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Investigating late Holocene variations in hydroclimate and the stable isotope composition of precipitation using southern South American peatlands: a hypothesis

T. J. Daley[1], **D. Mauquoy**[2], **and F. M. Chambers**[3]

[1]School of Geography, Earth and Environmental Sciences, Plymouth University, Drake Circus, Plymouth, PL4 8AA, UK
[2]School of Geosciences, University of Aberdeen, Elphinstone Road, Aberdeen, AB24 3UF, UK
[3]Centre for Environmental Change and Quaternary Research, School of Natural and Social Sciences, Francis Close Hall, University of Gloucestershire, Cheltenham, GL50 4AZ, UK

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Correspondence to: T. J. Daley (tim.daley@plymouth.ac.uk)

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Abstract

Ombrotrophic raised peatlands provide an ideal archive for integrating late Holocene records of variations in hydroclimate and the estimated stable isotope composition of precipitation with recent instrumental measurements. Modern measurements of mean monthly surface air temperature, precipitation and δD and δ^{18}O values in precipitation from the late twentieth and early twenty-first centuries provide a short but invaluable record with which to investigate modern relationships between these variables, thereby enabling improved interpretation of the peatland palaeodata. Data from two stations in the Global Network for Isotopes in Precipitation (GNIP) from Tierra del Fuego (Punta Arenas, Chile and Ushuaia, Argentina) were analysed for the period 1982 to 2008. In both locations, δD and δ^{18}O values have decreased in response to quite different trends in local surface air temperature and total precipitation amount. At Ushuaia, the fall in δ^{18}O values is associated with an increase in the mean annual amount of precipitation. At Punta Arenas, the fall in δ^{18}O values is weakly associated with decrease in the precipitation amount and an increase in local temperatures. The pattern in both records is consistent with an increase in the zonal intensity of the southern westerly wind belt. These regional differences, observed in response to a known driver, should be detectable in peatland sites close to the GNIP stations. There is currently insufficient availability of suitably temporally resolved data to test for these regional differences over the last 3000 yr. Existing peatland palaeoclimate data from two sites near Ushuaia, however, provide evidence for changes in the late Holocene that are consistent with the pattern observed in modern observations. Furthermore, the records suggest synchroneity in millennial-scale oscillations between the Northern and Southern Hemispheres.

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1 Introduction

1.1 A role for peatland palaeoclimate studies in southern South America

The strength and location of mid-latitude westerly weather systems are essential determinants of regional climate in both the Northern and Southern Hemispheres. Recently demonstrated linkage between changing Arctic sea-ice cover, the spatial variability of the northern polar jet and consequent intra-annual temperature and precipitation variability (Petoukhov and Semenov, 2010) implies that improved understanding of the long-term variability of the westerlies is a critical research priority with socio-economic importance. The modern climatology of the Southern Hemisphere (SH) westerlies is well-constrained both in terms of their strength and location (Garreaud, 2009; Garreaud et al., 2009). There is clear linkage between near-surface (850 hPa) zonal wind strength and precipitation amount (Garreaud, 2007; Garreaud et al., 2009). Of particular interest is the evidence that the mean annual latitude of the SH westerlies has changed through the late 20th and early 21st centuries (Thompson and Solomon, 2002; Marshall, 2003). The latitude of maximum 300 hPa zonal wind velocity through the period 1968–2001 has shifted southwards with reduced wind speeds observed between 35–55° S and increased wind speeds observed between 55–70° S (Garreaud, 2007; Garreaud et al., 2009). The southerly shift in the westerlies has been observed to have been associated with a trend towards an increase in the positive phase of the southern annular mode (SAM) (Kidson, 1999; Gong and Wang, 1999; Limpasuvan and Hartmann, 1999; Marshall, 2003; Jones et al., 2009). The SAM is a principal mode of variability in the atmospheric circulation of the Southern Hemisphere related to synchronous anomalies in the surface air pressure over Antarctica and the southern mid-latitudes (Gong and Wang, 1999; Marshall, 2003). Ocean carbon models indicate that SH climate variability, and indeed that linked to variations in the SAM, may significantly influence the ocean carbon cycle and CO_2 air-sea fluxes in temperate and high latitudes (Le Quéré et al., 2007). Whilst it has been suggested that this latitudinal shifting of the westerlies is possibly related to greenhouse gas accumulation in the

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atmosphere and/or ozone depletion (Thompson and Solomon, 2002; Toggweiler and Russell, 2008), variations in SH sea-ice extent (Kidston et al., 2011) or solar forcing on longer timescales (Varma et al., 2011), there remains confusion over the effect of this shifting pattern on atmospheric carbon drawdown by the Southern Ocean (Le Quéré et al., 2007).

Improved understanding of the drivers of variability in the strength and position of the SH westerlies necessarily relies on robust, synchronised, well-calibrated and continuous longer-term datasets. However, longer-term (centennial to millennial-scale) proxy-records of variability in these parameters are scarce. Only three high temporal resolution proxy-climate records are available for southern South America between 20° S and 55° S, with the longest record spanning only ~780 yr (Neukom et al., 2011). Ice core and dendroclimatological data offer excellent and well-dated records for the recent past, but existing Andean ice core records for southern Patagonia/Tierra del Fuego only go back to AD 1965 (Vimeux et al., 2009) Similarly, the longest currently available dendroclimatological reconstruction for the region starts at AD 1650 (Boninsegna et al., 2009). Relatively new lake core records have begun to extend these reconstructions further (Moy et al., 2008; Moreno et al., 2009), but there remains a pressing need to link the instrumental record appropriately with a widely distributed, accurately dated, continuous and longer term palaeoarchive to test the timing and direction of climatic responses at multi-decadal to centennial timescales.

Peatlands can provide that missing link (Chambers et al., 2012). Raised bog hydrology is particularly sensitive to the length of the summer water deficit (Charman, 2007; Charman et al., 2009). Peatlands respond to changes in meteoric conditions through the effect of the atmospheric moisture balance ($P-E$) on their water table depths (Barber and Langdon, 2007; Charman, 2007; Charman et al., 2009). Southern South American peatlands, therefore, are perfectly placed to record long-term changes in the SH westerlies, given that wind intensity affects precipitation mainly produced in winter by fronts and low-pressure systems embedded in the prevailing westerly circulation (Rojas et al., 2009). The Island of Tierra del Fuego, in particular, is situated in

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the core path of the southern westerlies during the Austral summer and is well-suited for studies of past variability in their intensity. The peatlands of Tierra del Fuego can provide high-resolution records of past climate. High vertical accumulation rates of organic matter have been recorded of ~5–10 $yr\,cm^{-1}$ (Pendall et al., 2001; Mauquoy et al., 2004; Chambers et al., 2007), providing sub-decadal records of environmental change over multi-millennial timescales. This accumulation rate naturally filters out high-frequency components ("noise") that can afflict annual climate archives such as ice cores and tree-rings (cf. Ciais et al., 1994; Jones et al., 1998). Furthermore, the records are continuous and overlap with the period of the instrumental record, enabling the vital comparison of palaeodata with meteorological observations. The suitability of peatlands is further demonstrated by their wide range of proxy indicators. In addition to the reconstruction of palaeohydrology, the southern South American peat archives have provided data on regional vegetation changes (Markgraf, 1993), fire regimes (Huber et al., 2004), pollution loading (Biester et al., 2002; Martínez Cortizas et al., 2007), dust loading (Sapkota et al., 2007) and explosive volcanism (Kilian et al., 2003).

