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Interactive
Comment

Interactive comment on "A system of conservative regridding for ice/atmosphere coupling in a GCM" *by* E. Fischer et al.

E. Fischer et al.

elizabeth.fischer@columbia.edu

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We thank the reviewer for the helpful comments, which have improved the manuscript. Below are our answers to the reviewer's comments.

`I miss at several places the intuitive explanation of the formal maths. I think this paper would gain a lot if the basic concepts are explained more intuitively in addition. I have to admit that I did not convincingly understand the core of this work, and therefore my review is incomplete.`

We have carefully reread the paper and have included intuitive explanation to the formal maths. In particular, edits were applied to Sections 2.2, 3, 4, 4.2, 4.3, 4.4, 6.1, 6.3, 7, 8.1, 8.5.

```
There should be made a convincing case that there is a need
for the use of an intermediate ice surface model.  After
reading the text this is not transparent to me.  Line 26
page 6498 argues vaguely about important problems.  Mapping
and regridding in one step may well circumvent the addition
of the ice surface model.  If combined with coupling at low
frequencies the two-way coupling may also be established.
```

We added this argument in section 2.1 ("Ice surface model").

```
Line 1, page 6494:  The method of elevation classes is probably
not familiar to every- body
```

A short definition of elevation classes was added to the abstract. It now begins (italics to show new text): “The method of elevation classes, *in which the ice surface model is run at multiple elevations within each grid cell*, has proven to be a useful way for a low-resolution general circulation model”

The paper also references a seminal paper on elevation classes (Leung Gang 1998) as well as an example of their use in GCMS with ice models (Lipscomb et al 2013).

```
Line 4-7, page 6494:  Past ...  downscaling to the ice model.
Please rewrite.
```

Rewritten, the new text is:

> Past uses of elevation classes have failed to conserve mass and energy because the transformation used to regrid to the atmosphere was inconsistent with the transformation used to downscale to the ice model. This would cause problems for two-way coupling.

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Line 3, page 6495:  the least to be mentioned is how this is
treated in AR5 (even omit reference to AR4)
```

At the time the original manuscript was prepared AR5 was not available to read or cite. As the AR5 report is now available, we have omitted reference to AR4 and instead updated the introduction to reflect the findings of the IPCC AR5. We note in particular that "The representation of glaciers and ice sheets within AOGCMs is not yet at a stage where projections of their changing mass are routinely available. Additional process-based models use output from AOGCMs to evaluate the consequences of projected climate change on these ice masses." Chapter 13, Sea Level Change, p 1145.

```
Line 20, page 6495 almost certainly arose is a bit a bold
statement rephrase to feed- backs play an role in many events
(e.g.  ...)
```

Text changed to: “This kind of feedback probably plays a significant role in many events in the paleo record (Dansgaard–Oeschger events, Heinrich events, the Younger Dryas).”

```
Line 15, page 6496:  replace "this" by e.g.  "the latter"
```

Done

```
Line 18, page 6496:  What kind of surface flux fields are
meant?  I guess these are vertical fluxes?
```

This has been rephrased to add clarity: “The key insight is that mass and energy fluxes between the atmosphere and an ice sheet vary approximately by elevation within a local region.”

