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Spatially coherent late Holocene Antarctic Peninsula surface air temperature variability

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ABSTRACT

The Antarctic Peninsula experienced a rapid rise in regional temperature during the second half of the 20th century, but the regional pattern of multi-centennial temperature changes and their dynamical drivers remain poorly understood. Here we use proxies of biological productivity in rare, deep moss banks to infer past surface air temperature changes on the Antarctic Peninsula and identify the drivers of these changes. Late Holocene temperatures are broadly consistent between the low-elevation moss bank records and a high-elevation ice core site, and we conclude that variation in the strength of the westerlies, linked to the Southern Annular Mode, is the most likely driver. Our data do not support a hypothesized persistent temperature dipole over the Antarctic Peninsula related to a strong influence of El Niño–Southern Oscillation. Rates of change in biological productivity on the peninsula over the 20th century are unusual in the context of the late Holocene, and further warming will drive rapid future increases in moss growth and microbial populations.

INTRODUCTION

The Antarctic continent and surrounding ocean have experienced significant climatic changes over the past 60 yr (Turner et al., 2005). These are especially pronounced in the Antarctic Peninsula (AP) region, with an increase in air temperature (Nicolas and Bromwich, 2014) and decreases in sea ice cover around the western AP linked to strengthening westerly air circulation and a stronger Southern Annular Mode (SAM) (Matear et al., 2015). Other physical consequences are loss of terrestrial ice mass (Cook et al., 2016), collapse in marine ice shelves (Cook and Vaughan, 2010), and changes in biological systems in the sea (Ducklow et al., 2013) and on land (Cannone et al., 2016). The direction and magnitude of regional changes since the mid–20th century are now well known, but longer-term patterns and dependencies are still poorly understood (Roberts et al., 2017). An ice core record shows that the recent rapid warming is unusual, but not unprecedented, over the past 2000 yr for the northeastern AP (Mulvaney et al., 2012), and a downturn in recorded AP temperature over the past two decades suggests that natural temperature variability in this region is high (Turner et al., 2016).

Critical questions remain over (1) whether temperature variability on the AP is spatially coherent over multi-centennial to millennial time scales; and (2) whether the relationships between past surface air temperature (SAT) and ocean records can satisfactorily explain the underlying causes of regional climate variability. It is now clear that SAT increase was spatially coherent over the AP during the late 20th century (Steig et al., 2009; Nicolas and Bromwich, 2014; Jones et al., 2016) and probably the past 300 yr (Thomas et al., 2009; Stenni et al., 2017), but there are no proxy data capable of testing the spatial pattern of SAT over longer multi-centennial and millennial time scales. Proxies for the marine environment around the AP suggest a more complex picture of variability. On the eastern AP, ocean proxies largely reflect SAT (Minzoni et al., 2015) as recorded in the nearby ice core record (Mulvaney et al., 2012). In contrast, a sea-surface temperature (SST) reconstruction from the Palmer Deep on the western AP (Shevenell et al., 2011) has been used as evidence of asynchronous temperature variability and an east-west dipole in temperature across the AP (Mulvaney et al., 2012) over millennial time scales, related to El Niño–Southern Oscillation (ENSO).

Here, we present novel proxy records from rare, deep moss banks (Fig. DR1 in the GSA Data Repository[1]) that primarily reflect annual and growing-season SAT (Royles et al., 2013; Jones et al., 2016; Amesbury et al., 2017) in the western and northern AP over the past 4000 yr. We suggest that millennial-scale SAT changes are spatially coherent across the AP and argue against a persistent temperature dipole. We contend that the observed shifts in late Holocene climate on the AP are largely explicable by changes in westerly atmospheric circulation and the SAM, and that long-term shifts in ENSO state were less important in driving AP surface air temperature.

