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The Cryosphere Discussions

Interactive comment on "The mass and energy balance of ice within the Eisriesenwelt cave, Austria" *by* F. Obleitner and Ch. Spötl

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Interactive comment on "The mass and energy balance of ice within the Eisriesenwelt cave, Austria" by F. Obleitner and Ch. Spötl Anonymous Referee #1 Many thanks for your thorough review to which we are responding to as follows:

General Comment: Through the whole paper I kept asking myself "Why is this important?" The authors failed to address why I should care about ice found in caves. What percent of terrestrial ice is found in caves? What effect would it have it disappeared? Response: The introduction is rewritten to better address these issues. In particular please note the passage: "Most of them host a few hundreds to thousands m3 of ice, but few of them contain substantial ice bodies in excess of 100,000 m3 (Silvestru, 1999). In a global perspective (climate change, sea level change) cave ice cannot

have the relevance of other cryospheric components like glaciers or ice sheets. However, cave ice serves as a local resource (water, tourism), it preserves environmental information and its degradation may destabilize underground galleries and chambers."

Comment: I also would like to see them expand more on the seemingly major changes they made to the model SNTHERM rather than a passing sentence. Too many times I felt that the authors made statements without supporting evidence. The basic ideas may be sound, but the presentation needs help. Response: SNTHERM is publically available and well documented (http://snow.usace.army.mil/model_info/sntherm.html), which is one of the reasons why we used it. We therefore kept the description of the model short. In response to this comment, we have extended the model section, though.

Specif Abstract: Comment 1. Line 1. What are "glaciological" measurements? Define. Response: We refer to measurements of ice-thickness changes (stake readings and sonic records) and vertical profiles of ice temperature and density as described later. We skipped the inappropriate expression.

Comment 2. Lines 2-3. Meteorological conditions can not feature anything. Response: The text has been changed correspondingly (..show the basic features..)

Comment 3. Line 5. The energy balance is determined not predetermined by the long-wave radiation. Response: The text has been changed as suggested

Comment 4. Line 15. Do you mean the summer air temperature or cave wall temperature or both? Response: The sensitivity studies are based on changing air temperature within the cave and the text has been changed accordingly (. . .cave air temperature. . .).

Introduction: Comment 1. Line 1. Defe IPCC. Comment 2. Line 1. Elaborate on terrestrial ice being a "climate indicator". Comment 3. Paragraph 3. "show cave" is not the proper term. "tourist attraction" is better. Response: We think that "show cave" would be appropriate. However, the introduction has been rewritten and does no more contain these terms at all.

The investigated site: 1. Line 6. Define GPR. Response: The abbreviation has been omitted in the new formulation reading now "Ground penetrating radar and several drillings to the bedrock revealed. . ."

2. Paragraph 2, Line 3. "visitors to the" instead of "visitors of the". Response: changed as suggested

Measurements: Comment 1. What is your measurement frequency? Response: The sensors were scanned in 10 minute intervals and these instant values were stored. We think that this is properly expressed in the text.

Comment 2. Line 2. What surface? – The ice, the cave floor? Response: At EP the cave floor is totally covered with ice (supplement Fig.1), thus the ice surface is concerned. The text is changed accordingly. " ..above the ice surface".

Comment 3. Paragraph 3, Line 2. What do you mean by "according logistic" efforts? Response: We meant that instruments must be prepared to be carried through rough terrain to cave entrances or through narrow passages, set up in the dark, no solar charging possible etc. But this is probably not that interesting and the sentence has been changed to: "Measurements in cave environments are challenging for e.g. limited accessibility of suitable sites and related problems to keep the instruments operative for longer periods."

Comment 4. Paragraph 3, Line 6. What are "standard research" components? Response: we meant: "research-grade instrument components." However, the misleading expression is no more used in this context.

Comment 5. Paragraph 3, Line7. What do you mean by "essential effort"? Response: The sentence in question is re-phrased to: "We therefore put essential effort into sensor calibration (laboratory calibration before and after field work, field intercomparison at the same level)."

The model: Comment 1. Paragraph 1, Line 8. The liquid water content in the rock does not change in sntherm from the initial conditions. Response: Right. A rock substrate is characterized by negligible void space. This is ensured by setting the "soil" properties accordingly which is one of the modifications to the model which was poorly explained. The relevant text passage now reads: "The rock substrate is represented as a soil species with appropriate physical and thermal characteristics (density and thermal conductivity corresponding to that of limestone, air and water transport prohibited)."

