Authors response to editors review of manuscript tcd-6-2575-2012, titled "Borehole temperatures reveal a changed energy budget at Mill Island, East Antarctica over recent decades" by Roberts et al. Items for each review have been listed sequentially with text from the reviews shown in *italics*. Locations in the text are referenced by page and line, e.g. page 2579 lines 19-20 is given as P2579 L19-20.

## 1 Review tcd-6-C1292-1293 (Anonymous Referee #1)

*General impression. Manuscript presents new borehole temperature data and its paleoclimatic interpretation. The new data and outputs are placed in the context of spatial and temporal climate change in the region where instrumental data are lacking. The technique (inverse models) applied for the research is proven valid for the borehole temperature data interpretation. The paper is well structured and provides almost sufficient number of illustrations. Paper will be greatly improved by referring to and comparing recently published results of similar work carried on in Antarctica. Presentation of the new results and analyses data of nearest meteorological stations (Mirny, Casey) , coastal borehole paleoclimatic proxy data and inland borehole temperatures (Muto et al, 2011) could extend and make more certain conclusions made in the paper. The article will be of interest for the Earth science researchers, it is definitely in the scope of The Cryosphere journal and can be recommended for publication with minor revisions.*

Specific comments:

- P2576 L5 *..."break in gradient between 49 and 69 m depth" A graph of the observed data versus depth would be helpful to illustrate that change in gradient.* Added in a new Figure 2 showing the subsurface temperature as a function of depth data given in Table 1. Figure 2 also shows the break in gradient calculated for a least squares two-linear segment data fit to the temperature observations below 15m using a brute force search algorithm (Mudelsee, 2009) which constrains the depth of the slope-break-point to correspond to one of the temperature measurement depths.

In addition made the following changes to the text

- P2576 L5 changed text from “break in gradient between 49 and 69m depth” to “break in gradient around 49m depth”
- P2578 L7 changed text from “Temperature readings are shown in Table 1” to “Temperature readings are shown in Figure 2 and Table 1”
- P2578 L16 added the following text “Analysis of the temperature data below 15m suggests a break in the gradient of temperature as a function of depth occurs at 49m below the surface. Specifically, the BREAKFIT algorithm (Mudelsee, 2009) was used to fit a two linear segment model to the temperature data using a discrete brute force search approach that constrains the depth of the gradient break point to correspond to the depth of one of the temperature measurements. The temperature gradient is $0.0165 \pm 0.0007 \mathrm{K m^{-1}}$ above the break point and $0.0034 \pm 0.0003 \mathrm{K m^{-1}}$ below it.”
- P2583 L8 changed “Table 1” to “Fig. 2”
- P2586 L9 changed text from “change of gradient between 49 and 69m below the surface” to “change of gradient around 49m below the surface”

- P2576 L7 *The warming of 0.37oC per decade reported in the manuscript is smaller than 0.8 oC over the last two decades determined in West Antarctic (Orsi, A.J. and others, 2012) under significantly lower present surface temperatures. The difference could be briefly touched in the Discussion.*

  Added the following text after P2586 L6 “It is interesting to consider these local changes in the context of wider regional changes. The borehole temperature trend of $0.37 \mathrm{K decade^{-1}}$ since 1980 can be compared with trends at Mirny ($0.54 \pm 0.64 \mathrm{K decade^{-1}}$ for 1987 to 2011) and Casey ($0.35 \pm 0.97 \mathrm{K decade^{-1}}$ from 1989 to mid 2012). Data from the nearby GF08 inland automatic weather station (68°29′36″S, 102°10′32″E, 2123m elevation) for the period October 1986 to Janurary 1998 also shows a warming trend in both 4m air temperature ($1.12 \pm$

$0.40$K decade$^{-1}$) and 3m subsurface firn temperature ($0.38 \pm 0.04$K decade$^{-1}$). The time period chosen for Casey reflects data availability after repositioning of the station while the time period for the Mirny analysis corresponds to the start of the GF08 record. For both Casey and Mirny the trends, while of comparable size, have large uncertanties. While the trends at GF08 are more significant, we note that both the air and subsurface senor height/depth was progressively lowering/deepening due to snow accumulation. The Casey and Mirny temperature changes are accompanied by increases in relative humidity. A peicewise linear data-fit allowing for a break in slope using the BREAKFIT algorithm (Mudelsee, 2009) shows a relative humidity trend at Casey for data from 1960 to mid 2012 of $-0.38 \pm 0.05\%$year$^{-1}$ before 1989 and a trend of $0.51 \pm 0.07\%$year$^{-1}$ after. A corresponding analysis for Mirny over the period 1956–2011 shows a trend of $0.09 \pm 0.09\%$year$^{-1}$ before 1985 and a trend of $0.20 \pm 0.11\%$year$^{-1}$ after this date.

This picture of regional warming in East Antarctica is consistent with a recent temperature reconstruction (Steig et al., 2009) and also supports model simulations (Goosse et al., 2012, Figure 3). Further, these results can be set in the context of wider Antarctic warming, with comparable Antarctic Peninsula warming (Mulvancy et al., 2012), a reconstructed recent temperature trend of up to 0.8K decade$^{-1}$ for the West Antarctic Ice Sheet divide (Orsi et al., 2012) and large but spatially variable temperature trends in inland Dronning Maud Land, East Antarctica (Muto et al., 2011). ”

- P2578 L16 *At the borehole temperatures reported in the manuscript one may expect surface melting that could be manifested in ice layers/lenses in the ice core. A short sentence on the ice core stratigraphy (thickness and concentration of ice layers/m versus depth) could clarify mechanism (melting, wet deposition, change of albedo, . . .) of the surface temperature rise.*

  Added the following text after P2578 L16 “The stratigraphy of the Mill Island ice core indicates past surface melting events as shown by the presence of melt layers in the 120m ice core record. The current stratigraphy suggests there is no discernible change in the thickness and concentration of melt layers throughout the entire length of the ice core."

