Author's response

We would like to thank the two anonymous reviewers for their reviews of our paper. In response to their suggestions, we did the following main changes to the manuscript:

1) the title was modified replacing 'glacier disintegration' with 'glacier fragmentation'
2) the three simpler and empirical methods for the calculation of the air temperature over glaciers (Khodakov, 1975; Davidovich and Ananicheva, 1996; Braithwaite et al.,2002) have been removed, as suggested by the Reviewer 1
3) as Reviewer 1 notes, we incorrectly choose weather stations with different flow path lengths for supporting the hypothesis of reduced cooling effect over smaller glaciers. The first part of the Discussion has been modified, comparing weather stations with similar flow path lengths.
4) a figure with the flow path length of the studied glaciers has been added to the manuscript

Reply to the Interactive comment by Referee 1 (anonymous)

R1-1) The authors present a new dataset from several high-elevation weather stations installed during summer 2010 and summer 2011 to study the air temperature distribution over three glaciers in the Italian Alps. This work aims to provide a comparison of different methods for calculating on-glacier temperature from off glacier data. The methods are commonly applied by mass balance models forced with off-glacier data and the paper demonstrates how the accuracy of air temperature estimations impacts the outputs of such a model. Overall the paper is well written. The motivation and methodology is clear and well described. However, on the basis of the data presented, I do not see any new insights regarding the effect of glacier disintegration on air temperature variability. Title, abstract and conclusion 1 suggest that the paper provides new experimental evidence about the changes in the air temperature field during glacier decay. This finding is supposedly supported by stronger cooling effects observed in the ablation area of the larger La Mare Glacier than on the very small Careser Occidentale Glacier. However, the authors ignore in their discussion that this difference in temperature depression can be very well explained by differences in flow path lengths (FPL), which is the most important variable of the tested methods to extrapolate air temperature over a glacier. The FPL explains perfectly the differences in the cooling effect observed at Car-gl_3144 (FPL 354 m, cooling effect -0.18°C) and Mar-gl_3140 (FPL 805 m, cooling effect -0.47°C) or Mar-gl_2973 (FPL 2132 m, cooling effect -0.9°C) in summer 2011. There is indeed no sign of a "reinforcement mechanism during glacier decay" (page 6148, line 13), and glacier disintegration seems to have no effect at all on air temperature variability in function of FPL. This is my major concern and I therefore doubt that the title of the paper reflects the content of the paper and major findings of the study.

As noted by the Reviewer, the FPL explains the differences in the cooling effect observed at the mentioned weather stations, and their choice was not appropriate for supporting our findings. Actually, they are supported by the stronger cooling effect observed on the larger Careser Orientale Glacier (-1.01°C at Car-gl_3082) than on the smaller Careser Occidentale Glacier (-0.18°C at Car-gl_3144), because the two sites have very similar FPL (Table 1). We have modified the first part of the Discussion accordingly.

R1-2) For a revised paper, the authors should consider calculating glacier-wide summer glacier mass balances and not only point mass balances at stake locations like in the current paper. The main interest of the different methods to distribute air temperature over a glacier is at the distributed scale, and not at the point scale. I also think the meteorological data that are available have the potential to provide insights for distributed modeling beyond the discussion of existing methods for air temperature distribution. In the current manuscript the authors stick to the methods available from literature although it is known that the methods are not valid for the specific conditions. For instance the G&B model is not valid close to the glacier borders (the G&B model only considers two processes of an air parcel traveling down an infinite glacier slope: adiabatic heating and turbulent cooling), and the G&B model is also not applicable to Car-gl since this glacier does not have a down-glacier wind, which is the main assumption of the model. In a revised paper the authors could therefore address several research questions regarding this issue: What would be the best modeling strategy for sites like Mar-gl_2709 or the Careser glaciers? How relevant is it for distributed glacier mass balance modeling to take into account 'border effects' on air temperature? The authors are aware of these open questions as they make clear by conclusion 2 ("these methods... still need refinements, in particular for areas close to the margins and for the smaller units..."). The paper would be much more interesting if some of these questions could be answered or at least addressed and if the relevance of these open questions for distributed mass balance modeling could be clarified.

We intended this paper as a first step of assessment of existing methods available in the literature. Based on these results, in a following step we aim to develop a generalized modeling strategy, to be implemented in a distributed mass balance model. However, probably more data are required to do that, and to assess the relevance and generalizability of our peculiar observations (i.e. the border effect at Mar-gl_2709, up-glacier wind at Car-gl_3082, reduced cooling at Car-gl_3144). For example, further investigations are needed to check if the up-glacier wind and relatively strong cooling effect at Car-gl_3082 are specific for this site, or if they are common features over the Careser Orientale Glacier and over glaciers with similar characteristics. For this reason, we preferred to test existing methods and to avoid developing a generally valid temperature transfer function. Moreover, the experimental setup was not intended to investigate in detail any peculiar aspect of the glacier boundary layer, which would probably require a higher density of measuring sites and different instrumentation. We added these considerations in the Discussion.

R1-3) Based on the text it seems that the method by Khodakov (1975) is valid only for the location of the firn line. It is not clear to me how this method can be used to calculate the cooling effect at all the stations. Is L in equation (1) equal to the Flow Path Length (FPL) or is it a constant?

R1-4) *A comment on the first three methods: All of them are empirical and the coefficients were calculated in very different environments. In my opinion, they oversimplify the problem and are clearly inferior to S&M and G&B methods, which reflect a better understanding of the physical processes involved in the air temperature distribution over melting glaciers. They are also not commonly applied by mass balance models. I wonder if it is necessary to include them in the paper*.

We agree with these considerations and removed these methodologies from the paper. Now they are only mentioned in the Introduction. The reasons why they have not been used (suggested by the Reviewer) were added in the Methods (par. 3.4)

R1-5) Title: not sure if 'glacier disintegration' is the correct term here. Maybe 'glacier fragmentation' or 'glacier retreat' would be more appropriate.

The title was modified replacing 'glacier disintegration' with 'glacier fragmentation'

R1-6) 6148 25: What is snowfall limit?

Ok, specified (snowfall '*elevation'* limit)

R1-7) 6149 20-30: Maybe more recent references than Charbonneau (1981) and WMO (1986) would be more appropriate.

Here we have cited four works that, in different epochs during the last decades, analyzed and assessed the issue of input data spatialization in model applications. Indeed in the following we cite the papers by Machguth et al., (2008) and Carturan et al., (2012).

R1-8) 6152 10: Which was the explanation gave by Petersen et al (2013) for this result?

They attribute this result to the fact that the thickness of the boundary layer is variable in space. Added in the text.

R1-9) 6152 17: Indicate by numbers what you consider small, medium and large glaciers

Ok, added

R1-10) 6153 22: What do you mean by "active" retreat?

Added 'towards higher altitudes'. The concept of active retreat is well explained in the paper by Small, (1995), which is already cited.

R1-11) 6156, Section 3.3: It seems most of this is repeated later in section 4.2. Consider removing this section.

In section 4.2 we explain in more detail the tested methods for the calculation of ambient temperature. In particular, in 4.2 we detail the phrase 'Different combinations of lapse rates (i.e. fixed standard or hourly-variable obtained by linear regression of temperature vs. elevation) and subsets of weather stations were tested' which is reported in 3.3. We considered the opportunity to move the explanation (in 4.2) just after this phrase (in 3.3), but we think that the explanation fits better in 4.2, because it enables improved comprehension of the results reported in the following. On the other hand, Section 3.3 is required to explain how the data have been analyzed.

R1-12) 6160: The mass balance model only considers clear sky radiation and not the daily cloudiness. Daily variations in cloudiness therefore represent a source of error for mass balance calculations. Since incoming shortwave radiation is measured at the AWSs, why not considering daily cloudiness for mass balance calculations?

We did not use the radiation measurements because we wanted to test a ‘general purpose’ model, applicable to glaciers with limited data availability. Often, the only available variables are the air temperature and the precipitation, whereas the incoming shortwave radiation is less commonly available. We tested a parameterization of the cloud cover in function of the air temperature, as suggested e.g. by Pellicciotti et al., (2005), but we didn’t find significant correlation between the two variables. Explanations added in the text.

R1-13) 6161 15 and elsewhere: I think is better to say that the lapse rates are ’steeper’ and not ’lower’.

Ok, replaced

R1-14) 6161 19-22: Here it is not clear when you are talking in general and when you refer to your data. Please re-phrase.

Ok, clarified

R1-15) 6161 20: Write standard deviation instead of SD.

Ok, replaced

R1-16) 6162 15: You do not know which is the best method to extrapolate above your highest off-glacier station (Bel_3328) since you have no data from there. Please re-phrase.

Based on our data, method (ii) provides the best results, but we agree that uncertainty persists in extrapolations at altitudes above the available weather stations. Rephrased for clarity.

R1-17) 6166 9-11: Could you explain better why x0 is larger (x0=1440) when the freezing level is above the top of the flow line than when the freezing level is below this point (x0=0)? This is not clear to me.

These settings were suggested in the paper by G&B. When the freezing level is above the top of the flowline, in order to take a climate sensitivity <1 at the top of the flowline into account, a distance x0 = 1440 m is added to the distance along the flowline. Added in the text.

R1-18) 6168 13: I do not agree that these results provide a quantification of mechanisms during glacier disintegration. Differences in the glacier cooling effect between Margl_2973 and Car-gl_3144 can be explained by differences in the FPL (see general comments above).

As explained in the reply to the first comment, the comparison between these two weather stations was not appropriate to support our findings, because their different cooling effect can be explained by differences in FPL. The comparison between Car-gl_3144 and Car-gl_3082 is more appropriate because they have almost equal FPL. We have modified this part of the Discussion accordingly.

R1-19) 6169 5-6: The loss of sensible heat does not have the opposite sign in the case of up-glacier wind.

We meant that, in katabatic flows, the loss of sensible heat is to some extent compensated by the adiabatic heating of descending air. Rephrased for clarity

R1-20) 6170 10-12: It needs to be mentioned that those methods also fail because there are other processes, apart from glacier cooling, influencing temperature at those sites.

These methods have been removed in the revised version of the paper (see the reply to comments R1-3 and R1-4).

R1-21) I think that the paper needs a Figure with the FPL of the studied glaciers. This is a key variable for all the methods (or at least S&M and G&B).

Ok, figure added.

R1-22) Figure 7 caption text: 'summer 2010 and 2010', please correct.

Ok, corrected.

Reply to the Interactive comment by Referee 2 (anonymous)

R2-1) The paper addresses the amplification of glacier melt while glaciers start to disintegrate and tries to explore a potential way to quantify this effect. This is definitely of interest for e.g. estimating rates and duration of melt water production in catchments where glaciers are about to disintegrate. At the same time, if going beyond simple parametrizations of gross amounts of melting, this is a non-trivial endeavor. The authors try to make use of an unusual data set, collected from 8 different weather stations both off and on the glaciers of the rapidly disintegrating ice bodies of the Careser-La Mare basin. The data availability and the interesting question are definitely motivational and, hence, the authors try to (i) improve mass balance modeling by (ii) developing a generally valid temperature transfer function from a measurement site to a glacier surface, based on (iii) analyzing the effects of glacier disintegration on near surface temperature distributions from the available records. Unfortunately, the authors fail to reach any of these targets due to incorrect assumptions and consequent misconceptions.

The implicit goal of this paper is obviously to provide a contribution to the improvement of distributed glacier mass balance models. However, as reported at the end of the Introduction, the specific aims are the following: i) analyze the temporal and spatial behavior of air temperature and glacier cooling effect in the study area, ii) test different methods for calculating on-glacier temperatures from off-site data, and iii) evaluate their impact in mass balance simulations using an enhanced temperature-index model.

As remarked by the Reviewer 1, in this paper we do not develop any general transfer function. At the contrary, we test *already-existing formulations* proposed in the literature (Khodakov, 1975; Davidovic and Ananicheva, 1996; Greuell and Böhm, 1998; Braithwaite et al., 2002; Shea and Moore, 2010) for calculating distributed fields of air temperatures over glaciers, and assess their impact on a existing enhanced-temperature index model, whose general approach is commonly used for applications on glaciers given the low requirement of input data (e.g. Cazorzi and Fontana, 1996; Hock, 1999; Hock, 2005; Pellicciotti et al., 2005; Huss et al., 2008a). We have clarified the objectives of the paper writing explicitly that the tested formulations and model already exist.

R2-2) Both the "glacier cooling" and the "glacier damping effect" over melting glacier surfaces, as compared to the environmental temperature, are the result of the melt rates. This is the principle of why positive degree day (PDD) type models function so successfully and the reason why they should only be used with temperatures measured outside the influence of the glacier. The sum of positive (above 0 C) Celsius temperatures measured outside the glacier stands for the environmental energetic potential for melting ice. Using on-glacier temperatures (being permanently close to the 0 C of the melting ice surface) can only weaken the potential of a PDD approach. There is, consequently, no reason for knowing the near ice surface temperature beyond the interest in the dynamics of katabatic winds and the respective role in a fully process resolving energy balance study.

