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Late-Holocene and Little Ice Age palaeoenvironmental change inferred from pollen analysis, Isla de los Estados, Argentina

Juan Federico Ponce [a, d, *], Ana María Borromei [b], Brian Menounos [c], Jorge Rabassa [a, d]

[a] CADIC-CONICET, Laboratorio de Geomorfología y Cuaternario, B. Houssay 200, 9410 Ushuaia, Argentina
[b] INGEOSUR-CONICET, Departamento de Geología, Universidad Nacional del Sur, San Juan 670, B8000ICN Bahía Blanca, Argentina
[c] Geography Program and Natural Resources and Environmental Studies Institute, University of Northern British Columbia, Prince George, British Columbia V2N 4Z9, Canada
[d] ICPA-UNTDF, Onas 450, 9410 Ushuaia, Argentina

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ABSTRACT

We present pollen and spore analysis from a peat-bog section from southwestern Isla de los Estados (Staaten Island), Tierra del Fuego to better understand late-Holocene environmental change in southernmost Patagonia. The island's position as the easternmost landmass at the southernmost of South America, places it squarely within the influence of the southern westerly winds (SWW) and the Antarctic Circumpolar Current, and so makes the island a unique location to document the palaeoecological response to climate change during the late Quaternary. We compare our *Nothofagus* pollen record from Bahía Franklin with other *Nothofagus* pollen records from Isla de los Estados and Tierra del Fuego. *Nothofagus* has been shown to respond to changes in mean annual temperature in the southern latitudes under cooler climate with little seasonality in precipitation. We also evaluate the correspondence between these changes in vegetation to other late-Holocene environmental proxies that include variations in sea surface temperature (SST) from the Beagle Channel and records of past glacier fluctuations. Our results show that low concentrations of *Nothofagus* pollen existed at Bahía Franklin at about 4000 cal yr BP. Climate ameliorated between ca. 3500 and 500 cal yr BP based on an increase in frequency and concentration values of *Nothofagus* and *Drimys winteri*. Between about 500 and 50 cal yr BP, the pollen record revealed a noticeable decline in the forest density. We interpret the decline in forest density in Isla de los Estados between 500 and ~50 yr cal BP as a response to cold and windy conditions during the Little Ice Age (LIA). Our interpretation from our *Nothofagus* pollen record broadly agrees with regional cooling recorded in reconstructed SST of the Beagle Channel and with glacier expansion in the Fuegian Cordillera.

1. Introduction

The Little Ice Age (LIA) comprises a period in which glaciers in the mountain areas of the world were generally more extensive. The term "Little Ice Age" was first introduced by Matthes (1939) with reference to the phenomenon of cirque glacier regrowth during the Holocene. Glacier advances are well documenting from many parts of the world, and particularly in western Europe, where summer temperatures cooled during the seventeenth and early nineteenth centuries (Bradley and Jones, 1993). Compared to Europe, there are few high-resolution records of past climatic conditions over the last millennium from the Southern Hemisphere. Neukom et al. (2014) reported a new millennial ensemble reconstruction of annually resolved temperature variations for the Southern Hemisphere based on a network of terrestrial and oceanic palaeoclimate proxy records. In conjunction with an independent Northern Hemisphere temperature reconstruction ensemble, this record reveals an extended cold period (1594–1677) in both hemispheres but no globally coherent warm phase during the pre-industrial (1000–1850) era.

According to Moy et al. (2009), the LIA event, is regionally complex and its timing, magnitude, and nature have not been clearly delineated in southern South America. In addition, the way in which the LIA affected vegetation is also related to local microclimates and individual sensitivities of the ecosystems as well as locally distinct available moisture depending on wind exposition and local soil types (Kilian and Lamy, 2012).

* Corresponding author. Laboratorio de Geología del Cuaternario, CADIC-CONICET, V9410BFD Ushuaia, Tierra del Fuego, Argentina.
E-mail address: jfponce@cadic-conicet.gob.ar (J.F. Ponce).

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In Isla Grande de Tierra del Fuego the LIA has not been clearly identified in pollen records along the Beagle Channel (Heusser, 1998, 2003), although variation in the influx of *Nothofagus* pollen suggests high climatic variability during the late Holocene. The LIA event has been reported by Mauquoy et al. (2004), Borromei et al. (2010) and Chambers et al. (2014) based on palaeoecological evidence from peat-cores taken at the inner valleys of the Fuegian Andes. Previous studies suggested that climatic anomalies associated to the LIA may have affected Isla de los Estados (Ponce et al., 2011).

The objectives of our study are to better understand the timing of late-Holocene vegetation change on Isla de los Estados and, in particular, whether these changes coincide with regional evidence for climate deterioration during the LIA. The position of Isla de los Estados as the south easternmost landmass in South America under the influence of the southern westerly winds (SWW) makes it a unique and important location to study the palaeoecological response to climate change during the Holocene. We compare our palynological data to previously reported palaeoenvironmental records that include pollen spectra, evidence of past glacier fluctuations and variations in sea surface temperature (SST) from northern Isla de los Estados and southern Isla Grande de Tierra del Fuego.

2. Regional setting

Isla de los Estados (54°51′S and 64°41′W) is part of the southeastern end of the Andes cordillera. The island is located ca. 30 km southeast from Península Mitre, Isla Grande de Tierra del Fuego (main island of Tierra del Fuego) and has a surface area of 496 km^2 (Fig. 1a).

The climate of Isla de los Estados is strongly influenced by a persistent area of low pressure that develops near the Antarctic Circle. The current climate of Isla de los Estados is cold and humid. The mean temperature during summer is 8.3 °C, with mean daily extremes of 16.2 °C and 3 °C. Winter mean temperature is 3.3 °C, with mean daily extremes of 7.4 °C and −4 °C. Mean annual precipitation is estimated to be 2000 mm yr^{-1} (Niekisch and Schiavini, 1998, unpublished data), but greater precipitation totals are likely for higher elevations. Prevailing winds are from the southwest and the northwest; they are active throughout the year.

Isla de los Estados belongs to the Subantarctic region, characterized by the presence of exuberant vegetation (Cabrera, 1976). This region and the southern coasts of Isla Grande de Tierra del Fuego represent the only locations in Argentina where forests descend to sea level. Dudley and Crow (1983) identified seven different vegetation types related to altitude and geomorphology. These vegetation types are similar to those described for Tierra del Fuego by Moore (1983). The more protected and lower mountain slopes and valleys contain *Nothofagus betuloides* and *Drimys winteri* forests typical of the true Subantarctic Evergreen Forest (Ponce et al., 2011). In those sites constantly exposed to continuously strong wind conditions, the main vegetation is the Magellanic Moorland Formation, a mosaic of interfingered and superimposed subunits (*Empetrum rubrum* association, *Caltha* association and *Astelia pumila* association) that cover rather small areas forming cushion bogs. The Meadows Formation extends through valleys and places where the dense growth of rushes gives the appearance of a grass meadows. The Scrub Formation exists on mountain slopes exposed to the prevailing southwesterly and westerly winds, whereas trees of *Nothofagus antarctica* and shrubs grow low and tortuous. Above approximately 450 m a.s.l., the so-called Alpine Formation occurs with sparse vegetation cover, and often includes dwarfed forms of *Nothofagus antarctica* and *Empetrum rubrum*.

Vegetation at the study site is typical of the Meadows Formation (Dudley and Crow, 1983), and the cored peatland features dominance of *Marsippospermum grandiflorum* with various bushes such as *Chiliotrichum diffusum*, *Pernettya mucronata*, *Empetrum rubrum* and *Berberis ilicifolia* (Fig. 2).

