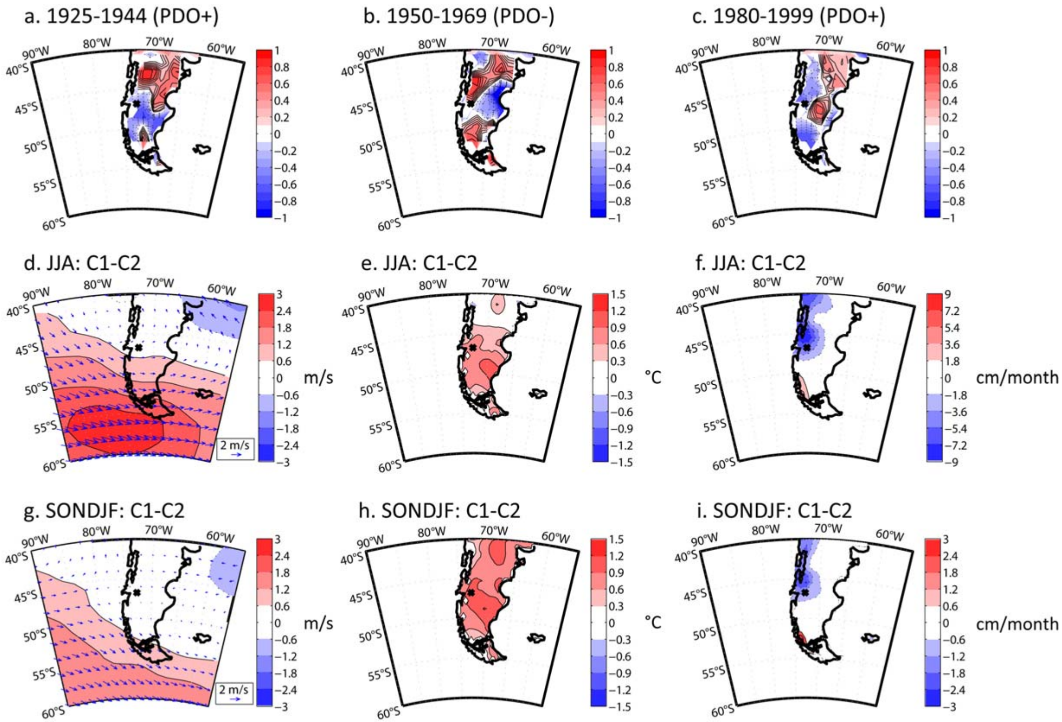

Fig. 6. Correlation fields between winter precipitation (JJA) and warm season surface air temperature (SONDJF) for **(a)** 1925–1944 (PDO+), **(b)** 1950–1969 (PDO−) and **(c)** 1980–1999 (PDO+). Each variable was previously smoothed by applying a 5 yr running mean. Colors every 0.2, continuous (dashed) contours every 0.1 depict positive (negative) values; zero contour omitted. Cross indicates the (46.5° S, 72.75° W) grid-point next to Lago Plomo. Composites of the difference between clusters (C1–C2; PDO+ minus PDO−) for **(d, g)** wind at 850 hPa (contours: zonal wind at 850 hPa); **(e, h)** surface air temperature; **(f, i)** precipitation. Note the different scales; zero contours omitted. The middle row shows winter JJA mean fields, the lower row summer SONDJF mean fields.

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