# Recent Antarctic Peninsula warming relative to Holocene climate and ice shelf history

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**The Antarctic Peninsula is a region that has experienced very rapid warming over the last 50 years, and this has been attributed with the collapse of a number of ice shelves and accelerating glacier mass loss[1-7]. In contrast, warming has been comparatively modest over West Antarctica and significant changes have not been observed over most of East Antarctica[8-9], suggesting that the ice core palaeoclimate records available from these areas may not be representative of the climate history of the Antarctic Peninsula. Here we present an ice core record from James Ross Island that provides the first complete Holocene temperature history for the Antarctic Peninsula. The Antarctic Peninsula experienced an early Holocene temperature optimum followed by a long interval from ~9,200 – 2,500 years before present (yrBP; 1950AD) of stable temperatures similar to modern day levels. We find that the late Holocene development of ice shelves on the northeastern Antarctic Peninsula was coincident with pronounced cooling from 2,500 to 550 yrBP, which was part of a millennial-scale climate excursion with opposing anomalies on the east and west Antarctic Peninsula. Whilst warming of the northeastern Antarctic Peninsula began around 600 years ago, the rapid rate of warming over the last century is unusual in the context of natural climate variability over the last two millennia. The connection shown here between past temperature and ice shelf stability suggests that warming for several centuries had left ice shelves on the northeastern Antarctic Peninsula poised for collapse, and that continued warming to temperatures that now exceed the stable conditions that persisted here for most of the Holocene is likely to see ice shelf instability encroach further southward along the Antarctic Peninsula.**

The Antarctic Peninsula is currently one of the most rapidly warming regions on Earth (Fig. 1a)[1]. Historical observations since 1958 at Esperanza Station (Fig. 1b) document warming equivalent to 3.5 ± 0.8 °C per century. During this time a series of ice shelves stretching from Prince Gustav Channel to Larsen B on the northeastern Antarctic Peninsula have been lost[2-5], causing an acceleration of the feeder glaciers that drain ice from the Antarctic Peninsula[6]. To assess these recent rapid changes, a longer-term perspective on Antarctic Peninsula climate and the role that past atmospheric temperature has played in ice shelf stability is urgently needed[7]. To address this, an ice core was drilled to the bed of the ice cap on James Ross Island. This site lies off the northeastern tip of the Antarctic Peninsula, adjacent to the area that has witnessed a series of catastrophic ice shelf collapses since 1995 (Fig. 1b).

The 363.9m long James Ross Island (JRI) ice core provides a temperature reconstruction, based on deuterium:hydrogen isotope ratios of the ice (δD), that spans the entire Holocene and into the last glacial interval (Fig. 2; Methods Summary; Supplementary Fig. 1). The glacial age ice occurs in the final 5 metres of the JRI ice core; initial estimates suggest the record may extend to ~50,000 yrBP, although an unrealistically rapid isotopic transition implies that an unconformity may be present in the early deglacial interval of the ice core. Taking into account changes in ocean isotopic values[10-11], the isotopic composition of the glacial ice on James Ross Island is equivalent to temperatures which were approximately 6.1 ± 1.0 °C cooler than present (where present is 1961-1990 AD) during the Last Glacial Maximum (LGM)[12-13]. By comparison, the LGM is found to have been 7.4 °C cooler in Dronning Maud Land (EDML) and 9.3 °C cooler at Dome C (EDC) on the East Antarctic plateau[14].

The reduced magnitude of LGM-Holocene temperature change on the Antarctic Peninsula most likely reflects its more northerly position and proximal maritime influence. An alternative explanation could be that the JRI ice cap experienced changes in elevation at the LGM making this site appear isotopically-warmer than continental Antarctica. However, this interpretation would require that the JRI ice cap at the LGM was ~150 - 360 m lower than present[13], based on EDML and EDC temperatures[14]. Such a reduction is inconsistent with glaciological evidence that the JRI ice cap had a confluence with the Antarctic Peninsula ice sheet in the Prince Gustav Channel until the early Holocene[15]. The JRI ice core thus adds to the glaciological history of the northern Antarctic Peninsula, with the reduced LGM-Holocene isotope contrast inferring that the ice cap cannot have thickened significantly at the LGM, and was not overrun by isotopically-colder ice from the south.