The IDE-2 (Isla de los Estados-2) peat core (54° 50′ 38,7″ S; 64° 38′ 48,1″ W) is located at Caleta Lacroix (northeast of Franklin bay, Fig. 1b) in an interdune area dominate by *Marsippospermum grandiflorum* peatlands in the inner part of a fossil longitudinal-sand-dune field currently covered by *Nothofagus* forest (Ponce et al., 2011) (Fig. 1b and c). The IDE-2 peat core lies 240 m a.s.l. to the southeast from IDE-1 pollen section (Ponce et al., 2011). The section IDE-1 comprises the past 13,000 years of pollen record. The section IDE-2 was studied to gain a better understanding of the timing and structure of the vegetation and climatic changes during the late-Holocene. The high-resolution pollen data coming from the studied IDE-2 section reinforce the pollen changes mainly observed in IDE-1 section during the LIA.

3. Materials and methods

We recovered 75 cm of peat from the IDE-2 site using a Russian-type peat corer with a chamber length of 0.5 m and a 5 cm diameter sampling barrel (Jowsey, 1966). Core segments were extruded in the field, wrapped in plastic film and stored in split plastic pipes. In the laboratory we split, described and sub-sampled the core at 5-cm intervals.

For palynological analysis we prepared peat samples according to standard techniques (Faegri and Iversen, 1989). We added *Lycopodium* spore tablets to each sample prior to treatment (Stockmarr, 1971) to allow calculation of pollen concentrations per unit mass of sediment. Frequencies (%) of tree, shrub and herb pollen of terrestrial origin typically represent sums of at least 300 grains. Pollen of Cyperaceae and cryptogams were calculated as percentages of the total sum of pollen and spores.

We divided the pollen record in zones to facilitate description through visual inspection taking to account the major transitions in the pollen stratigraphy, and supplemented with a stratigraphically constrained cluster analysis using the Cavalli-Sforza and Edwards Distance (TGVIEW 2.0.2, Grimm, 2004).

Pollen from the evergreen species *Nothofagus betuloides* and the deciduous species *N. pumilio* and *N. antarctica* are reported as the "*Nothofagus dombeyi* type", given the difficulty in the identification of the different species. Another special case is *Empetrum rubrum*, *Gaultheria*/*Pernettya* (Ericaceae) and *Lebetanthus myrsinites* (Epacridaceae) which are morphologically similar and occur as tetrads; for these reasons, they are considered as one taxonomic group on the pollen diagrams in the present study, named "*Empetrum*/Ericaceae type".

4. Results

4.1. Lithostratigraphy and chronology

The IDE-2 peat core consists of 5-cm thick dark grayish sands overlain by 10 cm of compact dark peat with clay. From 60 to 20 cm depth, the core is composed of light brown fibrous peat. The uppermost 20 cm of the core consists of dark brown very fibrous peat.

The peat core was constrained by three radiocarbon dates obtained from 1-cm thick peat samples. The sampled were submitted to the AMS Facility of the University of Arizona, U.S.A for analysis. We converted all radiocarbon ages, and those from prior studies discussed in this study, to calendar years BP using the CALIB 7.0 software (Stuiver et al., 2014) and the South Hemisphere curve (SHcal13) (Hogg et al., 2013) (Table 1). An age–depth model for the core was calculated with the OxCal 4.2.3 calibration software (Bronk Ramsey and Lee, 2013, Fig. 3).

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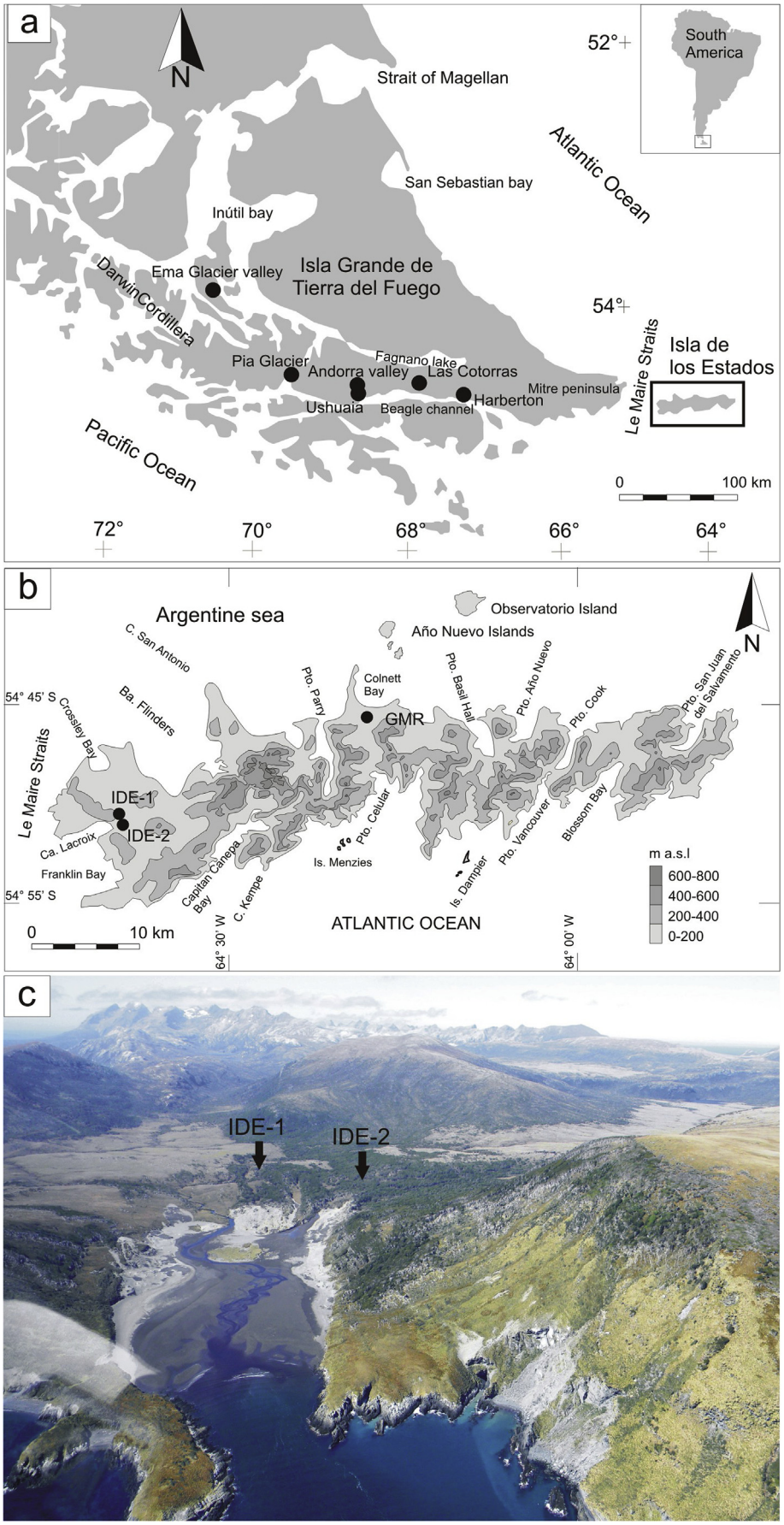

Fig. 1. (a) Location map. (b) Isla de los Estados and the sites mentioned in the text. IDE-1 (Ponce et al., 2011), IDE-2 (this paper), GMR: Galvarne Moraine Ridge (Björck et al., 2012). (c) Bahía Franklin area.