1.2 The nature of peatlands in Tierra del Fuego

Much of our systematic understanding of the palaeoclimate information that can be drawn from these archives has been derived from studies of European and North American peat systems (Barber et al., 1994; van Geel and Renssen, 1998; Hughes et al., 2006; Charman, 2007). Fortunately then, we observe that the microrelief elements (hummocks, lawns, and hollows) of the raised *Sphagnum* bogs in Tierra del Fuego resemble European and North American examples. The range of pH values recorded from pool microforms in these bogs (pH 4.3–4.6) is also consistent with those recorded from Northern Hemisphere *Sphagnum* raised bogs (Mataloni, 1998). The largest area in South America in which these ombrotrophic peat bogs, dominated by *Sphagnum magellanicum* with *Empetrum rubrum, Carex magellanica, Gunnera magellanica, Marsippospermum grandiflorum, Pernettya pumila*, and *Tetroncium magellanicum* are found, coincides with the distribution of *Nothofagus pumilio* (lenga) deciduous forests, which receive an annual precipitation of ∼400–800 mm (Roig et al., 1996). Raised *Sphagnum* bogs, dominated by *Sphagnum magellanicum* with *Donatia fascicularis, Oreobolus obtusangulus, Schoenus andinus*, and *Senecio trifurcates* occur in the Evergreen Forest zone (*Nothofagus betuloides*) to the south and west of Tierra del Fuego (annual precipitation up to ∼4000 mm). Two *Sphagnum* raised bogs ∼30 km from Ushuaia, Isla Grande, Tierra del Fuego, have been described by Mark et al. (1995). Their surfaces can be raised 4–6 m above the surrounding land surface, and the niche of *Empetrum rubrum* resembles its Northern Hemisphere equivalent, *Empetrum nigrum*, in that it is restricted to drier (hummock) microforms. Shrubs of *Nothofagus antarctica* (nirre) and the rush *Marsippospermum grandiflorum* characterize the crests of hummocks. There are pools 3–60 m long which are generally arranged in parallel crescentic lines and are similar to mires in southern New Zealand. Fringing these pools, *Sphagnum fimbriatum* has been recorded. There is a lower diversity of *Sphagnum* species in Fuegian bogs compared to European and North American peat bogs, and their surfaces can be entirely covered by *Sphagnum magellanicum*, extending from high hummocks (which can exceed 1 m in height) to pool margins. The wide range of water table depths *Sphagnum magellanicum* occupies in Tierra del Fuego bogs is similar to the broad habitat niche it displays in Northern Hemisphere peatlands.

1.3 An ideal archive for combined hydroclimate and water isotope analysis

Whilst this dominance by a single, relatively hydrologically insensitive *Sphagnum* species may prove problematic for a palaeoclimate investigation by plant macrofossil analysis, it provides the ideal opportunity for *Sphagnum* cellulose stable isotope analysis (Pendall et al., 2001; Chambers et al., 2007). It was isotopic investigation that was initially pioneered in the 1990s in exploration of southern South American peat archives (White et al., 1994; Pendall et al., 2001), later followed by hydroclimatic studies (van Geel et al., 2000; Mauquoy et al., 2004; Chambers et al., 2007). Early work on peatland stable isotopes in bulk samples from NW European sites discovered very large amplitude variations in measured isotope values (Brenninkmeijer et al., 1982; Dupont

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and Brenninkmeijer, 1984; van Geel and Middeldorp, 1988). This arose, in part, as a result of the sampling of both vascular and non-vascular plant species. The different internal water transport mechanisms in these groups of flora produce two quite separate populations of isotope data (Brenninkmeijer et al., 1982; Ménot-Combes et al., 2002). The noise, then, of variations in the abundance of vascular to non-vascular species through these records masked the more subtle changes in the source water isotope signal. The dominance of *Sphagnum magellanicum* in Tierra del Fuego, however, allowed for the isolation of *Sphagnum* and the first genus-specific records to be published (White et al., 1994; Pendall et al., 2001). For the earliest of these pioneers, the sample sizes required for stable isotope measurement were large (~5 g) inevitably resulting in the use of large samples of bulk peat. Recent advances in the use of continuous flow isotope ratio mass-spectrometry have made it possible to generate a value for δD and $\delta^{18}O$ simultaneously via online equilibration (Filot et al., 2006; Loader et al., 2007) on samples that are 0.3–0.35 mg in dry weight. Analysis of the cellulose in preserved subfossil *Sphagnum* remains has recently been demonstrated to provide reconstructions of the past isotopic composition of precipitation (Daley et al., 2009, 2010). So, understanding of the modern *Sphagnum* isotope system and analytical technology are both now sufficiently advanced for the development of new high-resolution palaeoclimate records for southern South America.

Recent work from North American and NW European peatlands has indicated a clear linkage between mid- to late Holocene hydroclimatic variations and changes in the estimated isotopic composition of precipitation (Daley et al., 2009, 2010). However, the topography and climatology of Tierra del Fuego is quite different to these examples. It is reasonable to hypothesise that, in a region where the climatology is so strongly affected by changes in precipitation patterns, spatial variations in bog surface wetness (BSW) and the isotopic composition of the precipitation source water over time should reflect changes in the SH westerly wind belt. So, where increased zonal flow at 850 Hpa in the late twentieth and early twenty-first centuries has led to an observed amplification of the rain shadow effect of the Andes in the mid-latitudes

(Garreaud, 2007, 2009), there should also be an identifiable gradient in the oxygen and hydrogen isotopic values in precipitation (meteoric waters). Here we investigate the isotopic signature of this observed variation using data from the GNIP database. We use these data to derive hypotheses for how past changes in the wind belt would be reflected in the peatland archive if the same mechanisms were operational. We subsequently test these hypotheses against a synthesis of the current set of peatland-based palaeohydrological and palaeo-isotope records from Tierra del Fuego that cover the last ~3000 yr. Comparisons are also made against recent palaeohydrological and palaeo-isotope data from a peatland in northern England.

2 The importance of δp in climatology

Records of past changes in the isotopic composition of precipitation (palaeo-δp) are rarely either simple palaeothermometers or palaeo-rain gauges (Araguás-Araguás et al., 2000; Daley et al., 2010, 2011). Rather, they are primarily indicators of changes in the rain-out history of air masses (Cole et al., 1999; Araguás-Araguás et al., 2000). The isotopic composition of precipitation (δp) is controlled by isotopic fractionation processes during the movement of water molecules through the hydrological cycle (Dansgaard, 1964). So, the labelling of the precipitation actually reflects complex variability in the hydrological system that includes changes in the conditions of the ocean surface from which the moisture was originally derived, the stable isotope composition of the ocean surface, the seasonality of precipitation and potential evaporation effects as well as the condensation temperature of precipitation (Siegenthaler and Oeschger, 1980; Rozanski et al., 1992, 1993; Jouzel et al., 1997; Cole et al., 1999; Araguás-Araguás et al., 2000; Darling and Talbot, 2003). There is good evidence that δp and temperature are closely associated at high latitudes (Leuenberger et al., 1999; Jouzel et al., 2000, 2007). Towards lower latitudes that correlation becomes weaker (Araguás-Araguás et al., 2000). The coastal regions of the northern mid-latitudes of both Europe and North America experience an annual variation in $\delta^{18}Op$ (e.g. ~15 ‰

