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Optimal site selection for a high-resolution ice core record in East Antarctica

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Abstract. Ice cores provide some of the best-dated and most comprehensive proxy records, as they yield a vast and growing array of proxy indicators. Selecting a site for ice core drilling is nonetheless challenging, as the assessment of potential new sites needs to consider a variety of factors. Here, we demonstrate a systematic approach to site selection for a new East Antarctic high-resolution ice core record. Specifically, seven criteria are considered: (1) 2000-year-old ice at 300 m depth; (2) above 1000 m elevation; (3) a minimum accumulation rate of 250 mm years^{-1} IE (ice equivalent); (4) minimal surface reworking to preserve the deposited climate signal; (5) a site with minimal displacement or elevation change in ice at 300 m depth; (6) a strong teleconnection to midlatitude climate; and (7) an appropriately complementary relationship to the existing Law Dome record (a high-resolution record in East Antarctica). Once assessment of these physical characteristics identified promising regions, logistical considerations (for site access and ice core retrieval) were briefly considered. We use Antarctic surface mass balance syntheses, along with ground-truthing of satellite data by airborne radar surveys to produce all-of-Antarctica maps of surface roughness, age at specified depth, elevation and displacement change, and surface air temperature correlations to pinpoint promising locations. We also use the European Centre for Medium-Range Weather Forecast ERA 20th Century reanalysis (ERA-20C) to ensure that a site complementary to the Law Dome record is selected. We find three promising sites in the Indian Ocean sector of East Antarctica in the coastal zone from Enderby Land to the Ingrid Christensen Coast (50–100° E). Although we focus on East Antarctica for a new ice core site, the methodology is more generally applicable, and we include key parameters for all of Antarctica which may be useful for ice core site selection elsewhere and/or for other purposes.

1 Introduction

Our knowledge of current climate change and our ability to predict future climate change depends on understanding past natural climate variability. Considerable uncertainties exist in the reconstruction of past climate, with ice cores playing an increasingly important role in understanding both climate impacts and forcings. In Antarctica, there is poor spatial coverage of high-resolution palaeoclimate data over the last 2000 years, which is articulated in IPCC synthesis reports as limiting present understanding of climate processes (Stocker et al., 2013). The last 2000 years have been recognised as an important interval of Earth history, as they contain both a significant natural period, prior to anthropogenic influence, and the full industrial era (PAGES 2k Consortium, 2013). Additionally, high-resolution (e.g. annual or seasonal) records of climate forcings over the past 2000 years are of importance to the climate modelling community, such as PMIP (Paleoclimate Modelling Intercomparison Project) (Braconnot et al., 2012), and will improve our knowledge of the dynamics of the climate system over this epoch. A recent 2000-year Antarctic-wide temperature reconstruction (PAGES 2k Consortium, 2013) revealed regional differences in temperature between East and West Antarctica during the same epoch. However, only four proxy sites were available to reconstruct all of East Antarctica, which comprises 84 % of the total Antarctic land mass (Bindschadler, 2006). It is unknown how much of this disparity is a true representation of the two regimes or how much is an artefact of data sparsity.

Filling in data-sparse regions with new ice core records will contribute to our understanding of regional- and global-scale climate processes, but the location of ice core sites requires careful site selection. Unfortunately, ice core site selection is not governed solely by the local climate response and its preservation in the ice core record. Rather, site selection is primarily restricted by both glaciological and logistical constraints, with optimal site positioning from a climate processes perspective being constrained to this restricted domain. Minimal layer and basal complexity is necessary to ensure that interpretation of the ice core record is as straightforward as possible. Additionally, sites where age models vary uniformly with depth simplify interpretation, provided radar data exists and are able to confirm suitable ice stratigraphy, accumulation rates, and basal conditions (e.g. Siegert and Payne, 2004). When high-resolution records are required, an additional constraint is to minimise surface reworking effects (e.g. wind movement of snow (Lenaerts et al., 2012a) or loss via ablation) and subsurface complexity (i.e. the basal ice flow regime). High-accumulation sites minimise the negative effects of any surface reworking, yet, logistically, this generally means being restricted to coastal locations, which often have complex basal topography, flow regimes and frequently inclement weather. High-accumulation sites can also mean that multi-year drilling campaigns may be required to achieve the required depth and associated ice age.

In reality, few such sites exist in Antarctica that incorporate a satisfactory level of all these criteria but with sufficiently high accumulation rates to resolve annual cycles. Three sites that do largely meet these criteria are the recently obtained West Antarctic Ice Sheet (WAIS) Divide core in West Antarctica (79.767° S, 112.133° W; 1766 m elevation) (Bisiaux et al., 2012), the James Ross Island core in the northern Antarctic Peninsula region (57.685° W, 64.2017° S; 1252 m elevation) (Abram et al., 2011; Mulvaney et al., 2012) and the Law Dome core (112.8069° W, 66.7697° S; 1370 m elevation) (Morgan et al., 1997; van Ommen et al., 2004; Roberts et al., 2015) in coastal East Antarctica. Airborne surveys across large swathes of East Antarctica (e.g. Roberts et al., 2011; Young et al., 2011; Greenbaum et al., 2015) mean that it is now possible to extend the climate information gleaned from these few records using a consistent, logical approach to choosing a new ice core site in East Antarctica based on prescribed desired parameters.

This study details the search for an East Antarctic ice core site that will fulfil a particular prescribed role – that of improving high-resolution climate reconstruction for the Southern Hemisphere over the last 2000 years. In particular, a number of studies have suggested that variability related to a broad latitudinal swathe of the southwest (SW) Pacific and southern Indian oceans, a region with poor observational records prior to the satellite era, may be recorded in ice core records from East Antarctica. Frezzotti et al. (2013) observed a relationship between changes in mean wind direction and accumulation disparities in the East Antarctic Plateau region encompassing Dome C and the incidence of synoptic blocking events in the SW Pacific, a study that neatly reinforced that of Massom et al. (2004), who had previously suggested that blocking in this sector may have a significant effect on the accumulation at inland sites of East Antarctica, as midlatitude cyclones were “steered” toward the interior of the continent. Delmotte et al. (2000) showed that the moisture sources for Law Dome have temperate to subtropical sources, while Masson-Delmotte et al. (2003) observed possible decadal cycling in isotopic records from a related Law Dome core (DE08) that may have been related to Pacific variability and a resultant change in meridional winds in the Law Dome region. Vance et al. (2015) demonstrated that there was a decadal change in meridional winds coherent with phase changes in the Interdecadal Pacific Oscillation (IPO) in the southern Indian Ocean. This teleconnection to Pacific decadal sea surface temperature (SST) and wind anomalies was exploited to produce a 1000-year annually dated IPO reconstruction. What can be surmised from these prior studies is that coastal to inland East Antarctica is subject to annual to multidecadal changes in the meridional aspects of the midlatitude westerlies, and ice core records in this region are capable of recording these signals. Given the paucity of high-resolution records from this region, new ice core sites have great potential to shed light on the drivers of these meridional wind variations. A new ice core record from East Antarctica complementary to the existing Law Dome record would be of great use for further study of climate history in the SW Pacific and Indian Ocean sector of the Southern Ocean and the Southern Hemisphere more generally.

2 Site criteria

In this study, seven criteria were proposed in order to locate an ideal site for a new ice core record. These seven criteria can be divided into site criteria (characteristics necessary to produce an appropriate record) and atmospheric circulation criteria (circulation characteristics that may be recorded at the proposed site). The site criteria were as follows:

1. 2000-year-old ice at 300 m depth; an achievable drilling target for a small field team in a single (summer) season.