METHODS

Moss banks are present sporadically along most of the length of the AP (Fig. 1). Cores were collected in A.D. 2012 and 2013 from a series of sites (Fig. DR1): Elephant Island (61.111°S, 54.824°W), Barrientos Island (62.408°S, 59.753°W), Norsel Point (64.759°S, 64.084°W), Green Island (65.322°S, 64.151°W), and Leonie Island (67.602°S, 68.343°W). Basal radiocarbon ages established the age of moss bank initiation, and age-depth models were developed

[1]GSA Data Repository item 2018414, full details of field, laboratory, and data analysis methods, and Figures DR1–DR3 and Tables DR1–DR3, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

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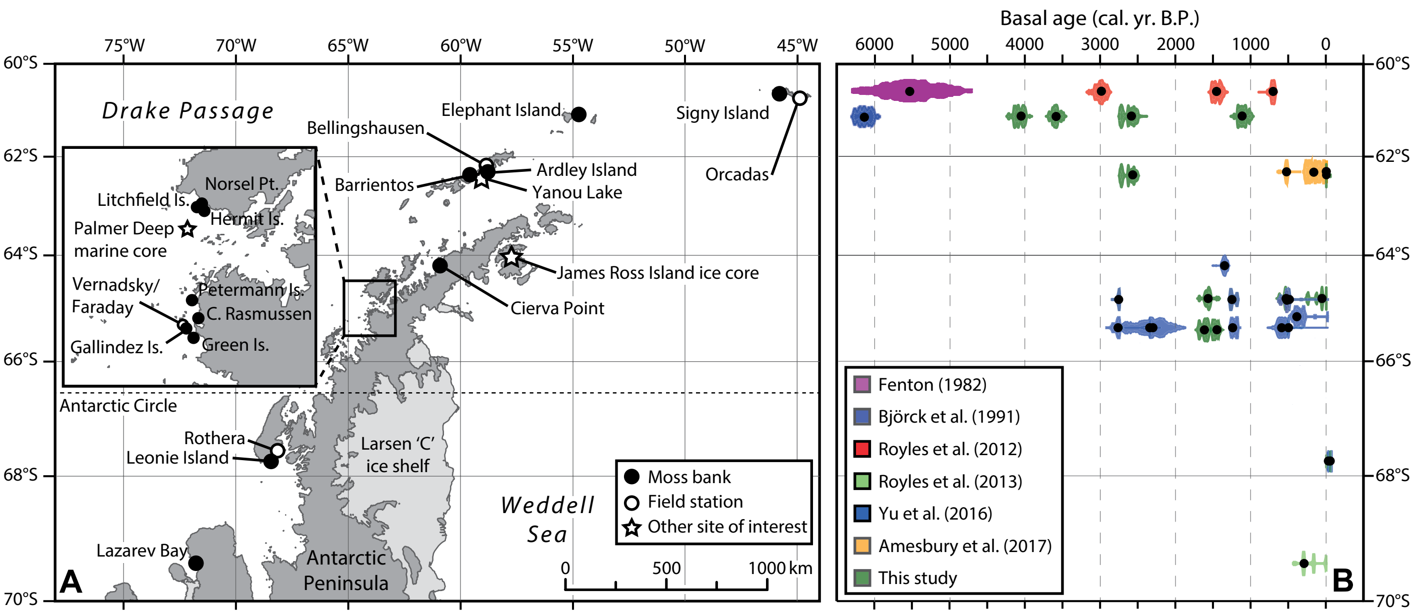

Figure 1. Location and dates of initiation of moss banks along the Antarctic Peninsula with other published data (Fenton, 1982; Björck et al., 1991; Royles et al., 2012, 2013; Yu et al., 2016; Amesbury et al., 2017). A: Site locations. B: Basal age estimates with 95% probability distributions. Cal. yr B.P. indicates calibrated radiocarbon years before A.D. 1950. Pt.—Point; Is.—Island; C.—Cape.

from radiocarbon and ^{210}Pb ages from five deep cores (Fig. DR2). Mass-accumulation rates were derived from bulk density measurements, and stable carbon isotopes in moss cellulose were expressed as carbon isotopic discrimination (Δ^{13}C), which is a proxy for seasonal photosynthetic conditions (Royles et al., 2012). Microbial productivity was estimated from counts of testate amoebae (Royles et al., 2013).

MOSS BANK INITIATION ON THE ANTARCTIC PENINSULA

Initiation ages for the moss banks vary between ca. 4.1 ka and the early 20th century, with the oldest moss banks occurring farther north (Fig. 1). This could indicate a gradual southward colonization of the mosses, but it is more likely that older moss banks existed farther south in the past but were destroyed by subsequent ice advance, as shown by patterns of initiation and kill ages of ice-entombed mosses at 65°S (Yu et al., 2016). Given the generally warmer conditions through the mid-Holocene (Mulvaney et al., 2012), moss banks probably grew somewhere on the AP for much of the Holocene, and the north-south trend in initiation age is a likely function of a combination of past fluctuations in climate and protection from later glacial activity in the more northerly locations.

