

Answer to Referee 1

First we would like to thank the referee for his/her comments on our work. We carefully considered your comments. You will find a detailed answer to each of your comments below. We hope that the revisions improve the quality of the paper and meet your expectations.

- 5 Reerink and van de Wal describe an updated version of their OBLIMAP mapping tool. This tool is designed for mapping fields between coarse-resolution GCM grids and fine-resolution ice sheet grids. The authors described OBLIMAP v. 1 in a 2010 GMD paper; this new paper describes updates made in v. 2 of this tool. Major new features include (1) a "fast scan" method that significantly improves the performance of the initial mapping step; (2) handling masked fields in the mapping; and (3) the capability to embed this tool within a GCM.
- 10 Based on citations of the original paper, it appears that v. 1 of this tool has proven to be quite useful to their research group. Indeed, it does sound like a useful tool, and it seems that v. 2 makes the tool even more convenient and generally useful, such as through robust handling of masked fields. I read this paper with interest because I am currently struggling with issues surrounding conservative online regridding of fields passed between a GCM and ice sheet model. However, in the end I was not convinced that OBLIMAP v. 2 has sufficient novelty or improvements relative to alternatives to warrant its publication in
- 15 GMD.

It is hard for me to tell how much this is a real issue vs. simply a presentation issue. In particular, the authors do not spend much time comparing this tool to other alternatives, so it was hard for me to tell what practical improvements it provides over alternatives. They briefly compare it with the OASIS coupler (p. 17, L. 7-14), although not in enough detail to convince me of its advantages. For example, what are the practical advantages of the additional projection step in OBLIMAP (p. 17, L. 8-9)?

- 20 We first have to point to the fact that the projection step is an essential obligatory step in case two models run on differently curved surfaces. So the discussion is not about "*what the practical advantages are of the additional projection step*", because one has to (inverse) project the surface and thus the coordinates of the grid nodes if the surfaces differ in curvature, which is the case when a GCM which runs on the Earth Sphere surface is coupled with an ISM which runs on a flat surface. This is different when regridding two ESM components which both run on the same Earth Sphere surface. In that case a projection is
- 25 not needed as one stays on the same curved surface and only the interpolation step is required to regrid.

- This additional (inverse) projection step in GCM – ISM coupling has a few important consequences for the cross grid search (the method to select at a given destination grid point the contributing destination points which are used for the interpolation). Due to the projection, it is in general a priori unknown how the grid nodes of the two grids are related to each other, the projected nodes can end up anywhere depending on the projection. The search method or as we call it the 'scan method' has to
- 30 robustly cope with that. Other typical different requirements in GCM – ISM coupling compared to ESM component coupling are: (1) The ISM grid concerns a local part of the GCM which requires a neat treatment of this mapped ISM domain border. (2) If the local mapped ISM field is mapped on the GCM this result has usually to be merged into the existing GCM field. (3) The range of resolution ratios is much larger, i.e. often the ISM grid resolution is much finer than that of the GCM. These rather specific requirements are the cause that GCM – ISM coupling is not standard included in the existing ESM component
- 35 couplers.

- OBLIMAP addresses these specific GCM – ISM coupling issues. Whereas the other mentioned couplers are hubs from which several ESM components are coupled and which include the sphere to sphere regridding. So it is not that we can discuss "*its advantages*" over couplers like OASIS, the ESMF coupler, the CPL6 coupler, the CPL7 coupler, the MCT-based couplers or the C-Coupler, as they serve different targets. Nevertheless, there are many functional similarities between these couplers and
- 40 OBLIMAP. Moreover, beside the option to embed the OBLIMAP routines in the GCM or ISM, in fact another option is to call an ISM with OBLIMAP embedded from one of the ESM component couplers. OBLIMAP itself is not that much a hub from which more than two ESM components are coupled. However for the two components, the GCM and the ISM, we expect that the design compares/integrates well with these ESM component couplers.

- Having said that the projection step is an inevitable step for GCM – ISM coupling and that OBLIMAP is a specific GCM
- 45 – ISM coupler, we checked our introduction and the discussion (p. 17, L. 7-14) whether this is clear. We think that the first

issue is clearly addressed at (p. 1, L. 16-18) and (p 2. L. 1-3), but have more emphasized this point in the abstract and the start of the discussion. However, we think that we can be more specific about the different purposes which are served by OBLIMAP and the other couplers like OASIS. Also more couplers can be mentioned and compared. This will be improved by a rewrite/addition of the first paragraph of the introduction and of the discussion (p. 17, L. 7-14).

- 5 I would also like to see comparisons with other tools that serve a similar purpose, such as ESMF's regriding tools (<https://www.earthsystemcog.org/projects/regridweightgen/>, https://www.earthsystemcog.org/projects/esmf/regridding_esmf_6_3_0rp1), and tools that have been written on top of those in NCL and python.

We are only able to compare the ESMF_RegridWeightGen routine based on the specification provided on their website, we found no other publication than Valcke (2012) and Liu et al. (2014) which shortly summarize several couplers. We studied chapter 12 and 23.2 of the ESMF reference documentation (Version 6.3.0rp1), but both sections seem to be not always mutual consistent. For example Sect. 12.1 mentions that the source and destination grid must be on the sphere, but Sect. 23.2 seems to suggest that the routine also works in case both grids are on the flat plane. In either case this is different from OBLIMAP, in OBLIMAP one of the grids coincides with the surface of the sphere or the ellipsoid while the other one represents the flat surface (or both represent the flat surface). Secondly, as far we can judge from this description OBLIMAP has a much more flexible and extended masking facility, which is entirely independent of the scan phase (the preceding offline weight factor generation). Thirdly, OBLIMAP actually does not store the weight factors in the SID file like SCRIP does, but the indices of the contributions and their distances which offers the flexibility in a post scan phase to change the mask and the distance weighting exponent. Note that zero entries, which can be a large amount depending on the participation mask, are not stored in the SID file. The SID file and DDO have been designed such that the required processor memory is minimized. Based on this design a well scalable parallel bitwise-identical implementation is expected to allow further future performance improvements. OBLIMAP does not use the matrix multiplication. Due to a possible large resolution ratio the sparse matrix could have a rather large amount of non-zero diagonals. Instead OBLIMAP uses the direct access via the DDO (which has to be loaded only at initialization) to the indices and distance of the contributions, which allows a very fast evaluation.

The ESMF_RegridWeightGen uses the SCRIP (Jones 1999) grid and weight file formats, it seems very likely that the package is largely based on SCRIP probably with some modifications (and extensions for flat surfaces) but this is not mentioned. Because the OASIS, CPL6 and CPL7 couplers also use SCRIP for generating the interpolation weights for the regriding, the comparison of OBLIMAP with one of them applies to all.

Parts of this discussion are added to the discussion section. And the difference between SCRIP's regriding for spherical coordinates and OBLIMAP (dealing with different curved surfaces) is now addressed at the begin of the introduction.

30 The fast scan method was the most intellectually interesting component of this paper. I am not familiar enough with mapping tools and techniques to know if this is a novel contribution to the field, and/or if it might be generally applicable to other mapping tools. If it is, then this aspect could make the paper worth publishing. However, I was left with a feeling of uncertainty about the conditions under which the fast scan was guaranteed to give identical results to the full scan, the conditions under which it would "likely" give identical results, and the conditions under which it is not expected to give identical results. I got the impression that the authors themselves are not confident of the situations under which it is guaranteed to work correctly, based on vague statements like, "Even if the additional dynamic block size method is omitted, the *majority* of the fast scan mappings yield identical results with the full scan method. However, including it *appears to be very effective* in obtaining identical results for the exceptional cases." (p. 7, L 19-21; emphasis mine). If this is published, then I would like to see these conditions made more clear. For example, is it guaranteed to work for regionally-refined grids? And is the tool able to detect when the fast scan will or won't work, or is the burden on the user to determine this? Also, in order for this technique to be more reproducible, I would like to see more precise descriptions in place of some of the vague statements such as, "an ample rounded b is taken" (p. 7, L. 1-2).

The referee asks to clarify the conditions under which the fast scan is guaranteed/applicable. We have rewritten the second part of the fast scan section (p. 6, L. 25 upto p. 7, L. 32) to make this conditions easier to understand and improved the description of the method. We replaced our former general restriction by stating that the fast scan method is applicable to structured grids (synonyms for structured grid are curvilinear grid or logically rectangular grid). A short subsection is inserted in Sect. 3.1 to define the terms structured and unstructured grids. Other parts in the text are adjusted as well to this terminology.

Regionally-refined grids do not satisfy the structured grid conditions, this is addressed in the revised text. The default fast scan method is robust for all structured grids. The OBLIMAP-package includes a verification script to verify situations in which a less robust but faster scan method is tested or if the method is tested for certain unstructured grids. The supplement (the OBLIMAP User Guide) describes this verification. The discussion shortly addresses a possible solution to make the fast mapping applicable for unstructured grids.

I was especially interested in the new capabilities of this tool for online coupling between a GCM and an ice sheet model. However, again, I was not convinced of the suitability of OBLIMAP for this purpose. As a GCM developer, I would need to be convinced that OBLIMAP provides enough benefits over the GCM's existing coupling technologies (e.g., Valcke et al. 2012) that it's worth using this additional package for regridding to/from the ice sheet grid. The authors did not convince me that this is the case. Again, it's hard to tell how much of this is merely a presentation issue: I would reconsider this paper for publication if the authors provided more detailed discussions of OBLIMAP's advantages.

As pointed out in our first comment the discussion is not about *OBLIMAP's benefits or advantages over the GCM's existing coupling technologies*, because they serve different targets. Because OBLIMAP is a specific GCM – ISM coupler with a sound performance (Reerink et al. 2010) and because its current release includes many extended user options (see the OBLIMAP User Guide for the full list), has an efficient design which enables embedded use, installs easy and is easy to configure, we think the current release is convincingly beneficial for users. We revised the manuscript to emphasis its specific GCM – ISM coupling tasks and widened the comparison with the ESM component couplers.

However, it does not appear that OBLIMAP provides the capability to handle either of the two major challenges that we are currently struggling with in ice sheet coupling: (1) regridding from coarse to high resolution grids in a conservative but relatively smooth fashion,

At several points in this review the issue of conservative mapping is addressed. We agree that conservation is a very relevant theme in mapping. However, to which extent a mapping has to be conserved could be subject of a discussion. We will discuss here several issues.

First we note that the ESM component couplers OASIS, CPL6, CPL7 and ESMF rely on SCRIP (Jones 1999). SCRIP is able to remap from sphere to sphere, the typical task for ESM component couplers. Jones (1999) shows that the remapping is much less accurate (especially for fields with large gradients) for first order area conservative interpolation than for e.g. bilinear interpolation. Jones (1999) therefore presents a more accurate second order area conservative interpolation. However, none of the ESM component couplers use the second order variant, all of them use the first order area conservative remapping. We think the reason for that is that the second order variant needs the gradient of the field, which is problematic because this does not allow prior offline generation of the interpolation weights, and would be field dependent. And, if we understand correctly, the areas are approximated by the line segments over which the line integrals are carried out for irregular overlapping grids, which makes it not exact area conservative.

The area distortion due to the projection is another complication if conservative interpolation in GCM – ISM coupling is considered. For a very local projection the LAEA projection could be used, but for larger scale ice caps it is important that (flow) directions are not affected by the projection in order to stay close to the physical representation of the models. This means that in general a SG projection deforms the area of each cell. The combination of a projection with an area conservative mapping leads to large errors. If e.g. the area of a cell shrinks by 1%, the value of that cell will increase by 1% to compensate due to the area conservation. However, the area mismatch is compensated after the reverse mapping, therefore the conservation of the GCM – ISM coupling should be judged by comparing the results after a to and fro mapping. This requires adequate tests, like those carried out by Reerink et al. (2010) which show results close to conservation. The quadrant and radius interpolation method which are based on the inverse squared distance weighting perform well with respect to conservation after to and fro mapping (Reerink et al. 2010). OBLIMAP uses the radius method to obtain a representative estimate for mapping from fine to coarse resolution grids.

We think that exact area conserved mapping should be not too much at the expense of the accuracy of the mapping, at least not for the fields which are involved in GCM – ISM mapping. Hence a balance has to be found between optimal accuracy and a conserved behaviour in the coupling. As we have to deal with the projection in GCM – ISM coupling, our strategy has been to reduce the area distortion. This is achieved by using oblique projections and is optimized by taking an optimal standard parallel. For less local mappings we prevail accuracy in mapped directions in order to stay close to the ice flow physics, instead

of exact area conservation. However, compared over the the to and fro mapping Reerink et al. (2010) show that OBLIMAP maps close to conservative.

We added a paragraph to the discussion to discuss this.

and (2) handling multiple elevation classes in the GCM – i.e., including vertical as well as horizontal remapping.

- 5 OBLIMAP 2.0 includes the mapping of spatial 1D, 2D and 3D fields with or without a time dimension. Like the C-Coupler (Liu et al. 2014) it concerns a 2D + 1D mapping for 3D fields, in the sense that the horizontal mapping includes the 2D interpolation with the distance weighting (with the prior scan option). Each vertical layer (or elevation class level) is treated with the same 2D horizontal interpolation but is not interpolated in the vertical direction by OBLIMAP. Returning the vertical layers just as vertical records is a conscious choice, it keeps the most flexibility. For example it allows the vertical coordinate to change without affecting the mapping, i.e. avoiding a repeated scan phase. This is particular important regarding the vertical zeta coordinate in ISM models which usually not only changes in time but even changes per grid node in time (a rather weird phenomenon for non-ISM modellers). In this way the vertical grid is allowed to match with either a real or scaled coordinate and could differ per field, again without affecting the mapping. It allows direct downscaling if one wishes, which in that case saves one interpolation step. This is all possible without losing much on the performance, because the vertical interpolation is computational straightforward and at low cost. Furthermore, it is independent of a possible future parallel domain decomposition as noticed by Liu et al. (2014). An added paragraph to the discussion addresses this remarks, and small adjustments have been made to Sect. 3.6.

Regarding (1), the authors state that the scheme is "close to conservative" (p. 2, L. 22), but do not quantify this. For coupled model simulations, a fully conservative mapping scheme is needed.

- 20 This *close to conservative* (p. 2, L. 22) addresses the projection part, minimizing the distortions improves conservation. This is achieved by using an optimal aligned oblique projection. An extensive quantification of the nearly conserved to and fro mapping is presented in Reerink et al. (2010). We changed the text at (p. 2, L. 27) to refer explicitly to the conservation tests in Reerink et al. (2010).

In terms of the actual mapping algorithms implemented by OBLIMAP, my sense is that "quadrant" interpolation is similar to bilinear interpolation, and "radius" interpolation is a blend between bilinear and area-conservative interpolation. However, it was hard for me to tell for sure. The authors should provide an overview of these two interpolation methods, and a brief comparison with other commonly-used interpolation methods. It was unclear to me why OBLIMAP uses these methods.

Although Sect. 2.3 in Reerink (2010) provides a straightforward and sound description of the quadrant and radius interpolation methods (to which is referenced (p. 2, L. 17) in the introduction), we agree with the referee that the motivation to choose these interpolation techniques could receive more attention. We therefore inserted the answer provided below as a section 3 of the updated supplement, and rewrote the paragraph (p.2, L. 15–19) in the introduction.

The quadrant and radius method are both inverse squared distance weighting interpolation methods based on Donald Shepard's famous paper 'A two-dimensional interpolation function for irregularly-spaced data' which he published in 1968. His introduction discusses the shortcomings of the bilinear (called double linear), bicubic and other interpolation methods if applied to irregularly-spaced data.

The inverse squared distance weighting function has a few very practical advantages when interpolating spatial data, it is suited to identically treat: (1) regular and irregular spaced grid nodes, (2) 1D, 2D and 3D spatial grids, (3) any curved destination surface, i.e. the surface of a sphere and ellipsoid or the flat surface, (4) any number of weighting contributions. The weighted average is based on weighting the inverse squared distances of all the selected contributions. Although the weighting factors are default taken equal to the inverse *squared* distance as recommended by Shepard, it is possible (also in OBLIMAP) to replace this exponent = 2 which makes it *squared*, by each exponent equal or larger than 1 instead.

This pure inverse squared distance weighting function has to be combined with a limiting influence distance in order to select only nearby points, as described by Shepard. The main reason for this limitation is the computational performance, but it also avoids the need of suppressing a possibly biased average in case there is a relative large number of distant points involved.

As noted by Shepard there are many ways to limit the number of contributions. In OBLIMAP we implemented two methods to limit the influence of distant contributions, based on three typical situations encountered by mapping: (1) a coarse grid is mapped on a fine grid, (2) a grid is mapped on a grid with a similar resolution, (3) a fine grid is mapped on a coarse grid.

- 5 The first and second situation are addressed by OBLIMAP's default interpolation method, the quadrant interpolation method, which draws a cross through the considered destination point, and selects in each quadrant the nearest projected contribution. It is a relative arbitrary choice to divide the surrounding area in four segments, in fact it could be divided in any number of segments. The choice for four segments is slightly inspired by the bilinear interpolation which also uses four surrounding points. This selection method does effectively shadow other contributions in the same segment/direction in a simple way. Note that with an increasing number of segments the shadowing becomes more direction sensitive.
- 10 In the third situation, in which a fine grid is mapped on a coarse grid, OBLIMAP uses the radius interpolation method which selects those contributions which lay within a certain radius. A reasonable radius typically equals half the departure grid size resolution. The basic idea is that the coarse destination grid cell obtains a representable average value. Because the number of selected contributions increases approximately squared with an increasing selecting radius (given a constant node density), more distant points are selected but they weight inversely squared. This squared and inverse squared effect compensates and
- 15 makes that the radius method generates a representable average estimate.

We preferred selecting within a radius over selecting the n nearest points which is another well known method, because the latter requires sorting which is notorious computational expensive for large n and complicates the interpretation of the results in situations with masks and data gaps, and also does not directly match the area size of the destination grid cell.

- 20 As the weighting function itself just weights over the number of detected contributions, segments are allowed to stay empty. Therefore the method is robust for destination grid domain edges, mapped departure grid domain edges, data gaps, and masked points where the mask is also allowed to differ per field and per vertical layer, and all these different masks are even allowed to change in time.

- 25 In both interpolation methods the distances between the considered destination point and a projected departure point are calculated over the destination surface along the great circle. Available surface curvatures in OBLIMAP are the surface of a sphere, an ellipsoid and of a flat plane.

Default OBLIMAP uses the quadrant interpolation method, but the radius interpolation method is automatically selected if the resolution of the destination grid is four times coarser than the resolution of the departure grid. The interpolation can be configured manually as well, for that and for all defaults see the OBLIMAP User Guide.

- 30 Independent of the interpolation method which has been used in the scan phase, the nearest point assignment can be used in the post scan phase and will match with masks which change in time and differ per field and layer.

- 35 Bilinear interpolation requires exception rules if situations are encountered with less than four contributions, and becomes a less well defined method for irregularly spaced contribution points. Bilinear interpolation is not the same as the quadrant interpolation. In case a regular Cartesian grid is remapped, the bilinear interpolation weights a contribution based on the surface of the opposite corner (see e.g. the third figure at https://en.wikipedia.org/wiki/Bilinear_interpolation), while the quadrant interpolation weights this contribution based on the inverse squared distance. For a 1 by 1 unit grid with a certain contribution at distance $(\Delta x, \Delta y)$ from destination point P, the weighting factor of this contribution to P is $\Delta x^2 + \Delta y^2$ for the quadrant interpolation instead of $(1 - \Delta x)(1 - \Delta y)$ for the bilinear interpolation. The normalizing factors, which also differ per method because they are a summation over the weights of all participating contributions, are omitted here.

- 40 The radius interpolation has no real similarities with the bilinear interpolation. As explained above the squared contribution covering area and the inverse squared distance weighting of each contribution compensate. This generates an estimate which represents an area average close to conservative as all local parts of the cell are in fact treated equally with respect to area weighting.