```
Line 27, page 6497:  replace "atmosphere" by "atmosphere
model".
```

Done

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`line 4-6, page 6498: remove, because it is repeated at line 11, page 6499.`

Removed.

`line 7, page 6499: Should be ice SURFACE model.`

Removed the entire (short) paragraph. It was no longer necessary after new text at the beginning of Section 2.1 explaining the need for the ice surface model (see comment above).

`Line 10-25, page 6500: I would suggest to replace the variable names (in Fig. 2 as well) as follows:`

A few orthogonal issues are brought up here.

Superscripts

There are two general proposals to handle superscripts: (a) Superscripts are just one letter, indicating which grid the vector belongs to, or (b) Superscripts indicate not just the grid the vector belongs to, but also the history of regriddings used to create the vector.

Notations (a) and (b) both have their merits and problems. Notation (a) is simple, but not always completely descriptive. Notation (b) is more descriptive, but can add clutter and could become unwieldy2. It can also be confusing, since $F^{A \to E}$ looks like F^A, but it is really on the E grid. The authors prefer (a) for its uncluttered simplicity, using accompanying text ot explain how vectors were computed.

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Base Variable Names

In the example, each upper-case letter represents a *bundle* of fields, represented collectively by one letter. The fields passed between different phases of the coupling are different. (For example, precipitation and downwelling shortwave radiation are passed from the atmosphere to the ice surface model. SMB and upwelling longwave radiation are passed from the ice surface model to the atmosphere. Accumulated SMB and small conductive heat flux are passed from the ice surface to the ice flow models. Changes in ice sheet configuration are passed from the ice flow model to the ice surface and atmosphere models.)

Because field bundles for each step are all different, they deserve different base variable names. On the other hand, there is commonality in variables in some cases. For that reason, we have take the reviewer's suggestion to rename variables in ways that enhance this commonality. SMB and associated fluxes on the ice surface is called F; the associated variables to the atmosphere are called $-F$, because they should in general be equal opposite to F. Accumulated SMB and energy fields are called $\bar{F}$.

Changes were made to the text to match this:

> On each atmosphere time step, flux outputs from the ice surface model are accumulated as $\bar{\boldsymbol{F}}^E$, named so because these fluxes are in general equal and opposite to fluxes sent to the atmosphere. Every coupling time step – about once a month – the accumulated $\bar{\boldsymbol{F}}^E$ is regridded to the ice grid ($\bar{\boldsymbol{F}}^I$) and passed to the ice flow model.

Delta

The Greek letter Delta is usually not used as a first-class symbol, but rather as a modifier. In order to reduce confusion, we have changed Δ –> D.

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Line 2, page 6501: Ambiguous definition of Δ^I.
Line 3, page 6501: unclear

Unambiguated and clarified. Text now reads:

> The ice flow model produces changes in ice surface topography and extent, as well as a small energy flux between the ice flow and ice surface models (together, we call these $\boldsymbol{D}^I$). Changes in ice topography and extent are regridded to the atmosphere grid ($\boldsymbol{D}^A$) and used to adjust the atmosphere's orography. The energy flux is regridded to the elevation grid ($\boldsymbol{D}^E$) and applied to the ice surface model.

Line 7, page 6502: The practitioner ... grid cell. Unclear sentence.

Clarified. Sentence now reads: "The practitioner must choose which elevations to use for each atmosphere grid cell."

Line18, page 6502: fE –SMB Do you mean fE =SMB?

Dash changed to colon to clarify that this is not math. Sentence now reads "Suppose we have computed a flux field $\boldsymbol{f}^E$: SMB, for example."