- P2580 L13 *Inverse models. A short message on how LSQR and PSO models differ or are similar to models used by MacAyel, Cuffey, Clow and others would allow for the comparison between interpretations presented in the manuscript and reconstructions published previously.*

  The following text has been added to the end of the introductory text on the numerical model, ie after P2579 L2 "Such an approach of using both a forward model and a method of optimising surface temperature histories has been used previously (see, for example Johnsen, 1977; MacAyeal et al., 1991; Johnsen et al., 1995; Cuffey et al., 1995; Cuffey and Clow, 1997; Dahl-Jensen et al., 1998, 1999; Barrett et al., 2009; Muto et al., 2011; Orsi et al., 2012). The forward models used in these studies all included the heating associated with firn densification with the exceptions of MacAyeal et al. (1991); Johnsen et al. (1995); Barrett et al. (2009); Muto et al. (2011). These studies all select which possible surface temperature history reconstructions to accept based on minimising the mismatch between the simulated and observed borehole temperature profiles. However, the method of generating possible surface temperature histories (to select from) differ, and fall into three broad categories (Orsi et al., 2012): (i) optimisations based on relationships between surface temperature and stable water isotope ratios (e.g., Johnsen, 1977; Cuffey et al., 1995; Cuffey and Clow, 1997; Johnsen et al., 1995), (ii) Monte Carlo based approaches (e.g., Dahl-Jensen et al., 1998, 1999; Barrett et al., 2009) and, (iii) generalised least-squares solution of a linearised version of the problem (e.g., MacAyeal et al., 1991; Muto et al., 2011; Orsi et al., 2012). The methods used herein, most closely resemble the later two methods for the PSO and LSQR methods respectively."

- P2581 L13 & P2582 L5,7–9 *"Effective Nye depth" not sure it is a common term.*

Changed the text from ", and allowing a typical 5/6 factor between the actual and effective depths, gives a maximum effective Nye depth for the velocity profile of 333 m." to ", and finally the depth that the Nye style vertical velocity profile acts over (herein referred to as the "effective Nye depth") is adjusted by a factor of 5/6 to ensure consistency between the vertical strain rate and the vertical velocity at the surface, yielding a maximum effective Nye depth of 333 m."

- P2583 L5 *A bit confusing statement. Measured data presented versus depth, while Fig. 4 shows reconstructed temperature versus time.*

  Changed the text from "measured temperature distribution" To "reconstructed surface temperature history"

- P2583 L23 *0.37 K decade-1 ??? - see above comment P2576 L7* Deleted the text "This rate is large by Antarctic standards and is only exceeded in regions of the Antarctic Peninsula (Turner et al., 2005)."

- P2584 L6 *Conclusions of the manuscript would be more robust if Discussion section will include data analyses of two coastal weather stations (Mirny and Casey).* Two new paragraphs have been added to the Discussion addressing this point, for details see response to comment P2575 L7 of reviewer #1 (tcd-6-C1292-1293). In addition the text on P2586 L13–19 was changed from " A synthesis of climate reconstructions, beyond the scope of the present work, may help to clarify the relative importance of these factors at the Mill Island site." to "Comparision of the Mill Island temperature trend with instrumental data suggests that these trends are regional in nature and not dominated by local scale effects."

## 2 Review tcd-6-C1401-2012 (Anonymous Referee #2)

*Roberts and others provide interesting findings on ground surface temperature reconstruction using borehole temperature profile measured at Mill Island. The* *conclusions are drawn from numerical modelling of the inverse diffusion/advection problem. The main conclusion of the paper is that changes in the surface energy budget occurred around 1980/1981 AD +-5 years. I suggest to make it a bit stronger by continuing on why it is important to know or what knowing of that will tell us in a global scale . The introduction needs more elaboration towards the end of the section on what has been done in order to understand when the sudden increase in observed ground temperatures occurred . Numerical Model requires a better explanation on the forward model setup (more detailed explanation on initial and boundary conditions). Inverse model needs to be changed to Inverse methods. This section needs major elaboration including formulas for the minimization functions used in both methods . In Surface temperature reconstruction section it is important to address how the initial temperature distribution is going to affect the reconstructed ground surface temperatures. The discussion section is well written, but I would suggest to include the insulation effect of fresh snow on the ground heat exchange budget. Overall, I recommend this paper for the publication after major revision.*

Section 1 Introduction *In the introduction section the authors should further elaborate on what exactly has been done to fill the knowledge gap on the past borehole temperature increase. What inverse method/s was/were used? (brief description of the method/s). Why the specific inverse method/s was/were chosen? Have the methods been employed in similar studies before?* An overview of previous inverse methods used for borehole temperature reconstructions has been added, see comment P2580 L13 for Review#1 (tcd-6-C1292-1293) for details.

P2577 L13 *It would be nice to have an entire map of Antarctica with the study site on it, where Fig 1 can be zoomed in a photo of the bigger map.*

Modified Figure 1 to include a whole of Antarctica map to show the location of the area covered in Figure 1. In addition, added latitude-longitude grid and a scale bar to the figure.

Section 2 Temperature observations P2577 L20 *What is a network of East Antarctica sites? Needs a reference.* Added a reference to Jones et al. (2009).

