Reply to reviewer 2: Dietmar Wagenbach

We marked all our replies to the comments of reviewer 2: D. Wagenbach in blue.

General remarks#

The englacial temperature of cold firn areas constitutes one of the most obvious, characteristic parameter of immediate climate relevance, which, moreover, is directly gathered in the field. Dealing with its spatio-temporal distribution in the high Alpine Monte Rosa region the authors present a wealth of new data, which they put in context to former loggings. Apart from backing up the respective database made freely available by the authors and from providing a well written, comprehensive state of the art (including respective bibliography) this conclusive work clearly merits publication in The Cryosphere. I feel, however, that the present version may be considerably improved by some, mostly not very substantial, revisions aimed at making the paper easier to read and thus to attract a broader audience within the glaciology community.

We appreciate the overall positive comments to our paper and we focus our reply to the specific recommendations given below.

Specific recommendations

1. Reading in the abstract: "The observed increase since 2000 is far beyond a modelled firn temperature increase based on the IPCC climate scenario from 2001", let me expect to find this issue elaborated in the paper. Since this is not really the case (just this sentence appears already in the Conclusions with a respective quotation of Suter, (2002) I suggest de-emphasizing this statement in the abstract. But I would prefer instead seeing this important aspect addressed more extensively in the Discussion (currently being relatively concise) e.g. by showing somehow the respective modelling result of Suter (2002) in the context with the data displayed in Fig. 10.

We have deleted the sentence in the abstract and included a more careful discussion in the corresponding discussion chapter.

2. It would be helpful getting, beyond the given instrumental accuracy, a very brief statement on the expected (typical) uncertainty range of the reported temperature data, especially since different procedures are deployed over an extensive period.

We added a short paragraph, in which we tried to discuss the expected accuracies in the method section:

The overall accuracy is determined by several different uncertainties such as the stability of the cold bath during the calibration process, the resolution and accuracy of the data logger, the characteristics of the thermistors and cables and the absolute accuracy of the temperature measuring device. The first three effects mentioned before have determined accuracies in a range of 0.01°K and 0.07°K according to intense calibration studies performed by Suter 2001 and Lüthi and Funk 2001. Taking into account all possible errors, the absolute accuracy of the thermistor measurements, including all different measurement devices used in the past is estimated to be up to 0.2°K according to the expected minimum accuracy given by the different manufacturers. The relative accuracy between the thermistors of an individual thermistor chain using the same data logger is however much higher.

However, discussing an overall uncertainty, which is typically related to such temperature measurements is in our opinion strongly coupled to many subjective assumptions. These do not really help to assess a better error range of the measurements because a sound quantification of several effects is probably not possible. However, we believe that with a careful calibration procedure, which was done with all of the new measurements and according to our knowledge as well as with the older measurements, our estimated accuracy seems to be very conservative and reasonable.

3. The expression "firn facies" is repeatedly used throughout the paper though it is not always clear to what the authors are exactly referring to. Since not all readers might be familiar with this terminus I recommend introducing it at page 2279, right where the various firn zones are characterized.

We provide the following paragraph at the beginning of the introduction chapter:

Cold firn and ice in glaciers, ice caps and ice sheets occur when the firn and ice show permanently negative temperatures over the minimum time span of a year. If this is not the case, glaciers are temperate, thus their temperature is at the pressure melting point. Most of the existing cold ice bodies are not cold throughout. These ice bodies are called polythermal Blatter and Hutter 1991, Cuffey and Paterson 2010.

According to the mean annual air temperature (MAAT), different temperature zones of the

glacier's accumulation area can be distinguished and are called in this study firn facies zones Benson 1961, Shumskii 1964:

4. Subjectively, I feel that the muddled data code and its application (referring somehow to boreholes, profiles, logging dates, drilling dates, etc.) contribute a good deal to my confusion and make it hard to follow the text without jumping back and forth to table 1 and respective maps. I can imagine that the authors are not happy changing their code in a more intuitive one (allowing for disentangling spatial and temporal as well as drilling and logging settings) if it is already deployed in their open access data base or elsewhere. Nevertheless, the dilemma needs to be overcome, at least by following measures: - give a brief advice somewhere how to read the code getting univocal information - dissect all three tables by drilling area or add a respective row - change figure legend or captions accordingly (as profile position and year can be directly identified, see minor comment No 15) - avoid mentioning a profile in the text by stating its code only.

We tried to find a more convenient way to describe the boreholes and logging sites. We introduced two different new codes. The first code is a 'reader friendly' code, which allows a better understanding of the different drill and measurement sites. The second code is a database code and is only given in table 1 together with the first code. The new code used in the paper reads as follows: CG95-1/97, the first two letters give the location of the measurements, the second two letters describe the year of the drilling of the borehole, the next letter is a numbering of the drillings in the specific year, whereas the last two letters represent the year of the temperature measurement. The newly introduced database code looks as follows: B95-1_971018, the first letters describe the borehole with its year of drilling, the following number is based on the historical numbering system of the individual boreholes within a certain year, then the next number is the date of measuring the temperature within the borehole. The new numbers now allow a clear distinguishing between borehole (drilling year) and temperature measurement. We hope with this system to clarify some uncertainties mentioned by the reviewers using this system.