BIOLOGICAL PRODUCTIVITY AND CLIMATE VARIABILITY

Moss accumulation rate and microbial population were used to estimate changes in biological productivity in three cores from Elephant Island in the northernmost AP and in two cores from Green Island, the southernmost extensive, deep, older moss banks (Fig. 1). The use of biological productivity measures as proxies for SAT is based on records of the past 150 yr (Royles et al., 2013; Amesbury et al., 2017) and correlations with the meteorological temperature record (Table DR1 in the Data Repository). The congruence between the 20th-century moss bank record, instrumental data, and other temperature proxies from ice cores, bore holes, and SST (Jones et al., 2016) also supports this interpretation. Stronger correlations with annual SAT than with summer SAT suggest that the length of the growing season is as important as the peak summer temperature in determining moss growth and microbial populations. Although growing degree day data are unavailable, monthly SAT data suggest that the growing season extends into March and even April in some years. Stable carbon isotope records (Δ^{13}C) provide a further proxy reflecting changes in growing conditions driven by a combination of temperature and moisture conditions (Royles et al., 2012; Royles and Griffiths, 2015).

All of the proxies at both sites show a significant change in the last century (Fig. DR3), with large increases in accumulation rate and microbial productivity but significant declines in Δ^{13}C. The decline in Δ^{13}C suggests that instantaneous growing conditions have deteriorated over this period, despite the increased growth rates. We interpret this combined evidence as an increased length of growing season rather than improved growing conditions throughout the season. For example, suboptimal moisture conditions, particularly an excess of water, during a longer growing season could reduce the instantaneous photosynthetic rate but result in increased annual growth rate. This is consistent with the increased precipitation over the past few decades (Marshall et al., 2017). CO_2 fertilization is an additional, though not sufficient, explanation for increased moss growth (Royles et al. 2012).

To derive a regional index of biological productivity over multi-centennial time scales, we standardized the biological productivity records for each core and calculated 100 yr means (see the Data Repository). This regional record (Fig. 2C) shows generally high and variable biological activity in the earlier record (before ca. 1500 cal. yr B.P. [calibrated radiocarbon years before A.D. 1950]). This is supported by Björck et al. (1991), who also identified peaks in carbon accumulation rates prior to 1500 cal. yr B.P. at Elephant Island (Fig. 2A), and by Yu et al. (2016), who inferred a warm phase at Galindez Island, close to Green Island (Figs. 1 and 2B). Biological productivity declined after ca. 1500 cal. yr B.P., with especially low values at 700–400 cal. yr B.P., followed by a minor recovery until A.D. 1850–1950, and then a very rapid rise since A.D. 1950; the latter is also recorded by Yu et al. (2016) at Cape Rasmussen (Figs. 1 and 2B).

To test the relationship between the moss bank records and temperature changes elsewhere on the AP, we compared these patterns with ice core and ocean temperature proxies from the wider region (Fig. 2). The James Ross Island (JRI) ice core (drilled by the British Antarctic Survey) temperature reconstruction (Mulvaney et al., 2012) (Figs. 1A and 2D) shows generally higher and variable temperatures prior to ca. 1400 yr B.P., similar to a period of higher productivity in the moss banks. A hiatus in the record for two of the Elephant Island moss banks

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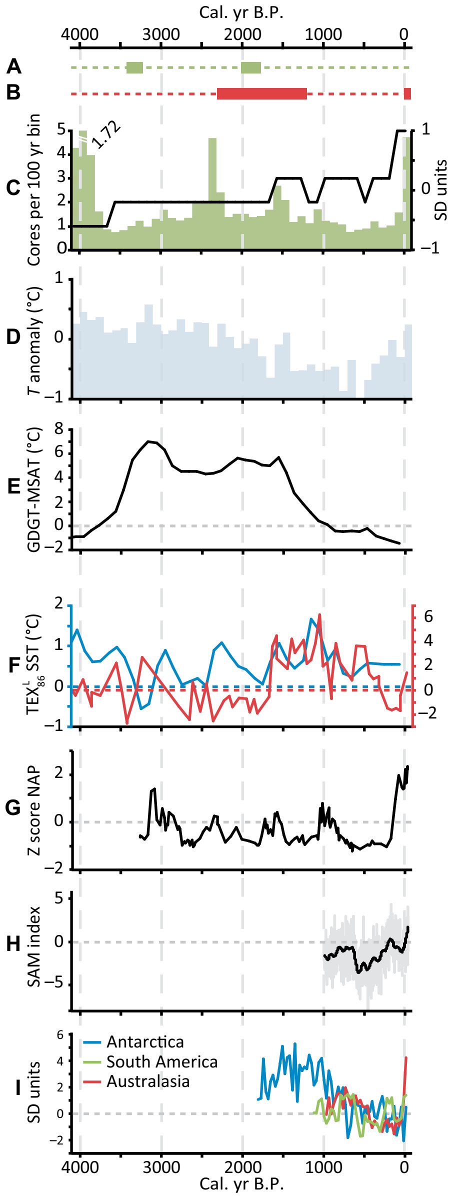