Comment 2. Paragraph 1, Line 11-12. Horizontal effects are not generally neglected, they are not considered in sntherm since it is a 1-D model. Response: The sentence was skipped.

Comment 3. Paragraph 2, Line 12. The precipitation is directly related to the energy balance equation through the PHF term in equation 1. Response: This is exactly what we wrote.

Comment 4. Paragraph 2, Line 16. A figure showing the node placements in the ice and rock would be nice. Also, why did you use so many? Did you try running the model with fewer nodes? Response: Due to the already large number of figures, it appears inappropriate to include an extra figure. Moreover, a suitable presentation would be difficult because of the wide range of grid distances ranging from 1 mm to 1 m. However, please note Fig.2 (supplement)demonstrating the location of the nodal mid points as well as the initial density and temperature profiles, the latter being addressed in the next comment (nodal mid points indicated by crosses). We used a fine mesh to reproduce the overall small changes in ice thickness (ca. 3 cm) with about the resolution of the sonic measurements. Moreover, the simulation results certainly benefit from higher resolution at the material boundaries (rock-ice and ice-air interface) thereby better resolving the gradients and conductive fluxes. Thus the ice domain is represented by 133 nodes with a resolution of 1 mm within the top 5 cm. The grid spacing gradually increases from 2 to 5 mm down to 10 cm below the surface; 1 cm is used down to 20 cm below the ice surface, followed by 5 to 10 cm for the main ice body. Approaching the rock boundary resolution was gradually increased towards 5 mm again. The rock domain contains 14 grid points with a resolution increasing towards 1 m at the deepest control volumes. Notably, the number of grid points (control volumes) changes during the course of the simulations in response to accumulation and ablation (nodes are updated in 1 mm steps). We ran the model with fewer nodes for preliminary runs and in order to check for numerical stability or other dependence of the results on grid resolution. In fact, numerical stability is implicitly ensured by the numerical scheme employing an adaptive adjustment of time steps to achieve a specified accuracy of the solution (Jordan 1991). The latter was specified as 0.01 K and 0.5 kgkg-1 for temperature and water content, respectively. To underline the above reasoning we performed a study employing different grid resolution (everything else remained unchanged). There were only small effects as documented (Tab.e 1, supplement).

Comment 5. Paragraph 3. Did you measure the rock temperature and water content? If not, how did you decide on an initial profile? Did you try other ice temperature profles besides a uniform one? Response: The initial ice temperature profile is based on a spline-interpolation matching the measured values (surface, -0.5m and -3m below the surface) on 01Dec2007, the starting point of the simulations. Rock temperature measurements at the base of the ice were not feasible. In March 2008, however, we installed 4 temperature sensors in a bore hole drilled horizontally ca. 50cm above at the level of the ice surface (Spötl et al. 2008). We considered data from the following winter (01Dec2008) to judge the thermal conditions in the rock at the start of the simulations. At that time of the year the rock temperature increases with distance from the cave wall and slightly positive temperatures were observed at a depth of 1.25m (+0.03°C on 01Dec2008). Note however, that at the measurements site the rock surface is not in contact with the ice. Therefore, these data may not be fully representative for a position underneath the ice because of an associated cooling effect and also because we do not exactly know the conditions at the interface itself (is the ice in direct contact with the rock or is there e.g. a gravel layer or air pockets?). In view of these uncertainties we

assumed that the rock temperature increases with depth thus enforcing a geothermal heat flux corresponding to 0.05Km-1. In the lowest nodes a constant temperature was prescribed in order to exclude fluxes at the bottom of the domain (see figure above). Thus we did not specify a “uniform” temperature profile. Initialization with a constant rock temperature (272.8K, everything else conforming to the reference run) has negligible effects on the calculated energy and mass balance of the ice (see supplement, Table 2) Nodal water content was neither measured nor input to the simulations.

