A higher-order ice-flow model applied to the dynamics of Greenland's outlet glaciers

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University of Bristol

Motivation for improved Ice Sheet Models

Current models do not capture observed ice sheet behaviour[1], because:

(1) fundamental physics are lacking (e.g. solving simplified equations, negating realistic simulation of outlet glaciers and ice streams)

(2) processes of fundamental importance are not accounted for (e.g. simplified, static treatment of basal boundary conditions, ignoring atmos. and ocean coupling, etc.)

Accurate predictions of future sea-level rise (SLR) will require advanced models which can demonstrate skill at reproducing and explaining recent dramatic ice sheet behaviors.

[1] *IPCC* (2007)

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(1) accounting for both vertical AND horizontal stresses (e.g. HO models)

(2) improved basal and lateral BCs (e.g. plastic bed, floating ice at margins)

(3) detailed treatment of grounding line[1] … e.g. Nick/Vieli and others[2] model mimicks Helheim glacier over last ~10 yrs (and, arguably, provides explanation for observed behaviour)

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Today: Introduce an "easy" tuning method that may allow us to fill the gap and make some useful predictions using improved, stand-alone models (along with some simple, perturbation experiments).

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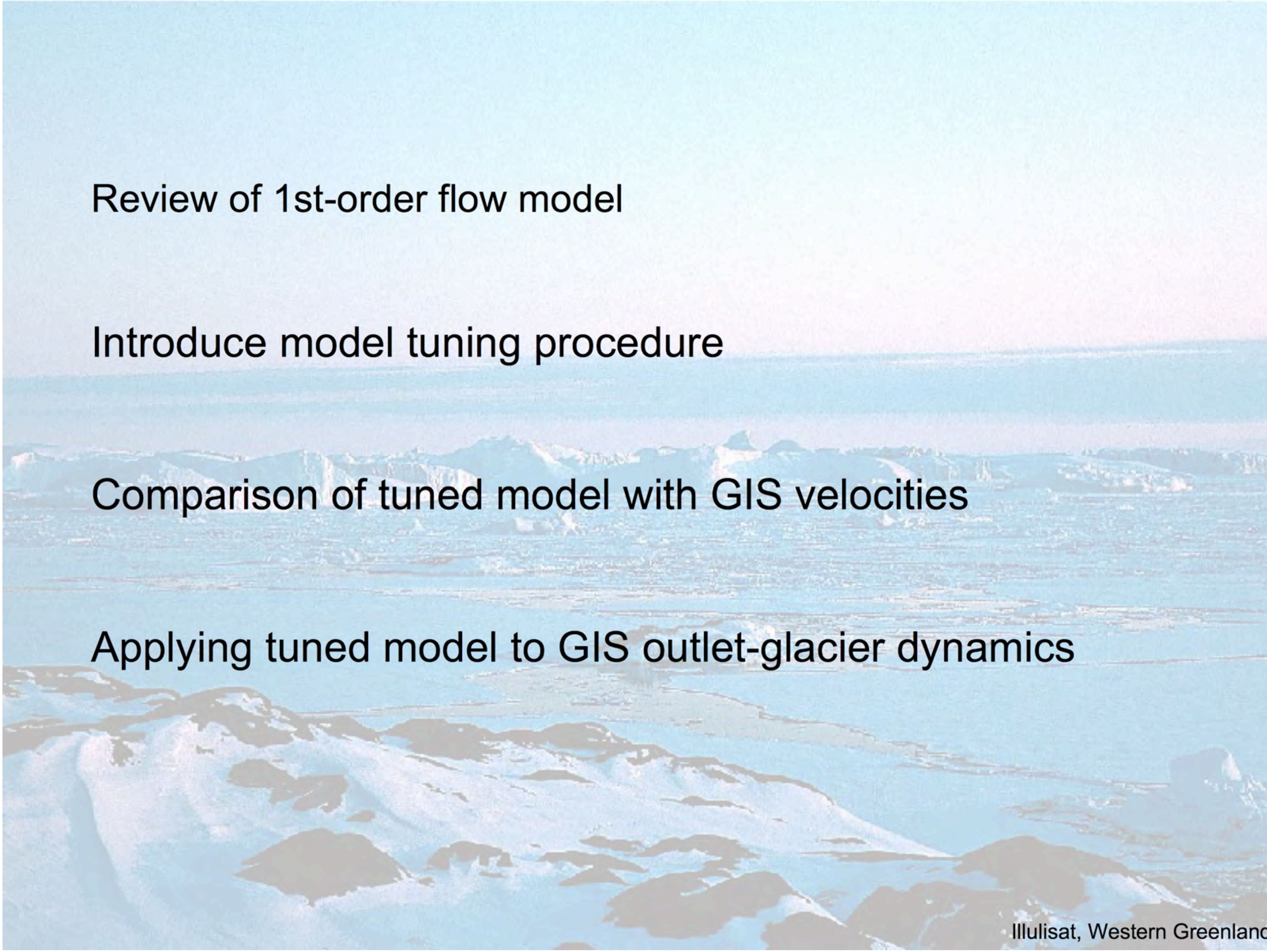
Review of 1st-order flow model

Introduce model tuning procedure

Comparison of tuned model with GIS velocities

Applying tuned model to GIS outlet-glacier dynamics



Illulisat, Western Greenland

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Equations of Stress Equilibrium in Cartesian Coordinates (Stokes Flow)

Assume static balance of forces by ignoring acceleration

$$x: \quad \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} - \frac{\partial P}{\partial x} = 0$$

$$y: \quad \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yz}}{\partial z} - \frac{\partial P}{\partial y} = 0$$

$$z: \quad \frac{\partial \tau_{zz}}{\partial z} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial x} - \frac{\partial P}{\partial z} = \rho g$$

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… apply some scaling based on *H*/*L* …

$$\dot{\varepsilon}_{xz} = \frac{1}{2}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)$$

$$\frac{\partial \sigma_{xz}}{\partial x} = \frac{\partial \sigma_{yz}}{\partial y} \approx 0$$

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“First-Order” Approximation

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… integrate w.r.t. *z* to get explicit expression for *P*…

First Order Approximation (unscaled)

…use definition of deviatoric stress to eliminate vertical-normal stress deviator in horiz. equations …

$$x: \quad \frac{\partial \tau_{xx}}{\partial x} - \frac{\partial \tau_{zz}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} = \rho g \frac{\partial s}{\partial x}$$

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$$\tau_{ij} = B\dot{\varepsilon}_e^{\frac{1-n}{n}} \dot{\varepsilon}_{ij}, \quad B = B(T)$$ (Glen's law)

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$ (strain rate tensor)

$$2\dot{\varepsilon}_e = \dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}$$ (effective strain rate)

$$\eta \equiv \frac{1}{2} B\dot{\varepsilon}_e^{\frac{1-n}{n}}$$ (effective viscosity)

$$\tau_{ij} = 2\eta\dot{\varepsilon}_{ij}$$ (constitutive relation)

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…use constiutive relation to write stresses in terms of strain rates and eff. visc., write strain rates in terms of vel. grads. …

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$$x: \quad 4\frac{\partial}{\partial x}\left(\eta\frac{\partial u}{\partial x}\right) + 2\frac{\partial}{\partial x}\left(\eta\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial y}\left[\eta\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right] + \frac{\partial}{\partial z}\left(\eta\frac{\partial u}{\partial z}\right) = \rho g \frac{\partial s}{\partial x}$$

First Order Approximation (solution)

Solve for *u* by moving *v* terms to RHS, vice versa for *v* (operator splitting)

Recover *w* through continuity

Equations discretized using Finite Difference Method

Vertical coordinates transformed to sigma coordinates

Iterate on effective viscosity using "unstable manifold correction[1]"

Conservation of energy (heat balance model) similar to GLIMMER model

Surface and basal boundary conditions are fully HO (not 0-order approx.)

[1]Hindmarsh and Payne (*Ann. Glac.*, 1996); Pattyn (*JGR*, 2003)

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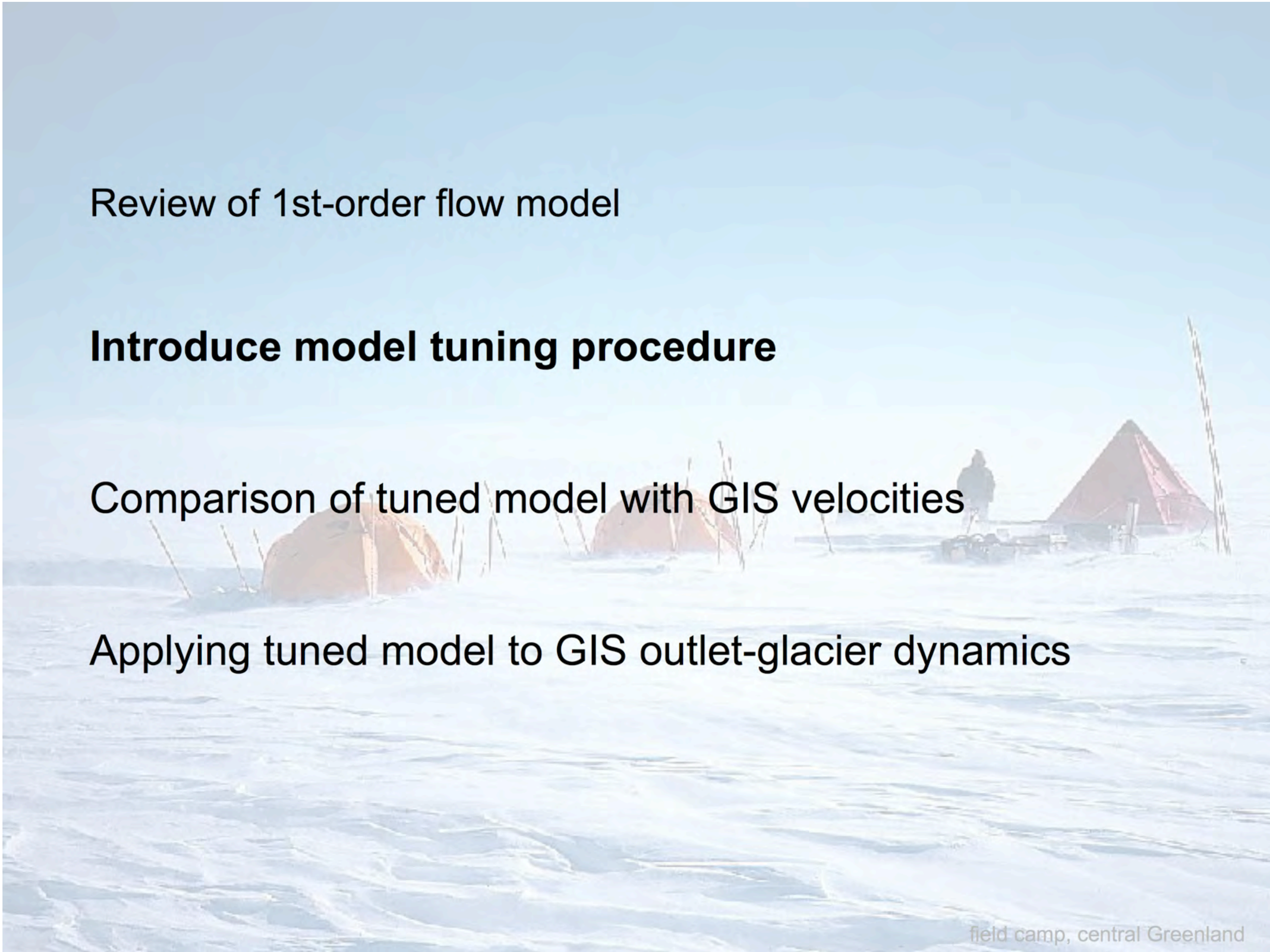

field camp, central Greenland

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How do model and target[1] velocity fields compare?

[1]Here, GIS balance velocities from Bamber et al. (*J.Glac.*, **46**, 2000)

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(3) must accept the use of a "compensatory accumulation rate" (=ss SMB implied by tuned velocity field … may or may not be a good representation of actual SMB). OK if main concern is the dynamic response?

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Greenland Ice Sheet: tuning assumptions

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- Observed velocities (InSAR) are not in equilibrium with known or actual geometry.
- InSAR vels are at a much higher resolution than our current geometry data, and so resolve features our model cannot.
- Arguably, better to tune sliding to (more conservative) ss velocities than to (more erratic) transient observed velocities (e.g. accelerated fields from Jak., Kang., and Hel. glaciers).