Additional specific comments follow:

1. The Introduction gets into too many details on projections, etc. Instead, I would want the Introduction to provide a high-level introduction to the problem, including a wider survey of other tools that serve a similar purpose. There could then be a separate section describing the details and limitations of OBLIMAP v. 1, which would include some of these details on projections.
- 5 As pointed out earlier, the projection is an essential and distinguishing part of the GCM – ISM coupling. We think that the relevant part of OBLIMAP’s first release should be summarized in the introduction. The projection description is an important part of that. We agree to widen the comparison with more couplers and to emphasis the difference between a GCM – ISM coupler like OBLIMAP and the other ESM component couplers. This will be addressed at the begin of the introduction and in the discussion.
- 10 2. p 9 L 1-5: It would be helpful if the API of OBLIMAP were laid out more explicitly here – what does the code interface look like in detail? This isn’t absolutely necessary, but would help GCM developers evaluate whether they want to include OBLIMAP in their system.
We agree that the reader is served by an more explicit description of the API, we will add a schematic code figure containing the OBLIMAP API indicating the location in the host model code. Some additional sentences discussing and referring to the figure will be added to this section.
- 15 3. It would also be helpful if an example were given of how to configure OBLIMAP for offline regridding (e.g., an example configuration file and/or command-line usage). Again, this isn’t necessary, but would help people decide if this is something they want to use.
We regret that the link to the supplementary information (the OBLIMAP User Guide) was not properly inserted in the discussion paper. These examples, including an example of a config file, are present in the OBLIMAP User Guide. We will suggest that this OBLIMAP User Guide pdf will be directly linked, like a usual supplementary pdf. This makes the supplement easier accessible, and avoids that a reader first has to download the OBLIMAP-package and search therein.
- 20 4. Section 4.2 and associated figures could be trimmed substantially. It seems that, relative to OBLIMAP v. 1, the main addition here is the masking, which could be illustrated with a single figure
- 25 Section 4.2 demonstrates that OBLIMAP is a powerful tool which is able to map diverse kinds of topographic and forcing data sets onto any ISM grid configuration with an optimal oblique projection. The public available high resolution topographic data sets are remapped (reprojected from a polar to an optimal oblique aligned projection for the ellipsoid) for each area on a certain ISM grid of preference, i.e. with the desired grid extensions and grid resolution. The atmospheric forcing data sets which are defined on a reduced gaussian grid of the regional RACMO2 model, are mapped from the sphere to the same ISM grids. The geothermal heat flux field which is defined on a global regular longitude-latitude grid, is also mapped from the sphere to these
- 30 same ISM grids. Besides, these different data sets cover a wide resolution range and map the two major ice sheets, in addition the Antarctic Peninsula example shows how a subregion is mapped with its own optimal oblique projection. Furthermore, masked mapping is shown for a relevant set of applications and different masking issues are discussed. We think that Section 4.2 shows the capabilities which OBLIMAP offers ice modellers, which we think is underlined by the comments made by the second referee. At the start of Sect. 4.2 the different purposes of this section are know summarized.
- 35 We realize, however, that these RACMO2 fields are not public available yet and the RACMO2.3 data sets for Greenland and Antarctica will therefore accompany the OBLIMAP 2.0 package, which will be a supplement on the GMD site. Because of his involvement in the production of these RACMO2.3 data sets, W.J. van de Berg is added as a co-author. The figures and text are updated as we use these present day time-averaged RACMO2.3 data sets which are made publicly available and because the
- 40 RACMO2.3 Greenland data set is a more recent data set than the one used before.
5. Section 4.2 should be expanded to add metrics on area-integrated sums, to help judge conservation. My sense is that these schemes are fundamentally non- conservative, which would be a problem for incorporating them in a GCM.

We refer to the area conservative discussion above, and point to the fact that the mapping quality of OBLIMAP has been the topic of Reerink et al (2010). The metrics on area-integrated sums are addressed at the end of Sect. 4 and in Table 4 in Reerink et al (2010).

6. p. 15 L 21-22: "The weaker second condition. . .": I don't understand this; the authors should reword to make this more clear.
- 5 After the rewrite of the second part of the section which describes the fast scan method, we now distinguish between structured grids and unstructured grids. Therefore this part of the discussion is rewritten as well.
7. There are numerous typos and grammatical errors. Just a few examples are:
- a. p 1 L 7: "frequent" should be "frequency"
- b. p 2 L 5: "constrains" should be "constraints"
- 10 c. There should not be an apostrophe in GCMs or ISMs
- We apologize for the typos and errors, we have corrected them.

References

- Valcke, S., Balaji, V., Craig, A., DeLuca, C., Dunlap, R., Ford, R. W., Jacob, R., Larson, J., O'Kuinghttons, R., Riley, G. D., and Vertenstein, M.: Coupling technologies for Earth System Modelling, *Geosci. Model Dev.*, 5, 1589-1596, doi:10.5194/gmd-5-1589-2012, 2012.
- 15 Jones, P.: First- and second-order conservative remapping schemes for grids in spherical coordinates, *Monthly Weather Review*, 127, 2204-2210, 1999.
- Liu, L., Yang, G., Wang, B., Zhang, C., Li, R., Zhang, Z., Ji, Y., and Wang, L.: C-Coupler1: a Chinese community coupler for Earth system modeling, *Geosci. Model Dev.*, 7, 2281-2302, doi:10.5194/gmd-7-2281-2014, 2014.
- 20 Reerink, T. J., Kliphuis, M. A., and van de Wal, R. S. W.: Mapping technique of climate fields between GCMs and ice models, *Geoscientific Model Development*, 3, 13-41, doi:10.5194/gmd-3-13-2010, <http://www.geosci-model-dev.net/3/13/2010/>, 2010.
- Shepard, D.: A two-dimensional interpolation function for irregularly-spaced data, *Proceedings-1968 ACM National Conference*, pp. 517-524, 1968.

Answer to Florence Colleoni (Referee)

- 25 First we would like to thank the referee for her compliments on the improvements of the OBLIMAP package, and for her comments on our work which improved our manuscript. You will find detailed comments and answers below. We hope that the revisions improve the quality of the paper and meet your expectations.

In this manuscript, Reerink et al. present an updated improved version of the interpolation tool OBLIMAP whose aim is to interpolate the GCM fields onto ice sheet models grid and vice-versa. I must say that I am myself a regular user of the first version of OBLIMAP since many years now. However, many of the ice sheets models that I use have grids projected on the ellipsoid and not on the sphere. Therefore at the time of OBLIMAP 1.0, I had to implement by myself the missing projection routines on ellipsoid grids.

30

We are pleased to notice that OBLIMAP has been regularly used by others as well. The final published release of OBLIMAP 1.0 actually does include the option to map on the ellipsoid. However, in OBLIMAP 2.0 all polar aspect forms for the ellipsoid projections are now included, and any ellipsoid shape can be configured from the config file now (the WGS84 is still the default).

35

In addition, because I also needed to interpolate ocean vertical data, or create my own ISM regional grid, I also had to implement the additional level dimension in the netcdf routine and produce a slightly modified version of the first version of OBLIMAP to create new ISM grids for boundary conditions. Recently, I needed to use the BEDMAP Antarctic topography, which comes in cartesian format already projected and the problem of re-interpolating it on a different grids surged. In this new version of

40

OBLIMAP, all the points that I mentioned above have been fully improved and implemented, which demonstrate that those points were really the main weaknesses of the first version.

Indeed OBLIMAP 2.0 enables mapping of spatial 1D, 2D and 3D fields, all with or without a time dimension. As setting the dimensional properties got laborious for the user, we enabled an option to automatically detect the dimensional shape of the input fields in any situation in the new release.

5 The expressed appreciation of the remapping feature of ISM data did us realize that running this simple two step procedure should be described in the OBLIMAP User Guide. Therefore we added this as a subsection (so it is easy to find from the index) of the 'Running OBLIMAP' section in the OBLIMAP User Guide.

10 Several improvements that have been made in this version: it provides the geographical projections on ellipsoid and not only on a sphere as in the previous version. In fact, many ice sheet models have their cartesian grid projected on the ellipsoid and not on the sphere. This was a limiting aspect of the first version since one had to implement the projection on the ellipsoid by himself. the computation time performance of the scan method to interpolate from grid with numerous points has improved substantially. This was effectively a limitation. A suggestion could also be to provide a parallel version of this code for this specific loop. the re-interpolation of cartesian projected topographic or climate data sets on a defined ISM cartesian grid.

15 Which is to me, one of the greatest improvements. it can maps 4D fields, such as ocean or winds, which is highly appreciable improvements.

We agree that with the fast scan method barriers are razed, e.g. the (re)mapping of high resolution data, like the currently available 1x1 km topographic fields for Greenland and Antarctica, was simply impossible before. Other more 'common sized' mappings, which typically took a few minutes with OBLIMAP 1.0, take less than a second now, which is also convenient.

20 However, a parallel implementation of the scan phase would certainly be beneficial. A start has been made: A proposal to work on a parallel scan phase of OBLIMAP for the Polar Science HPC Hackathon 2016 was accepted, so I went in July 2016 to XSEDE's conference in Miami and worked with HPC experts on that. A well scalable parallel domain decomposition could be implemented for the scan phase, the results remain bitwise identical for a changing number of processors. This is work in progress. Advancing insights due to this recent work are reflected in a rewrite of the discussed proposed parallel implementation at the end of the discussion.

25

OBLIMAP is a really useful tool for those who carry out ice sheet simulations and the difficulty of interpolating on cartesian grids can be understood only when facing this problem. On the coupling process, I would definitely say that OBLIMAP should be embedded in ice sheet models rather than in the coupler of coupled climate models. Given the variety of existing climate couplers, and sometimes their complexity (e.g. the NCAR model), it is much easier to host OBLIMAP within the ice sheet models. As I mentioned again in the Major comments below, the GLIMMER ice sheet model and I think also the CISM model (derived from GLIMMER), the TARAH ice sheet model (Pollard and Deconto) already embed the projection of the climate fields onto the ice sheet grid within the ice sheet code itself, and by experience with both ice sheet and climate models, I would also recommend to put OBLIMAP in the ISM code.

30

We once more thank for the compliments on the achievements which are realized with OBLIMAP's second release, and for summarizing the milestones from a regular user's perspective. We comment on the embedding issue in one of the next points. Based my comments above, except minor typos or reformulations, I recommend the publication of the manuscript in its current shape. Florence Colleoni

35

Major comments

Maybe a stand-alone version, as for the first version could also be useful, not everybody uses coupled system. Or maybe this version is stand-alone but this is not clear and should be clarified with a sentence or so in manuscript.

40

Sure there is a stand-alone version of OBLIMAP 2.0. The stand-alone version has already been mentioned in the abstract, introduction (twice), in the caption of Fig. 1 and in the text reference to Fig. 1 in Sec. 2. However, we added:"Its stand-alone version can be installed and compiled within a couple of minutes on any platform." to the last paragraph of the conclusion, in order to emphasize once more OBLIMAP's stand-alone version and to emphasis its user friendly install.

45 Line 50-55: after using OBLIMAP very often, I would say that perhaps hosting OBLIMAP in the ice sheet model is the most easiest way to deal with it. OBLIMAP is a small coupler model and very simple in its use, therefore, it is easily implemented

in an ISM, as for example GLIMMER does, rather than embedded in a GCM. But this is only my opinion of user. In addition the climate coupler are built to interpolate on lon-lat grids most of the time.

- There might be certainly some exploration on this theme. We think that with OBLIMAP's new version OBLIMAP itself is suited for several strategies: embedding OBLIMAP in the ISM, in the GCM or in another coupler. Because OBLIMAP is subdivided in the standard components: 'Initialize', 'Run' (map or inverse map) and 'Finalize', this allows direct embedding. Note that the mapping routines pass on all fields as an argument, which makes embedding of OBLIMAP low intrusive. The strategy might depend on the specific GCM – ISM combination as well on the coupling approach: one way or two way on-line coupling. In case of a two way on-line coupling we expect that embedding the ISM in the GCM might be easier because aside of embedding OBLIMAP, the ISM has to be embedded as well in the GCM which means that the ISM needs to be recoded in an Initialize-Run-Finalize form. While vice versa the GCM has to be embedded in the ISM which probably requires recoding of the GCM in such an Initialize-Run-Finalize form which might be much more challenging due to the complexity of GCMs. Changes have been made to Sec. 3.3 and Sec. 4.3 in order to clarify our view on embedding strategies and to include the suggestion of referee 1 to add OBLIMAP's API in Sec. 3.3.

Minor comments

- 15 line 45: substitute "albedo changes" by "ice sheet distribution" because an ISM does not provide albedo changes, it only provides ice distribution which affect albedo within the atmosphere model. A regional atmospheric model as RACMO on the contrary provides albedo changes, but this is not an ISM.
[Done](#)
- 20 line 48: "surface mass balance" put a space between "mass" and "balance"
[Done](#)
- line 52: substitute "ocean surface temperatures" by "ocean temperatures.". Most of the basal melting methods uses vertical ocean temperature and salinity distribution (Holland and Jenkins 1999, Pollard and Deconto 2012, Martin et al., 2011).
[Done](#)
- 25 line 63: substitute by "any regional energy balance model (e.g. RACMO or MAR)"
[Done](#)
- Figure 7: "surface mass balance" put a space between "mass" and "balance"
[Done](#)
- Interactive comment on Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-124, 2016.
[Done](#)

Fast GCM - ice sheet model coupling software OBLIMAP 2.0, including on-line embeddable mapping routines

Thomas Reerink, Willem-Jan van de Berg, and Roderik van de Wal

Institute for Marine and Atmospheric research Utrecht, Utrecht University, 3508 TA Utrecht, The Netherlands

Correspondence to: Thomas Reerink (tjreerink@gmail.com)

Abstract. This paper accompanies the second OBLIMAP open source release. The package is developed to map climate fields between a general circulation model (GCM) and an ice sheet model (ISM) in both directions by using optimal aligned oblique projections, which minimize distortions. ~~Both~~ The curvature of the surfaces of the GCM and ISM grid differ, both grids may be irregularly spaced and the ratio of the grids is allowed to differ largely. ~~The OBLIMAP's stand-alone version of OBLIMAP~~
5 ~~is a powerful tool to map various differently gridded datasets on one uniform ISM grid with an optimal centered projection. is~~
able to map data sets which differ in various aspects on the same ISM grid. Each grid may either coincide with the surface of a sphere, an ellipsoid or a flat plane, while the grid types might differ. Reprojection of e.g. ISM data sets is also facilitated. This is demonstrated by relevant ~~applicatons~~ applications concerning the major ice caps. As ~~this the stand-alone version~~ applies also for the reverse mapping direction, it can be used as an off-line coupler. Besides, OBLIMAP 2.0 is an embeddable GCM
10 - ISM coupler, suited for ~~high frequent~~ high-frequency on-line coupled experiments. A new fast scan method is presented for structured grids as an alternative for the former time consuming grid search strategy, realising a performance gain of several orders of magnitude and enabling the mapping of high resolution ~~datasets~~ data sets with a much larger number of grid nodes. Further a highly flexible masked mapping option is added. The ~~limitations~~ limitation of the fast scan method with respect to unstructured and adaptive grids ~~are is~~ discussed together with ~~several proposed parallel implementations in order to achieve~~
15 ~~another performance gain. a possible future parallel MPI implementation.~~

1 Introduction

Ice caps are part of the climate system and interact with the atmosphere and the ocean via various feedback mechanisms. In order to simulate their interaction, ice sheet models (~~ISM's~~ ISMs) need to be coupled with general circulation models (~~GCM's~~).
~~An atmospheric GCM (AGCM) and an oceanic GCM (OGCM) can be mutually coupled with e.g. the external OASIS coupler~~
20 ~~Valeke (2013), in order to study the ocean - atmosphere interaction~~ GCMs). In contrast to ~~the geographical coordinates which are used by the GCM's, the ice dynamic equations~~ GCMs which use geographical coordinates, ISMs are often solved on rectangular coordinates, due to the type of ~~its~~ the ice dynamic equations. This requires ~~an additional projection step (1) a projection step and (2) a regridding or interpolation step,~~ when coupling an ISM with ~~an a~~ GCM.

Because ~~ISM's~~ ISMs are predominantly influenced by the atmospheric forcing, coupling them with an ~~AGCM~~ atmospheric
25 GCM (AGCM) is from the ISM perspective self-evident. Nevertheless, if ice shelves are included in the ISM, the coupling

with an ~~OGCM~~ oceanic GCM (OGCM) makes sense as well because ice shelves are sensitive to the ocean temperatures, which strongly affect the dynamics of the shelves and the ice sheet behind the ice shelf (e.g. Holland and Jenkins, 1999). On the other hand an ISM model provides output in terms of bedrock, surface height and ~~albedo changes~~ ice sheet distribution which affect the climate and needs to be provided back to the GCM.

5 Earth system models (ESMs) consist of four basic component models for simulating the atmosphere, ocean, land surface and sea ice. Other components like e.g. for the atmospheric chemistry maybe added to ESMs. These components are coupled by
ESM component couplers like OASIS3 (Valcke, 2013), MCT (Larson et al., 2005), the ESMF coupler (Hill et al., 2004), the
CPL6 coupler (Craig et al., 2005), the CPL7 coupler (Craig et al., 2012) and the C-Coupler (Liu et al., 2014). Valcke et al. (2012, 2016) and
Liu et al. (2014) shortly describe and compare these and other couplers. These ESM component couplers have two main
10 functionalities: (1) They serve as a central hub between the different components, i.e. they manage the data transfer and
coordinate the execution of the components. (2) The fields are regridded. Nearly all the ESM component couplers use SCRIP
(Jones, 1999) for regridding between two spherical coordinate systems.

~~In~~ However, in order to couple ~~GCM's and ISM's~~ GCMs and ISMs, the GCM fields which are defined on a grid representing the curved Earth surface have to be mapped at the ISM grid which coincides with a flat surface, and vice versa. OBLIMAP
15 (Reerink et al., 2010) performs this technical mapping task, which comprises the combination of projection and interpolation in both directions. A consequence of the projection is that even the grid points of a regularly spaced grid end up irregularly
spaced, which requires a suited interpolation method. Aside from the additional projection step, the resolution of the GCM
and ISM grid often differ largely. Further, mapping ISM fields from a local ISM grid onto a larger scale GCM grid requires a
merge of the mapped parts into the existing GCM fields. These and other specific GCM – ISM coupling issues are addressed
20 by OBLIMAP. On the other hand in contrast to ESM component couplers, OBLIMAP is not that much a hub from which more
than two ESM components are coupled.

The oblique stereographic (SG) and the oblique Lambert azimuthal equal-area (LAEA) and their inverse projections are ~~available in OBLIMAP because they are~~ suited projections given the ~~constrains~~ constraints involved with this type of geographical mappings, and are therefore available in OBLIMAP. The conformal SG projection preserves angles which is a
25 welcome property for direction dependent geometries and velocity fields. The SG projection is nearly area conservative if the projection is optimally aligned. Areas remain conserved under the LAEA projection, while this projection is nearly conformal if optimally aligned. The area-invariant property of this projection is interesting with respect to conservative mapping. However, note that conserved mapping requires in addition a conserved interpolation method as well.

Both projection methods are azimuthal (i.e. perspective), which means that with exception of the point of projection itself,
30 the entire domain can be mapped without any singularities. Either a sphere or an ellipsoid is a natural choice to represent the Earth surface. Therefore in OBLIMAP the SG and LAEA projection can be used both in combination with the sphere and the (default WGS84) ellipsoid.

~~The projected points which are used to obtain interpolated values at~~ The interpolation methods have to cope with the fact
that the projected grid points end up irregularly spaced with respect to the destination grid points. OBLIMAP uses a quadrant
35 and radius interpolation method (Reerink et al., 2010), which are based on the inverse squared distance weighted interpolation

method for irregularly-spaced data (Shepard, 1968). The inverse squared distance weighting function has several practical advantages when interpolating spatial data, it is suited to identically treat: (1) regular and irregular spaced grid nodes, (2) 1D, are irregularly distributed with respect to this destination grid points. Furthermore 2D and 3D spatial grids, (3) any curved destination surface, i.e. the surface of a sphere, an ellipsoid or a flat plane, (4) a variable number of contributions in the weighting. The latter enables the mapping of data gaps, departure and destination grid domain edges, and masked grid points. This inverse squared distance weighting function is usually combined, mainly for computational performance reasons, with a selection method which excludes remote contributions. As the ratio of the grid resolutions vary may differ orders of magnitude among OBLIMAP's applications. Therefore OBLIMAP uses a quadrant and, two selection variants are available. The quadrant interpolation method is used in case a coarse grid is mapped on a fine grid or in case the grids have a similar resolution. It draws a cross through the considered destination grid point and selects in each quadrant the nearest projected contribution. The radius interpolation method (Reerink et al., 2010) in which the weighting is based on Shepard (1968). These interpolation methods are suitable for large resolution differences and data gaps, and robustly deal with the irregular located interpolation source points. Due to this approach OBLIMAP is also capable to cope with departure and destination grid coordinates which are irregularly spaced is used in case a fine grid is mapped on a coarse grid. It selects the contributions which lay within a certain radius from the considered destination grid point. A reasonable radius typically equals half the departure grid size resolution.

