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Late Holocene temperature variability in Tasmania inferred from borehole temperature data

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Abstract

Thirty six borehole temperature depth profiles were analysed to reconstruct the Ground Surface Temperature History (GSTH) from eastern Tasmania for the past five centuries. We used the Singular Value Decomposition method to invert borehole temperatures to produce temperature histories. The quality of borehole data was classified as high or low based on model misfit. The quality of the borehole data was not dependent on topography, or land use. Analysis reveals that 3-5 high quality borehole temperature depth profiles were adequate to reconstruct robust paleotemperature records from any area. Temperature changes were greatest around the north east coast and decreases towards midland of Tasmania. Warm East Australian Current (EAC) flow towards north east coast of Tasmania during summer was considered a prime driver of warmer temperatures observed for the north east coast. Average, GSTH reconstructed from Tasmanian boreholes shows temperature increases about 1.2 ±0.2 ^{o}C during the past five centuries. Some boreholes show temperature cooling in the beginning of 20th Century that may be an indication of late LIA response in Tasmania. Reconstructed temperatures were consistent with meteorological records and other proxy records from Tasmania during their period of overlap.

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1. Introduction

Reconstructions of past temperatures are essential for understanding the trajectory of future environmental change, especially with regards distinguishing between natural variability and anthropogenic effects on the earth's climate (Hulme et al., 1999; St. Jacques et al., 2010; Soltwedel et al., 2015). The late Holocene is an important time period as it contains some major global and regional climatic variability i.e. Medieval Warm Period (MWP; Polovodova et al., 2011; Quamar and Chauhan, 2014), Little Ice Age (LIA; Mann, 2002; Ponce et al., 2016) and 20th Century global warming, during a period when large scale climate parameters such as ocean circulation and ice sheet extent were broadly similar to today. Progress in hemispheric (Beltrami and Bourlon, 2004; Neukom and Gergis, 2011) and global (Huang et al., 2000) average temperature estimation over the last millennia are improving, but there are still significant uncertainties in understanding regional responses from global anthropogenic effect (Mann et al., 2009).

A dearth of paleotemperature records limits knowledge of past climate during the late Holocene in southern Hemisphere, and particularly Australia (Jansen et al., 2007; Jones and Mann, 2004) in comparison with the Northern Hemisphere (Mann and Jones, 2003; Neukom and Gergis, 2011). In Australia, proxies used to reconstruct past temperature history are clustered in Tasmania (Colhoun, 2000; Cook et al., 2000; Fletcher and Thomas, 2010; Mackenzie and Moss, 2014; Rees and Cwynar, 2010) and the eastern tropics (Moss et al., 2012; Moss et al., 2013; Moss and Neil, 2011; Petherick et al., 2013), which means they do not provide representative cover of the diverse climates across the continent. Paleotemperature reconstructions from borehole records have the potential to supplement existing climate proxy data and increase the spatial density of historical climate records across the Australian continent. However, in many areas of Australia and indeed worldwide the borehole data available to reconstruct past temperatures is limited and the number of boreholes required to reconstruct robust past temperature has not been established.

Tasmania is an island located 240 km to the south of the mainland of Australia between 41 and 43 ^{o}S. Tasmania is positioned in an area that is subject to significant climate variability and change. Components of global circulation patterns, such as the East Australian Current (EAC), Leeuwin current, Tasman front, and El Nino Southern Oscillation (ENSO) play a major role in South-East Australia and

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Tasmanian climate (Forootan et al., 2016; Hamilton, 2006; Herraiz-Borreguero and Rintoul, 2011; Meuleners et al., 2008; O'Kane et al., 2011). At the same time, global warming during the 20^{th} Century is observed to be accelerating and likely influencing local climate processes which is thought to be contributing to temperature rise and environmental change in Tasmania (Colhoun, 2000; Fletcher and Thomas, 2010; Rees and Cwynar, 2010).

Instrumental temperature records in Tasmania are usually only available for the last 100 years (Bureau of Meteorology, 2016a), and records of this length are restricted to around Hobart and Launceston. Reconstruction of past temperature histories prior to the late 1900's thus relies on climate proxies such as tree rings (Cook et al., 2000; Cook et al., 2006) chironomids (Rees et al., 2008; Rees and Cwynar, 2010), vegetation types (Colhoun, 2000; Mackenzie and Moss, 2014), lake levels (Colhoun et al., 1999; Fletcher and Thomas, 2010) and sediment (Townsend and Seen, 2012) each of which have drawbacks in reconstructing past climatic variability (Huang et al., 2000). For instance, in many cases, climate reconstruction from lake level, or pollen records are often a record of dry or wet conditions, rather than the quantification of past temperature history. Further, measurement of the magnitude and temporal variation of past climate from these proxies are quite challenging.

The Earths subsurface contains a memory of past surface temperatures (Beltrami and Mareschal, 1995; Chouinard et al., 2007; Pollack et al., 2006). The shallow sub-surface temperature is governed by the time varying boundary condition at the surface and by the heat emitted from the earth's interior. In the absence of surface temperature fluctuations, an 'ideal' equilibrium temperature profile in homogenous bedrock is characterized by a linear increase with depth. When surface temperature variations occur, a thermal front propagates downward (Appleyard, 2005; Pollack and Huang, 2000). The rate of downward propagation depends on subsurface rock thermal diffusivity (k), which in general for rock is very low k ≈10-^{6} m^{2} s^{-1} (Gosselin and Mareschal, 2003a), thus the downward propagation of climatic signals is slow i.e. the past 200 years of record is contained in the topmost 100 meters and the post glacial record is contained within 1000-2000 meters (Gosselin and Mareschal, 2003a; Huang et al., 2000). The measurements of present day temperatures down boreholes can therefore extract a record of past surface temperature conditions. This method is not limited to geographical location; it can theoretically be reconstructed at any location by drilling a borehole and recording precise downhole temperatures. These records provide direct, but low-temporal resolution paleoclimate records that complement both the climate proxies and instrumental records.