P2578 L2 *Reference is needed after Leeds and Northrup resistance bridge.*

Changed the text from "Leeds and Northrup resistance bridge to measure" to "Leeds and Northrup resistance bridge (model number 8078)"

P2578 L7 *Remove the sentence "Temperature reading are shown in Table 1". I suggest to make a figure plot (y-axis depth, x-axis temperature) instead of Table 1 and make a reference to the figure.*

The tabulated data has been retained, but a new Figure 2 has been introduced as suggested. The text has been changed from "Temperature readings are shown in Table 1" to "Temperature readings are shown in Figure 2 and Table 1"

P2578 L10 *Remove the sentence "The observed temperature distribution in the borehole is shown in the Table 1". In addition, changed the text at P2583 L8 from "Table 1" to "Fig. 2"*

This text has been deleted

P2578 L16 *It is not very clear why the upper three measurements are discarded? I suggest to add more sentences on how the model is going to be driven if the upper three layers neglected.*

Added the following text on P2578 L15 "Due to the lack of discernible seasonal temperature variations for most of the depth of the borehole, we limit the surface temperature reconstruction to annual averages. Furthermore, the upper three temperature measurements show a significant seasonal temperature imprint, and are thus not suitable for inclusion in a reconstruction that does not allow for seasonal variations."

Section 3 Numerical Model. P2578 L20 *How the surface temperature history was assigned if the upper 3 layers had been discarded? I suggest to elaborate* *more on this section with more detailed information on boundary and initial conditions set up for the forward model.* The upper 3 layers correspond to the most recent 6 years of surface temperature history, while the first temperature measurement included in the optimisation (at 19.07m below the surface) corresponds to a advection time of 8.5 years from the measurement date. Both the LSQR and PSO methods extrapolate the recent warming trend over the latest 8.5 years. The following text has been added at P2578 L16 "These upper three temperature measurements correspond to an advection time of 6years while the shallowest temperature measurement included in this analysis (at a depth of 19.07m below the surface) corresponds to an advection time of 8.5years (see Figure 3). The reconstructions of surface temperature history extrapolate any recent temperature trend over these final 8.5years."

P2579 L5 *"(See Sect.6 for nomenclature)" Since the nomenclature is not too long it would be good to move it after the equation (1).* The nomenclature has been moved from Section 6 to Table 2 and the reference on P2579 L5 changed from "(see Section 6 for nomenclature)" to "(see Table 2 for nomenclature)"

P2579 L6 *The authors started from describing the last term. I suggest the description of the first two terms be included as well (diffusion and advection). What do coefficients in the second term stand for?* changed the text from "

$$\frac{\partial T}{\partial t} = \frac{\kappa}{\rho C}\frac{\partial^2 T}{\partial z^2} + \frac{1}{\rho C}\left(\frac{\partial \kappa}{\partial z} - \rho C w\right)\frac{\partial T}{\partial z} + \frac{f}{\rho C} \tag{1}$$

Where the last term is the energy associated with firn densification (Patterson, 1994, chapter 10, equation 32)." to "

$$\frac{\partial T}{\partial t} = \frac{\kappa}{\rho C}\frac{\partial^2 T}{\partial z^2} - \rho C w\frac{\partial T}{\partial z} + \frac{f}{\rho C} + \frac{1}{\rho C}\frac{\partial \kappa}{\partial z}\frac{\partial T}{\partial z} \tag{1}$$

Where the terms on the right hand side are the rate of temperature change due to conduction, advection, firn densification (Patterson, 1994, chapter 10, equation 32) and the correction to the conduction term due to spatially varying thermal conductivity respectively."

P2579 L11 *It is not clear what the lower and the upper bounds are.* Added the following text at P2579 L13 "Specifically,

$$\kappa = \begin{cases} \kappa_{ice} & = 9.828\exp\left(-5.7 \times 10^{-3} T\right) & \text{ice} \\ \kappa_{firn} & = (\kappa_{van\_dusen} + \kappa_{schwerdtfeger})/2 & \text{firn} \\ \kappa_{van\_dusen} & = 2.1 \times 10^{-2} + 4.2 \times 10^{-4} \rho + 2.2 \times 10^{-9} \rho^3 & \\ \kappa_{schwerdtfeger} & = \frac{2\kappa_{ice} * \rho}{3\rho_{ice} - \rho} & \end{cases} \tag{2}$$

"

P2579 L15-16 *Could the data be fitted with a simpler function?* Added the following text to P2579 L17 "This particular functional form (piecewise exponential plus linear or dual exponential) was chosen based on previous analysis on the Law Dome ice core density profile (van Ommen et al., 1999) and the similarity between the density profiles at Mill Island and Law Dome (Figure 2a)."

P2579 L18–22 *Where does the input data come from? What dataset have been used to force the model? I suggest the last paragraph in this section be moved (P2580 L8-12) after this paragraph.*

- Added in a new section after P2579 L17 on "Initial and Boundary Conditions"
- The text had been changed from "The thermal boundary conditions applied to the model were a time varying, prescribed surface temperature, and a zero heat flux boundary condition at depth." to "The thermal boundary conditions applied to the model were a time varying, prescribed surface temperature (the optimisation of which is the purpose of the inverse models), and a zero steady-state heat flux boundary condition at depth (the depth at which the

upward conduction of the geothermal heat flux is balanced by the downward advective heat flux).”