We agree that, in principle, PDD model applications should use input temperatures measured outside the thermal influence of the glaciers, which can represent daily variations in the global radiation flux better than the damped boundary layer temperatures above the melting glaciers (Gudmundsson and others, 2009). However, given the very high spatial and temporal variability of degree-day factors, (in particular in steep mountain terrain, Hock, 2003, and references cited therein), and the interest in spatially distributed melt estimates, there is increasing need for *spatially distributed* temperature-index models (Hock, 2005). Enhanced Temperature-Index models (ETI models) are distributed models which vary degree-day factors in a fully distributed manner, using computed solar radiation. Such distributed models rely on accurate estimations of the air temperature, which is usually extrapolated from off-glacier weather stations using environmental lapse rates, assumed to be constant in space and time (e.g. Klok and Oerlemans, 2002; Hock and Holmgren, 2005; Machguth et al., 2006; Huss et al., 2008b; Farinotti et al., 2012). Measurements performed over melting glaciers, however, demonstrate that this assumption is not valid (e.g. Greuell and Böhm, 1998; Strasser et al., 2004; Shea and Moore, 2010; Petersen and Pellicciotti, 2011; Petersen et al., 2013; this work). Compared to environmental conditions, the peculiar glacier boundary layer leads to lower temperatures, different lapse rates and, most importantly, lower 'climatic sensitivity' (i.e. the ratio of changes in the 2 m temperature above a glacier to changes in temperature outside the thermal regime of that glacier), with significant inter/intra glacier variability. Neglecting these differences has strong impacts on model calibration/application (Marshall et al., 2007; Minder et al., 2010). In addition, as the cooling and damping effects are mostly related to the size of the glaciers, and as glaciers adjust their size in response to climatic changes, these processes are important feedbacks which modulate the response of glaciers to climatic changes (Khodakov, 1975; Greuell and Böhm, 1998; Paul, 2010; Shea and Moore, 2010). This is the reason why several authors have attempted to improve the on-glacier temperature calculation from off-site data, before applying PDD and ETI models (e.g. Khodakov, 1975; Davidovic and Ananicheva, 1996; Greuell and Böhm, 1998; Braithwaite et al., 2002; Shea and Moore, 2010; Petersen et al., 2013). Our results (Table 6, Figure 9) and previous model applications (Carturan et al., 2012) clearly demonstrate that, neglecting the dominant processes involved in the spatial distribution of the air temperature over glaciers, lead to recursive spatial clustering of simulation errors and to distortions in parameter calibration.

R2-3) Extrapolating from environmental temperatures to near glacier surface temperatures in order to feed an empirical statistical model, such as PDD day models of any degree of complexity, for estimating melt rates means weakening the potential of such a model. The centrally cited *authors Greuell and Böhm (1998), who have explored the temperature distribution on a glacier surface with great care, state this very clearly when they say: "....if a constant lapse rate is used to compute 2 m temperatures above the glacier from temperatures recorded at climate stations or predicted by atmospheric models, the sensitivity of ablation to variations in atmospheric temperature will be overestimated'.*

We think that the phrase from Greuell and Böhm (1998) does not support the statements of the Reviewer. Air temperature extrapolation from climate (also said 'environmental', or 'off-glacier') weather stations is required in distributed mass balance models, and can be performed in different ways. Greuell and Böhm (1998) are speaking about the use of constant (environmental) lapse rates to compute 2 m temperatures above the glaciers from temperatures recorded at climate stations or predicted by atmospheric models. According to them (and to other authors as for example Strasser et al., 2004; Brock et al., 2010; Minder et al., 2010, Petersen et al., 2013), this method has severe limitations if applied over glaciers, and given the peculiar distribution of the air temperature above them, it leads to overestimations of the sensitivity of ablation to variations in atmospheric temperature. The key concept that Greuell and Böhm (1998) want to stress, is that a *'suitable' calculation procedure* has to be implemented, and applied instead of the commonly-used constant (environmental) lapse rate, in order to achieve a better estimate of the surface mass balance sensitivity to changes in the temperature outside the thermal regime of glaciers.

R2-4) "The ideal solution to this problem is to use the temperature outside the thermal influence of the glacier as forcing and to compute melt by coupling a melt model to a mesoscale atmospheric model. The latter should extend beyond the thermal influence of the glacier and resolve details of the structure of the boundary layer above the glacier."(Greuell and Böhm, 1998).

As Greuell and Böhm, (1998) say, this is the best and more desirable solution, but they continue writing that "such an approach is computationally expensive, and appropriate models still have to be developed. This paper provides an alternative approach in the form of a simple thermodynamic model of the glacier wind".

We note that valid alternatives to the Greuell and Böhm, (1998) and to the Shea and Moore, (2010) methods have not been developed so far. For this reason, we tested these procedures in our paper. Several works in the literature clearly demonstrate that dominant processes, even with high complexity and spatial variability, can be accounted for in PDD-like models using statistical/empirical approaches, which enable improved modeling skill. This is the case, for example, of the snow redistribution by wind and avalanches, which can be effectively captured using topographic indexes extracted from a Digital Elevation Model (e.g. Gruber, 2007; Farinotti et al., 2010; Carturan et al., 2012), or of the snow albedo, which can be parameterized in function of surrogate variables (e.g. air temperature or cumulated melt), without accounting for all the variables that physically control its variability (e.g. Brock et al., 2000). It should be noted that capturing the dominant processes using statistical/empirical approaches is often the unique possibility in model applications with reduced input data availability.

R2-5) In other words: only if the structure of the boundary layer above the glacier is resolved in appropriate detail it makes sense to compute and use the 2m above the glacier surface temperature and Greuell and Böhm (1998) also make clear that any computation of the near ice temperature *from off-glacier temperatures is different from case to case. A generalizing solution can only be found in a model that accounts for and resolves all potential influences on air temperature changing from an off-glacier site to a glacier site. Such models could be found in the limited area atmospheric simulation approaches and by including the full dynamics of boundary layer meteorology. Yet, related degrees of freedom are usually far beyond the availability of data for the respective variables*.

The low requirement of meteorological input data is the main reason why PDD-like models are so frequently used. However, in our opinion, the simplicity of the modeling approach does not exclude a priori the possibility of capturing the dominant processes and feedbacks which control the climatic sensitivity of glaciers. The available experimental datasets provide increasing evidence that simple parameterizations in function of topographic attributes, as flow path length and slope, can account for much of the spatial variability of the air temperature over glaciers with very different geometric characteristics and geographic settings (Figures 5 and 7), with few exceptions. In our opinion these results are promising and potentially useful for future works aimed at developing generalized solutions, of any degree of complexity.

R2-6) This said, none of the targets envisaged in the presented draft can be reached: 1. The "effects of glacier disintegration on (near glacier surface) temperature variability" can only be studied by a full resolution of all processes acting between the free atmosphere and the complex surfaces of a glacierized mountain basin including high spatiotemporal resolution of boundary layer dynamics. This requires both a powerful model and respective data input considerably beyond what is available from the 8 weather stations.

Even if this aspect was not among the main objectives of our work, we think that it's worth discussing it, because it provides evidence of the reduced effectiveness of small glaciers (deriving from the fragmentation of larger glaciers) in cooling the air above, compared to wider glaciers or wider portions of the same parent glacier. This is suggested by the two weather stations on the Careser Occidentale and Orientale glaciers which, despite being at almost the same flowline distance from the upper glacier margin (Table 1), have very different cooling effects (Table 4, Figure 3), which largely explain errors in modeled ablation rates (Figure 9; Figure 8 from Carturan et al., 2012). In consideration of the high number and contribution to the world's total ice volume of smaller glaciers (Haeberli et al., 1989; Paul et al., 2004; Zemp et al., 2008; Bahr and Radić, 2012), and given the absence of previous experimental data from such small ice bodies, these results deserve discussion even if they are not conclusive.

R2-7) 2. For the same reasons, the search of a generally valid equation for linking off-glacier temperatures with on-glacier temperatures and, finally for calculation lapse rates above the glacier surface must fail. An "inter-comparison of calculation methods" is, thus, only of value per se but cannot lead to a generally valid solution. In particular, the parameter settings for the presented transfer models must be calibrated for each site and for each case individually. Again, a full process resolution approach would be the only promising one but cannot be reached with the proposed methods and the available data. 3. As a consequence, mass balance modelling cannot be improved from the available data and with the proposed approach.

As already mentioned before, the good match of the experimental data from our study area with the already- existing parameterizations proposed by Shea and Moore (2010) and by Greuell and Böhm (1998) (Figures 5 and 7) point to a good generalizability of these methods, without solving the full processes involved in boundary layer dynamics. This is even more remarkable, considering the heterogeneous physical characteristics and geographic setting of the investigated glaciers. In our opinion, and in agreement with the remarks of the Reviewer who says that "*related degrees of freedom are usually far beyond the availability of data for the respective variables*", it would be almost impossible to implement and use a modeling tool based on a full process resolution approach, given the large amount of input data required, with suitable spatio-temporal resolution.

I suggest the authors to find another use of the interesting data but I have, unfortunately, to recommend rejecting the present paper.

This point is difficult to understand, because the Reviewer does not provide any useful suggestion on how to modify or improve the manuscript, nor he suggests anything less generic than "another use" of our interesting data. Moreover, in his review he doesn't report any reference in support of his statements. From the comments above it is clear that, according to him, mass balance models cannot be improved from the available data and with the proposed approach (even if, as noted by Reviewer 1, this approach is commonly applied on mass balance models forced with off-glacier data). On the other hand, he clearly states that the only way to account for the spatial variability of 2 m temperature over glaciers is a full process resolution approach, which however 'has high degrees of freedom, far beyond the availability of data for the respective variables'. In our opinion, stating that distributed PDD and ETI models cannot be improved using the proposed approach, and that empirical/statistical procedures cannot account for the spatial distribution of the air temperature over glaciers, contradicts previous findings and published works from other Authors (see the references cited in our paper and in the comments above), whose proposed methods and results are corroborated by the results of our study.

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Air temperature variability over three glaciers in the Ortles-Cevedale (Italian Alps): effects of glacier ~~disintegration~~fragmentation, ~~inter~~comparison of calculation methods and impacts on mass balance modeling

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Abstract

Glacier mass balance models rely on accurate spatial calculation of input data, in particular air temperature. Lower temperatures (the so-called glacier cooling effect), and lower temperature variability (the so-called glacier damping effect) generally occur over glaciers, compared to ambient conditions. These effects, which depend on the geometric characteristics of glaciers and display a high spatial and temporal variability, have been mostly investigated on medium- to large-size glaciers so far, while observations on smaller ice bodies (< 0.5 km^2) are scarce. Using a dataset from 8 on-glacier and 4 off-glacier weather stations, collected in summer 2010 and 2011, we analyzed the air temperature variability and wind regime over three different glaciers in the Ortles-Cevedale. The magnitude of the cooling effect and the occurrence of katabatic boundary layer (KBL) processes showed remarkable differences among the three ice bodies, suggesting the likely existence of important reinforcing mechanisms during glacier decay and ~~disintegration~~fragmentation. ~~None of the~~The methods proposed by Greuell and Böhm (1998) and Shea and Moore (2010) ~~methods proposed in the literature~~ for calculating on-glacier temperature from off-glacier data did not ~~–~~ fully reproduc~~ed~~e our observations. Among them, the more physically-based procedure of Greuell and Böhm (1998) provided the best overall results where the KBL prevails, but it was not effective elsewhere (i.e. on smaller ice bodies and close to the glacier margins). The accuracy of air temperature estimations strongly impacted the results from a mass balance model which was applied to the three investigated glaciers. Most importantly, even small temperature deviations caused distortions in parameter calibration, thus compromising the model generalizability.

1 Introduction and background

Air temperature exerts a crucial control on the energy and mass exchanges occurring at the glacier surface. It regulates the accumulation processes via the snowfall elevation limit and the snowpack metamorphism (which affect redistribution phenomena), and regulates the ablation processes via turbulent fluxes and longwave radiation. It is also closely related to important feedbacks such as albedo, the mass balance–elevation feedback, and the glacier cooling effect, which changes as glaciers adjust their size in response to climatic fluctuations (Khodakov, 1975; Klok and Oerlemans, 2004; Paul et al., 2005; Raymond and Neumann, 2005; Haeberli et al., 2007; Fischer, 2010; Paul, 2010; Carturan et al., 2013).

Distributed models of different complexity have been proposed for calculating the mass balance of glaciers under different climatic scenarios at a variety of spatial scales and with different purposes. The current concern about sea level rise and future availability of water resources stored in glaciers, under projected global warming scenarios, has led to increased efforts to develop models able to account for i) direct effects of climate change, and ii) reinforcing mechanisms which control glacier decay (Hock, 2005; Barry, 2006).

These models rely on accurate spatial calculation of input data, in particular air temperature, which affects not only their final performance but also the calibration of parameters and model generalizability. Indeed, wrong temperature estimates lead to wrong calibration and/or distortion of parameters, possibly hampering the applicability of models to ungauged catchments, despite the good knowledge achieved for individual processes (Savenije, 2001; Sivapalan, 2006).