The Holocene temperature history from the JRI ice core is characterized by an early Holocene climatic optimum that was 1.3 ± 0.3 °C warmer than present (Fig. 3). The magnitude and progression of this early Holocene optimum is similar to that observed in ice core records from the main Antarctic continent[16] . A marine sediment record from offshore of the western Antarctic Peninsula also shows an early Holocene optimum where surface ocean temperatures were determined to be ~3.5 °C warmer than present[17], while the George VI ice shelf on the southwestern Antarctic Peninsula was absent during this early Holocene warm interval before reforming in the mid Holocene[7].

Following this widespread early Holocene climate optimum, temperature on the Antarctic Peninsula decreased and the JRI ice core documents a long interval of stable climate that persisted from ~9,200 yrBP to 2,500 yrBP (Fig. 3). During this interval the mean temperature anomaly of 0.2 ± 0.2 °C indicates that conditions at James Ross Island were comparable to the warm temperatures observed at this site over recent decades. Likewise, marine temperatures on the western side of the Antarctic Peninsula[17] declined to reach a long-term mean that was close to present day values by ~8,000 yrBP. Within this interval of mid-Holocene stability the JRI isotope record indicates that conditions may have been only marginally warmer from ~5,000 to 3,000 yrBP than present. Various proxy evidence exists for a mid-Holocene warm period on the Antarctic Peninsula[7], although the lack of a clear consensus on its timing in this region may be explained by the small magnitude of this feature in the JRI temperature record compared with the well defined mid-Holocene climate optimum in continental Antarctic ice core records[16].

The Holocene ice shelf history along the eastern Antarctic Peninsula shows a strong connection to Antarctic Peninsula temperatures. Following the deglacial transition from grounded to floating ice in Prince Gustav Channel at ~10,000 - 8,000 yrBP[3,15], this area experienced intervals of seasonally open water through to ~1,500 yrBP[3]. Marine sediments indicate that a permanent ice shelf was only established here after ~1,500 yrBP and that the maximum ice shelf extent may have been reached as recently as a few centuries ago[3]. Further south, there is evidence for instability of the Larsen A ice shelf between 3,800 yrBP to 1,400 yrBP[5]. Further south again, the Larsen B ice shelf likely remained intact throughout the Holocene, although there is evidence that the ice shelf was progressively weakened by melting[4]. Combining the JRI temperature reconstruction with the marine sediment evidence shows that temperatures similar to present occurred in this region for much of the Holocene resulting in a regime where ice shelves were only transient features along the northern most part of the eastern Antarctic Peninsula and were undergoing decay further to the south. An additional new perspective is that recent warming to levels consistent with the mid Holocene meant that the ice shelves along the northeastern Peninsula were poised for the succession of collapses observed here over recent decades.

The late Holocene development of ice shelves fed from the northeastern Antarctic Peninsula appears to be related to millennial-scale climate variability in the region (Figs. 3 and 4a). After 2,500 yrBP the JRI isotope record documents pronounced cooling to temperatures that were on average 0.7 ± 0.3 °C cooler than present day between 800-400 yrBP (1150-1550 AD), and on a decadal time scale temperatures may have at times exceeded 1.8 ± 0.3 °C cooler than present. Late Holocene cooling has also been inferred from northeastern Antarctic Peninsula lake records[7,18]. The prominent millennial-scale cooling at JRI is matched by a similarly prominent but opposite warm excursion in marine temperatures to the west of the Antarctic Peninsula[17,19]. On the central spine of the Antarctic Peninsula a 500 year long ice core record from Dyer Plateau shows that temperatures here were approximately the same as present day at 450 yrBP[20], suggesting an east-west divide across the Antarctic Peninsula in this late Holocene climate oscillation. Thus, while orbital-scale climate changes have been consistent across the whole of the Antarctic Peninsula region, millennial-scale climate variability was particularly strong during the late Holocene and appears to have been characterized by opposing east-west temperature anomalies across the Antarctic Peninsula.

