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RESEARCH ARTICLE

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Key Points:

- The pollen record of Mt. Usborne, East Falkland suggests that the upland plant pollen accumulation rates are a proxy for local productivity
- Pollen accumulation rates as a wind intensity indicator align with proxies for wet conditions, combined these records are a proxy for Southern Hemisphere Westerlies influence
- The consistent Holocene plant community composition suggests that diversity within the community is resilient to climate change

Supporting Information:

Supporting Information may be found in the online version of this article.

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A 13,000-Year Record of the Southern Hemisphere Westerlies Inferred From Pollen and Plant Wax Isotopes From the South Atlantic

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Abstract We compare a new pollen record with pre-existing plant-wax isotope data from lacustrine sediments retrieved from Mt. Usborne, East Falkland. These records document variations in plant productivity, wind intensity, and moisture availability, to measure the influence of the Southern Hemisphere Westerlies (SHW) over the last 13,000 years. Long-distance transported pollen (LDT) accumulation rates from South America record changes in SHW. Relatively wet conditions (i.e., from plant indicators, biomarker isotopes) and changes in productivity vary with LDT, suggesting that times of high productivity and wind intensity were associated with increased precipitation and/or fog. Together, we infer that these combined proxies record the effect of the SHW on the Falkland Islands. Combined, these data indicate that there were periods of increased SHW influence over the Falkland Islands from 11.8–10.5 ka BP (thousands of years before present) and 6.8–3.0 ka BP. In contrast, the interval 10.5–8.4 ka BP, characterized by dry, less windy conditions and lower productivity, may have been a time when the SHW were less influential at the site and were located away, likely south, from the islands. Our earth-system model experiments show a coupling between relative humidity and temperature and suggest that displacement of the SHW to the south of the Falkland Islands results in warming and drying of the islands, similar to conditions today. However, our pollen data also show that the local plant community diversity on Mt. Usborne appears resilient to climate change, on the scale of Holocene-variability.

1. Introduction

The Southern Hemisphere Westerlies (SHW) are a zonal band of high surficial winds and associated storm tracks occupying the southern mid latitudes. They are suspected to be a leading driver of climate change on a variety of timescales due to their outsized influence on the southern mid-latitude temperature gradient (Fletcher & Moreno, 2012), the expansion of the Indo-Pacific Warm Pool with its associated ocean currents and atmospheric water vapor (Denton et al., 2021), and the carbon upwelling potential of the Southern Ocean with its deep-ocean carbon storage (Russell et al., 2006). The SHW also influence upwelling of nutrients and carbon, as well as regional temperatures (Peterson & Whitworth, 1989). Thus, it is likely that the SHW play an important role in the spatial pattern and perhaps even the origin of late-glacial and Holocene climate variability on both regional and global scales (Caldeira & Duffy, 2000). For example, Villacís et al. (2023) identified hydrologic changes thought to be associated with migrations of the SHW varying between multi-millennial to sub-decadal scales following the termination of the last ice age in Patagonia. Recently, Moreno et al. (2021) and Zarate et al. (2023) reviewed data from the Patagonian sector to understand spatial differences in SHW behavior during the Holocene. These studies have all highlighted the importance of geography and temporal resolution in efforts to characterize the influence of the SHW on both abrupt and cyclical climate patterns. However, despite this recent work, numerous questions remain as to the nature and timing of past changes in the SHW and their link to both long-term and millennial climate variations.

Terrestrial studies in the Southern Hemisphere middle to high latitudes are relatively sparse in part due to geographic biases in sampling and the prevalence of ocean. South America has been used as a natural latitudinal transect to map the zonal movement of the westerlies. However, the interaction of the easterly winds, as well as the rain shadow effect of the Andes, have led to conflicting interpretations of climate patterns (i.e., Zolitschka

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et al., 2013; Moreno et al., 2018). The South Atlantic islands, particularly those of low elevation, thus provide climate archives that may more clearly reflect the position and intensity of the westerlies than those influenced by the Andes on the mainland.

Our overarching goal was to compare new pollen data with a previous plant wax isotope record from an alpine tarn (Spoth et al., 2023) to reconstruct not only the local plant community, but also to track the relative influence of the SHW on the Falkland Islands (52°S, 59°W; Figure 1) since the last deglaciation of the island about 19,000 years ago (Hall et al., 2020). As the SHW today are characterized by wet, windy conditions, we focused on reconstructing relative changes in these variables. Because the wind belt is predicted to move south in the future (Deng et al., 2022; Goyal et al., 2021), we also used an Earth System Model (ESM) to identify the possible temperature and moisture changes associated with southern-displaced SHW (relative to the Falkland Islands). Finally, as a parallel investigative line, we examined how the flora of the Falkland Islands varied in the Holocene. An understanding of the past productivity and plant-community composition of these islands yields information on the resilience or vulnerability of the Falkland flora in the face of future climate change.

2. Background

2.1. Geography and Climate

The Falkland Islands are situated in a climatically sensitive area between the subtropical and subantarctic ocean fronts within the modern position of the SHW. The archipelago contains more than 700 islands, totaling ~12,000 km², with East Falkland as the largest (5,000 km², Moore, 1968). These islands are part of the larger, submerged Falkland Plateau extending from the South American continental margin. This topography makes this region a pinning point for the equatorward migration of the subantarctic front. The relatively high relief of the site serves as the northern margin of the Antarctic circumpolar current (Arhan et al., 2002), as well as the interface of the warm Brazilian and the cold Falkland Currents. The region has a cool maritime climate with a mean annual temperature of 6.6°C and 559.2 mm of rainfall (Jones et al., 2013). A seasonal shift precipitation amount is driven in part by the southern migration of the SHW during the summer months and its effect on regional storm tracks (Groff et al., 2020). Conditions are thought to be wetter on islands during periods of increased SHW influence despite the increase in wind intensity associated with the SHW (Spoth et al., 2023).

Today, there are no glaciers on the islands. However, on Mount Osborne there is evidence of past alpine glaciers from cirques and moraines, which have been dated to the last glaciation ~20–60 ka BP (Clapperton, 1971; Hall et al., 2020). Glacial landforms are limited to the high-elevation regions of both East and West Falkland. The quartzite Wickham Heights form the central highlands of East Falkland with Mount Osborne (705 m asl) as the highest peak. Periglacial features—“stone runs”—are common at all elevations (Stone, 2010); some may be rock glaciers.

2.2. Modern Vegetation and Site Description

The Falkland Islands are host to several endemic and regionally protected plant species (Bokhorest et al., 2007) that are predicted to be influenced by anthropogenic climate change in the future (Upson et al., 2016). Mt. Osborne has wet, cushion mat taxa growing in hollows, with shrubs, herbs, and grasses subsisting on coarse, well-drained soils. Similarly, mosses are found preferentially in wet locales with some being partially submerged, whereas many of the high-elevation ferns are found only in wind-protected areas among boulders.

In a botanical survey, Upson and Lewis (2014) identified 181 native plant taxa from 59 families. About 75% of plant taxa are distributed widely across the islands, while 25% are limited to specific habitats, such as the climatically mild western islands or the coastline. Common species include *Empetrum rubrum* (diddle-dee shrub), *Cortaderia pilosa* (whitegrass), *Austroblechnum penna-marina* (known as small fern in the Falklands, or the Antarctic hard-fern elsewhere), *Lobelia pratiana* (berry-lobelia), *Juncus scheuchzerioides* (native rush), *Baccharis magellanica* (Christmas bush), *Gaultheria pumila* (mountainberry), and *Gunnera magellanica* (pigvine). Widespread and frequent genera include grasses (*Aira*, *Cortaderia*, *Deschampsia*, *Festuca*, *Hierochloe*, *Poa*), forbs (*Acaena*, *Anagallis*, *Apium*, *Bellis*, *Callitriche*, *Cerastium*, *Galium*, *Gamochaeta*, *Leptinella*, *Leucheria*, *Lilaeopsis*, *Lobelia*, *Luzula*, *Luzuriaga*, *Marsippospermum*, *Nassauvia*, *Nertera*, *Oreomyrrhis*, *Oxalis*, *Plantago*, *Ranunculus*, *Rostkovia*, *Rubus*, *Schizeilema*, *Senecio*, *Spergularia*, *Symphotrichum*), cushion mats (*Azorella*, *Bolax*, *Colobanthus*, *Chevruleia*, *Crassula*, *Nassauvia*, *Oreobolus*), and sedges (*Isolepis*). Notably, there are no