Charbonneau et al. (1981), for example, highlighted that issues in extrapolating meteorological input data are much more crucial than the possible choice between different approaches for modeling snow yields from a well-equipped catchment in the French Alps. Similarly, intercomparison projects of runoff models by the World Meteorological Organization (e.g. WMO, 1986) revealed that simple models provided comparable results to more sophisticated models, given the difficulties of assigning proper model parameters and meteorological input data to each catchment element. Machguth et al. (2008), analyzing model uncertainty with Monte Carlo simulations at one point on the tongue of Morteratsch Glacier in Switzerland, concluded that the output of well-calibrated models, when applied to extrapolate in time and space, is subject to considerable uncertainties due to the quality of input data. According to Carturan et al. (2012a), who compared three melt algorithms in a six-year application of an enhanced temperature-index model over two Italian glaciers, uncertainties in extrapolating temperature measurements from off-site data partly mask the peculiar behavior of each algorithm and do not allow definitive conclusions to be drawn.

Two main issues affect the correct estimation of air temperature distribution over glacial surfaces: i) the absence of on-site weather stations in most operational model applications, and ii) the development of a katabatic boundary layer (KBL) over the typically inclined glacier surfaces (van den Broeke, 1997). Several experiments with automatic weather stations deployed over glaciers demonstrated that general assumptions in extrapolating air temperature, based on the application of fixed lapse rates which account for the linear dependency of ambient (i.e. off-glacier) temperature on altitude, have serious limitations (e.g. Greuell et al., 1997; Strasser et al., 2004; Petersen and Pellicciotti, 2011).

In particular, these assumptions do not apply when katabatic flows and the KBL form, that is, during the ablation season on melting mid-latitude glacial surfaces, when the ambient temperature is higher than the surface temperature which cannot exceed 0°C. Katabatic winds are gravity winds originated by the cooling of the near-surface air layers, resulting in density gradients which force a downward movement of the air under the effect of gravity. The two main processes affecting the temperature of the air during this downslope movement are the cooling due to the exchange of sensible heat and the adiabatic heating. The interplay of these processes has a twofold effect, consisting in lower on-glacier temperatures (the so-called glacier cooling effect), and lower temperature variability (the so-called glacier damping effect, also referred to as reduced climate sensitivity), compared to ambient conditions (Braithwaite, 1980; Greuell and Böhm, 1998; Braithwaite et al., 2002; Gardner et al., 2009). As a result, on-glacier lapse rates generally differ from average environmental lapse rates (i.e. -0.0065°C m^{-1}). Cooling and damping effects are not homogeneous over glacial surfaces, and mainly depend on the size and geometric characteristics, in particular the slope, of single glaciers, and on the specific position along the glacier. Generally, they are directly related to the size of glaciers and the fetch distance along the flowline, and inversely related to the slope of glaciers. The latest controls the prevalence of the cooling due to turbulent exchanges over the adiabatic heating of air forced to move downward by katabatic winds.

Few methods have been proposed in the literature to model these processes, mainly due to the scarcity of glaciers instrumented for distributed measurements of air temperature. Among the first authors who measured the glacier cooling effect, defined as the temperature difference between an on-glacier and an off-glacier site with the same altitude, we can cite Schytt (1955) and Eriksson (1958), who detected temperature depressions ranging from 1.1 to 2.2°C on Storglaciären (Sweden) and 3 to 4°C on Skagastøl Glacier (Norway), respectively. Havens (1964) measured an average cooling effect ranging from 1.5°C to 2.7°C at a weather station located 1 km up-glacier from the terminus of White Glacier (Canada), recognizing maximum values during warm and sunny weather and minimum values during overcast and unsettled weather.

To our knowledge, the first attempt to parameterize the mean summer cooling effect at the firn line altitude was made by Khodakov (1975), who proposed a relationship with glacier length, based on temperature data obtained from mountain glaciers and ice sheets. Analyzing direct observations from glaciers in Caucasus, Pamir, Scandinavia, Thien Shan, and Altay, Davidovich and Ananicheva (1996) provided a simple relationship for calculating the mean summer temperature at the equilibrium line altitude (ELA) in function of the mean off-glacier summer temperature at the same altitude. The same authors suggested that the cooling effect is maximal at the ELA and decreases towards both the terminus and up-glacier (see details in Sect. 3.4).

The first comprehensive glacio-meteorological experiment providing distributed temperature measurements was carried out in summer 1994 on Pasterze Glacier, Austria, and comprised five automatic weather stations (AWS) placed along a flowline. From this experiment, Greuell and Böhm (1998) developed() a thermodynamic model for calculating air temperature in function of slope and distance along the flowline, accounting for sensible heat exchanges and adiabatic heating. Braithwaite et al. (2002) used an empirical approach and a formulation derived from data gathered in two Canadian Arctic glaciers (Sverdrup and White), similar to that proposed by Davidovich and Ananicheva (1996) but applied to monthly temperatures. Shea and Moore (2010) suggested empirical relationships based on piecewise linear regressions of on-glacier versus ambient temperatures collected in British Columbia (Canada) between 2006 and 2008, for calculating i) the threshold temperature triggering KBL development, and ii) the glacier damping effect, as a function of elevation and flow path length (i.e. the 'average flow distance to a given point starting from an upslope limit or ridge').

At present these methods have rarely been used by other authors, and they have not been compared using independent test sites. Petersen et al. (2013) tested the Greuell and Böhm (1998) model using a dataset of air temperature measurements from Haut Glacier d'Arolla, Switzerland, concluding that results of spatial extrapolations along the glacier are only a little better than using a constant linear lapse rate calculated between on-glacier data points, attributing this result to the spatial variability of the thickness of the glacier boundary layer.

The transferability of the proposed methods remains to be tested. In addition, it should be noted that many of them have been developed using temperature data collected from medium- (from 0.5 to 10 km^2) to large-sized ~~glaciers~~(larger than 10 km^2)~~.~~ glaciers. As the glacier cooling effect and the damping effect depend on the size of glaciers, it is opportune to investigate the thermal effects of ~~smaller~~ ice bodies ~~(<~~ smaller than 0.5 km^2~~)~~, which are widespread and increasing in number in mid-latitude mountain regions as a result of rapid shrinking and fragmentation.

In this work we present the results of a glacio-meteorological experiment, carried out in summer 2010 and 2011, deploying several automatic weather stations over three neighboring glaciers in the Ortles-Cevedale mountain group (Italian Alps). The study was focused on the variability of air temperature over the three glaciers, which differ in size, geometric characteristics, and reaction to climatic changes (Carturan et al., 2014). In this paper, we analyze the temporal and spatial behavior of air temperature and glacier cooling effect in the study area, testing ~~different~~ existing methods for calculating on-glacier temperatures from off-site data, and evaluating their impact in mass balance simulations using ~~an~~ a distributed enhanced temperature-index (ETI) model.

2 Study area

The investigated glaciers are located in the Alta Val de la Mare (AVDM), Eastern Italian Alps (Fig. 1). This 36 km^2 experimental watershed is the subject of detailed studies concerning the impacts of climate change on the cryosphere and hydrology. The area has previously been selected for studying the behavior of meteorological variables at high altitude (Carturan et al., 2012b) and for developing an enhanced temperature-index glacier mass balance model (Carturan et al., 2012a). The highest summit is Mt Cevedale (3769 m a.s.l.), while the basin outlet is located at 1950 m a.s.l. The catchment lies in the southern part of the Ortles-Cevedale massif, the largest glacierized mountain group in the Italian Alps. The Careser diga weather station (2607 m a.s.l.) has been operating since the 1930s, recording daily 2 m air temperature, precipitation, snow depth, and fresh-snow height. In the 1990s, an automatic weather station replaced the old manual instruments. At this site, the mean 1979–2009 annual precipitation (corrected for gauge errors) was 1233 mm and the mean annual air temperature in the same period was –0.5 °C.

The investigated glaciers are very different. Careser Glacier (2870– 3279 m a.s.l.) is flat and mainly exposed to the south. In 2005 it spread in two parts: Careser Orientale (2.13 km^2 in 2006) and Careser Occidentale (0.27 km^2 in 2006). La Mare Glacier (2650–3769 m a.s.l., 3.79 km^2 in 2006) faces to the east and is steeper. On all glaciers, topographic shading is of minor importance. The Careser glaciers have no accumulation area and exhibit down-wasting and fragmentation in smaller units (Carturan et al., 2013), while La Mare Glacier still has an accumulation area and shows 'active' retreat towards higher altitudes (Zanon, 1982; Small, 1995; Carturan et al., 2009 and 2014). Long-term monitoring programs started in 1967 on Careser and in 2003 on La Mare. In the last 10 years, the glaciers have been the subject of investigations on snow accumulation, snow and ice ablation, point energy balance, and runoff generation (Carturan, 2010).

3 Methods

3.1 Experimental setup

An automatic weather station (AWS) has been operating since July 2007 on the ablation area of La Mare Glacier (2973 m a.s.l.), measuring air temperature and relative humidity, wind speed and direction, incoming and outgoing shortwave and longwave radiation, and snow depth. The thermo-hygrometric probe is housed in a ventilated radiation shield. Data are sampled every 60 seconds, with 15 minute means being stored in a Campbell Scientific CR1000 datalogger; the AWS is powered by a 25 W solar panel. Data were periodically downloaded with a portable laptop until July 2011. Since August 2011, a satellite modem has automatically transmitted data at three-day intervals (Abbate et al., 2013).

On 3 July 2010 three Vantage Pro Plus (VPP) weather stations, manufactured by Davis Instruments, were placed along a longitudinal profile on La Mare Glacier at elevations ranging from 2709 m, close to the terminus, to 3438 m, near to the upper divide. Davis VPP stations are low-cost, commercial weather stations, characterized by a compact design and low weight, and can be moved rather easily along glaciers by few persons. Their thermo-hygrometric probe is shielded by a ventilated screen, which is important for air temperature measurements in high-radiation and/or low-wind speed conditions on glaciers (Georges and Kaser, 2002). Hourly mean data are stored in a Davis datalogger. During the experiment, the data were downloaded with a portable laptop every two weeks. The three VPP were removed on 23 September 2010.

On 7 July 2011 four VPP stations were deployed, two on Careser Glacier and two on La Mare Glacier. One weather station was re-positioned at 3438 m on La Mare Glacier because instrumentation failure occurred at that place in 2010, due to lightning damage. The other three weather stations were placed in areas where systematic errors in mass balance simulations were recognized by Carturan et al. (2012a), who applied a mass balance model using the standard environmental lapse rate for extrapolating air temperature from an off-glacier weather station, as commonly used in most model applications where on-glacier data are not available. The four VPP were removed on 12 September 2011.

Table 1 reports the configuration of the weather stations operated on Careser and La Mare glaciers, whose location is shown in Fig. 1. Four off-glacier weather stations (Table 1) were also used in this study for the calculation of the glacier cooling effect in comparison to ambient temperature, and for testing ~~various~~ two methods of calculation of on-glacier temperatures from off-site data. Two of them are part of the regional weather station networks (Bel_3328, at Cima Beltovo, 3328 m a.s.l.; Cog_1202, at Cogolo Pont, 1202 m a.s.l., Fig. 1). The other two weather stations consist of Hobo Pro dataloggers (Onset Computer Corporation) installed at Careser diga (Car_2607, at 2607 m a.s.l.) and close to Careser Glacier (Car_3051, at 3051 m a.s.l.). All these stations are far enough from the thermal influence of glaciers (minimum distance of 300 m from Car_3051 to the margin of Careser Glacier), and equipped with temperature probes housed in naturally ventilated radiation shields. Possible issues related to the use of different types of temperature sensors and radiation shields are addressed in the following section.

3.2 Data processing and accuracy assessment

For our analyses, hourly means were calculated from sub-hourly meteorological data. After being synchronized with local solar time, the data were checked for possible gaps, outliers, and inhomogeneities. The major gap concerned a few days in summer 2011 for the precipitation data at Careser diga, which were filled using the manual observations recorded by the personnel of the local hydropower company. Other gaps of 1-2 hours occurred during the maintenance of weather stations, and were filled by linear interpolation.

The spatial density and type of weather stations used in this study were decided based on i) the pre-existing network of regional AWSs and ii) the logistic constraints affecting the access to the glaciers and limiting the number of research-grade AWSs which could be deployed. These limitations are common in mountain regions, and imposed comparable or even lower densities of AWSs, as well as the use of different types of sensors with different radiation shields, in most similar studies on glaciers (e.g. Shea and Moore, 2010; Petersen and Pellicciotti, 2011; Petersen et al., 2013).

Intercomparison tests have been carried out in order to assess the impact of using different sensors and radiation shields for this study. The four VPP weather stations were run for some days within a 10-m radius, both before and after the glacio-meteorological experiment, confirming the almost identical readings of air temperature, wind speed, and wind direction. Mean differences in air temperature data during the tests were lower than 0.20°C (maximum STD = 0.16°C). For comparison purposes, one VPP was run close to the AWS of La Mare Glacier in summer 2009, revealing mean differences in air temperature readings of 0.10°C (STD = 0.12°C). A further comparison was carried out in the summers of 2007 and 2008, running a VPP close to the Hobo Pro datalogger and close to a temperature sensor of the regional weather service installed at Careser diga. These two instruments, which have natural ventilation systems, showed mean differences of 0.10°C (STD = 0.40°C) and 0.23°C (STD = 0.66°C), respectively, compared to the aspirated VPP. Based on these results, no corrections were applied to the measured air temperatures.