Opposing temperature anomalies on either side of the Antarctic Peninsula are a feature of the Antarctic Dipole, which is an interannual standing wave pattern that results in opposite temperature and sea ice anomalies between the Amundsen/Bellingshausen Seas and the Weddell Sea[21]. The observation of similar opposing climate oscillations on a millennial-scale provides an indication that the Antarctic Dipole may also influence long-term climate changes in the Antarctic Peninsula region. Deducing the exact mechanisms that have driven this late Holocene Antarctic Dipole-like pattern will require additional, well-dated palaeoclimate reconstructions to map the spatial extent of the climate anomalies. It is noted, however, that the development of this Antarctic Dipole-like feature during the late Holocene coincides with the well-documented maximum in El Niño activity (Supplementary Fig. 2), which plays a role in driving present day variability of the Antarctic Dipole[21]. Antarctic Dipole-like cooling of the Weddell Sea in the late Holocene, and the propagation of these ocean temperature and sea ice anomalies along the eastern Antarctic Peninsula by the Weddell Gyre, may have also aided the rapid establishment of ice shelves in this region during the late Holocene.

Sustained warming at James Ross Island began approximately 600 years ago (Fig. 4a). Lake sediments from Beak Island in Prince Gustav Channel also indicate warming beginning at ~1410 AD[18], and together these records demonstrate the absence of a widespread Little Ice Age signal on the Antarctic Peninsula that was comparable to northern hemisphere climate[22] (Fig. 4a). The overall rate of pre-anthropogenic temperature rise at JRI from 1400 AD to 1850 AD equates to 0.22 ± 0.06 °C per century. However, there are times in this interval when warming occurred at a much faster rate. Using annual-resolution data, trends were calculated for the JRI temperature record since 2,000 yrBP over moving 100-year intervals stepped by 1-year increments (yielding 1958 100-year analysis windows) (Fig. 4b). This analysis indicates that rapid warming trends exceeding 1.5 °C per century occurred at JRI during the intervals spanning 1518-1621 AD and 1671-1777 AD, and exceeded 1.25°C per century during the interval 296-415 AD.

Over the last 100 years the JRI ice core record shows that mean temperature has increased by 1.56 ± 0.42°C (Fig. 4a). This ranks as one of the fastest (upper 0.3%) warming trends at JRI since 2,000 yrBP based on the moving 100-year analysis windows, demonstrating that rapid recent warming of the Antarctic Peninsula is highly unusual although not outside the bounds of natural variability in the pre-anthropogenic era (Fig. 4b). The JRI ice core shows that the recent phase of warming on the northern Antarctic Peninsula began in the mid-1920s, and over the last 50 years has risen at a rate equivalent to 2.6 ± 1.2 °C per century. Repeating the temperature trend analysis using 50-year windows confirms the finding that the rapidity of recent Antarctic Peninsula warming is unusual but not unprecedented.

The long-term climate history provided by the JRI ice core shows that natural millennial scale climate variability has resulted in warming on the eastern Antarctic Peninsula that has been ongoing for a number of centuries and had left ice shelves in this area vulnerable to collapse during the recent phase of rapid warming. If warming continues in this region, as is suggested by its attribution in part to rising atmospheric greenhouse gas concentrations[7,23], then temperatures will soon exceed the stable conditions that persisted here for most of the Holocene. The association between atmospheric temperature and ice shelf stability in the past demonstrates that as warming continues ice shelf vulnerability is likely to progress further southwards along the Antarctic Peninsula coast to affect ice shelves that have been stable throughout the Holocene, and may make them particularly susceptible to changes in oceanographic forcing[24].