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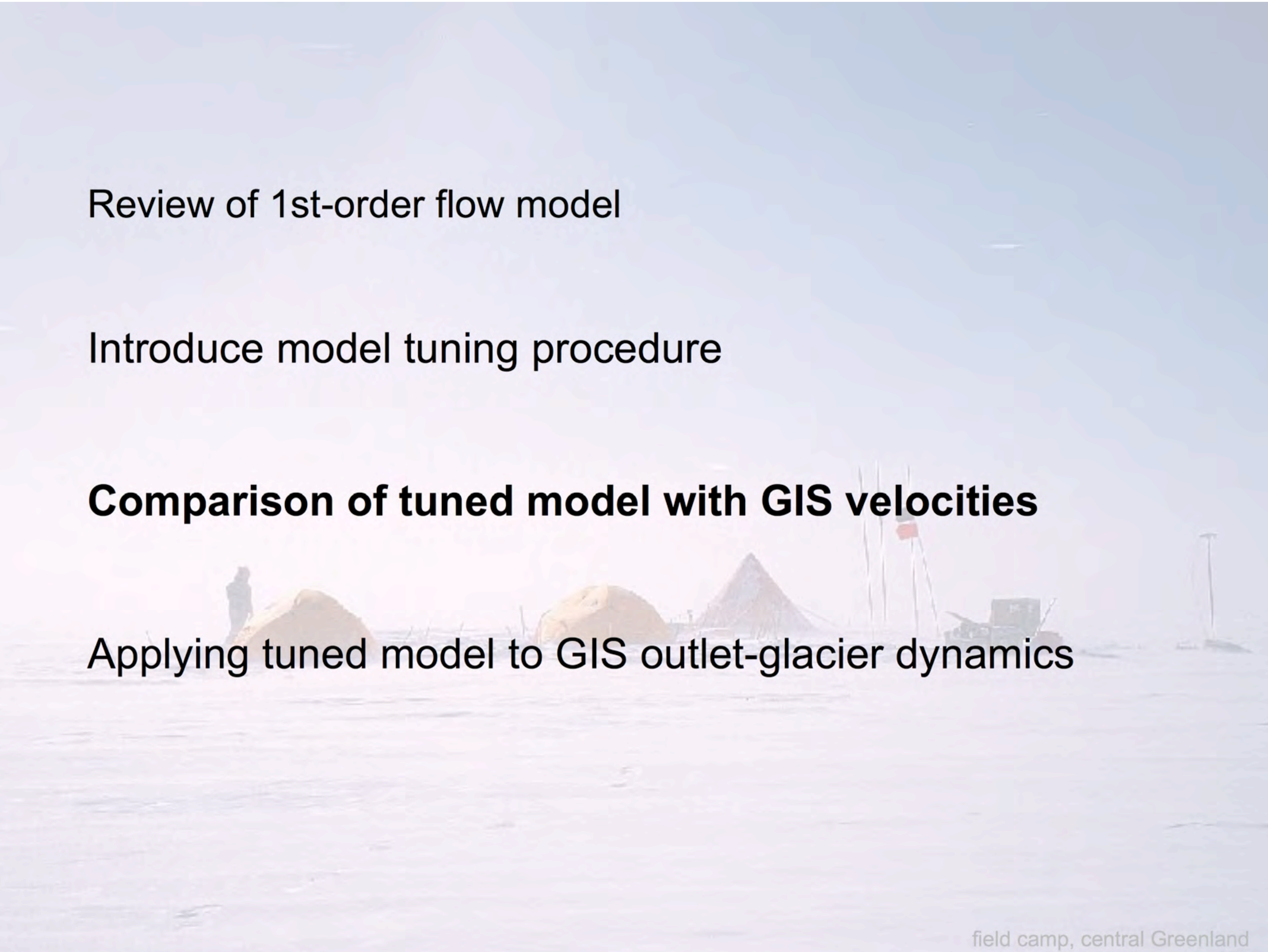

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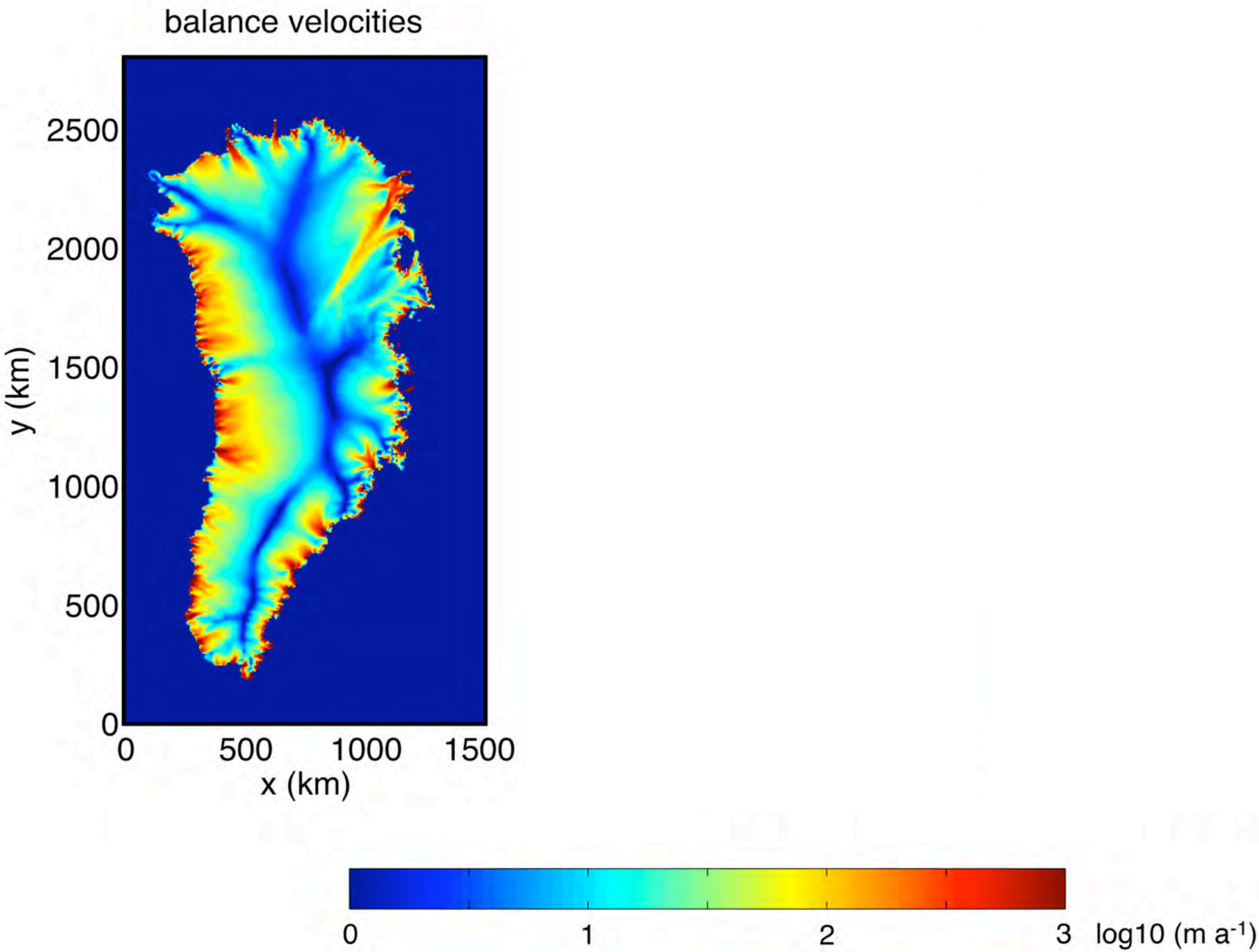
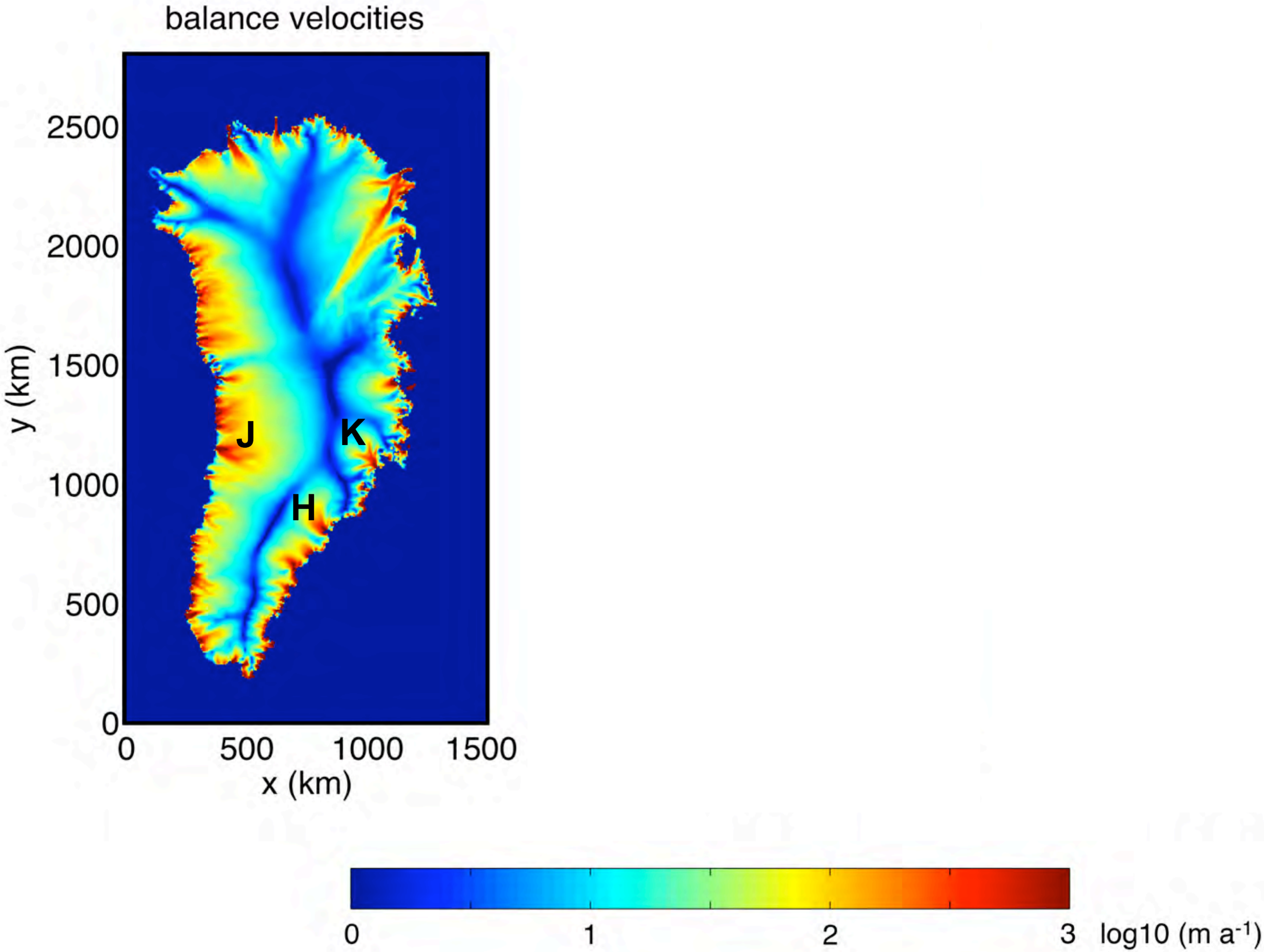

balance velocities
2500
2000
1500
1000
500
0
y (km)
0
500
1000
1500
x (km)
0
1
2
3
log10 (m a-1)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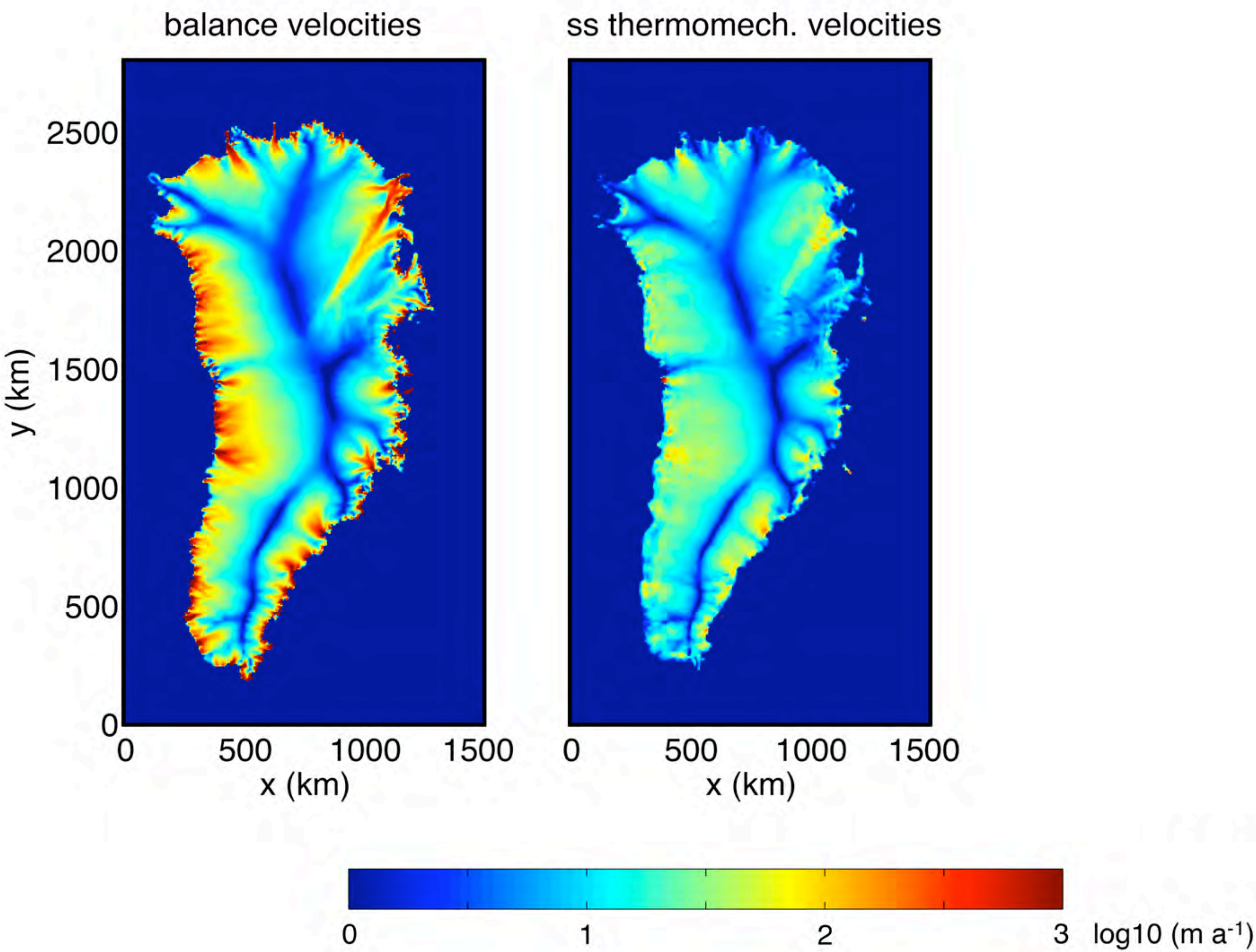