3.3 Analysis of field data

The meteorological data collected by the weather stations were firstly analyzed calculating descriptive statistics for each of the two summers 2010 and 2011 and focusing on vertical lapse rates. Afterwards, the data were analyzed at hourly resolution focusing on the calculation of ambient (i.e. off-glacier) temperature, which is crucial for estimating on-glacier near-surface temperatures, and is required by all methods proposed in the literature for this purpose. Moreover, the correct estimation of the ambient temperature is an essential prerequisite for quantifying the site-specific cooling effect on glaciers, which is defined as 'the difference between screen-level temperatures over glaciers compared to equivalent-altitude temperatures in the free atmosphere' (Braithwaite, 1980). Different combinations of lapse rates (i.e. fixed standard or hourly-variable obtained by linear regression of temperature versus elevation) and subsets of weather stations were tested (see details in Sect. 4.2).

The spatial and temporal variability of the cooling effect was then investigated, plotting the average diurnal cycle of the cooling effect versus average cycles of wind speed and direction, and drawing charts of the daily average cooling effect vs. daily temperature and precipitation recorded at Careser diga, in order to assess the role of different weather types in the glacial temperature regimes.

3.4 Calculation of on-glacier temperature from off-site data

The measured on-glacier temperatures served for testing five the methods proposed in the literature for calculating the air temperature distribution over glacierized surfaces. The first three methods were only useable for mean summer calculations, while theprocedures suggested by Shea and Moore (2010) and Greuell and Böhm (1998) (from now on "S&M" and "G&B", respectively) for calculating the air temperature distribution over glacierized surfaces. The empirical methods by Khodakov (1975), Davidovich and Ananicheva (1996), and Braithwaite et al. (2002) were not tested because they are more empirical, the coefficients were calculated in very different environments, and they methods could be used also for hourly temperature calculations, as they do not take into account the temporal variability of the cooling effect.

The first method (Khodakov, 1975) is expressed by the following:

$$\log\Delta T = 0.28\log L - 0.07 \quad (1)$$

where ΔT (°C) is the mean summer cooling effect at the firn line and L (km) is the 'characteristic size' of the glacier, defined as 'the distance between the ice divide and the start of the narrow tongue' of a mountain glacier.

~~The second method (Davidovich and Ananicheva, 1996) recommends the following equation:~~

~~$$T_g = 0.85T_{ng} - 1.2 \qquad (2)$$~~

~~where T_g (°C) is the on-glacier mean summer temperature at the ELA and T_{ng} is the off-glacier mean summer temperature (°C) at the same elevation. The cooling effect is linearly reduced to 0.2°C at the glacier terminus and to 0°C (i.e. same temperature on- and off-glacier) above the elevation where the mean summer temperature equals -4°C.~~

~~A similar formulation was proposed by Braithwaite et al. (2002):~~

~~$$T_{Glacier} = -0.7 + 0.85T_{Land} \qquad T_{Land} > -5°C \qquad (3)$$~~

~~$$T_{Glacier} = T_{Land} \qquad T_{Land} \leq -5°C \qquad (4)$$~~

~~where $T_{Glacier}$ and T_{Land} (°C) are monthly temperatures at the same elevation, the first on-glacier and the second off-glacier.~~

S&M suggested the use of a piecewise regression model:

$$T_g(x,t) = \begin{cases} T_1 + k_2(T_a - T^*), & T_a \geq T^* \\ T_1 - k_1(T^* - T_a), & T_a < T^* \end{cases}$$ (~~5~~1)

where $T_g(x,t)$ (°C) is the on-glacier temperature for site x at time t, T^* (°C) represents a threshold ambient temperature for KBL effects on T_g, T_1 (°C) is the corresponding on-glacier threshold temperature, k_2 (k_1) is the so called sensitivity of on-glacier temperature to ambient temperature (T_a, °C) changes when T_a is above (below) T^*. Empirical transfer functions were obtained by S&M, relating the fitted coefficients (T^*, k_1 and k_2) for each weather station used in their work to topographic attributes extracted from a digital elevation model (DEM):

$$T^* = \beta_1 + \beta_2 Z$$ (~~6~~2)

$$k_1 = \beta_3 \exp(\beta_4 FPL)$$ (~~7~~3)

$$k_2 = \beta_5 + \beta_6 \exp(\beta_7 FPL)$$ (~~8~~4)

where β_i are the coefficients of the transfer functions, Z (m) is the elevation, and FPL (m) is the flow path length, defined as 'the average flow distance to a given point starting from an upslope summit or ridge' (Shea and Moore, 2010). T_1 is calculated as $T^* \cdot k_1$.

The G&B model assumes the presence of a katabatic wind, and therefore it applies when the ambient temperature is higher than the surface temperature. In these conditions the potential temperature Θ (°C) at the distance x along the flowline ($x = 0$ at the top of the flowline) is calculated as:

$$\Theta(x) = (T_0 - T_{eq})\exp\left(-\frac{x - x_0}{L_R}\right) - b(x + x_0) + T_{eq}$$ (~~9~~5)

with

$$T_0 = T_{cs} - \gamma(z_{cs} - z_0)$$ (~~10~~6)

$$T_{eq} = bL_R$$ (~~11~~7)

$$L_R = \frac{H\cos(\alpha)}{C_H}$$

(~~12~~8)

$$b = \Gamma_d \tan(\alpha)$$

(~~13~~9)

where T_0 (°C) is the temperature at x = 0, T_{eq} (°C) is defined as the 'equilibrium temperature', x_0 and z_0 (m) are the location and elevation where the air enters the glacier-wind layer, T_{cs} (°C) and z_{cs} (m) are the temperature and the elevation at the off-glacier weather station, γ (°C m^{-1}) is the ambient lapse rate, H (m) is the height of the glacier wind layer, α (°) is the glacier slope, C_H is the bulk transfer coefficient for heat, and Γ_d is the dry adiabatic lapse rate (-0.0098°C m^{-1}). The potential temperature is converted into temperature by means of:

$$T(x,z) = \Theta(x) - \Gamma_d[z(x=0) - z(x)]$$

(~~14~~10)

where $z(x)$ is the surface profile of the glacier.

~~For all the described methods, t~~For both methods, the original formulations and parameters were tested unchanged against our experimental data, evaluating also p~~. P~~ossible modifications ~~were evaluated for the S&M and G&B methods,~~ as detailed in Sect. 4. The efficiency was evaluated by means of three different statistics: i) the mean error (ME), ii) the root mean square error (RMSE), and iii) the efficiency criterion by Nash and Sutcliffe (N&S, 1970). The topographic information required to apply these methods was extracted from a 2 x 2 m DEM surveyed by LiDAR in late summer of 2006. A map of the FPL was calculated from this DEM, using algorithms developed for drainage area calculations (Fig. 2, Tarboton et al., 1991).

3.5 Mass balance modeling

The impact that the calculation of on-glacier temperatures according to different methods has on mass balance modelling was assessed using EISModel (Cazorzi and Dalla Fontana, 1996), which was already applied to Careser and La Mare glaciers by Carturan et al. (2012a). EISModel employs an enhanced temperature-index approach for computing melt, using the clear-sky shortwave radiation ~~computed~~ calculated from the DEM as a distributed morpho-energetic index. The model, which is suitable for applications on glaciers with limited data availability, doesn't require incoming shortwave radiation measurements, which are less commonly available compared to air temperature and precipitation.

Three melt algorithms (multiplicative, additive, and extended) have been implemented and can be used alternatively in EISModel. In the present work we use the additive melt algorithm, which explicitly separates the thermal and radiative components:

$$MLT_{X,t} = [TMF \cdot T_{X,t}] + [RMF \cdot CSR_{X,t}(1 - \alpha_{X,t})]$$

(~~15~~11)

where TMF and RMF are empirical coefficients called the Temperature Melt Factor (mm h^{-1} °C^{-1}) and the Radiation Melt Factor (mm h^{-1}W^{-1} m^{2}), $T_{X,t}$ (°C) is the air temperature at pixel X in hour t, $CSR_{X,t}$ (W m^{-2}) is the clear sky shortwave radiation and $\alpha_{X,t}$ is the surface albedo (spatially variable for ice and spatially and temporally variable for snow). For a detailed description of the model we refer the reader to the work of Carturan et al. (2012a).

The cumulated mass balance measured at ablation stakes drilled in close proximity to the glacial weather stations (AWS and VPP) served for model calibration and validation. We used alternatively each of the two summer seasons of 2010 and 2011 as an independent dataset for calibration/validation. Point-based EISModel calculations at the weather stations were run, using four temperature series: i) measured data, ii) calculated temperature from Careser diga via the standard ambient lapse rate (-6.5°C km^{-1}), iii) calculated temperature according to the S&M method, and iv) calculated temperature according to the G&B method. Option ii) is commonly used in the absence of temperature data from glaciers (e.g. Gardner and Sharp, 2009; Michlmayr et al., 2008; Nolin et al., 2010).

4 Results

4.1 Seasonal characteristics of temperature data

A close dependency on altitude has been detected for mean summer air temperature, both outside the glaciers and, remarkably, over them (Table 2, Fig. ~~2~~3). Because of thermal inversions occurring at the lowermost weather station (Cog_1202) during the night and early morning, the vertical lapse rate was much ~~higher~~ steeper above Car_2607 (-8.0°C km^{-1} in 2010 and -8.3°C km^{-1} in 2011) than below (-5.3°C km^{-1} in 2010 and -5.2°C km^{-1} in 2011). At a given altitude, the on-glacier air temperature was systematically lower than ambient temperature, the difference decreasing with altitude. Lapse rates were also lower on the glaciers (-7.2°C km^{-1} in 2010 and -6.7°C km^{-1} in 2011), compared to high-altitude off-glacier weather stations, and close to the standard ambient lapse rate (-6.5°C km^{-1}). Much ~~higher~~ shallower on-glacier lapse rates and fewer dependency of air temperature on elevation were found by earlier works (e.g. Greuell and Böhm, 1998; Strasser et al., 2004; Petersen et al. 2013). As reported in Table 2, t~~T~~he average daily temperature range and the average ~~SD~~ standard deviation are largest at the valley floor and both decrease with altitude, reaching their minima over the glaciers as previously reported, for example, by Oerlemans (2001). Hourly temperatures among different weather stations in Val de La Mare were highly correlated (r > 0.9, significant at the 0.001 level), with the remarkable exception of Cog_1202, at the valley floor, whose correlation with the other weather stations ranged from 0.65 to 0.75, peaking at 0.84 with Car_2607.

4.2 Ambient temperature calculation

For the calculation of ambient temperature at the altitude of glaciers, which is crucial for the quantification of the glacier cooling effect, we tested the following methods: i) use of a fixed standard ambient lapse rate (-6.5°C km^{-1}), ii) use of a fixed calibrated lapse rate (seasonal mean value), and iii) use of an hourly-variable lapse rate. Methods ii) and iii) were implemented using different combinations of off-glacier weather stations, calculating linear regressions of hourly temperature vs. altitude. The methods were tested removing alternatively Car_3051 or Bel_3328 from linear regressions and using them for validation. The results, displayed in Table 3, show that regardless of the method used, the inclusion of the lowermost weather station gives poorer results. At Car_3051, the method iii) applied to Car_2607 and Bel_3328 works best, indicating that in our case hourly variable lapse rates ~~is~~ are the most appropriate solution while interpolating temperatures between two weather stations. Conversely, method ii) applied to Car_2607 and Car_3051 provides the best results at Bel_3328, which ~~means~~ suggests that a fixed calibrated lapse rate ~~is the most suitable option for extrapolations above our highest off-glacier weather station~~should be used while extrapolating above the uppermost station, even if uncertainty persists in these cases.

4.3 The glacier cooling effect

The cooling effect at each on-glacier weather station was calculated as the difference between the measured temperature and the ambient temperature at the same elevation, computed on the basis of the results described in Sect. 4.2 (i.e. hourly-variable lapse rate below Bel_3328 and fixed calibrated lapse rate above it). The average seasonal cooling effect (Table 4) was maximal at Car-gl_3082 (-1.01 °C in 2011) and at Mar-gl_2973 (-0.74°C in 2010 and -0.90°C in 2011). Null or negligible cooling was detected at Mar-gl_3438, close to the top of La Mare Glacier, and at Car-gl_3144 on the small Careser Occidentale Glacier. Minor cooling occurred at Mar-gl_3215 (-0.27°C in 2010), which was close to the balanced-budged ELA of the glacier, and at Mar-gl_3140 (-0.47°C in 2011), in the upper ablation area. Notably, the narrow and steep terminus of La Mare Glacier experienced a significant cooling effect in 2010 (-0.65°C).

Fig. ~~3~~ 4 reports the mean daily cycles of the cooling effect and wind regime. A common pattern emerges, with minimum cooling at night and maximum cooling around noon or in the afternoon, coherent with the diurnal cycle of ambient air temperature and deriving temperature differences from the glacier surface. For five out of the seven monitored sites, the cooling occurred almost exclusively during daytime. Nighttime cooling took place only at Mar-gl_2973 and Car-gl_3082, which are the two sites with higher mean cooling. Down-glacier winds dominated on La Mare Glacier, with higher speeds compared to Careser Occidentale and Orientale glaciers, where up-glacier winds prevailed. The wind speed was at its maximum at night on La Mare, especially in 2010, while it was at its maximum in the afternoon on the two Careser glaciers. A peculiar behavior was found at the terminus of La Mare Glacier (Mar-gl_2709), where down-glacier winds dominated at night, without a cooling effect, and were replaced by up-glacier winds from mid-morning to late afternoon, when the cooling effect increased sharply. Wind data were not available at Mar-gl_3438, due to instrumentation failure, but we can argue that katabatic winds were not prevalent at this site, which is close to the crest, based on results published for similar locations in previous works (e.g. Greuell et al., 1997; Strasser et al., 2004).

