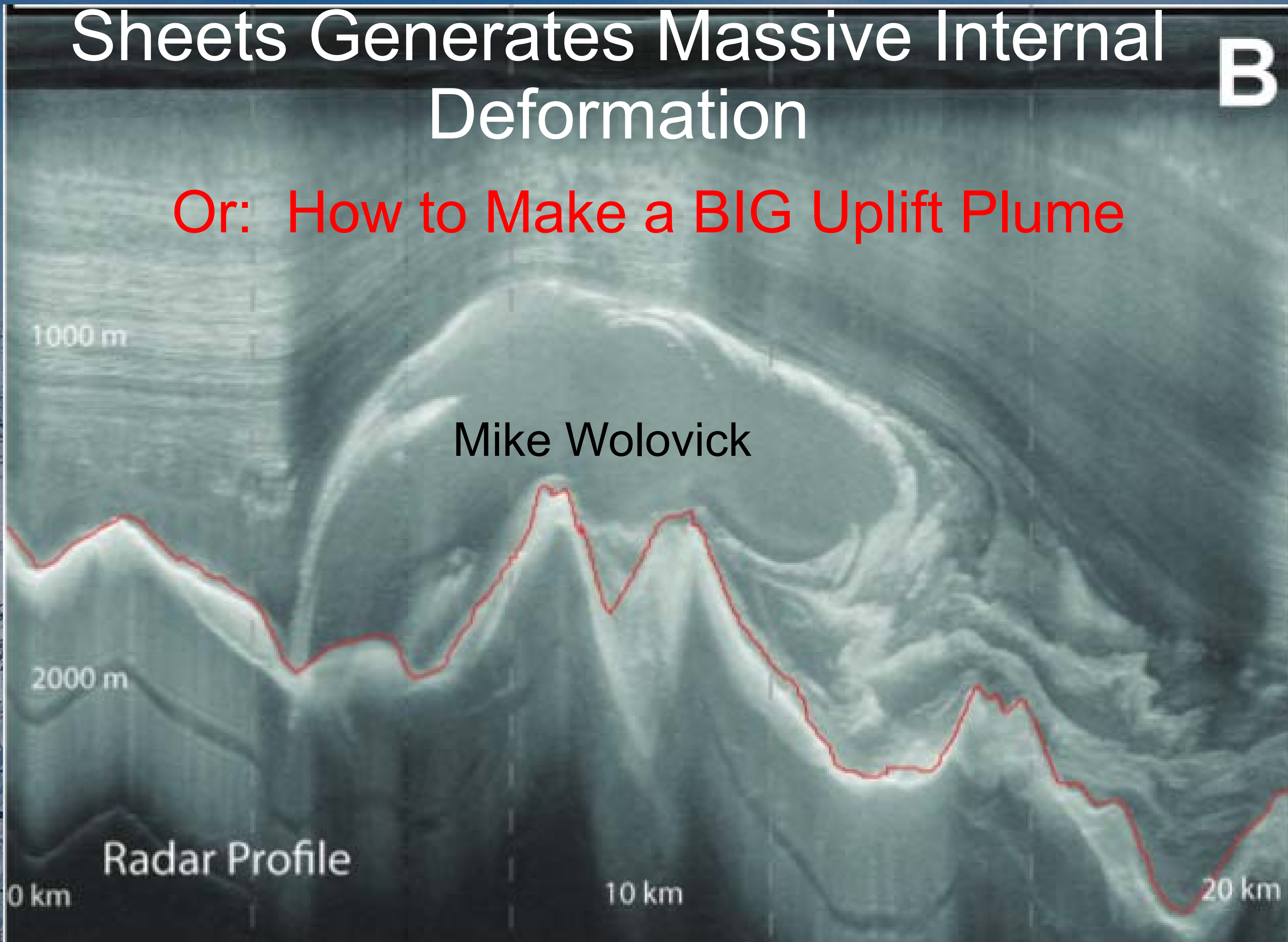
Dynamic Stick-Slip at the Base of Ice Sheets Generates Massive Internal Deformation