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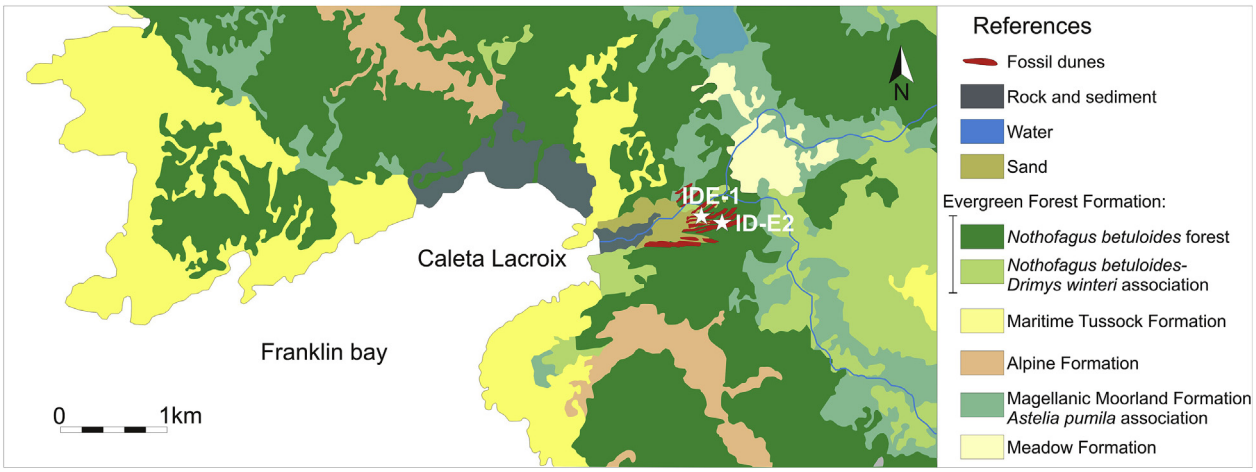

Fig. 2. Bahía Franklin vegetation units. IDE-1 (Ponce et al., 2011) and IDE-2 (this paper) sites (modified from Llavallol and Cellini, 2006).

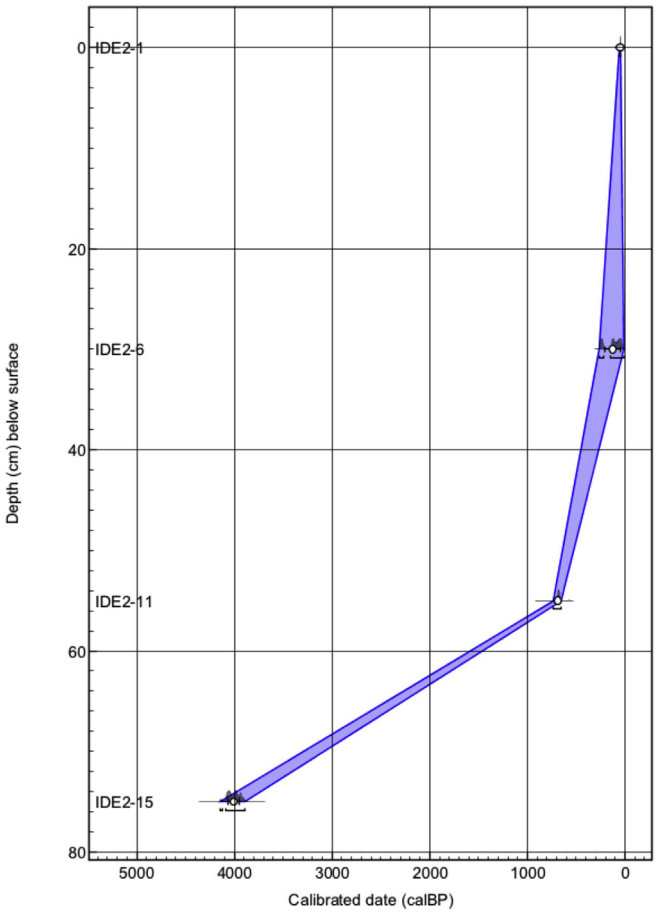

Fig. 3. Age–depth curve from IDE-2 pollen/spore section.

4.2. Pollen/spore analysis

We divided the palynological record from IDE-2 in three assemblage zones, IDE2-1 to IDE2-3 (Fig. 4). To assess the independence of pollen types and provide better insight into the direction of vegetation change around the mire, we calculated the pollen concentrations of the main taxa (Fig. 5).

Zone IDE2-1 (70–45 cm; 4000–400 cal yr BP): This zone is dominated by *Nothofagus dombeyi* type (97–75%). Frequencies of *Empetrum*/Ericaceae initially reach a maximum of 22% but decline to 1% near the top of the zone. *Drimys winteri* is low (<3%). *Misodendrum* (a hemiparasite on *Nothofagus* species), Poaceae, *Gunnera*, *Escallonia*, Asteraceae subf. Mutisieae, *Myrteola nummularia*, and fern spores are uncommon (<1%). Asteraceae subf. Asteroideae increases up to 7% towards the top of the zone.

Total pollen concentration values are high, varying between 19,550,000 and 600,000 grains g^{-1}. *Nothofagus dombeyi* type (9,370,000–226,000 grains g^{-1}) and *Drimys winteri* (250,800 grains g^{-1}) reach their maxima in this zone.

Zone IDE2-2 (45–5 cm; 400–~20 cal yr BP): this zone is characterized by low frequencies (14%) of *N. dombeyi* type, whereas *Empetrum*/Ericaceae reaches up to 80%, Asteraceae subf. Asteroideae and *Hymenophyllum* approach 9%. Other taxa such as *Misodendrum*, Poaceae, *Gunnera*, Asteraceae subf. Mutisieae, Cyperaceae and ferns are uncommon (<1%). Total pollen concentration abruptly decreases from 3,400,000 to 480,000 grains g^{-1}. The tree abundances display a noteworthy decline (260,000–60,000 grains g^{-1}), and *Empetrum*/Ericaceae type increases (1,330,000 grains g^{-1}) accompanied by Poaceae (7160 grains g^{-1}) and Asteraceae subf. Asteroideae (108,000 grains g^{-1}).

Zone IDE2-3 (5–0 cm; ~20 cal yr BP to the present): *N. dombeyi* type increases up to 70% and *Empetrum*/Ericaceae type decrease to 20%. *Misodendrum* is present with 9%. *Gunnera*, *Acaena*, *Astelia pumila* and ferns record low (<2%) values.

This zone records the lowest total concentration values (147,000 grains g^{-1}) throughout the profile.

Table 1
AMS ^{14}C dates and calibrated ages of selected samples from IDE-2 section, Bahía Franklin.

Sample	Depth (m)	^{14}C age (BP)	Cal age (BP) Median probability	Maximum 2σ BP	Minimum 2σ BP	$\delta^{13}C$ ‰	Sample material	Analysis no.
IDE1-6	0.30	86 ± 34	109	120	45	−26.4	peat	AA75287
IDE1-11	0.55	746 ± 34	654	719	563	−28.2	peat	AA75288
IDE1-15	0.70	3671 ± 38	3943	4084	3837	−26.4	peat	AA75291