ISMs usually cover a limited local area compared to GCMs. Therefore only a part of the GCM points will participate in the ISM to GCM mapping. These points are distinguished from the remaining points by a participation mask, and will default be merged with the pre-mapped field values of the points which did not participate in the mapping.

Using an optimized projection is fundamental in OBLIMAP's strategy to provide high mapping quality and to obtain results which are close to conservative after to and fro mapping. To achieve this OBLIMAP uses oblique projections, for which only with an optimal standard parallel in order to achieve this. The user only needs to specify the geographical coordinates of the center centre of the area of interest need to be specified in order to obtain an optimal centered this optimal centred projection. With the optimal centered centred projection the SG projection is close to area preserving and the. In addition the distortions of the mapped local distances are minimized. The point of projection, which is the only singular point in the mapping, is by definition at the opposite side of the the counter pole of the center of the area of interest. In addition the distortions of the mapped local distances is minimized. A range interest. A diverse set of to and fro mapping tests with OBLIMAP using this strategy proved prove the robustness of this method and showed accurate results OBLIMAP and show accurate results which are close to conservative (Reerink et al., 2010).

The stand-alone version of OBLIMAP is extremely suitable and convenient for mapping various input datasets on one ISM grid with an optimal centered projection. These input datasets may vary in grid resolution and in grid extent, and can be defined on either a grid representing the curved Earth surface or on an ISM domain coinciding with a flat surface. In the latter case a remapping is required if the selected projection and grid configuration differ.

Examples of typical input datasets data sets which are used to initialize and force an ISM are topographic datasets data sets including surface height, bedrock level and ice thickness fields, atmospheric forcing datasets containing surface mass balance data sets containing surface mass balance, surface temperature, refreezing and runoff run-off fields, and datasets data sets containing

fields like the geothermal heat flux, the ice surface velocities for validation or for initializing the ice shelf velocity field and for instance the ocean surface temperature which could be used in the ice shelf basal melt ~~parameterisation~~.

5 ~~Because the dynamics of the ice caps are supposed to be sensitive to the dynamics in the coastal zones, accurate mapping of the different datasets is essential in order to ensure that their complex mapped patterns, related to the varying topography, fully match.~~

~~ISM's usually cover a limited local area compared to GCM's. Therefore only a part of the GCM points will participate in the ISM to GCM mapping. These points are distinguished from the remaining points by a participation mask, and will default be merged with the pre-mapped field values of the points which didn't participate in the mapping~~parameterization.

10 For example, in order to equally map their initial topographic and atmospheric and other forcing fields on their ~~preferred~~ preferred ISM grids with an optimal ~~centered projection, Helsen et al. (2012, 2013); De Boer et al. (2013, 2014, 2015) used OBLIMAP's first release~~ centred projection, Helsen et al. (2012, 2013, 2016); De Boer et al. (2013, 2014, 2015) used OBLIMAP (Reerink et al., 2010) for preparing their ice sheet modelling input fields. Besides the use of GCM output as atmospheric forcing, the higher resolution fields provided by ~~regional climate models like RACMO (van Meijgaard et al., 2009)~~ any regional
15 energy balance model (e.g. RACMO (van Meijgaard et al., 2009) or MAR (Gallée and Schayes, 1994)) might be favoured as forcing of the ISM (Helsen et al., 2013), the more because they deliver direct applicable products like the surface mass balance (SMB) which are of interest for the ice sheet modeller.

With the RACMO2 ~~datasets for Greenland (van Angelen et al., 2014; Noël et al., 2015)~~ 3 data sets for Greenland (Noël et al., 2015) and Antarctica (Van Wessem et al., 2014, 2016) higher resolution atmospheric forcing ~~datasets~~ data sets are available. For instance
20 the ~~RACMO2~~ RACMO SMB is a field which contains only relevant valid values at ice covered grid points, distinguished by the assignment of a missing value for the remaining grid points. This requires a method which accurately maps masked fields. Therefore OBLIMAP 2.0 provides the new 'masked mapping' method.

At the time of OBLIMAP's first release OBLIMAP typically had to cope with situations in which GCM fields, which are defined on a rather coarse grid ($\sim 1^\circ$), are mapped on ISM grids with a resolution of about 10 km or coarser. In the meantime
25 new high resolution topographic ~~datasets~~ data sets for Greenland (Bamber et al., 2013) and Antarctica (Fretwell et al., 2013) have become publicly available. The large gain in resolution refinement for these ~~datasets~~ data sets confronted OBLIMAP with a performance challenge which has not been an issue at the time of OBLIMAP's first release. Mapping or remapping for instance the entire Greenland area with a 1x1, 2x2 or 5x5 km resolution is much more demanding with respect to the computational time of OBLIMAP's so called scan phase. The scan phase computes the projection of all grid coordinates
30 and calculates the distances over the surface of the destination grid, and based on them the nearby projected points which contribute to the interpolation are selected. With an alternative 'fast scan method' for structured grids OBLIMAP 2.0 realizes a large performance gain and therefore enables the mapping of the high resolution ~~datasets~~ data sets.

In order to simulate the interaction of an ice sheet with the ocean and atmosphere in sufficient detail, high-frequency on-line ~~high frequent~~ GCM - ISM coupling is required in which the mutual feedback processes are implicitly included. A solution
35 which is computational efficient, will use ~~embeddedable~~ embeddable coupling routines and for instance an ~~embeddedable~~ embeddable ISM. With on-line coupling we mean that the field exchange takes place during a simultaneous GCM - ~~IM~~ ISM

run, which can be achieved with either an external or an embedded coupler, the latter means that the coupling routines are directly called from for instance the GCM code ~~for instance~~. With OBLIMAP's redesign the mapping routines can be used embedded as well now. The introduction of a so called 'dynamic data object' solves the main I/O bottleneck. This combination
5 makes the OBLIMAP mapping routines suitable for ~~high-frequent~~ high-frequency on-line coupling, which ~~we consider also as~~ is one of the main achievements of OBLIMAP 2.0.

In Sect. 3 a few other new key features are described, whereas a complete description is available in the OBLIMAP ~~manual~~ User Guide (Reerink, 2016). The primary objective of this new ~~manual~~ OBLIMAP User Guide is to explain how the configuration variables can be configured ~~by the user~~. Using OBLIMAP's stand-alone version and applying it on (1) the
10 publicly available topographic and geothermal heat flux data sets and (2) on the RACMO2.3 atmospheric forcing data sets (provided as supplementary material) conveniently generates the input fields at any ISM grid of preference for modelling Greenland and Antarctica. The OBLIMAP-package, including the stand-alone OBLIMAP 2.0 code, two RACMO2.3 data sets, several applications and the OBLIMAP ~~manual~~ User Guide, is available at the GMD site (see supplementary material <http://www.geosci-model-dev.net/???-supplement.zip>) and is distributed under the terms of the GNU General Public License.

15 2 General overview of OBLIMAP 2.0

OBLIMAP is divided into two phases: a prior scan phase and a post scan phase. In the scan phase the departure grid points are projected on the destination surface corresponding with the destination grid. For each destination grid point the projected departure grid points which contribute to the interpolation, depending on the selected interpolation method, have to be selected. As this is time consuming, the resulting grid addresses and relative distances are stored by ~~writing~~ writing them to the scanned
20 indices and distances file: the SID file.

In the post scan phase the dynamic data object (DDO) is initialized by loading the SID file data. Thereafter the fast mapping of multiple fields, layers and records is that fast that the computational time is more or less negligible for most common applications. In a later stage the same mapping with the same departure grid - destination grid combination can be repeated with the scan phase switched off by reading the earlier produced SID file.

25 Beside the so-called full scan method a fast scan method is available in OBLIMAP 2.0, which is orders of magnitude faster than the full scan method. The fast scan method ~~can be applied both for regular~~ is applicable to structured grids, like regular Cartesian and gaussian reduced grids. A schematic representation of OBLIMAP 2.0 stand-alone is given in Fig. 1.

In order to couple an ISM on-line with a GCM, one of them should host the other model and the OBLIMAP mapping routines. Due to the complexity of most ~~GCM's~~ GCMs, the GCM will be in most cases the obvious host model candidate. The
30 current OBLIMAP 2.0 mapping routines are designed for embedded usage. Of course this approach requires an embeddable ISM as well.

Because in the on-line case the OBLIMAP mapping routines are used embedded, it is recommended to conduct the scanning in both mapping directions off-line and prior to the coupled run. In the initialization phase of the coupled run both ~~DDO's~~

DDOs are loaded by reading both SID files, and the fast mapping can be repeatedly used as shown in the scheme of Fig. 2, where the time steps of the ISM, the GCM and the coupling interval might differ from each other and change over time.

OBLIMAP 2.0 works with a ~~seperate~~-separate configuration file for each mapping direction. A configuration file is an ascii file containing the configuration variables which enables to configure each mapping. The number and order of the listed configuration variables in the configuration file is not prescribed. Those configuration variables which are not listed keep their predefined OBLIMAP settings. The 67 configuration variables are described in the OBLIMAP ~~manual~~ (~~see the supplementary OBLIMAP manual~~) User Guide (Reerink, 2016). Just one configuration file for both embedded mapping directions will be sufficient if, as recommended in an on-line coupled experiment, the coupled run itself uses only the fast mapping mode.

The post scan configuration parameters can be changed at any time without the obligation of repeating the scan phase. They could even be changed during an on-line coupled experiment. This contrasts with the scan configuration parameters, as soon as a user decides to alter them, the time consuming scan phase has to be repeated.

3 New OBLIMAP features and achievements

In this section and in Table 1 the most important new or extended OBLIMAP features and achievements are described.

Before we proceed we emphasize that a distinction is made between data gaps and invalid points in OBLIMAP. If for example a forcing field covers the Earth surface up to a latitude of 87°South, it means that there will be no departure grid points available within the polar area for the fields which are mapped on an ISM grid for Antarctica. This is what we call a data gap. In such cases with the quadrant interpolation method OBLIMAP succeeds in establishing a reasonable well interpolation of the forcing fields for the polar area on the ISM grid (Reerink et al., 2010). Data gaps are thus areas where no departure grid points are available. By contrast, invalid points are departure grid points which contain an invalid value. With OBLIMAP 2.0 they can optionally be excluded for the interpolation by masked mapping (see Sect. 3.2) in the post scan phase.

3.1 Scanning

The objective of the scan phase is to identify all departure grid points which are projected close to each considered destination grid point and thus contribute to their interpolation. Each projected departure grid point which is indeed used for the interpolation of the considered destination grid point is called a 'contribution' of this destination grid point. The number of detected contributing points per destination grid point varies due to the selected interpolation method, but also due to their availability near grid domain borders for instance. In this stage no ~~distinction~~-distinction is made between masked or non masked invalid value contributions, all of them are involved. The masking is a post-scan feature, see Sect. 3.2.

The departure grid indices of each contribution and the distance over the surface associated with the destination grid are written to the SID file. Per destination grid point one line is written to the SID file with the following format (see also the header of each SID file): The indices of the destination grid point are followed by n , the number of contributions for this destination grid point, whereafter the n contributions follow with for each contribution its departure grid indices and its relative distance

over the destination surface to the destination grid point. n may differ per destination grid point. This format which copes with the fluctuating amount of data per destination grid point is also the basis of the DDO.

In fact OBLIMAP needs in its scan phase the grid coordinates and has to know the grid shape. The actual values at the grid points are not used and therefore not required. The selection of the projected contributions is always based on their relative distance to the destination grid point measured over the destination grid surface. Also this distance calculation ~~requiers~~requires nothing more than the coordinates of the destination grid point and the projected departure grid point.

Assuming that the ISM grid area is a rectangle defined by the coordinates of the bottom-left and the upper-right corners, the participation mask for the GCM grid can be constructed with negligible computational costs.

3.1.1 Structured and unstructured grids

We distinguish between structured and unstructured grids. The nodes of a 2D structured grid are ordered along the coordinate axes (e.g. by two indices i,j) and the neighbour nodes of each node have to be neighbours in the real world space. I.e. based on the grid arrangement of the structured grid the neighbourhood relationships are defined which make them regular connected. With unstructured grids we denote all non-structured grids. Their elements can join in any manner while their neighbourhood relationships require explicit storage to be identified. The Cartesian, rectilinear and curvilinear grid are examples of structured grids, the tessellation and the surface curvature of the grid cell can differ. OBLIMAP supports three surface curvatures: the surface of the sphere, the ellipsoid and the flat plane. Logically rectangular grid and curvilinear grid are used as synonym for the term structured grid elsewhere.

3.1.2 Full scan

In the full scan method for each participating destination grid point a full scan over all projected departure grid points is conducted in order to select all contributions for this destination grid point. Of course this is computational not very efficient, but it is easy to implement and entirely robust with respect to grid configurations around the geographical poles, cyclic grids and data gaps. The full scan method ~~works well for any grid type: regular, gauss-reduced~~applies to structured and unstructured grids. OBLIMAP's prior version relied only on the full scan method.

3.1.3 Fast scan

The fast scan algorithm uses the fact that the closest projected departure grid point contributions of the previous neighbour destination grid point are known. The closest contribution is called the pivot. Searching the contributions for the destination grid point under consideration can be conducted within a limited block of grid points surrounding the pivot. If this block is constructed sufficiently wide, no relevant contributions will be missed.

At the very first considered destination grid point a full scan over all departure grid points is conducted in order to ensure that the correct contributions are determined. This yields a pivot for the next destination grid point. So for the second considered destination grid point the contribution scan will be conducted within a limited block of departure grid points, whereafter the

pivot will be updated for the next destination grid point. This is repeated until the end of the first row of the 2D-grid. When jumping to the next row of the destination grid, the nearest contribution of the neighbour destination grid point at the previous row is taken as the pivot for the first destination grid point at the next row. And so on.

5 The use of the participation mask in the reverse ISM to GCM mapping direction, complicates this approach. If there is a certain number of non-participating destination grid points at the start of a row, the 'jump approach' will be applied to the first participating destination grid point at this row. There are situations possible in which there is no participating point available at the previous row either. Or no contribution is detected at all at the previous scanned neighbouring points. In such **exceptional**
eases relative rare occasions a full scan has to be conducted for these destination grid points, decreasing the computational time
10 performance.

Evidently in the fast scan method a correct estimate of the block size is essential. ~~In order to do so OBLIMAP estimates a scan~~ A block size radius (b) ~~, which can be either manually specified in the configuration file or automatically estimated by OBLIMAP (default), in the latter case b is estimated locally for each destination grid point.~~ It should be as small as possible to obtain the fastest performance while at the same time it should be large enough to obtain identical results ~~as with to~~ the full
15 scan method (which serves as the quality-performance bench mark).

~~The~~ The automatic estimate of b depends on by OBLIMAP differs for the quadrant and radius interpolation method. For the quadrant interpolation method b equals the ratio of the local destination grid resolution over the local departure grid resolution ~~and differs for the quadrant and the radius method, because for the radius method an additional term is included to cover the entire possible area of radius method contributions. Note that the range of~~. For the radius interpolation method the
20 first term of b equals this same ratio as for the quadrant interpolation method, while an additional second term extends the block size in order to capture the entire area covered by the radius of the radius interpolation method. The second term equals the ratio of ~~the grids may be substantial. In the development phase this has been one of the key challenges to make the method general robust. The local grid resolution can differ in each grid direction, in the current method its estimate is based on the distance to the next grid point of the row. In general the projected grid points will not align with the destination grid points, but~~
25 ~~show a certain angle. Therefore an ample rounded b is taken which in fact for most cases yields a small under performance in computational time but ensures a robust quality performance.~~ this radius over the local departure grid resolution. This yields a sharp minimal estimate of b .

Fig. 3 shows ~~how b is determined~~ the construction of a scan block and the determination of the pivot for a regular example of a GCM to ISM mapping using the quadrant method. Fig. 4 shows ~~how b is determined~~ the same for a regular example of an
30 ISM to GCM mapping using the radius method. In general the projected grid points are not aligned with the destination grid points, as shown in these examples. Fig. 3 and Fig. 4 describe the main concept of the fast scan method: For each destination grid point a scan over a local block of departure grid points is conducted where the local block has to be well positioned. In fact the fast scan method basically uses the fact that the local block of the previous search will be close to the local block of the next search for common geographic structured grids.

35 ~~With the optional and~~ The estimate of the local grid resolution is based on the distance to the next grid point of the row. The distance is measured along the surface of the grid. The local grid resolution might vary gradually over the domain of

the departure grid and the destination grid. Due to this gradual trend the estimate of the local grid resolution might deviate for neighbour grid points which lay a few nodes away, which affects the estimate of b . The results with the fast scan method combined with the automatic estimate of b are identical to the full scan results for the majority of encountered mappings.

5 However, due to the possible under estimation of b , distant points could be missed resulting in deviations compared to the full scan result.

A robust automatic fast scan method saves the user to figure out optimal and correct scan parameter settings. In order to achieve a robust automatic fast scan method, the additional 'dynamic block size method' has been added. With the dynamic block size method the initial local estimated block size is increased step by step, until no additional contributions are found detected.

10 The method is coded in such way that only added block borders are checked (for ~~efficient~~ efficiency) and it is consistent with the hereafter mentioned cyclic approach. The dynamic block size method is default switched on, but can be switched off in the configuration file.

~~Beside, additional techniques-~~

In addition, complementary techniques are implemented: 1. In order to deal with cyclic longitudinal domain boundaries. At the east and west longitudinal border of a global departure grid, points at the other side of the departure grid might contain contributions as well. In these cases the block size is extended cyclic by a special treatment. 2. Some equidistant longitude - latitude geographical grids are constructed in such way that the grid row at highest latitude is so close to the geographical pole that all points in this row are situated nearly at the same location but spread in the full longitudinal width over the grid. This is an awkward case for the fast scan method because this requires, and OBLIMAP has to carry out a full scan in longitudinal direction in order to obtain identical results with to a full scan. The longwinded-long-winded description of the exact implementation of these additional techniques is omitted here.

15

20

~~Even if the additional dynamic block size method is omitted, the majority of the fast scan mappings yield identical results with the full scan method. However, including it appears to be very effective in obtaining identical results for the exceptional cases-~~

~~The fast scan method has one general restriction: real world geographical neighbour points must be neighbour points at the grid. Because by far the majority of geophysical applications satisfy this restriction, this might seem rather trivial. However, an example outside the scope of this work, is a long-winded river system which is folded on a more compact rectangular grid. Nearby located grid points may represent distant river locations due to the folding, and therefore erroneously fall inside the scan block. In that kind of cases the fast scan method might fail, and the-~~

25

The fast scan method is applicable to any structured grid. Various surface curvatures and grid cell shapes are allowed, the grid nodes are permitted to be irregularly spaced. The distance calculation is supported for distances over the surface of the sphere, over the ellipsoid and in the flat plane. Because the grid neighbourhood relationship of unstructured grids is not self evident from the grid ordering, the fast scan method is not expected to be applicable for unstructured grids. This applies also to regionally refined grids, which show a discontinuous increase in node density at certain internal grid boundaries and therefore not meet the structured grid conditions. In those cases the full scan method should has to be used. Unstructured grids can be another problematic case for the-

30

35

~~A robust automatic fast scan method, because their possible deviant way of storing the geographical neighbours on the grid. This neighbour ordering can become less straightforward in case in certain shaped areas the node density increases largely. The irregularity of the unstructured grid itself is not an issue for OBLIMAP.~~

- 5 ~~In combination with~~ has been achieved for grids with a gradually varying resolution by including the additional dynamic block size method, ~~the fast scan method is guaranteed applicable in case the 'connection criterion' is fulfilled, i.e. geographical neighbours have to be connected via a sequence of direct neighbours at the grid. In that case the fast scan method even works for unstructured grids yielding identical results to the full scan method.~~

3.2 Masked mapping

- 10 Not ~~seldomly~~ seldom field variables which have to be mapped are not everywhere available on the departure grid. In such cases it is important that masked points can be excluded for interpolation in order to ~~guarentee~~ guarantee the quality performance of the mapping at the borders of the mask. This applies for instance for field variables which are only available at an ice sheet mask, like the surface mass balance (SMB) and refreezing fields as produced by RACMO. In another example one might argue that the missing data at the exterior of the bottom topography field, might be a minor issue in a single mapping because of the
- 15 remoteness of the problem to the area of interest. However, after several times of to and fro mapping the error will propagate into the area of interest.