- The last paragraph of this section has been moved to after P2579 L17

P2579 L23 *Why is the resulting reconstruction of the surface temperature history independent of the assumed velocity profile?* Changed the text from “The vertical velocity distribution with depth is unknown, but the resulting reconstruction of surface temperature history is essentially independent of reasonable assumed velocity profiles. In particular, we assume that the surface vertical velocity” to “The vertical velocity distribution with depth is unknown, but because the borehole is relatively shallow compared to the likely icecap thickness the variation of age with depth for velocity profiles spanning the likely range of icecap thicknesses is small (see Figure 3 and Section 3.3). Therefore the resulting reconstruction of surface temperature history is essentially independent of reasonable assumed velocity profiles. We assume that the surface vertical velocity is equal to”

*Section 3.2 Inverse Models. Change to Inverse methods.* P2580 L13 changed “Inverse models“ to “Inverse methods”

*Subsection 3.2.1 LSQR reconstruction. Change to LSQR method. This and the next subsection are very concise. I would suggest more information be provided: Which minimization function was used to find the minimum between measured and calculated temperatures? How does the sensitivity matrix help to reduce the misfit or minimize the cost function? Why the QR scheme was chosen?*

- P2580 L14 changed “LSQR reconstruction” to “LSQR method”
- Changed the text from “The LSQR method uses an iterative greedy algorithm which reduces the largest temperature residual in each iteration. The sensitivity matrix for the response of the temperature at the depth of the largest residual to the surface temperature history was calculated using the Complex-Step derivative approximation (Martins et al., 2003). The surface

temperature history is incremented by the minimum variance solution of this residual equation using a least squares QR method (Paige and Saunders, 1982). The initial choice of the surface temperature history was a linear interpolation of the measured temperature profile with the depth mapped to time using the assumed vertical velocity profile (see Figure 3)." to "The LSQR method uses an iterative greedy algorithm which reduces the largest temperature residual in each iteration by adding a time varying update $\Delta T_j$ to each point in the surface temperature time history $T_j$. This residual minimisation is based on a local lineariston of the problem. Specifically, the sensitivity matrix $S_{ij}$ for the response of the temperature $\hat{T}_{model}(i)$ at the depth $i$ of the largest residual to the surface temperature history $T_j$ at time $j$ was calculated using the Complex-Step derivative approximation (Martins et al., 2003), so that

$$S_{ij} = \frac{\partial \hat{T}_{model}(i)}{\partial T_j} \quad (3)$$

Due to the diffusive nature of the thermal regime, the minimisation problem is under determined, with multiple time points in the surface temperature history (i.e. multiple $T_j$'s) contributing to the simulated temperature at any depth ($\hat{T}_i$). Therefore multiple updates to the surface temperature history that minimise $E_{rms}$ are possible, and the least squares QR method (Paige and Saunders, 1982) is used to select the particular update with minimum variance of the update $\Delta T_j$ (minimises the Euclidean norm $\left(\sum_j \Delta T_j^2\right)^{0.5}$). As the calculation of $S_{ij}$ is time intensive, this matrix is kept constant for multiple iterations. This results in some updates actually increasing $E_{rms}$. Rather than discarding such updates, the surface temperature history corresponding to the lowest $E_{rms}$ is recorded. The initial choice of the surface temperature history was a linear interpolation of the measured temperature profile with the depth mapped to time using the assumed vertical velocity profile (see Figure 3)."

*Subsection 3.2.2 PSO reconstruction. Change to PSO method. The same here.*

*I would like to see more explanation of this method, especially the minimization function which was used to find the minimum between measured and calculated temperatures and so on.*

- P2580 L23 changed “PSO reconstruction” to “PSO method”
- Added the following text before P2580 L24 “Particle Swarm Optimisation is an optimisation method well suited for non-linear problems with multiple minimum and a large dimensional subspace to search (i.e. a large number of variables to optimise). It works in an iterative manner by evaluating a number (or swarm) of candidate solutions (or particles) against a selection criteria and then updating each candidates location in the search subspace based on the selection criteria for the entire swarm. Each particle is initially assigned a random location in the search subspace and also a randomised velocity (change in subspace location for each iteration) with an associated inertia which acts to keep the particle moving along its current velocity trajectory. After the evaluation of the selection criteria for every particle at the current iteration, the velocity of each particle is nudged to move the particle toward the location where the best selection criteria has been found for the entire swarm. This combination of particle inertia and a force attracting each particle toward the location corresponding to the best selection criteria results in a broad investigation of the search subspace with a focus on areas corresponding to good selection criteria.”
- Changed the text on P2580 L24 from “Particle Swarm Optimisation solves for a group of particles (15 in this case)” to “Specifically, this study used a swarm of 15 particles”
- Changed the text on P2580 L25 from “(lowest RMS error)” to “(lowest $E_{rms}$)”
- Changed the text on P2581 L2–3 from “a piecewise linear surface temperature history was used, with 4 linear segments.” to “a piecewise linear surface temperature history was used, with 4 linear segments resulting in an eight

dimensional search subspace (an initial and final surface temperature and three intermediate time points where both temperature and time are free to evolve)."

3.3. Numerical convergence *Usually the choice of the initial condition is important for inverse type problems. Depending on different initial temperature distribution the reconstructed surface temperatures might be different. It would be interesting to see the sensitivity analysis of the initial condition as well.* Due to the dominance of the advection term for this particular problem, the solution is relatively independent of the initial temperature profile down the borehole. In addition both the LSQR and PSO methods assume an initial isothermal temperature distribution with the temperature equal to the surface temperature at the start of the simulation period. Therefore, both the LSQR and PSO methods optimise for the initial isothermal temperature distribution down the borehole. More details and modifications to the manuscript are given in response to comments P2580 L8–12 and P2580 L21–22 of review #3 (tcd-6-C1427-2012).