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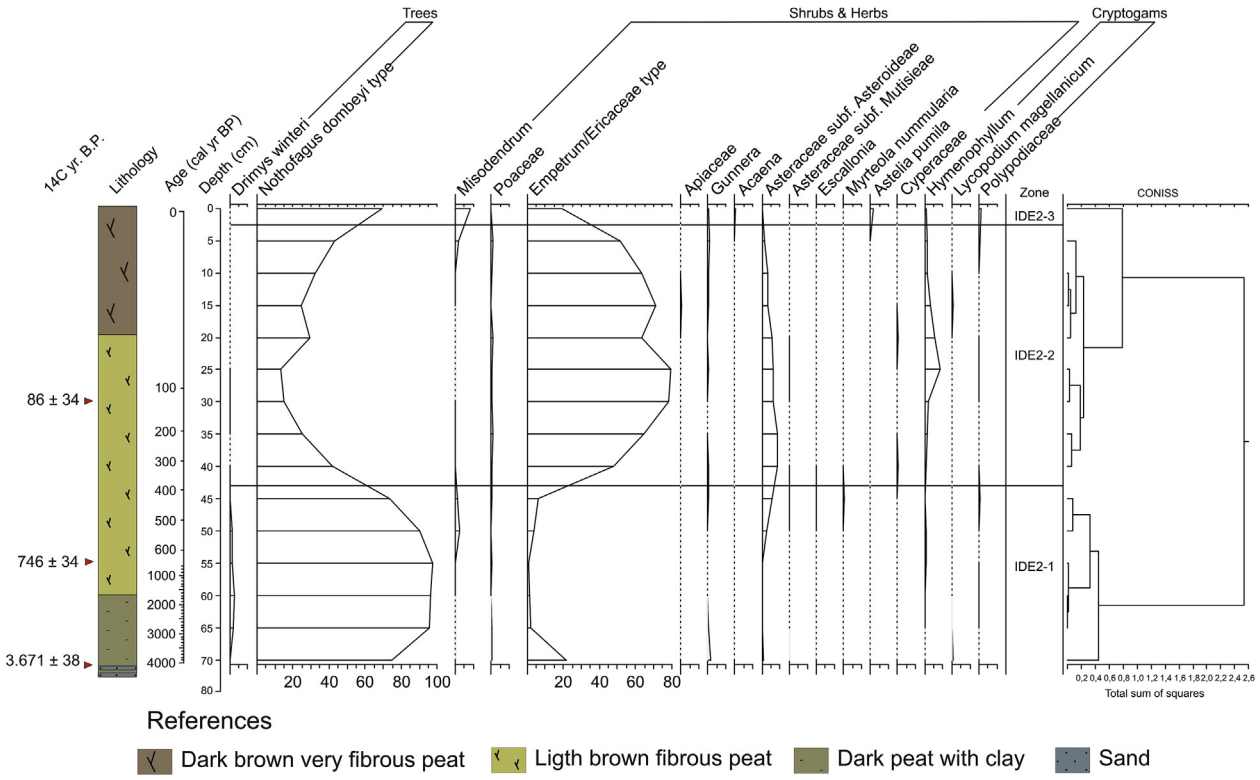

Fig. 4. Pollen/spore frequency (%) diagram, pollen zones based on cluster analysis and visual inspection, and lithology at IDE-2 section, Bahía Franklin.

5. Discussion

In this section, we discuss our interpretation of the pollen record from Isla de los Estados and its relation to late-Holocene vegetation change. After that, we discuss the climatic significance of major changes in *Nothofagus* and compare our own *Nothofagus* record to others from southernmost Patagonia. Finally, we evaluate regional records of *Nothofagus* against other climate proxies from the region to develop a multi-proxy record to assess the spatial coherence and amplitude of climate change events during the late-Holocene and LIA.

5.1. Vegetation history at IDE-2 section

The IDE-2 pollen record commences at about 4000 cal yr BP (Fig. 5) with low pollen concentrations of *Nothofagus* and *Drymis winteri* suggesting an open forest communities with an

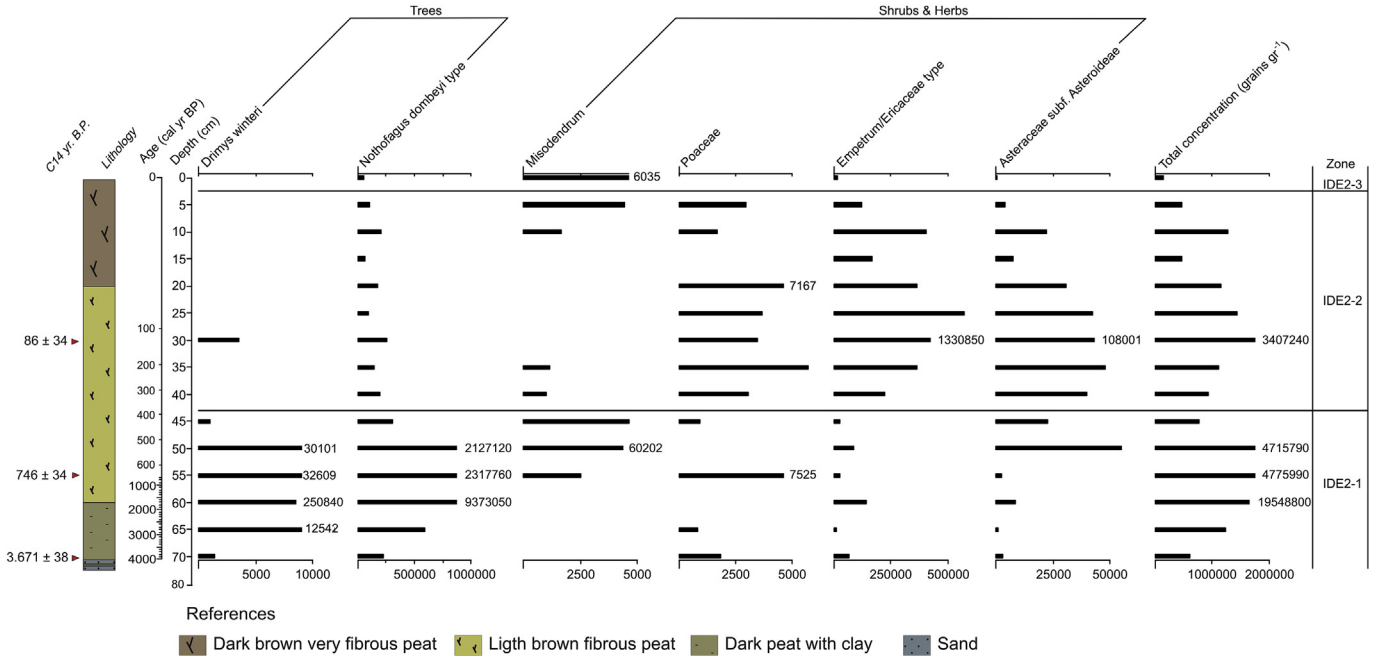

Fig. 5. Pollen concentration (grains g^{-1}) diagram at IDE-2 section, Bahía Franklin. Note the different scale among selected taxa.

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impoverished understory mainly represented by the presence of dwarf shrubs (*Empetrum*/Ericaceae type), scrubs (Asteraceae subf. Asteroideae) and grasses (Poaceae) (Fig. 6a). Afterward, the frequency and concentration values of the arboreal community increase notably. Between ~3500 and 500 cal yr BP, the pollen assemblage shows high concentration values of *Nothofagus* (possibly *N. betuloides*) in association with *Drimys winteri*, both of which are typical of Subantarctic Evergreen Forest communities (Pisano, 1977; Dudley and Crow, 1983) (Figs. 5 and 6b). These plant communities are common in the outer coastal zone of the Fuegian Archipelago where annual precipitation exceeds 700 mm (Tuhkanen, 1992). The margins and clearings of the forest are represented by dwarf shrubs (*Empetrum*/Ericaceae type, *Myrteola nummularia*), scrubs (Asteraceae subf. Asteroideae, *Escallonia*), herbs (Poaceae, *Gunnera*) and filmy ferns (*Hymenophyllum*) (Moore, 1983). After about 1000 cal yr BP *Nothofagus* and *Drimys winteri* concentrations start to decrease (Fig. 5), whereas *Misodendrum* concentrations abruptly increase and reaches a maxima at 550 cal yr BP implying that the forest was broadly infected by this hemiparasite.