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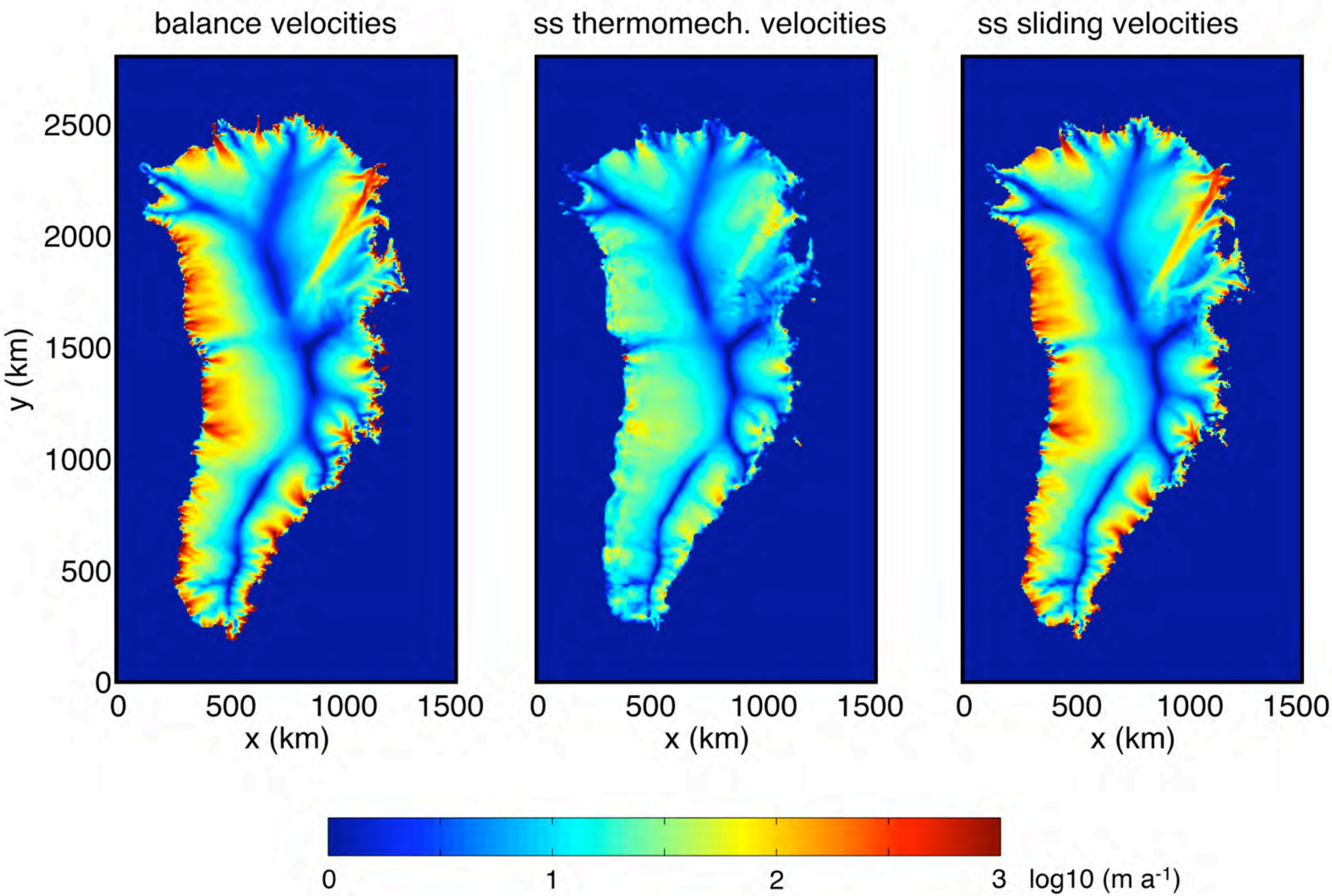

balance velocities
ss thermomech. velocities
ss sliding velocities
y (km)
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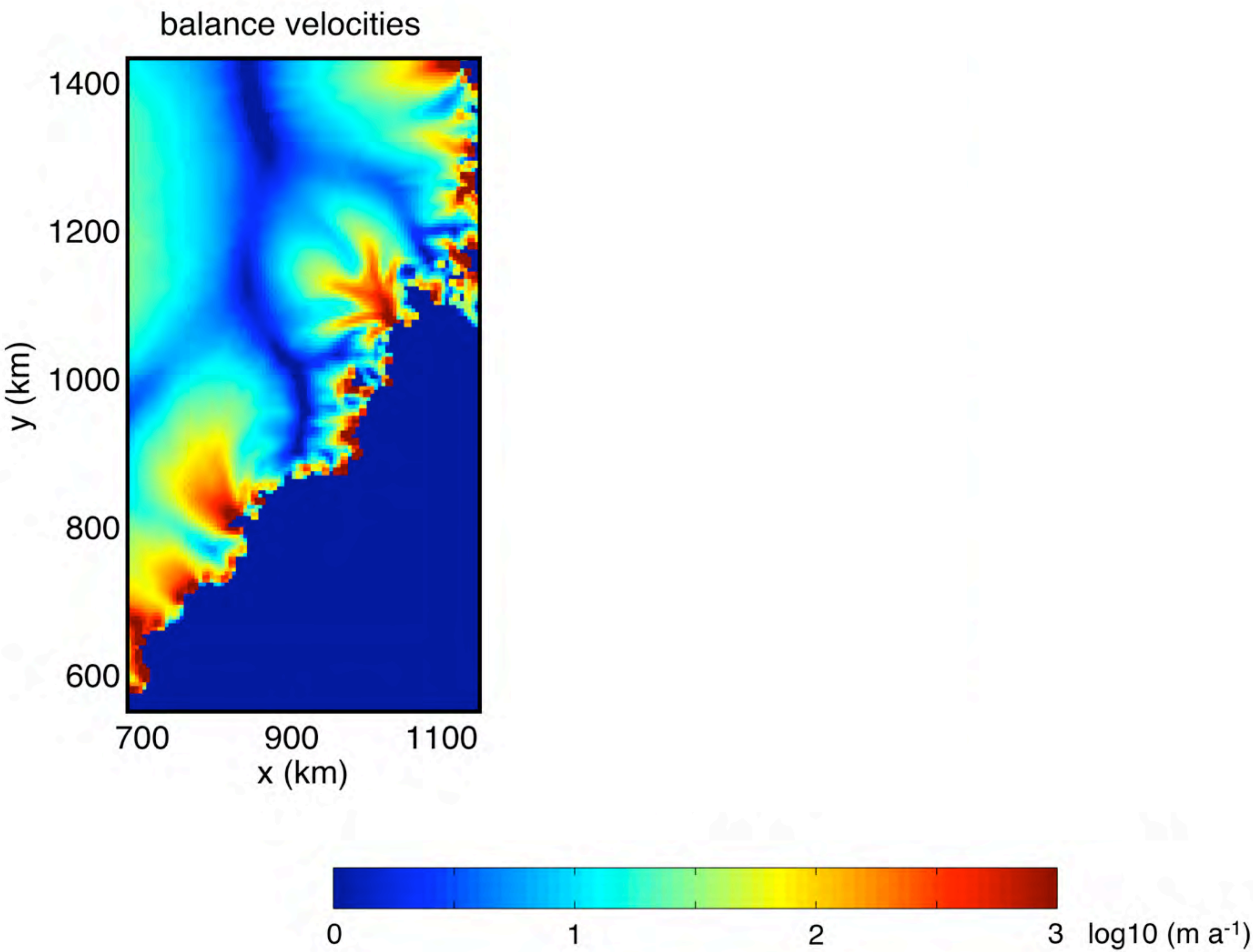

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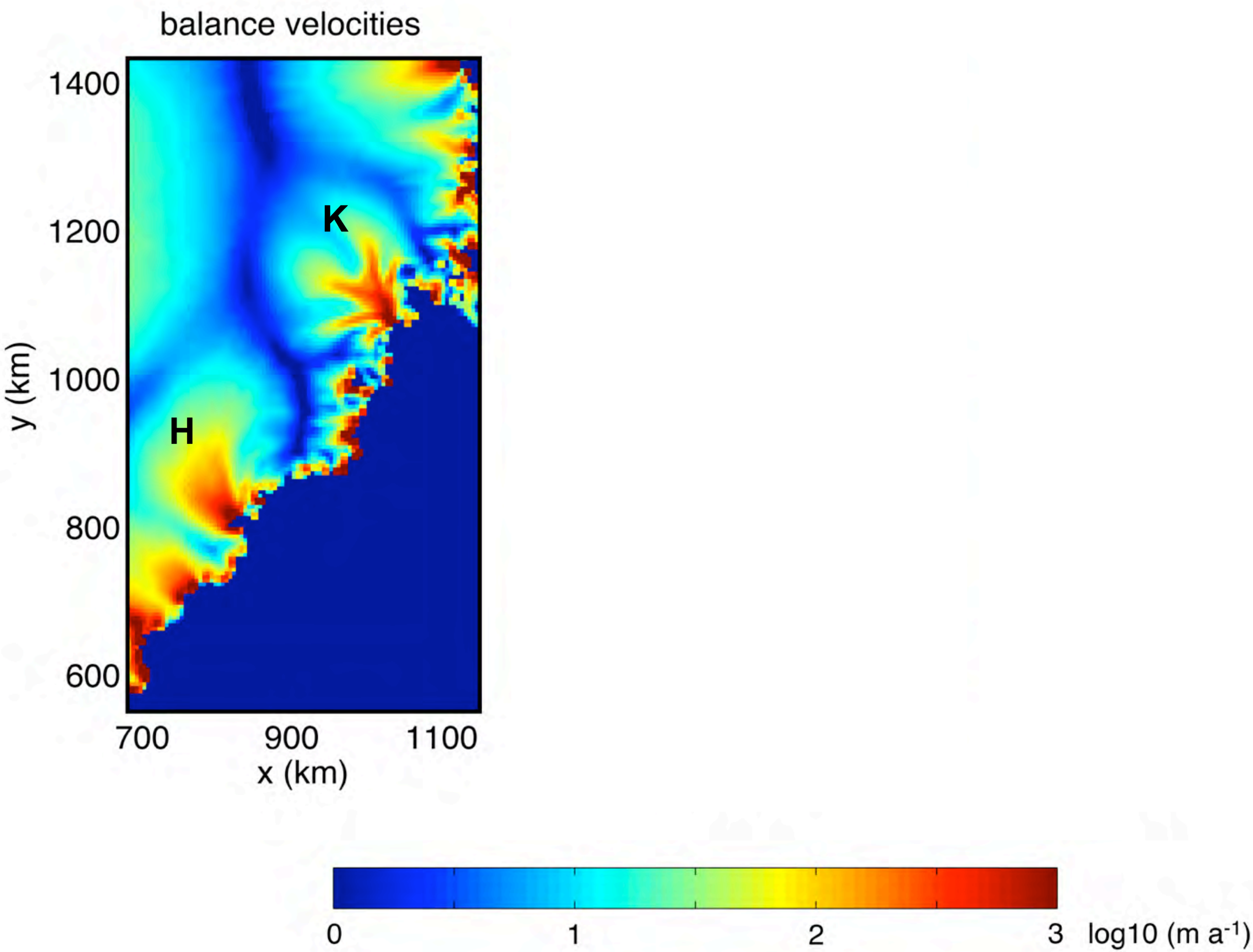

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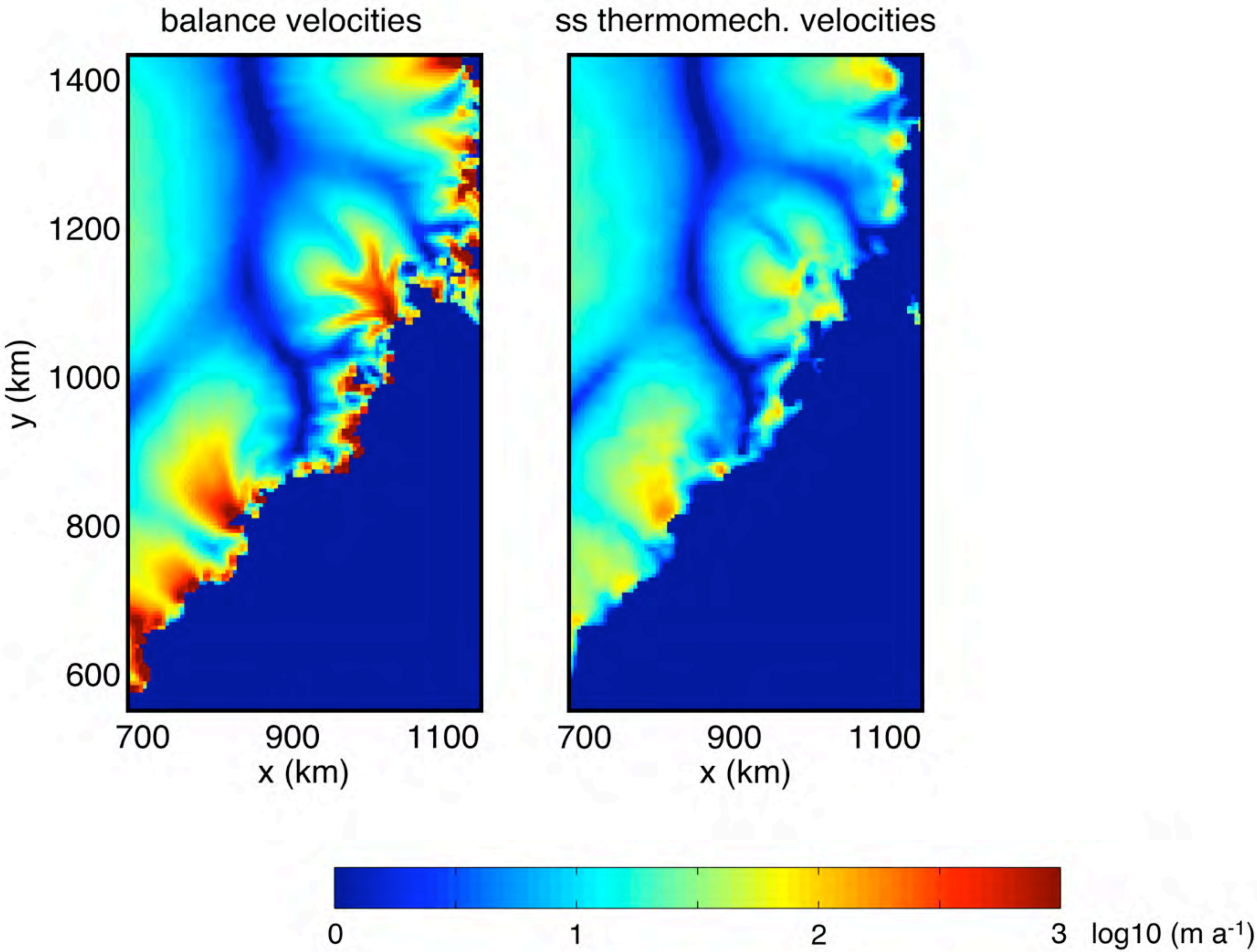