P2581 L13 *It would be reasonable to explain the rationale behind the authors choice of these three assumptions. Why these assumptions were chosen? Why is it important to test them?*

- This list has been expanded to include the parameterisation of the the upper firn thermal conductivity, for details see comment P2579 L8–13 of reviewer #3 (tcd-6-C1427-2012).
- This list was chosen to test the derived surface temperature reconstructions for sensitivity to both key discretisations of the forward model (spatial and temporal) and key boundary conditions with a large range of uncertainty (effective Nye depth and location of the zero flux lower boundary condition).
- Text was added (see Additional modification, comment P2580 L12) discussing the adaptive time stepping algorithm used to eliminate the time discretisation from the list of sensitivities requiring investigation.

P2581 L24-28 *It is not clear why the increase of grid spatial resolution should affect recovered at the ground surface temperatures.* If the spatial resolution used in the model is sufficient, then there should be no (or only minimal) change in the simulated temperature profile with depth for different spatial resolutions, as was the case herein. Such grid independence studies are standard practice for engineering simulations, to prove that the solution is independent of the spatial resolution of the simulation and therefore remove this as a source of error in the analysis.

4 Surface temperature reconstruction P2582 L13 *It would be helpful to show a formula for RMS error. Usually there are minimization methods employed to find the optimal solution that corresponds to the minimum of RMS.* Added the following text on P2578 L25 “Specifically, the two inverse models minimise the unweighted RMS error

$$E_{rms} = \left( \frac{\sum_{i=4}^{20} \left( \hat{T}_{model}(i) - T_{obs}(i) \right)^2}{\sum_{i=4}^{20} i} \right)^{0.5} \tag{4}$$

P2582 L26 *Elaboration is needed on how the minimization was done and which minimization method was used for LSQR method.* The section on the LSQR has been rewritten to address this issue, see response to comment Subsection 3.2.1 of reviewer #2 (tcd-6-C1401-2012) for details.

P2583 L5 *The measured temperature distribution on Fig. 4 is not shown.* Changed the text from “measured temperature distribution’ To reconstructed surface temperature history’

5 Discussion. *Fresh, recently fallen snow usually has a very low thermal conductivity and can alter the ground surface heat budget as well.*

– Changed the text on P2584 L11 from “a change in the radiative balance and latent heat processes” to “a change in the radiative balance, a change in the annual duration of fresh snow cover and latent heat processes”

- Added the following text after P2585 L22 “Key physical properties of snow alter as the snow ages, and are of direct relevance to the surface energy budget are a decrease in both surface albedo and thermal conductivity as snow ages (Zhang, 2005). A decrease in albedo results in more direct absorption of incoming radiation, while changes to thermal conductivity influence the insulating effect between the atmosphere and the deeper firn column. Changes in the frequency of snow fall events (and hence the annual duration of fresh snow cover), and other processes influencing the surface characteristics of the snow may therefore change the surface energy balance.”

## 3 Review tcd-6-C1427-2012 (Anonymous Referee #3)

General comments: *The study by Roberts et al. presents a surface temperature reconstruction based on a numerical heat transfer model which is fitted to the temperature measurements of a borehole. The study gives a brief overview of the used methods including two fitting procedures, provides some analysis of potential uncertainties of the temperature reconstruction, and gives some interpretation of the obtained results. The authors point out that such studies are important since long-term climate records are very sparse in Antarctica. The major finding of the study is that surface temperatures have increased since 1980 which is most likely associated with changes in the surface energy balance. The study will contribute to a better understanding of the local climate evolution at the study region in east Antarctica. However, there are some major concerns about the structure, the methods, and the results which should be addressed before final publishing.*

*The introduction is very short and gives only little specific information about the study and its motivation. In contrast, there are a lot explanations about palaeoclimate reconstruction which is not part of this study. The introduction should be more focused on the specific aims of the study and set them into a wider context.*

Changed the text at P2577 L6–12 from "In particular, the Mill Island record is situated partway between Law Dome and the Vestfold Hills where a relationship between Law Dome summer temperature and evaporation in Ace Lake in the Vestfold Hills has previously been reported (Roberts et al., 2001). There are very limited data records available for this broad region of East Antarctica before the 1957–1958 International Geophysical Year, so that palaeo-reconstructions are required to assess the long-term regional climate history." to " Previous regional studies on late Holocene paleoclimate have demonstrated a relationship between Law Dome summer temperature in Wilkes Land and evaporation in Ace Lake in the Vestfold Hills, Princess Elizabeth Land (Roberts et al., 2001). This indicates that the East Antarctic region spanning Wilkes Land, Queen Mary Land and Princess Elizabeth Land may experience a contiguous air temperature history on climatological time scales. In order to explore the regional sensitivity to temperature variability further, we focused our research on the most northerly limit of the East Antarctic Ice Sheet, in Queen Mary Land. There are very limited instrumental temperature data records available for this broad region of East Antarctica. The closest long-term record is from Mirny Station with observations since the 19571958 International Geophysical Year. Hence, we employed palaeoclimate reconstruction methods using ice cores and borehole measurements to investigate temperature variability."

*There are only little information about the study site. A more detailed site description about e.g. climate conditions and landscape features would make it much more easier for the reader to put the results into a geographic context. Also a map of Antarctica with a marker on the study site would support this. The description of the performed temperature measurements might be better placed in a* *separate method section together with the description of the model and the fitting procedures.*

Added the following text at P2577 L12. “The reconstructions were obtained from Mill Island (65°30′S, 100°40′E, see Figure 1), a small ice cap (∼40 km radius) which is detached from the East Antarctic Ice Sheet and lies at the northern edge of the Shackleton Ice Shelf. The Mill Island summit has an elevation of ∼500 m above mean sea level.”