5. There is a quantitative imbalance between the introductive, setting the stage and methodological chapters and the result and discussion parts being both relatively concise. Especially the text of -3 Results- is not intuitively structured (also lacking comments on the formal observations and motivation of figure presentations). It essentially repeats the information carried by the figures and tables in the order of their appearance, nevertheless, going through this text I quickly lost track. Although a detail, I missed here a comment on the role of the different borehole positions within the Colle Gnifetti north-west flank versus the saddle area (which is associated with a change in the surface energy balance), same hold true within Seserjoch area. For a potential extension of -4 Discussion- see No 6 below.

We tried to improve the result section to make it more clear and extended the description of the different sites to allow a better own comparison between the different locations. Together with the new numbering system and a grouping of the individual results according to their locations, we believe that we could improve the result section.

6. The finding displayed in Fig. 10 on the decadal scale change in the englacial temperature is perhaps the most essential one. It would deserve, therefore, some more critical discussion including e.g. following issues: - the atmospheric temperature level is significantly higher than the englacial one, I would have expected it vice versa. Perhaps it would be more straightforward dealing with temperature anomalies making the altitude correction obsolete (in this case one may use as well the more representative data compiled for the Colle Gnifetti grid in the HISTALP data base) - the englacial temperature is expected to lag the surface temperature signal by some years or so, this fact should be mentioned, at least. - the way the result are displayed leaves unclear if the borehole loggings refer to different positions or a common one. Thus, I wonder if the temperature effect might be biased by a spatial effect or not? - Perhaps, the extraordinary year 2003 might be mentioned (not standing out in the atmospheric record but expected to have considerably added latent heat to the firn body)

In addition to the Jungfraujoch air temperature measurements, we will also include the values of the Histalp database as a comparison. Here, we would like to thank the reviewer that he provided us with the new data. A discussion about why the atmospheric temperature level is

significantly higher than the englacial one is in our view very important. However, we have to admit that we have currently not a clear explanation for this question and we are aware that in theory it should be exactly vice-versa what we have presented in our paper. Also the new Histalp dataset shows even warmer temperatures than the temperatures extrapolated from Jungfraujoch with a lapse-rate of 0.65°C. Therefore, we decided to present in our paper instead of the absolute air temperatures of Jungfraujoch and the englacial temperatures, the temperature anomalies of the Histalp, the Jungfraujoch and the measured englacial temperature datasets according to the suggestions of the reviewer.
We agree also with the reviewer that we have a time lag of the temperature signal in 20 m of about 2 to 4 years depending on the assumed accumulation rates. We have added a sentence in the text as well as in the figure caption to make the reader aware of this effect.
We agree with the reviewer that the extraordinary year of 2003 have had probably a large effect on the warming of the cold firn on Colle Gnifetti. However, we believe that we are not able to show this effect by our measurements. However, we will discuss this in the new version of the paper.

Minor suggestions and comments

1. In the Abstract it is stated: "Air temperature records from the Jungfraujoch high- altitude station (MeteoSwiss-Station) from 1980 to 2008 show a mean annual increase of 0.05 ◦ C per year, indicating that the amount of infiltrating and refreezing of melt water at Colle Gnifetti has increased since 2000." I recommend re-wording here, since this statement is weak, lacks causality and belongs not to the fundamental outcomes of this paper.

We changed the wording in the abstract.

2. p 2279, line16: The expression "in the uppermost firn layer" - is unclear, I guess the authors mean confined to the uppermost annual layer

We changed the sentence according to the suggestions of the reviewer.

3. p 2280, line 26: Replace trace element analyses from ice cores by glacio-chemistry in ice cores, etc.

We changed the sentence according to the suggestions of the reviewer.

4. p 2281, line 2: It is not made clear why a high accumulation rate should be disturbing in this context. Probably it is meant, that a high accumulation rate comes along with a high balance velocity, however, this would be already included in the before mentioned ice flow disturbance. Perhaps, the time coverage of the borehole thermometry is the author's concern?

We changed the sentence and added … *and a reasonable time coverage* …

5. p2281, line 7: In view of firn/ice transition depth the reference Schotterer et al 1981 is not up-to-date enough. Depending on accumulation rate, respective depths range from 27m to 43m.

We added a newer reference of Lüthi (2000) and a personal communication D. Wagenbach and changed the sentence according the suggestion of the reviewer. We would like to express our thanks to the reviewer for providing us with this up-to-date information.