Using borehole data, past temperature history has been reconstructed many areas across the world: in North America (Beltrami et al., 2003; Chouinard et al., 2007; Gosselin and Mareschal, 2003b; Guillou-Frottier et al., 1998; Mareschal and Beltrami, 1992), Europe (Bodri et al., 2001; Bodri and Čermák, 1998; Bodri and Dövényi, 2004; Kukkonen and Clauser, 1994; Mareschal and Vasseur, 1992), Asia (Akkiraju and Roy, 2011; Goto et al., 2005; Roy et al., 2002; Roy and Chapman, 2012), Australia (Appleyard, 2005; Pollack et al., 2006) Hemisphere and Global average (Beltrami and Bourlon, 2004; Huang et al., 2000; Pollack and Huang, 2000). However, the quality of borehole data needed to reconstruct past temperature history and the minimum number of high quality boreholes required to reconstruct plausible past temperature history is not well addressed in the literature. Additionally, characterising the spatial variation of paleotemperatures is limited to studies in Canada (Beltrami et al., 2003; Gosselin and Mareschal, 2003a; Gosselin and Mareschal, 2003b) and for northern hemisphere (Beltrami and Bourlon, 2004) but it is essential to examine other parts of the globe particularly in different climatic context.

Using a borehole network from eastern Tasmania, this study investigates the quality of borehole data and the minimum number boreholes required to reconstruct plausible past temperature records. In addition, we explore intra-regional paleotemperature variability using the reconstructed Tasmanian paleotemperature record.

2. Study region

Tasmania is located at the southern-most extent of the Australasian continental plate. Tasmania was connected with mainland of Australia during glacial periods (Colhoun et al., 1999; Rees et al., 2008) but is presently separated from mainland Australia by the 250 km wide Bass Strait (Jackson, 2005). In spite of its association with Australia mainland, Tasmania is dominated by oceanic climate.

Westerlies known as the Roaring Forties provide round the year precipitation in Tasmania (Rees and Cwynar, 2010). However, the amount of precipitation strongly varies from west (super-humid) to east (sub-humid/semiarid) (Colhoun, 2000; Fletcher and Thomas, 2010). Average (1961-90) annual mean

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temperature is 10.4 °C with average annual maximum temperature 14.7 °C and average annual minimum temperature 6.0 °C in Tasmania (Bureau of Meteorology, 2016b). Sporadic intrusion of cold air from Antarctica can produce frost and snow at any time of the year. On the other hand, dry and warm air from mainland of Australia sometimes causes temperatures that may exceed 40 °C (Rees et al., 2008).

Borehole temperature and conductivity data required for paleotemperature reconstruction were available from 36 boreholes (Supplementary Table S1) collected from eastern Tasmania between 41°10'S to 43°33'S and 146°22'E to 148°14'E (Fig. 8). Bedrock in eastern Tasmania is mainly dolerite and metasediment (McIntosh et al., 2012) and the landscape is generally of low altitude and relief. Native land cover is mainly evergreen Eucalypt forest, alpine heathlands, cool temperate rainforest and moorlands. However, much of the area has been modified or cleared for agriculture, or been subject to forestry operations (Geoscience Australia, 2007).

3. Methods

Temperature reconstructions using data from boreholes relies on measuring the deviation from an 'ideal' constant temperature gradient. The difference between the temperature measured down a borehole and constant temperature gradient from centre of the earth represents the total amount of warming and cooling (Fig. 1) in the ground after change in surface boundary condition (Gosselin and Mareschal, 2003a). The temporal variation and the magnitude of the temperature changes are related to the depth and departure from steady state.

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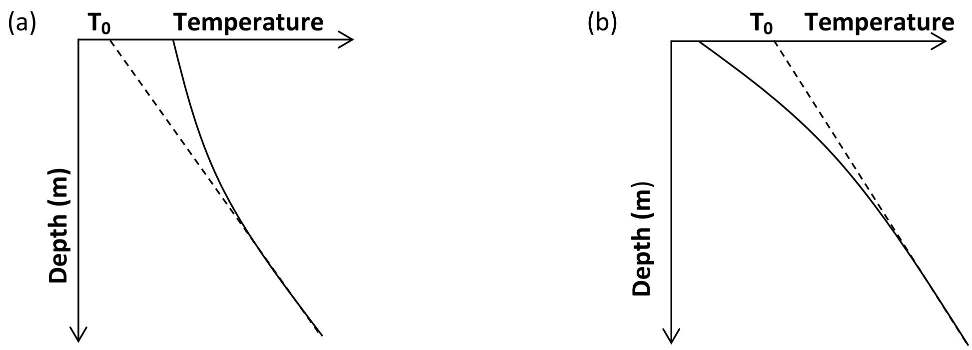

Fig. 1: Schematic diagram of borehole temperature depth profiles showing ground surface temperature (a) warming and (b) cooling

The thirty six borehole temperature depth profiles from Tasmania were inverted individually to reconstruct the past Ground Surface Temperature History (GSTH). Inversion of borehole temperature profile is an operation that transforms a temperature versus depth profile at a given time (the time of measurement) into a temperature versus time profile at a given depth. Basically, inversion yields a GSTH. The link between depth and time is through the thermal diffusivity and other thermo-physical properties of the rock through which the climate signal is propagated.

The perturbation at depth z, $T(z)$, caused by temperature changes at the earth surface, can be expressed considering the thermal conductivity variations, as the superimposition of the equilibrium temperature and the perturbation $T_t(z)$ induced by temporal surface temperature condition (Beltrami et al., 1992):

$$T(z) = T_0 + q_0 R(z) + T_t(z) \dots \dots \dots \dots \dots (1)$$

Where T_0 is the equilibrium surface temperature, q_0 is the surface heat flow density and $R(z)$ is the thermal resistance to depth z. The effect of heat production is small and can be neglected. In general, short period variations are filtered out by the earth. The surface temperature, estimated by the average surface temperature over k time intervals of equal duration Δ, can be expressed as,

$$T(t) = T_k (k-1)\,\Delta \leq t \leq k\Delta \dots \dots \dots \dots \dots (2)$$

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Equation (1) can then be modified as:

$$\theta_j = A_{jk} X_i \dots\dots\dots\dots\dots (3)$$

Where θ_j is the measured temperature at depth z_j, X_i, is a vector encompassing the unknowns $\{T_0, q_0, T_1, \dots\dots\dots T_k\}$, and A_{jk} is a matrix, each row of which contains 1 in the first column, the thermal resistance to depth z_j in the second column, and the K elements formed by evaluating the difference between complementary error functions at times $T_{k-1} = (k-1)\,\Delta$ and $T_k = k\Delta$:

$$A_{jk+2} = erfc\left\{\frac{z_j}{2\sqrt{kt_{k-1}}}\right\} - erfc\left\{\frac{z_j}{2\sqrt{kt_k}}\right\} \dots\dots\dots\dots\dots (4)$$

Equation (4) is a linear equation that can be solved by Singular Variable Decomposition (SVD; Beltrami et al., 1992; Beltrami and Mareschal, 1995; Mareschal and Beltrami, 1992; Menke, 1989). Borehole temperature inversions were completed using a Matlab SVD script (Clauser and Mareschal, 1995; Mareschal and Beltrami, 1992) based on the above equations. The inversion technique computes no temperature change at the deepest point of the borehole and starting time of the simulation. Thus the GSTH is reconstructed from the deviation of borehole temperatures from steady state considering no change at the deepest point.