2. minimal summer snowmelt, as surface melt redistributes water, stable water isotopes and trace chemistry, hindering the interpretation of an ice core. Large-scale studies indicate that surface layer melt occurs when monthly average temperatures are above about −4 to −2 °C (Zwally and Fiegles, 1994; Kaczmarska et al., 2006), and liquid water formation and near-surface melt layers in firn and ice occurs when air temperatures are greater than 0 °C (Das and Alley, 2005; Hock, 2005). As the air temperature decreases with altitude (with a rate determined by the adiabatic lapse rate), melting is reduced at higher elevations. For example, there was minimal surface melt at the Law Dome ice core site (1370 m elevation) (Morgan et al., 1997). Herein, we use a surface elevation above 1000 m a.s.l as a proxy for minimal surface melt in East Antarctica. This is consistent with satellite-based (Trusel et al., 2013) and modelling (Van Wessem et al., 2014) studies which show minimal surface melt at these elevations.

3. sub-annual resolution, which for the purposes of this study we propose requires a minimum of 250 mm $years^{-1}$ IE accumulation (where IE stands for ice equivalent using an ice density of 917 $kg\,m^{-3}$ to convert between $kg\,m^{-2}\,years^{-1}$ of water and the ice equivalent; van Ommen et al., 2004). Preference will be given to sites that also show relatively uniform annual accumulation (i.e. accumulation is not skewed toward a particular season).

4. minimal surface reworking to preserve the originally deposited climate signal, which we assess based on estimated surface roughness.

5. location on a ridgeline or dome or at a site where the ice at the target depth has undergone minimal displacement or elevation change.

The proposed circulation criteria are as follows:

6. a strong teleconnection with midlatitude (oceanic) climate. For instance, a clearly defined climatological flow pattern from the regional Southern Ocean to the site.

7. an appropriately complementary relationship to existing ice core records (i.e. a site that adds new information to the existing ice core array).

Any site selected also needs to fulfil the logistical requirement of being reasonably accessible for ice core drilling and retrieval.

3 Methods and data sets

To assess which regions of East Antarctica may fulfil the site criteria, we exploited the newly available aero-geophysical data from the Investigating Cryospheric Evolution through Collaborativ Aerogeophysical Profiling (ICECAP) surveys (Roberts et al., 2011; Young et al., 2011; Wright et al., 2012). This allowed us to make a comprehensive spatial assessment of the East Antarctic ice sheet to pinpoint regions of interest for closer study.

3.1 Nye depth

The age of ice at a given depth can be estimated by assuming a constant vertical strain rate throughout the ice column (equal to the ice equivalent accumulation rate divided by the ice thickness). This Nye age model (Nye, 1963) will underestimate the age for deep ice (Paterson, 1994) but should perform well for ice less than 70 % of the local ice sheet thickness, and it provides a conservative estimate of ice age (i.e. actual age should be older at any given depth).

Spatial maps of the age of ice at 300 m were calculated based on vertical strain rates from the regional atmospheric climate model, RACMO2.1/ANT, surface mass balance data for the period 1979–2012 (Lenaerts et al., 2012b), converted to ice equivalent using an ice density of 917 $kg\,m^{-3}$ and the BEDMAP2 ice thickness compilation (Fretwell et al., 2013).

3.2 Ice advection

To ease the interpretation of ice core records, ideally the ice should have all originated at the same spatial location, i.e. there has been minimal horizontal motion. Additionally, to simplify the interpretation of stable water isotope records, elevation change in the surface should be near zero. These conditions are only achieved near ice dome summits and ice divides (ridgelines). For all other locations, the ice at depth has originated further upstream and generally at higher elevations.

To assess the spatial variation in horizontal displacement and associated change in surface elevation as ice is advected towards the ice sheet margin, ice motion trajectories were calculated. Specifically, the horizontal displacement of ice was calculated over a 1000-year interval using a modified version of the Lagrangian streamline tracing routine of Roberts et al. (2011) with ice velocities from the MEaSUREs data set (Making Earth System Data Records for Use in Research Environments; Rignot et al., 2011). The associated change in elevation was estimated from the Bamber et al. (2009) digital elevation model (DEM), with the implicit assumption of no significant change in surface elevation over the last 1000 years.

3.3 Calculating surface reworking for all of Antarctica

We are not aware of any surface roughness data set for all of Antarctica, and a high surface roughness compared to accumulation rate can hinder the interpretation of high-resolution ice core records. To produce an all-of-Antarctica map of surface roughness, we use satellite imagery ground-truthed with ICECAP aero-geophysical data to estimate the spatial distribution of surface roughness.

3.3.1 Observational surface roughness data – laser altimetry

Surface roughness was estimated from Operation IceBridge, ICECAP and other University of Texas at Austin Institute of Geophysics Level 2 Geolocated nadir laser altimetry (Riegl) (Blankenship et al., 2012; Young et al., 2015). Specifically, surface roughness was estimated as the median absolute difference from a local linear regression (calculated using the robust Theil–Sen method; Sen, 1968) for 500 m sliding windows averaged onto a 50 km × 50 km grid.

3.3.2 MODIS Mosaic of Antarctica

We calculated a surface roughness estimate from the 125 m resolution 8 bit greyscale MODIS Mosaic of Antarctica (Scambos et al., 2007). To do this we considered 50 km × 50 km sub-windows, with both the sub-window intensity standard deviation (S) and high-pass-filtered (half-amplitude wavelength of 450 m) mean intensity (M) as parameters. Furthermore, as katabatic winds redistribute snow, especially below the 2000 m elevation contour (van den Broeke and Bintanja, 1995), we have used two different data fits for above and below this elevation threshold. Therefore, the ice sheet surface elevation (H) (Bamber et al., 2009) was used both as an explanatory variable in the data fitting and to segment the data fit. As the estimation of surface roughness is based on a single temporal snapshot, we have had to assume that surface roughness does not vary with time.

The laser altimetry data (R) were fitted (Eq. 1) using a reweighted trimmed least squares method (Rousseeuw, 1984). Data were separately fitted above and below the 2000 m elevation contour. As we are more interested in lower surface roughness values, a constant offset of -1.42×10^{-2} m (calculated from the offset of the least squares fit) was introduced to the fitted data to bring the lower bounds into agreement.

$$R = \begin{cases} (73.6 + 0.154M - 0.284S - 3.28 \times 10^{-3}H)/1000 \\ \qquad \text{if } H \leq 2000\text{ m}, r^2 = 0.54 \\ (92.0 + 1.09M - 2.20S - 2.50 \times 10^{-3}H)/1000 \\ \qquad \text{if } H > 2000\text{ m}, r^2 = 0.61 \end{cases} \tag{1}$$

The calculated surface roughness increases with increasing high spatial frequency content (increasing M) and decreases with increasing height (H) (general reduction in katabatic wind strength). Additionally, it also decreases with S, a measure of the longer spatial-scale variability.

3.4 Existing ice core records in East Antarctica

Some validation of our spatial interpolation and extrapolation can be provided by examining existing short-core records which have been taken in East Antarctica during prior glaciological surveys and traverses. The locations of some of these cores and details of their existing data sets are discussed below and shown in Table 1 and in the figures where appropriate. It is worth noting here that, while the majority of these records are published, for numerous reasons (such as time interval of coverage) many are not used in calibrating products such as RACMO 2.1/ANT. As a result there may be discrepancies between observations and model outputs of RACMO 2.1/ANT, especially in coastal regions with high spatial gradients.