Between about 500 and 50 cal yr BP, the decline in frequency and concentration of arboreal taxa along with expansion of dwarf-shrub heath (*Empetrum*/Ericaceae type), scrub (Asteraceae subf. Asteroideae) and grass (Poaceae) vegetation suggest a strong retraction of *Nothofagus*-dominated communities (Fig. 6c). The pollen assemblage resembles the *Empetrum rubrum* association, a subunit of the Magellanic moorland (Dudley and Crow, 1983). This association develops mainly in those areas of Isla de los Estados exposed to the fierce westerly gales and low temperatures (Moore, 1983). In these settings *N. betuloides* and *D. winteri* occur secondarily and are most widely scattered and have a much dwarfed and shrubby–scrubby habit. Filmy ferns (*Hymenophyllum*) are often present and form thick mounds around the lower branches of shrubby plants, especially *E. rubrum*, accompanied by herbs such as, *Gunnera* (Dudley and Crow, 1983). After 500 cal yr BP, the mistletoe *Misodendrum* steadily declines and eventually disappears. The presence of an open *Nothofagus* forest during the last 50 years is inferred by low *Nothofagus* frequency and concentration values (Figs. 5 and 6d). The pollen assemblage records cushion plants (*Astelia pumila*), herbs (*Gunnera*, *Acaena*) and ferns (*Hymenophyllum*, Polypodiaceae). The mistletoe *Misodendrum* is recorded again with high concentration values suggesting the local presence of *Nothofagus* communities.

5.2. *Nothofagus* and its relations to regional climate variability

Nothofagus is the most diverse and widespread tree genus in the Patagonian Andes forests, being the major constituent of these forests, between 33° and 56°S (Roig and Villalba, 2008). The spatial relationships between *Nothofagus* tree growth and climate show important variations in the relative importance of temperature and precipitation as environmental controls of tree radial growth (Lara et al., 2005). Which factors influences growth more, temperature or precipitation, appears to depend on the ecological characteristics of the forest environment (Roig and Villalba, 2008). Modern studies examining *Nothofagus* growth indicate that it is positively correlated with mean annual temperature in the southern latitudes under cooler climate with little seasonality in precipitation (Lara et al., 2005). Rapid changes in temperature regulate the start and conclusion of *Nothofagus* leaf phenological phases (Roig and Villalba, 2008).

5.2.1. Comparison with other pollen records

In Isla de los Estados, the peat bog section at IDE-2 (Fig. 1b and c) commences at 4000 cal yr BP with low percentage and concentration values of *Nothofagus* and *Drimys winteri*. The IDE-1 section (Fig. 1b and c) also contains low percentages and concentrations values of *Nothofagus* before 4000 cal yr BP (Ponce et al., 2011). *Nothofagus* minima are likewise present in the Galvarne Moraine Ridge (GMR) pollen section from the northern coast of Isla de los Estados (Fig. 1b) around 4000 cal yr BP (Björck et al., 2012). These pollen data imply unfavorable conditions for forest growth probably due to a less effective moisture under windy conditions. Nowadays, the southernmost headland of Isla de los Estados is the driest part of the island due to the influence of strong prevailing southwesterly to westerly winds. Here the evergreen forest communities are dwarfed and are almost entirely restricted to the ravines (Dudley and Crow, 1983).

Between 3500 and 1000 cal yr BP, the increase in frequency and concentration values of *Nothofagus* and *Drimys winteri* pollen in IDE-2 suggests the development of Evergreen Magellanic Forest communities. Between 4000 and 2700 cal yr BP, at IDE-1 section (Ponce et al., 2011), and between 4000 and 3000 cal yr BP at GMR section (Björck et al., 2012), *Nothofagus* also reached local maxima indicating dominance of rainforest communities. Taken together, these pollen data imply that the previous unfavorable conditions were soon followed by cool, wet and windless conditions that favored the development of hyper humid rainforest communities.

A substantial vegetation change is observed following 1000 cal yr BP at IDE-2 (this paper), IDE-1 (Ponce et al., 2011), and GMR (Björck et al., 2012) sections. These vegetation changes are inferred from decreases in the frequency and concentration values of *Nothofagus* pollen along with decline and/or absence of *Drimys winteri* pollen indicating the re-establishment of an open *Nothofagus* forest. Noticeable is the record of high concentration values of *Misodendrum* at IDE-2 section between ~700 and 550 cal yr BP. Today, the intensity of *Misodendrum* infestation depends upon light and host availability, being maximal under high luminosity conditions and intermediate *Nothofagus* densities (Moreno et al., 2014). The record of high values of *Misodendrum* at IDE-2 section was possibly caused by the increase in light availability when the closed-canopy rainforest communities started to decline after 1000 cal yr BP. In the IDE-1 pollen section was also reported a forest reduction between 1000 and 500 cal yr BP related to the Medieval Climate Anomaly (MCA, 1200–600 cal yr BP) (Ponce et al., 2011). In the Valle de Andorra (VA) site, about 10 km to the northeast of Ushuaia (Fig. 1a), evidence for drier and warmer conditions at a similar time as the MCA exist (Mauquoy et al., 2004).

In pollen sections IDE-2, IDE-1 and GMR, *Nothofagus* pollen reaches minimum values after about 500 cal yr BP. At IDE-2, dwarf shrub heath communities prevailed under cold and windy conditions. Noticeable, during this interval, is the decline and disappearance of the mistletoe *Misodendrum*. Nowadays, the mortality of mature mistletoes is frequently related to host and branch death. However, extreme climatic or disturbance events such as frosts, droughts or fire, may also cause the differential death of the mistletoe while hosts survive (Tercero-Bucardo and Kitzberger, 2004). We posit that climate deterioration coinciding with the onset of the LIA at about 500 cal yr BP, may have caused the decline in the *Misodendrum* pollen. The GMR section indicates drier conditions showing a notable decrease in the pollen-based wetness index values after ~900 cal yr BP, with lowest values during the last 500 yrs (Björck et al., 2012).

Fluctuations in the *Nothofagus* pollen record have been reported from central and southern Tierra del Fuego during the last millennium. In La Correntina (LCO) peat bog located in the southeastern coast of Lago Fagnano (Fig. 1a), the decline in frequency and concentration values of arboreal taxa along with increase in *Empetrum rubrum* and *Azorella* pollen by about 400 cal yr

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BP were indicative of a reduction of *Nothofagus* forest and a drier bog surface (Musotto et al., 2016). At Las Cotorras (LC) peat bog, a high Andean valley in proximity to the Beagle Channel (Fig. 1a), the arboreal pollen component reached a minima at about 400 cal yr BP (Borromei et al., 2010). Also, a period of cool, wet conditions between ca. 920 and 850 cal yr BP, and a later period of cooler/wetter conditions estimated at ca. 150–20 cal yr BP have likewise been recognized in the Valle de Andorra (VA) site (Mauquoy et al., 2004). In the Harberton section, located eastern Beagle Channel (Fig. 1a), Heusser (1989) also reported low *Nothofagus* pollen influx implying cooler episodes sometime prior to 380 cal yr BP.

5.2.2. Comparison of regional Nothofagus records with other climate proxies

Taking into account the dating uncertainties in the sediment records, we compare the regional *Nothofagus* pollen record from Bahía Franklin and those from the region (Fig. 1) to other late-Holocene climate proxies such as reconstructed sea surface temperature (SST) from the Beagle Channel, evidence of regional glacier fluctuations, and modeled changes in mean annual precipitation (Fig. 7).

The lack of high-resolution analyses in relation to LIA climatic changes in the Isla de los Estados and Tierra del Fuego makes interpretation of palaeotemperature still speculative in nature. However, both pollen (Mauquoy et al., 2004; Borromei et al., 2010; Ponce et al., 2011; Björck et al., 2012; Musotto et al., 2016), glacial geomorphology (Kuylenstierna et al., 1996; Strelin et al., 2008; Menounos et al., 2013), and seawater temperature (Obelic et al., 1998; Gordillo et al., 2015) proxies give us some evidence that during the LIA event, temperature varied both in the Isla de los Estados and Tierra del Fuego.

The Beagle Channel, is a fjord (estuarine) environment that was strongly affected by the fresh water discharge from neighboring glaciers during the late Holocene (Candel et al., 2016). The reconstruction of SST during the late-Holocene, based on $\delta^{18}O$ record from *Mytilus edulis* shells collected from archaeological sites along the Beagle Channel (Obelic et al., 1998), provide one proxy for SST variability. According to Strelin et al. (2008) times of cool SST during the late-Holocene promoted climatic conditions that favored the expansion of alpine glaciers in southern Tierra del Fuego.