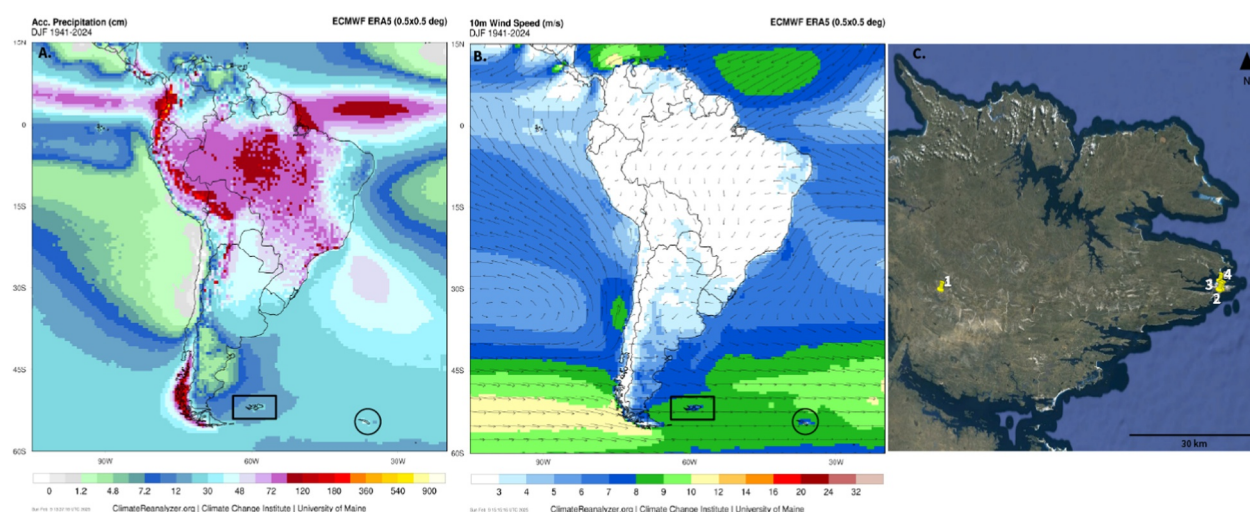


Figure 1. The Southern Hemisphere Westerly Winds (SHW) are characterized with increased precipitation (a) and increased wind speed (b). The Falkland Islands (box) and South Georgia (circle) are both located in the South Atlantic. Plotted on this map of northern East Falkland (c) are key sites used in this study including Mt. Usborne (this study, (1), Surf Bay (2), Hooker's Point (3), and Canopus Hill (4)).

native trees on the Falkland Islands, “common” and “frequent” taxa serve as the dominant species of the 14 known habitat classifications (Upson & Lewis, 2014). In the lowlands, there are commonly grasslands, peat-forming bogs, and fens, along with coastline-specific plant communities (e.g., dense tussock grass [*Poa flabellata*]). In the highlands, the stone runs, streams, tarns, and glacial deposits host a range of localized plant communities such as montane-feldmark, inland rock, open water, bogs, grassland, dwarf shrub heath, cushion beds, and fern beds.

Past studies have used multiple proxies to derive climate reconstructions from peat with a particular focus on pollen. For example, foreign pollen transported from South America commonly is used as a wind intensity proxy as first proposed by Barrow (1978) and utilized in subsequent records including this study. Other proxies include carbon and oxygen stable isotopes from *P. flabellata* cellulose (Groff et al., 2020), charcoal (Groff et al., 2020; Hamley et al., 2021; Mauquoy et al., 2020), diatom assemblages (Scaife et al., 2019), and elemental abundances (Groff et al., 2020; Monteath et al., 2022). These previous studies have documented millennial-scale climate changes during the Holocene characterized by what have been proposed to be significant shifts in marine conditions, wind intensity and hydrology linked to the SHW. However, the interpretations and timing of proposed changes are not all in agreement. This disagreement may be due to local site effects (e.g., seabird nutrients and coastal sand transport), use of different proxies and measurement units (e.g., pollen percentages vs. concentrations vs. accumulation rates), limited age control, and/or difficulty in regional interpretation (Barrow, 1978; Van der Putten, 2012).

Our study focuses on sediments from a small alpine tarn on the north slope of Mt. Usborne (705 m asl), here called Tarn 2, and represents the first pollen study from lacustrine sediments in the Falkland Islands. The tarn (0.007 km² catchment, 5 m water depth, 600 m elevation) is enclosed by a belt of bulky moraines dating to the last glaciation (Hall et al., 2020), as well as by a steep quartzite headwall. Corcoran et al. (2022) identified *E. rubrum*, *L. magellanica*, *C. pilosa*, and *Astelia pumila* (soft-camp bog) as the primary taxa at this elevation on Mt. Usborne today, with localized concentrations of *B. penna-marina*, *Lomariocycas magellanica* (tall fern), *Bolax gummiifera* (balsam-bog), *Gaultheria pumila* (mountainberry), and *Usnea* (beard lichen). Our lacustrine record avoids potential hiatuses created by coastal erosion and widespread grazing of peatlands, allowing an alternative view of pollen accumulation compared to lowland peat records, particularly as the accumulation of pollen through aeolian deposition in peat communities is still poorly understood in this region (Barrow, 1978; Groff et al., 2020). In addition, the elevation difference between Mt. Usborne and the existing peat records (mostly coastal) allows for any elevation effects to be analyzed.

3. Methods

The primary record for this study comes from core TAR2-18-1 (215 cm long with overlapping sections), which was obtained with a modified Livingstone-style piston corer deployed from a raft. All data is available at Spoth-Ascencio et al. (2026) through PANGAEA. Spoth et al. (2023) developed an age-depth model for this core from seven radiocarbon-dated plant macrofossils (Table S1 in Supporting Information S1) using R.Bacon (Blaauw & Andrés Christen, 2011) and determined that the sediments span 13.0–2.2 ka (Figure S1 in Supporting Information S1). Radiocarbon ages were calibrated using the INTCAL20 (Reimer et al., 2020) curve. We maintain the same age model with this study for ease of comparison with proxies of that study. The average 95th percentile confidence interval window over the entire core from R.Bacon iterations is 980 BP, within the precision of our interpretations. In addition, the age model during two periods of climatic shift identified in this study (10.5 and 6.8 ka BP) have a higher precision due to nearby radiocarbon dates (540 and 680 BP, respectively). To extend the proxy records to the modern sediment-water interface (which was lost while coring), Spoth et al. (2023) also collected a surface core using a Unicorer (core TAR2-19-1). This surface sediment was sub-sampled for analysis and assumed to be age 0 BP, referred to as “modern.” An age model was processed with R.Bacon using three radiocarbon dates in order to estimate the modern sample (0–1 cm) sedimentation rate for pollen analysis (Table S2 in Supporting Information S1). Supporting Information S1 contains additional chronological details.

For this study, we analyzed thirty-two 2-cm³ sediment samples (each spanning 1 cm of sediment depth) for pollen from TAR2-18-1, as well as one sample from the sediment-water interface of TAR2-19-1 for a modern baseline, using methods modified from Faegri and Iverson (1989). Processing was performed in house at the University of Maine using 10% potassium hydroxide and 10% hydrochloric acids for the removal of humic acids and carbonates, respectively, followed by sieving with a 250-μm mesh and hydrofluoric (HF) acid treatment to remove remaining silicates. Glacial acetic acid was used to dehydrate grains, remove byproducts of HF reactions, and prepare samples for acetolysis with sulfuric acid and acetic anhydride followed by rinses of deionized water, ethanol, and tertiary butyl alcohol before suspending the grains in 1000-centistoke silicone oil. Black ceramic microspheres were added (1.113×10^4 per sample) for quantification of pollen concentrations (Kitaba & Nakagawa, 2017).

Upland pollen was counted to 300 grains for most samples but to only 200 grains for the two basal samples (150–144 cm/12.7–12.4 ka BP), due to low abundance. Upland sums presented here exclude all spores (i.e., ferns, mosses and fungi) and aquatic taxa. Pollen accumulation rates (PAR, grains/cm²/yr) were calculated with the sedimentation rate from the age model (see Supporting Information S1). Concentration values (grains/cm³) also were calculated and compared to PAR. We used the R package Rioja to conduct a constrained incremental sum of square (CONISS) analysis and associated dendrogram to divide both the taxa percentage by upland sum and the PAR upland taxa into six distinct groups (Grimm, 1987; Juggins & Juggins, 2019). Principal components analysis (PCA) was constructed using EOF python library by Dawson (2016). The PCA matrix was built with the PAR values by age and the PAR of each pollen taxon.

To synthesize the pollen data, we sorted taxa into local habitat categories based on the regional guide of Moore (1968) and the local guide of Upson and Lewis (2014). Cushion plants include *A. pumila*, *B. gummifera*, and *Drapetes muscosus* (drapetes), all of which are found near the tarns today. Herbs include Asteraceae, *Gunnera*, Apiaceae undiff., Caryophyllaceae, and Rosaceae. Grasses dominate much of the Falklands, but cannot be distinguished to species (Groff et al., 2022), so is reported at the family level (Poaceae). The only shrubs on the island are low-growing, prostrate Ericaceae. The species in this study is likely *E. rubrum*, which is abundant in the Falkland Islands, with the genus *Gaultheria* possibly contributing to the record. We label all non-native taxa found in this study as long-distance traveled (LDT), most likely from South America, and include them in the upland sum. LDT taxa in our record are *Nothofagus* (southern beech), *Ephedra* (evergreen shrub), and *Podocarpus* (conifer). As the Falklands have been treeless since the Miocene (Thomas et al., 2024), all arboreal pollen must be LDT. The cushion plants, shrubs, LDT, herbs, and grasses together comprise the plant taxa for upland PAR. The spores of mosses and ferns are grouped together for analysis. Cyperaceae is categorized as an aquatic species, as it is typically found partially submerged at the margins of lakes, including the tarns analyzed in this study.