3.5 Analysis of Southern Hemisphere warm season circulation

The proposed circulation criteria for site selection in this study are centred around finding a site that will produce a record similar and complementary to the existing Law Dome ice core, that is, a site that records annual- to decadal-scale variability of the western sector of the southern Indian Ocean, as Law Dome samples the more easterly sector (e.g. Masson-Delmotte et al., 2003). Primarily, this is likely to mean finding a site geographically removed from the Law Dome region but with similar glaciological characteristics. We have used investigation with reanalysis products to shed further light on possible circulatory source regions for a new ice core site. We explored circulation characteristics using both the ERA-Interim (ERA-Int; Dee et al., 2011) (1979–2014) and ERA 20th Century (ERA-20C; Poli et al., 2013) (using 1960–2010) reanalysis products to search for a site with incident circulation complementary to Law Dome and coherent with decadal-scale anomalies that may be related to the Interdecadal Pacific Oscillation (IPO – see below). The ERA-20C incorporates surface pressure and wind measurements only, while the ERA-Int incorporates all available observations, including satellite information, and is widely regarded as the most reliable product for the data-sparse Antarctic region at the surface and Z500 level (Bracegirdle and Marshall, 2012). Both products were used to compare and contrast results in the data-sparse region of interest (SW Pacific and southern Indian Ocean). The longer, 20th-century reanalysis product covers some of the most recent, completely negative IPO phase (1944–1975), along with some of the current negative phase, which is likely to have started in the late 1990s or early 2000s. We acknowledge that the

Table 1. Details of existing firn and short ice core records in coastal East Antarctica that are proximal to the areas of interest identified in this study.

Core site	Latitude (° S)	Longitude (° E)	Borehole depth (m)	Elevation (m a.s.l)	Accumulation ($kg\,m^{-2}\,a^{-1}$)	Interval covered	RACMO2.1/ANT ($kg\,m^{-2}\,a^{-1}$)
Promontory–Cape Darnley region							
MGA	68.646	60.225	23.62	1830	227.7±81.4[a]	1942–1992	137.2
LGB00	68.650	61.117	15	1832	270[b]		99.7
EO65	68.622	59.705	18	1870	232[b]		190.8
LGB16	72.817	57.333	15.18	2689	125.2±40.0[c]	1933–1992	57.8
Mt Brown region							
LGB69/AWS	70.835	77.075	102.18	1850	286[d]	2002–2003	136.6
LGB65/DT001	71.846	77.922	51.85	2325	130.7±42.8[e]	1751–1996	57.8
DT085	73.367	77.017	50.65	2577	153.3±61.6[f]	1940–1997	19.8
LGB70	70.576	76.868	45	1651	163[g]		196.5
U1	70.445	79.317	3.86	2044	197±38[h]	1988–1997	157.7
MB10/2	68.910	78.850	5.13	933	306±44[h]	1990–1998	272.3
MB15/2	69.203	79.789	5.13	1447	276±42[h]	1990–1998	166.8
MB18/2	69.500	80.749	5.13	1764	251±21[h]	1989–1998	118.6
U2	69.682	81.416	4.65	1973	352±49[h]	1991–1997	95.3
MB8/3	68.004	81.004	4.93	611	267±38[h]	1990–1998	408.1
MB9/4	67.724	83.659	3.16	494	368±70[h]	1995–1998	221.6
MB12/4	68.005	83.649	5.01	981	244±8[h]	1989–1998	276.5
MB15/4	68.350	83.998	4.97	1425	408±60[h]	1993–1998	207.7
MB18/4	68.778	84.30	6.15	1800	225±20[h]	1985–1998	186.6
U4	69.279	84.565	5.41	2048	461±58[h]	1992–1997	182.1
MBS	69.131	85.999	10.22	2078	255±24[h]	1979–1998	128.8
U5	68.973	87.290	5.49	2047	329±44[h]	1990–1997	254.5
MB10/6	67.232	88.245	4.79	837	442±51[h]	1993–1998	461.0
MB15/6	67.911	88.346	4.88	1406	383±56[h]	1992–1998	396.8
MB18/6	68.389	88.603	4.83	1733	242±26[h]	1989–1998	282.9
U6	68.834	88.934	6	2048	315±33[h]	1988–1997	220.1
MB10/8	66.911	91.754	6.11	983	461±122[h]	1993–1998	530.7
MB15/8	67.518	92.186	5.08	1550	238±32[h]	1988–1998	184.2
MB18/8	68.001	92.558	5.16	1822	324±35[h]	1991–1998	187.9
U8	68.427	92.868	4.96	2075	261±30[h]	1988–1997	185.0
Bunger Hills region							
GF12	68.483	97.183	41.6	2320	537[i]	1940–1984	255.9

[a] Goodwin et al. (1994); Ren and Qin Dahe (1999); Wen et al. (2006) [b] Goodwin et al. (1994); Higham and Craven (1997); Goodwin (1995) [c] Ren and Qin Dahe (1999); Wen et al. (2006) [d] Ding et al. (2011); Li et al. (2012); Xiao et al. (2005) [e] Wen et al. (2006); Zhang et al. (2002, 2006) [f] Wen et al. (2006) [g] Edwards and Sedwick (2001) [h] Smith and Ruddell (2001); Smith et al. (2002) [i] Goodwin (1995)

lack of observations prior to 1979 may give uncertain results. However, we felt that it was more important to use the ERA 20th Century product, as it samples negative IPO years that span the full range of the IPO cycle (i.e. negative years that occur when the IPO is trending negatively, as well as negative years that occur when the IPO is trending positively). ERA-Int can likely only sample negative years that are trending negatively, as it is unlikely that the post-2000s negative phase has begun to trend positively at this stage (although end effects make this difficult to establish absolutely). However, we acknowledge that ERA-Int is the benchmark product to use; thus, we conducted the same analyses over the 1979–2014 period using ERA-Interim and include this analysis as a Supplement.

3.5.1 The expression of the IPO in the Indian Ocean

The IPO is the basin-wide expression of the Pacific Decadal Oscillation (Power et al., 1999). Both modes represent multidecadal sea surface temperature (SST) anomalies in the Pacific Ocean and have significant and far-reaching effects on climate (e.g. winds, rainfall and surface air temperature; e.g. Power et al., 1999; Kiem et al., 2003; Thompson et al., 2015). Limited studies have shown a signature of the IPO in the Indian Ocean region (e.g. Crueger et al., 2009). Recently the Law Dome ice core was used to produce a millennial-length IPO reconstruction by exploiting IPO-related multi-decadal wind anomalies in the midlatitudes of the southern Indian Ocean (Vance et al., 2015).

For the analysis here, IPO positive and negative years were computed from the 13-year filtered Tripole Index for the Interdecadal Pacific Oscillation (TPI), which represents the IPO (Henley et al., 2015; available at http://www.esrl.noaa.gov/psd/data/timeseries/IPOTPI/). TPI values half a standard deviation above or below zero were defined as periods of positive and negative IPO. The mean atmospheric and surface states for positive and negative IPO events were examined over the global oceans and in Australian rainfall percentiles in order to highlight any connections between the IPO, the East Antarctic coast and Australian rainfall.

This analysis used composites of anomalies in geopotential height at 500 hPa (Z500) to highlight the mean circulation, as well as SST anomalies and Australian precipitation anomalies. The anomalies of all data except SSTs were computed relative to the complete length time series, which varied depending on the analysis. The SST anomalies are precomputed in the HadISST3.1.1 data set, relative to 1980–2010 (Kennedy et al., 2011). Composite maps were produced and compared over 1960–2010 for positive and negative TPI years using the ERA-20C. For comparison, the ERA-Interim reanalysis is also provided from 1979 to 2014 in the Supplement (see Fig. S2).

4 Site selection in East Antarctica

4.1 Areas that fulfil the minimum site criteria

In order to first provide a preliminary assessment of the broad regions of the Antarctic continent that may yield high-resolution ice core records, we applied a less conservative subset of our stated criteria. Specifically, we identified regions above 1000 m elevation where local accumulation rates were $\geq 200\,\mathrm{mm\,years^{-1}}$ IE and simultaneously ice age at 300 m depth was at least 500 years. These criteria are less stringent than the specified criteria used for site selection for this study and identify a broad, largely coastal band in East Antarctica, primarily in the Indo-Pacific sector, and a large proportion of West Antarctica, including the continental divide that may contain sites for high-resolution ice cores. As this analysis was outside the core criteria for this study but may be useful to other researchers, we include this preliminary assessment in the Supplement (see Fig. S1).