Comment 6. Paragraph 5. How different is the Yen heat conduction parameterization compared to what sntherm uses? Also, SNTHERM already bases the turbulent heat ?ux parameterization on Monin-Obukhov. Further, changing the way metamorphism and water transport processes are modelled is a signi?cant model change and warrants further discussion. Response: For snow and (thus for ice, too) SNTHERM employs an effective thermal conductivity treating the combined effect of conduction and vapour diffusion. The parameterisation considers the thermal conductivity of air and ice as well as density (Jordan 1991). The coefficients are adjusted to match the conductivity of ice (2.29 Wm-1K-1 at 917kgm-3; Yen 1962) as the nodal density approaches that of ice. Calculation of the turbulent fluxes is based on M-O framework. Mentioning this under the heading “modifications” was misleading. In fact, a bulk transfer approach is employed (following Andreas and Murphy, 1989), neutral exchange coefficients are calculated from a prescribed roughness parameter (0.001 m) and stability functions conform to Högstrom (1988). Specific adaptations to the cave environment include: windless exchange coefficients not used in this simulation, stability correction for stable conditions has a lower limit at Ri>0.16 and scalar roughness lengths are calculated following Andreas (1987; Boundary-Layer Meteorology 38, 159-184). Notably, all these settings were applied by modifying the parameter list. The only change to the code itself concerned prohibition of metamorphism (densification) and some adaption of the i/o procedures. We reformulated the model section to introduce the above mentioned details.

Local meteorological and glaciological conditions: Comment 1. Paragraph 1. Why are the outside winds important? What is the orientation of the cave compared to the dominant wind direction? How do the outside winds compare to those inside the cave? Response: Cave air circulation essentially responds to temperature (density) and pressure differences in and outside the cave. Outside winds reflect large scale (synoptic) or regional wind systems (slope and valley winds) and induce different meteorological conditions at the cave entrances thus directly modifying the driving density and pressure gradients. Further, strong winds induce dynamic pressure gradients across a mountain ridge, which may be of particular importance for dynamic cave systems with their multiple entrances at different elevations or at different sides of a mountain range. As regards ERW, this issue has been addressed by Hauser and Oedl (1923), Thaler (2008) and Schöner et al. (2010). Thaler (2008) showed that that strong northerly synoptic winds and associated pressure gradients across the mountain ridge are weakly correlated with colder air masses at the cave entrance, which in turn induce associated pressure gradients favouring advection of air from outside into the cave interior. The orientation of the ice bearing section of ERW is SSW-NNE. We added an arrow indicating to support orientation in Fig. 1.

Comment 2. Paragraph 3. Line 9.Awkward wording “found also elsewhere”. Please change. Why mention “Trapping. . .”unless you further expand on this idea? Response: The text in question is reformulated to: “This meteorological regime is rather typical for a dynamically ventilated cave system. Overall, the temperature, humidity and wind measurements reveal a distinct winter and summer regime terminating in May and November, respectively. This is corroborated by the seasonal pattern of the air flow (Fig. 4). Cold air is advected into the cave during winter and cools the host rock to about -1.5°C. Summer is characterized by a weak outflow of colder air from within the cave. Mean annual air temperature is slightly negative, thus just matching a basic condition for the existence of perennial ice. The subzero temperature regime is mainly supported by advection of cold air during periods of inflow during winter (Fig. 4) and associated sublimation of ice.“

Comment 3. Paragraph 5. Line 1. Again, what do you mean by “glaciological measurements”? Is it a standard set of measurements unique to glaciers? Please elaborate. Response: The text was changed to: “About 3.5 cm of ice were lost during the reference period (Table 1) and about 90% of this value was achieved during the melt period lasting from June until November.”

Model verification: Comment 1. Paragraph 1. Line 2. I am not quite sure what you are trying to say in the sentence “Proper veri?cation.. Response: We just wanted to point out the importance of verification. This may not be necessary and the questioned sentence is skipped.

Comment 2. Paragraph 1. Line 4. Sntherm doesn’t assume constant density. Did you change this part of the code too? Response: Densification due to settling or metamorphosis was prohibited, as pointed out in the model section. However, small changes occur in the upper layers due to varying liquid water content (Fig.8). The text is changed to: “Figure 6 demonstrates that the simulation captures the seasonal evolution of ice thickness, which is considered as a measure of mass balance.”