To understand the local climate effects of a southward migration of the SHW, we performed Earth System Model (ESM) simulations with the ESM 2M (Dunne et al., 2012, 2013) run using CMIP6 with fixed pre-industrial conditions. This model has been used previously to assess the mechanisms and effects of shifting SHW

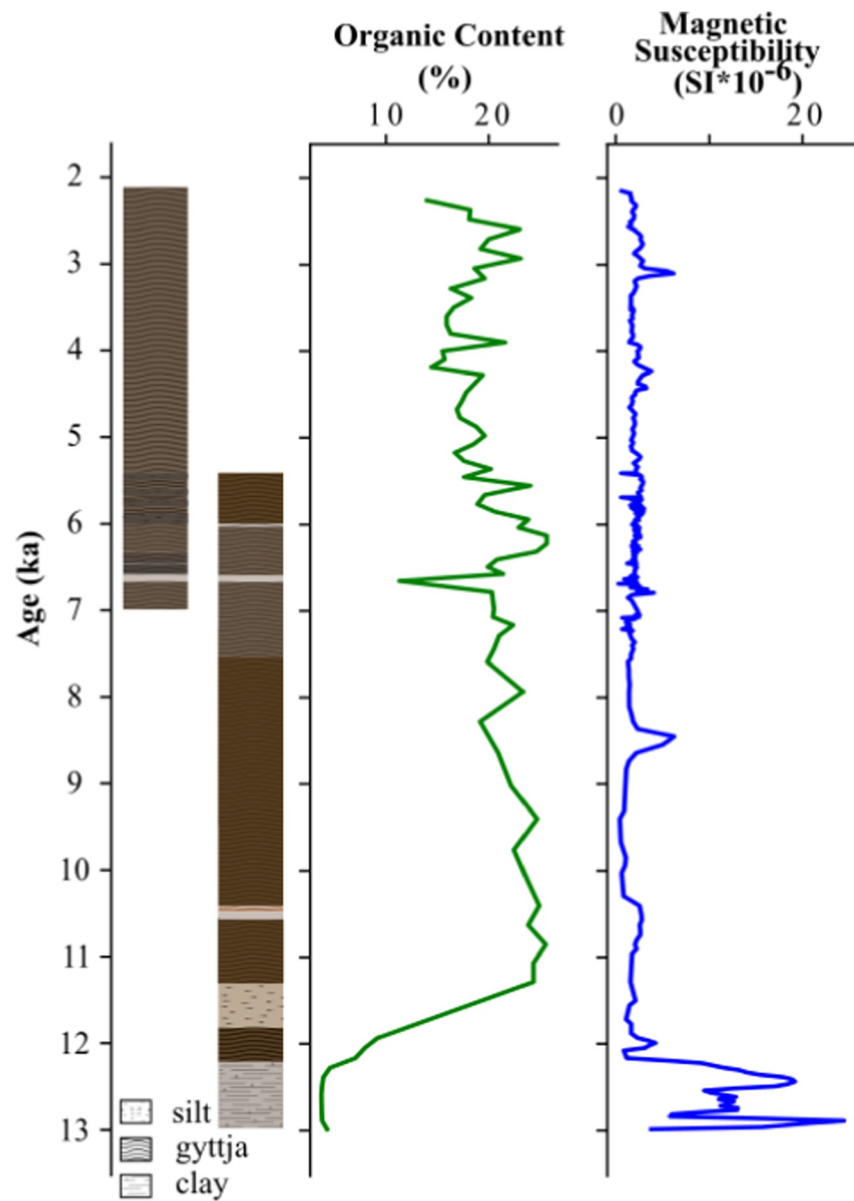


Figure 2. Stratigraphy of TAR2-18-1 piston core plotted by age in thousands of calendar years (modified from Spoth et al., 2023). The legend (bottom) denotes symbols for the sediment types: gyttja, silt, and clay, and the underlying colors reflect the in-field Munsell color observations. To the right is the organic content from loss-on-ignition (LOI; green) and magnetic susceptibility (blue) all processed from the piston core.

(e.g., in the southwest Pacific, Denton et al., 2021). We focus here on a poleward displacement of the SHW to 53°S, approximately one degree of latitude south of our field site.

4. Results

4.1. Sediments and Stratigraphy

The Tarn 2 sediment record (TAR2-18-1 piston core) spans 13.0–2.2 ka BP (Figure 2). Accumulation rates range from 0.025 to 0.005 cm/yr and the modern sediment interface (0–1 cm) from the Unicore has an accumulation rate of 0.009 cm/yr (Figure 3). The pre-Holocene sediment consists of inorganic clays with the highest magnetic susceptibility (MS) value of the record. Near 12 ka BP, MS values drop to a low background level, while organic content steadily increases and sediment accumulation rate decreases. The start of Holocene is characterized by

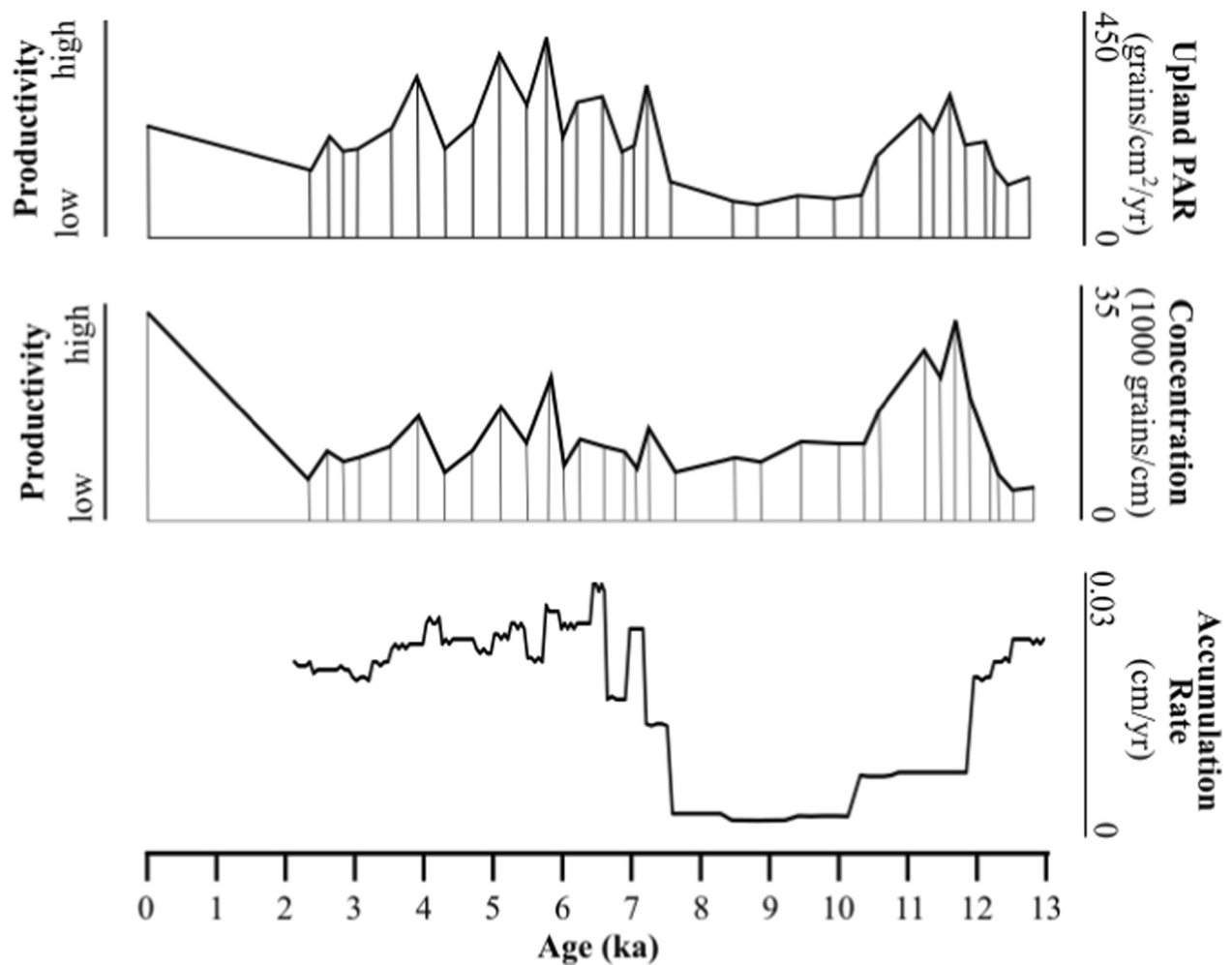


Figure 3. Comparison of pollen reporting methods to sediment accumulation of Tarn 2. (a) Pollen accumulation rate (grains/cm²/yr) is calculated by accounting for the sediment accumulation rate while (b) pollen concentration (grains/cm³) does not. (c) The sediment accumulation rate (cm/yr) is plotted below.

interbedded gyttja, moss, and silt layers, with low MS values and relatively high organic content (25%). The early Holocene (11–5.5 ka BP) shows an increase in sediment variability and fluctuation in organic content values (~10–25%), with MS values remaining low. In contrast, the late Holocene (5.5–2 ka BP) sediments have continuous gyttja and a return to relatively high organic content values (~20%) with increased sediment accumulation rates. The sediment record of TAR2-19-1 similarly reflects the core top of TAR2-18-1 and is composed entirely of gyttja.

4.2. Pollen

Community composition is dominated by Poaceae (grasses), which make up about 60% of the total pollen sum (Figure 4), followed by (in order of abundance): *Nothofagus* (LDT) at 10%, undifferentiated monolete spores (undiff.; likely *Austroblechum*, a fern), *D. muscosus* (cushion-type), trilete spores (likely *Lycopodium*), *B. gummifera* (a cushion-type evergreen), Ericaceae (a shrub, likely *E. rubrum*), *A. pumila* (a cushion-type evergreen), Asteraceae (herb), *Gunnera* (herb), Apiaceae undiff. (herb), *Ephedra* (LDT), Cyperaceae (aquatic), *Podocarpus* (LDT), Caryophyllaceae (herb), and Rosaceae (herb). Figure 4 plots the CONISS cluster analysis for the pollen taxa by percentage for Unit 1 (12.7–12.4 ka BP), Unit 2 (12.1–12.4 ka BP), Unit 3 (10.3–12.1 ka), Unit 4 (8.8–10.3 ka BP), Unit 5 (7.2–8.8 ka BP), and Unit 6 (7.2–2.3 ka BP).