- With OBLIMAP's masked mapping, invalid masked points are ignored for the interpolation. If for a certain destination grid point the nearest projected departure grid point has an invalid mask, default this destination grid point will be set to that invalid value. However, this ~~behavior~~ behaviour can be changed for each mapped field individually by altering the mask criterion, as
- 20 with the other option all valid contributions are considered irrespective if the nearest contribution has an invalid mask. For each mapped field a ~~seperate~~ separate invalid value can be specified. The mask of each field for the masked mapping is shaped by the pattern of the invalid value for that field. Each mask is allowed to vary in time, and might vary per vertical layer in case the masking is based on a spatial 3D field. Default a mask of a certain field can be based on the invalid value pattern of that field itself, but the mask can also be based on the pattern of one of the other mapped fields. Because masked mapping is a
- 25 post-scanning option it can be switched on and off at any time.

Excluding the masked area might allow a significant decrease of α , the angle which controls the standard parallel, which induces a further ~~optimisation~~ optimization of the projection. In case of a masked mapping and a raised message level OBLIMAP will inform the user about an optimal masked α , estimated by:

$$\alpha = \arcsin \left(\frac{1}{R} \sqrt{\frac{1}{2\pi} (\text{COUNT}(\text{mask})) \Delta x \Delta y} \right) \quad (1)$$

- 30 with R the Earth radius, Δx and Δy the ISM grid spacing in the x and y direction and the 2D mask is 0 for invalid values and 1 otherwise. Eq. (1) equals Eq. (2.2) in Reerink et al. (2010) except that the total number of ISM nodes $N_x N_y$ is replaced by the number of ISM points which have a valid value, being $\text{COUNT}(\text{mask})$.

3.3 Embedded mapping

Once a certain grid combination has been scanned the scanning phase can be omitted if this mapping is repeated off-line or on-line afterwards. With OBLIMAP 2.0 the data of the SID file (for each destination grid point the indices of each contribution and its relative distance to the destination grid point) is stored in the dynamic data object (DDO). With that the off-line performance becomes faster for the multiple field, multiple layer and multiple record mapping. But more importantly, it solves the I/O bottleneck for ~~high-frequent~~ high-frequency on-line coupling.

The redesign and recoding of the OBLIMAP package enables the embedded calling of the same mapping routines which are used in the off-line stand-alone mode. Embedding the OBLIMAP mapping routines basically requires five code additions to the host model: 1. Adding the OBLIMAP initialization routine, which reads the OBLIMAP configuration variables, in the initialization of the host model. 2. Loading the ~~DDO's~~ DDOs for both mapping directions by reading both the SID files in the initialization of the host model. 3. Declaring a vector of spatial 3D fields where the vector length equals the number of mapped fields. 4. Calling the OBLIMAP mapping routines in both directions within the host model time loop. 5. Deallocate the ~~DDO~~ DDOs in the finalizing stage of the host model. OBLIMAP's Application Programmer Interface (API) for additions 2 to 5 is outlined in Fig. 5. The first addition concerns a call to the *initialize-config-variables()* routine, which is usually called one level higher.

The introduction of the DDO in combination with OBLIMAP's redesign solved the I/O bottleneck for ~~high-frequent~~ high-frequency coupling and enables the embedded calling of the mapping routines, which makes OBLIMAP suitable as GCM - ISM coupling software for on-line coupling projects.

3.4 Nearest point assignment

The 'nearest point assignment' is a post scan alternative to the quadrant and radius interpolation method. Instead of interpolating the nearby projected source points on the destination nodes, with this option each destination node obtains the field value of the nearest projected source point ~~disregarding~~ disregarding any other contributions. This method can be combined with masked mapping, in that case a destination node will be always invalid if the nearest projected point has an invalid mask. Regardless which interpolation method has been used during the scan phase, the 'nearest point assignment' can be used in the post scan phase. This option can be considered in case both grids have about the same resolution. The 'nearest point assignment' performs faster than both interpolations methods in the post scan phase.

3.5 Vincenty method for distances on the ellipsoid

An ISM to GCM mapping projects ISM grid points on the Earth ellipsoid. In that case the interpolation requires the distance over the curved surface for the Shepard distance weighting between each projected ISM point and the GCM point. The geodesic, which is the shortest route between two points on the Earth's surface along the great circle, can locally be approximated accurately by the geodesic on the ~~auxiliary~~ auxiliary Earth sphere. OBLIMAP uses this estimate default for the distances on the Earth ellipsoid, because this saves computational time in the scan phase and because the contributions are located close

to each other compared to the Earth radius so the deviations will be small. However, OBLIMAP 2.0 provides the option to calculate the precise geodesics for the ellipsoid by Vincenty's method. Vincenty's inverse numerical approximation (Vincenty, 1975a) is implemented in OBLIMAP.

5 3.6 Mapping multiple layers of spatial 3D fields

In the most common OBLIMAP applications spatial 2D geographical fields are mapped for none, one or more time records. With OBLIMAP 2.0 it is ~~also~~ possible to map spatial [1D, 2D and 3D](#) fields for none, one or more time records. The mapping of 3D fields is in fact limited to the mapping of several parallel vertical layers where each layer simply uses the same mapping, [a so called 2D + 1D approach \(c.f. Liu et al., 2014\)](#). The layers are assumed to be close to each other in comparison with the Earth radius, because for each layer the same Earth radius is applied. Furthermore the horizontal grid distribution of all layers is assumed to be identical to the grid distribution of the top layer. And the fields are only interpolated in the horizontal directions for each vertical layer.

The new OBLIMAP 2.0 netcdf I/O routines automatically detect the spatial dimension of each input field and whether it contains the (unlimited) time dimension. The spatial 2D and 3D fields, including or excluding the time dimension, can be mapped simultaneously and in arbitrary order. With this combination a convenient way of mapping dimensionally different fields is achieved.

3.7 Automated selection of scan parameters

The radius method is recommended as soon as the destination grid resolution is four times larger than the departure grid resolution (Reerink et al., 2010). In all other cases the quadrant method is ~~favoured~~[favoured](#). Based on this criterion the interpolation method is default automatically selected in OBLIMAP 2.0 by checking the ratio of the grid resolutions of the grid ~~centers~~[centres](#). However it is also possible to select the interpolation method manually.

Similarly the optimal radius is default automatically determined for the radius method, if the radius method is selected. OBLIMAP checks whether the geographical grid has cyclic longitudinal grid borders, if so default the cyclic mode will be switched on automatically. Finally OBLIMAP can also determine automatically the optimal angle α which controls the standard parallel of the projection, but this is not default the case.

3.8 Data architecture, messaging and ~~manual~~[the User Guide](#)

OBLIMAP 2.0 stores all fields in a vector of fields with each field a spatial 3D field. In case the spatial dimension of a certain field is lower than 3D, its dimension is reduced when written to a netcdf. This applies also to symmetric dimensions, they will be default reduced if they are fully symmetric in one dimension. The field vector is reused and updated for successive records or time steps.

The geographical scientific climate database conventions are followed in the fully recoded I/O-netcdf interface, which has become highly flexible and which has been largely automatized. The package has been professionalized in the sense that for any

user warning or error we ~~endeavor~~endeavour to provide a meaningful message (see items 11-13 in Table 1). The embedding of the OBLIMAP mapping routines requires the addition of a minimum of code in the host model, for that reason programmer error messages are added in order to prevent improper software usage. The ~~newly added OBLIMAP manual~~new OBLIMAP User Guide (Reerink, 2016) serves the user to correctly configure the mappings and OBLIMAP's options.

5 4 Performance and applications

4.1 Computational time performance

Sixty benchmark mapping experiments have been used, representing a diverse set of mappings which differ in number of nodes, grid resolution, mapping direction, interpolation method, location and thus also in projection. This relative arbitrary set of benchmarks has been used to evaluate the computational efficiency of the fast and full scan method.

10 The mapping experiments in Fig. 6 are subdivided by different symbol colours: ISM to GCM mappings are plotted red and purple for the quadrant and radius interpolation method respectively. GCM to ISM mappings are plotted blue and light blue for the quadrant and radius interpolation method respectively. The typical error in the time measurements is twice the size of the plot symbol in the figure, and is obtained by repeating the mapping many times.

The part of the Earth's surface which is covered by ice is limited in comparison with the entire ocean - atmosphere surface. 15 Therefore the number of grid nodes which are involved in the mapping is significantly lower than the total number of GCM nodes. This is relevant with respect to the time performance plotting. Therefore the performance is plotted in Fig. 6 as function of N the number of participating destination grid points multiplied with the number of departure grid points. The data is plotted on a logarithmic scale for both axes in Fig. 6, which improves the visualization of the trends compared to the otherwise rather sparse clustered plotting.

20 The time spent in the full and fast scan routines are measured by including built-in Fortran time counting routines inside the OBLIMAP code, and are shown for this set of mappings respectively in Fig. 6a and Fig. 6b. Fig. 6c shows the gain factor (equal to the full scan time divided by the fast scan time) for these mappings if the fast scan method is used instead of the full scan method. Fig. 6d shows the total gain achieved per individual 2D field in case the post scan fast mapping is used instead of the full scan method. For the latter the fast mapping time is divided by the number of fields, layers and records because they 25 might differ for each of the mappings.

Fig. 6a shows a strong increase of the computational time with N for the full scan method. Clearly visible are the ~~seperate~~separate branches for the different mapping directions though their trend is similar. In contrast no significant differences are caused due to the selected interpolation method. As can be seen from Fig. 6b the computational time for the fast scan method is much lower, and though it increases with N , it is important to observe that it levels off for higher N which is also reflected 30 in Fig. 6c where the gain factor strongly increases with N . The scattering in Fig. 6b is larger than in Fig. 6a because the size of the local scan block is sensitive to the individual grid configurations. Because the fast scan times are relative fast, this causes a relative large influence. As a consequence the gain factor and the total gain factor are influenced by this scatter of the fast scan method measurements. The large values of the gain factor in Fig. 6c show that the fast scan method is orders of magnitude faster

than the full scan method. Fig. 6d shows a strong increasing trend of the total gain factor up to $\sim 10^6$ at $N = 10^{12}$. ~~The typical~~
For example the fast mapping time of one individual 2D field is about $\sim 10^{-2}$ seconds for $N = 10^{10}$, which corresponds with
an high resolution application in which the Greenland area is mapped between a 0.1° GCM grid and a 5x5 km ISM grid.

5 4.2 Masked and non-masked mapping applications

~~We start with some general remarks-~~

This section shows masked mapping for a relevant set of applications and different masking issues are discussed. At the
same time this section demonstrates that OBLIMAP's stand-alone version is a powerful tool which is able to map diverse
kinds of topographic and forcing data sets onto any ISM grid configuration with an optimal oblique projection. The publicly
available high resolution topographic data sets are remapped (reprojected from a polar to an optimal oblique aligned projection
for the ellipsoid) for each area on a certain ISM grid of preference, i.e. with the desired grid extensions and grid resolution.
The atmospheric forcing data sets which are defined on a reduced gaussian grid of the regional RACMO2.3 model, are mapped
from the sphere to the same ISM grids. The geothermal heat flux field which is defined on a global regular longitude-latitude
grid, is also mapped from the sphere to these same ISM grids. Besides, these different data sets cover a wide resolution range
and map the two major ice sheets Greenland and Antarctica, in addition the Antarctic Peninsula example shows how a local
subregion is mapped with its own optimal oblique projection.

Table 2 lists the mapping parameters for each mapping on the three ISM grids in the various mapping examples. In case
a data set is remapped, the coordinates are projected twice, however the fields are only interpolated at the final destination
grid in order to minimize the mapping error. The first projection leaves the field data unaffected, only the (x,y)-coordinates are
converted to (longitude, latitude)-coordinates. This task can be conducted by the oblimap convert program which is part of the
OBLIMAP-package (see the OBLIMAP User Guide (Reerink, 2016)).

4.2.1 Plotting projected data

Some general remarks are made concerning the plotting of the pre and post mapped data displayed in Figs. 7-12. The high
quality data itself is saved in netcdf files. In order to visualize those fields, pythons matplotlib and its basemap ~~extention~~
extension are used to script the plotting. For plotting fields which are defined on grids which are based on geographical
coordinates, a projection has to be specified with basemap.

The plotting interpolates the fields once projected by the plotting. Though the selection of the plotting projection can be
independently and arbitrary chosen from the mapping projection, we used for most GCM field plots a plotting projection which
is similar to the mapping projection. The fields on the ISM grid are plotted as true grid values, i.e. no plotting interpolation has
been applied. In several subfigures one black or a few coloured contours are plotted on top of the data. In several subfigures the
ETOPO dataset-data set (Amante and Eakins) is used as background for the masked mapped areas or for a surrounding area
with a constant value. Usually this concerns the ocean basin and remote areas. Plotting the data on the ETOPO dataset-data set
also serves as a check because all coastline contours should coincide.

The availability of the high-resolution topographic and atmospheric forcing datasets for the Greenlandic and Antarctic ice caps opens in combination with the OBLIMAP 2.0 package the opportunity to model the major Earth ice caps or parts of them with an optimal centered projection. These applications are shown here as mapping examples. Additional examples show the local mapping of the Antarctic Peninsula and the mapping of a geothermal heat flux forcing dataset. lists the mapping parameters for each mapping on the three ISM grids in the various mapping examples.

In case of remapping a dataset, the coordinates are projected twice, however the fields are only interpolated at the final destination grid in order to minimize the mapping error. The first projection leaves the field data unaffected, only the (x,y)-coordinates are converted to (longitude, latitude)-coordinates. This task can be conducted by the oblimap-convert program which is part of the OBLIMAP-package.

4.2.2 Topographic fields for Greenland

The publicly available topographic ~~dataset~~ [data set](#) for Greenland (Bamber et al., 2013) contains the surface topography, the bedrock topography and the ice thickness for the present day situation and is projected by (Bamber et al., 2013) with a polar SG projection on an ISM grid with a 1x1 km resolution. In a post-processing phase some manual corrections are applied to this 1x1 km ISM grid (Bamber et al., 2013).

In order to obtain an optimal ~~centered projection this dataset~~ [centred projection this data set](#) has been remapped by first applying the inverse polar projection on all coordinates of this data set (see Fig. 7a and Fig. 7c) and thereafter this result is mapped with an optimal ~~centered~~ [centred](#) oblique SG projection on an ISM grid with a 5x5 km resolution (see Fig. 7c and Fig. 7d).

No masked mapping is used for the mapping of the surface topography on the ISM grid in Fig. 7b because it concerns a field which literally levels off to ~~sealevel~~ [sea level](#) (the zero level). Because the bedrock topography contains missing values (see the white bottom corner areas in Fig. 7c), a masked mapping is used for this field. Resulting in a properly mapped mask border, as can be seen at the bottom right corner of Fig. 7d.

Note that in fact it would be possible to directly map the irregular spaced measured data points, but then the manual applied corrections are lacking.

4.2.3 Atmospheric forcing fields for Greenland

The [present day RACMO2 atmospheric forcing dataset for Greenland \(van Angelen et al., 2014\) containing the surface mass balance .3 atmospheric forcing data set for Greenland \(Noël et al., 2015\) which is provided as supplementary material and contains the surface mass balance \(SMB\), the surface air temperature, the surface refreezing, runoff-run-off](#) and other fields, is defined on a ~~gaussian-reduced~~ [reduced gaussian](#) grid with an approximate horizontal resolution of about 11 km (see Fig. 8a and Fig. 8c). These fields are mapped with the same projection on a grid with the same 5x5 km resolution and extent as used in Sect. 4.2.2. The SMB field in Fig. 8a only contains valid values for ice covered grid points, and is therefore masked mapped on the ISM grid (see Fig. 8b). The same applies for the refreezing in Fig. 8c which is also masked mapped on the ISM grid (see Fig. 8d).

4.2.4 Topographic fields for Antarctica

The publicly available Bedmap2 topographic ~~dataset~~data set for Antarctica (Fretwell et al., 2013) contains the surface topography, the bedrock topography and the ice thickness for the present day situation and is projected by (Fretwell et al., 2013) with a polar SG projection on an ISM grid with a 1x1 km resolution.

10 In order to obtain a ~~dataset~~data set which can be mapped on any (local) grid with OBLIMAP, the inverse polar projection is applied on all coordinates of this data set (see Fig. 9a and Fig. 9c). Thereafter this result is mapped with the same polar SG projection on an ISM grid with a 20x20 km resolution (see Fig. 9c and Fig. 9d). Though this might seem superfluous, the advantage is that from this longitude - latitude based ~~dataset~~data set a grid of any grid extent and resolution can be created with OBLIMAP. In addition any optimum ~~centered~~centred local grid can be created ~~as well from this dataset~~from this data set
15 as well, like for instance the local area of the Antarctic Peninsula (see Sect. 4.2.6). We choose the common polar SG projection for entire Antarctica, however given the position of the Antarctic continent a slightly oblique projection might in fact yield the optimal projection.

No masked mapping is used for the mapping of the surface topography on the ISM grid in Fig. 9b because it concerns a field which literally levels off to ~~sealevel~~sea level (the zero level). Because the bedrock topography contains missing values (see the
20 white corner areas in Fig. 9c), a masked mapping is used for this field. Resulting in a properly mapped mask border, as can be seen at the corners of Fig. 9d.

4.2.5 Atmospheric forcing fields for Antarctica

The ~~present day RACMO2~~atmospheric forcing dataset.3 atmospheric forcing data set for Antarctica (Van Wessem et al., 2014) ~~containing which is provided as supplementary material and contains~~
25 ing, ~~runoff~~run-off and other fields, is defined on a ~~gaussian-reduced~~reduced gaussian grid with an approximate horizontal resolution of about 27 km (see Fig. 10a and Fig. 10c). These fields are mapped with the same projection on a grid with the same 20x20 km resolution and extent as used in Sect. 4.2.4. The SMB field in Fig. 10a only contains valid values for ice covered grid points, and is therefore masked mapped on the ISM grid (see Fig. 10b). The same applies for the refreezing field in Fig. 10c which is also masked mapped on the ISM grid (see Fig. 10d)

30 The refreezing field in Fig. 10c is an example of a source field with an inadequately defined value for the missing data which equals zero in this case. This zero value is inconvenient here because the field values themselves reach zero in the interior of Antarctica. Coincidentally this implies that a masked mapping based on an invalid value which is taken equal to zero, will affect the mapping of the zero contour inside the interior of Antarctica as well. Despite this error the masked mapping is still to be preferred over the non masked mapping in this case because the latter one yields large errors at grid points in the vicinity of the coastline. Here we circumvent this problem by using the ice-cover mask, which is co-distributed as part of the RACMO2~~dataset.3~~data set. In this case the ice-cover mask is used as the mask for the masked mapping of the refreezing, which illustrates the flexibility of the masked mapping options. Preferably the invalid value for the missing values of the source
5 fields have a value outside the range of the actual field values in order to avoid this problem.

4.2.6 Local mapping of the Antarctic Peninsula

In contrast to the polar projection used in Sects. (4.2.4-4.2.5), a local mapping of the Antarctic Peninsula demonstrates an oblique projection example with the same ~~datasets~~data sets. The Bedmap2 surface topography (Fig. 9a) and the Bedmap2 bedrock topography (Fig. 9c) have been mapped on a local 5x5 km ISM grid for the Antarctic Peninsula with an optimal ~~entered~~centred oblique projection without using a mask (see Fig. 11a and Fig. 11b). The RACMO2.3 SMB (Fig. 10a) and the RACMO2.3 refreezing (Fig. 10c) ~~for the year 2006~~ have been masked mapped on the same local 5x5 km ISM grid with the same optimal ~~entered~~centred oblique projection (see Fig. 11a and Fig. 11b).