Or: How to Make a BIG Uplift Plume



Mike Wolovick

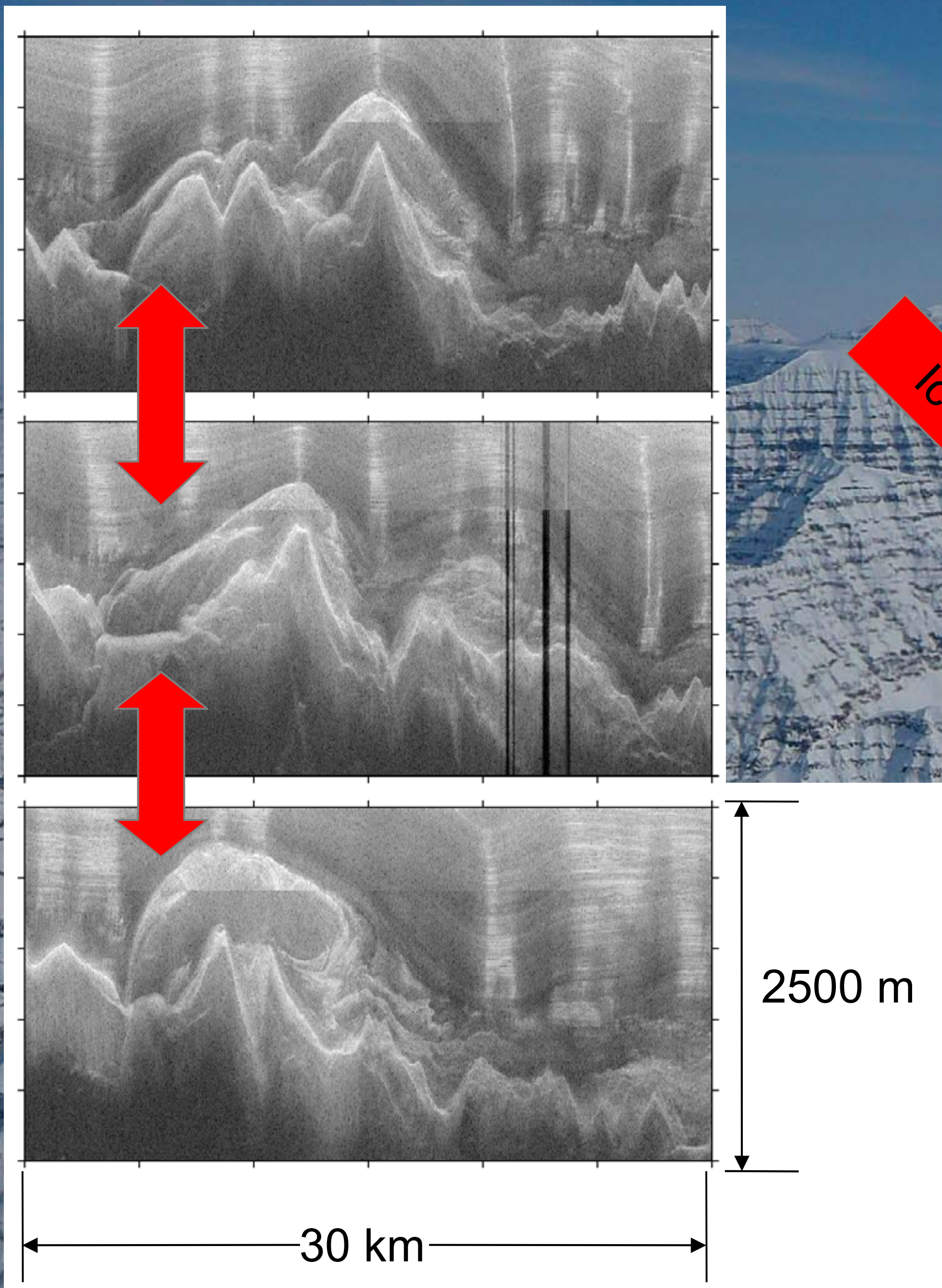
Robin Bell, Tim Creyts, Roger Buck

Outline

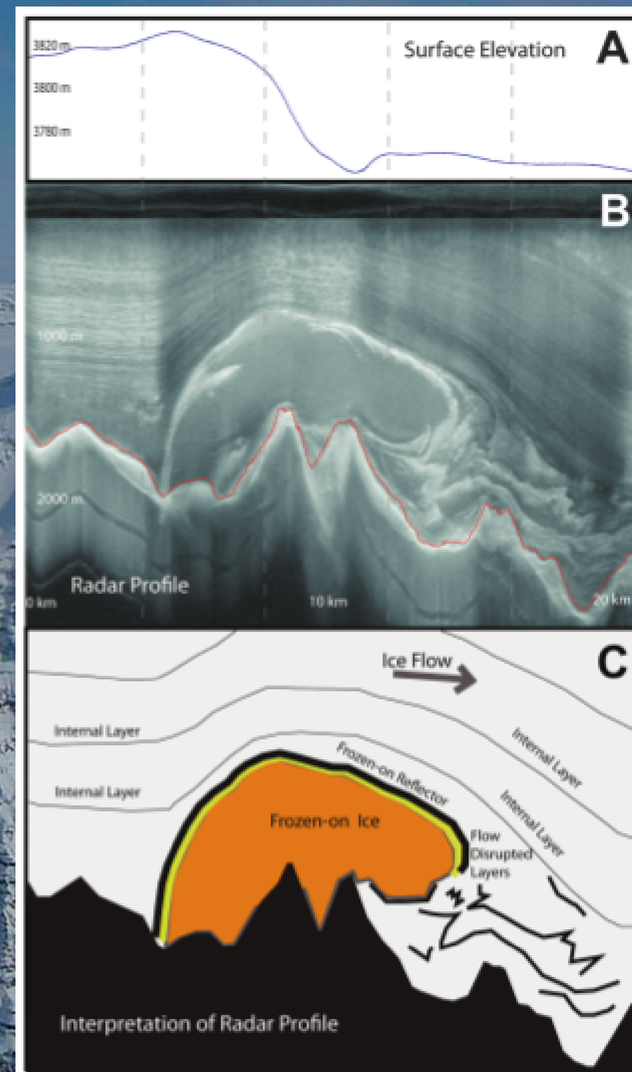
- Observations
- Modeling
- Parameter Tests
- Conclusions