## Methods Summary

The James Ross Island (JRI) ice core presented in this study was drilled in January-February 2008 at a site (057°41.10'W, 64°12.10'S, 1542 m elevation; Fig. 1) near the summit of Mount Haddington. The ice core was recovered to bedrock at a depth of 363.9 m. Mean annual temperature at this site is -14.4 °C, and mean annual accumulation is 0.63 m water equivalent[12,25]. The Holocene age scale for the JRI ice core, termed JRI-1, is based on a glaciological flow model with additional age control provided by fixed time markers derived from local and global volcanic events (Fig. 2; Supplementary Table 1). The temperature reconstruction was based on deuterium isotope (δD) measurements (relative to VSMOW2 and VSLAP2) along the length of the ice core, with a typical precision of 1.0 ‰. Temperature anomalies were calculated using a δD-temperature dependence of 6.4 ± 1.3 ‰ $^{o}C^{-1}$ (ref. [12]), using the assumption that the modern day calibration holds over the entire record[26], and are given with reference to 1961-1990 AD. Consistent palaeotemperature results are produced using the oxygen isotopic ratio ($\delta^{18}O$) of the ice (Supplementary Fig. 1), confirming that the isotopic record primarily reflects changes in temperature at the JRI site during the Holocene. Uncertainties on mean temperature anomalies are the combined standard error on the calibration dependence and standard deviation of variability on 100-year binned data. Full method details are provided in the electronic version of the paper.

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**Supplementary Information** is linked to the online version of the paper at www.nature.com/nature.

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**Author Contributions**: RM designed the project. RM, NJA and RCAH constructed the age scale, and RM, NJA, CA, LF and JT performed the isotopic, chemical and physical measurements to characterise the ice. RM, NJA, JT, LCS, OA and SF were involved with the logistics and fieldwork that enabled the ice core drilling. RM and NJA wrote the paper as co-first authors, with contributions from the other authors.

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**Figure captions**

**Figure 1. Regional and climatic setting of the Antarctic Peninsula**. a, Temperature trends for the 50 years from 1958-2008 show the rapid regional warming of the Antarctic Peninsula. Trends are shown for Jan-Dec annual averages of gridded land and ocean surface temperature data[27-28]. b, James Ross Island (JRI) is located near the northeastern tip of the Antarctic Peninsula, within the zone of rapid regional warming, and adjacent to the former Prince Gustav, Larsen A and Larsen B ice shelves.

**Figure 2. Isotope and depth-age profile of the JRI ice core**. The $\delta D$ isotope profile for the James Ross Island ice core is shown at a 100 yr average (black) for the whole of the Holocene and at a 10 yr average (grey) since 4000 yrBP. The JRI depth-age scale, JRI-1 (blue), was constructed based on a glaciological flow model for this site (red) with adjustment derived from fixed time markers (black diamonds; horizontal error bars give estimated age uncertainty on the fixed markers). Further details are provided in Methods and Supplementary Table 1.

**Figure 3. Holocene temperature history of the Antarctic Peninsula**. The JRI ice core temperature reconstruction relative to the 1961-1990 mean (black curve, 100yr averages; grey band indicates the combined standard error on the calibration dependence and the standard deviation of the 100yr binned data within each interval) is shown alongside a sea surface temperature reconstruction from offshore of the western Antarctic Peninsula (blue curve)[17], and temperature reconstructions from the Dome C (red)[29] and Dronning Maud Land (green)[30] ice cores from East Antarctica. Black bars show intervals in the Holocene when marine sediment cores indicate that open water was present in the area of the Prince Gustav (solid; top to bottom are north to south core sites; original $^{14}C$ ages have been calibrated)[3] and Larsen A (grey)[5] ice shelves that collapsed in 2002 AD.

**Figure 4. 2,000 year climate history of the Antarctic Peninsula**. **a**, The JRI temperature reconstruction (black curve, 100 yr average; grey curve, 10 yr average; relative to 1961-1990 mean) is shown alongside the SST record from ODP site 1098 to the west of the Antarctic Peninsula (blue curve)[17], and reconstructed Northern Hemisphere temperature anomaly (dark green curve, relative to 1961-1990 mean; light green envelope indicates the 95% confidence interval)[22]. While SST to the west of the Antarctic Peninsula shows similarities to northern hemisphere climate over the last 2,000 years, the JRI record shows an opposing temperature excursion that demonstrates that the Antarctic Peninsula did not experience a widespread Medieval Warm Period (MWP) – Little Ice Age (LIA) sequence comparable to northern hemisphere climate at this time. Warming at JRI has been ongoing for several centuries, although the 1.56 $^{o}$C warming over the last 100 years (red line in a and b) is highly unusual in the context of natural variability, as shown by **b**, histogram analysis of temperature trends calculated on moving 100-year windows of annual resolution data from the JRI ice core since 2,000 yrBP. 100-year warming trends exceeding 1.5$^{o}$C per century also occurred in the intervals spanning 1518-1621 AD and 1671-1777 AD, while the trends exceeded 1.25°C per century during the interval 296-415 AD.