Most of the Tasmanian boreholes are shallow ranging in depth from about 200 to 300 m. This depth can potentially record the last 500 years temperature history. Therefore, we used a linear time step distribution, whereas for longer history (>10,000 years) a logarithmic distribution is usual practice (Mareschal and Beltrami, 1992).

Prior to temperature inversions, where appropriate, borehole temperatures were corrected for variations in thermal conductivity. Most of the boreholes used for our temperature reconstructions were drilled through dolerite that has limited variations in thermal conductivity and thus required no temperature correction. Twelve boreholes were located in lithologies with variable thermal conductivity (indicated by * in Supplementary Table S1), and temperature profiles were corrected to improve precision in GSTH reconstruction. For the 12 boreholes requiring correction, average thermal conductivity was calculated for all sub-surface lithologies and subsequently harmonic mean of thermal conductivity was calculated to have a single value for the borehole. Heat flow was calculated using all sub-surface

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thermal conductivity values and downhole temperature data was recalculated through back propagation using calculated heat flow and harmonic mean of thermal conductivity of the borehole.

The thermal diffusivity (*k*) of rock is expressed by following equation:

$$k = \frac{\lambda}{c * \rho} \dots\dots\dots\dots\dots (5)$$

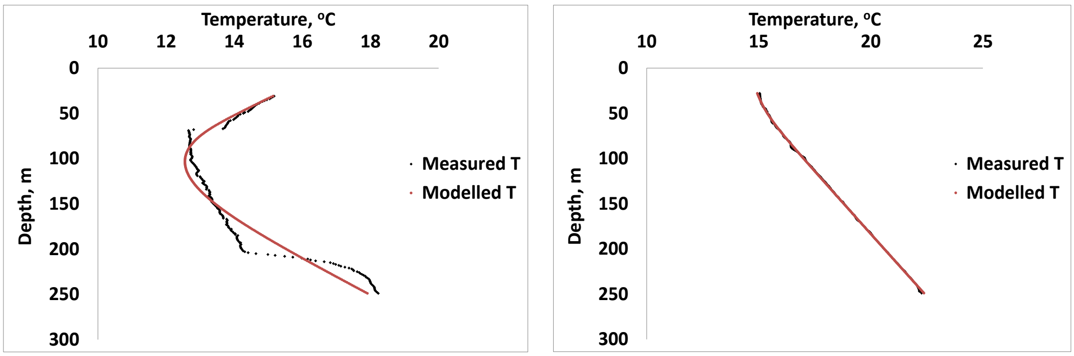
Where λ is the thermal conductivity and for most minerals and rocks, the product of $c*\rho$ is about $2.3*10^{6}$ $Jm^{-3}K^{-1}$ (Beardsmore and Cull, 2001). Small variation in thermal conductivity does not affect much in thermal diffusivity as well as in reconstruction of GSTH. In the present research, for simplicity thermal diffusivity was used $1.0e^{-6}$ $m^{-2}s^{-1}$ for all boreholes.

We also collected commonly measured topographic, geologic, and climatic data that may have an effect on past temperature reconstruction. Geographic character i.e. slope, aspect, relief, and distance from coast were measured from Shuttle Radar Topography Mission (SRTM) 30 m resolution digital elevation model (Rabus et al., 2003; Zyl, 2001) using ArcGIS v10.2.1. Land use and the change in land use since 1982 were compiled from Landsat, Google Earth satellite imagery and from Forestry Tasmania. Core samples and drill chips were used to determine the subsurface lithology. Details of data compilation are described by Suman and White (in review). High quality climate networks data were used to assess local climate variations for the 20^{th} Century (Bureau of Meteorology, 2016b). In addition, we compared our reconstruction with tree ring (Cook et al., 2000), and sea surface temperature using HadSTT 3.1.1.0 data (Kennedy et al., 2011).

4. Results:

4.1 Detection of reliable borehole data

In principle, in a conductive thermal regime, a precise temperature inversion process will provide a modelled temperature depth profile that coincides closely with the measured temperature depth profile. Deviation between modelled and measured temperature depth profiles indicates the modelled GSTH is inaccurate, or at least, imprecise. Here, we test whether or not the misfit (i.e. difference) between measured and modelled temperature data down the borehole can be used as a guide to the reliability of any given borehole-derived GSTH (Fig. 2).



(a) Oatlands borehole (b) Beaconsfield borehole

Fig. 2 (a) High deviation between measured and modelled temperature depth profile and classified as low quality borehole records (b) Very low deviation between measured and modelled temperature depth profile and classified as high quality borehole records

Normally, misfits are generated during inversion at every point throughout the borehole where measured data are available. We assessed two measures of model-data misfit to determine if they were a reliable means of measuring the quality of the borehole records. The first was 'sumsq misfit' calculated as the sum of the squares of all misfit data, based on the sum of the variance between the model and measured data at each depth of temperature logging. The second method, termed 'cumulative area misfit', was calculated in a similar way, but the misfit values were first smoothed to remove the high-frequency noise present in most borehole data. Smoothing was achieved with a low-pass filter that averaged 49 data points, 24 above and 24 below each value, at each temperature logging point. The smoothed misfit was then summed across each depth to produce the single 'cumulative area misfit' value (Fig. 3). Based on sumsq and cumulative area misfit we found 3 boreholes possess low quality borehole temperature data.