Observations

East Antarctica



Ice Flow

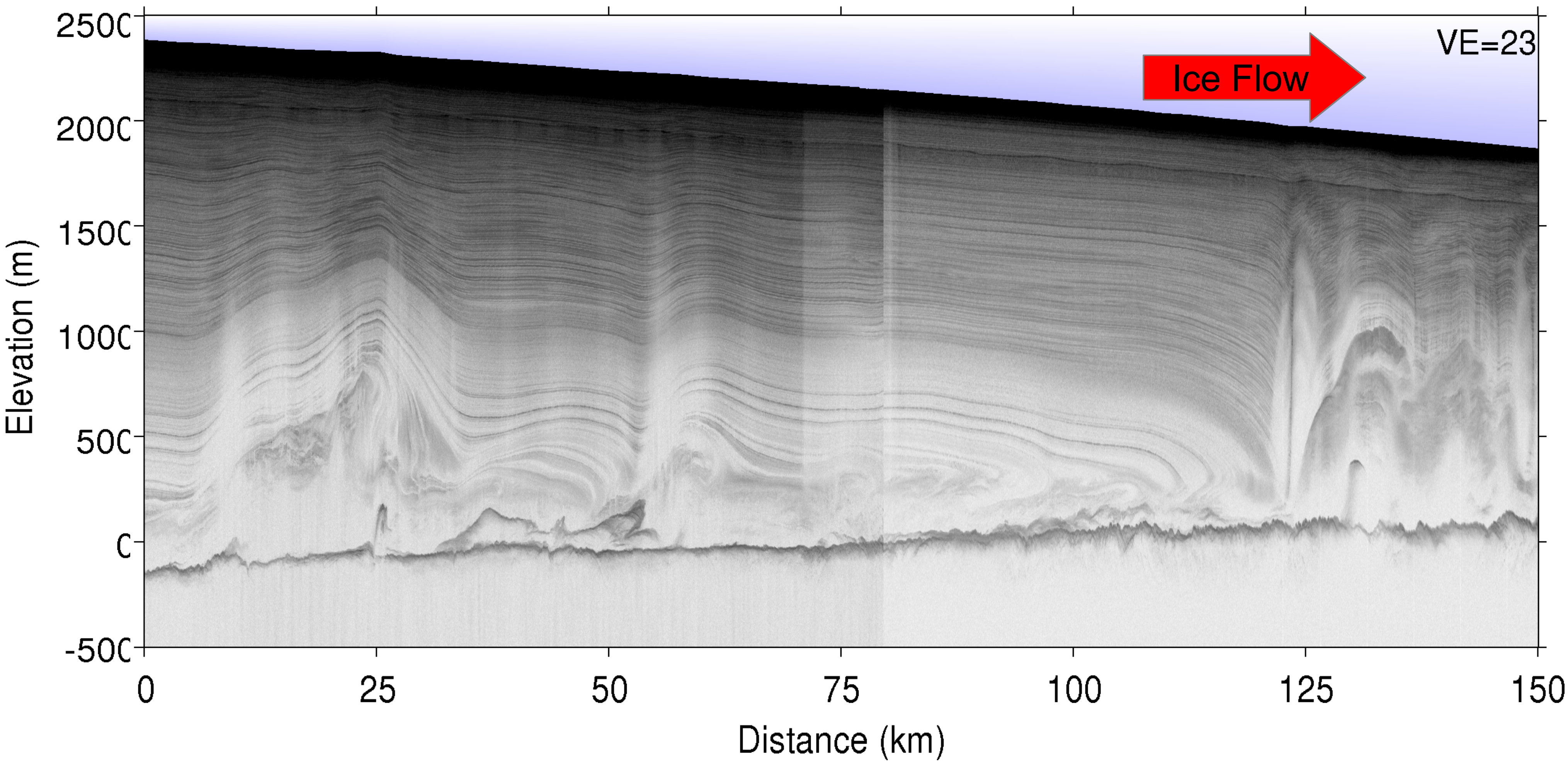


High-volume interpretation