## Methods

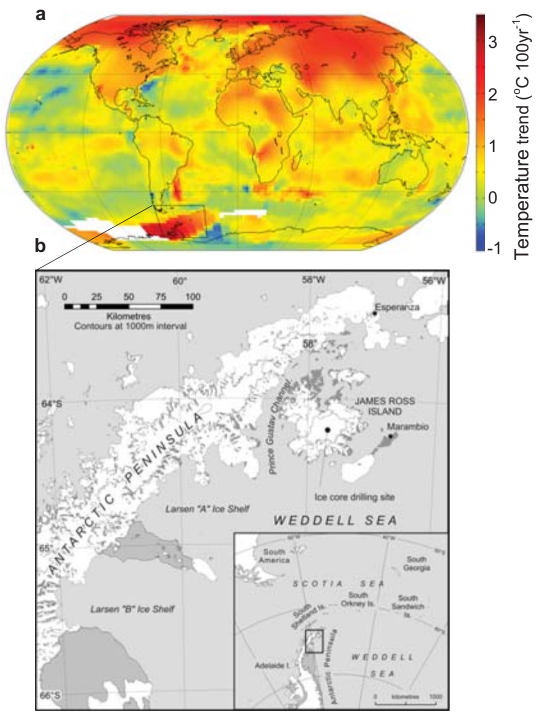
**Site details**. The James Ross Island (JRI) ice core presented in this study was drilled in January-February 2008 at a site (057°41.10'W, 64°12.10'S, 1542 m elevation; Fig. 1) near the summit of Mount Haddington. The ice core was recovered to bedrock at a depth of 363.9 m using an electromechanical drill and winch system and a fluid filled borehole after the firn-ice transition. Annual layers determined by chemistry measurements record a mean annual snow accumulation at this site of 0.63 m water equivalent[12]. Borehole temperature measurements indicate a mean annual site temperature of -14.4 °C, in agreement with earlier studies at this site[25]. The basal temperature of the ice sheet measured in the borehole was -8.5 °C, which is consistent with a normal geothermal heat flux of around 50 mW $m^{-2}$ at this location.

**Age scale**. The Holocene age profile for the JRI ice core is identified as the JRI-1 age scale (Fig. 2). It is based on a glaciological flow model that accounts for firn compaction and characterises the expected vertical and horizontal ice flow caused by internal deformation, plug flow and Raymond-Reeh flow. Application of the glaciological model uses the assumption that flow at the site hasn't changed through time, which is expected to be a reasonable first-order assumption over the Holocene interval that this paper focuses on. The glaciological flow model was run using the input parameters of mean annual site temperature, accumulation, ice sheet thickness and geothermal heat flux (see above). A number of fixed time markers were then used to drive adjustments in the modeled depth-age profile. These fixed time markers include the local Deception Island eruption tephra in December 1967 (ref. [12]), the global-scale sulphate anomaly caused by the 1815 eruption of Tambora, the 1259 AD volcanic sequence seen in dielectric profiling on this core, and matching of 14 tephra layers in the JRI ice core to widely documented tephra horizons in marine and lake sediment cores from the Antarctic Peninsula region. The isotopic anomaly of the Antarctic cold reversal was also used to tie the lower portion of the modeled JRI chronology to the EDC3 age scale. Age control on the tephra horizons used for refining the chronology is derived from radiocarbon dating and the estimated age uncertainty in the early Holocene is ± 500 years, in the mid Holocene is ± 200 years and in the late Holocene is ± 100 years. For the 1259 and Tambora eruption events the estimate age uncertainty is ± 5 years and ± 1 year, respectively. Full details of the time markers used to establish the Holocene JRI-1 age scale and their estimated uncertainty are provided in Supplementary Table 1.