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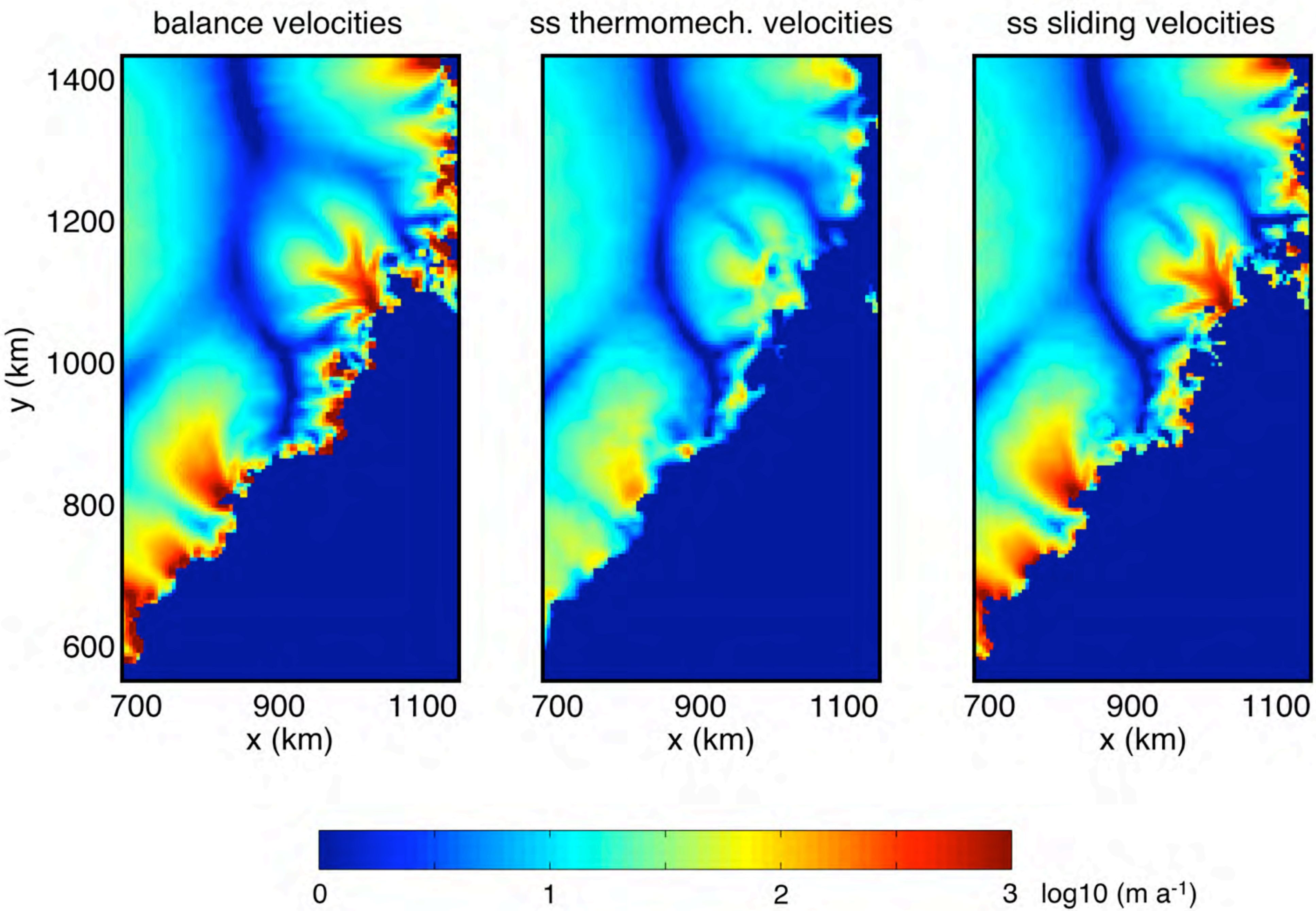

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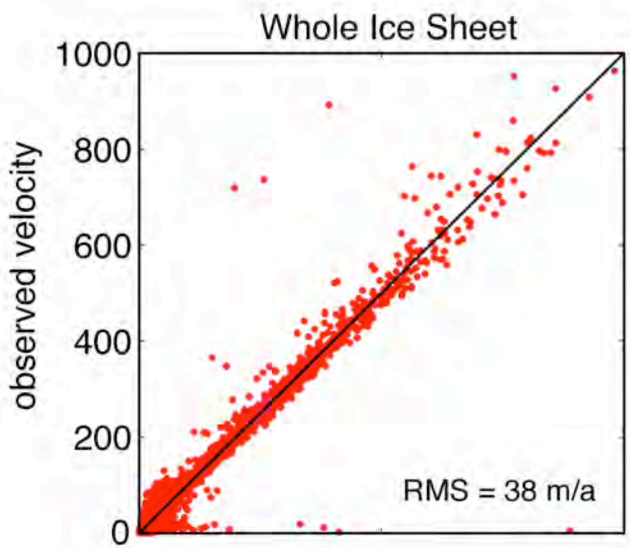

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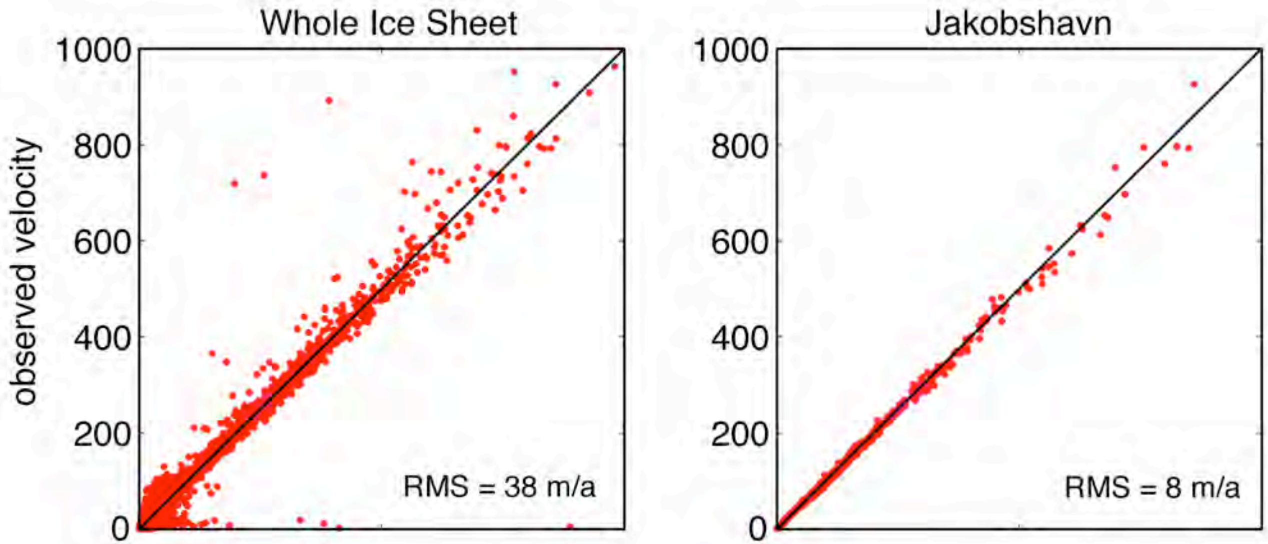

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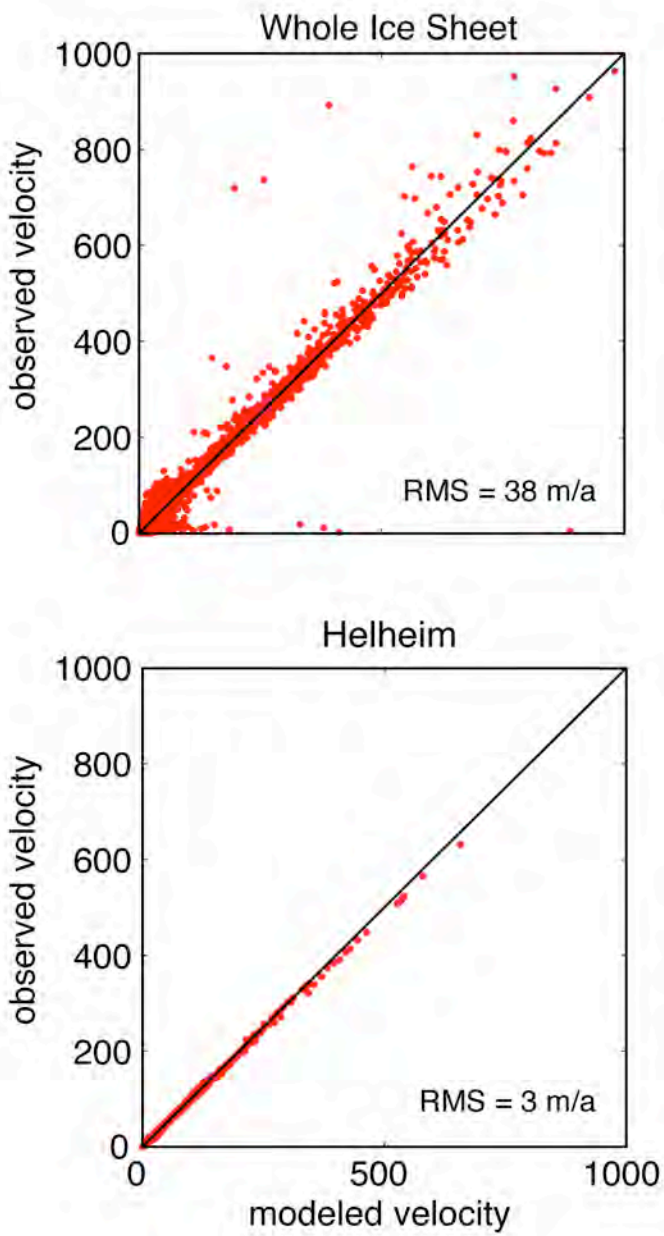

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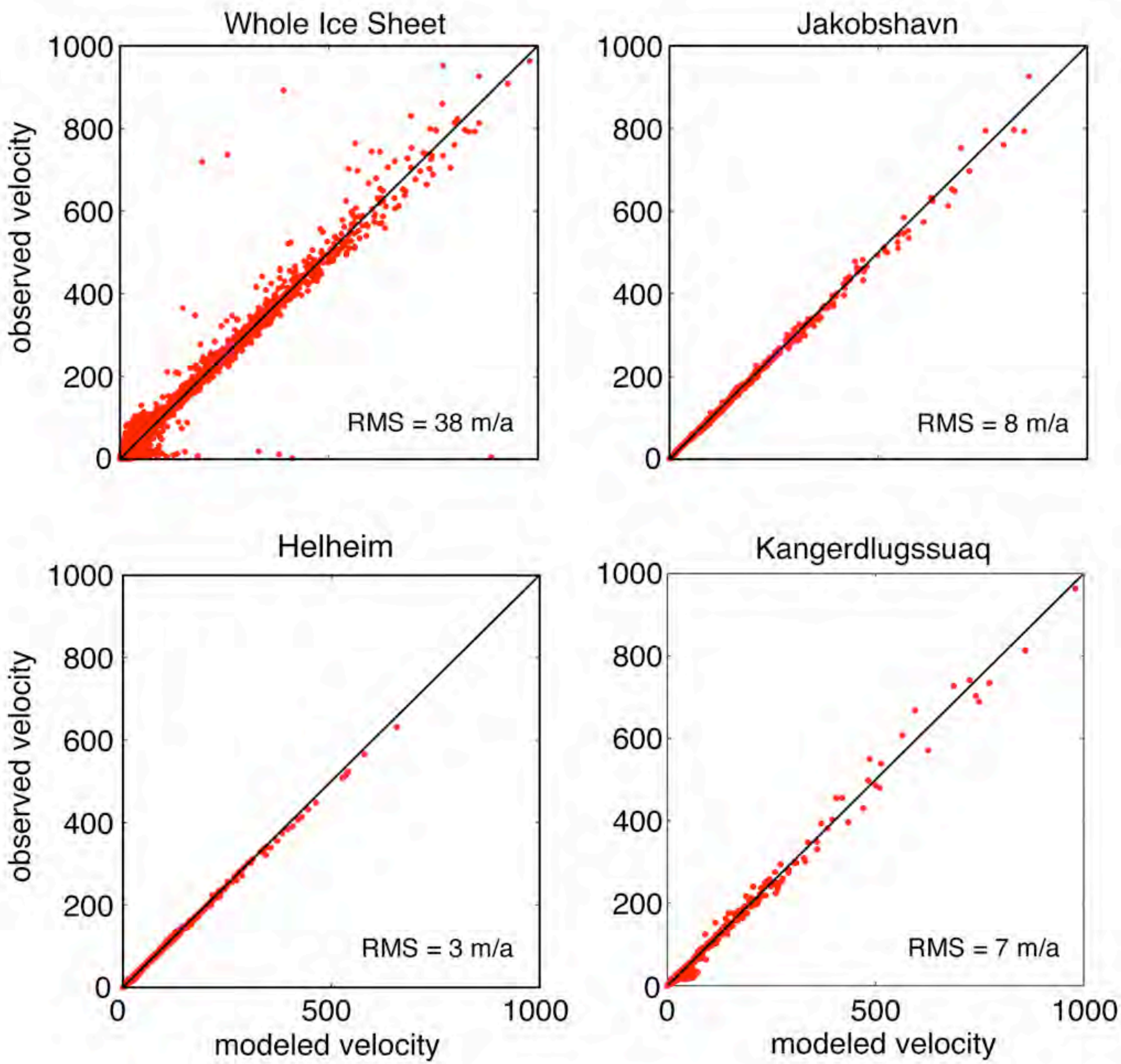

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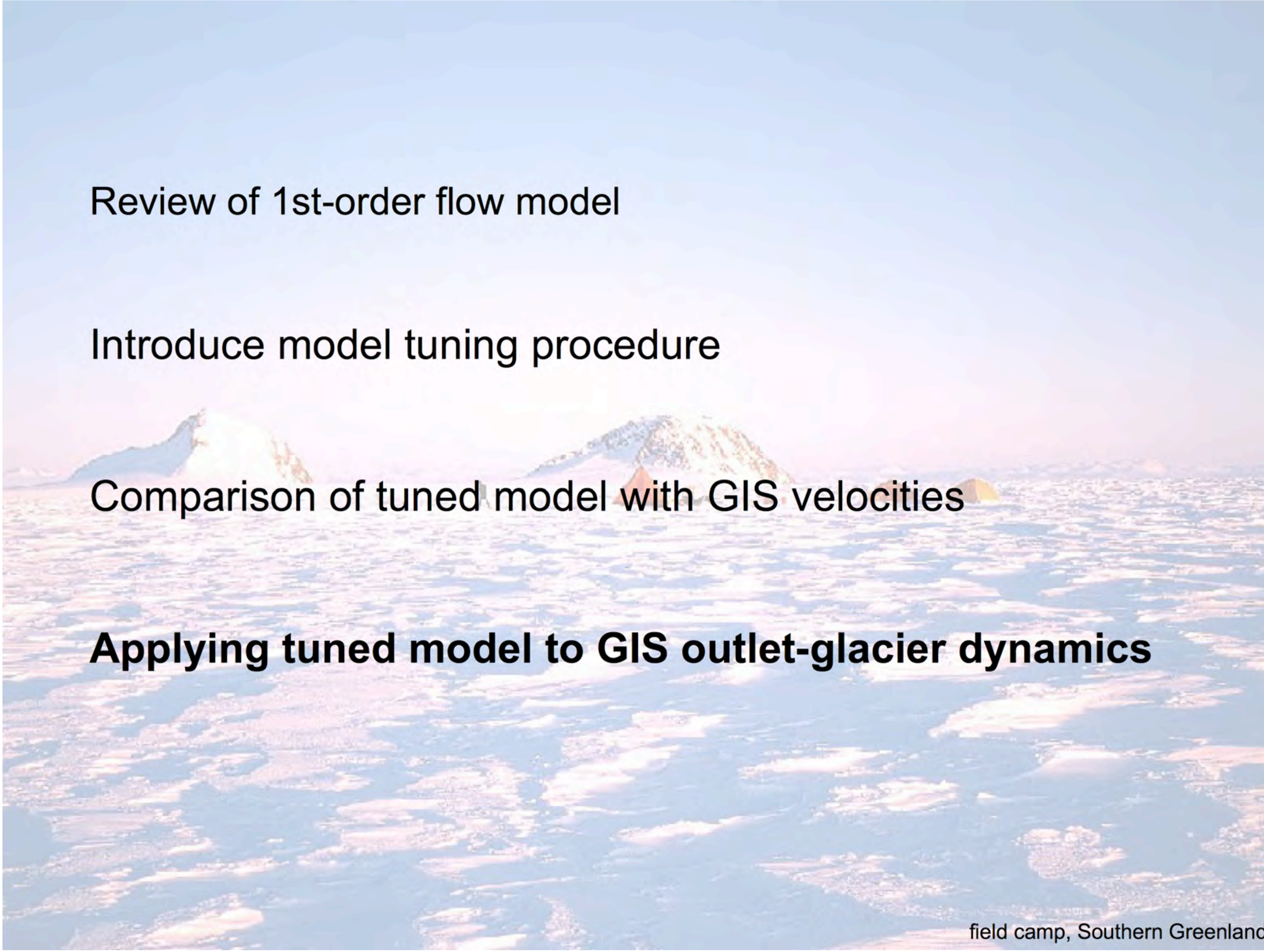

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The total represents a ***minimum*** estimate for SLR over that time period from GIS outlet glacier dynamics.