Due to the grass-dominated plant community of the Falklands (Groff et al., 2020), we focus primarily on the pollen accumulation rate (PAR) records. In grass-dominated systems, PAR often provides a more faithful signal

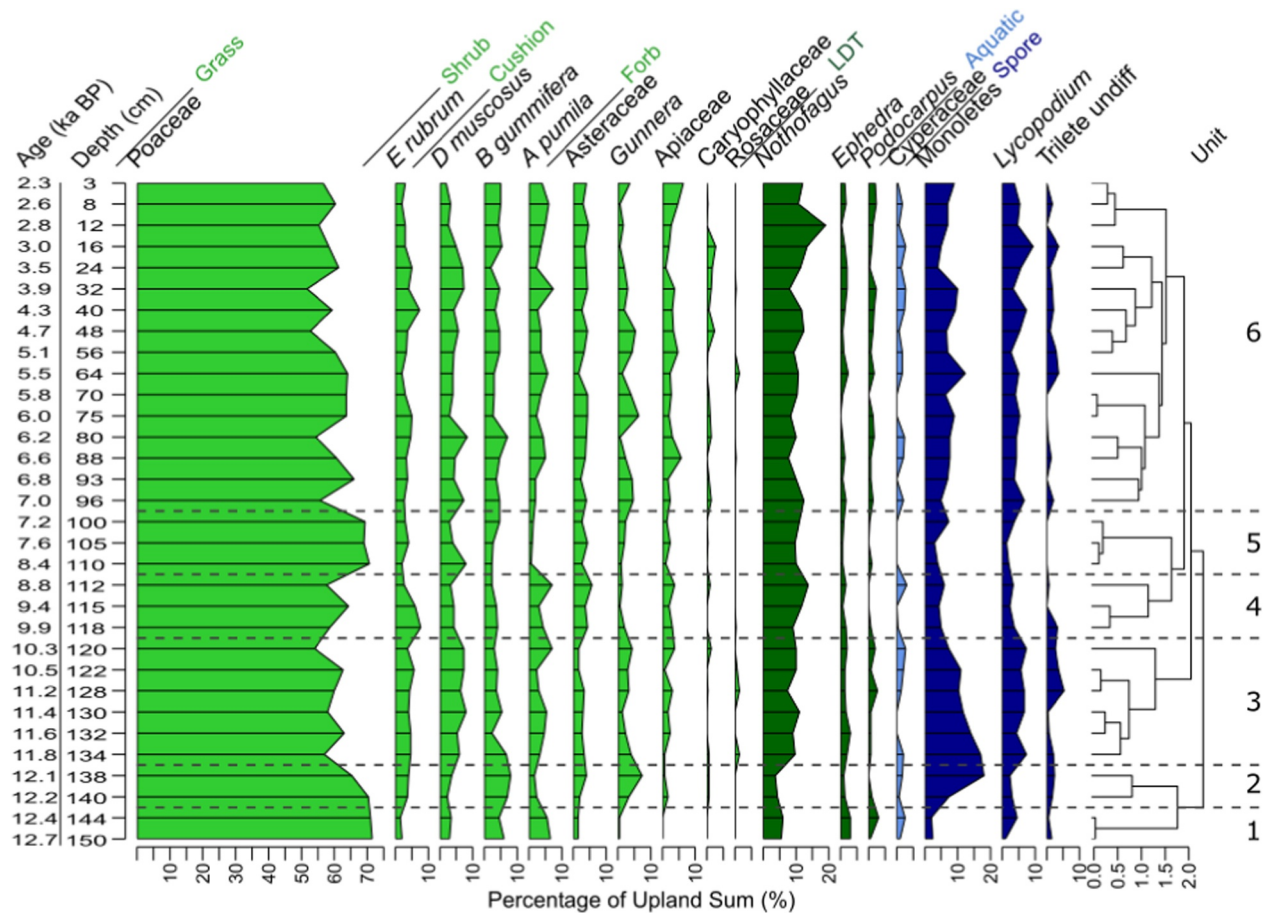


Figure 4. Pollen assemblage sorted by age (cal. yr BP), total core depth (cm), and sample number to the left. Data are plotted as pollen taxa percentage of the upland sum (%), with taxa sorted into the plant groups: grass, shrubs, cushion, herb, LDT, aquatic, and spore (top). Upland plant sums include grass, shrub, cushion, herb, and LDT (light and dark green). The CONISS clusters (indicated by the dendrogram) are identified by letter (1–6).

of vegetation abundance than percentages due to the overproduction of grass pollen (Groff et al., 2020; Hall, 1994; Julier et al., 2017). However, this advantage depends on having reliable accumulation/chronology data. A CONISS cluster analysis grouped the pollen PAR time series into six units (Figure 5; a–f). The basal Unit A spans 12.1–12.7 ka BP followed by Unit B (11.2–12.1 ka BP), Unit C (8.4–11.2 ka BP), Unit D (7.0–7.6 ka BP), Unit E (3.5–7.0 ka BP), and Unit F (2.3–3.5 ka BP). We also compare our PAR record to the pollen assemblage plotted as concentration in Figure S2 in Supporting Information S1. The Tarn 2 pollen record shows variable upland PAR through the last 13,000 years. The upland taxa PAR peaked at >200 grains/cm²/yr at 11.6–11.2 ka BP and 6.6–3.3 ka BP, with notable variation within individual peaks. This pattern of upland PAR is the same across plant groups (LDT, cushion, grass, herbal taxa, aquatics and spores) suggesting that peaks in pollen accumulation are concurrent. This pattern is also seen in the sediment–water interface sample from TAR2-19-1 as a modern baseline. Pollen concentration and accumulation rates were compared to the sediment accumulation rate (cm²/year) to account for any changes in sedimentation rate using two PCAs (Figure S2 in Supporting Information S1). We found that the upland concentration data broadly show a similar pattern to the accumulation rates, indicating that the large-scale changes we observed in the relative abundance of pollen likely reflect real changes in the abundance of constituent taxa, rather than solely changes in sedimentation or our choice of age model.

4.3. Earth System Modeling

We selected four outputs from the ESM model simulation of a poleward displacement of the SHW to a latitude (53°S), a degree south of the Falkland Islands (Figure 6) to show spatial changes in air temperature, relative humidity, sea-surface temperature (SST), and surface air temperature (SAT). Model output indicates that South