**Analytical details**. Deuterium isotope (δD) measurements were made along the whole length of the ice core at the NERC Isotope Geosciences Laboratory using an online Cr reduction method with a EuroPyrOH-3110 system coupled to a Micromass Isoprime mass spectrometer. Analytical precision is typically 1.0 ‰ for δD. Measurements were made at 11cm resolution from the surface to 300 m snow depth, at 5 cm resolution from 300 m to 350 m, and at approximately 1.5 cm resolution from 350 m to bedrock. Duplicate measurements of δD were also made at the British Antarctic Survey using a Los Gatos Research DLT-100 cavity ringdown laser spectroscopy instrument with a precision of typically 1.0‰ for δD. Across 770 duplicates the mean difference in δD results obtained by the mass spectrometry and laser spectroscopy methods is 1.02 ‰. A total of 5116 discrete δD results were used for the temperature reconstruction. Oxygen isotope ($\delta^{18}O$) measurements were made at the NERC Isotope Geosciences Laboratory, using the $CO_2$ equilibration method with a VG Isoprep 18 device and a VG SIRA 10 mass spectrometer. The $\delta^{18}O$ measurements have a typical precision of 0.08 ‰ and the data presented in Supplementary Figure 1 is comprised of 4592 analyses. The relationship of $\delta^{18}O$-δD in the JRI ice core data has a slope of 8.02, consistent with the meteoric water line. Isotope measurements used internal standards calibrated against the international standards VSMOW2 and VSLAP2.

**Temperature reconstruction**. A comparison with recent temperature records has shown that at this site δD has a temperature dependence of 6.4 ± 1.3 ‰ $^{o}C^{-1}$ (ref. [12]), consistent with the modern day spatial δD-temperature relationship across Antarctica[13]. For $\delta^{18}O$ a temperature dependence of 0.80 ± 0.14 ‰ $^{o}C^{-1}$ was used[12-13]. It has been shown that snowfall at this site occurs year-round and doesn't appear to bias the isotopic record towards any specific season[12]. Comparison of δD and