Different weather conditions led to a considerable temporal variability of the glacier cooling effect during the two summer seasons of 2010 and 2011 (Fig. ~~4~~5). Cooling was maximal during warm anticyclonic periods and nearly absent during cold unsettled weather. Differences among sites increased with warmer temperatures, whereas they nearly disappeared during cold and unstable periods. The highest variations occurred at Mar-gl_2973, Mar-gl_3215, Mar-gl_3140, and Car-gl_3082 while at Mar-gl_3438 and Car-gl_3144 there was a smaller temporal variability. A warming, rather than cooling, effect was observed on some days, mainly at the upper weather stations of La Mare Glacier. A close check on the wind and temperature data revealed that this was ascribable to local föhn conditions, that is, forced adiabatic heating brought by strong northerly winds.

4.4 Calculation of on-glacier temperature from off-site data

~~4.4.1 Seasonal temperature~~

~~Table 5 reports the seasonal temperatures calculated by the five different methods described in Sect. 3.4 and their comparison with actual measurements on glaciers. The methods of Khodakov (1975), Davidovic and Ananicheva (1996) and Braithwaite et al. (2002), applicable to only seasonal temperatures, provided similar results in terms of mean errors, which were for the most part negative (i.e. excessive cooling effect). The only method which accounts for the spatial variability of the cooling effect (Davidovic and Ananicheva, 1996) provided the worst results in terms of RMSE and N&S index, being correct in the lower ablation area of La Mare Glacier (Mar-gl_2709 and Mar-gl_2973) but strongly underestimating temperatures elsewhere. The least problematic site for all methods was Mar-gl_2973, whereas the most problematic sites for most methods were Mar-gl_3438, Car-gl_3144, and Mar-gl_3215 (i.e. the sites where the measured cooling effect was lowest). The terminus of La Mare Glacier was less challenging, except for the method of Braithwaite et al. (2002).~~

Comment [LC1]: given that the three methods by Khodakov (1975), Davidovich and Ananicheva (1996), and Braithwaite et al. (2002) have been removed, we deleted this part, the Table 5 and the separation in two sub-sections.

~~Mean seasonal temperatures calculated from the hourly values obtained by the G&B and S&M methods (see the following section for details) matched the measurements better, with the mean errors among all the weather stations being closer to zero. The G&B method was the best at capturing the spatial variability of air temperature, even if significant underestimations persisted at the two sites with the lowest cooling effect (Mar-gl_3438 and Car-gl_3144). The S&M method was not so efficient, in particular at Mar-gl_2709, where the temperature was underestimated by 1.6°C, and at Mar-gl_3438, where an overestimation of 0.9°C occurred.~~

~~4.4.2 Hourly temperature~~

According to the S&M method, piecewise linear regressions of on-glacier hourly temperature versus ambient temperature at the same elevation have been calculated for each glacial weather station. The values of the parameters k_1 and k_2 (i.e. temperature sensitivities for ambient temperatures below and above the threshold temperature T^*, respectively) were well aligned with the transfer functions proposed by S&M, using the *FPL* as predictor (Fig. ~~5~~6). On the other hand, the transfer function for T^* suggested by S&M, using station elevation as a predictor, could not be used in AVDM given the different geographic and climatic setting of the two study areas. We therefore propose to substitute Eq. (~~6~~2) with the following function:

$$T^* = \frac{a \cdot FPL}{b + FPL} \quad (\sout{16}12)$$

which uses the *FPL* (m) rather than elevation as a predictor, thus being potentially more generalizable. The outlier already excluded by S&M was not included in our calculation of Eq. (~~16~~12), nor was Mag-gl_2709, both due to under-sampling at below-zero temperatures. Fig. ~~5~~ 6 shows data points, transfer functions, and parameters. Calculated versus measured temperature is shown in Fig. ~~6~~ 7 along with related statistics. Four out of the five sites where the method works satisfactorily (ME < 0.5°C in absolute value and N&S index > 0.87) have prevailing katabatic winds. On the contrary, lower performance affects sites close to the glacier margin (Mar-gl_3438 and, in particular, Mar-gl_2709), where katabatic winds are disrupted by valley winds or synoptic winds, and Car-gl_3082, where up-glacier winds prevail. The efficiency statistics for all sites are: ME = -0.06°C, RMSE = 0.73°C and N&S = 0.692.

According to the G&B method, the location x_0 where the air enters the glacier wind layer, and the length scale L_R, can be calculated by an exponential function which expresses the 'climatic sensitivity' in function of the distance x along the flowline:

$$\frac{dT(x)}{dT_{cs}} = \exp\left(-\frac{x + x_0}{L_R}\right) \quad (\sout{17}13)$$

Climatic sensitivities were calculated, comparing daily mean temperature at our on-glacier sites to daily mean temperature at Car_3051, and have been added for comparison to the data displayed in Figure 5 of the Greuell and Böhm (1998) paper. The results are shown in Fig. ~~7~~ 8 and indicate a fairly good alignment of our data with the other glaciers' data and with the best fit calculated by G&B for the Pasterze weather stations. It therefore seemed appropriate to use the values of x_0 and L_R calculated by those authors, that is, 1440 and 8340 m respectively. According to the G&B procedure, the hourly temperature above the freezing level was set equal to the ambient temperature (Sect. 4.2). Below the freezing level, the glacier-wind model of G&B was applied, setting i) $x_0 = 0$ if the freezing level was below the top of the flowline, and ii) $x_0 = 1440$ m if it was above this point, in order to take into account a climate sensitivity < 1 at the top of the flowline. z_0 was set equal to the freezing level in case i) and equal to the altitude of the top of the flowline in case ii). These settings are the same as those used in the G&B paper. Nevertheless, no corrections were applied to the computed temperatures, as was done by G&B, who applied a fixed offset of -0.74°C.

Fig. ~~8~~ 9 displays the results of the G&B method. Calculated temperatures matched the measured temperatures fairly well and~~, as reported in Table 5,~~ the efficiency statistics for all sites were better than for the S&M method: ME = -0.27°C, RMSE = 0.40°C, N&S = 0.908~~, with a lower mean RMSE and a higher N&S index~~. Improvements were observed, in particular, at Mar-gl_2709, Car-gl_3082, and Mar-gl_3438, even if these sites lack predominant katabatic winds. A clear step is observable at Mar-gl_2709 and, slightly less obvious, at Mar-gl_2973 in both summer 2010 and 2011, attributable to the jump of x_0 from 0 to 1440 m when the freezing level exceeds the top of the flowline.

4.5 Mass balance modeling

EISModel applications using measured temperature datasets resulted in RMSE values well below the mass balance measurement error from ablation stakes readings (~200 mm w.e., Thibert et al., 2008; Huss et al., 2009), thus confirming the good skill of the modeling tool. On the other hand, the RMSE was nearly double when calculated temperature datasets were used as input, and considerable differences also exist in the calibration parameters (Table ~~6~~5).

The spatial distribution of modeling errors using temperature extrapolations from Car_2607 via the standard lapse rate (Fig. ~~9~~10, scatterplots b1 to b4) replicated the findings of Carturan et al. (2012a) for the six previous years (2004 to 2009). In particular, the modeled vertical gradient of mass balance on La Mare Glacier in summer 2010 was lower than the observed one, in both calibration and validation runs, due to uneven errors in estimating air temperature (+0.77, +1.17, and +1.14°C at Mar-gl_2709, Mar-gl_2973, and Mar-gl_3215 respectively). This dataset of overestimated temperatures led to significantly lower calibration parameters compared to the measured temperature dataset. Moreover, including critical points close to the lower margin of the glacier (Mar-gl_2709 in summer 2010) led to wrong calibration at the other two points, which are likely to have a higher spatial representativeness given the larger distance from the glacier margin.

The calibration parameters obtained with the G&B temperature dataset were closer to those obtained with the measured temperature dataset, as could be expected given the smaller errors in temperature estimations (~~Table 5,~~ Fig. ~~8~~9). In summer 2010, modeling results with the G&B temperature dataset were also the best among the three tested methods for air temperature calculation, in both calibration and validation runs. The same cannot be stated for summer 2011, due to the larger temperature underestimation at Mar-gl_3140 and Car-gl_3144. Similar errors occurring at Mar-gl_3438 did not impact mass balance estimations because they mainly happened at below-zero temperatures (Fig. ~~8~~9).

The S&M temperature dataset led to the worst results in summer 2010 due to the strong underestimation of air temperature at Mar-gl_2709 (-1.6°C). Calibrated parameters in 2010 were thus overestimated and led to mass balances that were too negative, on average, in 2011. On the contrary, when used for calibration, the data of 2011 led to parameters much closer to the measured temperature dataset, leading to correct mass balance estimations in summer 2010 with the exception of the already mentioned Mar-gl_2709.

5 Discussion

The temperature distribution and wind regime were found to be remarkably different for the three investigated glaciers (Tables 2 and 4, Fig. ~~3~~4). The most significant differences were detected between La Mare Glacier, where the KBL and the cooling effect were clearly recognizable, and the Careser Occidentale Glacier, where the air temperature was not significantly different from the ambient temperature and where prevailing up-glacier winds (i.e. valley winds) dominated. Differences were even more prominent during warm and stable weather (Fig. ~~4~~5), brought by persistent anticyclonic systems (as detected by inspection of reanalysis weather charts from www.wetterzentrale.de, last access: 31 October 2014).

~~In these periods, when the ablation is highest, the cooling effect is much more effective for example at Mar-gl_2973, causing a temperature depression of 2 to 3°C compared to 1°C at Car-gl_3144. These findings provide a first quantification for an important reinforcing mechanism during glacier decay, that is, the disintegration of parent glaciers into smaller units, which have reduced effectiveness in cooling the air above and in triggering katabatic flows.~~

The Car-gl_3082 site, on Careser Orientale Glacier, also displayed peculiar conditions compared to most weather stations operated on La Mare Glacier. On the one hand a prevailing up-glacier wind was recognized, but it cannot be attributed unequivocally to valley winds because the direction roughly corresponds to prevailing synoptic winds in the Ortles-Cevedale area (Gabrieli et al., 2011). On the other hand, although katabatic flows were generally absent, this site was the coldest in summer 2011, exhibiting a mean depression of 1°C compared to the ambient temperature (Table 4). In addition, during warm anticyclonic periods ~~(as detected by inspection of reanalysis weather charts from www.wetterzentrale.de, last access: 31 October 2014)~~ it displayed a cooling effect similar to Mar-gl_2973 and Mar-gl_3140, located in the middle part of La Mare Glacier. This is unusual for locations close to the top of glacier flowlines, which normally display a low cooling effect and high temperature sensitivity (e.g. Greuell and Böhm, 1998; Shea and Moore, 2010; Petersen et al., 2013). The efficient cooling at Car-gl_3082 could have been caused by the combination of adiabatic cooling of ascending air and cooling by loss of sensible heat due to the rather long fetch (780 m from the lower edge of the glacier), whereas in katabatic flows the loss of sensible heat is to some extent compensated by the adiabatic heating of descending air. ~~these two energy exchanges have opposite signs (i.e. loss of sensible heat and adiabatic heating of descending air).~~

The behavior of the two weather stations on Careser Occidentale and Orientale glaciers provides evidence of the reduced effectiveness of small glaciers (deriving from the fragmentation of larger glaciers) in cooling the air above, compared to wider glaciers or wider portions of the same parent glacier. This is suggested by the fact that these two weather stations, despite being at almost the same flow path distance from the upper glacier margin (Table 1, Fig. 2), have very different cooling effects (Table 4, Fig. 4), which largely explain errors in modeled ablation rates (Fig. 10; Figure 8 from Carturan et al., 2012).

In consideration of the high number and contribution to the world's total ice volume of smaller glaciers (Haeberli et al., 1989; Paul et al., 2004; Zemp et al., 2008; Bahr and Radić, 2012), and given the absence of previous experimental data from such small ice bodies, these results provide a first quantification for an important reinforcing mechanism during glacier decay, that is, the disintegration of parent glaciers into smaller units, which have reduced effectiveness in cooling the air above and in triggering katabatic flows. Clearly, these results are not conclusive and require further experimental data to assess their generalizability, and to develop generalized strategies for calculating air temperature over glaciers with similar characteristics, to be implemented in distributed mass balance models.~~These findings provide a first quantification for an important reinforcing mechanism during glacier decay, that is, the disintegration of parent glaciers into~~

~~smaller units, which have reduced effectiveness in cooling the air above and in triggering katabatic flows.~~

A clear dependency of air temperature on elevation was found on La Mare Glacier, where the weather stations were placed along a longitudinal profile, exploring a large range of elevations (Fig. ~~2~~3). The on-glacier lapse rate was ~~higher~~ steeper than the standard ambient lapse rate, unlike in previous works which mostly report lower values, ranging from -2.8 to -8.1°C km^{-1} and averaging -4.9°C km^{-1} (Petersen and Pellicciotti, 2011, and references cited therein; Petersen et al., 2013). The high lapse rate measured on La Mare Glacier is likely due to its physical characteristics and to the specific location of weather stations. For example, Mar-gl_2973, which is located 2.13 km downslope from the upper margin of the glacier, displayed only a moderate cooling effect (-0.74°C in 2010 and - 0.90°C in 2011), due to the presence of a steep slope causing adiabatic heating right above the weather station. An even more unusual behavior was measured at Mar-gl_2709, close to the terminus of the glacier. Here the cooling effect was detected only during daytime, with valley winds prevailing over katabatic winds, while at night the adiabatic heating of the air descending the steep tongue prevailed over the cooling due to turbulent exchanges. Besides the physical characteristics of the glacier, however, the steep lapse rates might also have been influenced by the high lapse rate measured outside the thermal influence of glaciers.