In East Antarctica, applying the more stringent criteria 1 and 3 (2000-year age achievable at 300 m and $\geq 250\,\mathrm{mm\,years^{-1}}$ IE respectively) greatly restricts possible sites from the broader region identified in Fig. S1 to a narrower band inland but parallel to the coastal margin. In general, these primary criteria also satisfy site criterion 2, that the site chosen be at an elevation above 1000 m, as sites below this generally do not yield old enough ice. The fulfilment of site criteria 1–3 is shown in Fig. 1. Panel a of Fig. 1 identifies the predominantly inland, high-elevation regions where 2000-year-old ice is within 300 m of the surface (darker blue regions), although there are notable exceptions where this occurs closer to the coast, such as the Ingrid Christensen Coast, the Mawson Coast and the Bjerkø Peninsula–Cape Darnley region. When the minimum requirement of $250\,\mathrm{mm\,years^{-1}}$ IE accumulation is considered (Fig. 1b), most of the previously identified coastal regions have lower accumulation than this minimum requirement and are thus ruled out, although there are a few regions that remain. Note that we include the less stringent criteria of $200\,\mathrm{mm\,years^{-1}}$ IE, identified in Fig. S1 as a dotted boundary for reference and comparison. The region between these accumulation boundaries may in fact be the most fruitful zone, as the maximum ice sheet thickness inferred by the Nye age–depth model is thicker and therefore expands the possible regions of interest. In addition, Fig. 1c shows that accumulation is generally uniform throughout the year for most of East Antarctica, with the exception of a few small regions upstream of the Amery Ice Shelf.

As previously stated, our interest is in obtaining an ice core that reflects features of the circulation and climate of the western sector of the southern Indian Ocean. As a result, we focus on the region between Enderby Land and the Bunger Hills. We identify four regions that may contain sites that fulfil our initial three site criteria, which we then investigate further for fulfilment of our remaining criteria (see below). These regions are Law Promontory–Enderby Land, Cape Darnley, Mt Brown and the Bunger Hills (Figs. 1–3 and 5, fuchsia boxes).

4.2 Assessing surface roughness and estimating surface reworking

Figure 2 shows the calibration of the surface roughness estimated from MODIS satellite imagery against the ICECAP laser altimetry data to produce a whole-of-Antarctica estimate of surface roughness. Figure 2c shows that our four selected regions of interest have minimal surface roughness. Figure 2d, e indicate that large swathes of East Antarctica have surface roughnesses that are much less than the average annual accumulation, although this is not the case in the Lambert Glacier basin, inland of the Amery Ice Shelf. Nonetheless, our four selected regions of interest appear to have a relatively smooth surface compared to the accumulation rate (Fig. 2e). Additionally, a prior analysis of drifting snow (Lenaerts et al., 2012a) suggests that these regions have a favourable drifting-snow-to-accumulation ratio, allowing for the preservation of annual layers within the ice core.

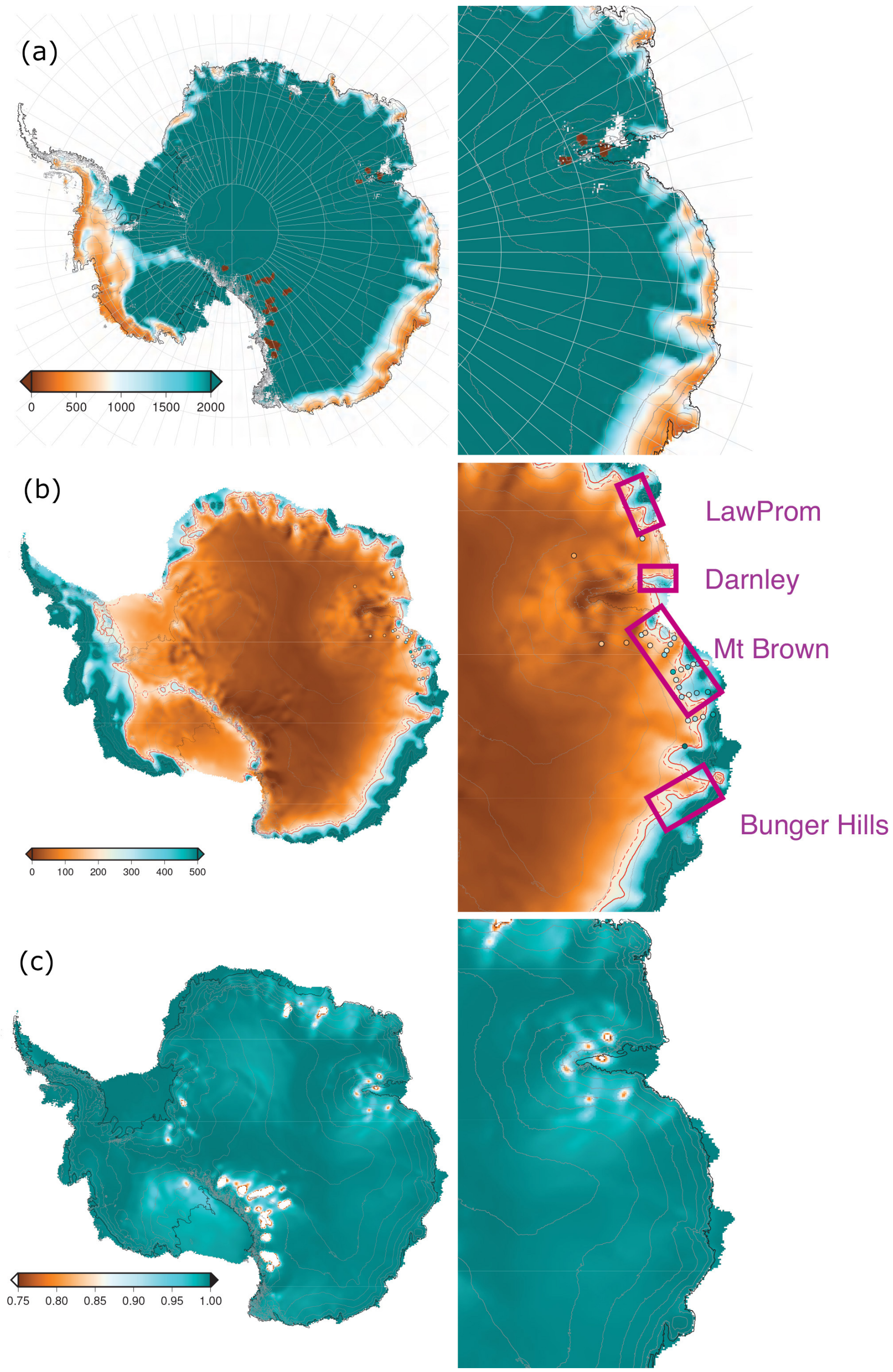

Figure 1. Assessing continental East Antarctica for areas that fulfil the specified high-resolution, multi-millennial record length site criteria for this study, with all of Antarctica on the left and the Indian Ocean sector of East Antarctica on the right. Contour intervals (grey) are 500 m. Panel **(a)** shows ice age at 300 m (colour bar) using the process described previously. Panel **(b)** shows annual snowfall accumulation rate, with areas that receive > 250 mm years^{-1} IE shown using a solid red boundary, and areas that receive > 200 mm years^{-1} IE shown using a dashed red boundary. Panel **(c)** is a representation of uniformity of snowfall accumulation through the year (blue represents more seasonally uniform accumulation). Labelled boxes in panel **(b)** identify possible sites after site criteria 1–3 are assessed; see the "Results" section for more detail. LawProm: Law Promontory–Enderby Land region; Darnley: Cape Darnley region; Mt Brown: Mt Brown region; Bunger Hills: Bunger Hills region.