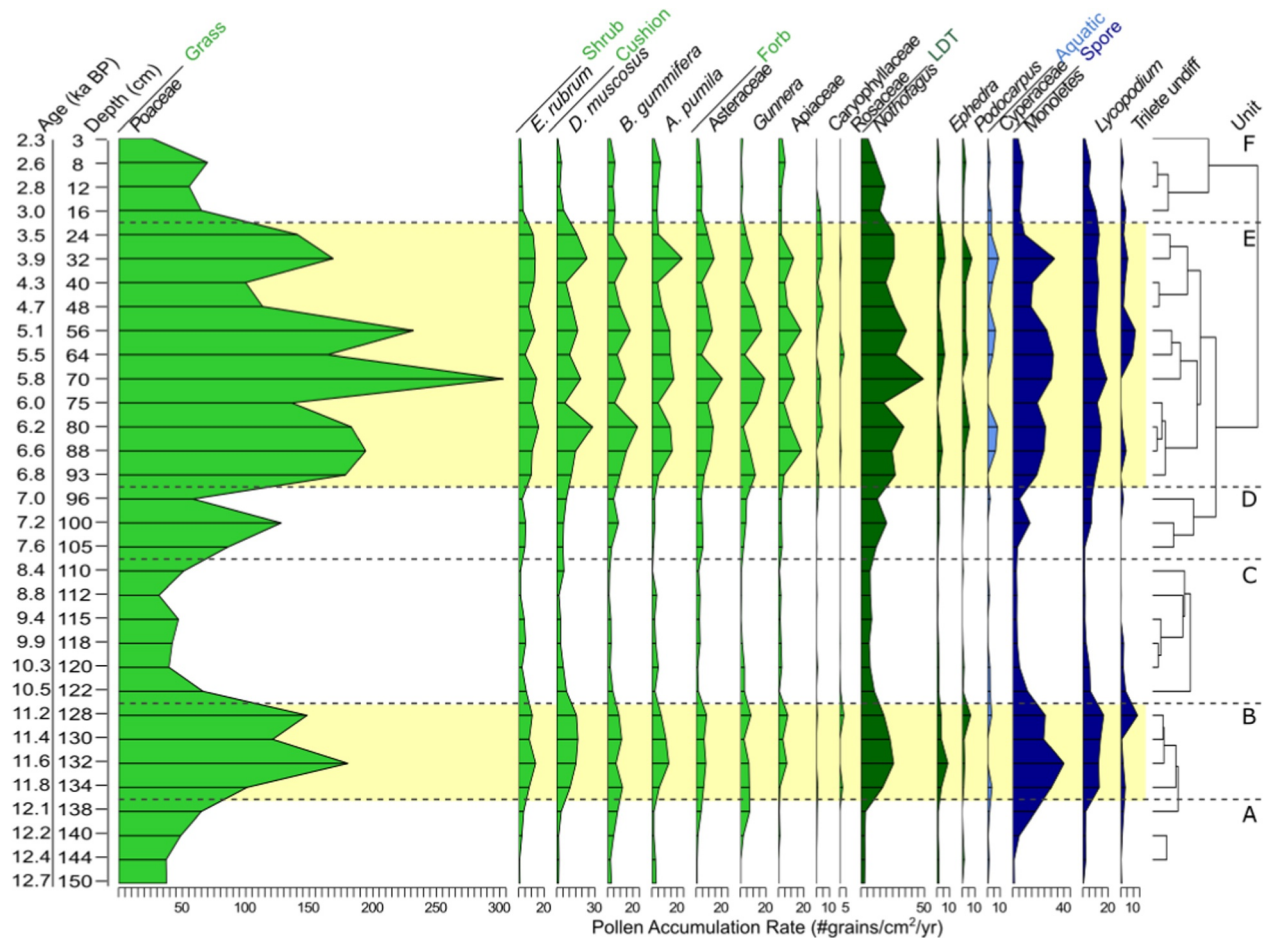


Figure 5. Pollen assemblage sorted by age (cal. yr BP), total core depth (cm), and sample number to the left. Data are plotted as pollen accumulation rate (#grains/cm²/yr), with taxa sorted into the plant groups: grass, shrubs, cushion, herb, LDT, aquatic, and spore (top). Upland plant sums include grass, shrub, cushion, herb, and LDT (light and dark green). The CONISS clusters (indicated by the dendrogram) are identified by letter (a–f). The yellow bands highlight the two units of increased PAR values across taxa.

Atlantic air temperatures at the latitude of the Falkland Islands become warmer as the SHW move south. This warming is enhanced at higher elevations, peaking at 400 hPa (7,000 m asl), and follows a west-to-east gradient. Relative humidity exhibits a shift to overall drier conditions with a southward-displaced wind belt. These drier conditions are particularly noticeable just at and east of the Falkland Islands at mid-elevation, 900–400 hPa (7,000–1,000 m), above the surface of the islands. SSTs and SATs both increase in the Falkland Plateau compared to similar latitudes in the Southeast Pacific, where SSTs cool but SATs warm. Surrounding our field site, the model predicts an increase of 0.6–0.7°C in regional SSTs and 0.8–0.9°C in SATs. At the elevation of Tarn 2 (~940 hPa), the climate dries, with a ~0.7% decrease in humidity and 0.7–0.8°C warming.

5. Discussion

5.1. Pollen Assemblage as an Indicator of SHW Shifts

Our Mt. Usborne pollen assemblage suggests that plant community composition remained broadly resilient throughout the Holocene. This pattern is the same for LDT, cushion, grass, and herbal taxa, and there are similar trends in both aquatics and spores (Figure 5 and Figure S5 in Supporting Information S1). The paleo and modern (e.g., surface) pollen assemblages reflect the taxa growing on the Mt. Usborne uplands today (Corcoran et al., 2022; Upson & Lewis, 2014). Other studies have noted that most taxa on the Falkland Islands and similar islands were established well before the start of the Holocene, possibly due to isolation of the islands (Barrow, 1978; Scaife et al., 2019) or potentially as glacial refugia (Barrow, 1978; Van der Putten et al., 2010).

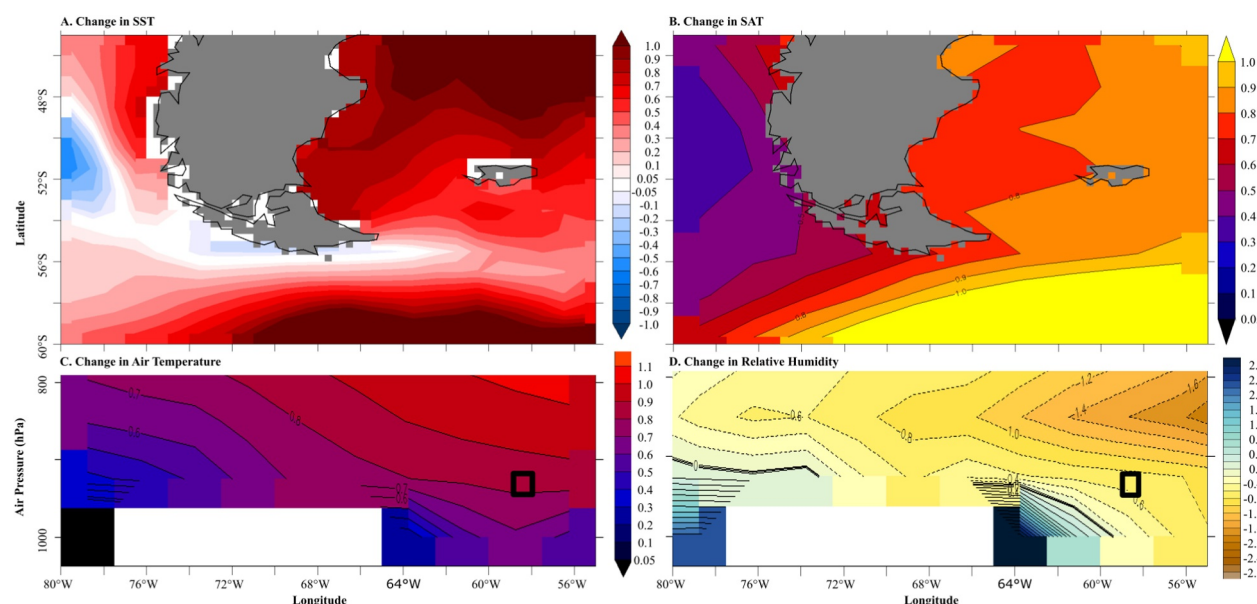


Figure 6. ESM model simulations showing changes in different climate variables resulting from a poleward shift of the SHW to 53°S, with Mt. Usborne marked with a black box. (a) Atmospheric temperature with elevation showing a 0.05°C–1.5°C warming, (b) change in relative humidity with elevation, ranging from 3.2% to –3.2%, (c) Map view of change in SST on a scale of 1°C to –1°C, and (d) change in surface air temperature (SAT) ranging from 1°C to 0.05°C.

The relatively constant taxa composition suggests that this plant community structure may be highly resistant to change, having persisted through 13,000 years of variable climate. Because taxa composition does not vary through time, we interpret increases in total upland PAR (and pollen concentration values) as reflecting increased productivity of the entire plant community, though this may be challenging to do with pollen alone.

Despite the relative resilience of the plant community composition, variations useful for climate reconstruction stand out in the pollen record. For example, changes in LDT pollen in the Falkland Islands long have been attributed to variations in SHW intensity, through wind strength, over the South Atlantic (Barrow, 1978; Groff et al., 2020; Monteath et al., 2022; Scaife et al., 2019; Thomas et al., 2018; Turney et al., 2016). Thus, we also infer that times of high LDT in our record reflect intervals of stronger SHW influence on the Falkland Islands via either more intense SHW or due to positioning of the wind belt closer to the islands. In addition, aquatic plants, mosses, and ferns that are indicative of wet conditions show the same pattern, increasing during periods of high LDT. This suggests that times of high wind intensity also were wet, linked with a possible increase in storm tracks. Moreover, our upland PAR/productivity record of local taxa also correlates strongly with LDT, suggesting that the wet, windy periods had more favorable growing conditions for Falkland Islands plants. We interpret the covariance among these three variables (upland PAR, LDT, wet taxa) as reflecting the underlying influence of the SHW, which form a zone of high wind intensity, precipitation, and overall storminess.

Other factors have the potential to affect our interpretation of the covariance of LDT and local plant productivity. For example, it is possible that some South American plants common to the Falkland Islands could be contributing to the local plant pollen sums (Moore, 1968; Zwier et al., 2022). We assume this overlap is minimal for most species as actualistic studies focusing on Poaceae have found only a limited number of long-distance transport grains even in windy locales (Frisk et al., 2022; Waudby et al., 2022) suggesting that Poaceae (which dominates our record, ~60%) is likely an indicator of local grass productivity. Another factor that potentially could affect our LDT record would be plant succession following deglaciation in South America, which would determine what pollen taxa would be available to be transported. However, *Nothofagus*, the most prolific LDT in our record, has been shown to be an early colonizer in deglaciated landscapes of South America (Moreno et al., 2019) and likely reached Tierra del Fuego (55°S) by ~17–15 ka BP (Heusser, 1989; Moreno et al., 2023). Pollen diagrams show the continuous presence of *Nothofagus* in southern South America since that time, and thus its pollen would have been available for transport to the Falkland Islands throughout the duration of our record. This LDT record may also be affected by SHW intensity as well as position. Variation in wind

velocity, in addition to latitudinal position, may impact the amount of aeolian transported materials (Perren et al., 2020). To address this issue, we rely on a multiproxy approach to determine SHW behavior.

Combined, the data suggest that the SHW had strong influence over the Falkland Islands producing highly productive but wet, windy conditions at 11.8–10.5 ka BP and 6.8–3 ka BP. We infer the wind belt may have been centered over the islands (~52°S) at those times. Less windy, drier periods of low productivity would correspond to times when the winds were weaker or migrated away from their modern position. For example, our ESM results suggest that displacement of the core of the westerlies to 53°S would result in warmer and moderately drier conditions in the Falkland Islands with relative humidity dropping by 0.7% with temperatures increasing by at least 0.7°C on Mt. Usborne. Overall, our data suggest that as the SHW decreased in local influence in the early Holocene (10.5–7.5 ka), likely by migrating south of the Falkland Islands, the terrain dried out and productivity decreased. As the westerlies are projected to continue a southern migration in the future (Goyal et al., 2021), our data imply that there could be a serious risk to the productivity of the islands' plant community as the warm, dry conditions return. However, our records also indicate that plant biodiversity is likely to be preserved on the genus level, provided conditions do not exceed those experienced in the early Holocene.