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Discharge ($km^3\ a^{-1}$) from select GIS basins:

Basin	*model (% error)*	*observations*[1]
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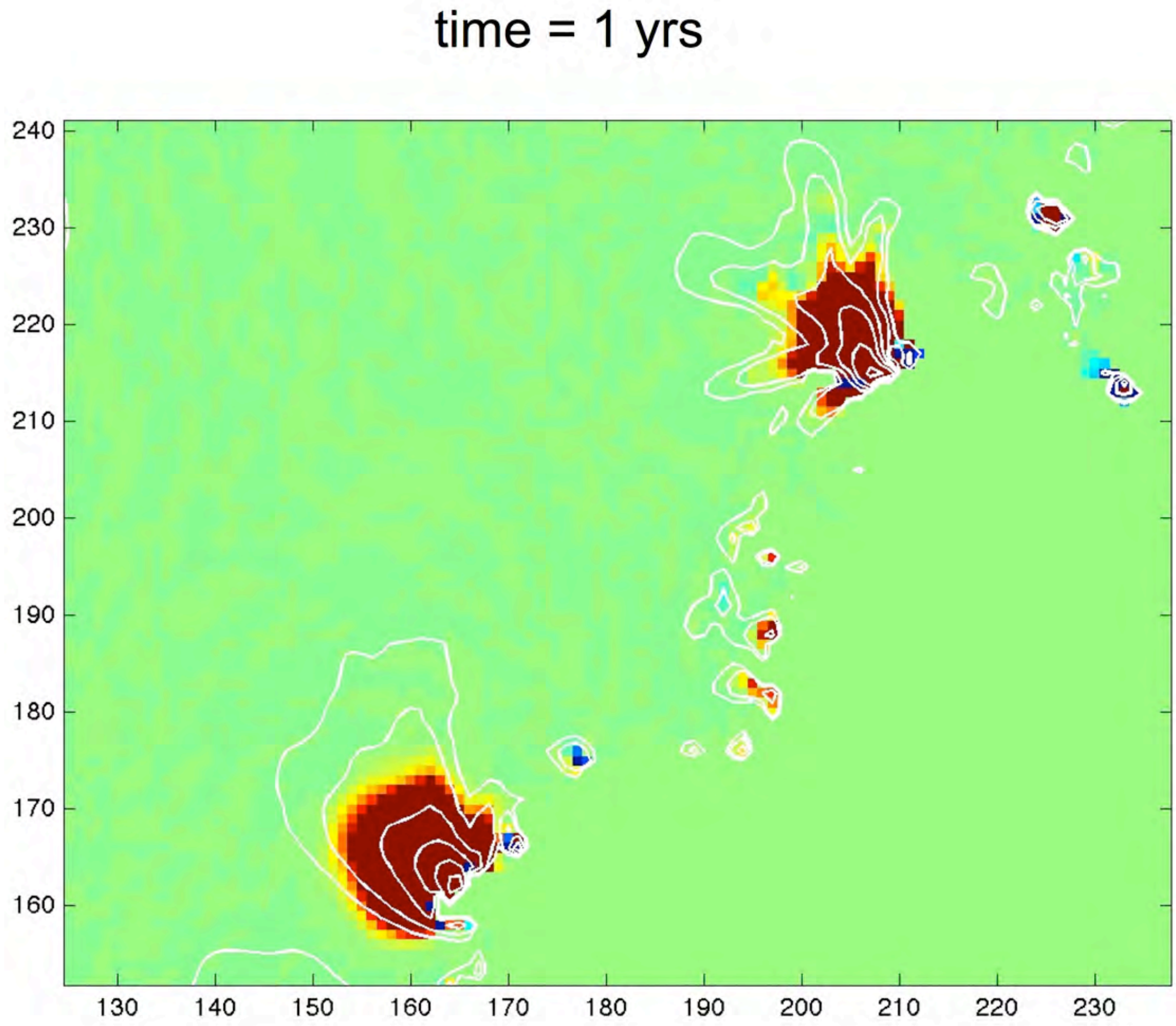
… Next, time series showing change in speed over Kang. and Hel. Glacier catchments from year 1 to year 9 …


time = 1 yrs
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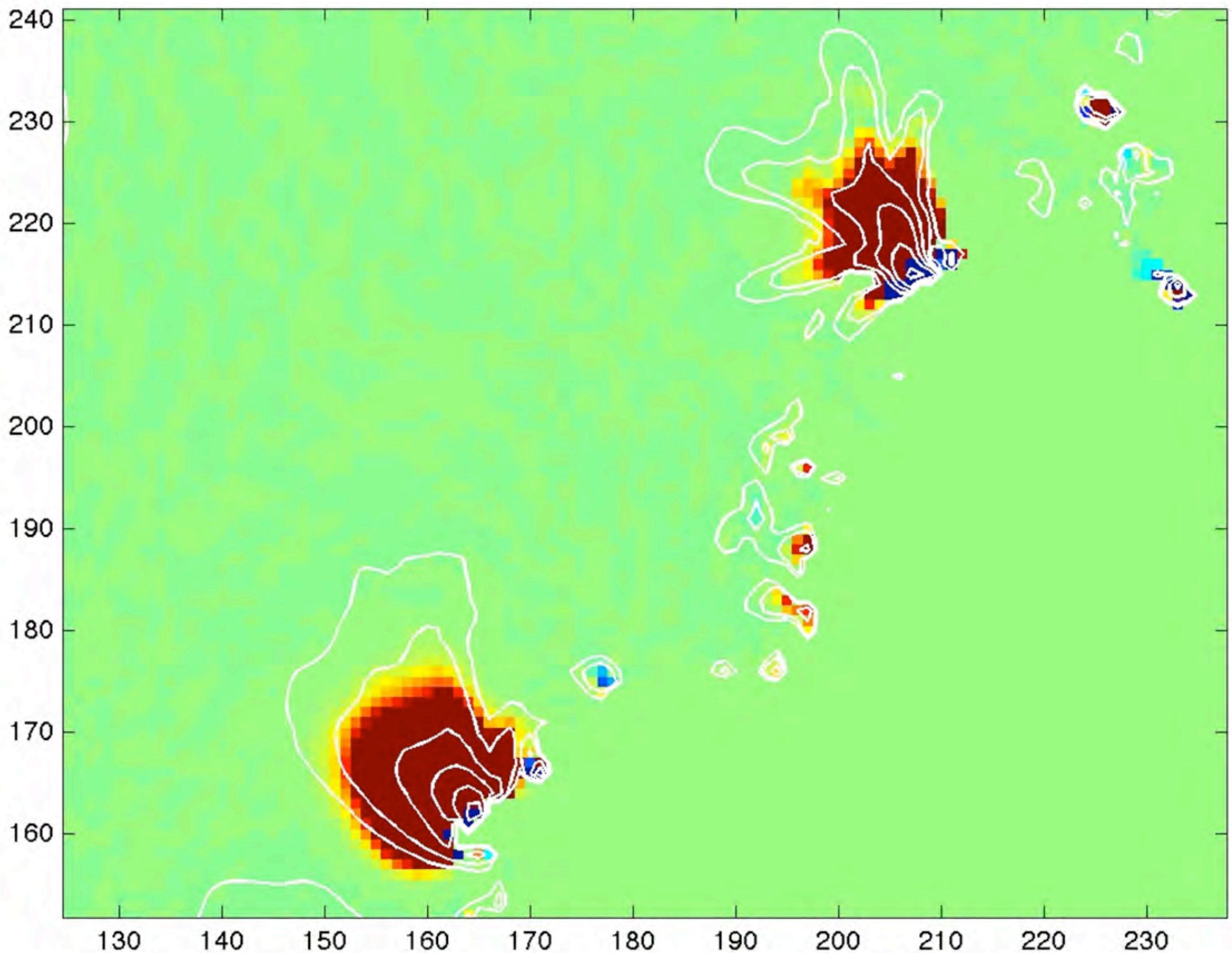
time = 2 yrs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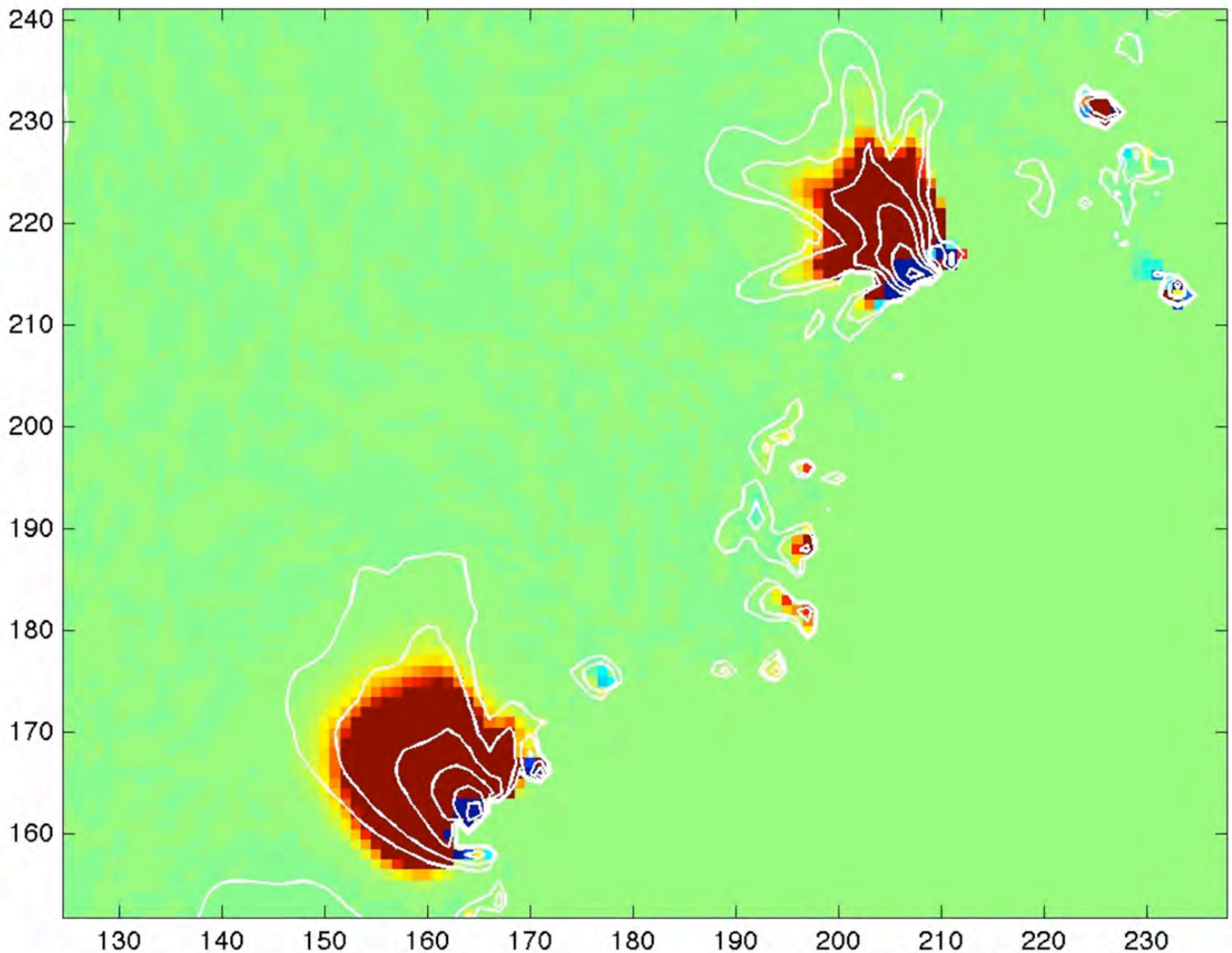
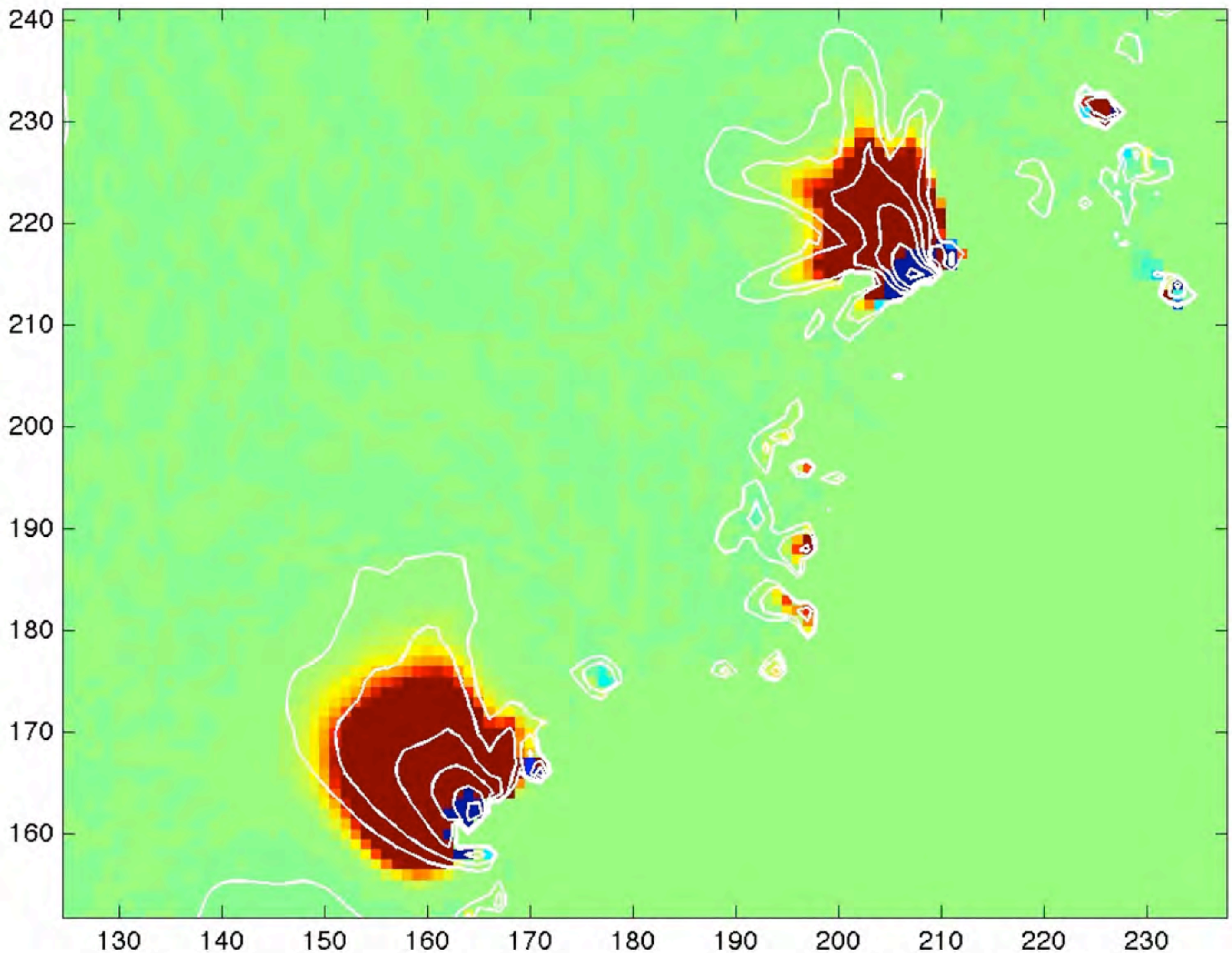
230