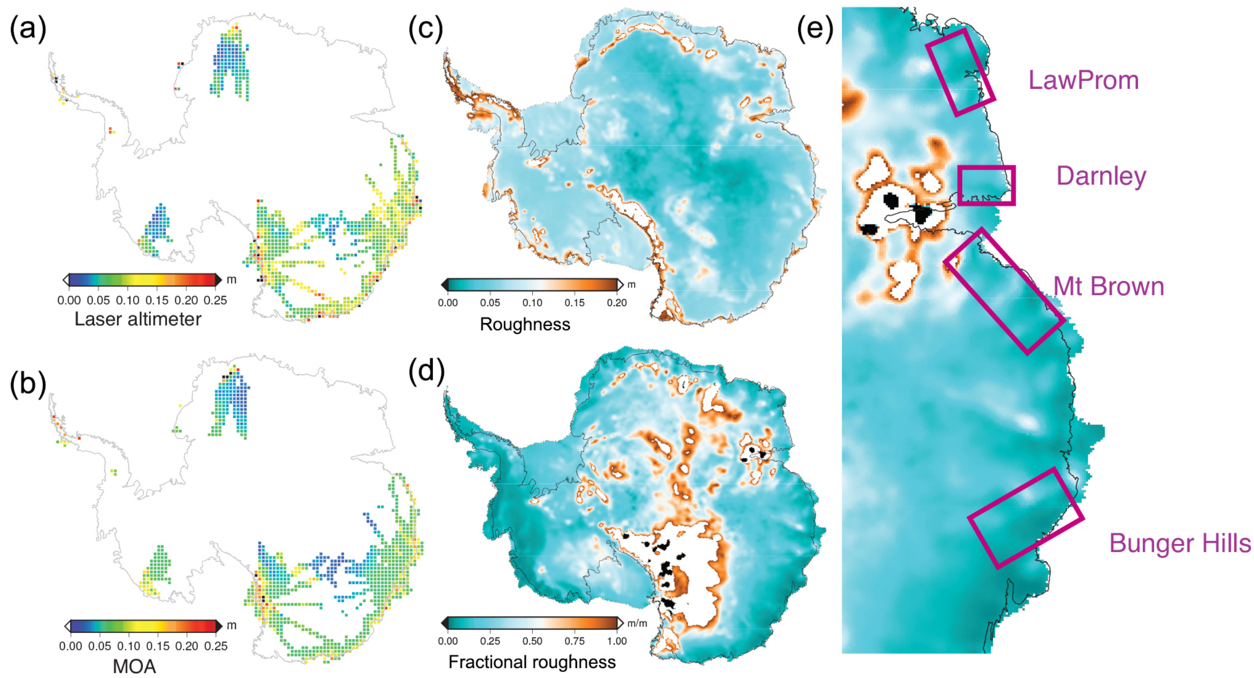

Figure 2. MODIS-based surface roughness estimates. Panel **(a)** shows the calculated average surface roughness in each $50 \times 50\,\mathrm{km}^2$ grid, from Operation IceBridge, ICECAP and other University of Texas at Austin Institute of Geophysics Level 2 Geolocated nadir laser altimetry flight-line data (Blankenship et al., 2012; Young et al., 2015). Panel **(b)** shows the resultant estimate of surface roughness from MODIS Mosaic of Antarctica (MOA) imagery, by calibrating it with the averaged surface altimetry calculated in panel **(a)** (see the "Method" Section (Sect. 3.3.2)). Panel **(c)** shows the estimated (modelled) surface roughness for Antarctica using the laser altimetry-calibrated MOA imagery, while panel **(d)** shows estimated surface roughness as a fraction of estimated annual snowfall accumulation rate from RACMO2.1. In this instance, blue regions (low fractional roughness) indicate regions with minimal surface reworking as a fraction of snowfall accumulation rate and hence potential high-resolution ice coring sites. Panel **(e)** is the enlarged coastal East Antarctic section of the fractional roughness (panel **d**).

4.3 Existing firn and ice core records

An array of shallow firn (5–10 m) and ice cores (50–100 m) exists from previous glaciological traverses and survey work in East Antarctica (Figs. 1, 5, Table 1), some of which are near or within the regions specified above. These existing firn and ice cores have been analysed for a series of glaciochemical measurements. These include electrical conductivity, water stable isotopes (δ^{18}O), hydrogen peroxide (H_2O_2), density, snow accumulation and trace ion chemistry.

4.3.1 Existing records near the Law Promontory and Cape Darnley regions

Ice core and historical in situ measurements in the Law Promontory and Darnley regions west of the Amery Ice Shelf are limited to four records on the eastern boundary of the Law Promontory region. These were collected as part of the Australian National Antarctic Research Expedition (ANARE) Lambert Glacial basin traverse program (Higham and Craven, 1997) and the Chinese National Antarctic Research Expedition (CHINARE) inland traverses (Dahe et al., 2000). Accumulation rates from cores and stake measurements along the west Lambert Glacial basin traverse route 150 to 250 km inland are highly variable ranging from 0 to $500\,\mathrm{kg\,m^{-2}\,a^{-1}}$ and averaging $\approx 230\,\mathrm{kg\,m^{-2}\,a^{-1}}$ (Ren and Qin Dahe, 1999; Fig. 2). The high variability is likely due to the steepness of the ice sheet topography and associated strong katabatic winds in this area (Ren and Qin Dahe, 1999), while further inland from 350 to 550 km accumulation rates are less variable and average $350\,\mathrm{kg\,m^{-2}\,a^{-1}}$ (Ren and Qin Dahe, 1999). Repeat annual accumulation rate measurements in the west Lambert Glacial basin show similar spatial variability but also indicate large temporal variability (Qin et al., 2000). The model accumulation rate (Fig. 1b) underestimates the observed snow accumulation rates as well as the spatial variability (Ren and Qin Dahe, 1999; Dahe et al., 2000; Wen et al., 2006). Therefore, a combination of further analysis of existing data and modern radar site survey techniques would be required prior to drilling.

4.3.2 Existing records near the Mount Brown region

The Mount Brown region contains the most comprehensive and detailed spatial distribution of firn and ice cores in Wil-

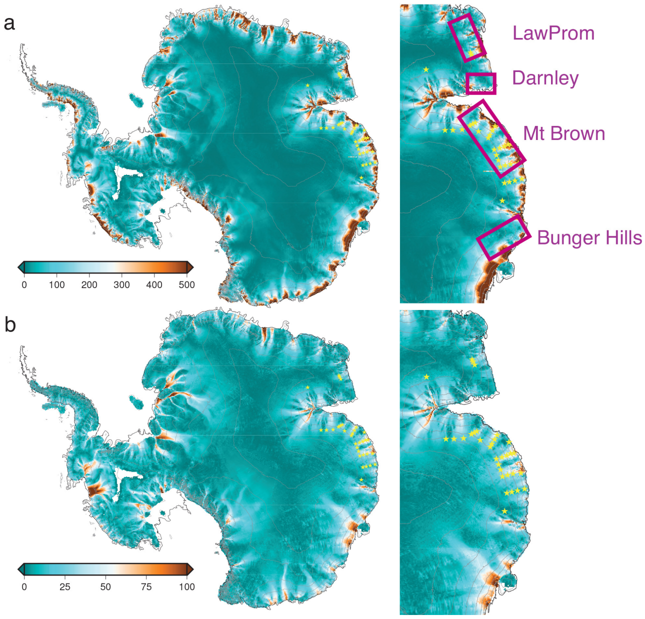

Figure 3. Elevation change (metres; **(a)**) and ice advection (kilometres; **(b)**) over 1000 years, calculated using a modified version of the Lagrangian streamline tracing of Roberts et al. (2011), with ice velocities from the MEaSUREs data set (Rignot et al., 2011). Blue areas show comparatively little elevation change and/or advection over 1000 years. The right-hand panels are the enlarged coastal East Antarctic section of each panel. Stars indicate historical ice core locations for short records.

helm II Land (Smith and Ruddell, 2001; Smith et al., 2002; Foster et al., 2006). Twenty-one shallow firn cores were collected between 79.3 and 92.9° E, ranging between 500 and 2100 m elevation (Figs. 1, 5; Table 1). Many of the cores display well-resolved annual layers, which record regional climate signals (Smith et al., 2002; Foster et al., 2006). For example, at Mount Brown South, Foster et al. (2006) reported a correlation between methanesulfonic acid (MSA) and sea-ice extent. Similar to Law Dome, the Mount Brown South MSA sea-ice proxy record is a regional indicator of sea-ice extent (Foster et al., 2006).