5.2. Paleohydrology on Mt. Usborne

Our interpretation of the pollen data in terms of moisture availability and influence of the SHW is broadly consistent with previous work by Spoth et al. (2023), who reconstructed hydrologic conditions on Mt. Usborne from plant wax isotopic records. Plant wax isotopes provide information about precipitation sources, hydrologic regimes, plant types, productivity, and soil erosion rates (Diefendorf & Freimuth, 2017). Spoth et al. (2023) specifically used isotopes from *n*-alkanes, in conjunction with a local modern calibration study (Corcoran et al., 2022), to infer the former position of the SHW, as well as relative evapotranspiration, from 23 ka BP to present (Figure 7). Here, we focus on indicators for relative evapotranspiration rates ($\epsilon_{\text{terr-aq}}$, difference in terrestrial and aquatic plant $\delta^2\text{H}$), moisture availability (from $\delta^{13}\text{C}$ values of terrestrial plant waxes), and relative position of the SHW compared to the Falkland Islands ($\delta^2\text{H}$ values of terrestrial plants; Spoth et al., 2023). The data suggest relatively high evapotranspiration and low water availability at the start of the Tarn 2 record (13 ka BP). The corresponding low PAR values, reflected by the aquatic taxa and spores, indicate either dry or locally inhospitable conditions for plants, with vegetation likely sparse. By 12.2 ka BP, however, water availability appears to rise, and evapotranspiration drops. These wetter conditions persisted until roughly 10 ka BP and coincide with a wet, windy period with increased productivity independently inferred from the pollen assemblage. We attribute these changes to stronger SHW influence at ~12 to 10.5 ka BP.

The upland PAR minimum, along with decreases in both LDT and wet indicators at 10.5–6.8 ka BP, coincides with a pronounced period of low moisture availability and high relative evapotranspiration at roughly 10–6 ka BP, based on plant waxes. We suggest that these changes reflect movement of the SHW away from the latitude of the Falkland Islands starting at ~10 ka BP. From isotopic values of past precipitation inferred from terrestrial plant wax $\delta^2\text{H}$, Spoth et al. (2023) suggested that the SHW moved to a position south of the Falkland Islands at that time. A similar interval in South America, the “Early Holocene Warm/Dry Period” (Moreno et al., 2018) also has been linked to a southern-shifted wind belt (Lamy et al., 2010; Villacís et al., 2023). This interval also has been linked to a vegetation composition shift on East Falkland (see Section 5.3). Introduction of warm, dry conditions at the latitude of the Falkland Islands is consistent with model results showing the effects of a southward shift of the wind belt.

After ~6 ka BP, the long-chain (terrestrial) hydrogen isotopes reflective of precipitation source suggest a gradual northern migration of the SHW to their modern position over the Falkland Islands (Spoth et al., 2023). This proposed migration coincides with decreased relative evapotranspiration with increasing water availability in the plant-wax record paired with an increase in LDT, wet taxa and upland productivity in the pollen data. Combined, these trends are suggestive of a SHW location near the Falkland Islands. Overall, there is a general agreement among these independent proxies derived from the tarns on Mt. Usborne.

5.3. Comparison to Prior Pollen Records From the Falkland Islands

Pollen data are typically represented as a percentage of the upland sum, which allows for an interpretation of the relative abundance of taxa in a community through time. In contrast, pollen accumulation rates ($\# \text{grains}/\text{cm}^2/\text{year}$) represent fluctuations in a given taxon that are independent from other constituents in the community (e.g., von

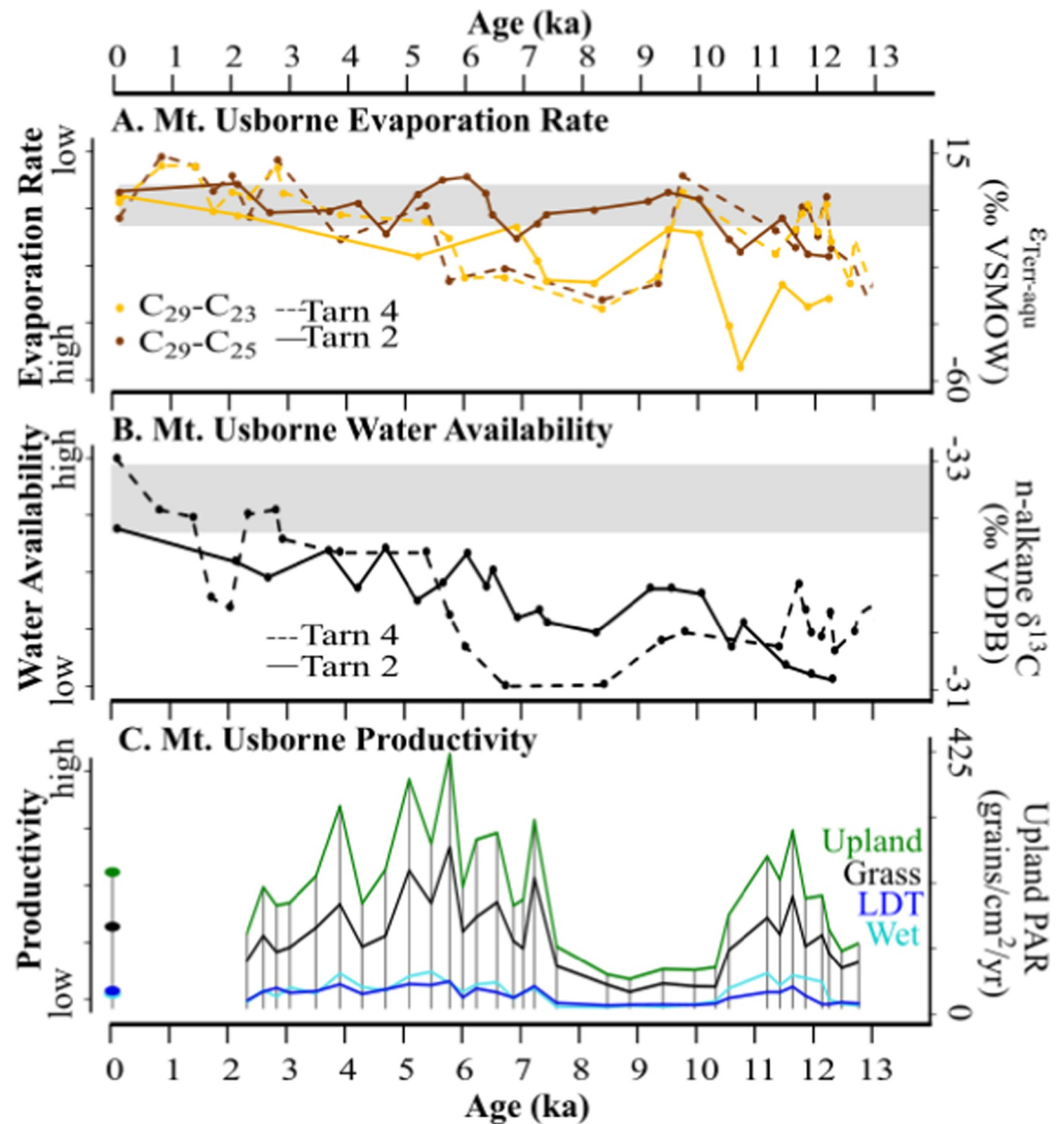


Figure 7. A compilation of pollen and plant wax biomarker isotope proxies from Mt. Usborne. Panels (a) and (b) are the plant wax proxies from Spoth et al. (2023): (a) relative evaporation rate using $\epsilon_{\text{terr-aq}}$, and (b) water availability from terrestrial plant wax $\delta^{13}\text{C}$. Panel (c) plots the upland sum PAR (green) from this study as a productivity indicator along with grasses (black), LDT (blue) and wet indicators (moss, ferns, aquatics; light blue) for comparison.