Line 28 page 6502: You basically suggest that there is no ablation at all in the accumu- lation area, that does not seem to be necessarily true.

Good point. Traditionally, the ELA is defined based on yearly averages. The energy balance model computes things at an instant in time; therefore, the "instantaneous ELA" or "freezing line" is important at any single timestep. Over the course of a coupling timestep (eg, 1 month), the freezing line will move up and down, creating a zone in which there is some ablation. If this process is carried out for a year, the "true" ELA will be somewhere inside that zone.

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The text describes this situation later in the paragraph; but is somewhat of a distraction to the main point, that the SMB function vs. elevation will be constant above some equilibrium "zone." We have changed “constant” to “constant to first order” in order to help focus reader attention on the main point. The text now reads: “In the face of spatially invariant precipitation, one would expect SMB to be constant to first order above the equilibrium line altitude (ELA), and to decrease linearly with elevation below the ELA.”

Line 20, page 6503: fundamentals IN SECT. 4 and projection issues IN SECT. 5.

Done, changes made.

Line 18, page 6504: In left hand side: f should be fG I presume, and probably in line 15 as well.

Yes, fixed. (Appendex A notation, item 5 descries this convention)

Sect. 5.1: The use of an (optimal) oblique stereographic projection or the oblique Lambert Equal Area Projection projection, as used in OBLIMAP (Reerink et al., 2010, GMD), instead of a polar projetcion, reduces this error.

I suggest: Line 13-16, page 6508: Even ... 2008) can be moved in between line 5 and 6 of page 6508.

We do not expect the oblique stereographic projection to make much difference because the SeaRISE projection already minimizes errors along the 71N parallel (see “standard parallel” with respect to the Stereographic projection).

The Lambert Equal Area Projection is mentioned in the paper. It is, by definition, area-preserving. Therefore, it makes no difference in theory where the origin is placed, as long as the computation involved does not become ill-conditioned. Due to these numerical issues, we would expect an oblique LAEA projection centered over Greenland to perform no more than slightly better than a polar LAEA projection.

We have modified text to specify that an LAEA projection is centered on the north pole, when that is what we mean (Section 5.2, Fig. 5). In cases where what we are saying applies to all LAEA projections, we leave the center unspecified. In Section 5.2, we now say “onsider a typical latitude–longitude grid on the sphere with a Lambert Equal Area Projection centered at the North pole (Fig. 5).” The accompanying caption for Figure 5 now reads “This map, made using a Lambert Equal Area Projection centered on the north pole, shows a set of latitude/longitude grid cells – a kind commonly used in atmosphere models...”

Our discussion is focused on area-preserving projections in general, using the LAEA as one example. Ice modelers wishing to use an area-preserving projection might use any projection they choose. This is easy in the accompanying coupling software because it relies on the PROJ.4 library for projections. (PROJ.4 implements a wide variety of projections that people have found useful).

In response to both reviewers, Section 5 has been rewritten to better separate three issues: (a) How to correct for errors, (b) How to eliminate projection error, (c) How to minimize geometric error.

`And the rest of Sect. 5.2 and Sect. 5.3, Fig. 5 and Fig. 6 can be omitted.`

Section 5.3 and Fig. 6 have been eliminated. Sections 5.2 and Fig 5 have not been eliminated (see discussion on comment immediately above this).

`Line 10, page 6530: IS only required`

Done

`Line 3, page 6535: transformations ARE linear`

Not all regridding transformations described in this paper are linear. Text changed to

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"Many but not all of these transformations linear, and can be represented by matrices."

Figures and Captions