at Truro, Nova Scotia and Cuxhaven, northern Germany) (IAEA/WMO, 2004) in response to a variety of factors including variations in moisture source, temperature of atmospheric condensation and amount of rainfall (Rozanski et al., 1993; Darling and Talbot, 2003). The equivalent latitudes in southern South America experience a similar amplitude of variability in $\delta^{18}Op$ (e.g. ∼10 ‰ per year from Ushuaia and ∼20 ‰ per year from Punta Arenas) (IAEA/WMO, 2004), but a noticeably narrower range in annual temperature (∼30 °C, Truro, Nova Scotia and ∼20 °C at Cuxhaven versus ∼10 °C at Ushuaia) (IAEA/WMO, 2004), implying, perhaps, a more direct linkage with mean moisture source and amount of precipitation. It would be wrong, however, to suggest that records of palaeo-δp in southern South America could be converted to a single meteorological variable (Schmidt et al., 2007). The greatest benefit of the ability to estimate palaeo-δp is that the amplitude of variation is directly related to physically based fractionation mechanisms which can be modelled numerically (Jouzel et al., 2000; LeGrande et al., 2006; Tindall et al., 2009; Tindall and Valdes, 2011). There is therefore the potential for data-model comparison with records of palaeo-δp that avoid uncertainties with any conversion of those data to meteorological variables (Schmidt et al., 2007).

3 Modern variation in the isotopic composition of precipitation (δp) and meteorological parameters

The region of southern South America is reasonably well-covered by stations that have recorded the isotopic composition of precipitation since the late twentieth century. The data from these stations are available via the Global Network for Isotopes in Precipitation (GNIP) database (IAEA/WMO, 2004). All data from this database were collected and archived according to IAEA standard protocols. We have focused our analysis of these modern records on those sites that fall within the same latitudinal and longitudinal ranges as those peatlands that are suitable for palaeoclimate investigation. Additionally, we have selected those sites that exist within the climate space whose meteorological conditions are strongly associated with variations in the southern annular

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mode. Two records are available of sufficient length to be able to cover at least decadal-scale variation: Punta Arenas, Chile (53°0′ S, 70°30′ W, 37 m a.s.l.; 1990–2008) and Ushuaia, Argentina, (54°46′ S, 68°16′ W, 10 m a.s.l.; 1982–2002). A record from Stanley on the Falklands Islands (Las Malvinas) is available but is restricted to measurements from the 1960s only. From the raw monthly measured values for δD and δ^{18}O in precipitation and from the associated total monthly precipitation in any month, we have calculated the amount-weighted annual isotope value for δD and δ^{18}O for each year for which data are available from the two sites. It is our contention, in the absence of more detailed measurements of growth rate in *Sphagnum* mosses, that this represents a reasonable estimation of the isotopic value of the precipitation source water that would have been "sampled" by *Sphagnum* moss growing contemporaneously. This is valid given (1) that empirical evidence has demonstrated that *Sphagnum* mosses, under sufficiently humid conditions, will continue to grow at mean temperatures in excess of ∼4 °C (Clymo and Hayward, 1982; Clymo, 1984), (2) that the mean monthly temperature for both Punta Arenas and Ushuaia exceeds 4 °C for much of the year and (3) that evidence for continuous annually accumulating growth has been observed previously in oxygen isotopic data from living *Sphagnum* from an oceanic peat bog in NW Europe (Daley et al., 2010), where conditions are similar to those in the locations selected here.

Bi-plots of measured monthly δD and δ^{18}O values in precipitation during the 1980s through to the early 2000s are presented for Punta Arenas and Ushuaia in Fig. 1. Also presented are monthly surface air temperature and precipitation values in relation to the oxygen isotopic composition of precipitation. It should be noted that there is no evidence for an obvious linear relationship between precipitation or temperature and $\delta^{18}O_{\text{precipitaiton}}$ values at either of the sites (Fig. 1), confirming the complexity of the precipitation isotope signal in this region.

The Global Meteoric Water Line (GMWL; Craig, 1961) relates measured values of δD and δ^{18}O in meteoric waters on a global scale. The line for the GMWL is $\delta D = 8(\delta^{18}\text{O}) + 10$. Deviations in measured waters from this line can be used to infer information about the environmental processes that acted to "label" those waters. For both Punta Arenas and Ushuaia, it is evident that the δD and $\delta^{18}O$ values in precipitation in the 1980s and 1990s have plotted on gradients of 5.7 (Punta Arenas) and 6.4 (Ushuaia) (Fig. 1), significantly lower than that of the GMWL. It should also be noted that the deuterium excess (the value for the intercept of the y-axis; d) for both these sets of data is remarkably low (−20, −14, respectively). Separation of the data by season (Fig. 1) indicates that the gradient of the local MWL at both locations changes throughout the year. Precipitation in austral summer falls along a low gradient (5.3 at Punta Arenas, 6.7 at Ushuaia). During the winter months, these gradients are closer to the GMWL. Precipitation at Punta Arenas in austral winter is, in fact, steeper than the GMWL (9.0). Interestingly, the deuterium excess for the austral winter rainfall is −16 at Punta Arenas and +22 at Ushuaia (Fig. 1). The low overall deuterium excess at Ushuaia results from the influence of the austral summer precipitation.

Whilst the summer precipitation curves for both Punta Arenas and Ushuaia exhibit characteristics similar to those observed when the measured waters fall on a local evaporative line, we must discount that possibility as these were measured on meteoric waters, recorded according to IAEA guidelines. Deuterium excess variations are recognised to relate most strongly to variations in conditions at the moisture source site (Dansgaard, 1964; Gat, 1980; Rozanski et al., 1993). A deuterium excess of +22 (observed during the winter months at Ushuaia, here) is characteristic of moisture sourcing via oceanic evaporation in a relatively low humidity environment. Similarly, d from summer precipitation (Fig. 1) indicates a moisture source that was considerably more humid. The most rational explanation for the variations in these modern data, then, is that annual precipitation in the last ~20 yr has been sourced from very different oceanic sources through the course of the year. For this region, then, the MWL is distorted relative to the GMWL by the influence of two quite different end members for moisture source region. The implications for the reconstruction of the palaeo-MWL from combined δD and $\delta^{18}O$ values from peatland *Sphagnum* cellulose are that, where sufficiently resolved records can be derived, a lower gradient in the reconstructed palaeo-MWL should not be unexpected if the isotopic composition of precipitation in the last ~20 yr provides a good analogue for changes in the late Holocene. Previously, it might well have been argued that such a gradient in the *Sphagnum* cellulose isotope data would indicate that there had been isotopic enrichment by kinetic fractionation (evaporation) of the moss source water before incorporation into the plant via photosynthesis. Now, we should recognise that, for this region, a gradient in the palaeo-MWL of <7 would be consistent with modern measurements of meteoric waters.