4.2.7 Mapping the geothermal heat flux

The spatial variable geothermal heat flux (Shapiro and Ritzwoller, 2004) which is defined on a global regular $1^\circ \times 1^\circ$ longitude - latitude grid (see Fig. 12a) for the present day situation, is another forcing ~~dataset~~data set which can be mapped on the same grid. In Fig. 12b this geothermal heat flux has been mapped on the same 5x5 km ISM grid with the same optimal ~~entered~~centred projection for Greenland as in Sect. 4.2.2. In Fig. 12c the geothermal heat flux has been mapped on the same 20x20 km ISM grid with the same optimal ~~entered~~centred projection for Antarctica as in Sect. 4.2.4. Finally in Fig. 12d the geothermal heat flux has been mapped on the same 5x5 km ISM grid with the same optimal ~~entered~~centred projection for the Antarctic Peninsula as in Sect. 4.2.6.

4.3 Coupling and embedding

An experiment in which a GCM is on-line coupled with an ISM consists of much more than the technical coupling task. Perfectly mapped fields may require a successive downscaling step. Several ~~deecissions~~decisions have to be made concerning issues like to which degree the on-line coupling will be conducted, which fields are available for a particular GCM - ISM combination and can be effectively used, which model time steps and coupling time step will be used and does that require certain time averaging prior to each coupling step, and for which fields only the perturbations will be used in the coupling. Examining the results should learn whether the coupling is numerically stable, if the feedback mechanisms do properly work and to which extent the resolution differences limit the coupling of the models. Presenting coupled results requires the evaluation of these issues and the description of the used GCM and ISM, but that is far beyond the scope of this paper.

Instead we only shortly report that we coupled the IMAU-ICE model with CLIMBER-2 (Petoukhov et al., 2000) by using OBLIMAP's mapping routines embedded. We benefit from CLIMBER's Fortran77 implementation in which all relevant variables for the coupling are globally defined. This makes it possible to embed CLIMBER in the ice sheet model without major recoding of CLIMBER. Therefore in this case the ice sheet model is taken as the host model and the OBLIMAP mapping routines are embedded in the ice sheet model as well. The low CLIMBER resolution certainly limits the coupling degree, but appeared to be suitable for practical and technical learning purposes, because the IMAU-ICE - CLIMBER coupled model technically easily operates on a laptop. In general however, due to its complexity, it is preferable to take the GCM as the host model.

5 Discussion

OBLIMAP's full scan method is robust and suitable for any GCM - ISM grid combination regardless of the irregular spacing of the grids and their arbitrary ~~ordering~~ ordering including unstructured grids. ~~It~~ The full scan method is used for benchmarking, but can also be used in special cases like ~~the embedment of~~ embedding a flow line model or ~~the embedment of a very~~ embedding a low resolution model like CLIMBER. The ~~withdrawal~~ withdrawal of the full scan method is its slow performance. This becomes a serious bottleneck for larger grid combinations, i.e $N \gg 10^{12}$.

The fast scan method is orders of magnitude faster, especially for larger grid combinations, ~~but the involved grid ordering has to suffice one of the following rather general conditions (see also):~~ 1. Geographical neighbour points must be neighbours on the grid (except for cyclic longitudinal borders which are also allowed). 2. The neighbour connectivity criterion. The first condition is the most severe restriction as it will often not hold for unstructured grids, though for many geographical grids it is a rather general and trivial condition. The weaker second condition requires that two geographical neighbour points are connected via a sequence of direct neighbours. In that case, The fast scan method is applicable to structured grids. It would require an additional index mapping of the external stored neighbourhood relationships, to enable the fast scan method works ~~if the dynamic block size is switched on, even for unstructured grids which satisfy the second condition.~~

For large datasets it is important to note that if suddenly a tremendous slow down is encountered with increasing N , it is likely that the size of the processor memory is the bottleneck. ~~In that case it is recommended to switch to a platform with a larger processor memory.~~ This index mapping methods are expected to vary across different unstructured grid applications. OBLIMAP's fast scan method reduces the search time. The same objective has been addressed in OASIS4 (Redler et al., 2010) in a parallel approach, though Valcke (2013) reports that its development is not pursued.

~~In fact there are various~~ There are three variants of the fast scan method ~~variants~~ available in OBLIMAP 2.0, ~~and although the fastest ones work in the most situations, there:~~ 1. A fixed block size radius (b) is manually specified, each search uses the same b which should be large enough. 2. A local b is estimated by OBLIMAP itself. 3. The second variant is extended with the dynamic block size method. The differences in computational time performance between the variants is limited. There is a trade off between the best performance and robustness. ~~With robustness we mean that the fast scan method yields~~ The third variant is robust in any situation ~~identical results as~~, and is therefore the default. Robust means that the results are identical to those obtained by the full scan method. ~~The differences in performance between the various fastscan methods is limited. In OBLIMAP 2.0 contains an option which determines the (fast) scan parameters automatically, in order to avoid that the fast scan method requires expert knowledge to configure it, OBLIMAP 2.0 comes with an option which determines the fast scan parameters automatically~~ expert knowledge is required to configure the scan parameters. This option is default switched on.

~~The situation in which a regular~~ Some simple longitude - latitude ~~grid is defined up to the pole in such way that for instance grids include a full row of longitude nodes near or at 90° North. In that case the location of N_{LON} points coincide with almost the same loction (while nodes coincide, while in practice the field values of these nodes are not identical), requires the addition of a full longitude search in the vicinity of the poles as discussed in in order to obtain identical results with the full scan method. For the sake of guaranteed robustness with~~ In order to guarantee the robustness of the automatic fast scan mode, the in these

cases, a full longitude scan is applied ~~for the near polar area of any grid with $|\text{latitude}| \geq 87^\circ$. For in the vicinity of the polar area for all nodes with $|\text{latitude}| > 87^\circ$ (as discussed in Sect. 3.1.3). The scanning of~~ this kind of grids themselves is usually fast enough, so this is not a major issue, ~~their scanning is usually fast enough.~~ But this full longitude scan at high latitudes also applies to other high resolution grids, leading to a performance decrease. Automatic detection, whether a situation requires a full longitude scan, would be an advantage in a future OBLIMAP release, avoiding unnecessary performance loss.

~~In case~~ If the quadrant interpolation method is used in combination with the full scan method, ~~sometimes a rather remote contribution is detected it is possible that~~ in one of the quadrants ~~in comparison with the detected contributions in a relative remote contribution is detected compared to~~ the other quadrants, ~~because~~. This can occur due to nearby missing data while the quadrant interpolation method continues searching for the nearest contribution until it is found ~~(Reerink et al., 2010). This is usually due to missing data or because it concerns a contribution originating from the vicinity of the departure grid border.~~ The remote contribution has a very limited influence on the interpolation due to the distance weighting. However, with the fast scan method the limited block size deselected this remote ~~byte~~ catch by catch and accordingly the results are not identical but deviate insignificantly. In fact the fast scan result is ~~even favourable~~ favourable in this case.

~~We conclude that the default automatic fast scan method is robust, indispensable for large grid combinations (i.e. for large N) and can be safely used by non-expert users.~~

OBLIMAP is able to map between models which differ largely in resolution. ~~But in~~ In particular if the destination grid is much coarser than the departure grid, the computational time ~~inevitably increases~~ increases inevitably for both the fast scan method and the fast mapping due to the large radius in the radius interpolation method. For large data sets it is important to note that if a sudden tremendous slow down is encountered while N is increased step by step, it is likely that the size of the processor memory is the bottleneck. In that case it is recommended to switch to a platform with a larger processor memory.

We conclude that the default automatic fast scan method is robust, indispensable for large grid combinations (i.e. for large N) and can be safely used by non-expert users.

Various examples for different resolution combinations show that the masked mapping works well, i.e. artefacts are absent in the vicinity of the mask borders and the fields represent realistic values as shown in Figs. 7-11. The masked mapping method is ~~indispensible~~ indispensable for products like the SMB, the refreezing and the ~~runoff~~ run-off, because their values differ strongly along the mask border. In case fields like the surface topography are mapped frequently to and fro, masked mapping prevents the propagation of artefacts into the domain of interest. Besides, these figures show the high quality of the masked and non-masked fields with high resolution.

~~If the available datasets~~ OBLIMAP is a powerful tool to map data sets which might differ in grid ~~extent~~ surface curvature, grid type, grid resolution and grid ~~type are based on longitude – latitude coordinates or as soon they have been converted to that,~~ OBLIMAP is a powerful tool to map them all extent on an equal arbitrary ISM grid by the same optimal ~~centered projection, and vice versa. centred projection.~~ Although 'optimal' and '~~centered~~ centred' are the recommended preferences, neither of them is a prerequisite. This is demonstrated for the topographic, atmospheric forcing and geothermal ~~heatflux datasets~~ heat flux data sets by the applications in Sect. 4. Similar, the ice surface velocity ~~dataset~~ data set for Greenland (Rignot and Mouginot, 2012) could also be mapped on ~~the an~~ an ISM grid for Greenland. The topographic and geothermal heat flux data sets for Greenland

and Antarctic are public available. The present day time-averaged RACMO2.3 atmospheric forcing data sets for Greenland (Noël et al., 2015) and Antarctic (Van Wessem et al., 2014) are provided as supplementary material.

The redesign and recoding of OBLIMAP in combination with the DDO introduction ~~ensure~~ ensures that the embeddable OBLIMAP 2.0 mapping routines are suited to bridge the ~~techniqua~~ technical task of on-line coupling in both directions. As indicated in Sect. 3.3 and in Fig. 5, five code items have to be added in the host model in order to embed the OBLIMAP mapping routines. ~~Preferably the ISM is embeddable, because usually it will be beneficial if the GCM is the host model candidate due to its complexity.~~ OBLIMAP is subdivided in the standard components: 'Initialize', 'Run' (map and inverse map) and 'Finalize', this allows direct embedding in the ISM, in the GCM or in an ESM component coupler. Note that the mapping routines pass on all fields as an argument, which makes embedding of OBLIMAP low intrusive. The embed strategy might depend on the specific GCM – ISM combination as well on the coupling approach: one way or two way on-line coupling. In case a two way on-line coupling is considered, we suggest to embed the ISM in the GCM or in the ESM component coupler. The ISM has then to be recoded in 'Initialize', 'Run' and 'Finalize' components, but this approach avoids invasive modifications of the GCM code. For this reason we plan to ~~seperate~~ separate the initialization phase and the time loop for IMAU-ICE. At the same time, an embeddable ISM allows the simultaneous embedment of multiple ISM domains like e.g. Greenland and Antarctica, each with its own projection and configuration file. In addition it enables the simultaneous simulation of several ice cap domains by the ISM in case they are mutual connected by the ~~sealevel~~ sea level evolution, similar with the approach of De Boer et al. (2014).

Like the C-Coupler (Liu et al., 2014) the 3D field mapping concerns a 2D + 1D mapping, in the sense that the horizontal mapping includes the 2D interpolation. Each vertical layer is treated with the same 2D horizontal interpolation but is not interpolated in the vertical direction by OBLIMAP. Returning the vertical layers just as vertical records is a conscious choice, because it keeps the best flexibility. For example it allows the vertical coordinate to change without affecting the mapping, i.e. avoiding a repeated scan phase. This is particular important regarding the vertical zeta coordinate in ISM models which usually not only changes in time but even changes per grid node in time. In this way the vertical grid is allowed to match with either a real or scaled coordinate and could differ per field, again without affecting the mapping. It allows direct downscaling if one wishes, which in that case saves one interpolation step. This is all possible without losing much on the performance, because the vertical interpolation is computational straightforward and at low cost.

The projection step is an essential obligatory step in case two models run on differently curved surfaces. This is the case for GCM – ISM coupling when a GCM which runs on the surface of the Earth Sphere is coupled with an ISM which runs on a flat plane. In contrast, regridding between two ESM components which both run on the same Earth Sphere surface requires only the interpolation step and the projection is not needed as one stays on the same curved surface. The additional (inverse) projection step in GCM – ISM coupling has a few important consequences for the cross grid search. Due to the projection, it is in general a priori unknown how the grid nodes of the two grids are related to each other, the projected nodes can end up anywhere depending on the projection. The scan method has to robustly cope with that. Other specific requirements in GCM – ISM coupling are: (1) The ISM grid concerns a local part of the GCM which requires a neat treatment of this mapped ISM domain border. (2) Mapping ISM fields from a local ISM grid onto a larger scale GCM grid requires a merge of the mapped

parts into the existing GCM fields. (3) The range of resolution ratios is much larger, i.e. often the ISM grid resolution is much finer than that of the GCM. These specific requirements are the cause that GCM – ISM coupling is not standard included in the existing ESM component couplers like OASIS3 or OASIS3-MCT, the ESMF, CPL6 and CPL7 couplers, or the C-Coupler.

10 OBLIMAP addresses these specific GCM – ISM coupling issues, whereas the ESM component couplers are complex hubs from which a variable amount of ESM components are coupled. Nevertheless, there are also many functional similarities like cross grid searching, interpolating, off-line generation of weight factors, reading the weights and using them for a fast interpolation, generic field exchange, embedding and strategies to parallelize the high cost cross grid search method. OBLIMAP's masking facility is comprehensive and highly flexible compared to the other couplers, it is independent of the scan phase. Each
15 field can be masked based on a user specified masking value, this masking pattern is allowed to change in time and per vertical layer. Masking of a certain field can also be based on the mask pattern of another field. OBLIMAP actually does not store the weight factors like SCRIP does, instead the indices of the contributions and their distances are stored in the SID file. This offers the flexibility in a post scan phase to change the mask and the distance weighting exponent. The SID file and DDO have been designed such that the required processor memory is minimized. Non-participating destination points are not stored in
20 the SID file. OBLIMAP does not use the matrix multiplication like several ESM component couplers. If a fine grid is mapped on a coarse grid the large number of contributions per destination grid point cause a rather large amount of non-zero diagonals in the sparse matrix. Instead OBLIMAP uses the direct access to the indices and distance of the contributions via the DDO (which has to be loaded only at initialization), which allows a very fast evaluation.

OBLIMAP does not include an area conserved interpolation method. Jones (1999) shows that first order area conservative
25 interpolation is much less accurate (especially for fields with large gradients) than e.g. bilinear interpolation. Jones (1999) therefore presents a more accurate second order area conservative interpolation. The second order variant needs the gradient of the field, which is problematic because this does not allow prior off-line generation of the interpolation weights, and is field dependent. Therefore the ESM component couplers use the first order area conservative remapping of SCRIP (Jones, 1999) which is able to regrid between two spherical coordinate systems.

30 For large scale ice caps it is important that flow directions are not affected by the projection in order to stay close to the physical representation of the models. This means that a SG projection is used which slightly deforms the area of each cell. The combination of a projection with an area conservative mapping leads to large errors: If for instance the area of a cell shrinks by 1%, the value of that cell will increase by 1% to compensate due to the area conservation. However, the area mismatch is compensated after the reverse mapping. OBLIMAP's strategy is to reduce the area distortion by using oblique
35 projections and an optimal standard parallel. The accuracy of the direction dependent ice flow physics is preferred over exact area conservation, the latter would be only possible in combination with a LAEA projection. The conservation of the GCM – ISM coupling should be judged by comparing the results after to and fro mapping. This requires adequate tests, like those carried out by Reerink et al. (2010). The quadrant and radius interpolation method which are based on the inverse squared distance weighting show results close to conservation. OBLIMAP uses the radius method to obtain a representative estimate
5 for mapping from fine to coarse resolution grids.

OBLIMAP is dedicated to the GCM - ISM mapping and coupling task in both mapping directions and developed from that perspective. However, OBLIMAP might be very well applicable to other geophysical mapping problems because the included mapping components like the projection, the regridding and the fast scan method for structured grids are based on a generic implementation.

10 ~~Although the subjects which are treated by OBLIMAP for example rather resemble those of a frequently used GCM component coupler like OASIS, it is remarkable how much the implementations differ (cf. Valeke, 2013). One obvious difference is the additional projection step in OBLIMAP. Further, OBLIMAP's interpolation methods are able to cope with the irregular spaced locations where the projected points end up after they have been projected on the destination surface, which make them at the same time suitable for irregular spaced departure and destination grids. Moreover the OBLIMAP interpolation~~
15 ~~methods have to be robust for relative large resolution differences. OBLIMAP 2.0 comes with the fast scan method in order to reduce the search time. The same objective has been addressed in OASIS4 (Redler et al., 2010) in a parallel approach, though Valeke (2013) reports that its development is not pursued.~~ Could OBLIMAP become an ESM component coupler? Actually it is not our goal as there are several ESM component couplers available. Adding to OBLIMAP the sphere to sphere mapping without a projection step, will be straightforward. In addition a MCT (Larson et al., 2005) combination with OBLIMAP could
20 then provide the hub functionality. An inventory of the design of the ESM component couplers seem to show that this matches well with OBLIMAP. Concerning the primary functionalities there seems thus to be no obstruction.

Adaptive grids require ~~continuous scanning~~, repeated scanning each time one of the grids ~~changes the scan has to be repeated~~ has changed. With the current ~~sequential-serial~~ OBLIMAP code only lower-frequency on-line coupling of low resolution adaptive grid models is feasible using the fast scan method. Embedding the mapping routines ~~, including in combination~~
25 with allowing repeated scanning, changes the list of code addition as indicated in Sect. 3.3 as follows: The second item is replaced by an allocation statement inside the time loop in the host model, with a successive call to the embeddable scan routine for each mapping direction. The fifth item, the ~~deallocation~~ deallocation of the DDO needs to move inside the time loop at its end. However, a parallel implementation will be beneficial for on-line coupling of adaptive grids and will extend the possibilities.

30 ~~On platforms which have at least the same number of processors available as the number of participating destination grid points, a possible new efficient and straightforward parallel implementation of OBLIMAP's full scan method can be developed. In that case the expected time for the parallel full scan method will be reduced and is~~

It is possible to implement an efficient scalable parallel domain decomposition of the full and fast scan method. The results of this parallel MPI implementation are expected to be faster than the sequential fast scan method. This yields two advantages:
35 1. The full scan method becomes fast, e.g. the scanning of any kind of grid including unstructured grids becomes fast. 2. On-line coupling of adaptive grids becomes feasible as long N is not too large but remains limited to ordinary applications.

An alternative hybrid approach combines the fast scan method with a parallel approach. As explained in the bitwise identical for a changing number of processors. The same is expected for the fast mapping scheme. The challenge will be to reduce the used processor memory per node, as in a straightforward parallel approach each core will allocate its own copy, which will
5 limit the scalability for large grid applications. A parallel full scan method will serve applications which use unstructured grids.

~~A parallel~~ fast scan method slows down if situations are encountered in which none of the previous scanned neighbours is a participating point at the row jump or if no contributions were detected. An effective hybrid approach therefore could use one processor per row, starting with a full scan at the first participating point of each row. Whereafter each processor continues the scan of its row with the fast scan method. This hybrid approach requires a much smaller number of processors than the first proposed parallel approach, and is expected to be almost as fast. will serve applications which use structured grids, in particular if this concerns on-line coupled adaptive grid applications which require the scan phase each time one of the grids change.

We expect that both proposed parallel implementations scale well because the slave processors do not need any mutual communication during their task. They only need access to the DDO and their results have to be collected by the master processor afterwards.

The hybrid approach could serve as the starting point for heavier applications. An extra performance

An extra performance gain could be realized ~~by using more processors to carry out each full scan at the start of each row. The~~ when the single initial full scan over the departure grid points ~~is then split up between several processors, this however is a slightly~~ at the start of a destination grid row (which is at some points required), is split up over more processors. However, this concerns a more complex parallel task. ~~Because after a first scan the pivots off all points are known, in another combinational approach implementation. Apart from this another strategy~~ for adaptive grids could be to make use of the pivots of the previous mapping ~~could be used for a local block search if they are remembered and updated~~ step by remembering and updating them. This works under the assumption that the adaptive grid changes are locally smooth. It could potentially realize a large performance gain for ~~both the parallel and the sequential implementation~~ a parallel and serial approach.

6 Conclusions

With a significant ~~extended larger~~ range of applications than its prior version, OBLIMAP 2.0 has become much faster and easier to configure. ~~A manual~~ The OBLIMAP User Guide has been added to precisely describe OBLIMAP's ~~user comprehensive~~ options. The increase in performance, the ability to map ~~much larger grid combinations~~ grids with much more grid nodes, the extensive and flexible way of masked mapping, and the fact that the OBLIMAP mapping routines can be used embedded in an high-frequency on-line ~~high frequent~~ coupled application, are among the main achievements of OBLIMAP 2.0 while OBLIMAP's high accuracy and robustness is maintained.