time = 3 yrs



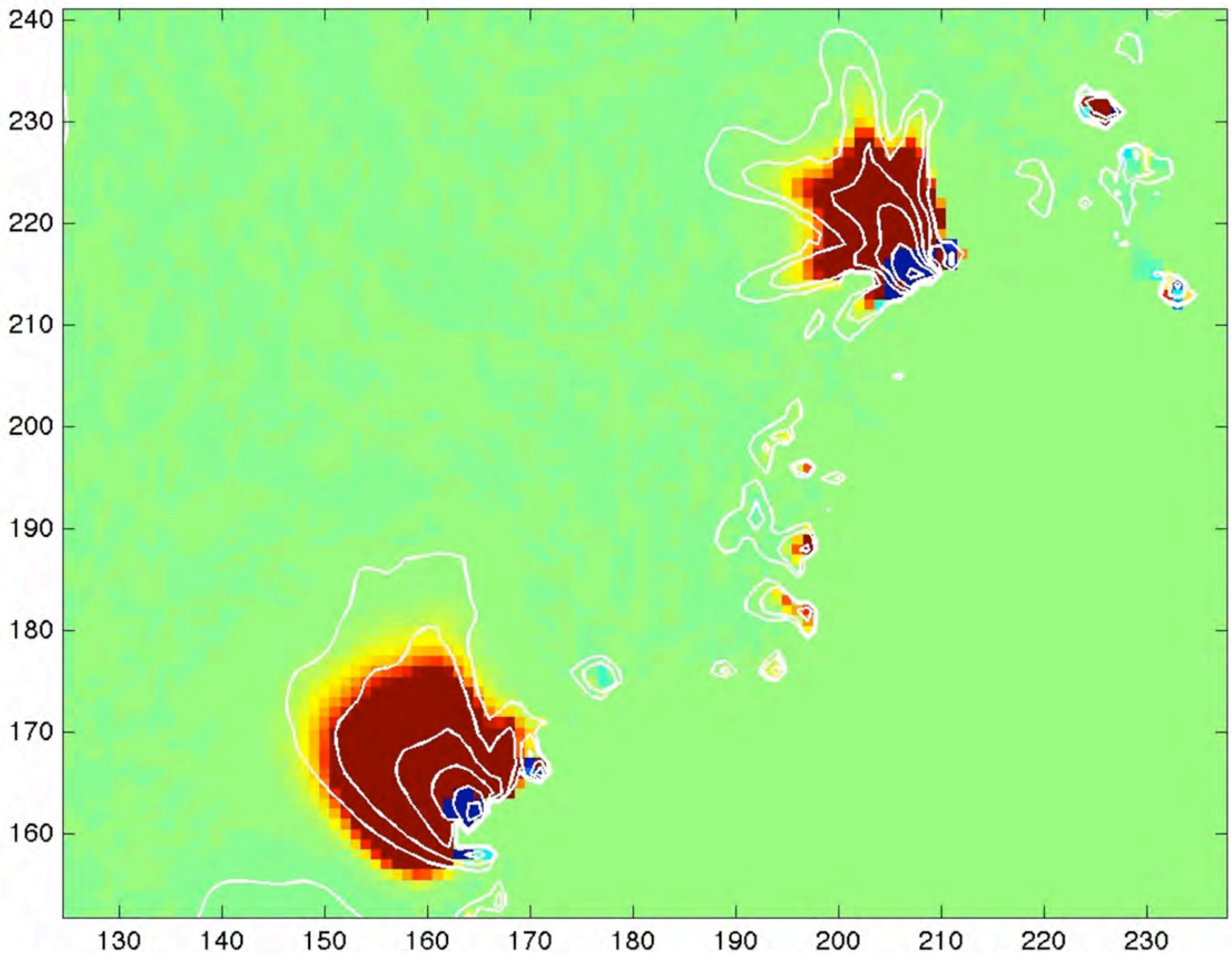
240
230
220
210
200
190
180
170
160
130
140
150
160
170
180
190
200
210
220
230

time = 4 yrs



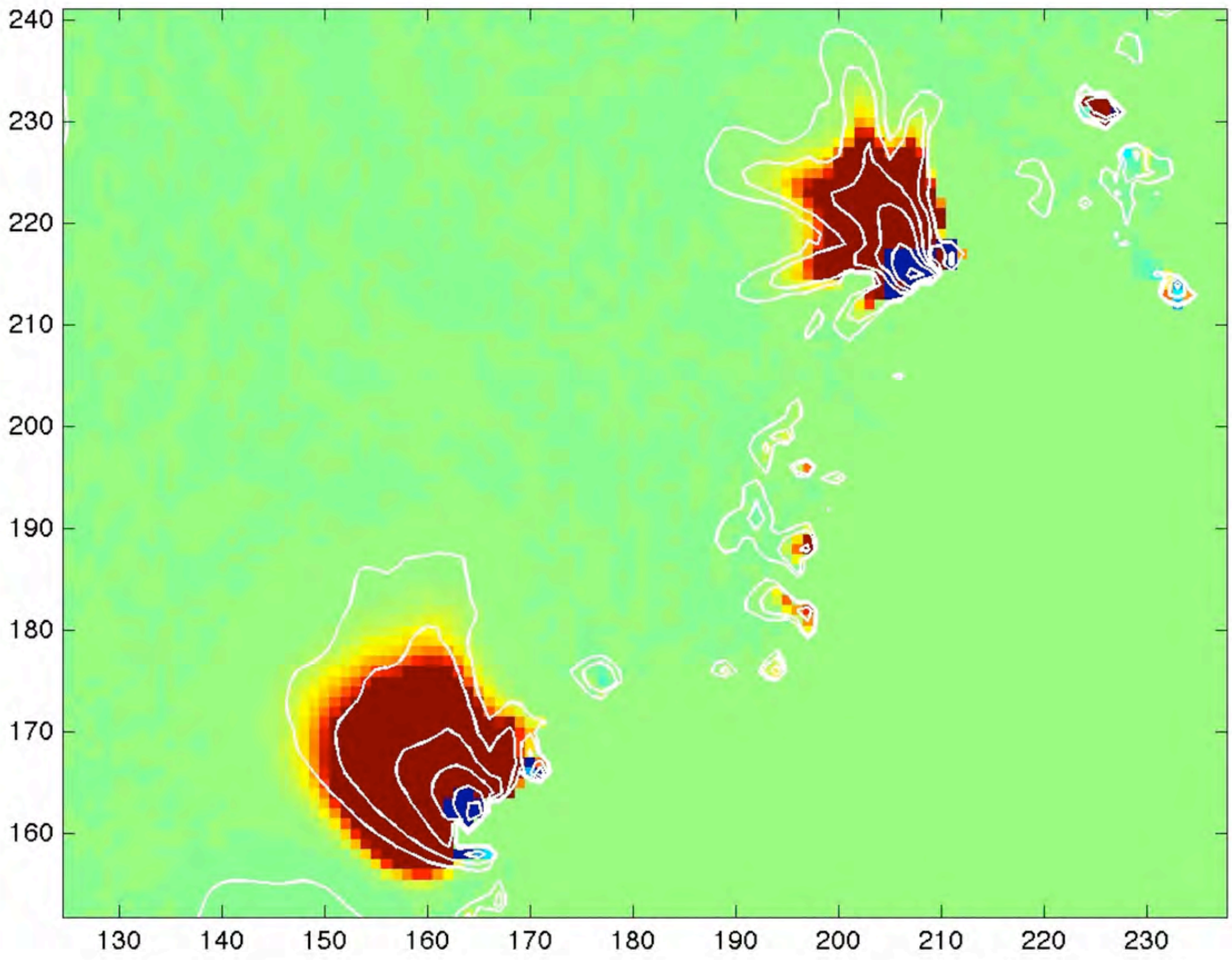
240
230
220
210
200
190
180
170
160
130 140 150 160 170 180 190 200 210 220 230

time = 5 yrs



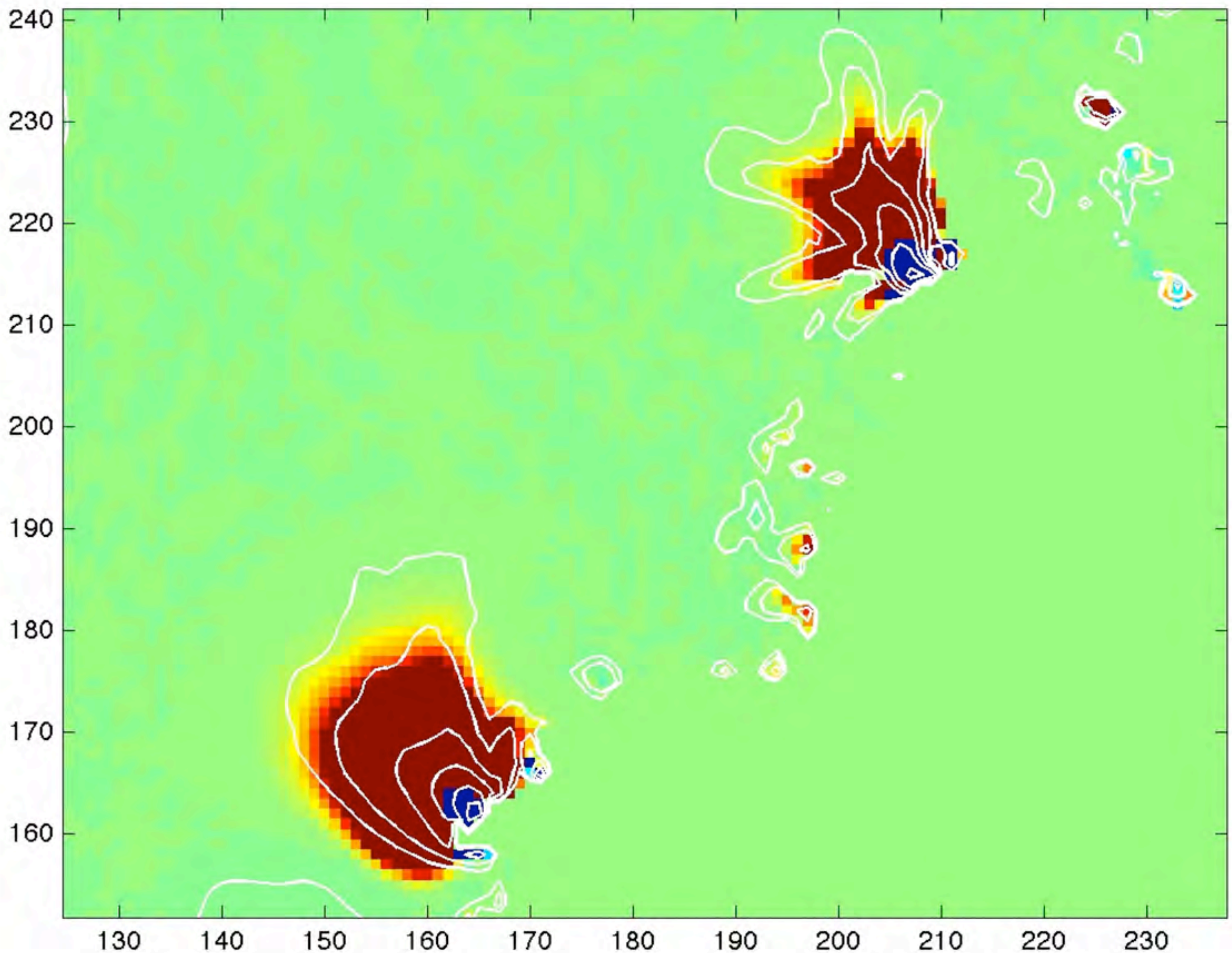
240
230
220
210
200
190
180
170
160
130
140
150
160
170
180
190
200
210
220
230