Figure 2 shows the amount-weighted average annual δD and $\delta^{18}O$ values for both GNIP locations (Punta Arenas, Fig. 2c and Ushuaia, Fig. 2f) along with variation in the total annual precipitation (Fig. 2b and e) and mean annual surface air temperature (Fig. 2a and d) over time. Several relationships stand out in these data. First, through the period of the 1980s to the early twenty-first century, $\delta^{18}O_{precipitaiton}$ values at Punta Arenas and Ushuaia have decreased. The amplitude of the decrease and its statistical significance (shown by the 95 % confidence limits) is greater at Ushuaia (Fig. 2f) than at Punta Arenas (Fig. 2c). Secondly, associated with these falls in $\delta^{18}O_{precipitaiton}$ values, total annual precipitation has increased at Ushuaia (Fig. 2e) but has fallen at Punta Arenas (Fig. 2b), indicating that the amount of precipitation is not a consistent driver of the isotopic composition of precipitation at these two locations. Thirdly, associated with the falls in $\delta^{18}O_{precipitaiton}$ values, surface air temperatures have largely oscillated around the mean with no obvious trend at Ushuaia (Fig. 2d), but show some evidence for having increased at Punta Arenas (Fig. 2a).

The fall in $\delta^{18}O_{precipitaiton}$ values with increasing amounts of precipitation observed at Ushuaia is consistent with what would be expected if annual temperature variability was relatively low, the seasonality of that precipitation had not changed and there was minimal change in the isotopic composition of the surface ocean and the conditions at the site of moisture sourcing. Indeed, the record from Ushuaia exhibits a structure similar to records from lower latitudes., The linkage between rising total amounts of precipitation and lower $\delta^{18}O_{precipitaiton}$ values is consistent with the literature (Gat, 1980; Rozanski et al., 1993; Araguás-Araguás et al., 2000).

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The records from Punta Arenas are more complex but may be explained by consideration of the interaction of increased zonal flow of the SH westerlies and local topography. Typically, either increasing precipitation or decreasing condensation temperature drive a lowering of measured $\delta^{18}O_{precipitaiton}$ values (Gat, 1980; Rozanski et al., 1993; Araguás-Araguás et al., 2000). Neither trend is observed in the records from Punta Arenas. However, it has been reported that precipitation on the windward side of the Andes in the mid-latitudes has increased in response to increased zonal flow in the late twentieth and early twenty-first centuries (Garreaud, 2007). The enhanced rain shadow developed as a result of this atmospheric variation inevitably leads to increased rainout of the heavier isotope on the windward side of the Andes. The precipitation that penetrates through to the leeward side is now relatively depleted in $\delta^{18}O$, similar to an enhanced continentality effect (Araguás-Araguás et al., 2000). Rising temperatures observed at Punta Arenas could result from the effects of adiabatic heating along a line closer to the dry lapse rate than that experienced previously. Rising temperatures may also be a response to a southward shift in the mean westerly wind belt over this period (Thompson and Solomon, 2002; Marshall, 2003).

This modern understanding provides the foundation for improved interpretation of the hydroclimatic and palaeoisotope records from the peatlands of Tierra del Fuego. Evidently, there is clear linkage between patterns of changing precipitation amount and the isotopic composition of that precipitation in this region. It seems, however, that those patterns are noticeably different to those that would be recorded in the bogs of NE North America and NW Europe. These modern measured δD and $\delta^{18}O$ values in precipitation, whilst from relatively short records, provide insight into clear regional differences. Were these fairly short-term trends captured in the annual increases in *Sphagnum* growth from nearby peat bog sites, it would be expected for the bogs near Punta Arenas to exhibit a markedly different record to those near Ushuaia. In response to the climate variations in the late twentieth and early twenty-first centuries, it would be expected that the bogs of both areas would show a lowering of estimated $\delta^{18}O_{precipitaiton}$ values. However, the bogs near Punta Arenas would be expected to show biological

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evidence for lowering of the depth to water table, due to increased summer moisture deficit (Charman, 2007; Charman et al., 2009). Conversely, bogs near Ushuaia would be expected to show a move to increased bog surface wetness over the same period. The exact changes, will, of course, relate to the specific topographical context of the peat bog site and its similarity to that of the GNIP stations, from which these modern data have been measured. However, the expectation of regional differences in the proxy records is valid.

It can be hypothesised, then, that where suitable peat bog sites are selected, and in the absence of significant extra-regional changes in the isotopic pathway from moisture source to precipitation, it should be possible mechanistically to associate changes in the southern westerly wind belt (intensification) to variations in its hydroclimatic and stable isotopic "footprint" (lower $\delta^{18}O_{precipitaiton}$ values and *increased* BSW at Ushuaia, lower $\delta^{18}O_{precipitaiton}$ values and *decreased* BSW near Punta Arenas) as recorded by a spatial array of peat bog sites over the late Holocene (cf. McDermott et al., 2011).

4 Peatland palaeoclimate records from Tierra del Fuego

Despite the potential for palaeoclimatic investigation of the *Sphagnum* bogs in Tierra del Fuego, relatively few records have been published to date. Palaeoecological records of estimated changes in past water table depth are available from macrofossil analyses of two peat profiles from the Andorra Valley ca. 10 km to the northeast of Ushuaia, Tierra del Fuego, Argentina (54°45′ S, 68°18′ W, ca. 180 m a.s.l.) (Mauquoy et al., 2004; Chambers et al., 2007). Palaeoisotope records from peat samples, largely dominated by *Sphagnum magellanicum*, have been published from Harberton Bog, east of Ushuaia (54°53′ S, 67°10′ W, 20 m a.s.l.) (White et al., 1994; Pendall et al., 2001). The record of *Sphagnum* δD values from Harberton bog (Pendall et al., 2001) and the plant macrofossil-derived hydroclimatic index from Andorra bog (AND-1) (Mauquoy et al., 2004) are compared with similar records from a site in northern England (Daley and Barber, 2012; Daley et al., 2010) in Fig. 3. The record from Walton

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Moss (WLM22) presented here has been selected for comparison as the data are similarly temporally resolved to those in AND-1 and because *Sphagnum* stable oxygen isotope data are available, permitting comparison with δD values from Harberton bog.

The temporal resolution of the data from AND-1 and Harberton bog is sufficiently different to preclude a direct assessment of hydroclimatic and palaeo-isotope variation here. However, the data do tentatively indicate that periods of drier (wetter) bog surface conditions at Andorra bog were associated with relatively higher (lower) δD values in *Sphagnum* moss from Harberton bog. Both bogs fall into the current climate space represented by the modern GNIP data from Ushuaia and would be consistent with the pattern in the instrumental period for increasing precipitation and lower δp values. AND-1 is, however, sufficiently resolved and well-dated to allow a comparison with changes from a peat bog in northern England. The longer-term (millennial-scale) variations in AND-1 were associated with similar changes in WLM22 that were opposite in direction (Fig. 3). Drier conditions on the palaeo-surface of Andorra Bog were coincident with wetter conditions on the surface of Walton Moss. A similar pattern may be suggested from a comparison of the δD values from Harberton bog and the $\delta^{18}O$ values from WLM22, but sampling resolution is insufficient. It has been reported that the palaeoecological records from Andorra bog have provided evidence to suggest that Southern Hemisphere climate changes were synchronous with, and opposite in direction to, those in the Northern Hemisphere (Mauquoy et al., 2004; Chambers et al., 2007). The basal stratigraphy of a second profile from the same site (AND-2) records a change to anomalously dry surface conditions ^{14}C wiggle-match dated to ~2820–2744 cal. BP (Chambers et al., 2007). This date range is also synchronous with abrupt climate shifts recorded from Northern Hemisphere European mires (van Geel and Renssen, 1998; Speranza et al., 2002).