Comment: 3. Paragraph 1. Line 10-11. You can just say “stake” instead of “stake environment”. Response: changed as suggested

Comment: 4. Paragraph 1. Line 11-end. How do you know that the model is underestimating sublimation, etc.? Why are these inherent shortcomings? Response: Fig. 6 (upper left panel) shows that during winter the simulated decrease in ice thickness is smaller than observed. At this time only sublimation can reduce ice thickness, and the effect is admittedly small. The questioned sentence is changed to: “As shortcomings of the simulations we note that sublimation is underestimated, ablation starts too late, while the subsequent melt rate is overestimated.”

Comment: What time step did you run the model at? Response: The model is forced with hourly input data. As now noted in the model description, SNTHERM employs an adaptive time step adjusting to the desired accuracy of the solution. Typical time steps range from a few seconds (with strong liquid water transports) to 10 minutes (cold conditions).

Comment: What do you mean by “There was no straightforward”? If you feel that the grid resolution was to blame for the model not better ?tting the measured data, did you try different node placements? It seems that you are putting all blame for the model not better matching on the model and no blame on the inaccuracies in the measurements. From ?gure 6 I would argue that the model does a good job replicating the data. Reponse: We agree that the noted deficiencies are not only due to shortcomings in the simulations. The most serious deviation concerns the overestimated melt rate which we can not explain so far. A corresponding problem with the verification data is unlikely. Firstly, the two independent records agree regarding the melt rate. Secondly, a systematic underestimation could only be explained by sinking of the stakes or the support of the sonic device. Both can be excluded because they were based at the rock underneath the ice. This points towards a problem of the model itself or its input data. Our studies indicate that the symptomatic calculation of excess energy during summer is most likely not related to turbulent fluxes or to meteorological input. At least changes of the roughness parameter within a reasonable range and using input data from the upper measurement level (4m) do not have a corresponding effect. This leaves the long-wave radiation measurements as a likely source of uncertainty, which cannot be quantified further. Limited grid resolution is not a factor, as is indicated by the studies documented above. The text has been changed to: “As shortcomings of the simulations we note that sublimation is underestimated, ablation starts too late, while the subsequent melt rate is overestimated. We could not yet identify the reason for these deficiencies. Fortunately, the individual effects cancel each other out on a seasonal time scale.”

Comment: 5. Paragraph 2. Line 8. Change “used thermometers” to “thermisters used” Response: The sentence is changed to “Note that the nominal accuracy of the sensors is.."

Energy and mass balance: Comment 1. Paragraph 1. Line 6. By “rock dome” do you mean the cave roof? Walls? Explain. Response: The sentence is changed to “This is related to the higher temperature of the cave roof compared to the ice surface.”

Comment 2. Paragraph 3. Line 3. The December net radiation is nearly as low as that in March. How does this affect your analysis? Response: We cannot offer a convincing explanation of this feature. However, it is likely related to a simulation deficit. We argue this by investigation of the measured monthly temperature differences between the ice surface and the cave roof. There is indication that in Jan/Feb the ice cooled stronger than the cave roof. But the accuracy of these data may be insufficient in view of the small signal. On the other hand the verification studies show that the model tends to overestimate the ice surface temperature. Qualitatively, this introduces a negative bias in the calculated net radiation but it is not obvious why that should be more pronounced during December. In view of this uncertainty and its small effect we sought for a neutral formulation: “Net radiation reaches a minimum in March when successive cold events penetrate far into the cave and cool the rock surfaces to about - 1.5 °C.

Comment 3. Paragraph 3. Line 4. Should be “events penetrate” instead of “events penetrates”. Response: see above

Comment 4. Paragraph 4. The ?rst sentence needs to be rewritten. As is I can’t tell what you are trying to say. Response: The sentence was meant as an introduction, but is not necessary and therefore omitted.