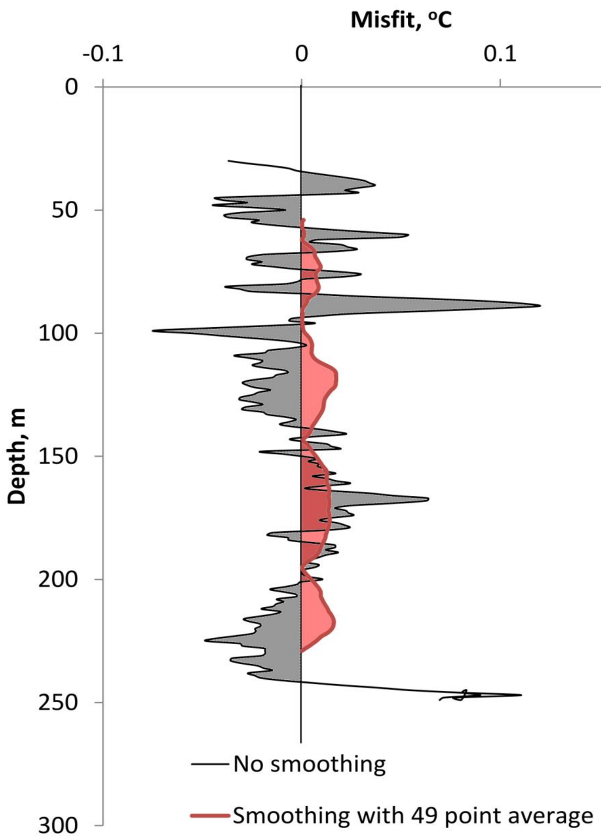


Fig. 3 Misfit between measured and modelled temperature profiles at Beaconsfield. The raw misfit contains substantial high-frequency noise, while the smoothed misfit is much more representative of the low-frequency variations that are more significant for the accuracy of paleotemperature reconstructions. 'Sumsq misfit' and 'Cumulative area misfit' values referred to in the text are effectively the area between the curves and the y-axis of the unsmoothed and 49 point smoothed misfit values respectively.

To test if the sum square and cumulative area misfit also provides a measure of the accuracy of the past temperature history, we conducted an empirical test. Each borehole GSTH was compared to the average from the thirty three borehole with high quality temperature data. The average of the 33 borehole

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temperature profiles had previously been shown to have good agreement with the meteorological record (Suman and White, in review) during their period of overlay. Thus the difference between each borehole and the average could be considered to provide a reliable measure of the accuracy of each borehole temperature reconstruction.

Both the sumsq and cumulative area misfit correlate with differences of paleotemperature from average GSTH. So, both misfits could be used as basis of quantifying the accuracy of the borehole record. However, the cumulative area misfit was calculated from an average of 49 m (in general Tasmanian borehole temperature data was collected at 1 m intervals) which reduces the magnitude of any specific trends in the misfit data. Therefore, we consider that the cumulative area misfit provides the more reliable measure and will use it from here on. Boreholes with low model misfit and lower differences in paleotemperature between individual and the average reconstruction of all boreholes are considered better quality.

Based on the cumulative area misfit and maximum temperature change we classified the Tasmanian borehole data set into two broad groups: boreholes with high and low quality data. From 36 boreholes, the data from three boreholes produced very high cumulative area misfits and inconsistent temperature change, therefore, were categorised as low quality (Fig. 4). These three profiles may be affected by ground water flow or downhole temperature measurement errors during logging. The remainder produce low cumulative area misfit and consistent temperature change and therefore, were classified as being of high quality (Fig. 4).

In boreholes with high quality data, the maximum temperature varies from 0.57 to 1.92 °C with relatively low cumulative area misfit in last 500 years (Fig. 4). In this category, most boreholes show comparably consistent maximum temperature change during the last 500 years. Five boreholes with the lowest area misfit <0.01 m^2/m (Fig. 4, holes are circled) can be considered to provide a robust reconstruction of past temperature from that region. In borehole with low quality data, the maximum temperature varies considerably, from 2.5 to 6.5 °C, and displays a high model misfit in the last 500 years (Fig. 4).

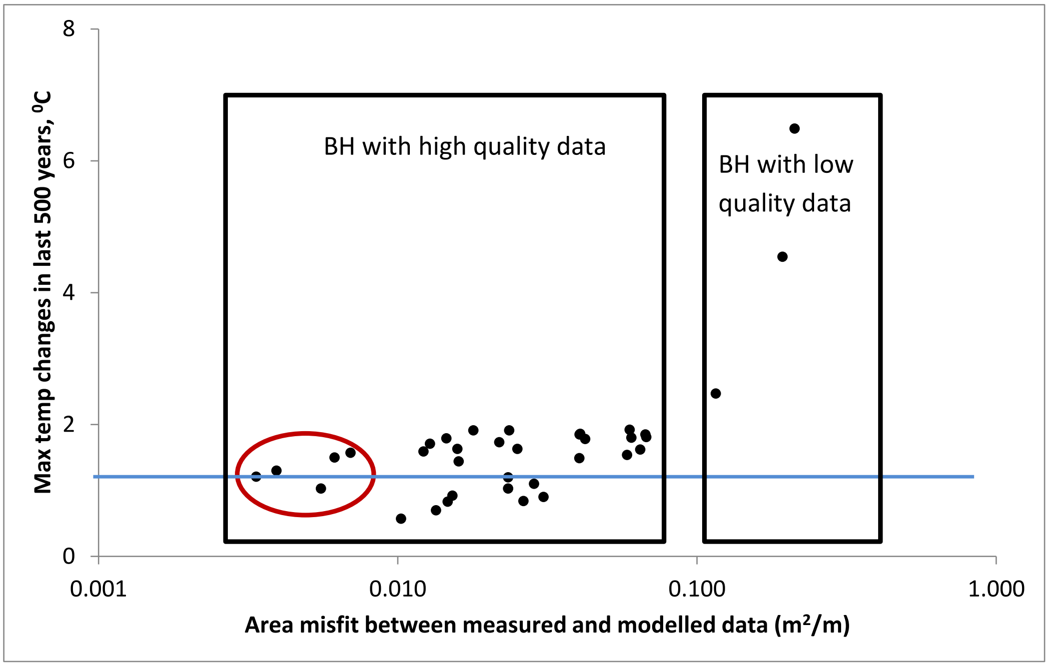

Fig. 4 Maximum temperature change with area misfit between measured and modelled data – Blue lines shows average temperature change reported from surrounding five (Low Head #091293, Launceston #091311, Hobart #094029, Cape Bruny Island #094010 and Eddystone Point #092045) meteorological stations.