The power of OBLIMAP is its ability to map various ~~kind of datasets which can~~ data sets, which are defined on different curved surfaces and may largely differ in grid resolution ~~and grid extent,~~ extent and type, by an optimal ~~centered projection~~ centred projection on one destination grid of arbitrary configuration. This potential has been demonstrated by ~~a few~~ relevant examples in which topographic, atmospheric forcing and geothermal heat flux fields from various ~~datasets~~ data sets have been mapped on grids for the two major ice caps.

The fast and fully ~~sequential~~ serial OBLIMAP 2.0 package is lightweight and suitable to run on a laptop. ~~Future implementation~~ of one of the discussed parallel approaches Its stand-alone version can be installed and compiled within a couple of minutes

on any platform. A future parallel approach, using MPI, offers the possibility of an additional performance gain in a next OBLIMAP release.

Code and data availability

The OBLIMAP 2.0 code, the present day averaged RACMO2.3 atmospheric forcing data sets for Greenland and Antarctica and
10 the OBLIMAP ~~manual~~User Guide are available as supplementary material (<http://www.geosci-model-dev.net/???-supplement.zip>)
and are distributed under the terms of the GNU General Public License. A git checkout can be obtained from OBLIMAP's Github: https://github.com/oblimap/oblimap-2.0. If any problems are encountered with the code, please feel free to contact us (tjreerink@gmail.com).

Acknowledgements. We thank Melchior van Wessem ~~and Jan van Angelen~~ for providing the RACMO2.3 data of Antarctica ~~and Greenland~~.

We thank Bas de Boer, Michiel Helsen, Heiko Goelzer and Sarah Bradley for their user feedback over the years on the OBLIMAP package.

5 This project has been funded by Kennis voor Klimaat (KvK) and by a grant from the Netherlands Earth System Science Centre (NESSC) from the ~~netherlands organization for scientific~~ Netherlands Organization for Scientific research (NWO). The ~~RACMO datasets~~ RACMO2.3 data sets could be provided ~~due to~~ within a NESSC-WP3 collaboration.

References

- Amante, C. and Eakins, B.: ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA, 2009, <http://www.ngdc.noaa.gov/mgg/global/global.html>, doi:10.7289/V5C8276M.
- Bamber, J. L., Griggs, J. A., Hurkmans, R. T. W. L., Dowdeswell, J. A., Gogineni, S. P., Howat, I., Mouginot, J., Paden, J., Palmer, S., Rignot, E., and Steinhage, D.: A new bed elevation dataset for Greenland, *The Cryosphere*, 7, 499–510, doi:10.5194/tc-7-499-2013, <http://www.the-cryosphere.net/7/499/2013/>, 2013.
- Craig, A. P., Jacob, R., Kauffman, B., Bettge, T., Larson, J., Ong, E., Ding, C., and He, Y.: CPL6: The New Extensible, High Performance Parallel Coupler for the Community Climate System Model, *International Journal of High Performance Computing Applications*, 19, 309–327, doi:10.1177/1094342005056117, <http://hpc.sagepub.com/content/19/3/309.abstract>, 2005.
- Craig, A. P., Vertenstein, M., and Jacob, R.: A new flexible coupler for earth system modeling developed for CCSM4 and CESM1, *International Journal of High Performance Computing Applications*, 26, 31–42, doi:10.1177/1094342011428141, <http://hpc.sagepub.com/content/26/1/31.abstract>, 2012.
- De Boer, B., van de Wal, R. S. W., Lourens, L. J., Bintanja, R., and Reerink, T. J.: A continuous simulation of global ice volume over the past 1 million years with 3-D ice-sheet models, *Climate Dynamics*, 41, 1365–1384, 2013.
- De Boer, B., Stocchi, P., and Van De Wal, R. S. W.: A fully coupled 3-D ice-sheet-sea-level model: Algorithm and applications, *Geoscientific Model Development*, 7, 2141–2156, 2014.
- De Boer, B., Dolan, A. M., Bernales, J., Gasson, E., Goelzer, H., Gollidge, N. R., Sutter, J., Huybrechts, P., Lohmann, G., Rogozhina, I., Abe-Ouchi, A., Saito, F., and Van De Wal, R. S. W.: Simulating the Antarctic ice sheet in the late-Pliocene warm period: PLISMIP-ANT, an ice-sheet model intercomparison project, *Cryosphere*, 9, 881–903, 2015.
- Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., Bianchi, C., Bingham, R. G., Blankenship, D. D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A. J., Corr, H. F. J., Damaske, D., Damm, V., Ferraccioli, F., Forsberg, R., Fujita, S., Gim, Y., Gogineni, P., Griggs, J. A., Hindmarsh, R. C. A., Holmlund, P., Holt, J. W., Jacobel, R. W., Jenkins, A., Jokat, W., Jordan, T., King, E. C., Kohler, J., Krabill, W., Riger-Kusk, M., Langley, K. A., Leitchenkov, G., Leuschen, C., Luyendyk, B. P., Matsuoka, K., Mouginot, J., Nitsche, F. O., Nogi, Y., Nost, O. A., Popov, S. V., Rignot, E., Rippin, D. M., Rivera, A., Roberts, J., Ross, N., Siegert, M. J., Smith, A. M., Steinhage, D., Studinger, M., Sun, B., Tinto, B. K., Welch, B. C., Wilson, D., Young, D. A., Xiangbin, C., and Zirizzotti, A.: Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, *The Cryosphere*, 7, 375–393, doi:10.5194/tc-7-375-2013, <http://www.the-cryosphere.net/7/375/2013/>, 2013.
- Gallée, H. and Schayes, G.: Development of a three-dimensional meso- γ primitive equation model: katabatic winds simulation in the area of Terra Nova Bay, Antarctica, *Monthly Weather Review*, 122, 671–685, 1994.
- Helsen, M. M., van de Wal, R. S. W., van den Broeke, M. R., van de Berg, W. J., and Oerlemans, J.: Coupling of climate models and ice sheet models by surface mass balance gradients: application to the Greenland Ice Sheet, *The Cryosphere*, 6, 255–272, doi:10.5194/tc-6-255-2012, <http://www.the-cryosphere.net/6/255/2012/>, 2012.
- Helsen, M. M., van de Berg, W. J., van de Wal, R. S. W., van den Broeke, M. R., and Oerlemans, J.: Coupled regional climate–ice-sheet simulation shows limited Greenland ice loss during the Eemian, *Climate of the Past*, 9, 1773–1788, doi:10.5194/cp-9-1773-2013, <http://www.clim-past.net/9/1773/2013/>, 2013.

- Helsen, M. M., van de Wal, R. S. W., Reerink, T. J., Bintanja, R., Sloth Madsen, M., Yang, S. L. Q., and Zhang, Q.: Albedo parameterisations as calibration tool for a coupled Greenland ice sheet model and EC-Earth, *The Cryosphere*, in prep., 2016.
- 10 Hill, C., DeLuca, C., Balaji, Suarez, M., and Da Silva, A.: The architecture of the Earth system modeling framework, *Computing in Science and Engineering*, 6, 18–28, doi:10.1109/MCISE.2004.1255817, <http://scitation.aip.org/content/aip/journal/cise/6/1/10.1109/MCISE.2004.1255817>, 2004.
- Holland, D. and Jenkins, A.: Modeling thermodynamic ice-ocean interactions at the base of an ice shelf, *Journal of Physical Oceanography*, 29, 1787–1800, 1999.
- 15 Jones, P.: First- and second-order conservative remapping schemes for grids in spherical coordinates, *Monthly Weather Review*, 127, 2204–2210, [http://journals.ametsoc.org/doi/abs/10.1175/1520-0493\(1999\)127%3C2204:FASOCR%3E2.0.CO;2](http://journals.ametsoc.org/doi/abs/10.1175/1520-0493(1999)127%3C2204:FASOCR%3E2.0.CO;2), 1999.
- Larson, J., Jacob, R., and Ong, E.: The Model Coupling Toolkit: A New Fortran90 Toolkit for Building Multiphysics Parallel Coupled Models, *International Journal of High Performance Computing Applications*, 19, 277–292, doi:10.1177/1094342005056115, <http://hpc.sagepub.com/content/19/3/277.abstract>, 2005.
- 20 Liu, L., Yang, G., Wang, B., Zhang, C., Li, R., Zhang, Z., Ji, Y., and Wang, L.: C-Coupler1: a Chinese community coupler for Earth system modeling, *Geoscientific Model Development*, 7, 2281–2302, doi:10.5194/gmd-7-2281-2014, <http://www.geosci-model-dev.net/7/2281/2014/>, 2014.
- Noël, B., van de Berg, W. J., van Meijgaard, E., Kuipers Munneke, P., van de Wal, R. S. W., and van den Broeke, M. R.: Evaluation of the updated regional climate model RACMO2.3: summer snowfall impact on the Greenland Ice Sheet, *The Cryosphere*, 9, 1831–1844, doi:10.5194/tc-9-1831-2015, <http://www.the-cryosphere.net/9/1831/2015/>, 2015.
- 25 Petoukhov, V., Ganopolski, A., Brovkin, V., Claussen, M., Eliseev, A., Kubatzki, C., and Rahmstorf, S.: CLIMBER-2: A climate system model of intermediate complexity. Part I: Model description and performance for present climate, *Climate Dynamics*, 16, 1–17, 2000.
- Redler, R., Valcke, S., and Ritzdorf, H.: OASIS4 - a coupling software for next generation earth system modelling, *Geoscientific Model Development*, 3, 87–104, doi:10.5194/gmd-3-87-2010, <http://www.geosci-model-dev.net/3/87/2010/>, 2010.
- 30 Reerink, T. J.: OBLIMAP User Guide, version 1.0, accompanying OBLIMAP 2.0, Tech. rep., Institute for Marine and Atmospheric research Utrecht, Utrecht University, 3508 TA Utrecht, The Netherlands, <https://github.com/oblimap/oblimap-2.0/blob/master/documentation/oblimap-user-guide.pdf>, 2016.
- Reerink, T. J., Kliphuis, M. A., and van de Wal, R. S. W.: Mapping technique of climate fields between GCM's and ice models, *Geoscientific Model Development*, 3, 13–41, doi:10.5194/gmd-3-13-2010, <http://www.geosci-model-dev.net/3/13/2010/>, 2010.
- 35 Rignot, E. and Mouginot, J.: Ice flow in Greenland for the International Polar Year 2008–2009, *Geophysical Research Letters*, 39, doi:10.1029/2012GL051634, 2012.
- Shapiro, N. and Ritzwoller, M.: Inferring surface heat flux distributions guided by a global seismic model: Particular application to Antarctica, *Earth and Planetary Science Letters*, 223, 213–224, doi:10.1016/j.epsl.2004.04.011, 2004.
- Shepard, D.: A two-dimensional interpolation function for irregularly-spaced data, *Proceedings-1968 ACM National Conference*, pp. 517–524, 1968.
- Valcke, S.: The OASIS3 coupler: a European climate modelling community software, *Geoscientific Model Development*, 6, 373–388, doi:10.5194/gmd-6-373-2013, <http://www.geosci-model-dev.net/6/373/2013/>, 2013.
- 5 Valcke, S., Balaji, V., Craig, A., DeLuca, C., Dunlap, R., Ford, R. W., Jacob, R., Larson, J., O'Kuinghtons, R., Riley, G. D., and Vertenstein, M.: Coupling technologies for Earth System Modelling, *Geoscientific Model Development*, 5, 1589–1596, doi:10.5194/gmd-5-1589-2012, <http://www.geosci-model-dev.net/5/1589/2012/>, 2012.

- Valcke, S., Craig, A., Dunlap, R., and Riley, G.: Sharing experiences and outlook on coupling technologies for earth system models, *Bulletin of the American Meteorological Society*, 97, ES53–ES56, doi:10.1175/BAMS-D-15-00239.1, <http://journals.ametsoc.org/doi/10.1175/BAMS-D-15-00239.1>, 2016.
- 10 van Angelen, J., van den Broeke, M., Wouters, B., and Lenaerts, J.: Contemporary (1960-2012) Evolution of the Climate and Surface Mass Balance of the Greenland Ice Sheet, *Surveys in Geophysics*, 35, 1155–1174, doi:10.1007/s10712-013-9261-z, 2014.
- van Meijgaard, E., van Ulft, L. H., Van de Berg, W. J., Bosveld, F. C., Van den Hurk, B. J. J. M., Lenderink, G., and Siebesma, A. P.: The KNMI regional atmospheric climate model RACMO version 2.1, Tech. Rep. 302, KNMI, P.O. box 201, 3730 AE, De Bilt, the Netherlands,
- 15 2009.
- Van Wessem, J., Reijmer, C., Morlighem, M., Mouginit, J., Rignot, E., Medley, B., Joughin, I., Wouters, B., Depoorter, M., Bamber, J., Lenaerts, J., Van De Berg, W., Van Den Broeke, M., and Van Meijgaard, E.: Improved representation of East Antarctic surface mass balance in a regional atmospheric climate model, *Journal of Glaciology*, 60, 761–770, doi:10.3189/2014JoG14J051, 2014.
- Van Wessem, J., Ligtenberg, S., Reijmer, C., Van De Berg, W., Van Den Broeke, M., Barrand, N., Thomas, E., Turner, J., Wuite, J., Scambos,
- 855 T., and Van Meijgaard, E.: The modelled surface mass balance of the Antarctic Peninsula at 5.5 km horizontal resolution, *The Cryosphere*, 10, 271–285, doi:10.5194/tc-10-271-2016, <http://www.the-cryosphere.net/10/271/2016/>, 2016.
- Vincenty, T.: Direct and inverse solutions of geodesics on the ellipsoid with application of nested equations., *Surv Rev*, pp. 88–93 [addendum: *Surv Rev* 23(180):294 (1976)], http://www.ngs.noaa.gov/PUBS_LIB/inverse.pdf, 1975a.

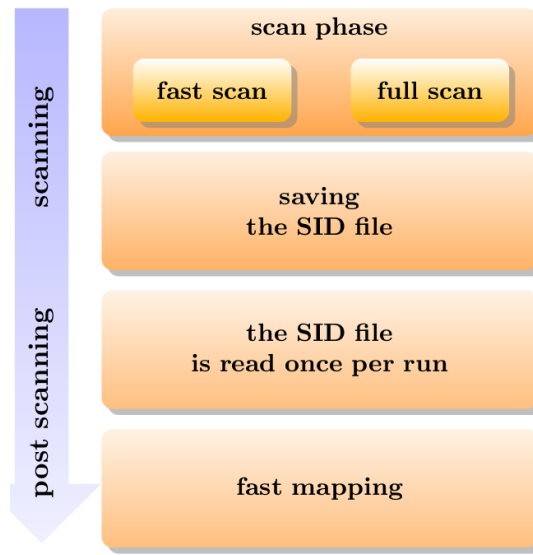


Figure 1. Schematic representation of the OBLIMAP 2.0 stand-alone version. The scanning consists of the scan phase and results in a SID file. The post scanning consists of reading the SID file and loading its content in the DDO, whereafter the fast mapping of multiple fields, layers and records can be repeated as often as required.

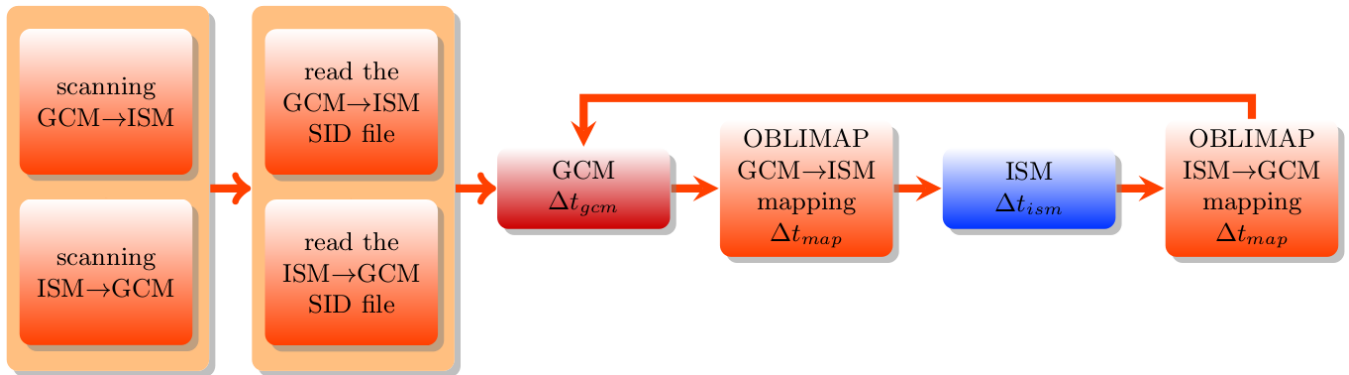


Figure 2. Schematic representation of an embedded ISM within a GCM run. At the initialization of the on-line coupled run the SID files are read, which have been created by off-line scanning prior to this run. The GCM and ISM are coupled with the embedded OBLIMAP routines at each coupling interval Δt_{map} . The GCM and the ISM evolve with their own time step Δt_{gcm} and Δt_{im} depending on their specific numerical stability criteria.

Table 1. Shortlist of the new OBLIMAP 2.0 features and changes. The stars indicate the categories of the new features. For the full list and more details see the supplementary OBLIMAP User Guide. The terms in bold are used for short reference to the described feature.

Feature number	Most important	Extended functionality	User comfort	Description of the new OBLIMAP 2.0 features
1	★	★		The mapping of large grid combinations has become feasible with the fast scanning option, as a result of the dramatic performance improvement in the scanning phase.
2	★	★		With masked mapping points which are part of an invalid mask will not contribute to the interpolation. The invalid mask covers the area for which the field values of a certain user specified field matches with a certain user specified invalid value.
3	★	★		With multiple masked mapping each field can use its own mask. This mask is allowed to vary in time, and might vary per vertical layer in case the masking is based on a spatial 3D field.
4		★	★	The redesign of OBLIMAP allows embedded calling of the OBLIMAP mapping routines.
5	★	★		The introduction of a dynamic data object avoids superfluous reading of the scanned file. This improved the post scanning phase performance, in particular in combination with multiple record, multiple field and multiple layer (3D) mapping.
6	★	★		On-line coupling of an ISM with a GCM is possible by using the OBLIMAP routines embedded. Prior off-line scanning is recommended for both mapping directions, so the embedded OBLIMAP mapping routines can use the fast post scan mapping relying on the dynamic data object.
7		★		Nearest point assignment , a post scan alternative to the quadrant and radius interpolation method. I.e. each destination node obtains the field value of the nearest projected point, which implies that no interpolation is required. This option can be considered in case both grids have about the same resolution.
8	★	★		Multiple field , multiple record and multiple layer mapping . The 2D and 3D fields can be mapped simultaneously, while each field might also contain the unlimited time dimension. In the embedded case the fields will be mapped at each coupling time step.
9		★		The precise calculation with the Vincenty method of the great distance over the ellipsoidal arc is added as an option.
10		★	★	With the automatic scan option the scan parameters are determined by OBLIMAP itself.
11			★	Automatic OBLIMAP advice concerning the correct and optimal settings of the scan parameters.
12			★	Extended OBLIMAP messaging including four levels of message intensity.
13			★	Automatic dimension shape determination while reading the netcdf input files.
14			★	Separate configuration files have to be used for each mapping direction.
15		★		The ISM grid is allowed to be irregularly spaced.
16	★		★	An OBLIMAP User Guide accompanies OBLIMAP 2.0

Table 2. The grid sizes N_x , N_y and the grid resolution Δ of the three ISM grids which result from the mapping applications in Sect. 4.2, using the oblique SG projection for the sphere or the WGS84 ellipsoid with the projection parameters α and the coordinates of the projection centre (λ_M, ϕ_M) .