Added the following text after P2577 L15. “Mill Island experiences a polar maritime climate with four primary influences: (i) the passage and decay of circumpolar low pressure systems (cyclonic eddies and polar frontal depressions) that transport moist and relatively warm air masses from the Southern Ocean, and result in orographic precipitation over the ice cap; (ii) high pressure ridging associated with the circumpolar longwave connecting the Antarctic and the Indian Ocean subtropical high; (iii) strong katabatic wind drainage from the Denman Glacier valley, drains over the Shackelton Ice Shelf to Mill Island transporting relatively, cold, dry air mass; and, (iv) localised summer season sea-breezes associated with sea-ice breakout that result in low level cloud, fog and rime formation over the ice cap summit. In the absence of long-term meteorological observations, the general climate overview for Mill Island can be approximated from Mirny Station at 66°33′S, 93°01′E, that indicates a prevailing east-southeasterly winds (Turner and Pendlebury, 2004).”

*The method descriptions should be better structured. On the one hand there are several redundancies while on the other hand there is a lack of important information (see specific comments).*

The methods section has been restructured and substantially rewritten to improve clarity and include more details.

*In general, there are some structural inconsistencies which make it hard to follow the manuscript. It might be better to clearly separate methods, results, and* *discussion (see also specific comments).*

The methods and results section has been restructured to help with clarity. Specific details are given against the specific comments below.

*The discussion is very general. Instead of explaining what processes could have changed the surface energy balance, the authors should focus on the interpretation of the results. Are there any studies which support that e.g. sea ice coverage or cloudiness has changed after 1980? Are there any known environmental changes that correlate with the timing of the temperature increase? I suggest to put this study into a much wider context than just showing that the temperatures have increased after 1980. The obtained results could be compared more extensively with other data sources and studies. Although direct measurements from climate stations are not available at the site, there might be other sources such as reanalysis products (as suggested by the authors themselves) or the drilled ice core.*

The discussion has been expanded to include comparison with both station meteorology and automatic weather station data and with other Antarctic borehole and climate reconstruction analysis. Details are given against comment P2584 L6 of review #1 (tcd-6-C1292-1293).

Specific comments:

- P2576 L4 *I would call this "zone of zero annual amplitude"* changed the text from "temperature difference over the approximate 100m depth below the seasonally varying zone." to "temperature difference over the approximate 100m depth in the zone of zero annual amplitude below the seasonally varying zone."
- P2576 L22–P2571 L3 *This sentence could be written more understandable.* Changed text from "In particular, while recent Northern Hemisphere temperatures have, on average, been warmer than anytime in at least the last 1300

years (Mann and Jones, 2003; Mann et al., 2008), the recent Southern Hemisphere warming is only of comparable size to the relatively large uncertainties (likely because of data sparsity) in palaeo-reconstructions for the Southern Hemisphere (Mann and Jones, 2003; Mann et al., 2008)." to "In particular, recent Northern Hemisphere temperatures have, on average, been warmer than anytime in at least the last 1300 years (Mann and Jones, 2003; Mann et al., 2008). In contrast, the relatively large uncertainties (likely due to data sparsity) in Southern Hemisphere palaeo-reconstructions (Mann and Jones, 2003; Mann et al., 2008) are of comparable size to the recent warming, so that the Southern Hemisphere situation is more ambiguous."

- P2578 L22 *"contributing up to 0.06 K" This is a result and should be placed there.* deleted the following text "(contributing up to 0.06K in these simulations)." In addition the following text has been added at P2582 L23 "The heating associated with firn densification was found to be a small but not insignificant term at this site. In particular, this term contributed a warming of up to 0.06K which is similar to the approximate 0.1K in the top 50m for the Crete ice core in Greenland (Johnsen, 1977)."

- P2579 L6 *EQ. 1 is perfectly correct but could be written more comprehensive so that the single heat flux terms can be directly distinguished.* changed the text from "

$$\frac{\partial T}{\partial t} = \frac{\kappa}{\rho C}\frac{\partial^2 T}{\partial z^2} + \frac{1}{\rho C}\left(\frac{\partial \kappa}{\partial z} - \rho C w\right)\frac{\partial T}{\partial z} + \frac{f}{\rho C} \quad (1)$$

  Where the last term is the energy associated with firn densification (Patterson, 1994, chapter 10, equation 32)." to "

$$\frac{\partial T}{\partial t} = \frac{\kappa}{\rho C}\frac{\partial^2 T}{\partial z^2} - \rho C w\frac{\partial T}{\partial z} + \frac{f}{\rho C} + \frac{1}{\rho C}\frac{\partial \kappa}{\partial z}\frac{\partial T}{\partial z} \quad (1)$$

  Where the terms on the right hand side are the rate of temperature change due to conduction, advection, firn densification (Patterson, 1994, chapter 10, equation 32) and the correction to the conduction term due to spatially varying thermal conductivity respectively."