To check whether there was a geophysical basis for the misfit observed in the boreholes with low quality data, we also checked the shape of the down-hole temperature records (Fig. 5a) and the core retrieved from these boreholes (Fig. 5b). In each of the three boreholes with low quality data, it appears that it was function of ground water that affected temperature depth profiles. This is indicated by profiles with inconsistent temperature gradient, break in temperature profile, data missing etc, and corresponding to fractured drill core indicating permeable lithologies (Fig. 5).

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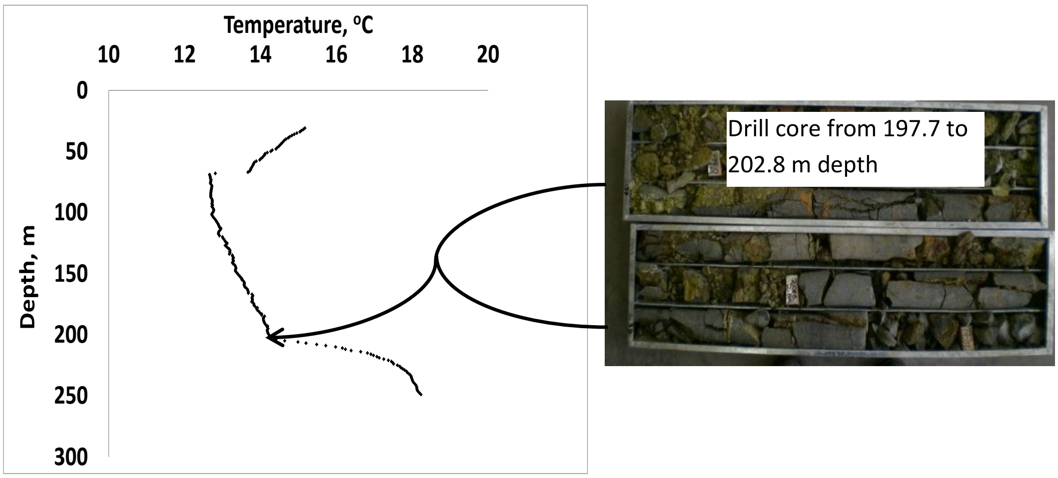

(a) (b)

Fig. 5 (a) Borehole temperature profile (Oatlands borehole) suspected to have been affected by ground water movement at ~ 200 m. The upper discontinuity may be due horizontal ground water flow, (b) Broken drill core from 197.7 to 202.8 m. The high frequency of fractures suggests highly permeable rock, and ground water movement (Photo Courtesy: Oatlands borehole, KuTH energy, Tasmania)

We also investigated whether the amount of model-data misfit correlated with geographic or topographic properties. Lithology appears to correlate with borehole data-model misfit. Analysis shows boreholes are located in sedimentary rocks produce lower area misfit in comparison to boreholes are located in dolerite, or in mixed lithologies (Fig. 6). However, the significance of the correlation is not clear, as many of the factors likely to produce perturbed temperature profiles (e.g. rock fracture density, uncorrected variability in thermal conductivity) are higher in the sedimentary rocks.

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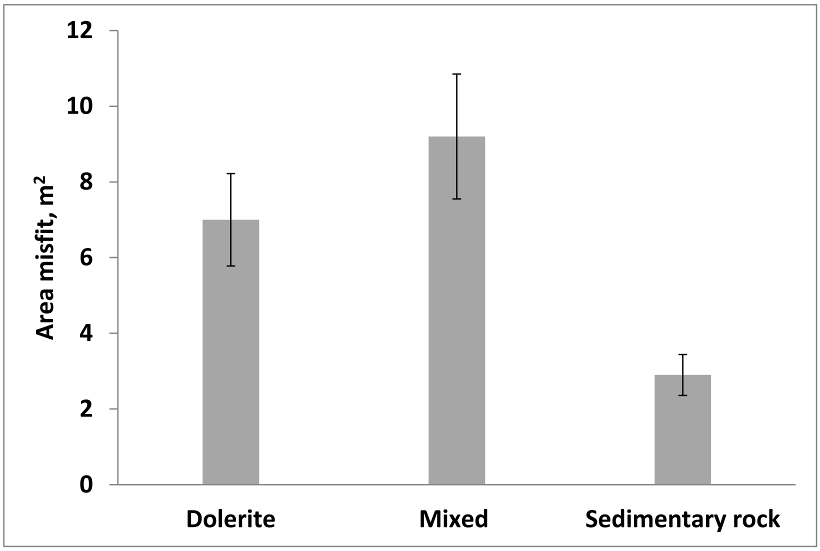

Fig. 6 Relationship between area misfit and boreholes sub-surface lithology. Error bars represent standard errors, with a 1σ confidence interval.

Topographic and geographic factors such as elevation, slope, aspect, relief, easting and distance from coast were not significantly correlated with cumulative area misfit (Table 1, p-values are calculated at 95% confidence interval). However, the northing is significantly correlated with the cumulative area misfit (p-value 0.03). Boreholes with low area misfits are located in higher northing area. This is perhaps due to the pattern of sub-surface lithology. South-East area of Tasmania is rich in Parmeener and Dolerite whereas north-east region is dominated by mixed geology i.e. Devonian granites, Ordovician Mathinna beds etc (Seymour et al., 2007). Beside this, most of the sediment boreholes are located in the south of Tasmania.

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Table 1: The relationship between potential geographical and topographical attributes with cumulative area misfit.