```
The authors should carefully read and check all their caption
texts.
```

We did this, and modified a number of them.

```
line 1 caption Fig.3, page 6546:  "bass" should be "mass".
```

Done

```
Fig.  4 can be merged with Fig.  12.
```

Figs 4 and 12 illustrate different issues. Figure 4 visualizes the definition of an exchange grid, as defined elsewhere in (eg) ESMF literature. Figure 12 shows how the transformation $E \rightarrow A$ is derived from the transformation $E \rightarrow I$ and standard area-weighted remapping. It describes a core concept of the paper.

```
Fig.  9 can be combined with Fig.  7 to one figure with two
panels.
```

Done. This gives a nice side-by-side comparison of Z Interpolation and Bilinear Interpolation.

```
I do not understand Fig.  10 and its caption text.
```

The caption has been redone:

> Traditional elevation class schemes are equivalent to running the ice surface model on an L0 grid, where grid cell outlines are created by the intersection of the atmosphere grid and elevation contours. One such grid is shown in this figure. Note that grid cells extend only as far as the ice sheet;

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the grey line shows the Greenland coast.

The figure has also been redone, as a line drawing on a map. It show how the elevation grid (in this case) is created by the intersection of the atmosphere grid with elevation contours.

```
Fig.  11 can be omitted or merged with Fig.  3.
```

Traditional elevation class schemes are equivalent to running on an L0 grid with funny-shaped grid cells, as shown in Fig. 9. GCM modelers are comfortable with this approach because it fits in with traditional notions of fractional cell areas used in a number of GCMs. The downside of the traditional schemes is the zeroth-order accurate “interpolation” in the vertical, as shown in Fig. 10.

This paper generalizes traditional elevation class schemes, and seeks to give the “lay of the land” of what choices are possible to the modeller, and what their consequences would be. It begins by describing the generalized “elevation points” set of schemes, and then specializes them to produce the traditional elevation class scheme.

In this context, Fig. 11 allows for a direct comparision of traditional elevation classes to the elevation points scheme based on Z Interpolation — making it clear that traditional elevation class schemes should provide a significantly less accurate SMB for the same number of elevation points. Not all variations of the elevation points schemes presented in this paper will be palatable to GCM authors. However, Z Interpolation should be a relatively easy drop-in replacement to traditional elevation class schemes, and it offers a number of advantages with few or no drawbacks. Traditional elevation class interpolation is therefore not on the efficient frontier of regridding methods for any situation.

Fig. 11 therefore helps make the case for why it is worthwhile to go to through the more mathematically rigorous procedures of this paper, rather than just using a traditional elevation class scheme. The caption has been changed to better reflect the intention,

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it now reads:

> Interpolated SMB function within one atmosphere grid cell, when using elevation classes. The resulting piecewise constant interpolation is almost never preferable to the piecewise linear interpolation in Fig. 3. Traditional elevation class schemes are discouraged because they offer no benefit over first-order Z Interpolation.

`The color bar in Fig. 13 misses a quantity-units caption. I do not really understand this part of the story. What is gray in Fig. 13, what the black lines, what the white lines (I guess the latter are the contour lines?).`

The caption has been rewritten to account for all these questions. It now reads:

> Unitless basis functions for the elevation grid E, constructed using 20 elevation points and Z Interpolation (the exchange grid was used as the interpolation grid). The grey box represents one atmosphere grid cell on the west coast of Greenland, with the coastline shown as black lines. White lines in the atmosphere grid cell represent elevation contours corresponding to each elevation point. The basis functions corresponding to elevation points at 950 m, 1150 m and 1350 m are shown. Note that basis functions overlap and are not orthogonal. Because of the Z Interpolation, each basis function has maximum value at its corresponding elevation, but it has a non-zero support up to one elevation point away.

`There is a reference to Fig. 14 before Fig. 6 is cited.`

The early reference to Fig. 14 has been removed. It is not essential to the text where it occured, and Fig. 14 has not been explained yet at that point in the paper.

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Fig. 15 can be combined with Fig. 16 to one figure with two panels.

Done. Combined with Fig. 17 as well.

There are no references in the text to Fig. 17, 21 and 22. The latter two are only mentioned in the captions of Fig. 22-23.

See p. 6523 line 1. The reference in the text was "Figure 17" instead of "Fig. 17". The problem was similar for Fig 21 and 22. All instances of "Figure" in the text have been fixed to "Fig." All figures are referenced.

If Fig 21-22 are kept they can be placed in one figure with two panels.

Done

Fig. 24 can be omitted or merged with Fig. 14.

Fig. 14 describes the five grids used in the coupling problem. It is the “basic map” of regridding transformations, and should serve as the primary guide on “how to regrid from point A to point B.”

Fig. 24 shows how to regrid ice surface model state from one elevation grid to another, when ice extent or elevation changes. It is derived from Fig. 14 in two ways: (1) The elevation grid is duplicated (E and F) because we're regridding from one elevation grid to another, and (2) Portions of the diagram not central to elevation regridding are omitted for clarity.

The caption for Fig. 24 now reads:

> When ice extent, ice topography or elevation points change, the basis functions for the elevation grid E change along with it. Ice surface model state,

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which exists on E, must be regridded to the new set of basis functions.

Shown is a grid system that can serve as a map for this regridding: E is the old elevation grid, F is the new one and G is the interpolation grid (same for old and new). Ice surface model state may be regridded from E to F by first regridding $E \rightarrow G$, then $G \rightarrow F$. Note that this diagram is a simplified version of Fig. 12 in which two different elevation grids have been acounted for.

```
Fig 25 can be omitted, refer to Fig.  2 instead at line 19 page
6529.
```

Fig. 2 shows how a two-way coupled GCM operates, assuming it has the five required transformations at its disposal. Fig. 25 shows the data GLINT2 needs to produce these transformations. The caption of Fig. 25 has been updated to make this clear. Fig. 2 caption has been edited to better explain the meaning of the graphics used.

Fig 2 caption:

Data flow for the coupling between atmosphere, ice surface and dynamic ice flow models. Outputs (blue arrows) from each model (boxes) are fed as inputs into the next. Since the three models run on different grids, regridding operations (ovals) are required at each step. Fig. 20 shows the inputs required to compute these regridding operations.

Fig 25 caption:

The GLINT2 workflow used to compute the regridding operations required by the fully coupled system (Fig. 2). GLINT2 produces regridding operations based on a variety of factors: atmosphere and ice grid geometry, ice topography and extent, and levels chosen for the elevation grid. GLINT2 must recompute the operations when any of these factors changes.

Interactive comment on Geosci. Model Dev. Discuss., 6, 6493, 2013.

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