- P2579 L13 *The equation should be written separately as EQ. 2. Also some further information on the equation would help to better understand the approach. Please provide some references at least.* changed the text from "The firn densification term in Equation 1 is given by $f = \frac{wg}{\rho}\frac{\partial\rho}{\partial z}\int_0^z \rho(\gamma)d\gamma$." to "The firn densification term in Equation 1 accounts for the work required to strain the firn and is given by (Patterson, 1994, chapter 10, equation 38)

$$f = \frac{wg}{\rho}\frac{\partial\rho}{\partial z}\int_0^z \rho(\gamma)d\gamma \tag{2}$$

"

- P2579 L8–13 *This is not a comprehensive and satisfying description of the applied parametrization especially of the thermal conductivities. A realistic parametrization of the thermal conductivities especially of the upper most layers is very crucial for the calculations. Please explain why the used assumptions are adequate and if possible give uncertainty ranges.* Indeed, the thermal conductivity of snow is strongly dependant on the snow microstructure (Strum et al., 1997) and evolves over time (Zhang, 2005; Domine et al., 2007), and this variation in thermal conductivity must be accounted for in simulations of the upper firn capturing high frequency thermal variations. However, in the forward model used herein such variations in thermal conductivity only modify the spatial distribution of heat, not the total energy content of the firn. Furthermore, we are only interested in temperatures below the zone where seasonal variations in temperature are detectable. Therefore, we expect that such details of the upper firn thermal conductivity are not important in this study, as any variations in the temperature profile with depth associated with such variations in the thermal conductivity will have diffused along with the season thermal cycle. This is confirmed by simulations using the LSQR optimisation method, where modifying the thermal conductivity in the upper 10m of firn to vary linearly with density from 63% to 100% of it unmodified value results in an optimal surface temperature history that differs (in an RMS sense) by only $4.9 \times 10^{-3}$K.

Made the following modifications to the manuscript to clarify this:

- P2581 L12–14 Changed the text from "In particular the three key assumptions of the numerical scheme (numerical spatial resolution, effective Nye depth and the depth of the bottom zero heat flux boundary condition)" to "In particular the four key assumptions of the numerical scheme (numerical spatial resolution, effective Nye depth, the depth of the bottom zero heat flux boundary condition and the parameterisation of the upper firn thermal conductivity)"
- P2582 L16 Added the following text "The thermal conductivity of snow is quite variable and dependent on the snow micro-structure (Strum et al., 1997) and evolves over time (Zhang, 2005; Domine et al., 2007). Such variability in thermal conductivity in the upper firn column should have negligible influence on the reconstructed surface temperature history, as such variations only alter the spatial distribution of heat rather than the total heat content of the forward model (Section 3.1). Such spatial variations will have diffused away along with the seasonal temperature cycle by the time the snow has reached 19.07m, the depth of the first temperature measurement used herein to constrain the surface temperature history reconstructions. This insensitivity to the details of the upper firn thermal conductivity was confirmed by LSQR simulations where the thermal conductivity ($\kappa_{modified}$) in the upper 10m from that given in Equation 2 ($\kappa_{orig}$), by
$$\kappa_{modified} = \frac{\kappa_{orig}}{2}\left(1 + \frac{\rho}{583}\right) \qquad (3)$$
where 583 is the density of the firn at 10m. The RMS difference in the

reconstructed surface temperature history between the control simulation using $\kappa_{orig}$ and the simulation using the modified thermal conductivity ($\kappa_{modified}$) was only $4.9 \times 10^{-3}$K.

- P2579 L18–22 *It would be helpful to have some further information on the boundary conditions. What exactly is a time varying prescribed surface temperature? What kind of function is assumed  a polynomial?* The form of the prescribed surface temperature distribution varies for the two optimisation methods. For the PSO simulation it is the sum of a series of least variance additions to the remapped temperature as a function depth starting condition, while the PSO simulations use a 4 segment piecewise linear representation of the time surface temperature history. This has been clarified with text added addressing comment P2580 L8–12 of reviewer #3 (tcd-6-C1427-2012)
- P2579 L22 *“see below” Please refer to a specific section. This statement is not a method but a result.* Changed the text from “see below“ to “see Section 3.3”
- P2579 L23–26 *Why are the assumed velocity profiles reasonable? Are there any other studies supporting this?* Added the following text at P2580 L7 “This assumed verlocity profile is consistant with initial analysis of annual layer thickness derived from chemical concentration measurements of the ice core, and in particular the thinning of the annual layers near the bottom of the ice core is not suggestive of a significantly thinner icecap.”
- P2580 L8–12 *How is the initial temperature condition set? I recommend to check whether a 10yr initialization period is long enough for a 130yr run down to a depth of 100m. The initial temperature conditions could strongly determine the temperature evolution and affect the fit. Hence, a sensitivity test on the initial conditions is strongly recommended. It is also recommended to extend the sensitivity tests to all parameterizations including the thermal*

*properties of the firn layer.* Added the following text after P2580 L8 “The initial temperature profile down the borehole is chosen to be isothermal, with a value equal to the prescribed surface temperature for the start of the simulation period. This initial temperature profile was chosen to simulate steady conditions prior to the simulation period. Furthermore, due to the relatively (by East Antarctic standards) high accumulation rate and warm temperatures the problem is strongly dominated by the advective component of the heat flux. The advection parameter is of order 20 (the absolute value of which is the *Péclet Number* Patterson (1994)), indicating that the system is relatively insensitive to downstream conditions and therefore also insensitive to the initial temperature profile down the borehole. Furthermore, as this initial temperature distribution down the borehole varies for each simulation as the optimal solutions for both the LSQR and PSO methods include optimisation of the initial temperature distribution down the borehole. The initial choice of the surface temperature history differs in both form and values for the LSQR and PSO methods and are detailed in Sections 3.2.1 and 3.2.2 respectively.”