$\delta^{18}O$-based temperature reconstructions, and calculation of deuterium excess, also indicates that changes in source temperature have been negligible for this site and that the isotope history primarily reflects changes in temperature at the JRI site (Supplementary Fig. 1). The temperature reconstruction was calculated using the assumption that the modern δD-temperature calibration holds over the entire record and that any changes in the seasonality of snow fall exert a negligible effect on the mean isotopic changes, which is believed to be a reasonable assumption for Antarctic ice cores extending through the Holocene and into the LGM[10,13,16], but may be less robust for climates significantly warmer than present day[26]. The temperature reconstruction also takes into account changes in the isotopic composition of the ocean using the method of Jouzel et al. (ref. [10]) and ocean isotope values calculated by Bintanja et al. (ref. [11]). Temperature anomalies were calculated with reference to the 1961-1990 AD interval of the JRI ice core, and mean temperature anomalies are reported with uncertainties that combine the standard error on the calibration dependence and the standard deviation of the 100yr binned data within each interval. For temperature trends, the certainty estimates denote the standard error of the trend determination.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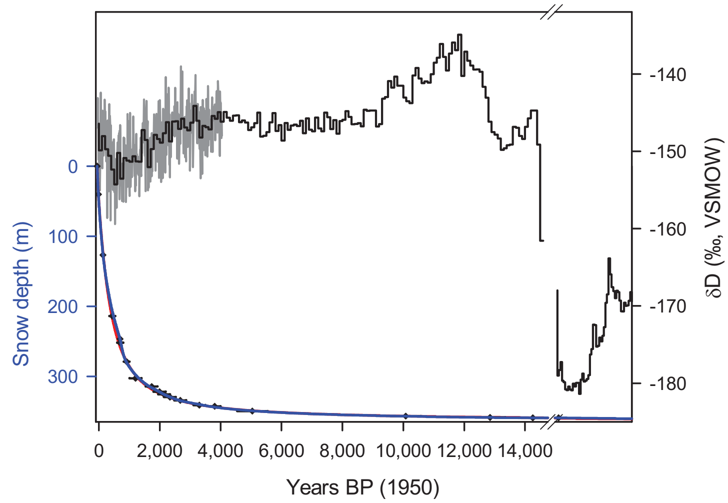
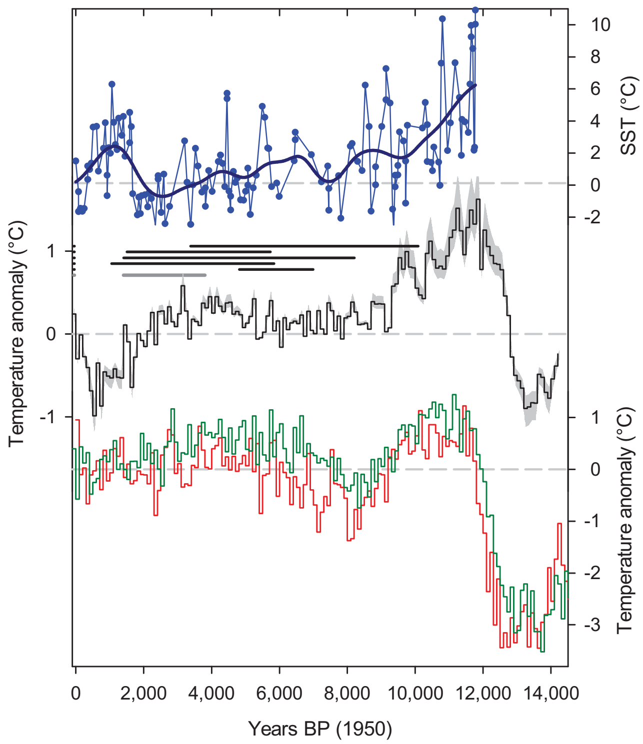
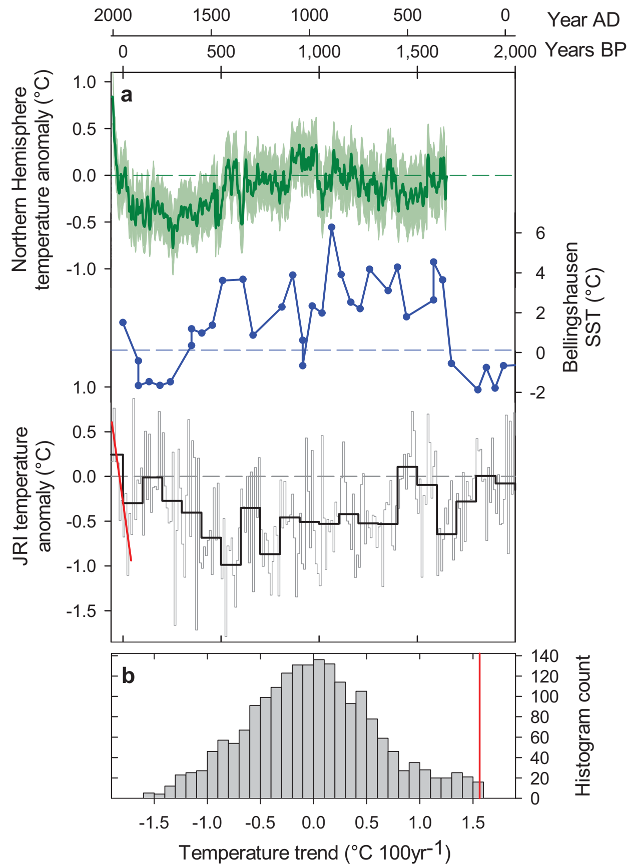
WEDDELL SEA
0 kilometres 1000



Snow depth (m)
0
100
200
300
δD (‰, VSMOW)
-140
-150
-160
-170
-180
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
Years BP (1950)



10
8
6
4
2
0
-2
SST (°C)
1
0
-1
Temperature anomaly (°C)
1
0
-1
-2
-3
Temperature anomaly (°C)
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
Years BP (1950)



2000
1500
1000
500
0
Year AD
0
500
1,000
1,500
2,000
Years BP
a
Northern Hemisphere temperature anomaly (°C)
1.0
0.5
0.0
-0.5
-1.0
Bellingshausen SST (°C)
6
4
2
0
-2
JRI temperature anomaly (°C)
1.0
0.5
0.0
-0.5
-1.0
-1.5
b
Histogram count
140
120
100
80
60
40
20
0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
Temperature trend (°C 100yr$^{-1}$)