time = 6 yrs



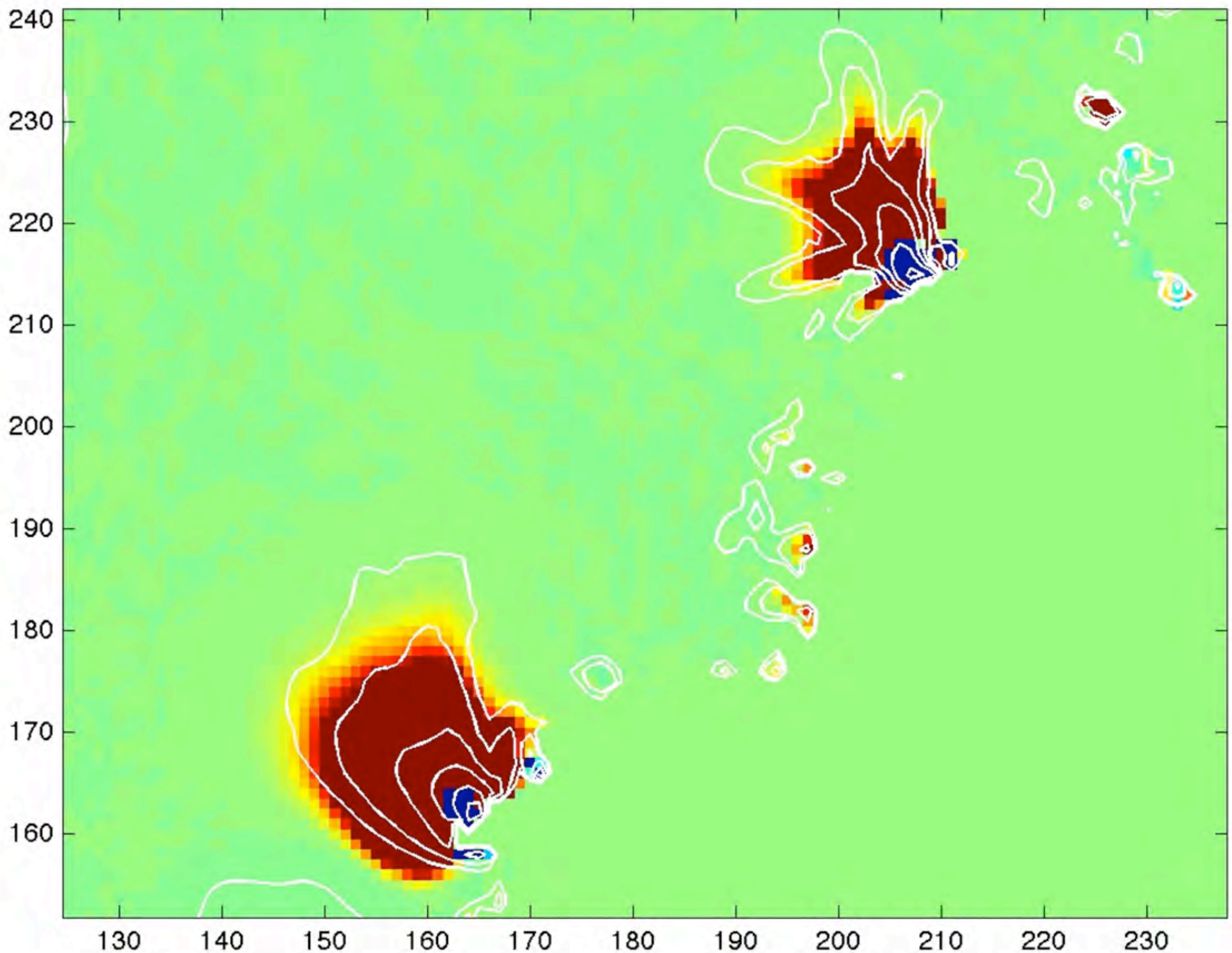
240
230
220
210
200
190
180
170
160
130
140
150
160
170
180
190
200
210
220
230

time = 7 yrs

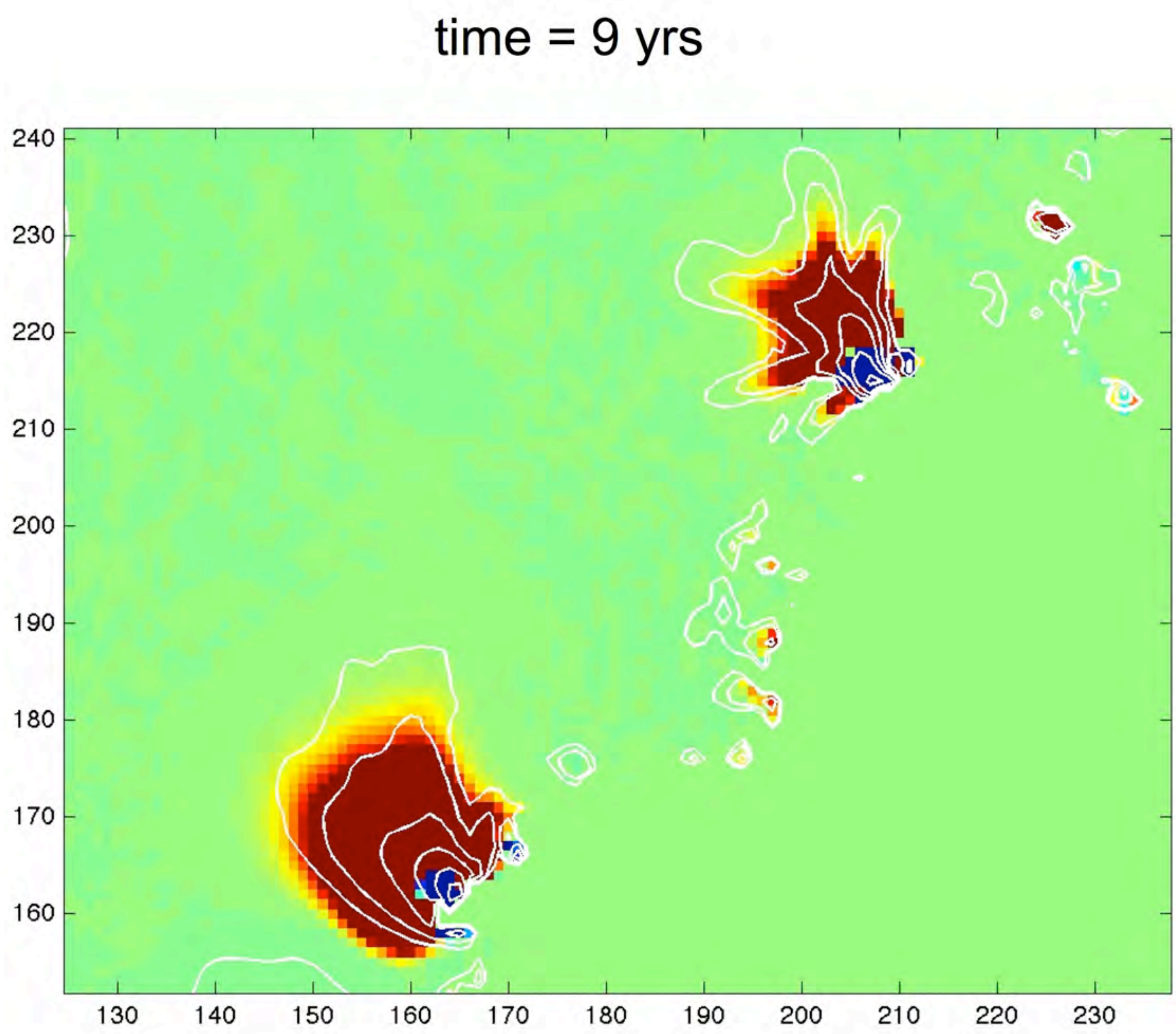


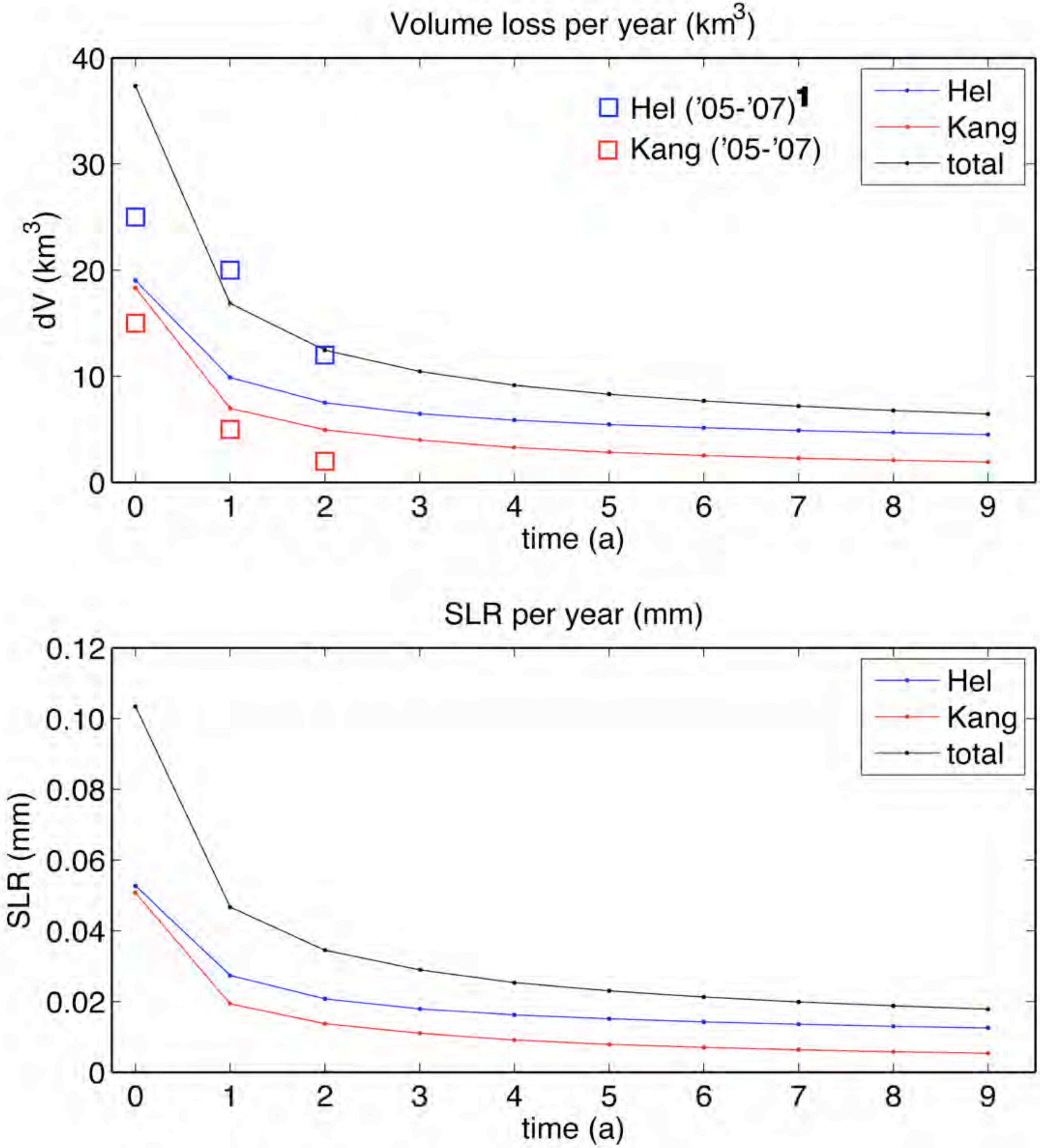
240
230
220
210
200
190
180
170
160
130
140
150
160
170
180
190
200
210
220
230