Comment 5. Paragraph 4, Line 3. What do you mean by “atmospheric at the surface”? Response: thanks for the hint on a missing word: “atmospheric forcings at the surface”

Comment 6. Paragraph 4, line 7. Change “runs off finally” to finally runs off”. Response: done

Comment 7. Paragraph 5. What is a “constellation” of the energy balance? It is not hard for turbulent fluxes to be larger anywhere else in the cave as the modeled ?uxes at the site are negligible, especially in summer. A lot of unsupported assertions are made in this paragraph. Further explanations are needed. Response: The new formulation is: "Putting these results in a broader context, we may compare them with the accompanying investigations by Schöner et al. (2010) in the outer parts of ERW (Odinsaal and Posselthalle). They neither measured radiation nor calculated the turbulent fluxes. However, their temperature and humidity data qualitatively confirm the prevalence of sublimation during winter and condensation during summer. The comparatively strong gradients (±2°C and ±1hPa) suggest that the magnitude of the turbulent fluxes must be larger in the outer cave sections. Further, there is evidence of a larger variability of the annual mass balance of ice in the outer parts of ERW (± 15 cm) compared to EP. This is related to a correspondingly different meteorological regime (air temperature varying between +2 and -12°C) and topographic effects (sloping surfaces, different water sources)..

Comment 8. Paragraph 7. Did Ohata et al. use the sntherm to calculate the energy balance? Are your ?ux comparisons monthly/yearly. . .? Response: Ohata et al. did not use SNTHERM. They calculated an energy balance for the whole cave system and for the period December 1985 to November 1986. The results must be compared with care because of a quite different approach employing many assumptions and referring to the whole cave system and not only to local conditions above the ice (as we did). Thus they calculated "advective sensible and latent heat" from monthly temperature and humidity measured in and outside the cave which may be compared with our SHF and LHF. Heat exchanges due to melt and freeze were derived from observed ice changes and a residue comprises changes in heat storage, heat conducted from the surrounding ground layer and sensible heat transported by water penetrating to the cave. Net radiation is not explicitly mentioned but we assume that net radiation is the major contribution to the residue (ground heat flux almost cancelling throughout the year, leaving unspecified but minor contribution from refreezing seepage water). We recalculated the numbers from their Table 3 to Wm-2 and the questioned paragraph is reformulated to: "Ohata et al. (1994 a,b) investigated the energy balance of perennial

ice in a collapsed lava tube on Mt. Fuji (Japan). They considered monthly data during the period December 1985 to November 1986 and focused on the energy balance of the whole cave system. The turbulent fluxes were calculated from temperature and humidity in and outside the cave, net radiation, ground heat flux and refreezing seepage water are contained in a residue. Conversion of the documented data to Wm-2 yields NR+GHF+PHF=2.0, SHF=-1.6, LHF=-0.8 Wm-2. The authors also note a prevalence of sublimation during winter, a decrease of ice thickness (5 cmyr-1 during 1989 until 1992) and a considerable variability in different parts of the cave."

Comment Line 7. "We also note" should be "They also note". Response: see above

Comment 9. Paragraph 8. Line 4. Sentence starting with "Referring" needs to be reworked. Response: see response to the next comment

Comment 10. Paragraph 8, Line 8. Why can the turbulent ?uxes be compared (not transferred) more straightforwardly than the radiative and conductive ?uxes? Who assumed higher wind speeds? Higher that at EP? Response: To our understanding their calculated turbulent fluxes correspond to energy exchanges due to forced convection and referring to the whole cave surface area (rock and ice). The sentences in question are changed as follows: "The authors followed a similar approach as Ohata et al. (1994a), thus considering the energy balance of the whole cave system and data for a year with a negative mass balance (-10 cm during 2002/2003). Converting the given data to Wm-2 yields NR+GHF =1.0, SHF=-0.3, LHF=-0.2Wm-2. We are not aware of documented energy balance data from another ice cave. However, it is remarkable that at least for these three ice caves (Fuji, Monlesi and ERW) the order of magnitude and the sign of the calculated fluxes are remarkably consistent."

Effects due to uncertainties of the input data: Comment 1. Paragraph 1, Line 5. "additionally lost" instead of "lost additionally" Response: changed as suggested

Comment 2. Paragraph 1, Line 5. "as a cooling save 4mm of ice" is confusing. Reword. Response: "Consideration of a -0.1°C deviation saves 4 mm of ice compared to the reference run (Table 2c)."

Potential climate impacts: Comment 1. Paragraph 1,Line 6. "outstanding loss" is awkward. Better wording is "additional loss". Response: we prefer using "enhanced loss" because the 10cm are not in excess of the "normal" value.