6. p2281, line21: The sentence is misleading in saying, " we bring all existing ...data together".

We changed the sentence in the following way: *In this study, we bring together some selected already existing englacial temperature data and focus on repeated temperature measurements at different drill sites in the Monte Rosa area at the border of Switzerland and Italy.*

7. p2283, line14: Better to use mechanical instead of electrical for the drill characterisation, change the respective row in table1 accordingly.

We changed the word from electrical to mechanical in the whole text and in table 1.

8. p2284, equation 1: The denominator should be 4πKt instead of 4πK.

We corrected the equation.

9. p 2286, sentence starting in line 8: The mentioned "a little bit further down the saddle" is clearly associated with much less wind actions accordingly decreasing the (latent) heat flux out of firn especially during potential melt conditions. Thus, aspect or altitude (temperature) appears to be less important for that sudden change.

We agree with the reviewer that this effect is also very important. Therefore, we have added a paragraph in the paper to discuss these effects in more detail.

10. p2287, line15: the given 0.05◦ C warming should be higher by one order of magnitude or instead related it to the annual rate.

We have changed the sentence by adding 0.05°C per year.

11. p2289, sentence starting in line3: It is not straightforward that polar firn areas subject to a comparable (mean annual) temperature as Colle Gnifetti would be comparable as well in their thermal regime and sensitivity to warming trends. This is simply because the seasonal and diurnal insolation cycles are largely different between these locations. For example the Academii Nauk ice cap at 80◦ noth clearly belongs to the cold infiltration zone, though MAAT is -15,7◦ C (thus somewhat lower than at Colle Gnifetti) while, as expected, the firn temperature is significantly higher reaching -10◦ C at 10m depth (Fritzsche et al. 2005, Annals of Glaciology, 42, No 1, 361-366) aufpassen bei Einstrahlungsunters

This is a very important and good statement by the reviewer. We have added now a short paragraph in the paper, where we discuss this important statement.

12. Table 1 and table 2 listing temperature logging site contains the deep borehole B95-1 but not the down stream B95-2 one, though temperature loggings are performed here as well.

We have changed this. New, we have included the borehole B95-2 and replaced the former Figure 8 by a new figure, which contains all measurements in deep boreholes in the past (B82-1, B95-1, B95-2, B03-1 and B07-1). In addition, we added a figure showing all temperature gradients of the deep boreholes presented in figure 8 to discuss the effects of the long-term warming.
New, we included also a figure, which shows the warming at borehole B95-1 covering a time span of 13 years. We believe with these new figures and the corresponding presentation in the result and discussion chapter to improve the current paper remarkably.

13. Fig.1 is somewhat confusing: There are more sites indicated than addressed in the paper, so distinguish visually the available from those reported in this paper, or instead skip the sites not addressed here and differentiate the old and novel ones, only. The only Grenzgletscher site reported here should be indicated as well.

This site is indicated on Figure 3 too. We have made this more clear in the text and Figure caption. The sentence is now: *The first site was on Colle Gnifetti at altitudes between 4400 and 4500 m a.s.l. with three new and two already existing boreholes (Figure 2), the second site was close to the Seserjoch at altitudes between 4250 and 4340 m a.s.l., with three new boreholes (Figure 3) and the third site was on Grenzgletscher at an altitude of around 4250 m a.s.l. with one new borehole (also displayed in Figure 3).* Together with the new numbering system, we hope that we could clarify the situation with the different boreholes at the different sites.

14. The captions of figures 2 and 3 are not clear. Indicate there the meaning of the double notations at single borehole positions.

We changed the figure caption to: *Location of the borehole sites on Seserjoch and on Grenzgletscher. We hope that now it is more clear that on Figure 3 are both locations are shown the Seserjoch ones and the one on Upper Grenzgletscher*

15. Again the caption of figure 4 is not appropriate for immediately conceiving what is shown. I guess that the Colle Gnifetti site is common to all profiles, but I cannot attribute the measuring year to the profiles without consulting table 1 or being advised on the profile code.

We changed the figure caption accordingly: *Temperatures measured in 1982, B82-1 (Haeberli and Funk 1991), 1991 B91-A (Laternser 1992), 1999 B99-2 and 2000 B00-A (Suter 2002) compared with the new measurements at B08-1 and B08-2 at Colle Gnifetti site shown in Figure 2.* (In the paper we will use then the new numbering system!)

16. It is not obvious to me what the essential difference between fig. 4 and fig. 5 might be. Strictly speaking, what is the reason distributing the old-new Colle Gnifetti comparisons on the two figures as it was done?

The boreholes B82-1, B91-A, B99-2 and B00-A are measured on the saddle point of Colle Gnifetti within a very short distance, whereas the boreholes B91-B, B07-1 and B08-9 are measured in the northern slope of Signalkuppe at a completely different exposition and altitude.