ISM grid	N_x	N_y	Δ (km)	α ($^\circ$)	λ_M ($^\circ$)	ϕ_M ($^\circ$)
Greenland	301	551	5	7.1	319.0	72.0
Antarctica	281	281	20	19.0	0.0	-90.0
Peninsula	271	351	5	5.54	293.5	-70.2

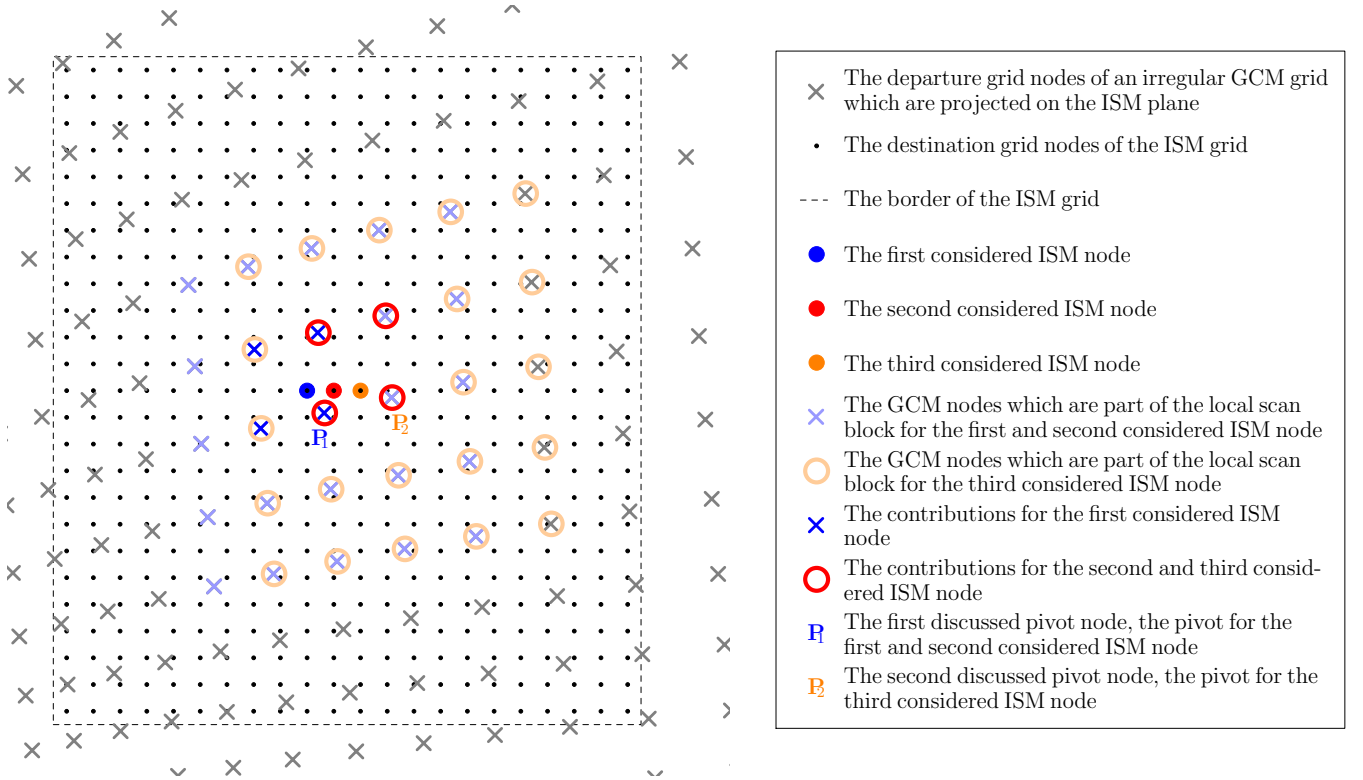


Figure 3. Situation sketch of the procedure to find a next scan block for a GCM to ISM mapping, supposed that the quadrant interpolation method is used. Consider the situation for which the four contributions (\times) are found for the first considered ISM node (\bullet). In order to find the contributions for the second considered ISM node (\bullet), a scan over a local block is conducted. This local block is constructed by taking the nearest contribution (the pivot) and extending the block in all directions by b . In this case P_1 is the pivot and the block is extended by two \times nodes in each direction. For the second considered ISM node this results in a different set of contributions (\circ). Because P_1 is the nearest contribution for the second considered ISM node as well, P_1 stays the pivot. Therefore the scan block remains unchanged in the next scan. Though for the third considered ISM node (\bullet) the contributions are the same as for the second considered ISM node, now P_2 becomes the pivot of the third considered ISM node. So the next scan is conducted over the \circ -marked GCM nodes.

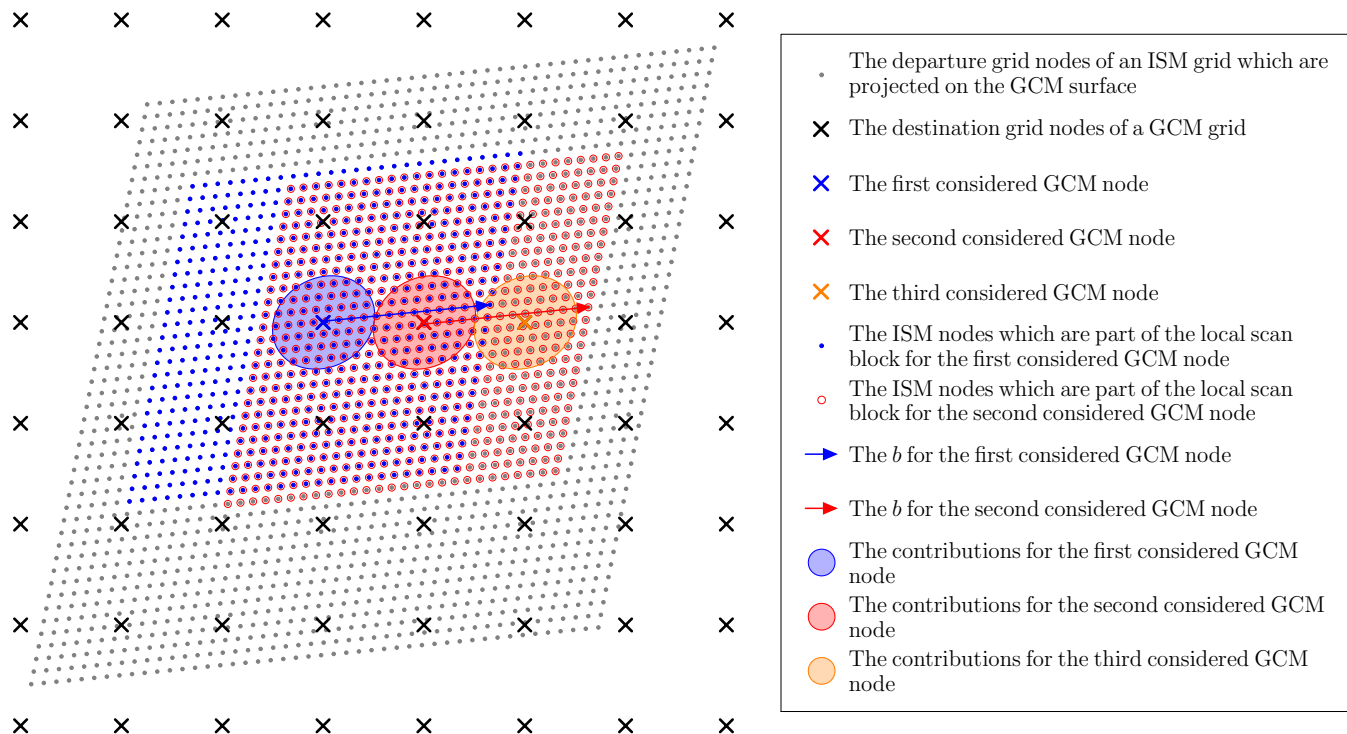


Figure 4. Situation sketch of the procedure to find a next scan block for an ISM to GCM mapping, supposed that the radius interpolation method is used. Consider the situation for which the contributions (the ISM nodes in the blue shaded circle) are found for the first considered GCM node (×). In order to find the contributions for the second considered GCM node (×), a scan over a local block is conducted. This local block is constructed by taking the nearest contribution (the pivot) and extending the block in all directions by b (indicated by the arrows in the figure). In this case the pivot is the ISM node under the ×-marker and the ●-marked block is extended as indicated by the blue arrow. The contributions for the second considered GCM node lay in the red shaded circle. The pivot shifts to the GCM node under the ×-marker. The scan for the third considered GCM node (×) is conducted over the ○-marked ISM nodes in order to find the orange shaded contributions. Thereafter the pivot shifts again to the ISM node under the ×-marker for the next scan.


```

MODULE example_gcm_host_model_module

CONTAINS
SUBROUTINE example_gcm_host_model ()
! A BLOCK OF: USE statements of the Host Model
USE oblimap_configuration_module , ONLY: dp, C
USE oblimap_mapping_module , ONLY: oblimap_ddo_type , oblimap_deallocate_ddo
USE oblimap_embedded_mapping_module , ONLY: oblimap_initialize_embedded_mapping , &
oblimap_embedded_gcm_to_im_mapping , oblimap_embedded_im_to_gcm_mapping
IMPLICIT NONE

! A BLOCK OF: Declaration statements of the Host Model
REAL(dp) , DIMENSION(C%number_of_mapped_fields , C%NX , C%NY , C%number_of_vertical_layers) :: ism_field
REAL(dp) , DIMENSION(C%number_of_mapped_fields , C%NLON , C%NLAT , C%number_of_vertical_layers) :: gcm_field
REAL(dp) , DIMENSION(C%number_of_mapped_fields , C%NLON , C%NLAT , C%number_of_vertical_layers) :: prev_gcm_field
TYPE(oblimap_ddo_type) :: ddo_gcm_to_im
TYPE(oblimap_ddo_type) :: ddo_im_to_gcm

! Output: -
CALL initialize_ISM()

! Output: ddo_gcm_to_im , ddo_im_to_gcm
CALL oblimap_initialize_embedded_mapping(ddo_gcm_to_im , ddo_im_to_gcm)

! A BLOCK WITH: The initialization of the Host Model

! Start time loop of the Host Model:
! A BLOCK WITH: The Host Model time loop code (including the update of gcm_field)

! Keeping the previous gcm_field: 1. For merging with points which do not participate in the mapping.
! 2. Eventually for time interpolation.
prev_gcm_field = gcm_field

! Output: ism_field
CALL oblimap_embedded_gcm_to_im_mapping(ddo_gcm_to_im , gcm_field , ism_field)

! In/Output: ism_field
CALL embedded_ISM(time_start_ISM , time_stop_ISM , ism_field)

! Output: gcm_field
CALL oblimap_embedded_im_to_gcm_mapping(ddo_im_to_gcm , ism_field , prev_gcm_field , gcm_field)

! A BLOCK WITH: The Host Model time loop code
! End time loop of the Host Model:

! A BLOCK WITH: The finalization of the Host Model

! Output: -
CALL oblimap_deallocate_ddo(ddo_gcm_to_im)
! Output: -
CALL oblimap_deallocate_ddo(ddo_im_to_gcm)
END SUBROUTINE example_gcm_host_model

END MODULE example_gcm_host_model_module

```

Figure 5. A schematic outline shows how to use the OBLIMAP API for embedding an ISM with OBLIMAP in a GCM host model. The *initialize-ISM* and *embedded-ISM* are hypothetical ISM routines which are not part of OBLIMAP but embed the ISM.

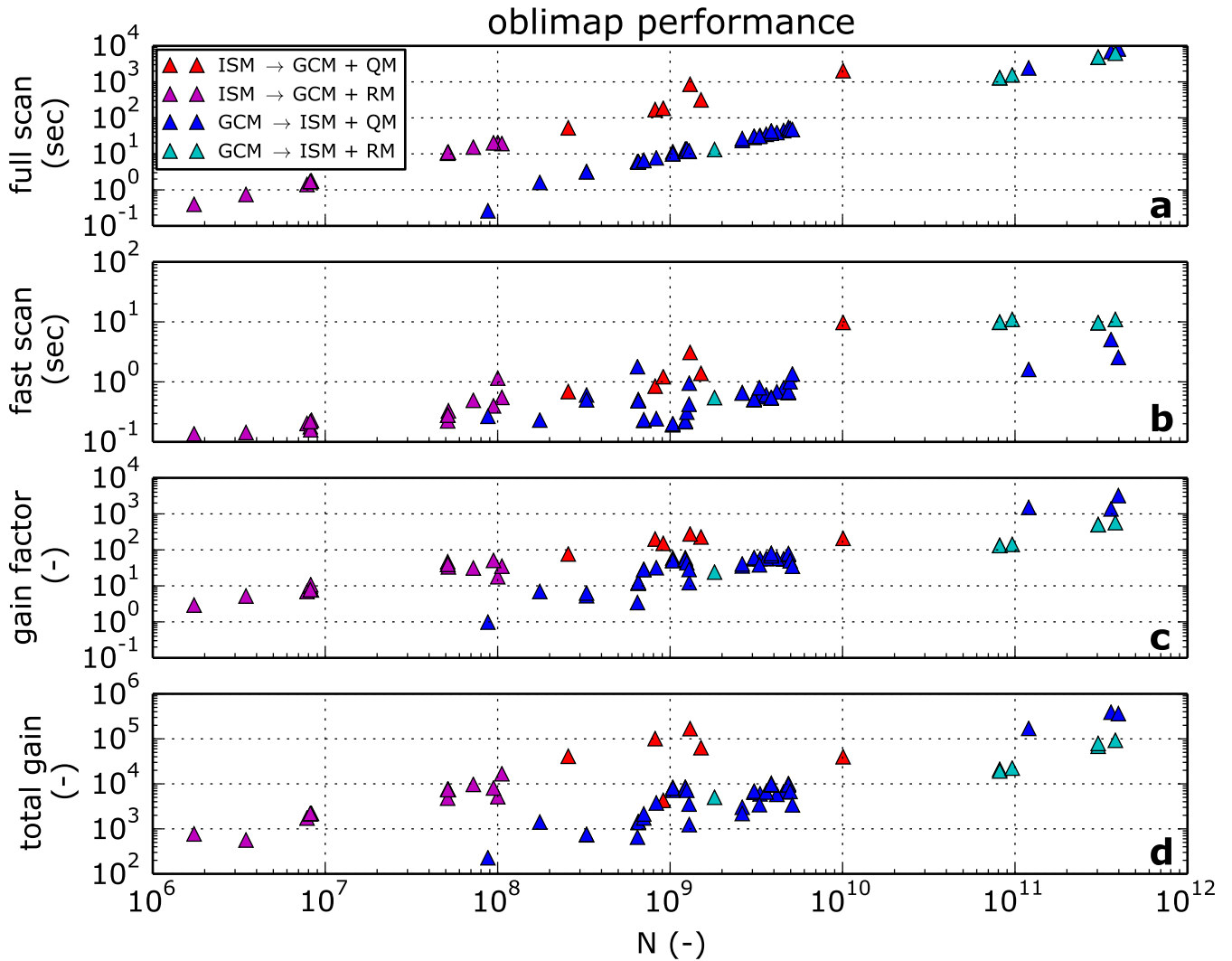


Figure 6. Sixty mapping experiments representing a diverse set of mappings which differ in number of nodes, grid resolution, mapping direction, interpolation method, location and thus also in projection, have been used to compare the time performance of the full scan method (a) and the fast scan method (b) as function of N , the number of participating destination grid points multiplied with the number of departure grid points. Subfigures c and d show the gain factor if respectively the fast scan method or the fast mapping per individual 2D field is used instead of the full scan method. Four colours distinguish between experiments which differ in mapping direction and which use either the quadrant interpolation method (QM) or the radius interpolation method (RM).

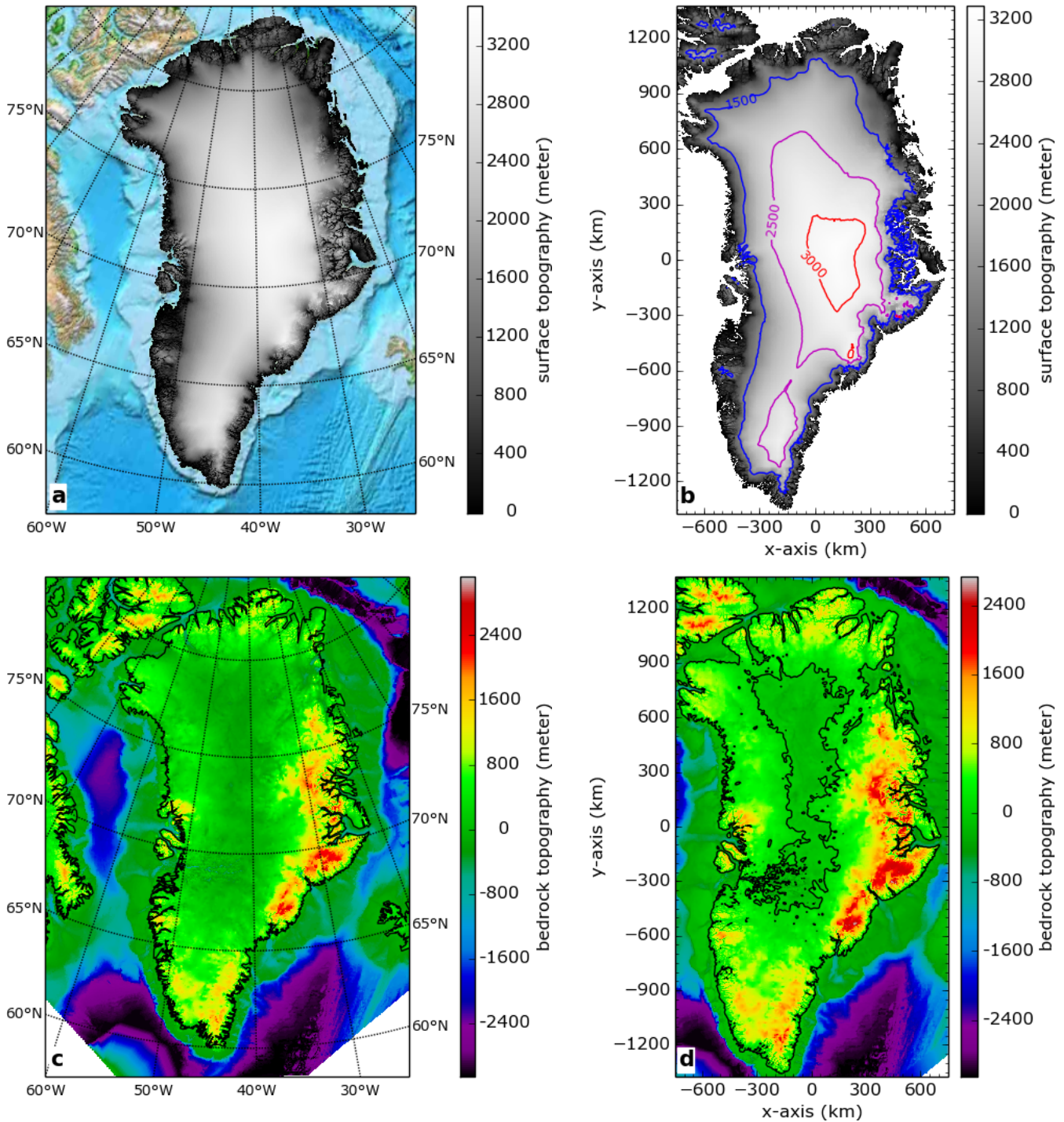


Figure 7. Subfigure **a** and **c** show respectively the surface topography and the bedrock topography of the 1x1 km resolution [dataset](#) [data set](#) for Greenland after an inverse projection on the Earth WGS84 ellipsoid. In **a** a coloured ETOPO background replaces the part at [sealevel](#) [sea level](#). In **c** the missing values are white coloured and the continental contour is plotted black. In **b** the surface topography has been mapped on a 5x5 km ISM grid with an optimal [eentered](#) [centred](#) projection without using a mask, but points at [sealevel](#) [sea level](#) have been plotted white in order to visualize the coastline contours. In **d** the bedrock topography has been masked mapped on a 5x5 km ISM grid with an optimal [eentered](#) [centred](#) projection, the bottom right corner shows the proper resulting mask border. In **a** a few coloured contours are plotted on top of the data, and in **d** the zero contour is plotted black