Post, 1916; Welten, 1944). Pollen accumulation rates can be informative not only as productivity indicators, but also in records with periods of high taxonomic turnover or where one taxon is particularly abundant, as is the case in the Falklands. We first compare our PAR pollen record to that of Groff et al. (2020) from the area of Surf Bay, East Falkland and Thomas et al. (2018) from Canopus Hill, East Falkland (30 m asl), because they are the only published studies for the Falkland Islands plotted as PAR. Notably, there are not many similarities between the lowland peat derived pollen records and Mt. Usborne records (Figure 8). Some of the differences between these records may arise from the distinct ecosystems (coastal tussock grass and Ericaceous-grass peatlands vs. montane-feldmark) and the different mediums (peat vs. lacustrine) for the paleorecord. As noted by Groff et al. (2020), coastal productivity is primarily controlled by seabird population which, in turn, is driven by sea ice influencing migration and hunting behavior. In contrast, inland sites may have a more direct link with SHW shifts as relatively few fauna are present at elevation, and seabirds are not typically observed there. Productivity on Mt. Usborne increased at ~11.5 ka BP and in the mid-Holocene at 6.8–3 ka BP, whereas at Surf Bay, it does not

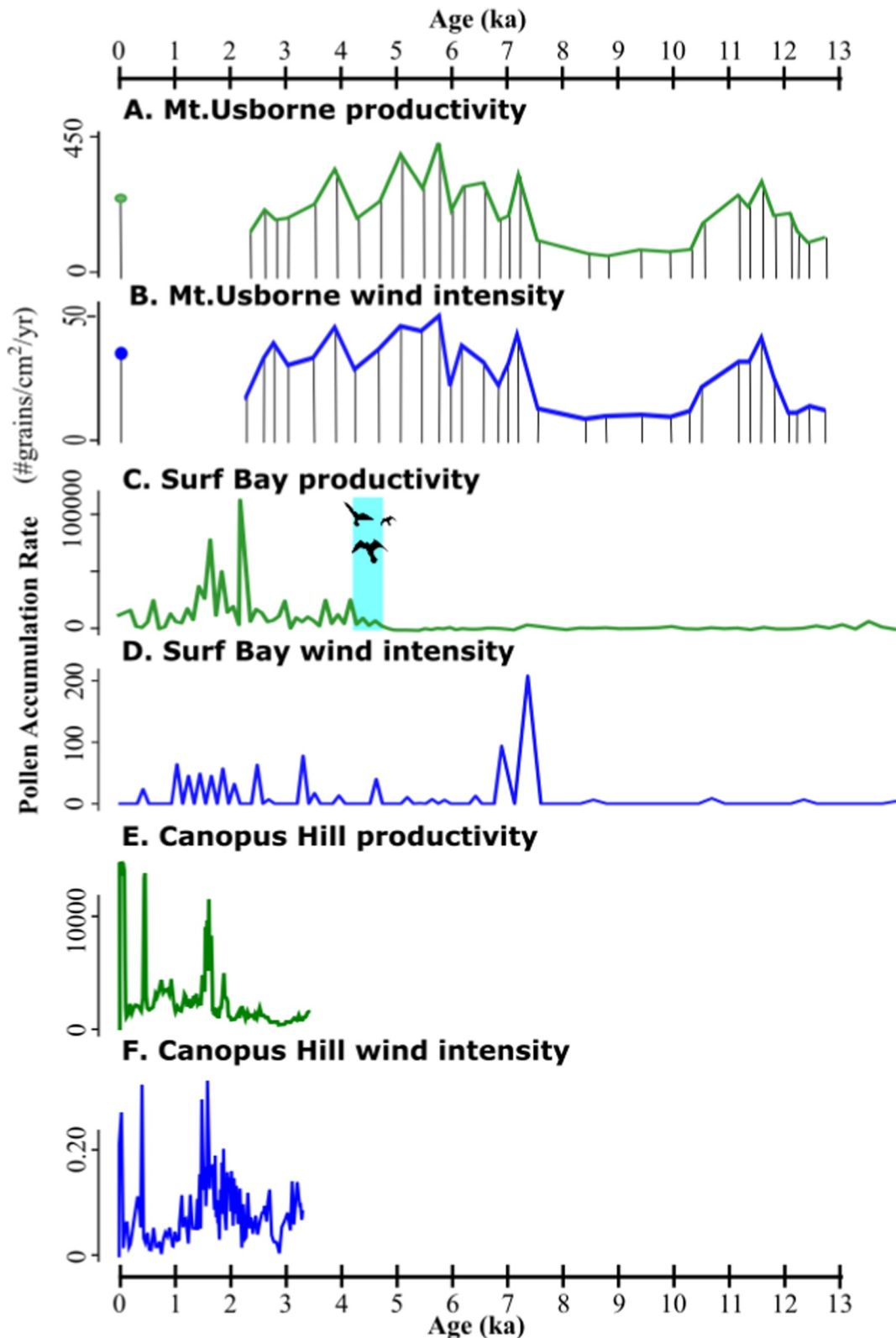


Figure 8. A compilation of pollen assemblages from East Falkland from the last 13,000 years. The upland sum PAR of Mt. Usborne (panel a, this study) is plotted in green with two yellow boxes highlighting periods of increased productivity along with wind intensity plotted in blue (panel b). Surf Bay pollen assemblage (panels c and d, Groff et al., 2022) and the Canopus Hill assemblage (panels e and f, Thomas et al., 2018) was extracted from a coastal peatland. Coastal productivity is plotted as upland sum PAR (green, c and f) and wind intensity is plotted in blue with the PAR of LDT (d and f). A period of seabird introduction to the Surf Bay site is highlighted in light blue.

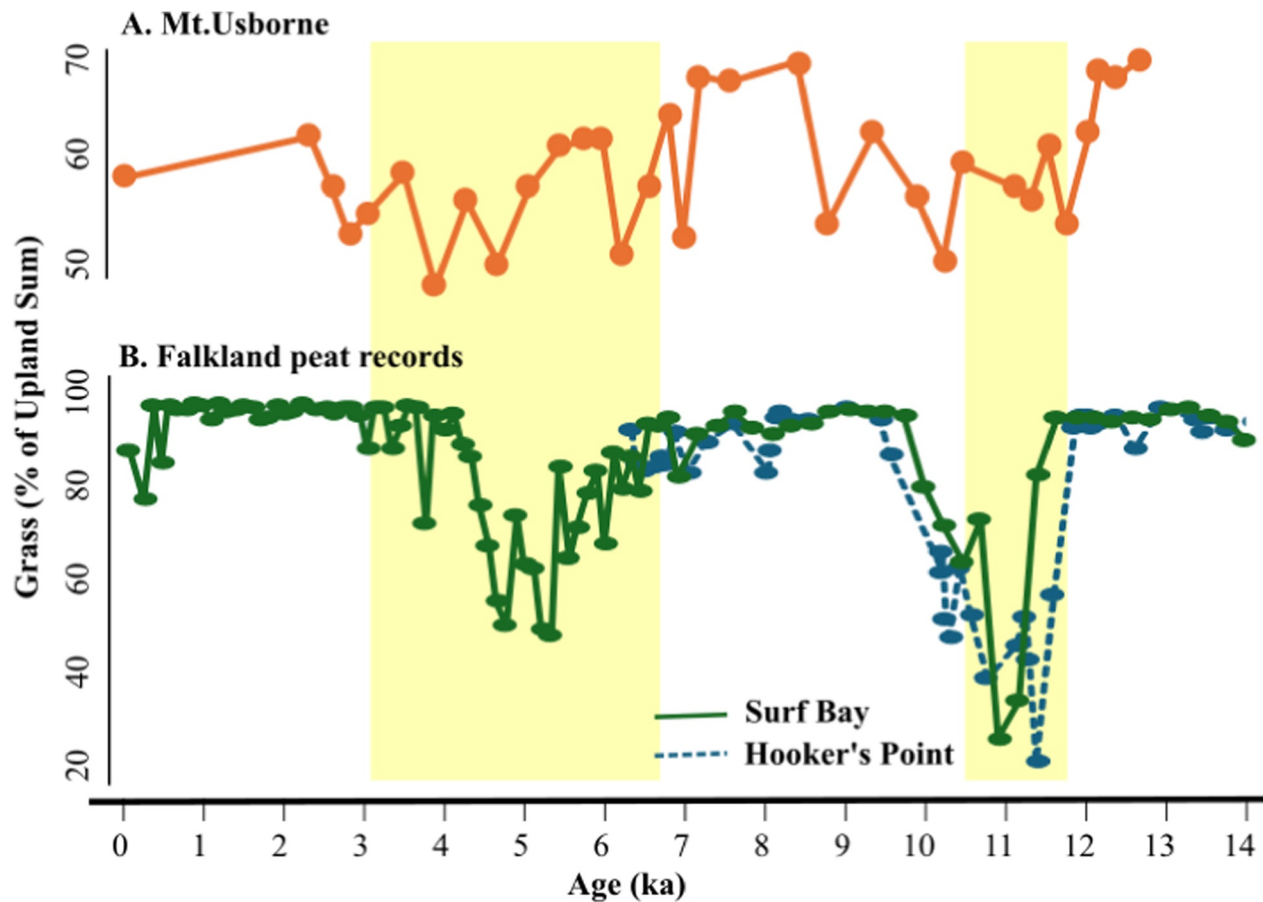


Figure 9. Comparison of grass percentage across Falkland pollen assemblages. Mt. Usborne (a) grass percentage of upland sum is plotted with the yellow bands representing intervals of increased productivity at the site. Panel (b) plots the grass percentage of the upland sum from Monteath et al. (2022, dashed line) and Groff et al. (2020, solid line).

increase until after 5 ka BP (Figure 8c). Moreover, this increase in coastal productivity has been linked to biochemical signatures related to the first incursions of sea birds at 4.8 ka BP (Groff et al., 2020), which deposited marine-derived nutrients onto coastal grasslands. This lag in coastal productivity until the mid-Holocene previously has been attributed a delayed accumulation of the peatlands (Payne et al., 2019). However, comparison of these two sites before 4 ka BP indicates that upland PAR pattern and shifts in community composition are not responding to the same drivers even before the seabird influence. In contrast, the Canopus Hill record of Thomas et al. (2018; Figures 8e and 8f) shows a pattern for upland PAR and LDT *Nothofagus* similar to Mt. Usborne, suggesting that increased SHW influence may drive the productivity of this Ericaceous-grass peatland and the montane-feldmark of Mt. Usborne more so than the Tussac grass-dominated Surf Bay site (Groff et al., 2020) occupied by seabirds. Unfortunately, any further comparison between Canopus Hill and Mt. Usborne is limited by the marginal temporal overlap of the pollen records.