Accumulation records from these cores suggest that RACMO 2.1/ANT in general underestimates the accumulation rates in this region, and also the spatial variability, although this variability is likely to be less pronounced in this region than in the west Lambert Glacial basin described earlier.

4.3.3 Existing records near the Bunger Hills region

There is limited published ice core data from within or proximal to this region. Ice core data for site GF12 (see map) suggests that the snow accumulation is 536 $\mathrm{kg\,m^{-2}\,a^{-1}}$, with well-resolved annual layers (Goodwin, 1995). Initial comparisons between Law Dome and GF12 (not shown) suggest that they share a similar regional climate signal. In addition, RACMO 2.1/ANT significantly underestimates accumulation in the vicinity of GF12, probably due to the lack of published data. This means that sites further inland from GF12 could be suitable for high-resolution 2 kyr ice core records, albeit with a climate signal similar to that of Law Dome.

4.4 Elevation and advection

Figures 3 and 5a show that due to ice advection, the elevation at deposition varies down the length of an ice core record. These figures also show that these elevation artefacts can be highly variable in the coastal zone. This is due to the increasing horizontal ice velocities in the coastal region, along with the steeper topography at the margins of the ice sheet. In the Law Promontory region, there is significant elevation change in the NE coastal segment as well as in the western inland region. There are subregions with minimal horizontal displacement of ice over a 1000-year time frame, although these regions are not as extensive as in the other identified regions of interest. In the Cape Darnley region, there is minimal elevation change except in the far south of this box, and displacement of ice over the 1000-year time frame is minimal. Nonetheless, there is evidence of larger displacement change in the same far southern area. In the Mt Brown region, three clear zones of minimal elevation change over 1000 years and associated minimal displacement are identified: a ridge in the far western portion, a less pronounced ridge in the central portion and the area near the existing Mt Brown South record (indicated in Fig. 5a) in the centre of the eastern half of this region. There are also clear regions of high elevation (and displacement) change over time, but these are generally restricted to the coastal margins below 1000 m a.s.l. The majority of the Bunger Hills region shows minimal elevation change and/or displacement over the 1000-year time frame with the exception of a small portion in the eastern segment, which is probably related to drainage of the numerous glaciers to the west of Law Dome.

4.5 Representative temperature from reanalysis

Figure 4 is a representation of the approximate distance required to obtain partial decorrelation (decoupling) of the surface temperature signal. Specifically, the orange spectrum shows that a particular point contains a temperature signal representative ($r \geq 0.7$) of a broad (greater than 600 km) area. For example, the Bunger Hills region is broadly within the same representative surface air temperature regime as Law Dome, which has a temperature radius of ~ 550 km. The other three identified regions show that they are likely to produce temperature proxy records representative of large areas (frequently > 750 km) in regions that are currently poorly sampled for millennial-length temperature proxy records.

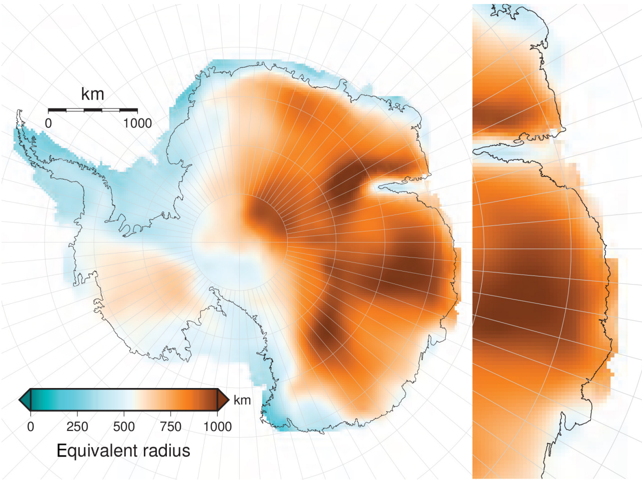

Figure 4. A spatial plot of the areal extent that a temperature record is representative of, calculated from ERA-Interim surface (2 m) temperature. Equivalent radius is the correlation length, i.e. the distance from a given point, with which surface temperature is highly correlated (> 0.7). The right-hand panel is the enlarged coastal East Antarctic sector.

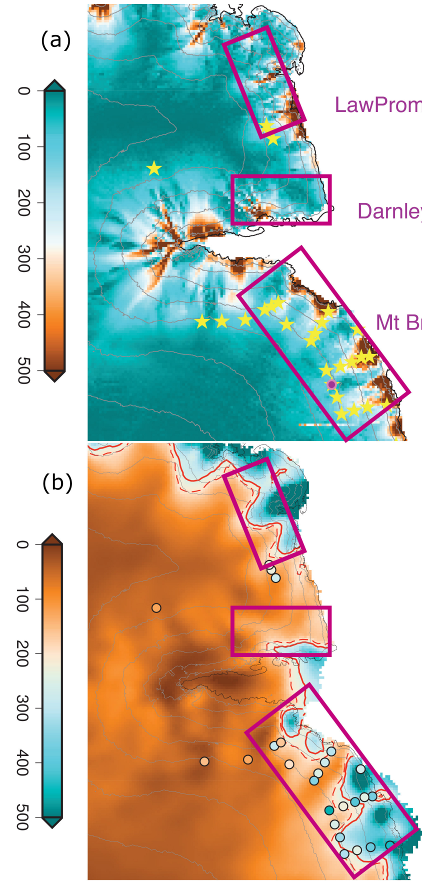

Figure 5. Panel **(a)** shows a further enlargement of Fig. 3b (elevation change in metres), with the existing Mt Brown South ice core record identified (fuchsia dot), while panel **(b)** shows a further enlargement of Fig. 1b (annual snowfall accumulation with < 250 and < 200 mm years^{-1} IE shown as solid red and dashed red lines respectively).

4.6 Decadal-scale circulation and complementarity to Law Dome

Anomalies in geopotential height (GPH), SST and rainfall percentiles for the TPI positive and negative composites produced following the method previously outlined are shown in Fig. 6 for 1960–2010 (ERA 20C). A total of 14 positive years make up the positive TPI composite, while 23 negative years make up the negative TPI composite. In addition, Fig. S2 shows the same analysis using ERA-Interim (1979–2014), which has 15 years for each composite. Figure 6 shows the difference between the mean state of the surface ocean and atmosphere during TPI-defined IPO positive and negative years for the Southern Hemisphere warm season (November–March) which showed the strongest pattern, as well as the average response of Australian rainfall, with reductions in rainfall of 5–15 % during IPO positive and increases of up to 20 % or more during the wetter IPO negative phase. The SSTs show the canonical IPO pattern in the tropical Pacific, with the warmer tongue of SSTs in the central and east equatorial Pacific flanked by cooler SSTs west and further from the Equator. In the high latitudes southeast (SE) of Africa, IPO positive years are associated with higher geopotential heights compared to IPO negative years. Conversely, IPO positive years are associated with regions of lower heights to the southwest of Australia. Although the magnitude of these circulation anomalies differs depending on the data set used, both sets of analysis consistently indicate that positive IPO phases are associated with a stronger southerly component of the atmospheric circulation, while negative IPO phases are associated with a more northerly component of this circulation.