Figure 2. Composite record of changes in biological productivity as a temperature proxy compared with other paleoclimate proxies. A,B: Periods of rapid moss growth, from Björck et al. (1991) (A) and Yu et al. (2016) (B). C: Biological productivity derived from combining moss accumulation and biological productivity proxies from five cores (green bars), and number of cores covering each time period (black line). D: Temperature (*T*) reconstruction from James Ross Island ice core (drilled by the British Antarctic Survey) (Mulvaney et al., 2012; Fig. 1A). E: Summer mean surface air temperature (MSAT) record based on glycerol dialkyl glycerol tetraethers (GDGT) from Yanou Lake, Antarctic Peninsula (Roberts et al., 2017; Fig. 1A). F: Palmer Deep (Fig. 1A) sea-surface temperature (SST) reconstructions (Etourneau et al. [2013] in blue; Shevenell et al. [2011] in red). TEX$_{86}^{L}$—TetraEther index of 86 carbons (SST proxy). G: Pollen-based reconstruction of Southern Hemisphere westerlies (Moreno et al., 2014). NAP—non-arboreal pollen. Z core is an indicator species score. H: Southern Annular Mode (SAM) reconstruction for the past 1000 yr (Abram et al., 2014). I: Continental-scale 30 yr mean temperature reconstructions for Antarctica, Australasia, and South America (PAGES 2K Consortium, 2013).

(Fig. DR3) also occurs at that time, suggesting that growing conditions deteriorated, perhaps due to temporary extension of permanent snow banks at the higher elevations of these sites. The past millennium is characterized by low values in both the moss bank and ice core records, with an increase from ca. 500 yr B.P. and a rapid acceleration in the rate of change since A.D. 1950. The overall correlation between the AP biological productivity record and the JRI temperature record is 0.33 ($p < 0.03$), and for the past 1500 yr is 0.61 ($p < 0.009$). This suggests that there is broad correspondence between the records over the past 4000 yr, but that we can have more confidence in this relationship for the past 1500 yr, when correlation is stronger and the replication of the moss bank records is greatest. Both mass accumulation rate ($r = 0.65$, $p = 0.005$) and microbial productivity ($r = 0.56$, $p = 0.02$) have similar correlations with the JRI temperature record over the past 1500 yr.

TEMPERATURE CHANGE AND CLIMATE DRIVERS

The moss bank records and a lake record (Roberts et al., 2017) (Figs. 1 and 2E) suggest that late Holocene patterns of SAT change on the northwestern AP were similar to those shown by the JRI ice core on the eastern peninsula (Mulvaney et al., 2012), especially over the past two millennia. The combined terrestrial records therefore do not support the hypothesis of a persistent Antarctic temperature dipole, based on the antiphase behavior of an SST record from the Palmer Deep (Fig. 2F) with the JRI record (Mulvaney et al., 2012). The spatial coherence of the terrestrial proxy climate data, including our new data of SAT from the northwestern AP (Fig. 2A), suggest that other drivers of change need to be invoked.