– P2580 L21–22 *What is meant by initial temperature history? Is it the used initial temperature condition or is it the initial temperature time series for the fitting procedure? If it is the initial time series, what is the intention behind the “depth to time” transfer function? Temperature transport by vertical ice advection is much more inefficient than heat diffusion. The authors state this by themselves (P2579 L24). Hence, the question arises how sensitive is the fit to the used starting condition?*

  - The “initial temperature history” was referring to the initial time series and this has been reflected by changing the text from “The initial temperature history” to “The initial choice of the surface temperature history”.
  - The “depth to time” transfer function is simply based on the assumed vertical velocity profile, and this has been clarified by referencing Figure 5 in the text.

- P2579 L24 states that the reconstructed surface temperature history is essentially independent of the vertical velocity profile. While this independence could be obtained by a diffusion dominated thermal regime, it can (and in this case is) also be obtained by an advection dominated thermal regime where, due to the relatively shallow borehole depths (compared to the local icecap thickness) there is little difference in the advection time with differing velocity profiles. This has been clarified with text added to address comment P2580 L8–12 from the same reviewer.
- The forward model is expected to be relatively insensitive to the initial temperature distribution down the borehole due to the dominance of the advection term of the heat flux. Furthermore, this initial temperature distribution down the borehole is assigned for each simulation (as the value of the surface temperature history at the start of the simulation period) the chosen optimal solutions for both the LSQR and PSO methods already include optimisation of the initial temperature distribution down the borehole. This point has been clarified with text added to address comment P2580 L8–12 from the same reviewer.

– Sect. 3.2.2 *Please provide a more precise description of this method. E.g. it is hard to understand what parameter of a piece wise linear function is considered a particle.* This section has been substantially rewritten to clarify the method. Specific details of the revision to the text are given against comment Subsection 3.2.2 of reviewer #2 (tcd-6-C1401-2012)

– P2582 L18–23 *This is repeated several times in the manuscript.* Deleted the text on P2582 L18–23. Added the following text on P2582 L26 "Due to highly diffusive nature of the problem, no high frequency information is retained, and therefore it is not possible to reconstruct a unique solution."

– P2583 L7 *It would be helpful to provide a figure with the temperature profile. Also the results from the fitting procedure could be illustrated. This would help to gain a better impression of the quality of the fit.* A new figure (Fig 2) had been added showing the measured temperature distribution. A second figure (Fig. 6) has been added showing the temperature distributions with depth simulated by the forward model using both the LSQR and median PSO surface temperature reconstructions as the time varying surface boundary condition. The text at P2583 L15–16 has been changed from “In general the inverse surface ground temperature reconstructions from the two methods (LSQR and PSO) agree well (see Fig.4)” to “In general the inverse surface ground temperature reconstructions from the two methods (LSQR and PSO) agree with the observations (see Fig.4) and with each other (Fig.5)”

## 4 Additional modifications

In addition to modifications to the manuscript to address the reviewers comments and concerns, the following modifications were made to improve clarity and reduce repetition.

- Abstract Changed the text at P2576 L7–14 from “This warming of approximately 0.37K per decade is large by Antarctic standards and is only exceeded in regions of the Antarctic Peninsula. While this warming may reflect regional scale air temperature increases, the lack of comparable trends for other East Antarctic sites suggests local influences are largely responsible for the observed trend. Alteration of the surface energy budget arising from changes in radiation balances due to local cloud, the amount of liquid deposition and local air temperatures associated with altered air/sea exchanges potentially play a key role at this location due to the proximity of the Shackleton Ice Shelf and sea-ice zone.” to “This warming of approximately 0.37K per decade is consistent with trends seen in both instrumental and other reconstructions for Antarctica, and therefore suggests that regional rather than local scale processes are largely responsible. Alteration of the surface energy budget arising from changes in radiation balances due to local cloud, the amount of liquid deposition and local air temperatures associated with altered air/sea exchanges also potentially play a role at this location due to the proximity of the Shackleton Ice Shelf and sea-ice zone."

- P2577 L17–18 Deleted the following text "Mill Island is located at 65°30′S, 100°40′E (see Figure 1), just offshore from the Bunger Hills in East Antarctica and bordering the Shackleton Ice Shelf."
- P2580 L12 Added the following text "The influence of the size of time step used for the forward time discretisation on the calculated temperature profile with depth was minimised by using an adaptive time step. In particular, the time step was successively halved until the absolute difference in simulated temperatures at all simulated depths calculated using the current time step and a time step twice as large was less than $5 \times 10^{-3}$K."
- P2580 L8–12 Moved this text to after P2579 L17
- P2583 L1 Changed "and a more scholastic Particle ¿ Swarm Optimisation (PSO) method that produces" to "whereas the probabilistic Particle ¡ Swarm Optimisation (PSO) method produces"
- P2583 L8 Changed "such as the vertical velocity profile are not known" to "such as the vertical velocity profile have not been measured to date"
- P2583 L9 Changed "circa 1980/81 AD ±5yrs, and this result" to "circa 1980/81 AD ±5yrs. This result"
- P2584 L6–9 Changed the text from "There is insufficient evidence to attribute the changed surface energy budget at the borehole site to any individual mechanism. Indeed several processes are likely to have contributed." to "Several processes both local or regional are likely to have contributed to the changed surface energy budget at the borehole site."
- P2584 L20 Changed the text from "climate conditions are unusual over" to "climate conditions are, in at least some respects, unusual over"

- P2585 L5 Added the following text "This local driver is not, in itself, a complete explanation as it still requires a cause for the ice shelf retreat."
- Nomenclature Added in definitions of $E_{rms}$, $\hat{T}_{model}(i)$ and $T_{obs}(i)$

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