It is encouraging that composite anomalies produced by both ERA-20C and ERA-Int over their common period of 1979–2010 showed generally the same atmospheric anomalies. However, the patterns were amplified in the ERA-20C suggesting it may overestimate the magnitudes of changes between the IPO phases, although we cannot discount the possibility that the ERA-20C may record more detail as it samples negative years before and after IPO minima (i.e. negative years from when the IPO is trending both negatively and then positively). While caution must be applied to the interpretation of data prior to the introduction of satellite data in 1979, Fig. 6 suggests that IPO phase changes may result in anomalies that could be recorded in ice cores in East Antarctica, as suggested by Vance et al. (2015).

5 Discussion

This application of mapping and numerical methods to identify a suitable ice coring site is useful provided the initial

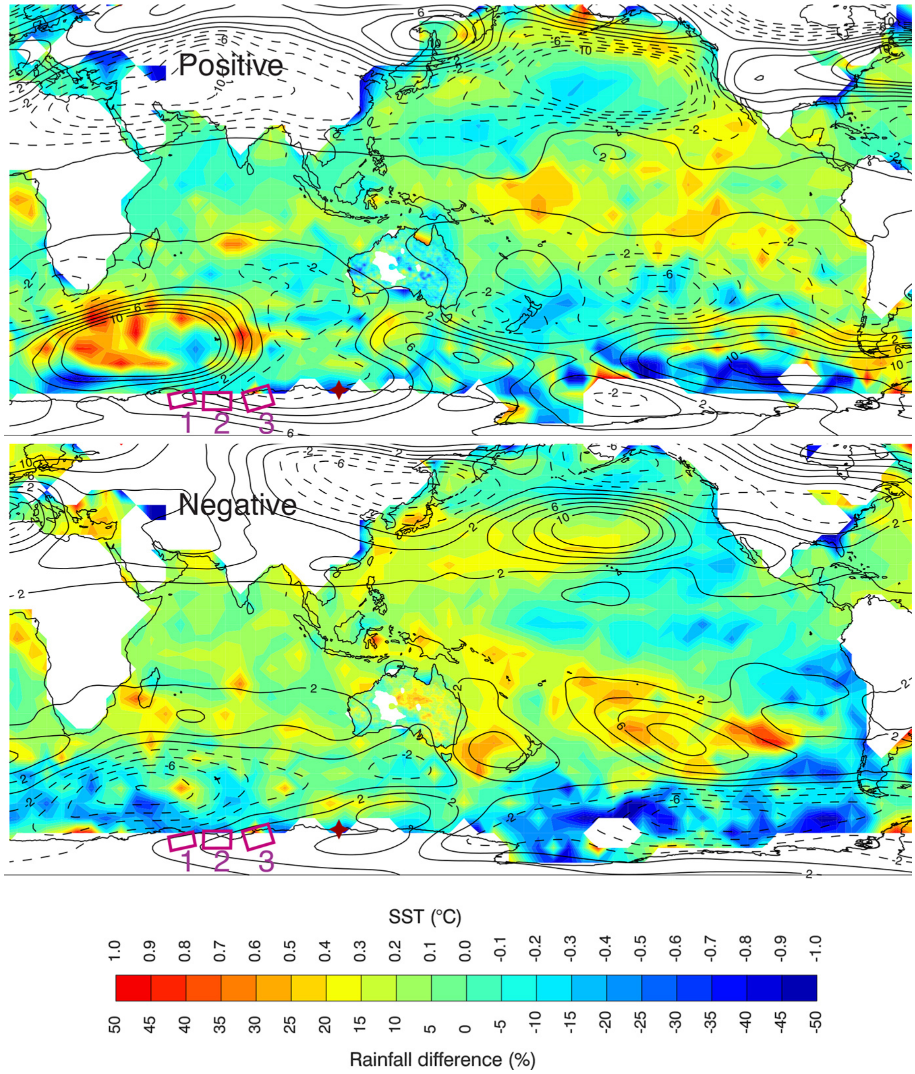

Figure 6. Sea surface temperature, 500 m geopotential height and Australian rainfall correlation analysis with IPO during the warm season (November–March) for positive (top) and negative (bottom) years. For this analysis we used ERA-20C over 1960–2010, defining positive and negative years as 0.5 SD above or below the average respectively. See the Supplement for this analysis performed using ERA-Interim over 1979–2014. Note that the colour bar defines a rainfall increase over Australia, as well as warm SSTs, as the red spectrum (conversely, a rainfall decrease and cool SSTs are blue). Identified in fuchsia are regions shown in previous figures: 1 – Law Promontory and Enderby Land; 2 – Cape Darnley; and 3 – Mt Brown. Law Dome is shown as a red star to the east of the three regions.

criteria are stringent enough so as to reduce the possible sites rapidly but not so stringent that no reasonably accessible site is available. In this study, the requirement of high annual snowfall combined with a 1000–2000-year ice age within 300 m of the surface were the two primary criteria for site selection, as high accumulation generally precludes millennial-length records within 300 m of the surface.

However, we acknowledge that the numerical analyses performed here have several shortcomings and assumptions that may be invalid, at least locally, and are due to the quality and spatial density of the observational data available. One of the principal shortcomings is the use of a modelled accumulation product; however, we note that the product used here (RACMO 2.1/ANT) has exceptional skill in many parts of the continent. Due to the spatial resolution of the underlying model (27 km), small-scale topography variations which affect the local accumulation regime are not resolved. In our region of interest, in general RACMO appears to underestimate the accumulation rate, the result of which is younger ice at depth than is predicted. A mitigating factor is that the Nye age model tends to underestimate age at depth; thus, the impact of the underestimation of accumulation rate may not be as severe.

There are also several limitations with the surface roughness analysis. The length scale used to calibrate it against – 500 m – is most likely too broad and therefore not entirely appropriate for modelling processes that distort the seasonal signals recorded in the ice core. The regression for surface roughness obtained for the MODIS imagery only accounts for around 25 % of the variance in the roughness measured from the laser altimetry. Additionally, while areas with high surface roughness are unlikely to be suitable for obtaining an annually resolved ice core, a smooth surface is not a sufficient condition to define suitability for high-resolution ice coring. Importantly, blue ice and wind-glazed areas are both unsuitable for high-resolution ice coring but are characterised by smooth surfaces and would not be excluded with this analysis.

We also acknowledge here that this study is only the initial step in selecting a new, high-resolution ice core site. Additional analysis and ground-truthing from both geophysical surveys and short cores are required to ultimately confirm the suitability of a particular site.

5.1 Optimal site selection – site criteria

Site criteria 1–3 significantly narrowed the suitable sites in East Antarctica for very high-resolution ice coring. Four likely regions remained after the site criteria were applied: the Law Promontory and Enderby Land region inland of the Mawson Coast, the region encompassing Cape Darnley and the Bjerkø Peninsula, the region encompassing Mt Brown on the Ingrid Christensen Coast near Davis station, and the Bunger Hills region to the west of Law Dome. The Bunger Hills region is comparatively close to Law Dome compared to the other three regions, and limited studies suggest a similar regional climate signal to Law Dome. Furthermore, Fig. 4 indicates that a similar representative surface air temperature regime to Law Dome, while Fig. 6 indicates the Bunger Hills region has a similar decadal wind signal to Law Dome. On the strength of this, we rule out Bunger Hills as a site for this study, as our circulation criteria, which specify a circulation regime complementary to Law Dome, are unlikely to be fulfilled. Nonetheless, the Bunger Hills region has strong potential for high-resolution ice core records.