Attribute	R-Squared (area)	P-values
Elevation	0.025	0.38
Distance from coast	0.000	0.98
Slope	0.036	0.29
Aspect	0.011	0.56
Relief	0.021	0.42
Northing	0.146	0.03
Easting	0.014	0.51

4.2 Reconstruction of GSTH

Thirty three borehole temperature depth profiles (Supplementary Fig. S1) show relatively consistent temperature gradient throughout the holes, with the exception of temperature increases toward the surface, indicative of recent warming. The reconstructed GSTH show relatively stable temperature trends (Fig. 7) until the end of the nineteenth century. As the diffusive nature of the borehole temperature record filters out high-frequency variability, the temporal resolution of the record decreases exponentially with time. Thus, the data should be considered to provide stable centennial-average temperature trends prior to the 20th Century. At the beginning of twentieth century, the reconstructed temperature profiles indicate ground surface warming. This is consistent with other studies from Australia (Appleyard, 2005; Pollack et al., 2006), Canada (Beltrami et al., 1992; Beltrami et al., 2003; Chouinard et al., 2007; Gosselin and Mareschal, 2003a), Europe (Bodri et al., 2001; Bodri and Dövényi, 2004; Veliciu and Šafanda, 1998) and Asia (Goto et al., 2005; Roy et al., 2002; Roy and Chapman, 2012).

Most of the reconstructed Tasmanian GSTH from boreholes recorded a consistent increase in temperature since 1900. However, seven holes considered to have high quality data (Rocherlea, Epping, Temple Bar, Weymouth, Elizabeth, Frankford and Tunbridge) show cooling during the early to mid-20th Century before rapid warming in late 20th Century. Most of these boreholes are located in consistent

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dolerite (Rocherlea, Epping, Temple Bar, and Elizabeth) and mudstone (Weymouth) lithologies that are likely to have produced a highly reliable GSTH record. We did not find any relation between these boreholes and topographic and geologic factors to cluster them separately. Thus, we consider the period of cooling recorded in these holes reflects the mid-20th Century cooling event present in the average meteorological record (Fig. 7) from surrounding five meteorological stations. Mid-20th Century cooling is a global pattern as well that has observed different location across the globe and reported in other studies (Chouinard et al., 2007; Gosselin and Mareschal, 2003a; Gosselin and Mareschal, 2003b).

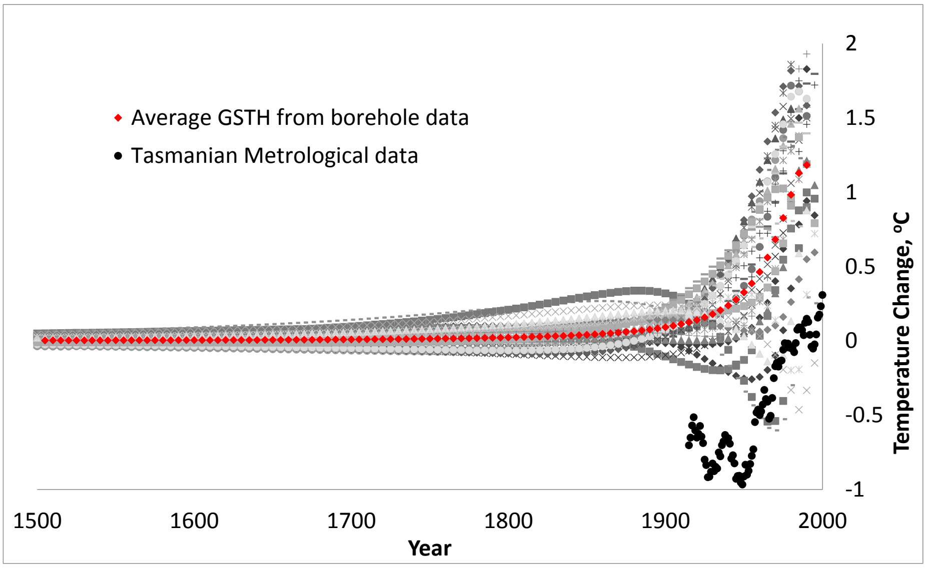

Fig. 7 Reconstructed GSTH from Tasmanian high quality data set, black circles represent average temperatures from meteorological data compiled from surrounding five meteorological stations. Note that the meteorological data has been offset by 1°C for clarity.

The average reconstructed ground surface temperature warming was found to be 1.2 ± 0.2 °C in last 500 years across eastern Tasmania. Most of this warming occurred in the late twentieth century and agrees well with the warming observed in the high quality metrological record from Tasmania (Fig. 7).

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The reconstructed changes in Temperature were observed to vary spatially across the region (Fig. 8). Higher temperature change is observed around north east coast of Tasmania. We did not find any significant relation between the maximum temperature change and geologic and topographic factors. Details were reported in Suman and White (in review). Thus, only climatic factors and land use are responsible for this observed spatial variability.

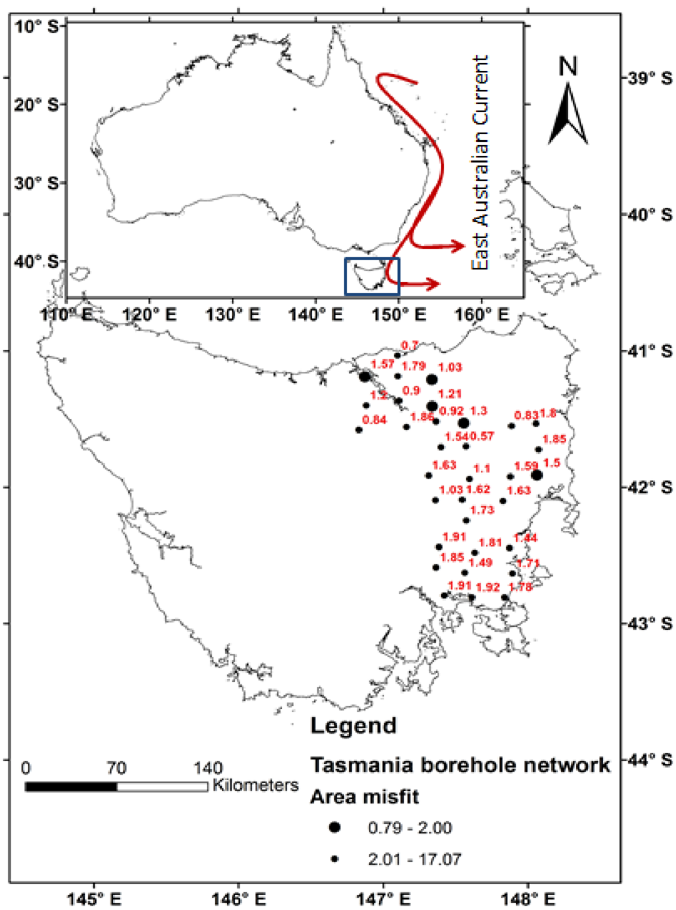

Fig. 8: Spatial variation of regional maximum temperature changes in Tasmania during the past 500 years. The size of the circle represent cumulative area misfit between measured and modelled downhole temperature data. Symmetric representation and flow directions of EAC are presented in the inset.