Pollen relative abundance data from Surf Bay by Groff et al. (2020) and an adjacent study at Hooker's Point (~5 m asl; published by first Scaife et al. (2019) then expanded by Monteath et al. (2022)) provide additional insights about the compositional changes at Mount Usborne. Hooker's Point is described as a coastal grassy peat dominated by *Cortaderia pilosa* (whitegrass) and *Poa alopecurus* (bluegrass) today. Both coastal sites identify a decrease in grass percentage at 12–10 ka BP to 40%–20% and Surf Bay has a second decrease at 6–5 ka BP to ~60% (Figure 9b). Mt. Usborne also shows decreases in grass at 12–10 ka BP and 6–3 ka BP (Figure 9a). Notably, the decrease in the percentage of grass for these three records occur during the two high productivity units identified in the PAR-derived CONISS diagram at 11.8–10.5 ka BP (Unit B) and 7.0–3.5 ka BP (Unit E). These comparisons across sites highlight the different ecological responses across the islands and the importance of spatial context. Notably, both coastal sites and Mt. Usborne (Figure 9 and Figure S5 in Supporting

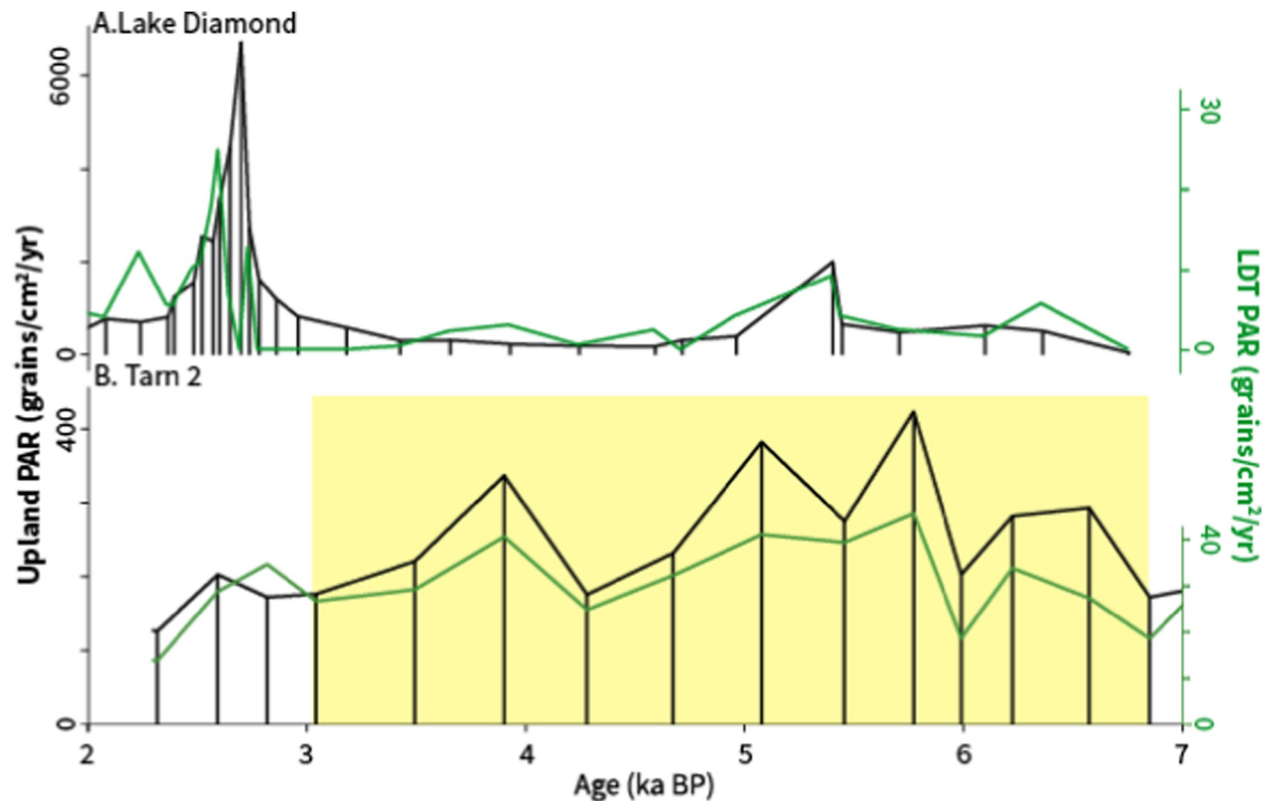


Figure 10. Pollen assemblage records from Tarn 2, Falkland Islands and Lake Diamond, South Georgia between 7 and 2 ka BP. The Lake Diamond (a) pollen assemblage record plots the upland sum (black) as a proxy for productivity and LDT (green) as a proxy for wind intensity. Panel (b) displays the upland sum (black) and LDT (green) as proxies for increased SHW influence. The yellow box depicts Unit B from the CONISS (Figure 4) tied to increased SHW influence for the Falkland Islands.

Information S1) have a relatively high percentage of grass during the Early Holocene Warm Dry Interval between ~10 and 6 ka BP. Combined with biomarker record interpretations, we suggest this agreement is consistent with a more regional, South American-South Atlantic scale, dry climate signal.

5.4. South Atlantic Comparison

A latitudinal transect of climate records provides insights into the behavior of the SHW and their influence on regional climate. Here, we compare our data from the Falkland Islands with similar records from Lake Diamond (16 m asl) on South Georgia (54°S; Zwier et al., 2022; van der Bilt et al., 2022) on the opposite side of the Antarctic Convergence. Both sites have pollen and plant wax isotope records interpreted to reflect SHW behavior over the Holocene. Similar to the Mt. Osborne pollen assemblage, the South Georgia plant community is composed primarily of grasses, and the PAR of individual species, including LDT taxa, broadly follow the pattern of upland PAR (Zwier et al., 2022), also similar to Mt. Osborne. Zwier et al. (2022) linked the overall pattern in PAR in South Georgia to coeval migration of the Subantarctic front and the southern margin of the SHW, both of which drive regional temperatures. Thus, based on interpretations from both records, the shift of the SHW south of the Falkland Islands should decrease productivity and cause drier and less windy conditions at Mt. Osborne but wetter and windier conditions in South Georgia with an overall increase in productivity (Figure 10). Lake Diamond also has a plant-wax isotopic record constructed from the same *n*-alkane chain lengths and similar source taxa as the data at Mt. Osborne. However, in contrast to interpretations for the Falkland Islands, where times of high wind intensity correspond to wet conditions, van der Bilt et al. (2022) suggested that high relative evapotranspiration ($\epsilon_{\text{terr-aq}}$) at Lake Diamond (dry conditions) occurred during periods of increased SHW influence, with a poleward position of the westerlies closer to South Georgia. This opposing relationship between evapotranspiration and SHW influence at these two sites highlights the importance of modern calibration studies to

elucidate the local response to changing climate systems. Future work should focus on the geographic and ecological factors that influence these differences.

The upland PAR and LDT records of Lake Diamond and Mt. Usborne are broadly inverse of each other; periods of high PAR and LDT on Mt. Usborne are coeval with low PAR and LDT for the Lake Diamond region. The temporal offset of these records, paired with their latitudinal difference, suggests that LDT and plant productivity could be interpreted as shifts in the position of the SHW. The Lake Diamond sediment core record transitions from a peat core to a lacustrine core at 7.3 ka BP, with pollen PAR values that remain low until 3 ka BP. This period of low PAR at South Georgia is mirrored by a peak in upland PAR, LDT, and wetness indicators in the Falkland Islands, interpreted to represent an equatorward shift of the wind belt at 7–3.5 ka. At ~3–2.5 ka BP, Lake Diamond had a period of high PAR and LDT while PAR and LDT at the Falkland Islands decreased slightly during an interval of overall high productivity. This may reflect the superposition of short-term (possibly centennial) fluctuations on top of a longer-term shift that cannot yet be resolved with the existing records. There are no data from the piston core for the last 2 ka, however, the sample from the sediment-water interface suggests continuation of this pattern with a period of relatively high productivity and LDT corresponding to relatively low values at Lake Diamond today.

6. Conclusions

- The pollen assemblage at Mt. Usborne suggests that the plant community composition has been consistent over the last 13,000 years and has been relatively resilient to climate change.
- Upland PAR, interpreted as a measure of plant productivity, varies directly with long-distance traveled pollen (LDT), moss, ferns, and aquatic plants, as well as with plant-wax isotopes reflecting moisture availability and evapotranspiration. We link high productivity with periods of increased wind intensity and greater water availability and attribute these intervals to stronger influence of the SHW over the Falkland Islands.
- Based on pollen and plant-wax isotope data, we infer increased influence of the SHW at Mt. Usborne at 11.8–11.2 ka BP and 6.8–3.5 ka BP. We reconstruct a decrease in influence at 10.5–7.5 ka BP, which we attribute to movement of the wind belt south of the islands. This interval falls during the Early Holocene Warm Dry Period (as defined in South America).
- Similar to our findings, ESM simulations show that movement of the SHW to a position south of the Falkland Islands results in warming and drying at Mt. Usborne. The model also shows that drying is greater at elevation and that there is a west-to-east gradient.
- Preliminary comparison of pollen records between Mt. Usborne and Diamond Lake in South Georgia suggests an out-of-phase relationship between the two regions, particularly in LDT and upland PAR. Further research is needed to fully understand the differences in plant wax indicators at these two sites.

Inclusion in Global Research Statement

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

All data are available at PANGAEA (Spath-Ascencio et al., 2026).

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