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5 Conclusions

Modern GNIP data indicate that the response of the isotopic composition of precipitation in Tierra del Fuego to observed variations in the southern westerly wind belt in the last ~20–30 yr has been complex and geographically specific. In Punta Arenas and Ushuaia, isotope values in precipitation have decreased, but apparently in response to quite different trends in local surface air temperature and total precipitation amount. The fall in δ^{18}O values at Ushuaia is associated with an increase in the mean annual amount of precipitation. However, the fall in δ^{18}O values in Punta Arenas is weakly correlated with *decrease* in the precipitation amount and an increase in local temperatures. The observations from Punta Arenas would seem consistent with suggestions of intensification of the Andes rain shadow over the instrumental period.

Peat bog *Sphagnum* cellulose isotope data should be able to detect these changes but currently published records have insufficient temporal resolution to address this question. It is hypothesised that changes in the past 3000 yr, if associated with patterns of shifting latitudinal position and intensity of the westerlies, should be reflected in variations in the isotopic composition of the *Sphagnum* in sites near Punta Arenas and Ushuaia that are in phase, but in which hydroclimate records would vary in anti-phase. Peatlands offer an excellent archive for testing both the hydroclimatic and palaeoisotope variations. Techniques are now sufficiently advanced to test these hypotheses and are opening these archives to investigation following the pioneering work of White et al. (1994) Mauquoy et al. (2004), Pendall et al. (2001) and Chambers et al. (2007). Developing records of sufficient temporal and spatial resolution to test this hypothesis inevitably sets the agenda for southern South American peat palaeoclimate research.

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References

Araguás-Araguás, L., Froehlich, K., and Rozanski, K.: Deuterium and oxygen-18 isotope composition of precipitation and atmospheric moisture, Hydrol. Process., 14, 1341–1355, 2000.

Barber, K. E. and Langdon, P. G.: What drives the peat-based palaeoclimate record? A critical test using multi-proxy climate records from northern Britain, Quaternary Sci. Rev., 26, 3318–3327, 2007.

Barber, K. E., Chambers, F. A., Maddy, D., Stoneman, R. E., and Brew, J. S.: A sensitive high-resolution record of Late Holocene climatic change from a raised bog in Northern England, Holocene, 4, 198–205, 1994.

Biester, H., Kilian, R., Franzen, C., Woda, C., Mangini, A., and Schöler, H. F.: Elevated mercury accumulation in a peat bog of the Magellanic Moorlands, Chile (53° S) – An anthropogenic signal from the Southern Hemisphere, Earth Planet. Sci. Lett., 201, 609–620, 2002.

Boninsegna, J. A., Argollo, J., Aravena, J. C., Barichivich, J., Christie, D., Ferrero, M. E., Lara, A., Le Quesne, C., Luckman, B. H., Masiokas, M., Morales, M., Oliveira, J. M., Roig, F., Srur, A., and Villalba, R.: Dendroclimatological reconstructions in South America: A review, Palaeogeography, Palaeoclimatology, Palaeoecology, 281, 210–228, 2009.

Brenninkmeijer, C. A. M., van Geel, B., and Mook, W. G.: Variations in the D/H and $^{18}O/^{16}O$ ratio in cellulose extracted from a peat core, Earth Planet. Sci. Lett., 61, 283–290, 1982.

Chambers, F. M., Mauquoy, D., Brain, S. A., Blaauw, M., and Daniell, J. R. G.: Globally synchronous climate change 2800 years ago: Proxy data from peat in South America, Earth Planet. Sci. Lett., 253, 439–444, 2007.

Chambers, F. M., Booth, R. K., De Vleeschouwer, F., Lamentowicz, M., Le Roux, G., Mauquoy, D., Nichols, J. E., and van Geel, B.: Development and refinement of proxy-climate indicators from peats, Quaternary Int., doi:10.1016/j.quaint.2011.04.039, in press, 2012.

Charman, D. J.: Summer water deficit variability controls on peatland water-table changes: implications for Holocene palaeoclimate reconstructions, Holocene, 17, 217–227, 2007.

Charman, D. J., Barber, K. E., Blaauw, M., Langdon, P. G., Mauquoy, D., Daley, T. J., Hughes, P. D. M., and Karofeld, E.: Climate drivers for peatland palaeoclimate records, Quaternary Sci. Rev., 28, 1811–1819, 2009.

Ciais, P., Jouzel, J., Petit, J. R., Lipenkov, V., and White, J. W. C.: Holocene temperature variations inferred from six Antarctic ice cores, Ann. Glaciol., 20, 427–436, 1994.

Clymo, R. S.: The Limits to Peat Bog Growth, Philos. T. Roy. Soc. London, Series B, Biological Sciences (1934–1990), 303, 605–654, doi:10.1098/rstb.1984.0072, 1984.

Clymo, R. S. and Hayward, P. M.: The ecology of Sphagnum, in Bryophyte Ecology, edited by: Smith, A. J. E., Chapman and Hall, London, 229–289, 1982.

Cole, J. E., Rind, D., Webb, R. S., Jouzel, J., and Healy, R.: Climatic controls on interannual variability of precipitation δ^{18}O: Simulated influence of temperature, precipitation amount, and vapor source region, J. Geophys. Res.-Atmos., 104, 14223–14235, 1999.

Craig, H.: Isotopic variations in meteoric waters, Science, 133, 1702–1703, 1961.

Daley, T. J. and Barber, K. E.: Multi-proxy Holocene palaeoclimate records from Walton Moss, northern England and Dosenmoor, northern Germany, assessed using three statistical approaches, Quaternary Int., doi:10.1016/j.quaint.2011.10.026, in press, 2012.

Daley, T. J., Street-Perrott, F. A., Loader, N. J., Barber, K. E., Hughes, P. D. M., Fisher, E. H., and Marshall, J. D.: Terrestrial climate signal of the '8200 yr B.P. cold event' in the Labrador Sea region, Geology, 37, 831–834, 2009.

Daley, T. J., Barber, K. E., Street-Perrott, F. A., Loader, N. J., Marshall, J. D., Crowley, S. F., and Fisher, E. H.: Holocene climate variability revealed by oxygen isotope analysis of Sphagnum cellulose from Walton Moss, northern England, Quaternary Sci. Rev., 29, 1590–1601, 2010.

Daley, T. J., Thomas, E. R., Holmes, J. A., Street-Perrott, F. A., Chapman, M. R., Tindall, J. C., Valdes, P. J., Loader, N. J., Marshall, J. D., Wolff, E. W., Hopley, P. J., Atkinson, T., Barber, K. E., Fisher, E. H., Robertson, I., Hughes, P. D. M., and Roberts, C. N.: The 8200 yr BP cold event in stable isotope records from the North Atlantic region, Global Planet. Change, 79, 288–302, 2011.

Dansgaard, W.: Stable isotopes in precipitation, Tellus, 16, 436–468, 1964.

Darling, W. G. and Talbot, J. C.: The O and H stable isotope composition of freshwaters in the British Isles. 1. Rainfall, Hydrol. Earth Syst. Sci., 7, 163–181, doi:10.5194/hess-7-163-2003, 2003.