The Law Promontory region (LawProm) shows some promise and has associated prior records. The 1000–1500 m contour interval neatly encloses a region of $> 250\,\mathrm{mm\,years}^{-1}$ IE accumulation and is also positioned on a dome or ridgeline (Fig. 5a) and hence has favourable ice dynamics. There is significant elevation change in the near neighbourhood of this region, suggesting some danger that isotope records may be less straightforward to interpret, hampering both the ability to infer temperature and moisture sources at the site and the precise dating of the record. Nye age modelling suggests that obtaining 1500–2000 years within 300 m of the surface may be possible with $> 250\,\mathrm{mm\,years}^{-1}$ IE accumulation but that the region where this is possible is restricted to a very small site, on the ridge, at between 1000 and 1500 m elevation. Unfortunately, no existing ice core records are known of in the immediate vicinity of this ridge. Historically, logistical access to this site has been problematic, due largely to frequently inclement weather. Additionally, this region is outside of the traditional logistical shipping routes (for Australian Antarctic station resupply). Nonetheless, another promising site in this region is the saddle in Enderby Land, behind the Napier Mountains Dome, at between 1000 and 1500 m elevation, that has accumulation of 200 to above $250\,\mathrm{mm\,years}^{-1}$ IE. We note that there are numerous nunataks in this subregion and this may indicate complex basal features in this region. Detailed aerogeophysical surveys would be required to further specify an appropriate site in this subregion.

Of the four promising sites considered here, the temperature signal in the Cape Darnley region (Darnley) is representative of the largest area in East Antarctica. Figure 1a shows that on the easterly facing slope of the Darnley region, ice age at target depth increases with elevation, and obtaining an ice age of 1500–2000 years at 300 m is achievable. However, the requirement of $> 250\,\mathrm{mm\,years}^{-1}$ IE accumulation means that, as with much of the East Antarctic coast, there is only a very small band at around 1000 m where both criteria are satisfied (Fig. 5b). This very small region is situated almost precisely on the ridgeline and therefore is likely to have favourable ice dynamics. Figure 5a shows this as there is little in the way of major elevation changes over time in the immediate area. Existing accumulation measurements in this coastal region indicate that there is reasonably high variability in annual accumulation rates (Table 1). This means that pinpointing an ideal high-resolution site in the Darnley region would require ground-truthing to confirm site-specific accumulation rates.

The Mount Brown region already has numerous existing short-core records for validation of accumulation rate estimates, and these existing records have also shown compelling evidence of the preservation of seasonally varying glaciochemical properties. The Mt Brown region has three promising subregions: two ridges and an area of quiescent ice flow associated with Mt Brown. The accumulation estimates from RACMO suggest that accumulation rates may be too low for our stated site selection criteria. However, as stated above, the numerous existing short-core records for this area indicate higher accumulation rates, sufficient for annual resolution.

5.2 Go west: capturing a new southern Indian Ocean climate signal

Pacific decadal variability is a strong driver of climate variability across the Pacific (Zhang et al., 1997) and in the Antarctic region (e.g. Ding et al., 2011). The incidence of extreme events (e.g. floods and droughts) changes significantly across the Pacific Basin depending on the state of the IPO phase. As an example, eastern Australia experiences increased drought risk during IPO positive phases and increased flood risk during IPO negative phases (Kiem et al., 2003; Kiem and Franks, 2004). This IPO-related variability in the Australian hydroclimate is also clear in Fig. 6, with, for example, on average 10–20 % higher rainfall during the IPO negative phase.

As previously described, there is some evidence that IPO-like decadal variability has hemispheric influences at high latitudes of the Southern Hemisphere expressed as changes to the zonal wave-3 pattern (Garreaud and Battisti, 1999). More recently, Yeo and Kim (2015) highlighted differences in the Southern Hemisphere climatic response by comparing two intervals that coincided with the warm (1979–1998) and cool (1999–2012) phases of the IPO. Although they did not directly address decadal variability in the Pacific (i.e. IPO-like variability) as a mechanism for these changes, they did highlight concurrent changes in the structure of the Southern Annular Mode and the El Niño–Southern Oscillation between the two epochs. Their results highlight a connection between tropical Pacific and Southern Hemisphere high-latitude climate variability on the decadal timescale. Moreover, Yeo and Kim (2015) showed that these differences occurred in the non-annular spatial component of the Southern Annular Mode, providing corroborating evidence for changes in the wave-like structures of the Southern Hemisphere circulation between these two intervals, similar to Garreaud and Battisti (1999). Further evidence of Pacific decadal variability, possibly related to the IPO, has been shown in the Indian Ocean region and includes local hydroclimate records from Madagascan corals (Crueger et al., 2009), tree ring records from Myanmar (D'Arrigo and Ummenhofer, 2014), Antarctic stable water isotope variability (Masson-Delmotte et al., 2003), and an Australian rainfall and IPO reconstruction (Vance et al., 2013, 2015) from the Law Dome ice core.

Currently, there is limited understanding around tropical Pacific forcing of high-latitude climate variability. The Law Dome ice core has provided valuable insight into this tropical–extra-tropical teleconnection (Vance et al., 2013, 2015). Therefore, a new, annually resolved ice core that collected a record complementary to these existing, but limited, studies of Pacific decadal variability in the Indian Ocean region would be valuable.

Figure 6 shows a signature of IPO-related variability in the atmospheric circulation in the southern Indian Ocean, SE of the African continent. This is a similar location to the centre of action of the zonal wave-3 structure identified in Garreaud and Battisti (1999), although displaced slightly to the west. Even with the uncertainty in the circulation analysis due to the limited length of the observational data records (see Fig. 6 and Supplement), travelling west from Law Dome toward our three primary regions suggests that an ice core here might either sample this centre of action directly or a complementary part of it. Therefore, a record from one of these regions should provide a record complementary to Law Dome, possibly with a stronger IPO signal. It should be noted that, in using data from 1960 to 2010 (1979–2014 Supplement), we are only sampling a small subset of the known instrumental-period behaviour of the IPO. However, this is a limitation of all studies characterising decadal variability in the high latitudes of the Southern Hemisphere and should not preclude the use of these observational results from a site selection analysis.

As discussed above, Yeo and Kim (2015) have shown that changes in high-latitude climatic anomalies are coincident with those in El Niño–Southern Oscillation (ENSO) in the tropical Pacific. This suggests that IPO-like anomalies may be related to the multidecadal variability of the Southern Annular Mode (SAM), specifically, in its non-annular component (Yeo and Kim, 2015). By definition, this would affect the meridional component of the circulation more than the zonal component, potentially affecting the advection of heat and moisture onto the Antarctic continent. A new high-resolution record from this region could complement and enhance the existing SAM reconstructions from James Ross Island (Antarctic Peninsula) (Abram et al., 2014) and Law Dome (Goodwin et al., 2004) to produce a hemispheric record of annual SAM variability for the last 1–2 millennia, which incorporates these differences in basin-to-basin behaviour. Evidence provided here and in the literature (e.g. Garreaud and Battisti, 1999) shows that the ability to capture any IPO-related anomaly in the southwest Indian Ocean is likely to be improved by choosing a site directly south of the central Indian Ocean, e.g. the Law Promontory–Enderby Land region. However, we also note that logistical constraints may become more prohibitive in the more westerly regions, due to weather considerations and the increasing distance from both Antarctic stations and the normal associated shipping routes. International collaboration would ameliorate the more prohibitive aspects of access to these sites.

6 Conclusions

This study details a systematic method for selection of a new ice core site – in this instance, one with annual resolution and an ice age of 1000–2000 years at 300 m depth. This method demonstrates that having clear, specific and stringent criteria for site selection narrows the available area for further focus considerably. As a result, specific regions can be examined in greater detail. We have identified three sites in coastal East Antarctica spanning the region from Enderby Land to the Ingrid Christensen Coast that approach the fulfilment of all of our specified criteria. For targeting high-resolution regions, we have found that sites are generally restricted to a coastal band within 1000–1500 m elevation.

In addition, the analysis presented here suggests that the three sites we have identified may sample a region of the Indian Ocean not previously sampled at high resolution over the last 2 millennia. This broadening of the geographical extent of the 2000-year ice core array in Antarctica will help refine reconstructions of both regional and hemispheric climate and global climate indices.

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