The specific reasons for the steepness of the high-altitude ambient lapse rates are not easy to identify. According to Marshall et al. (2007) and Minder et al. (2010), for example, they could have been caused by the prevailing synoptic circulation, local energy balance regime, persistence of snow cover, geographic position (windward or leeward with respect to the prevailing synoptic wind). Apart from these considerations, it has to be noted that the interpolation and extrapolation of ambient temperature at high altitudes, as a starting point for the computation of the on-glacier temperature fields, are strongly dependent on the availability and/or selection of suitable weather stations. As already suggested e.g. by Oerlemans, (2001), measurements from high-altitude weather stations are preferable to measurements from valley-floor sites, which are prone to thermal inversions and subject to high temperature oscillations during the day.

~~None of the five tested methods were able to fully reproduce the spatial variability of air temperature observed on the Careser and La Mare glaciers (Table 5). The 'seasonal' methods generally underestimated temperature, in particular close to the edge of glaciers and in the small Careser Occidentale, because they have been developed using data from larger glaciers (e.g. Braithwaite et al., 2002) and/or they were conceived for applications at the ELA or at the firn line (e.g. Khodakov, 1975). The method by Davidovich and Ananicheva (1996), which explicitly accounts for the spatial variability of the cooling effect, was fairly effective in the lower ablation area of La Mare Glacier (Mar-gl_2709 and Mar-gl_2973), but underestimated temperature elsewhere. None of these three methods were able to differentiate between the 'cold' Car-gl_3082 and the 'warm' Car-gl_3144.~~

The good alignment of our data points with the transfer functions of Shea and Moore (2010), which can be seen in Fig. ~~5~~6, is remarkable given the different characteristics of glaciers and geographic setting of the two study areas. This result points to a good generalizability of the S&M method, which we have tried to improve by implementing a transfer function for *T** based on the *FPL* rather than on elevation. The S&M method was fairly successful at sites where the KBL was detected (Mar-gl_3140, Mar-gl_3215), that is, for the conditions under which the method has been implemented. Nevertheless, at Mar-gl_2973 it significantly underestimated the temperature, probably because it does not account for gradients upslope of the weather station, which causes a local prevalence of adiabatic heating. A larger error occurred at Mar-gl_2709, which is however influenced by valley winds and thermal emission from the surrounding bare rocks, determining high temperature sensitivity and unusual *T** at such a long FPL (2896 m, Fig. ~~5~~6). ~~As already seen for~~

~~'seasonal' methods, also with~~With this method it was not possible to reproduce the temperature differences between Car-gl_3082 and Car-gl_3144, as expected, because they have similar values of down-glacier FPL (313 and 354 m, respectively).

The G&B method provided the best overall results. Among sites with prevailing katabatic winds, the improvement was clearest at Mar-gl_2973, where the method was able to account for the combined effect of adiabatic heating and turbulent exchanges, which were regulated by the slope variations along the upstream flowline. On the other hand, it was worse than the S&M method at distinguishing between the two Careser glaciers, ~~(Table 5),~~ and the better results in terms of lower mean errors at Mar-gl_2709, Mar-gl_3438 and Car-gl_3082, compared to the S&M method, are coincidental because at these sites the KBL was almost absent or not prevailing.

Other combinations of parameters x_0 and L_R have been tested to evaluate whether they are valid alternatives, for example for eliminating the artificial step in calculated versus observed temperature at Mar-gl_2973 and Mar-gl_2709 (Fig. ~~8~~9), caused by the jump of x_0 from 0 to 1440 m when the freezing level exceeds the top of the flowline. The tested combinations were: i) x_0 = 0 m (constant) and L_R = 8340 m, ii) x_0 = 1440 m (constant) and L_R = 8340 m, and iii) x_0 = 1835 m (constant) and L_R = 12682 m. The last combination results from the best fit to AVDM data in Fig. ~~7~~8, excluding the outlier Mar-gl_2709. We also tested the calculation using the unmodified ambient temperature. Tests indicate that at sites with almost no cooling effect (Mar-gl_3438 and Car-gl_3144) the unmodified ambient temperature or the combination i) (x_0 = 0) provide the best results (mean errors < 0.2°C in absolute value). At the four sites with prevailing KBL the best overall solution was iii), but this combination is specific for the AVDM and not generalizable, due to the rather small size of our glaciers. At Mar-gl_2973, options ii) and iii) completely removed the step and provided the best statistics. At Mar-gl_3215, option iii) provided almost identical results to a variable x_0, while options i) and ii) led to excessive overestimations and underestimations, respectively. At Mar-gl_3140, the best option was iii).

These findings highlight site-specific and glacier-specific conditions which still need investigation in order to generalize the G&B procedure, possibly by including smaller or disintegrating glaciers in the datasets used for the generalization. Sites where the KBL no longer exists and is replaced by prevailing valley winds and/or synoptic winds also need to be included as they reveal important controlling mechanisms during glacier shrinking, which require modifications to the main G&B algorithms in order to be taken into account.

The results of EISModel applications underline the importance of correct on-glacier air temperature estimation for reliable mass balance calculations (Table ~~6~~5, Fig. ~~9~~10). Even small estimation errors induce significant distortions in calibration parameters and compromise model generalizability. The 2010 dataset on La Mare Glacier clearly demonstrates how single points, especially if they are displaced along altitudinal profiles, can affect the calibration of the model and its capability to account for the vertical gradients of the mass balance. This problem is clearly emphasized in our case study, with only three weather stations along the flowline of La Mare Glacier in 2010. The spatial representativeness of Mar-gl_2973 and Mar-gl_3215 is likely much higher than that of Mar-gl_2709, at the glacier terminus, which reflects the conditions close to the lower edge of glaciers. However, mass balance models should be improved in order to account for the decreased thermal offset in these areas and in smaller glacier units resulting from the fragmentation of larger glaciers, because they represent important processes involved in the response of glaciers to climatic changes.

6 Concluding remarks

The results of this work have interesting implications for the knowledge of glacier's reactions to climatic changes, and for their modeling. The main conclusions from this study are the following:

1) our findings provide a first experimental evidence for the reduced effectiveness of small glaciers (< 0.5 km^2) in cooling the air above and in triggering katabatic flows. This represents an important reinforcing mechanism during glacier decay and ~~disintegration~~fragmentation.

2) ~~none of the methods proposed in the literature for calculating on-glacier temperature from off-glacier data fully accounted for the spatial variability detected by our measurements. However,~~ a good match between our temperature measurements and~~with~~ the parameterizations proposed by Shea and Moore (2010) and, best of all, Greuell and Böhm (1998) was found, at least for the on-glacier weather stations were katabatic flows prevail. This represents a step forward for the generalization of these methods, which on the other hand still need refinements, in particular for areas close to the margins (e.g. the front) and for the smaller units resulting from glacier ~~disintegration~~fragmentation

3) even small deviations of calculated on-glacier temperature from observations significantly impacted the calibration of EISModel and its efficiency, thus confirming that accurate temperature estimations are an essential prerequisite for model development, calibration and generalizability.

Author contribution

L. Carturan, F. Cazorzi and G. Dalla Fontana designed the glacio-meteorological experiment and carried it out. L. Carturan and F. De Blasi processed and analyzed the experimental data. F. Cazorzi and L. Carturan developed the EISModel and performed the glacier mass balance simulations. L. Carturan prepared the manuscript with contributions from all co-authors.

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Tables

Table 1. Location, flow path length (*FPL*), period of observation and used variables for glacier and ambient weather stations[a]. The periods with common records are 3 July to 23 September 2010 and 7 July to 12 September 2011.

Weather station	Easting (m)	Northing (m)	Elevation (m a.s.l.)	*FPL* (m)	Period of observation		Used variables
					Summer 2010	Summer 2011	
La Mare Glacier							
Mar-gl_2709	626692	5143668	2709	2896	x		T, W
Mar-gl_2973	625960	5143483	2973	2132	x	x	T, W
Mar-gl_3215	625205	5143101	3215	1278	x		T, W
Mar-gl_3140	625290	5143523	3140	805		x	T, W
Mar-gl_3438	624199	5142924	3438	40	damaged	x	T, W
Careser Glacier							
Car-gl_3082	632283	5145512	3082	313		x	T, W
Car-gl_3144	629690	5145375	3144	354		x	T, W
Ambient weather stations							
Cog_1202	629915	5135988	1202	\	x	x	T
Car_2607	630570	5142410	2607	\	x	x	T, P
Car_3051	630799	5145553	3051	\	x	x	T
Bel_3328	624957	5151212	3328	\	x	x	T

[a]T = air temperature, W = wind speed and direction, P = precipitation. On-glacier sites are in bold type.

Table 2. Descriptive statistics for air temperature data recorded by the weather stations. On-glacier sites are in bold type.

Weather station	Minimum	Maximum	Mean	Standard deviation	Mean daily range
		Summer 2010			
Mar-gl_2709	-1.9	14.2	5.9	3.3	2.2
Mar-gl_2973	-4.4	11.6	3.8	3.1	2.5
Mar-gl_3215	-6.6	10.6	2.2	3.4	2.9
Cog_1202	2.3	29.8	14.8	5.5	10.2
Car_2607	-2.4	18.4	7.3	4.1	4.6
Car_3051	-5.6	14.1	3.9	4.0	2.8
Bel_3328	-10.5	13.9	1.5	4.5	3.6
		Summer 2011			
Mar-gl_2973	-4.8	12.0	4.3	2.7	2.6
Mar-gl_3140	-6.2	9.7	3.3	2.8	2.1
Mar-gl_3438	-7.9	9.5	1.1	3.1	3.2
Car-gl_3082	-6.0	10.8	3.3	2.9	2.6
Car-gl_3144	-6.1	10.9	3.5	3.1	2.3
Cog_1202	4.0	29.8	15.4	4.9	10.5
Car_2607	-0.9	19.5	8.1	3.6	4.9
Car_3051	-5.3	13.7	4.6	3.5	2.8
Bel_3328	-8.2	13.5	2.1	3.8	3.5

Table 3. Validation statistics for ambient temperature calculations (global dataset including summer 2010 and 2011)[a]

Lapse rate (°C m^{-1})	Used weather stations	Calculation of air temperature at Car_3051			Calculation of air temperature at Bel_3328		
		Mean Error (°C)	RMSE (°C)	N&S index	Mean Error (°C)	RMSE (°C)	N&S index
Moist adiabatic lapse rate							
-0.0065	1	-1.14	3.81	-0.019	-0.51	3.59	0.276
-0.0065	2	0.59	1.32	**0.878**	1.22	2.02	0.771
-0.0065	3	\	\	\	0.63	1.46	**0.880**
-0.0065	4	-0.63	1.46	0.851	\	\	\
Fixed calibrated lapse rate							
-0.0053	1, 2	1.13	1.64	0.812	2.11	2.65	0.605
-0.0059	1, 3	\	\	\	0.81	1.54	0.866
-0.0063	1, 4	-0.70	1.49	0.845	\	\	\
-0.0078	2, 3	\	\	\	0.27	1.34	**0.899**
-0.0082	2, 4	-0.17	1.32	**0.877**	\	\	\
-0.0057	1, 2, 3	\	\	\	0.85	1.56	0.863
-0.0061	1, 2, 4	-0.74	1.51	0.841	\	\	\
Hourly variable lapse rate							
Hourly variable	1, 2	1.13	1.55	0.831	2.11	2.89	0.529
Hourly variable	1, 3	\	\	\	0.81	1.74	0.830
Hourly variable	1, 4	-0.70	1.51	0.840	\	\	\
Hourly variable	2, 3	\	\	\	0.27	1.64	**0.849**
Hourly variable	2, 4	-0.17	1.01	**0.929**	\	\	\
Hourly variable	1, 2, 3	\	\	\	0.85	1.76	0.826
Hourly variable	1, 2, 4	-0.74	1.55	0.831	\	\	\

[a]Weather stations: 1 = Cog_1202, 2 = Car_2607, 3 = Car_3051, 4 = Bel_3328. N&S index is the efficiency criterion according to Nash and Sutcliffe (1970). Bold type indicates the best results for each tested method.

Table 4. Mean values of cooling effect, wind speed and wind direction recorded at the on-glacier weather stations.