In Isla de Estados the pollen data showed by about 4000 cal yr BP, low *Nothofagus* densities, a time when surface water in the Beagle Channel cooled. The seawater temperature of the channel was 1.5 °C below the present temperature value (Obelic et al., 1998). Between ca. 3500 and 2700 cal yr BP, the pollen records (Ponce et al., 2011; Björck et al., 2012) showed an increase in the *Nothofagus* input. A climate amelioration have been observed for the Beagle Channel with a seawater temperature increase shortly before 3000 yr BP (Obelic et al., 1998). In James Ross Island, Antarctica Peninsula, this warming occurred between ca. 3900 and 3000 cal yr BP (Strelin et al., 2005).

The Ema Glacier valley (Strelin et al., 2008), is located on the eastern slopes of Monte Sarmiento Massif, in Darwin Cordillera, 400 km to the west of Bahía Franklin (Fig. 1a).

Neoglacial advances have been reported from this glacier at ca. 3300 cal yr BP (Strelin et al., 2008), and also from Fiordo Pía (Kuylenstierna et al., 1996) about 75 km from east of Monte Sarmiento Massif. These neoglacial advances may coincide in Isla de los Estados with the abrupt decline in *Nothofagus* pollen observed in the IDE-1 section at 2700 cal yr BP (Ponce et al., 2011), and in the GMR pollen section between 3000 and 2000 cal yr BP (Björck et al., 2012). In central part of Tierra del Fuego, at La Correntina (LCO) peat bog, the closed-canopy *Nothofagus* forest was replaced by more open forest communities after 3000 cal yr BP (Musotto et al., 2016). During this time, the seawater temperature at the Beagle Channel showed a decreasing trend with colder temperatures of about 1 °C below the present mean value (Obelic et al., 1998). This cold event likely caused the new neoglacial advance in the Ema Glacier, as quoted above (Strelin et al., 2008).

In the tributary glacier valleys of Fuegian Andes, near Ushuaia (Fig. 1a), several moraine deposits related to a Holocene glacier expansion have been identified (Rabassa et al., 2000; Strelin et al.,

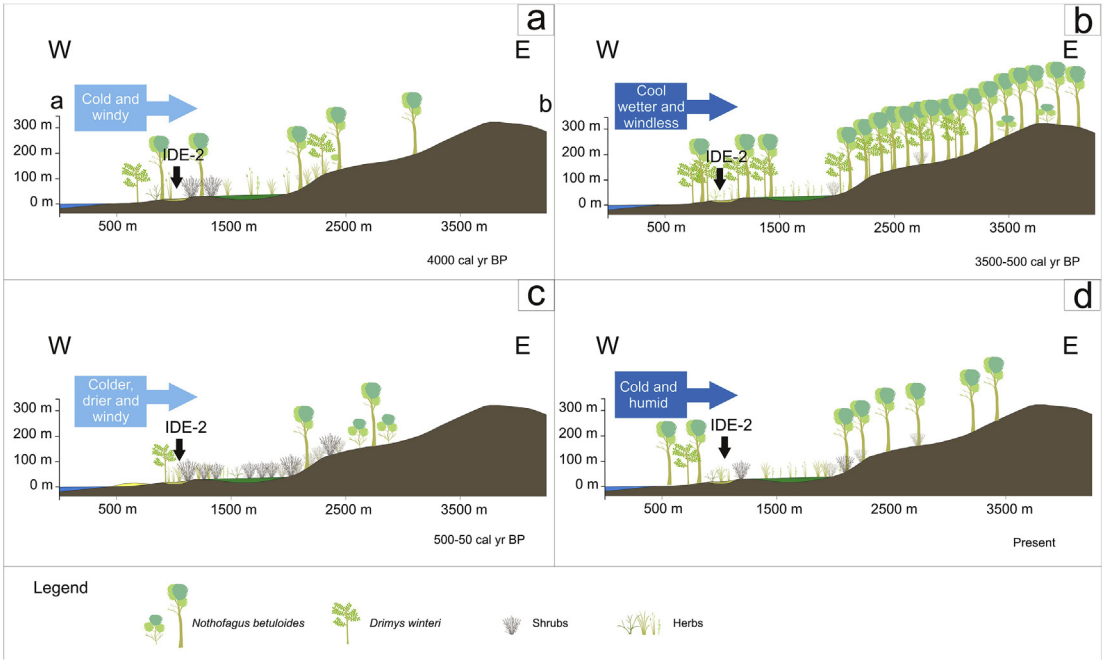

Fig. 6. Vegetation reconstruction based on the pollen record at IDE-2 site and the palaeoclimatic data mentioned in the text to the Bahía Franklin area.

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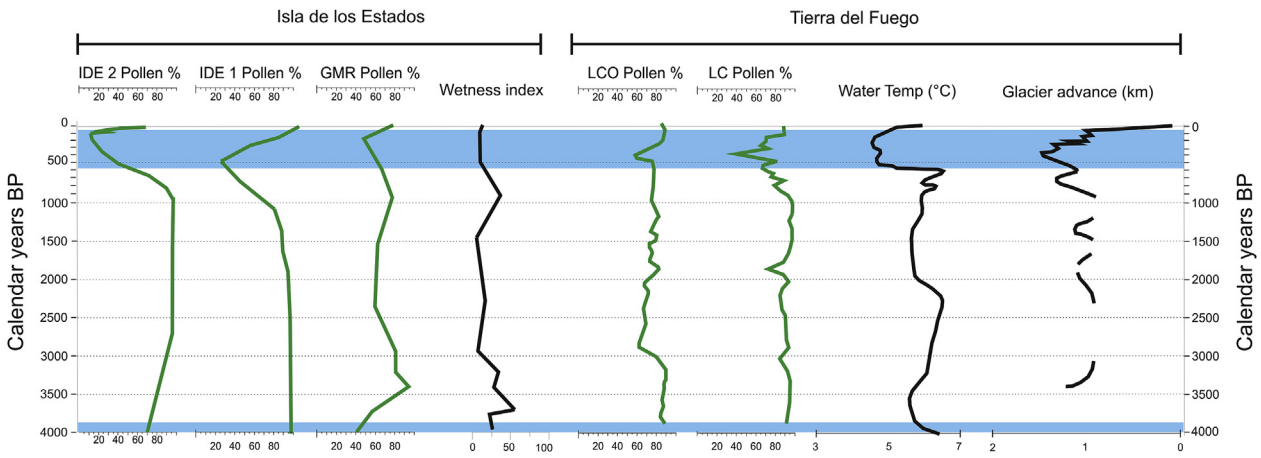

Fig. 7. Relationship between IDE-2 *Nothofagus* pollen data and other palaeoclimatological proxies. *Nothofagus* pollen records from: IDE-2 (this paper). IDE-1 (Ponce et al., 2011). GMR: Galvarne Moraine Ridge (Björck et al., 2012). Pollen-based wetness index values from Isla de los Estados (Björck et al., 2012). LCO: La Correntina (Musotto et al., 2016). LC: Las Cotorras (Borromei et al., 2010). Water palaeotemperature in the Beagle Channel (Obelic et al., 1998). Glacier advance phases from Ema Glacier valley (Monte Sarmiento Massif), Tierra del Fuego (Strelin et al., 2008). Blue bars indicate coldest conditions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2001; Planas et al., 2002; Menounos et al., 2013). Although no absolute ages are available, Menounos et al. (2013) identified the LIA moraines based on their fresh, non eroded form, proximity to existing ice, and similarity of their positions to moraines in the vicinity that previously have been assigned to the LIA (Strelin and Iturraspe, 2007; Strelin et al., 2008; Maurer et al., 2012). According to Menounos et al. (2013), the LIA event was the more extended neoglacial advance in the region. In contrast to these findings, Kuylenstierna et al. (1996) found no evidence for LIA glacier activity from Bahía Pía (Fig. 1a) on the southern side of the Cordillera Darwin (Tierra del Fuego), and noted that the maxima glacial activity have been radiocarbon dated to sometime before 3060 BP, prior to 940 BP, and between 940 and 675 BP. At the moment, only one geomorphological evidence of Holocene advances has been mentioned from Isla de los Estados by Ljung and Ponce (2006). These authors described a small frontal moraine located in San Juan del Salvamento at 390 m a.s.l. (Fig. 1b). The crest of the moraine ridge is partly barren, probably as a consequence of exposure. The authors assigned tentatively a Neoglacial age for this moraine.