Higher temperature change was found close to the coast compared with the midlands of Tasmania. The distance of the borehole from the coast is negatively correlated with the maximum temperature change (Fig. 9; correlation coefficient r = -0.4 and P-value 0.03).

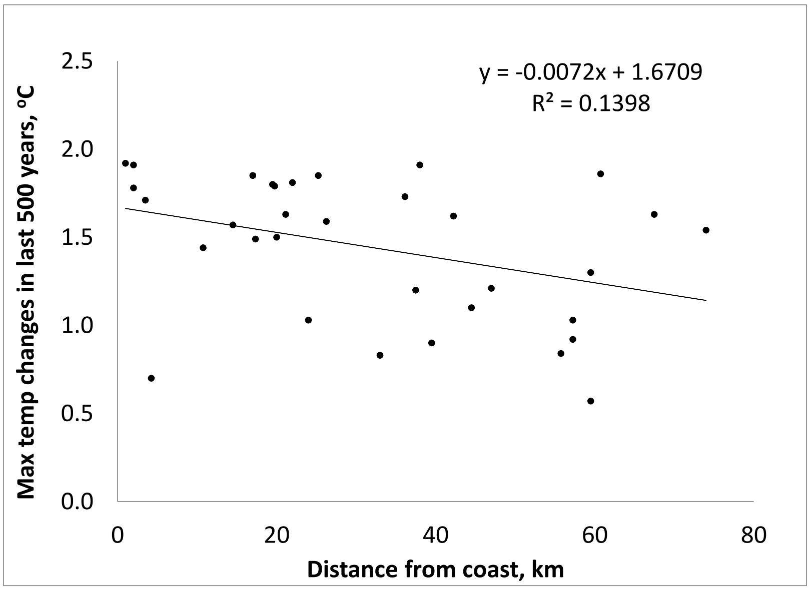

Fig. 9 Correlation between maximum temperature changes and borehole location from coast

4.3 Variation due to land use:

Our study showed that land use has some spatial and temporal correlation with reconstructed temperatures. The reconstructions found higher temperature changes using data from the boreholes located in grass area compared with those from forested areas and the difference between them were higher in the end of 20th Century. This was established using only available land use data since 1980 that provided limited opportunity to test spatial and temporal variation of paleotemperature based on land use change during whole period of simulation since 1500 AD. Long term land use data are required for further investigation into paleotemperature change based on land use.

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5. Discussion

Detection of good boreholes is very important for reconstruction of plausible past temperature history as well as for the area where availability of borehole data is limited. In this study, we proposed a new technique to define the quality of borehole data for paleotemperature reconstructions based on area misfit. We have found boreholes with low area misfit produce a consistent temperature changes in last 500 years (Fig. 4). These temperature changes are comparable with average meteorological data from the same area during their period of overlay (Fig. 7). Analysis shows that it is possible to reconstruct robust paleotemperature by ~3 to 5 high quality boreholes from a region with area misfit <0.01 m^2/m depth of borehole.

Temperature changes during five century at continental average are in North America 1.2K, South America 1.4 K, Europe 0.8 K, Africa 0.8 K and Asia 1.2 K (Huang et al., 2000; Pollack and Huang, 2000) which are comparable with our reconstructed average maximum temperature change.

5.1 Comparison with proxy result:

Reconstructed temperature records using the Tasmanian borehole data agrees well (Pearson correlation co-efficient: 0.839 and P value: 0.000) with records of the southern Hemisphere sea surface temperature (SST, Fig. 10) during their period of overlay. SST anomalies are relative to 1961-1990 and increased about 1.0 ^{o}C during in the 20th Century (Kennedy et al., 2011)

Temperature reconstruction from our boreholes also agree well with the Mt Read Huon pine dendrochronology (Cook et al., 2000), Pearson correlation co-efficient: 0.333 and P value: 0.001, Fig. 10). The low-temporal resolution (c. centennial) of the borehole GSTH in the early part of the record means that the decadal variability seen the reconstructed tree ring result (Cook et al., 2000) is not observed in the boreholes, leading to low Pearson correlation co-efficient. However, importantly, both boreholes and tree ring temperature reconstructions show relatively stable centennial average temperature between 1500 to 1850 AD. Some correlation between boreholes and tree rings is also seen with a short (20-30 year) cool period in the early 20th Century, with seven boreholes recording temperature cooling at this time that may correlate with the ~0.5 ^{o}C dip seen in the tree ring record

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(Cook et al., 2000). Finally, both our borehole reconstruction and tree ring records show rising temperatures toward the end of the record, although the magnitudes differ, with the boreholes in north-east Tasmanian coast recording larger increases than the tree rings on the central upland plateau.

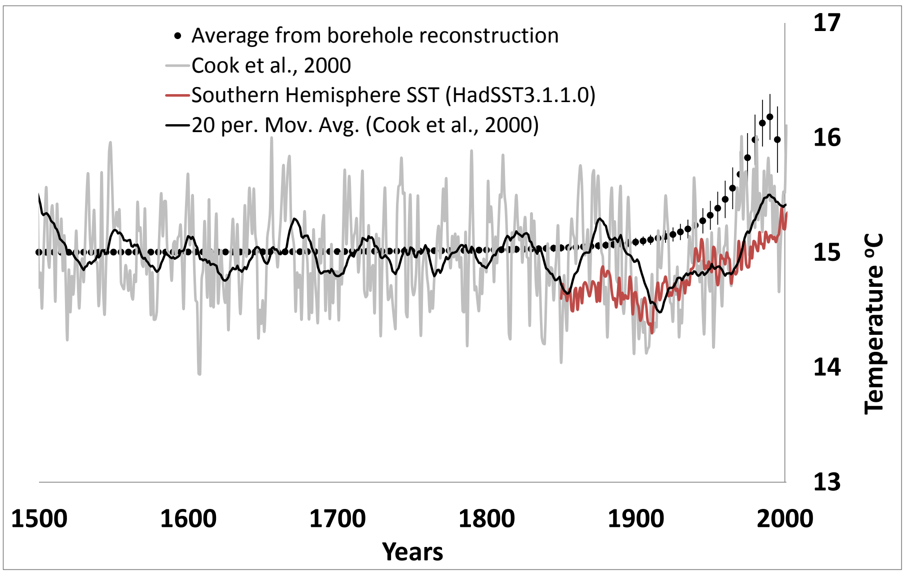

Fig. 10 Comparison of temperature histories reconstructed using borehole data with those from Tasmanian dendro-climatological reconstruction and sea surface temperature data.