Comment 2. Paragraph 3, Line 3. Change "has mainly effects during the melt" to "mainly effects the melt". Response: changed as suggested

Comment 3. Paragraph 3, Line 7-8. I'm not sure what you mean by "we firstly recall the relevant environmental conditions". Please explain. Response: "To realistically constrain such effects we recall that the regional weather conditions are characterized by a precipitation maximum in June and a snow melt run-off maximum in May/June (ZAMG, 2010)."

Comment 4. Paragraph 3, Line 9. What does ZAMG stand for? Response: ZAMG: Central Institute for Meteorology and Geodynamics, as written in the reference ZAMG (2010).

Temporal and spatial representativity: Comment 1. Representativity is not a word. Response: "representativness" is used now

Comment 2. Paragraph 1, Line 5-6. What do you mean by "closed snow pack"? Response: To characterize the snow conditions, ZAMG distinguishes between "closed" and "broken" snow cover.

Comment 3. Paragraph 2. I find it very hard to discern what the authors are trying to say here. Response: "Fig. 10 documents the evolution of mass balance for an extended period (June 2007 until September 2009). Note that this series covers the reference period (year 2008, dashed lines in Fig. 10), but is interrupted afterwards due to a logger failure. We nevertheless consider the remaining data because it reveals a considerable interannual variability of the mass balance components. As regards ablation, there is only a small difference within the two subsequent years (3.9 cm vs. 3.2

cm) while accumulation strikingly differs (negligible in spring 2008 vs. 7.3 cm in spring 2009). This finding is supported by independent data (stake and sonic ranger) and is explained by a different availability of refreezing seepage water during the two years. This reasoning is based on observations of an ice column in the neighbourhood of the measurement site (Fig. 1, background) where an associated water conduit provided unusual amounts of water during spring 2009. This water gradually spread over the rear parts of EP, thereby refreezing at the measurement site, too."

Summary: Comment 1. Paragraph 2, Line 5. Change "therof" to "therefore". Response: corrected

Comment 2. Paragraph 5, Line 9-end. I don't see from figure 8 that the multiple cold waves progressively cool below the rock-ice interface. It appears that temperatures below 0.5m are constant throughout the year. Response: We apologise that this can be hardly seen in figure 8 due to its limited graphical resolution. In fact the temperature at the ice-rock interface decreases by 0.1°C with a minimum in April/May, as shown in Fig.2.

References Comment: Listed but not cited in the paper are: De Feitas, C. and Littlejohn, R. Ford, D. and William, P. Klappacher, W. et al. Marshall, P. and Brown, M.C. Steiner, H. Trimmel, H. Response: the references are updated.

Figures/Tables: Comment Figure 3. What is the "dome" – The cave walls, ceiling, both? Response: This data is derived from lw-radiation measurements employing pyrgeometers. These instruments receive their signal from the upper hemisphere. In the cave, the latter corresponds to ceiling and walls which is denoted as "dome".

Comment: Is the temperature at -3m the rock/ice interface temperature? Response: yes.

Comment Figure 7. Is the conduction through the ice to the surface or from the rock to the bottom of the ice? Response: GHF denotes the latter

Comment Figure 8. The units for liquid water content is an odd choice, i.e. as a density instead of volume/volume or mass/mass. How does this relate to the porosity of the ice? What assumptions are you making?' Response: We adopted the units of model output that generally refer to nodal bulk properties. Thereby, bulk (or better partial) liquid water density (kgm-3) denotes the mass of liquid water per unit volume of the medium (snow, ice, soil). Contrary, intrinsic density is defined as the mass of liquid water per volume occupied by liquid water itself. These parameters are related to each other through the volume fraction (m3m-3) of liquid water. Porosity determines the maximum volume that can be occupied by water.

Comment Figure 9. Where do you show the reference run? Response: The results are plotted as deviations from the reference run, which is represented by the zero-line. We improved the legend to clarify this.

Comment Table 1. Put the units in column 1 instead of column 4. Are the radiations listed from the model or measured? Is the energy change within the ice due to temperature changes within the ice or due to changes between the two surface energies? Response: Radiation data must be considered as model results; more precisely, incoming radiation was measured (input to the model) and outgoing radiation was simulated (corresponding to surface temperature). Please note the correspondingly revised version of the table.

Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/4/C1455/2011/tcd-4-C1455-2011-supplement.pdf

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Interactive comment on The Cryosphere Discuss., 4, 1741, 2010.