However, some correspondence is observed between the Ema Glacier chronology of the last millennium and the *Nothofagus* pollen values in Isla de los Estados. The advances of Ema glacier centered at ~620 cal yr BP, and between ~390 cal yr BP and 60 cal yr BP coincide with the *Nothofagus* pollen minimum values between ~500 and ~50 (IDE-2), at ~500 (IDE-1), and between ~500 and ~50 (GMR) cal yrs BP. Minimum values of *Nothofagus* pollen have been also reported during this period, from La Correntina and Valle de Andorra peat bogs in Tierra del Fuego. This climate oscillation associated with the glacier advance and retreat that occurred in the Fuegian Andes, was clearly recorded by the seawater temperature proxy at the Beagle Channel (Obelic et al., 1998). The sclerochronological study of bivalve mollusks recovered from marine Holocene deposits along the Beagle Channel also indicated a cooling period at ca. 500 cal yr BP (Gordillo et al., 2015).

Other sedimentary records from southernmost Patagonia record climate deterioration during the last millennium. In a sediment core from Lago Fagnano (~54°S), for example, the LIA event was recognized by high iron content levels attributed to the intensification of the SWW and an increase in relative humidity (Waldmann et al., 2010). The authors observed that the high iron content values recorded in the Fagnano record, followed similar patterns in the oxygen isotope record from an ice-core in Antarctica (Steig et al., 1998) and in the iron content offshore from Chile at 41°S (Lamy et al., 2001).

6. Conclusions

The IDE-2 peat core showed low *Nothofagus* pollen concentration values by about 4000 cal yr BP, a time when surface water in the Beagle Channel cooled. Favorable climate conditions to forest growth were recorded between ca. 3500 and 1000 cal yr BP, with an increase in frequency and concentration values of *Nothofagus* and *Drimys winteri*. After that, the density in the forest communities started to decline reaching a minimum between ~500 and ~50 cal yr BP. The decrease in *Nothofagus* pollen concentration values coincides with the coolest surface water period in the Beagle Channel at least during the last 4000 yrs; it also broadly accords with two glacier advances recognized in the Ema Glacier valley at ~620 cal yr BP, and between ~390 cal yr BP and 60 cal yr BP. The decline in forest density in Isla de los Estados between about 500 and 50 yr cal BP could be a response to coldest and windiest conditions during LIA time.

The interpretation from our *Nothofagus* pollen record broadly agrees with regional cooling recorded in reconstructed SST of the Beagle Channel and with glacier expansion in the Fuegian Cordillera. Times of cool SST in Beagle Channel reflect coldest conditions that favored expansion of alpine glaciers and decline in forest density during the late-Holocene in southern Tierra del Fuego, especially during LIA time. These interpretations demonstrate that SST cooling in Beagle Channel could be response to atmospheric cooling.

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References

Björck, S., Rundgren, M., Ljung, K., Unkel, I., Wallin, A., 2012. Multi-proxy analysis of a peat bog on Isla de los Estados, easternmost Tierra del Fuego: a unique record of the variable Southern Hemisphere Westerlies since the last deglaciation. Quaternary Science Reviews 42, 1–14.

Borromei, A., Coronato, A., Lars, F., Ponce, J.F., López Sáez, J.A., Maidana, N., Rabassa, J., Candel, M.S., 2010. Multiproxy record of Holocene paleoenvironmental change, Tierra del Fuego, Argentina. Palaeogeography, Palaeoclimatology, Palaeoecology 286, 1–16.

Bradley, R.S., Jones, P.D., 1993. 'Little Ice Age' summer temperature variations: their nature and relevance to recent global warming trends. The Holocene 3 (4), 367–376.

Bronk Ramsey, C., Lee, S., 2013. Recent and planned developments of the program OxCal. Radiocarbon 55 (2–3), 720–730.

Cabrera, A.L., 1976. Regiones Fitogeográficas Argentinas. In: Kugler, W.F. (Ed.), Enciclopedia Argentina de Agricultura y Jardinería, Fascículo 1, Buenos Aires, segunda edición, tomo II, p. 85.

Candel, M.S., Louwye, S., Borromei, A.M., 2016. Reconstruction of the late Holocene paleoenvironment of the western Beagle Channel (Argentina) based on a palynological analysis. Quaternary International. http://dx.doi.org/10.1016/j.quaint.2016.01.074.

Chambers, F.M., Brain, S., Mauquoy, D., Mc Carroll, J., Daley, T., 2014. The 'Little Ice Age' in the Southern Hemisphere in the context of the last 3000 years: peat-based proxy-climate data from Tierra del Fuego. The Holocene 24 (12), 1649–1656.

Dudley, T.R., Crow, G.E., 1983. A contribution to the Flora and Vegetation of Isla de los Estados (Staaten Island), Tierra del Fuego, Argentina. In: American Geophysical Union, Antarctic Research Series, vol. 37, pp. 1–26.

Faegri, K., Iversen, J., 1989. Textbook of Pollen Analysis, fourth ed. John Willey and Sons, Copenhague, p. 328.

Gordillo, S., Brey, T., Beyer, K., Lomovasky, B.J., 2015. Climatic and environmental changes during the middle to late Holocene in southern South America: a sclerochronological approach using the bivalve Retro tapes exalbidus (Dillwyn) from the Beagle Channel. Quaternary International 377, 83–90.

Grimm, E., 2004. Tilia and TG View 2.0.2.Illinois State Museum. Research and Collection Center, Springfield, Illinois.

Heusser, C.J., 1989. Climate and chronology of Antarctica and adjacent South America over the past 30,000 yr. Palaeogeography, Palaeoclimatology, Palaeoecology 76, 31–37.

Heusser, C.J., 1998. Deglacial paleoclimate of the American sector of the Southern Ocean: late Glacial-Holocene records from the latitude of Beagle Channel (55 S), Argentine Tierra del Fuego. Palaeogeography, Palaeoclimatology, Palaeoecology 141, 277–301.

Heusser, C.J., 2003. Ice Age Southern Andes – a Chronicle of Paleoecological Events. In: Developments in Quaternary Science, vol. 3. Elsevier, Amsterdam, p. 240.

Hogg, A.G., Hua, Q., Blackwell, P.G., Buck, C.E., Guilderson, T.P., Heaton, T.J., Niu, M., Palmer, J.G., Reimer, P.J., Reimer, R.W., Turney, C.S.M., Zimmerman, S.R.H., 2013. SHCal13 Southern Hemisphere calibration, 0–50,000 years cal BP. Radiocarbon 55 (4), 1889–1903.

Jowsey, P.C., 1966. An improved peat sampler. New Phytologist 65, 245–248.

Kilian, R., Lamy, F., 2012. A review of glacial and Holocene paleoclimate records from southernmost Patagonia (49–55°S). Quaternary Science Reviews 53, 1–23.

Kuylenstierna, J.L., Rosqvist, G.C., Holmlund, P., 1996. Late-Holocene glacier variations in the Cordillera Darwin, Tierra del Fuego. The Holocene 6 (3), 353–358.

Lamy, F., Hebbeln, D., Röhl, U., Wefer, G., 2001. Holocene rainfall variability in southern Chile: a marine record of latitudinal shifts of the Southern Westerlies. Earth and Planetary Science Letters 185, 369–382.