time = 8 yrs

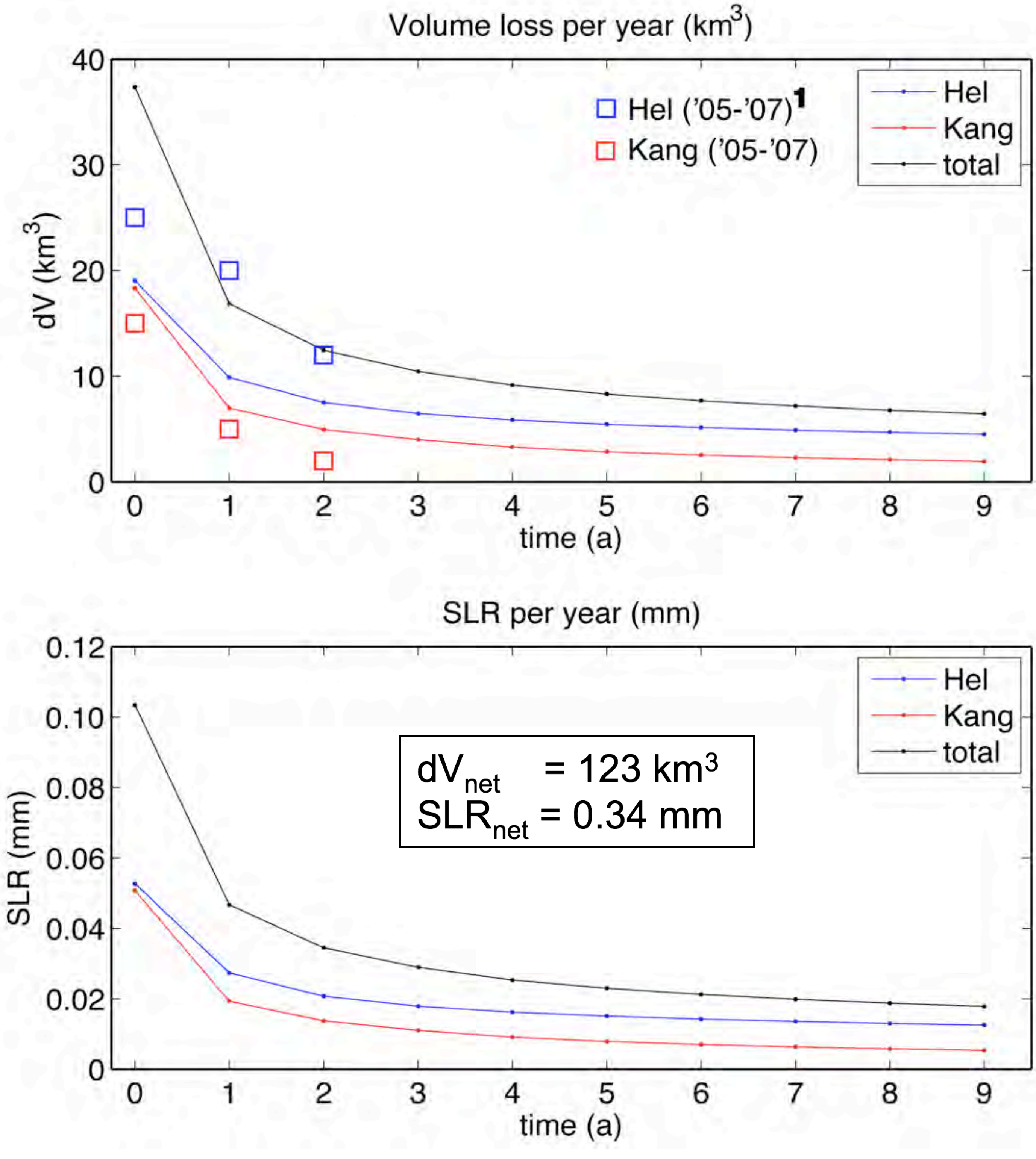


240
230
220
210
200
190
180
170
160
130
140
150
160
170
180
190
200
210
220
230

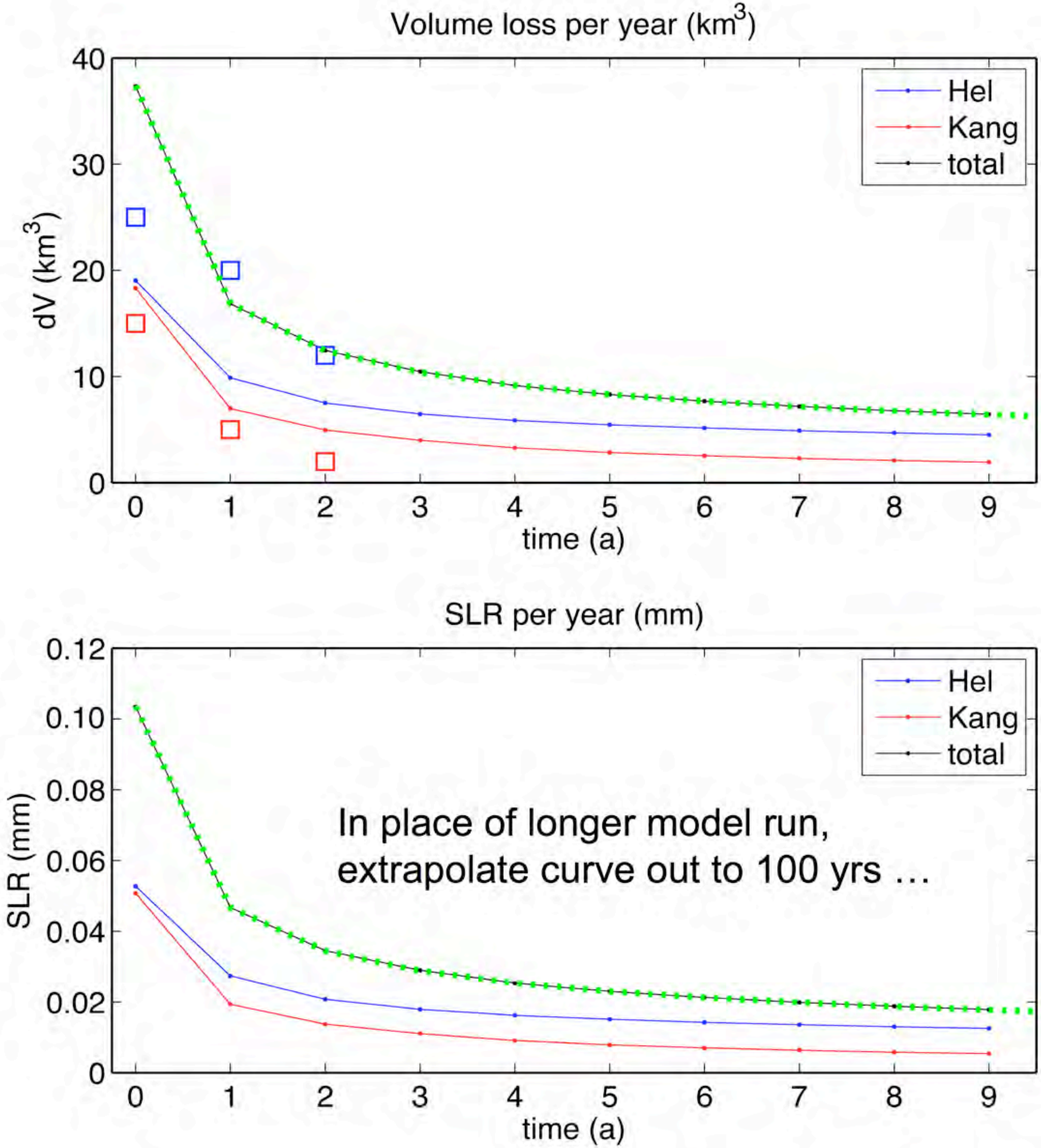

time = 9 yrs
240
230
220
210
200
190
180
170
160
130
140
150
160
170
180
190
200
210
220
230



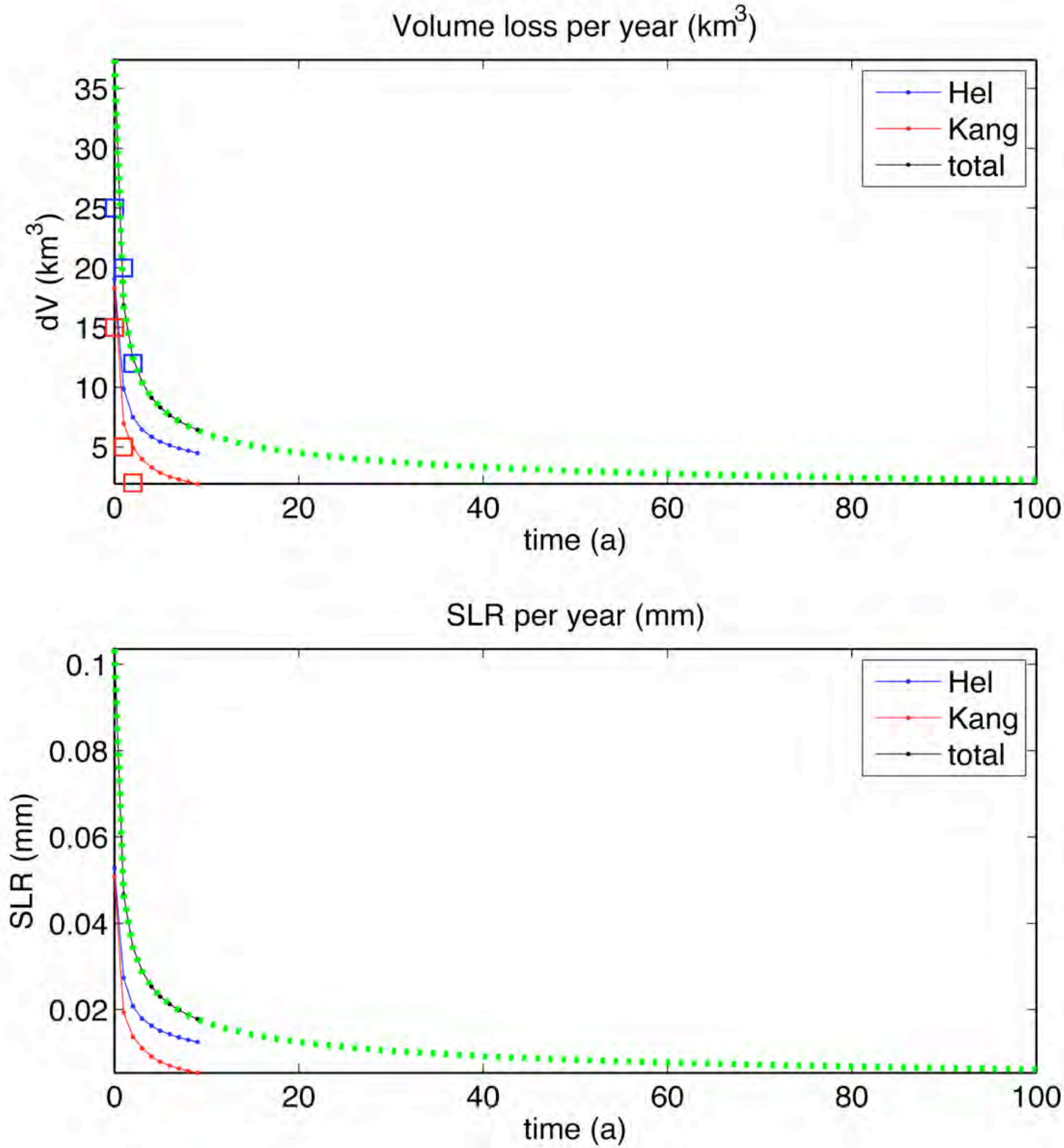
[1]Howat et al.
(*Science*, **315**, 2007)



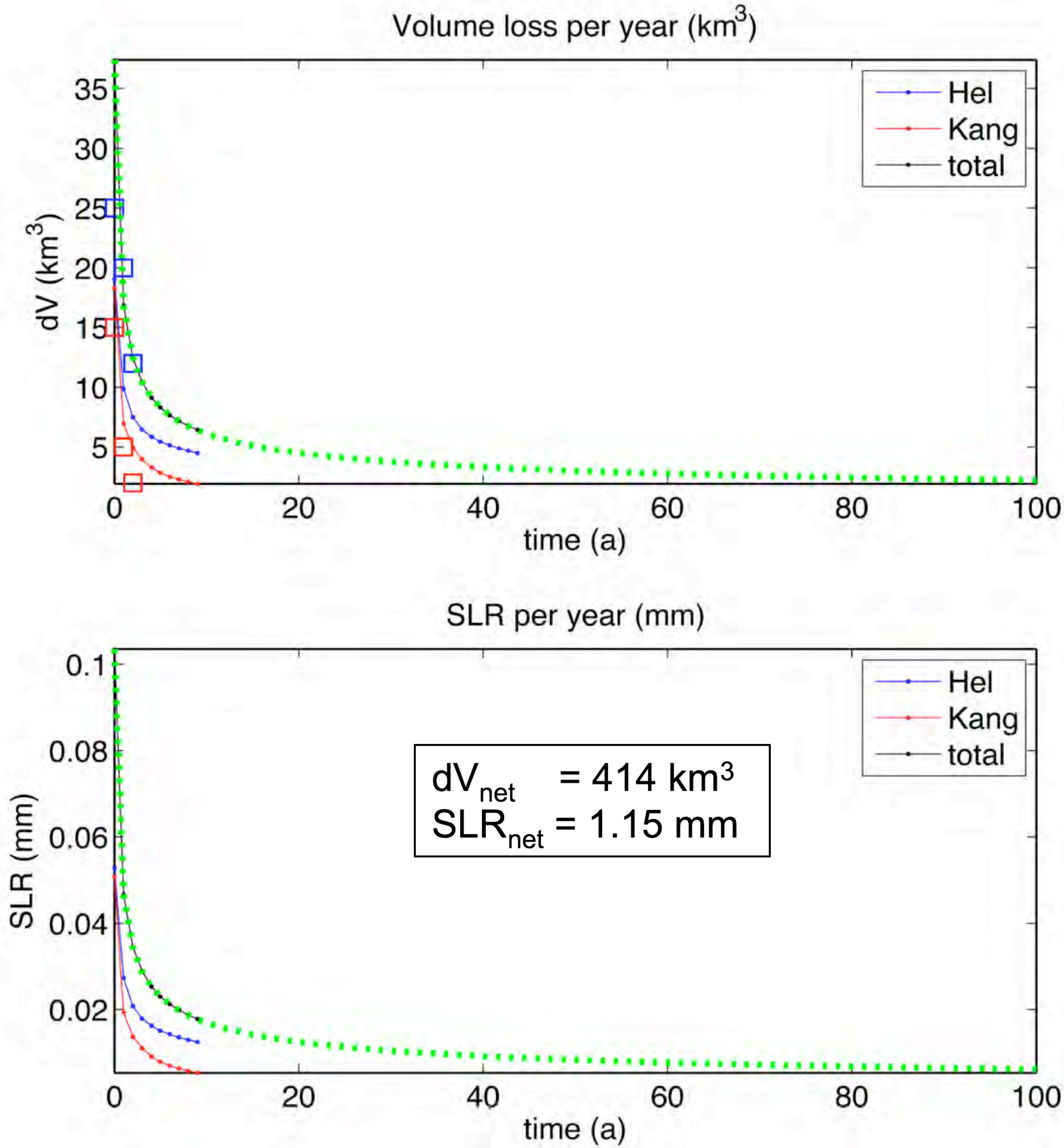
[1]Howat et al.
(*Science*, **315**, 2007)



Volume loss per year (km^3)
dV (km^3)
time (a)
Hel
Kang
total
0
10
20
30
40
0
1
2
3
4
5
6
7
8
9
SLR per year (mm)
SLR (mm)
time (a)
Hel
Kang
total
0
0.02
0.04
0.06
0.08
0.10
0.12
In place of longer model run,
extrapolate curve out to 100 yrs …



Volume loss per year (km3)
dV (km3)
35
30
25
20
15
10
5
0
20
40
60
80
100
time (a)
Hel
Kang
total
SLR per year (mm)
SLR (mm)
0.1
0.08
0.06
0.04
0.02
0
20
40
60
80
100
time (a)
Hel
Kang
total


Volume loss per year (km3)
dV (km3)
time (a)
Hel
Kang
total
SLR per year (mm)
SLR (mm)
time (a)
dVnet = 414 km3
SLRnet = 1.15 mm

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Jakobshavn, in a continual state of retreat since the late ‘90’s, would raise these numbers significantly (as would the contribution of numerous other marine outlets that have retreated and thinned during the last decade).


END

Diagnostic Velocity Field

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Momentum Balance BCs:

surface:	free surface
bed:	u=v=0
sides:	u=v=0

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Energy Balance BCs:

surface:	specified T	(ERA 40)
bed:	specified dT/dz	(Q_{geo} = 55 mW)
sides:	upwinding	

Diagnostic Velocity Field

Momentum Balance BCs:

surface:	free surface
bed:	$u=v=0$
sides:	$u=v=0$

Energy Balance BCs:

surface:	specified T	(ERA 40)
bed:	specified dT/dz	(Q_{geo} = 55 mW)
sides:	upwinding	

Calculation:

… hold geometry, T_{surf}, Q_{geo} steady …
… allow $B(T)$, $\boldsymbol{u}$, and η_{eff} to evolve to steady state …

[1]Blatter (*J. Glac.*, **41**, 1995)

Illulisat, Western Greenland