CPD
8, 595–620, 2012

Investigating late Holocene variations

T. J. Daley et al.

Dupont, L. M. and Brenninkmeijer, C. A. M.: Palaeobotanic and isotopic analysis of late Subboreal and early Subatlantic peat from Engbertsdijksveen-Vii, the Netherlands, Review of Palaeobotany and Palynology, 41, 241–247, 1984.
Filot, M. S., Leuenberger, M., Pazdur, A., and Boettger, T.: Rapid online equilibration method to determine the D/H ratios of non-exchangeable hydrogen in cellulose, Rapid Communications in Mass Spectrometry, 20, 3337–3344, 2006.
Garreaud, R. D.: Precipitation and circulation covariability in the extratropics, J. Climate, 20, 4789–4797, 2007.
Garreaud, R. D.: The Andes climate and weather, Adv. Geosci., 22, 3–11, 2009, http://www.adv-geosci.net/22/3/2009/.
Garreaud, R. D., Vuille, M., Compagnucci, R., and Marengo, J.: Present-day South American climate, Palaeogeogr. Palaeoclimatol. Palaeoecol., 281, 180–195, 2009.
Gat, J. R.: The isotopes of oxygen and hydrogen in precipitation, in: Handbook of Environmental Isotope Geochemistry, edited by: Fritz, P. and Fontz, J. C., Elsevier, Amsterdam, 21–47, 1980.
Gong, D. and Wang, S.: Definition of Antarctic Oscillation index, Geophys. Res. Lett., 26, 459–462, 1999.
Huber, U. M., Markgraf, V., and Schäbitz, F.: Geographical and temporal trends in Late Quaternary fire histories of Fuego-Patagonia, South America, Quaternary Sci. Rev., 23, 1079–1097, 2004.
Hughes, P. D. M., Blundell, A., Charman, D. J., Bartlett, S., Daniell, J. R. G., Wojatschke, A., and Chambers, F. M.: An 8500 cal. year multi-proxy climate record from a bog in eastern Newfoundland: contributions of meltwater discharge and solar forcing, Quaternary Sci. Rev., 25, 1208–1227, 2006.
IAEA/WMO: Global Network of Isotopes in Precipitation, the GNIP database, available at: http://isohis.iaea.org, 2004.
Jones, J. M., Fogt, R. L., Widmann, M., Marshall, G. J., Jones, P. D., and Visbeck, M.: Historical SAM variability. Part I: Century-length seasonal reconstructions, J. Climate, 22, 5319–5345, 2009.
Jones, P. D., Briffa, K. R., Barnett, T. P., and Tett, S. F. B.: High-resolution palaeoclimatic records for the last millennium: Interpretation, integration and comparison with General Circulation Model control-run temperatures, Holocene, 8, 455–471, 1998.

CPD
8, 595–620, 2012

Investigating late Holocene variations

T. J. Daley et al.

Jouzel, J., Alley, R. B., Cuffey, K. M., Dansgaard, W., Grootes, P., Hoffmann, G., Johnsen, S. J., Koster, R. D., Peel, D., Shuman, C. A., Stievenard, M., Stuiver, M., and White, J.: Validity of the temperature reconstruction from water isotopes in ice cores, J. Geophys. Res.-Oceans, 102, 26471–26487, 1997.

Jouzel, J., Hoffmann, G., Koster, R. D., and Masson, V.: Water isotopes in precipitation: data/model comparison for present-day and past climates, Quaternary Sci. Rev., 19, 363–379, 2000.

Jouzel, J., Stievenard, M., Johnsen, S. J., Landais, A., Masson-Delmotte, V., Sveinbjornsdottir, A., Vimeux, F., von Grafenstein, U., and White, J. W. C.: The GRIP deuterium-excess record, Quaternary Sci. Rev., 26, 1–17, 2007.

Kidson, J. W.: Principal modes of Southern Hemisphere low-frequency variability obtained from NCEP-NCAR reanalyses, J. Climate, 12, 2808–2830, 1999.

Kidston, J., Taschetto, A. S., Thompson, D. W. J., and England, M. H.: The influence of Southern Hemisphere sea-ice extent on the latitude of the mid-latitude jet stream, Geophys. Res. Lett., 38, L15804, doi:10.1029/2011GL048056, 2011.

Kilian, R., Hohner, M., Biester, H., Wallrabe-Adams, H. J., and Stern, C. R.: Holocene peat and lake sediment tephra record from the southernmost Chilean Andes (53–55° S), Revista geologica de Chile, 30, 23–37, 2003.

Le Quéré, C., Rödenbeck, C., Buitenhuis, E. T., Conway, T. J., Langenfelds, R., Gomez, A., Labuschagne, C., Ramonet, M., Nakazawa, T., Metzl, N., Gillett, N., and Heimann, M.: Saturation of the southern ocean CO_2 sink due to recent climate change, Science, 316, 1735–1738, 2007.

LeGrande, A. N., Schmidt, G. A., Shindell, D. T., Field, C. V., Miller, R. L., Koch, D. M., Faluvegi, G., and Hoffmann, G.: Consistent simulations of multiple proxy responses to an abrupt climate change event, P. Natl. Acad. Sci. USA, 103, 837–842, 2006.

Leuenberger, M. C., Lang, C., and Schwander, J.: Delta(15)N measurements as a calibration tool for the paleothermometer and gas-ice age differences: A case study for the 8200 BP event on GRIP ice, J. Geophys. Res. Atmos., 104, 22163–22170, 1999.

Limpasuvan, V. and Hartmann, D. L.: Eddies and the annular modes of climate variability, Geophys. Res. Lett., 26, 3133–3136, 1999.

Loader, N. J., McCarroll, D., van der Knaap, W. O., Robertson, I., and Gagen, M.: Characterizing carbon isotopic variability in *Sphagnum*, Holocene, 17, 403–410, 2007.

Mark, A. F., Johnson, P. N., Dickinson, K. J. M., and McGlone, M. S.: Southern hemisphere patterned mires, with emphasis on southern New Zealand, Journal – Royal Society of New Zealand, 25, 23–54, 1995.

Markgraf, V.: Paleoenvironments and paleoclimates in Tierra del Fuego and southernmost Patagonia, South America, Palaeogeogr. Palaeoclimatol. Palaeoecol., 102, 53–68, 1993.

Marshall, G. J.: Trends in the Southern Annular Mode from observations and reanalyses, J. Climate, 16, 4134–4143, 2003.

Martínez Cortizas, A., Biester, H., Mighall, T., and Bindler, R.: Climate-driven enrichment of pollutants in peatlands, Biogeosciences, 4, 905–911, doi:10.5194/bg-4-905-2007, 2007.

Mataloni, G.: Ecological studies on algal communities from Tierra del Fuego peat bogs, Hydrobiologia, 391, 157–171, 1998.

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

McDermott, F., Atkinson, T. C., Fairchild, I. J., Baldini, L. M., and Mattey, D. P.: A first evaluation of the spatial gradients in +|18O recorded by European Holocene speleothems, Global Planet. Change, 79, 275–287, 2011.

Ménot-Combes, G., Burns, S. J., and Leuenberger, M.: Variations of $^{18}O/^{16}O$ in plants from temperate peat bogs (Switzerland): implications for paleoclimatic studies, Earth Planet. Sci. Lett., 202, 419–434, 2002.

Moreno, P. I., François, J. P., Villa-Martínez, R. P., and Moy, C. M.: Millennial-scale variability in Southern Hemisphere westerly wind activity over the last 5000 years in SW Patagonia, Quaternary Sci. Rev., 28, 25–38, 2009.