Lara, A., Villalba, R., Wolodarsky-Franke, A., Aravena, J.C., Luckman, B., Cuq, E., 2005. Spatial and temporal variation in Nothofagus pumilio growth at tree line along its latitudinal range (35° 40′–55° S) in the Chilean Andes. Journal of Biogeography 32, 879–893.

Ljung, K., Ponce, J.F., 2006. Periglacial features on Isla de los Estados, Tierra del Fuego, Argentina. In: Actas I. III Congreso Argentino de Cuaternario y Geomorfología, pp. 85–90.

Llavallol, C.I., Cellini, J.M., 2006. Informe técnico: "Mapa de vegetación de la Isla de los Estados" Programa de Investigación Geográfico Político Patagónico. Instituto de Ciencias Políticas y Relaciones Internacionales; Grupo Ambiental Patagónico, Facultad de Ciencias Fisicomatemáticas e Ingeniería. UCA. 2 mapas + informe 17 pp.

Matthes, F., 1939. Report of committee on glaciers. Transactions American Geophysical Union 20, 518–523.

Mauquoy, D., Blaauw, M., van Geel, B., Borromei, A., Quattrocchio, M., Chambers, F.M., Possnert, G., 2004. Late Holocene climatic changes in Tierra del Fuego based on multiproxy analyses of peat deposits. Quaternary Research 61, 148–158.

Maurer, M., Menounos, B., Clague, J., Osborn, J., 2012. Patagonian glacier advances in concert with those in western North America. In: 45th Annual Fall Meeting of the American Geophysical Union. December 3–7, 2012. San Francisco, California.

Menounos, B., Clague, J., Osborn, G., Ponce, J.F., Davis, P.T., Goehring, B., Maurer, M., Rabassa, J., Coronato, A., Maar, R., 2013. Latest Pleistocene and Holocene Glacier Fluctuations in southernmost Tierra del Fuego, Argentina. Quaternary Science Reviews 77, 70–79.

Moore, D.M., 1983. Flora of Tierra del Fuego. Nelson, Oswestry, p. 396.

Moreno, P.I., Vilanova, I., Villa-Martínez, R., Garreaud, R.D., Rojas, M., De Pol-Holz, R., 2014. Southern annular mode-like changes in southwestern Patagonia at centennial timescales over the last three millennia. Nature Communications 5, 4375.

Moy, C.M., Moreno, P.I., Dunbar, R.B., Kaplan, M.R., Francois, J.P., Villalba, R., Haberzettl, T., 2009. Climate Change in Southern South America During the Last Two Millennia. In: Past Climate Variability in South America and Surrounding Regions, vol. 14, pp. 353–393.

Musotto, L.L., Borromei, A.M., Coronato, A., Menounos, B., Osborn, G., Marr, R., 2016. Late Pleistocene and Holocene palaeoenvironmental changes in central Tierra del Fuego (~54°S) inferred from pollen analysis. Vegetation History and Archaeobotany 25 (2), 117–130.

Neukom, R., Gergis, J., Karoly, D.J., Wanner, H., Curran, M., Elbert, J., González-Rouco, F., Linsley, K., Moy, A., Mundo, I., Raible, C., Steig, E., Ommen, T., Vance, T., Villalba, R., Zinke, J., Frank, D., 2014. Inter-hemispheric temperature variability over the past millennium. Nature Climate Change 4 (5), 362–367.

Niekisch, M., Schiavini, A., 1998. Desarrollo y conservación de la Isla de los Estados (unpublished report). CADIC, Ushuaia, p. 70.

Obelic, B., Álvarez, A., Argullós, J., Piana, E., 1998. Determination of water paleotemperature in the Beagle Channel (Argentina) during the last 6000 yr through stable isotope composition of Mytilusedulis shells. Quaternary of South America and Antarctic Peninsula 11, 47–71.

Pisano, V.E., 1977. Fitogeografía de Fuego-Patagonia chilena. I. Comunidades vegetales entre las latitudes 52 y 56° S. In: Anales del Instituto de la Patagonia, vol. 8, pp. 121–250. Punta Arenas, Chile.

Planas, X., Ponsa, A., Coronato, A., Rabassa, J., 2002. Geomorphological evidence of different glacial stages in the Martial cirque, Fuegian Andes, southernmost South America. Quaternary International 87, 19–27.

Ponce, J.F., Borromei, A.M., Rabassa, J., Martínez, O., 2011. Late Quaternary palaeoenvironmental change in western Staaten Island (54.5°S, 64°W), Fuegian Archipelago. Quaternary International 233, 89–100.

Rabassa, J., Coronato, A., Bujalesky, G., Salemme, M., Roig, C., Meglioli, A., Heusser, C., Gordillo, S., Roig, F., Borromei, A., Quattrocchio, M., 2000. Quaternary of Tierra del Fuego, Southernmost South America: an updated review. Quaternary International 68–71, 217–240.

Roig, F.A., Villalba, R., 2008. Understanding climate from Patagonian tree rings. In: Rabassa, J. (Ed.), Late Cenozoic of Patagonia and Tierra del Fuego, Developments in Quaternary Sciences, vol. 11. Elsevier, Amsterdam, pp. 411–436.

Steig, E.J., Brook, E.J., White, J.W.C., Sucher, C.M., Bender, M.L., Lehman, S.J., Morse, D.L., Waddington, E.D., Clow, G.D., 1998. Synchronous climate changes in Antarctica and the North Atlantic. Science 282, 92–95.

Stockmarr, J., 1971. Tablets with spore used in absolute pollen analysis. Pollen et Spores 13, 615–621.

Strelin, J., Iturraspe, R., 2007. Recent evolution and mass balance of Cordón Martial glaciers, Cordillera Fueguian Oriental. Global and Planetary Change 59, 17–26.

Strelin, J., Casassa, G., Rosqvist, G., Holmlund, P., 2001. Glaciaciones Holocénicas en el valle del glaciar Ema, monte Sarmiento, Tierra del Fuego. In: Abstract symposium: Cambios vegetacionales y climáticos durante el último ciclo glacial–interglacial a lo largo de Chile continental. La Serena, Chile.

Strelin, J., Casassa, G., Rosqvist, G., Holmlund, P., 2008. Holocene glaciations in the Ema Glacier valley, Monte Sarmiento Massif, Tierra del Fuego. Palaeogeography, Palaeoclimatology, Palaeoecology 260, 299–314.

Strelin, J.A., Sone, T., Mori, J., Torielli, C.A., Nakamura, T., 2005. New data related to Holocene landform development and climatic change from James Ross Island, Antarctic Peninsula. In: Fütterer, D.K., Damaske, D., Kleinschmidt, G., Miller, H., Tessensohn, F. (Eds.), Antarctica: Contributions to Global Earth Sciences. Springer-Verlag, Berlin, Heidelberg, and New York, pp. 453–458.

Stuiver, M., Reimer, P.J., Reimer, R.W., 2014. Calib 7.0. http://calib.qub.ac.uk/calib/.

Tercero-Bucardo, N., Kitzberger, T., 2004. Establishment and life history characteristics of the southern South American mistletoe Misodendrum punctulatum (Misodendraceae). Revista Chilena de Historia Natural 77, 509–521.

Tuhkanen, S., 1992. The climate of Tierra del Fuego from a vegetation geographical point of view and its ecoclimatic counterparts elsewhere. Acta Botanica Fennica 125, 4–17.

Waldmann, N., Ariztegui, D., Anselmetti, F.S., Austin Jr., J.A., Moy, C.M., Stern, C., Recasens, C., Dunbar, R.B., 2010. Holocene climatic fluctuations and positioning of the Southern Hemisphere Westerlies in Tierra del Fuego (54° S), Patagonia. Journal of Quaternary Science 25, 1063–1075.

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