Weather station	Mean cooling effect (°C)	Mean wind speed (m/s)	Mean wind direction (°)
Summer 2010			
Mar-gl_2709	-0.65	2.00	247
Mar-gl_2973	-0.74	3.13	230
Mar-gl_3215	-0.27	3.47	258
Summer 2011			
Mar-gl_2973	-0.90	2.82	224
Mar-gl_3140	-0.47	3.00	239
Mar-gl_3438	0.06	\	\
Car-gl_3082	-1.01	2.40	249
Car-gl_3144	-0.18	1.98	90

Table 5. Mean seasonal on-glacier temperature calculated by five different methods, compared to measurements[a]

Weather station	Measured (°C)	Khodakov (1975) (°C)	Davidovic and Ananicheva (1996) (°C)	Braithwaite et al. (2002) (°C)	Shea and Moore (2010) (°C)	Greuell and Böhm (1998) (°C)
Summer 2010						
Mar-gl_2709	5.91	5.49 (-0.42)	6.21 (+0.30)	4.87 (-1.04)	4.30 (-1.61)	5.69 (-0.22)
Mar-gl_2973	3.79	3.46 (-0.33)	3.53 (-0.26)	3.15 (-0.64)	3.36 (-0.43)	3.85 (+0.06)
Mar-gl_3215	2.25	1.44 (-0.80)	0.94 (-1.31)	1.44 (-0.81)	2.36 (+0.11)	1.97 (-0.27)
Summer 2011						
Mar-gl_2973	4.29	4.12 (-0.17)	4.14 (-0.15)	3.71 (-0.58)	3.95 (-0.34)	4.36 (+0.06)
Mar-gl_3140	3.30	2.70 (-0.60)	2.28 (-1.02)	2.50 (-0.80)	3.45 (+0.16)	2.83 (-0.46)
Mar-gl_3438	1.14	0.01 (-1.13)	-0.14 (-1.28)	0.22 (-0.92)	2.07 (+0.93)	0.55 (-0.59)
Car-gl_3082	3.28	3.44 (+0.16)	2.45 (-0.83)	2.94 (-0.33)	3.94 (+0.66)	3.33 (+0.06)
Car-gl_3144	3.55	2.96 (-0.59)	2.14 (-1.41)	2.47 (-1.08)	3.58 (+0.03)	2.80 (-0.75)
Summer 2010 and 2011						
Mean error (°C)		-0.49	-0.75	-0.78	-0.06	-0.27
RMSE (°C)		0.61	0.95	0.81	0.73	0.40
N&S index		0.782	0.470	0.617	0.692	0.908

[a]Values in brackets are mean seasonal errors at each weather station.

Comment [LC2]: Removed table. Efficiency statistics for all sites reported in the text, Section 4.4

Table 65. Calibration parameters and mass balance statistics from EISModel applications with four different datasets of air temperature[a]

Temperature dataset	Calibrated parameters: TMF ($mm\ h^{-1}\ °C^{-1}$)	Calibrated parameters: RMF ($mm\ h^{-1} W^{-1}\ m^{2}$)	Calibration run (summer 2010): ME (m w.e.)	Calibration run (summer 2010): RMSE (m w.e.)	Calibration run (summer 2010): N&S	Validation run (summer 2011): ME (m w.e.)	Validation run (summer 2011): RMSE (m w.e.)	Validation run (summer 2011): N&S
Measured temperature	0.246	0.00117	-0.027	0.080	0.992	+0.052	0.156	0.888
Standard lapse rate	0.202	0.00100	-0.049	0.252	0.918	-0.160	0.261	0.686
G&B method	0.251	0.00109	-0.006	0.113	0.984	+0.156	0.314	0.545
S&M method	0.291	0.00128	-0.049	0.359	0.832	-0.282	0.366	0.381

	Calibrated parameters: TMF ($mm\ h^{-1}\ °C^{-1}$)	Calibrated parameters: RMF ($mm\ h^{-1} W^{-1}\ m^{2}$)	Calibration run (summer 2011): ME (m w.e.)	Calibration run (summer 2011): RMSE (m w.e.)	Calibration run (summer 2011): N&S	Validation run (summer 2010): ME (m w.e.)	Validation run (summer 2010): RMSE (m w.e.)	Validation run (summer 2010): N&S
Measured temperature	0.246	0.00138	+0.006	0.152	0.893	-0.095	0.119	0.982
Standard lapse rate	0.175	0.00111	-0.008	0.210	0.796	+0.178	0.346	0.844
G&B method	0.265	0.00141	+0.045	0.288	0.618	-0.172	0.226	0.934
S&M method	0.236	0.00129	-0.018	0.241	0.732	+0.315	0.522	0.647

[a]Calibration in 2010 and validation in 2011 in the upper table, vice versa in the lower table. Measured vs. modeled values are displayed in Fig. 910.

Figures

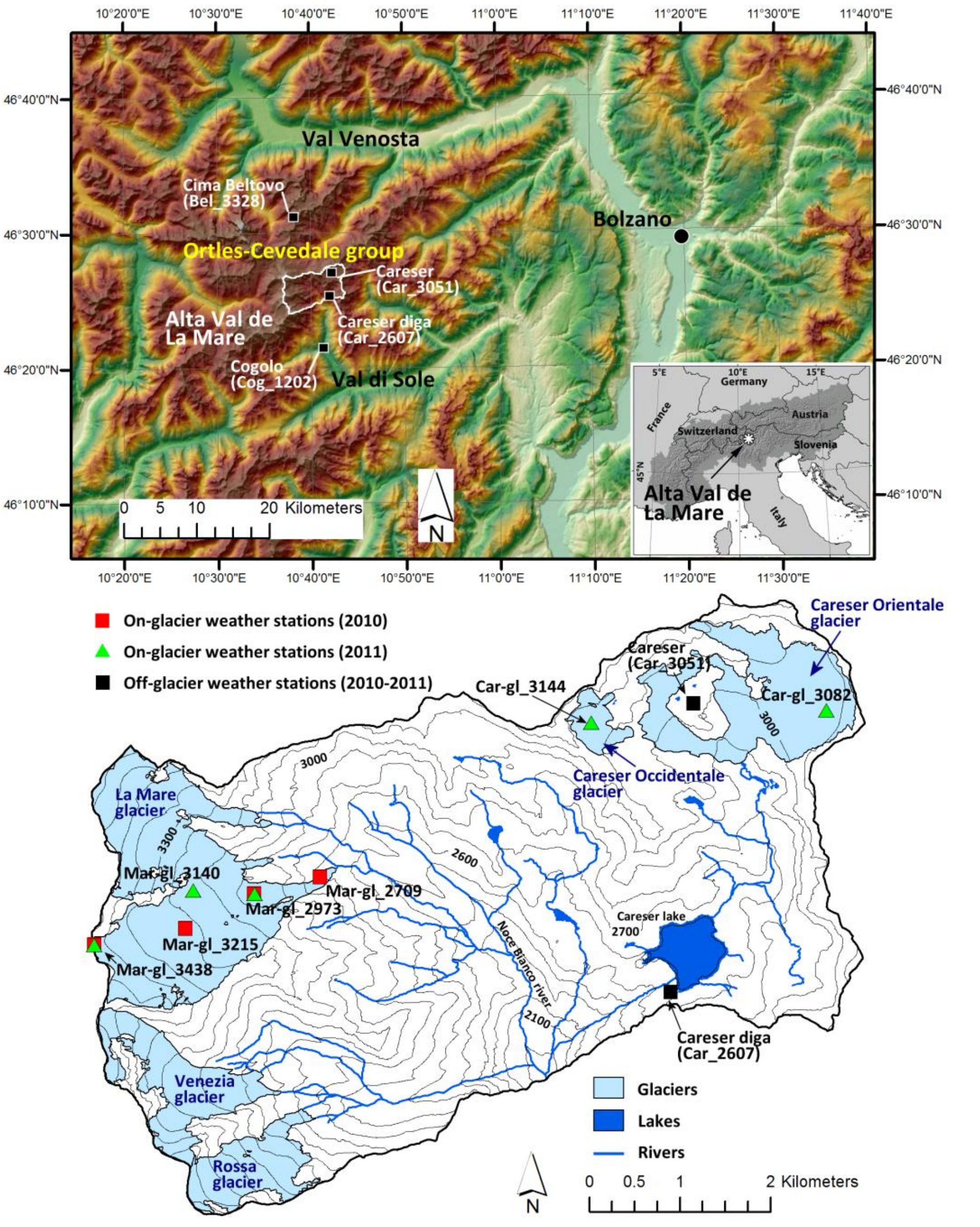

Figure 1 - Geographic setting of Alta Val de La Mare and location of the automatic weather stations.

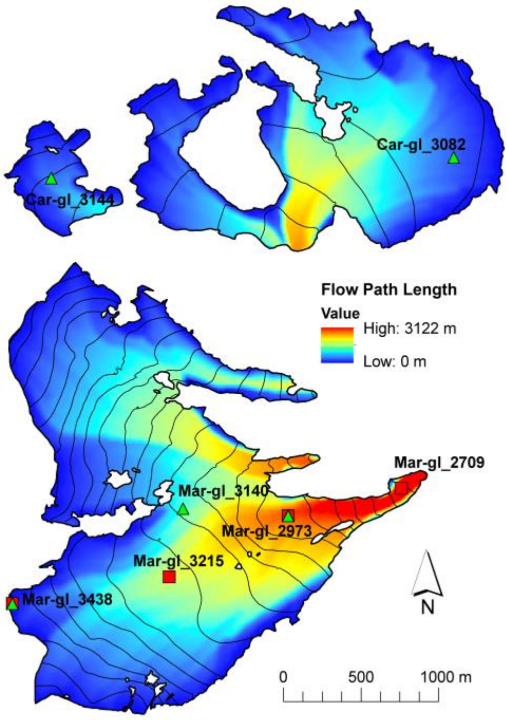

Figure 2 – Map of the flow path length calculated for Careser and La Mare glaciers.

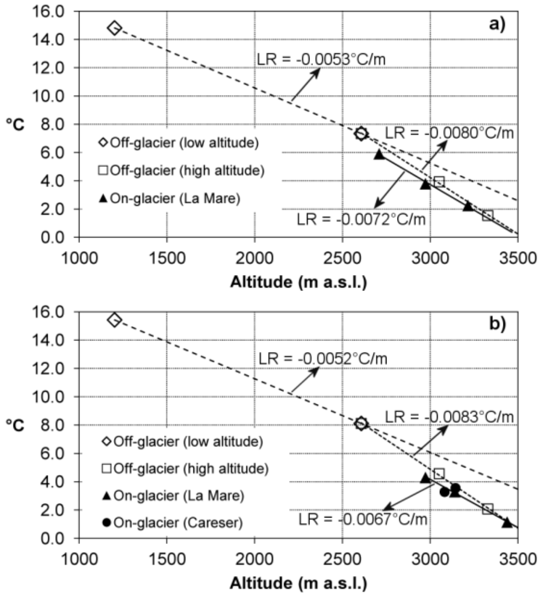

Figure ~~2~~ 3 - Mean temperature vs. altitude: a) from 3 July to 23 September, 2010, and b) from 7 July to 12 September, 2011. Lines indicate linear regressions of temperature vs. altitude for subsets of weather stations. LR = vertical lapse rates.

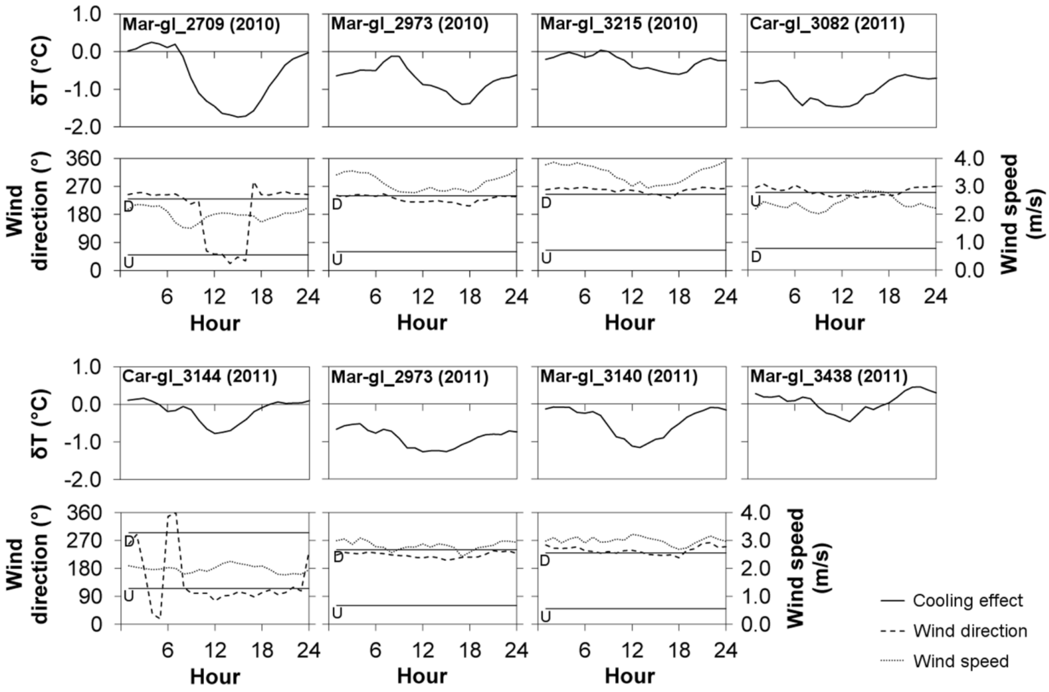

Figure ~~3~~ 4 - Mean daily cycle of the glacier cooling effect (δT), wind direction and wind speed at the eight on-glacier weather stations. The operation period of each station is indicated in brackets. Down-glacier and up-glacier wind directions are indicated with straight lines marked with 'D' and 'U'. Mar-gl_3438 lacks wind data because of anemometer failure.