Temperature reconstruction using the Chironomid record from Platypus Tarn in Tasmania also shows an increase in temperature of about 1°C during 19th and 20th Century (Rees and Cwynar, 2010). The 20th Century warming captured by the Chironomid proxy data is comparable with the borehole reconstruction. Pollen record (Anker et al., 2001; Fletcher and Thomas, 2010; Mackenzie and Moss, 2014), lake record (Colhoun et al., 1999; Hopf et al., 2000) from Tasmania indicates recent warming/drying with stable climate during late Holocene that also shows some correlation with our borehole reconstruction.

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5.2 Spatial variation:

Ocean climatology is an important driver of the Tasmanian climate. The East Australian Current (EAC) (O'Kane et al., 2011; Ridgway and Dunn, 2003; Wilkin and Zhang, 2007) flows around eastern Australia from north to south and flows eastwards into Tasman sea from east coast of Tasmania (Fig. 8; (Ridgway and Dunn, 2003)). During summer time (January–May) EAC flows a warm current towards the north and east coast of Tasmania (Ridgway, 2007; Ridgway and Dunn, 2003) may be a driver of higher temperature changes around north east coast of Tasmania.

Our GSTH provide evidence for higher 20^{th} Century increases in temperate near to the coast from the overall borehole dataset. Further, this increase is also reflected in the five boreholes that we have higher confidence in the GSTH. Here, [Nunamara (1.21^{o}C), Ben Lomond (1.3^{o}C), Swan (1.5^{o}C), Lisle (1.03^{o}C), and Beaconsfield (1.57^{o}C)] which are produced very low area misfit (<0.01 m^2/m) (Fig. 4 and 8). Beaconsfield is located at the north coast and Swan is located at the east coast of Tasmania (Fig. 8). These two boreholes show higher temperature change in compare to others. It gives confidence that EAC is likely a driver of higher temperature change around north east coast of Tasmania. High quality meteorological network also shows higher temperature change at north eastern Tasmanian coast during 20^{th} Century (data available period, Fig. 11)(Bureau of Meteorology, 2016b).

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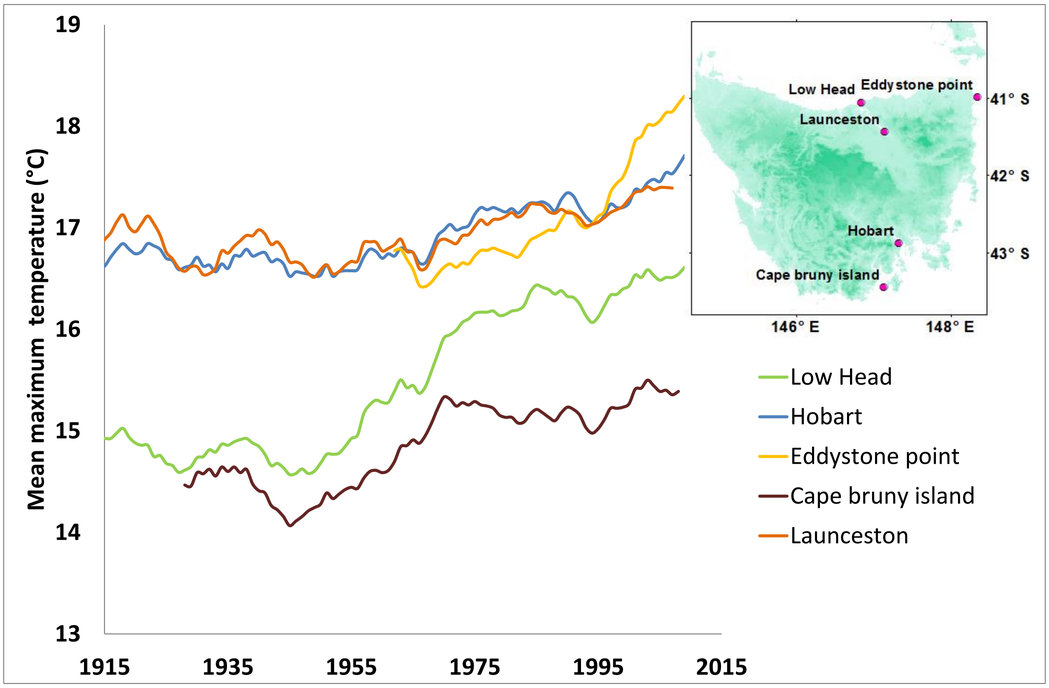

Fig. 11: Meteorological record from eastern Tasmania(Bureau of Meteorology, 2016a)

6. Conclusion

Temperature depth profiles from 36 boreholes across eastern Tasmania were analysed to reconstruct GSTH for the past five centuries. Detailed analysis reveals that not all borehole temperature depth data are suitable for inversion to reconstruct GSTH. Boreholes data can be categorised as high and low qualities based on sum squared and cumulative area misfit. While sub-surface lithology may be a factor of determining borehole quality, we did not find any specific relationship between the quality of borehole and topography, and land use. Overall, between 3 and 5 high quality borehole temperature depth profiles are enough to reconstruct robust paleotemperature from any area.

Five century temperature reconstruction is characterized by a temperature increase of 1.2±0.2 ^{0}C, with most of the warming is occurred during in the 20th century. Average temperature reconstruction from boreholes agrees well with high resolution Tasmanian surface air temperature during their period of overlay. GSTH reconstructed from borehole also agrees well with others proxy reconstruction around in Tasmania. Reconstructed temperature profiles shows higher temperatures around the coast and decreases towards midland of Tasmania. Warmer ocean temperatures due to a strengthened East Australian Current during summer may be the driver of warmer north-eastern coast of Tasmania.

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