Moy, C. M., Dunbar, R. B., Moreno, P. I., Francois, J. P., Villa-Martínez, R., Mucciarone, D. M., Guilderson, T. P., and Garreaud, R. D.: Isotopic evidence for hydrologic change related to the westerlies in SW Patagonia, Chile, during the last millennium, Quaternary Sci. Rev., 27, 1335–1349, 2008.

Neukom, R., Luterbacher, J., Villalba, R., Küttel, M., Frank, D., Jones, P., Grosjean, M., Wanner, H., Aravena, J. C., Black, D., Christie, D., D'Arrigo, R., Lara, A., Morales, M., Soliz-Gamboa, C., Srur, A., Urrutia, R., and von Gunten, L.: Multiproxy summer and winter surface air temperature field reconstructions for southern South America covering the past centuries, Clim. Dynam., 37, 35–51, 2011.

CPD
8, 595–620, 2012

Pendall, E., Markgraf, V., White, J. W. C., Dreier, M., and Kenny, R.: Multiproxy record of late Pleistocene-Holocene climate and vegetation changes from a peat bog in Patagonia, Quaternary Res., 55, 168–178, 2001.
Petoukhov, V. and Semenov, V. A.: A link between reduced Barents-Kara sea ice and cold winter extremes over northern continents, J. Geophys. Res.-Atmos., 115, D21111, doi:10.1029/2009JD013568, 2010.
Roig, F., Roig, C., Rabassa, J., and Boninsegna, J.: Fuegian floating tree-ring chronology from subfossil Nothofagus wood, Holocene, 6, 469–476, 1996.
Rojas, M., Moreno, P., Kageyama, M., Crucifix, M., Hewitt, C., be-Ouchi, A., Ohgaito, R., Brady, E. C., and Hope, P.: The Southern Westerlies during the last glacial maximum in PMIP2 simulations, Clim. Dynam., 32, 525–548, 2009.
Rozanski, K., Araguas-Araguas, L., and Gonfiantini, R.: Relation between long-term trends of oxygen-18 isotope composition of precipitation and climate, Science, 258, 981–985, 1992.
Rozanski, K., Araguas-Araguas, L., and Gonfiantini, R.: Isotopic patterns in modern global precipitation, Climate Change in Continental Isotopic Records, 1–36, 1993.
Sapkota, A., Cheburkin, A. K., Bonani, G., and Shotyk, W.: Six millennia of atmospheric dust deposition in southern South America (Isla Navarino, Chile), Holocene, 17, 561–572, 2007.
Schmidt, G. A., LeGrande, A. N., and Hoffmann, G.: Water isotope expressions of intrinsic and forced variability in a coupled ocean-atmosphere model, J. Geophys. Res., 112, D10103, doi:10.1029/2006JD007781, 2007.
Siegenthaler, U. and Oeschger, H.: Correlation of ^{18}O in precipitation with temperature and altitude, Nature, 285, 314–317, 1980.
Speranza, A., van Geel, B., and van der Plicht, J.: Evidence for solar forcing of climate change at ca. 850 cal BC from a Czech peat sequence, Global Planet. Change, 35, 51–65, 2002.
Thompson, D. W. J. and Solomon, S.: Interpretation of recent Southern Hemisphere climate change, Science, 296, 895–899, 2002.
Tindall, J. C. and Valdes, P. J.: Modeling the 8.2ka event using a coupled atmosphere-ocean GCM, Global Planet. Change, 79, 312–321, 2011.
Tindall, J. C., Valdes, P. J., and Sime, L. C.: Stable water isotopes in HadCM3: Isotopic signature of El Nino Southern Oscillation and the tropical amount effect, J. Geophys. Res., 114, D04111, doi:10.1029/2008JD010825, 2009.
Toggweiler, J. R. and Russell, J.: Ocean circulation in a warming climate, Nature, 451, 286–288, 2008.

CPD
8, 595–620, 2012

van Geel, B., Heusser, C. J., Renssen, H., and Schuurmans, C. J. E.: Climatic change in Chile at around 2700 BP and global evidence for solar forcing: a hypothesis, Holocene, 10, 659–664, 2000.
van Geel, B. and Middeldorp, A. A.: Vegetational history of Carbury bog (Co. Kildare, Ireland) during the last 850 years and a test of the temperature indicator value of $^2H/^1H$ measurements of peat samples in relation to historical sources and meteorological data, New Phytol., 109, 377–392, 1988.
van Geel, B. and Renssen, H.: Abrupt climatic change around 2,650 BP in north-west Europe: Evidence for climatic teleconnections and a tentative explanation, in: Water, environment and society in times of climatic change, edited by: Issar, A. S. and Brown, N., Kluwer, Dordrecht, 21–41, 1998.
Varma, V., Prange, M., Lamy, F., Merkel, U., and Schulz, M.: Solar-forced shifts of the Southern Hemisphere Westerlies during the Holocene, Clim. Past, 7, 339–347, doi:10.5194/cp-7-339-2011, 2011.
Vimeux, F., Ginot, P., Schwikowski, M., Vuille, M., Hoffmann, G., Thompson, L. G., and Schotterer, U.: Climate variability during the last 1000 years inferred from Andean ice cores: A review of methodology and recent results, Palaeogeogr. Palaeoclimatol. Palaeoecol., 281, 229–241, 2009.
White, J. W. C., Ciais, P., FIGGE, R. A., Kenny, R., and Markgraf, V.: A High-Resolution Record of Atmospheric Co2 Content from Carbon Isotopes in Peat, Nature, 367, 153–156, 1994.