Changes in the westerlies and the SAM have been an important influence on both ocean and atmospheric temperatures over the past few decades (Thompson and Solomon, 2002) and may also be the primary driver of changes on longer time scales. We examined reconstructions of Southern Hemisphere westerlies and the SAM, which are best developed for the past 1000 yr (Figs. 2G and 2H), the same period for which moss bank records are most robust. The SAM is thought to have undergone significant changes over the past 1000 yr with a marked downturn ca. A.D. 1400 (550 yr B.P.), followed by a gradual increase and strong upward trend in the past 100 yr (Figs. 2F and 2G), paralleling the pattern shown by the moss bank record. Longer-term relationships with the SAM are harder to establish, partly because of the reduced replication in the moss records before ca. 1500 cal. yr B.P. and partly because of increased uncertainty in other proxy records of the SAM. However, on the basis of the strong correspondence between the AP temperature and SAM records over the past 1500 yr, we conclude that the SAM is likely the dominant driver of centennial-scale late Holocene SAT variability on the AP. The AP warm phases inferred from moss growth records (Figs. 2A and 2B) and the long-term cooling trend after 1500 cal. yr B.P., in our new continuous record (Fig. 2C), are also reflected in Antarctic composite temperature records (PAGES 2K Consortium, 2013; Stenni et al.. 2017) (Fig. 2I), and the cooler conditions between 500 and 100 cal. yr B.P. are paralleled in Southern Hemisphere temperatures (Fig. 2I; Gergis et al. 2016), suggesting that multi-centennial AP temperatures are coupled with both regional and hemispheric temperature trends. All of the SAT records that cover the recent period except for the Antarctica composite (PAGES 2K consortium, 2013) (Fig. 2I) show a strong temperature rise beginning in the late 19^{th}–early 20^{th} centuries and especially post–A.D. 1950, suggesting that AP temperatures are closely linked to lower-latitude temperature changes rather than those of the rest of the Antarctic continent (Jones et al., 2016), although two other regions (West Antarctic Ice Sheet and the Dronning Maud Land coast) also now show a warming trend (Stenni et al., 2017).

RATES OF CHANGE AND IMPLICATIONS FOR THE FUTURE

Temperature rise on the AP over the late 20^{th} century was very rapid (Nicolas and Bromwich, 2014), but the JRI ice core record demonstrates that these recent (the past 50 and 100 yr) rates of change on the AP were not completely outside the bounds of natural variability (Mulvaney et al., 2012). The rates of moss bank growth since A.D. 1950 are also similar to those observed for some periods of more rapid growth before this time, but the majority of data values either exceed or are at the very upper end of the distribution of values recorded over the past 2000 yr (Fig. 3C), similar to the results from the JRI ice core. Periods of equally rapid growth are however recorded in individual moss banks at ca. 4000 cal. yr B.P. and 2300 cal. yr B.P. (Fig. 3A), based only on mass accumulation rate data. Agreement between all proxies, including the very high accumulation rates since A.D. 1950, the substantial changes in microbial productivity, and the shifts in $\Delta^{13}C$ values over the past 100 yr, however, suggest that the temperature-driven changes in these and other biological systems are unusual in the context of the late Holocene, particularly because they are recorded in every profile. In addition to rapid

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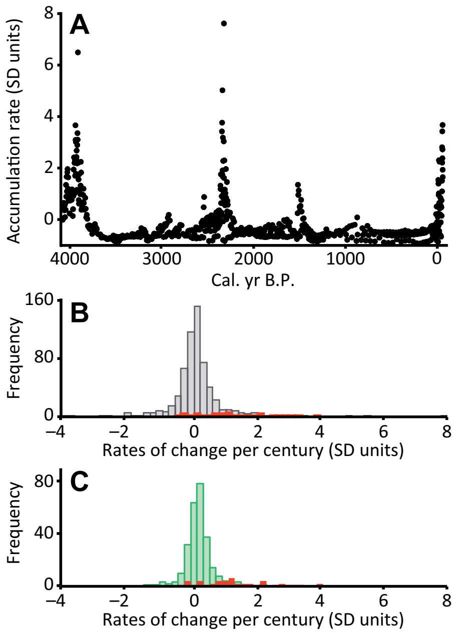

Figure 3. Previous 100 yr rates of change for moss accumulation data on the Antarctic Peninsula. A: All data points are from five cores for the whole record. B: Frequency distribution between start of record and A.D. 1950 (gray) compared with post–A.D. 1950 (red). C: Frequency distribution for past 2000 yr before A.D. 1950 (green) compared with post–A.D. 1950 (red)

increases in annual total moss and microbial productivity, a reduction in the quality of photosynthetic conditions indicated by declining $\Delta^{13}C$ in the moss suggests that the recent changes are driven by a rather different combination of climatic and environmental factors than earlier changes, likely including moisture conditions. Although very recent temperature rise on the AP has stalled temporarily since A.D. 2000 (Turner et al., 2016), longer-term future changes in the SAM may drive further warming in the region and result in large-scale terrestrial biological changes, alongside the predicted changes in the cryosphere and ocean.

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