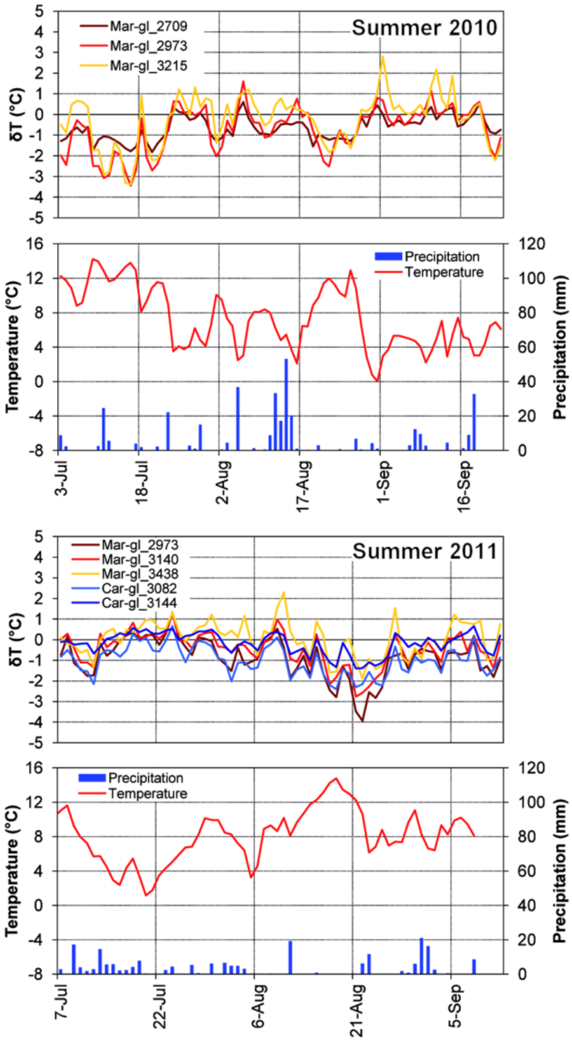

Figure ~~4~~ 5 - Mean daily cooling effect at the on-glacier weather stations, and corresponding daily precipitation and mean temperature at Careser diga (Car_2607).

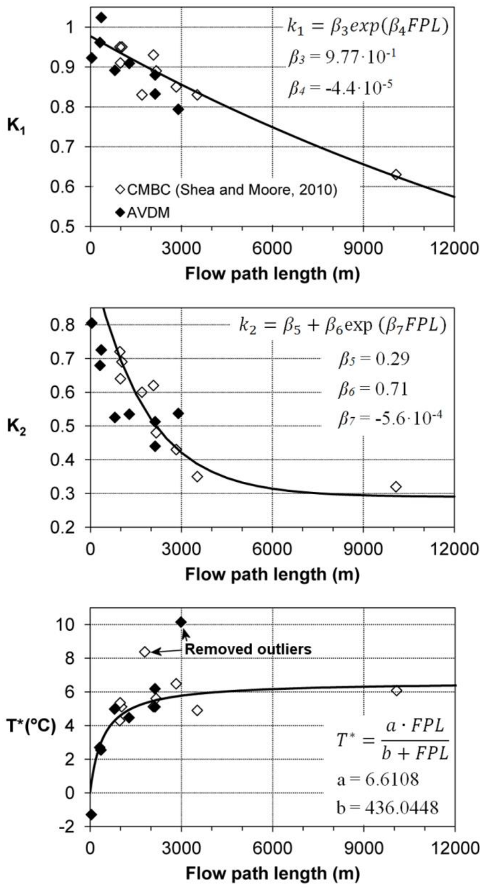

Figure ~~5~~ 6 - Transfer functions for the coefficients K_1, K_2 and T^* of the Shea and Moore (2010) method. CMBC = S&M study area; AVDM = our study area. Outliers due to under-sampling at freezing temperatures have been removed (as in the S&M work). β_3 to β_7 are coefficients from S&M (J. M. Shea, personal communication), while the transfer function and coefficients for T^* are new results from the present work.

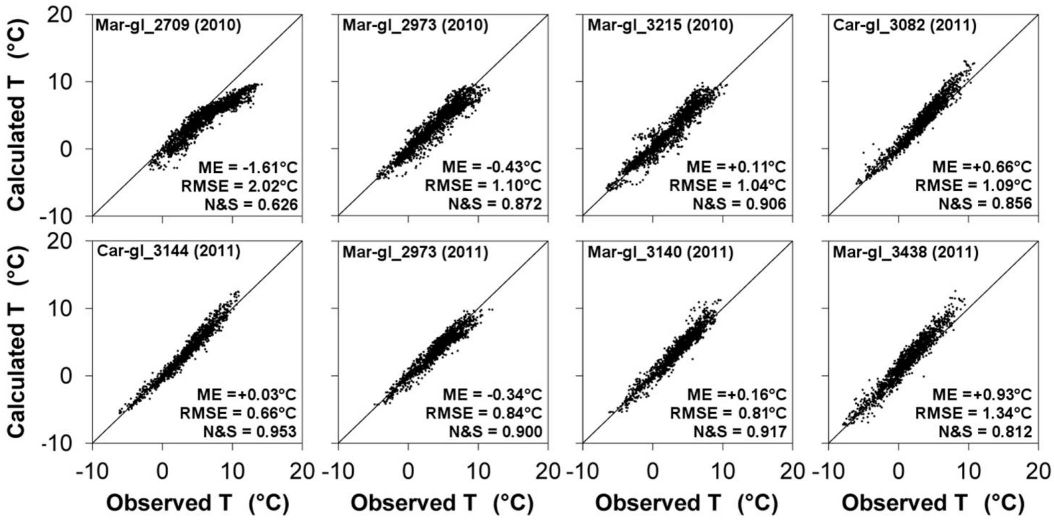

Figure ~~6~~ 7 - On-glacier temperature calculated with the Shea and Moore (2010) method vs. observed temperature.

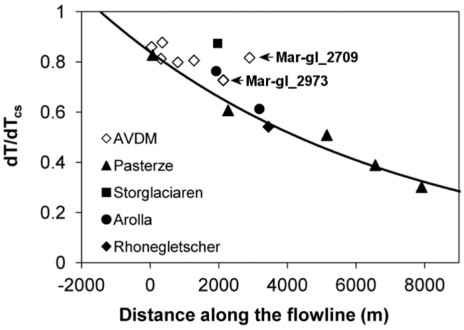

Figure ~~7~~ 8 - Sensitivity of on-glacier temperature to temperature outside the thermal influence of glaciers and best fit of Eq. (~~17~~13) to Pasterze data. Redrawn figure from Greuell and Böhm (1998). Values measured on Careser and La Mare glaciers (AVDM) have been added for comparison. Mar-gl_2973: two overlapping points (summer 2010 and ~~2010~~ 2011 have identical sensitivity).

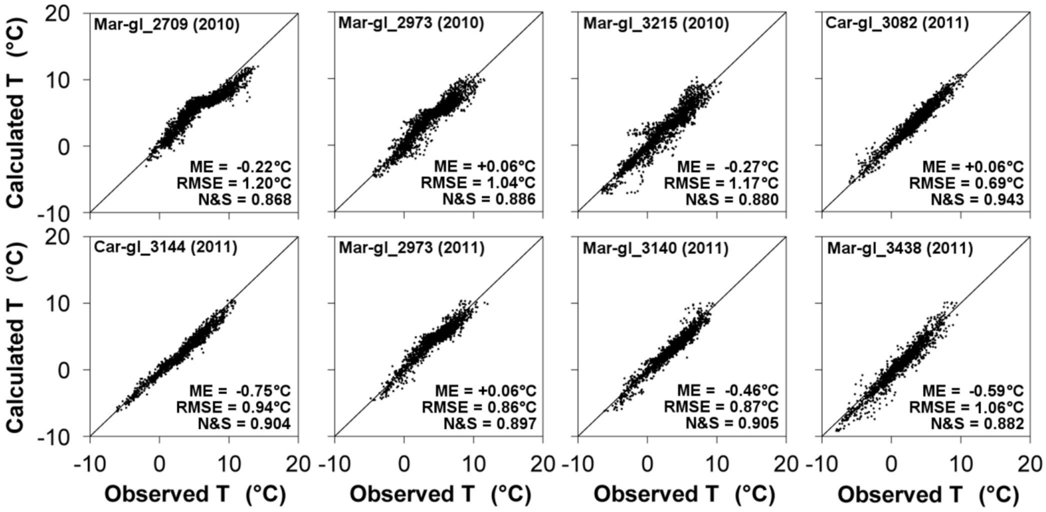

Figure ~~8~~ 9 - On-glacier temperature calculated with the G&B method vs. observed temperature.

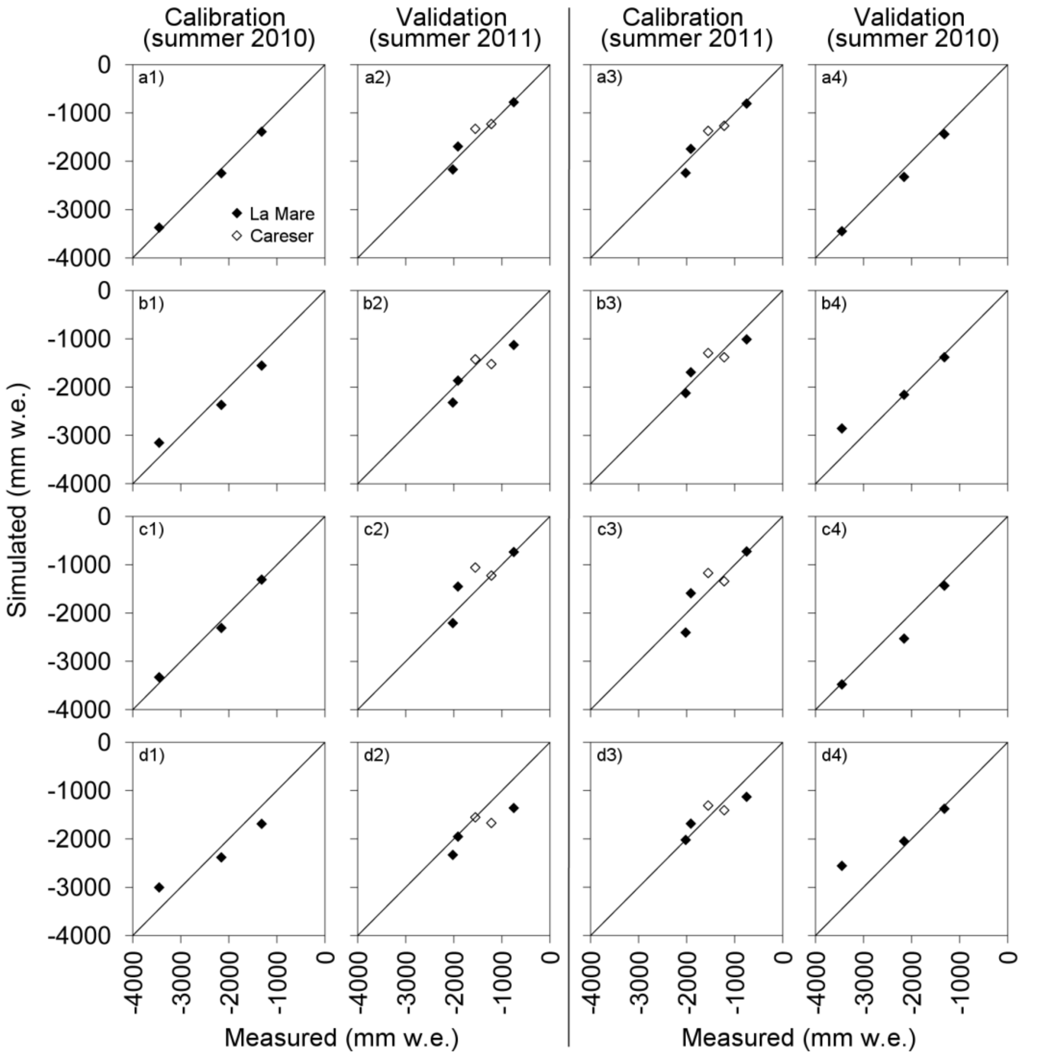

Figure ~~9~~ 10 - Measured vs. modeled mass balance at the eight glacial weather stations, using EISModel with four different air temperature inputs: a1 to a4 = measured; b1 to b4 = extrapolated from Car_2607 via the standard lapse rate (-6.5°C km^{-1}); c1 to c4 = calculated via the G&B method; d1 to d4 = calculated via the S&M method. Corresponding statistics are reported in Table 6.