CPD
8, 595–620, 2012

Investigating late Holocene variations

T. J. Daley et al.

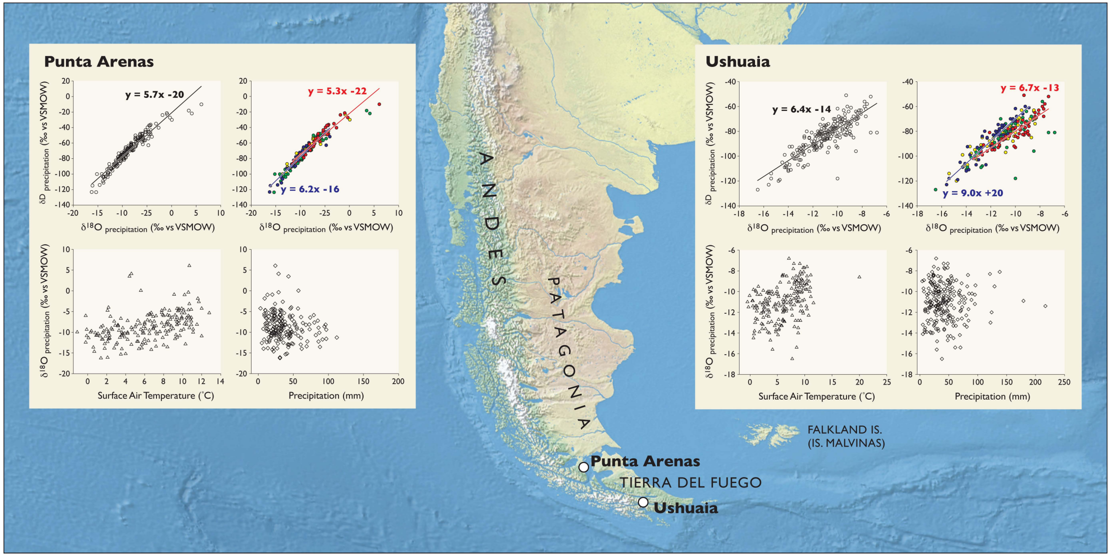

Fig. 1. Modern isotopic and climate data from Global Network of Isotopes in Precipitation (GNIP) [International Atomic Energy Agency – World Meteorological Organization (IAEA/WMO), 2004] stations at Punta Arenas, Chile and Ushuaia, Argentina. For each site: Upper left graph = δD and δ^{18}O values in meteoric waters for 1990–2008 (Punta Arenas) and 1982–2002 (Ushuaia). Local meteoric water lines (MWL) are indicated: $\delta D = 5.7(\delta^{18}\text{O})$ -20 at Punta Arenas and $\delta D = 6.4$ $(\delta^{18}\text{O})$ -14 at Ushuaia. Upper right graph = Variation in isotopic composition of meteoric waters by season (blue circles, June–August; green circles, September–November; red circles, December–February; yellow circles, March–May). Seasonal MWLs are indicated. For Punta Arenas: June–August, $\delta D = 6.2(\delta^{18}\text{O})$ -16; December–February, $\delta D = 5.3(\delta^{18}\text{O})$ -22. For Ushuaia: June–August, $\delta D = 9.0(\delta^{18}\text{O})$ $+20$; December–February, $\delta D = 6.7(\delta^{18}\text{O})$ -13. Lower left graph = monthly air-temperature (T) values and oxygen isotopic composition of monthly precipitation (IAEA/WMO, 2004). Lower right graph = monthly total precipitation values and oxygen isotopic composition of monthly precipitation (IAEA/WMO, 2004).

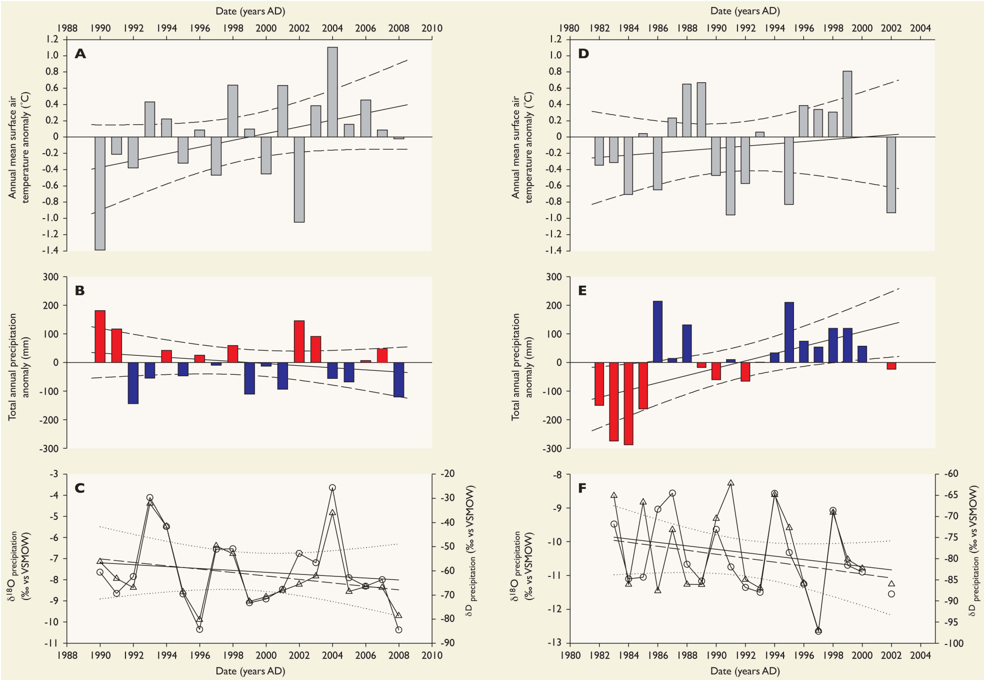

Fig. 2. Modern isotopic and climate timeseries from GNIP stations at Punta Arenas, Chile and Ushuaia, Argentina. For Punta Arenas: **(A)** mean annual surface air temperature anomaly (°C) relative to the 1990–2008 mean. **(B)** Mean annual precipitation anomaly (mm) relative to the 1990–2008 mean. **(C)** Mean annual amount-weighted δD values (open diamonds) and δ^{18}O values (open circles) in meteoric waters for 1990–2008. For Ushuaia: **(D)** mean annual surface air temperature anomaly (°C) relative to the 1982–2002 mean. **(E)** Mean annual precipitation anomaly (mm) relative to the 1982–2002 mean. **(F)** Mean annual amount-weighted δD values (open diamonds; linear regression – solid line) and δ^{18}O values (open circles; linear regression – dashed line) in meteoric waters for 1982–2002. Dotted lines = 95 % confidence limits on linear regressions.

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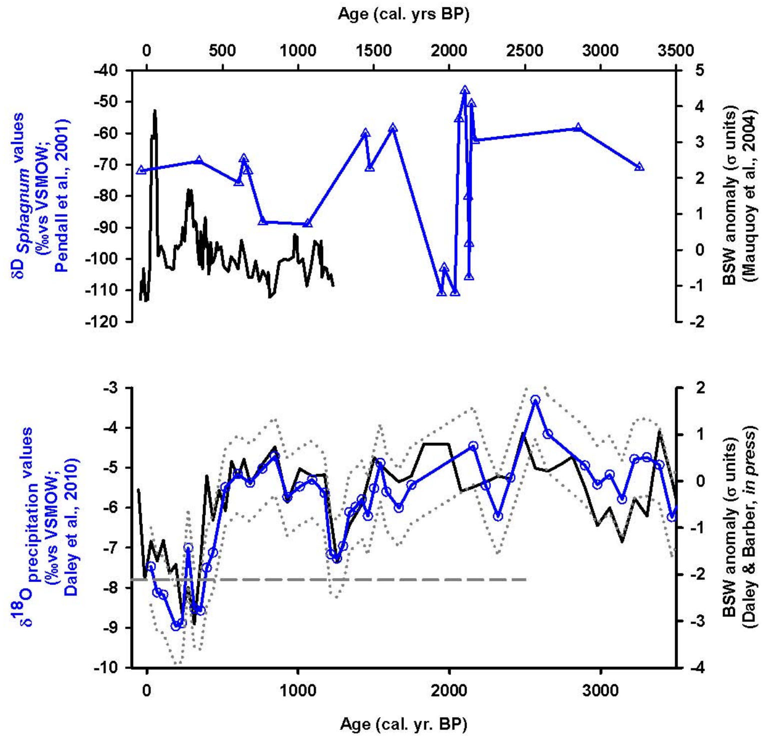

Fig. 3. Peatland hydroclimatic (AND-1; Mauquoy et al., 2004) and stable isotopic records (Harberton bog; Pendall et al., 2001) from Tierra del Fuego (TdF) compared with variations in hydroclimate and estimated palaeo δ^{18}O*p* values from Walton Moss, northern England (Daley and Barber, 2012; Daley et al., 2010). Blue lines = palaeo stable isotope records, with 1σ error estimate (dotted lines). Black lines = Bog Surface Wetness reconstructions. Grey dashed line = modern annual mean δ^{18}O*p* values near to Walton Moss.