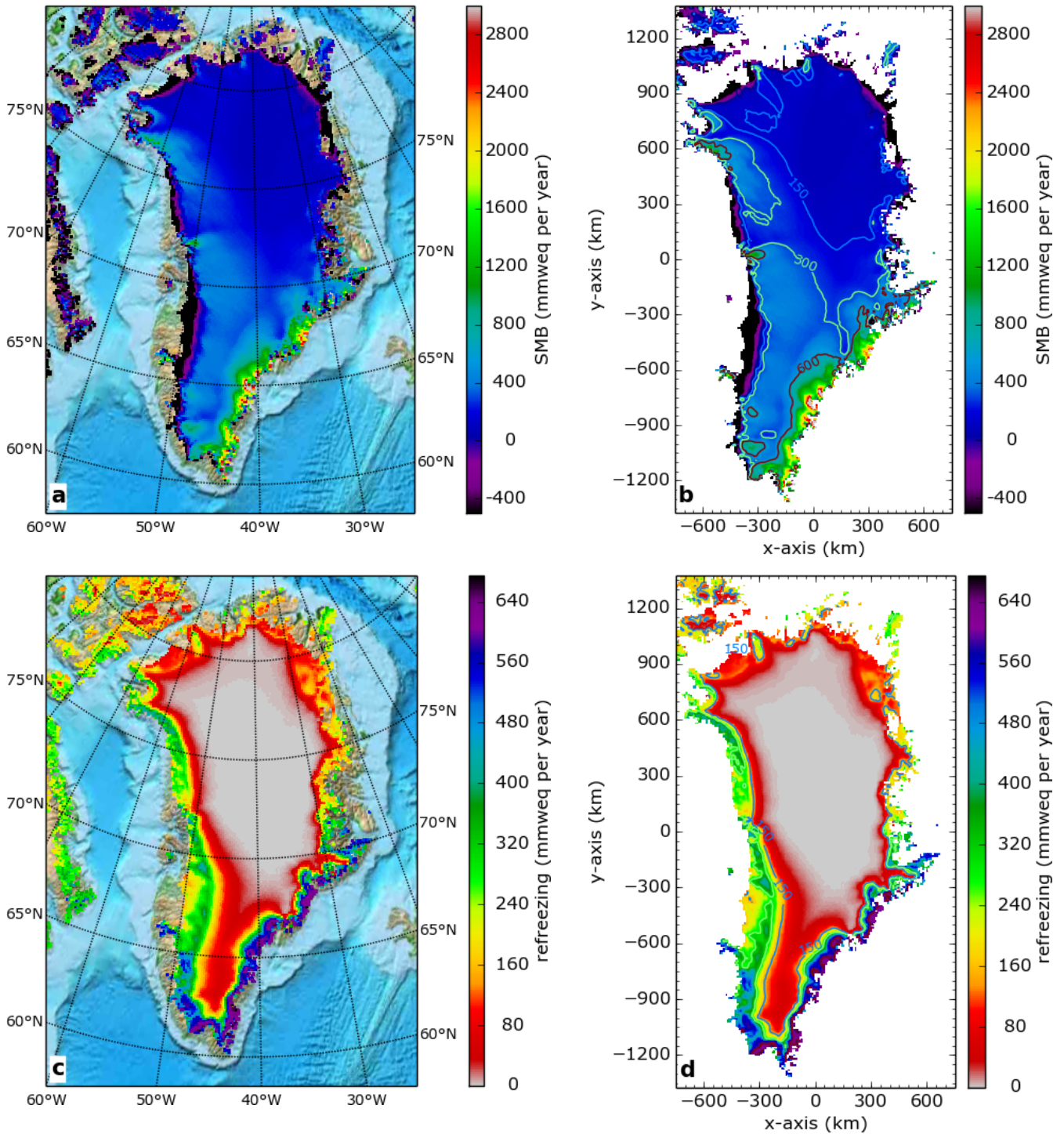


Figure 8. Subfigure **a** and **c** show respectively the surface ~~massbalance~~ mass balance (SMB) and the refreezing ~~for~~ of the ~~year~~ 2006 ~~1958–1989 time average~~ of the RACMO2 ~~dataset~~ dataset-3 data set for Greenland on a ~~gaussian~~ reduced ~~reduced gaussian~~ grid with an horizontal resolution of about 11 km, the coloured ETOPO background replaces the masked area. In **b** and **d** the SMB and the refreezing have been masked mapped on a 5x5 km ISM grid with an optimal ~~centered~~ centered ~~35d~~ projection. Both fields are expressed in millimeter water equivalent (mmweq per year).

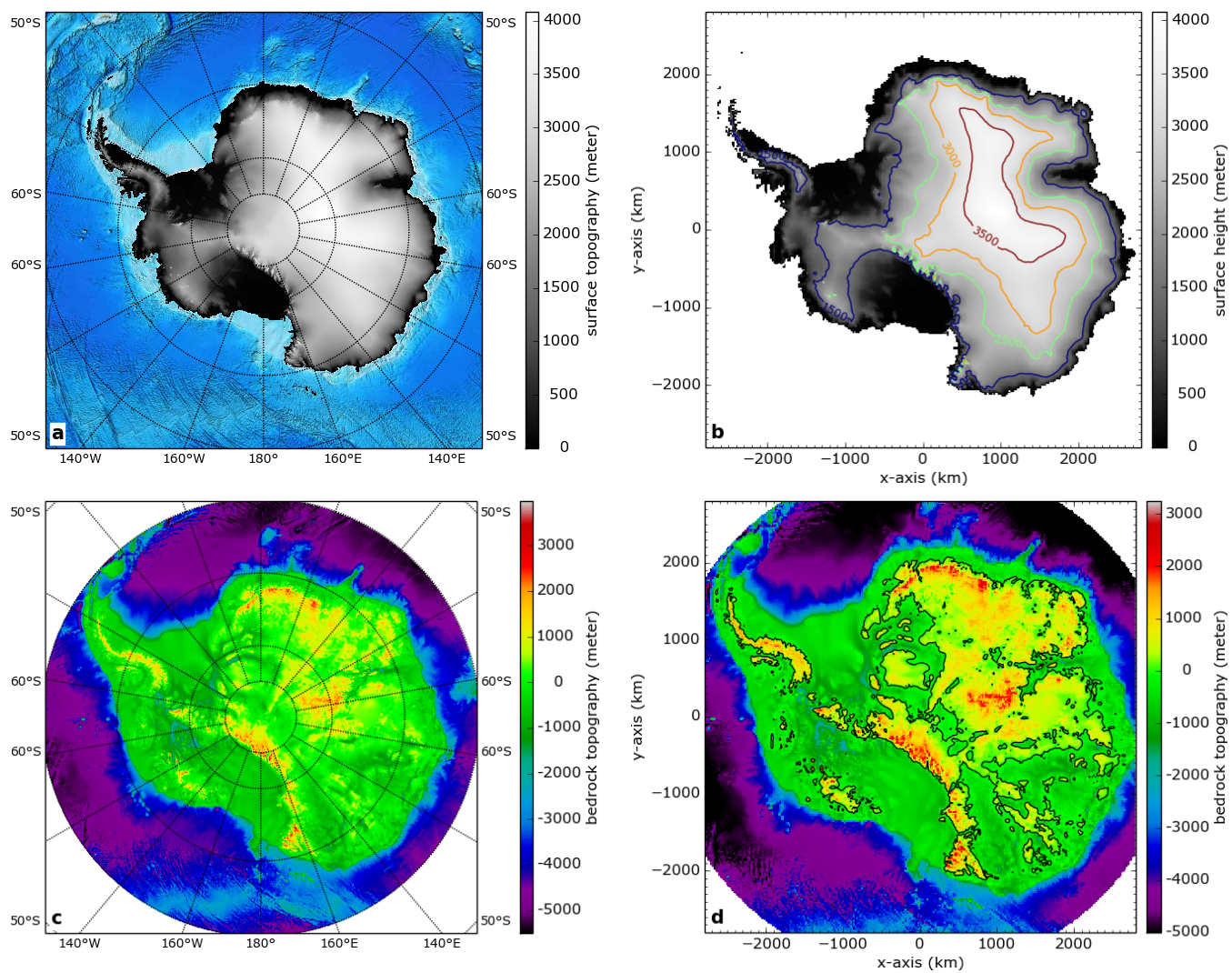


Figure 9. As Fig. 7 but for Antarctica, the Antarctic ISM grid resolution in **b** and **d** is 20x20 km.

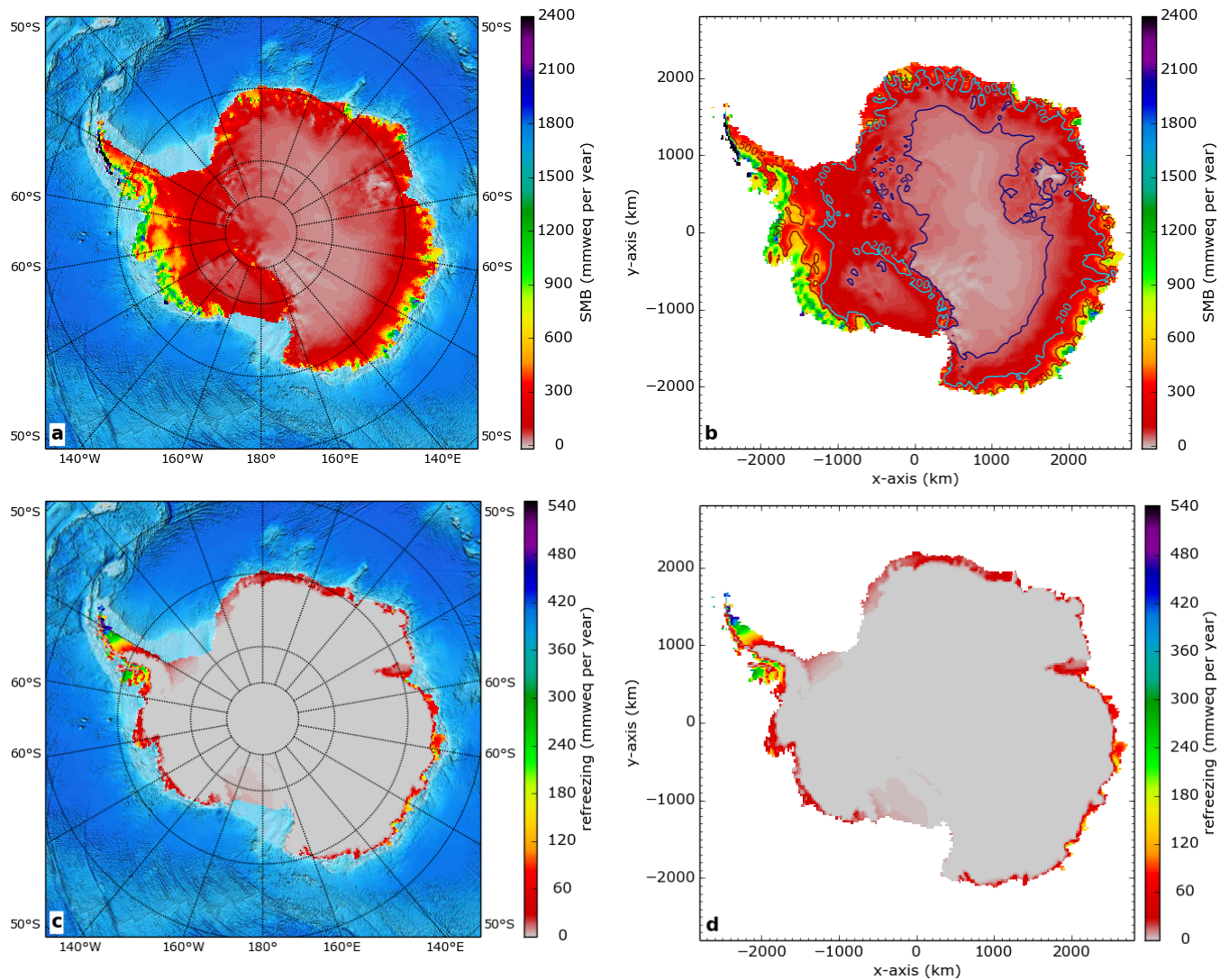


Figure 10. As Fig. 8 but for Antarctica, the Antarctic RACMO2.3 data set is a time average over the 1979–2014 period and the Antarctic RACMO2.3 grid resolution in **a** and **c** is about 27 km and the Antarctic ISM grid resolution in **b** and **d** is 20x20 km.

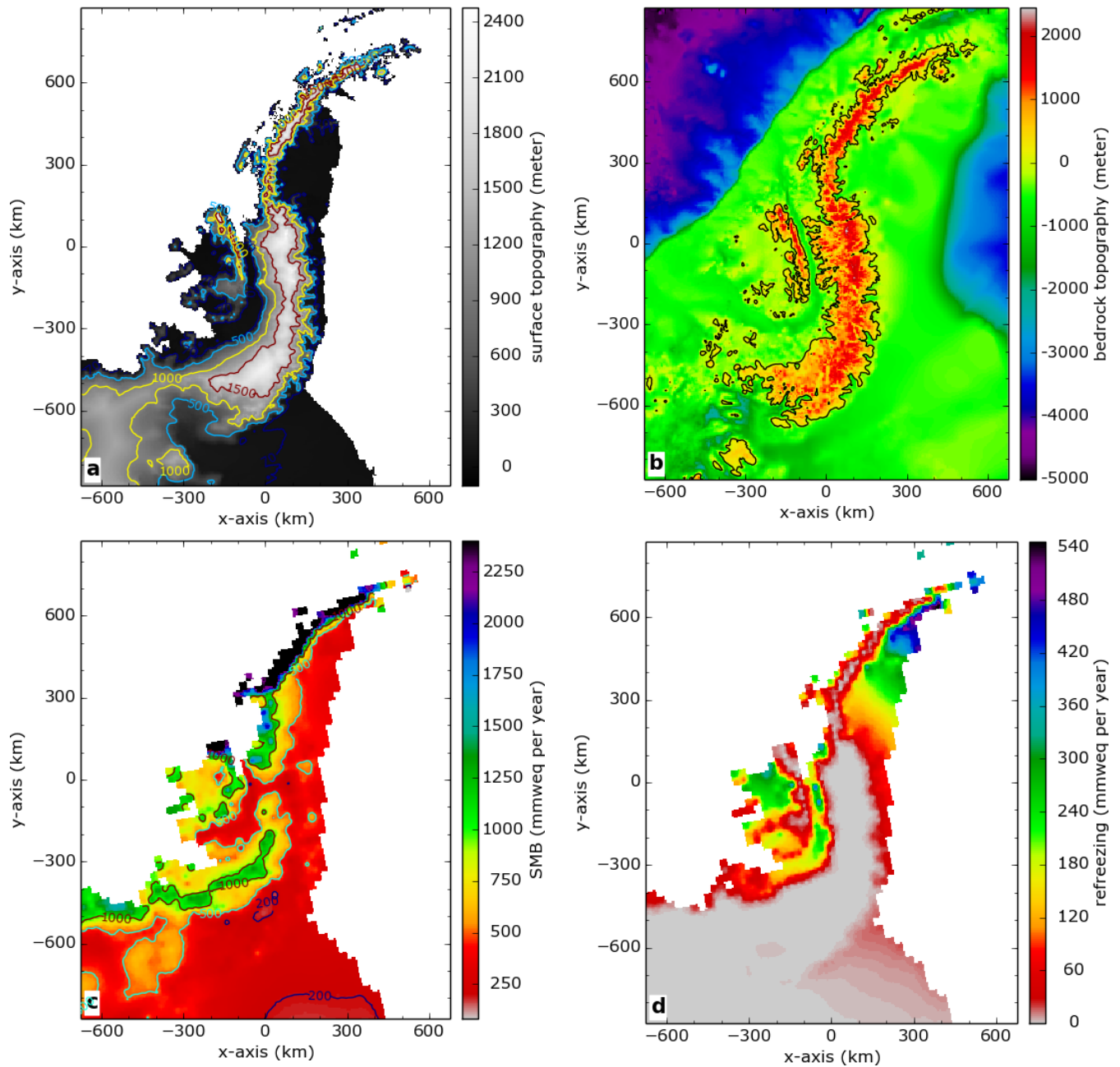


Figure 11. The Bedmap2 surface topography (Fig. 9a) and the bedrock topography (Fig. 9c) have been mapped on a local 5x5 km ISM grid for the Antarctic Peninsula with an optimal [centered-centred](#) oblique projection without using a mask (see [a](#) and [b](#)). In [a](#) points at [sealevel](#) [sea level](#) have been plotted white in order to visualize the coastline contours. The [1979-2014 time-averaged](#) RACMO2.3 SMB (Fig. 10a) and the refreezing (Fig. 10c) [for the year 2006](#) have been masked mapped on the same local 5x5 km ISM grid with the same optimal [centered-centred](#) projection (see [c](#) and [d](#)).

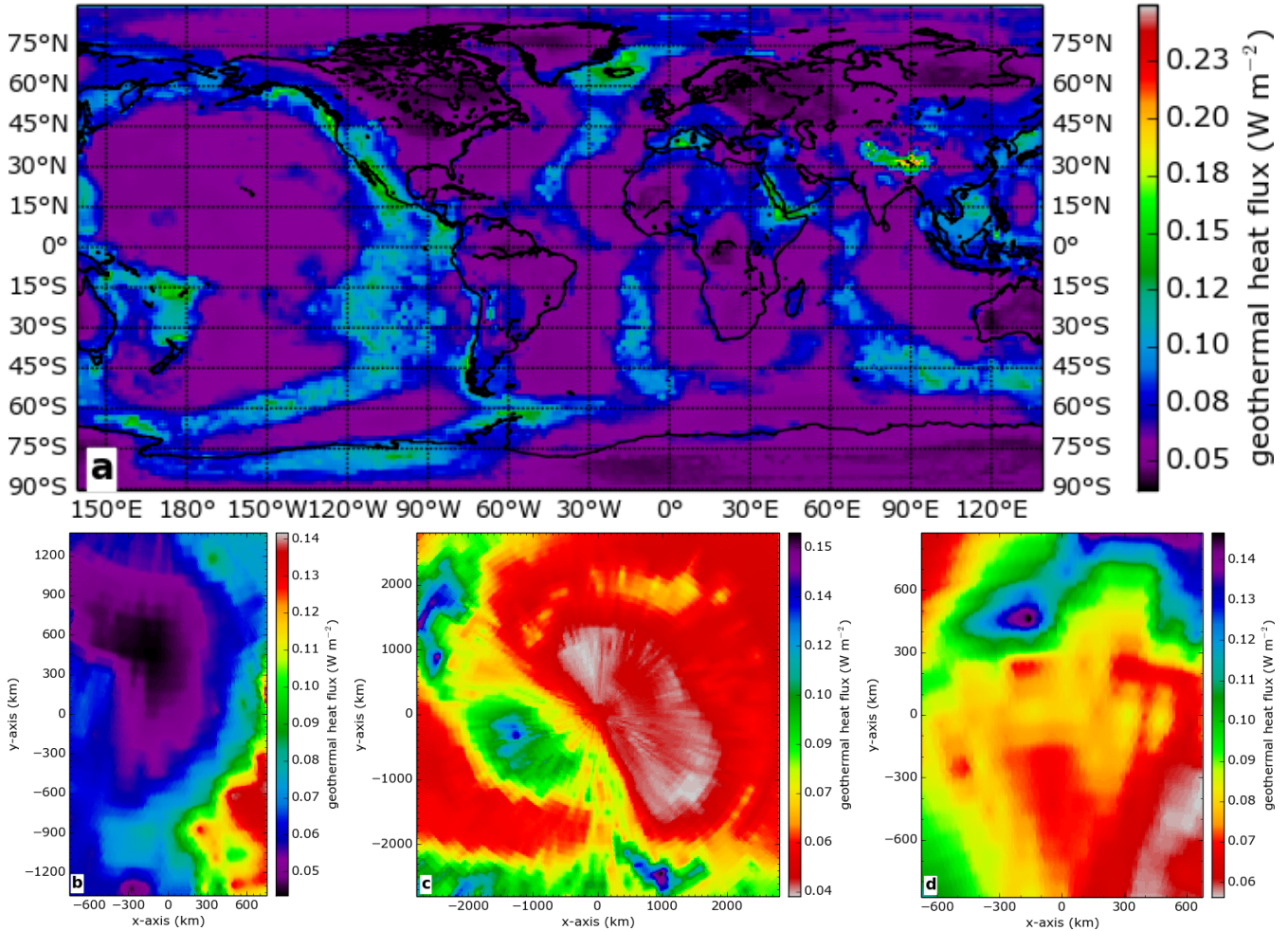


Figure 12. Subfigure **a** shows the geothermal heat flux (Shapiro and Ritzwoller, 2004) on a global regular $1^\circ \times 1^\circ$ longitude - latitude grid, the continental contours are plotted black. This geothermal heat flux has been mapped with optimal [centered-centred](#) projections on a 5x5 km ISM grid for Greenland (**b**), a 20x20 km ISM grid for Antarctica (**c**) and a 5x5 km ISM grid for the Antarctic Peninsula (**d**).