Bell et al., 2011

Observations

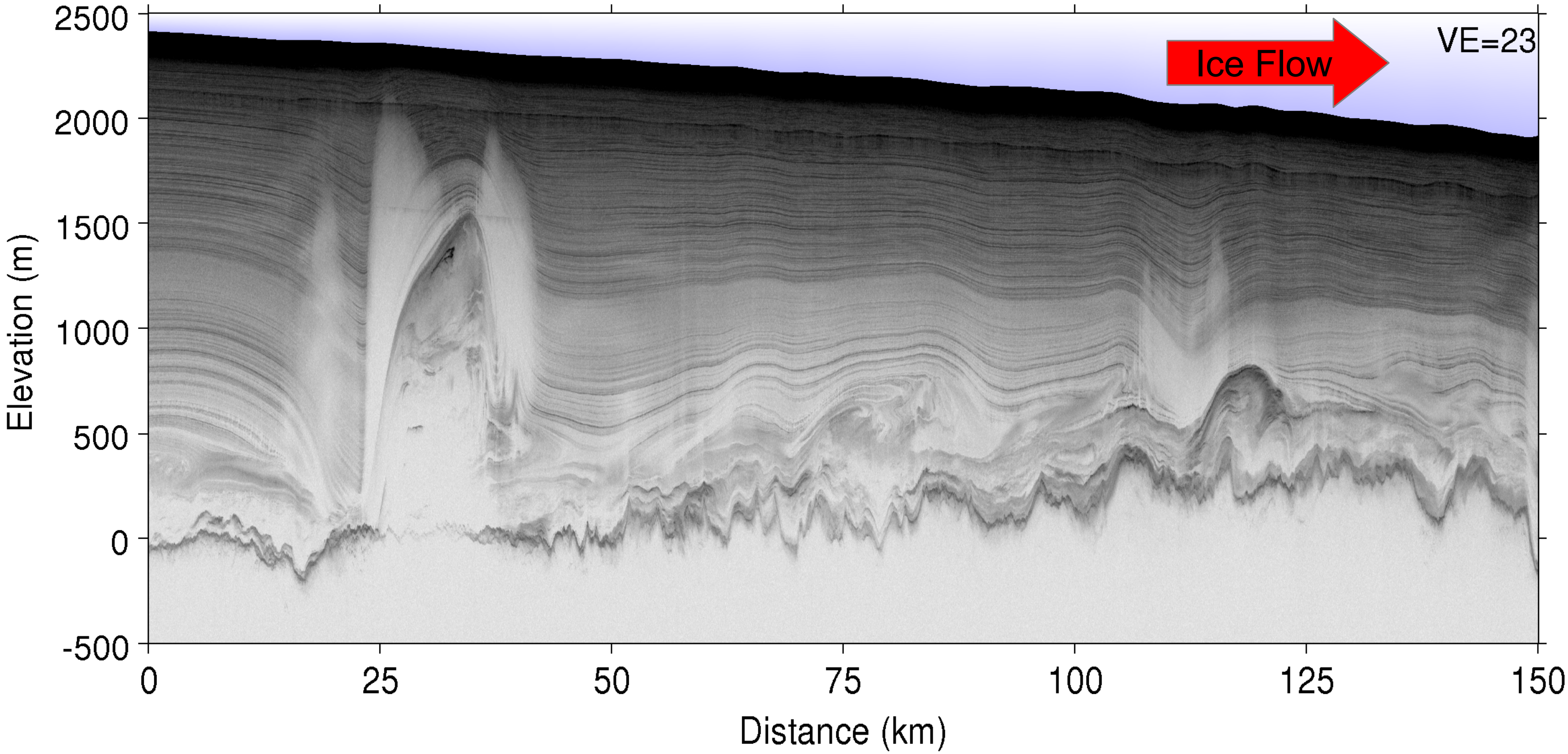
North Greenland



CReSIS, OIB
2011/2012

Observations

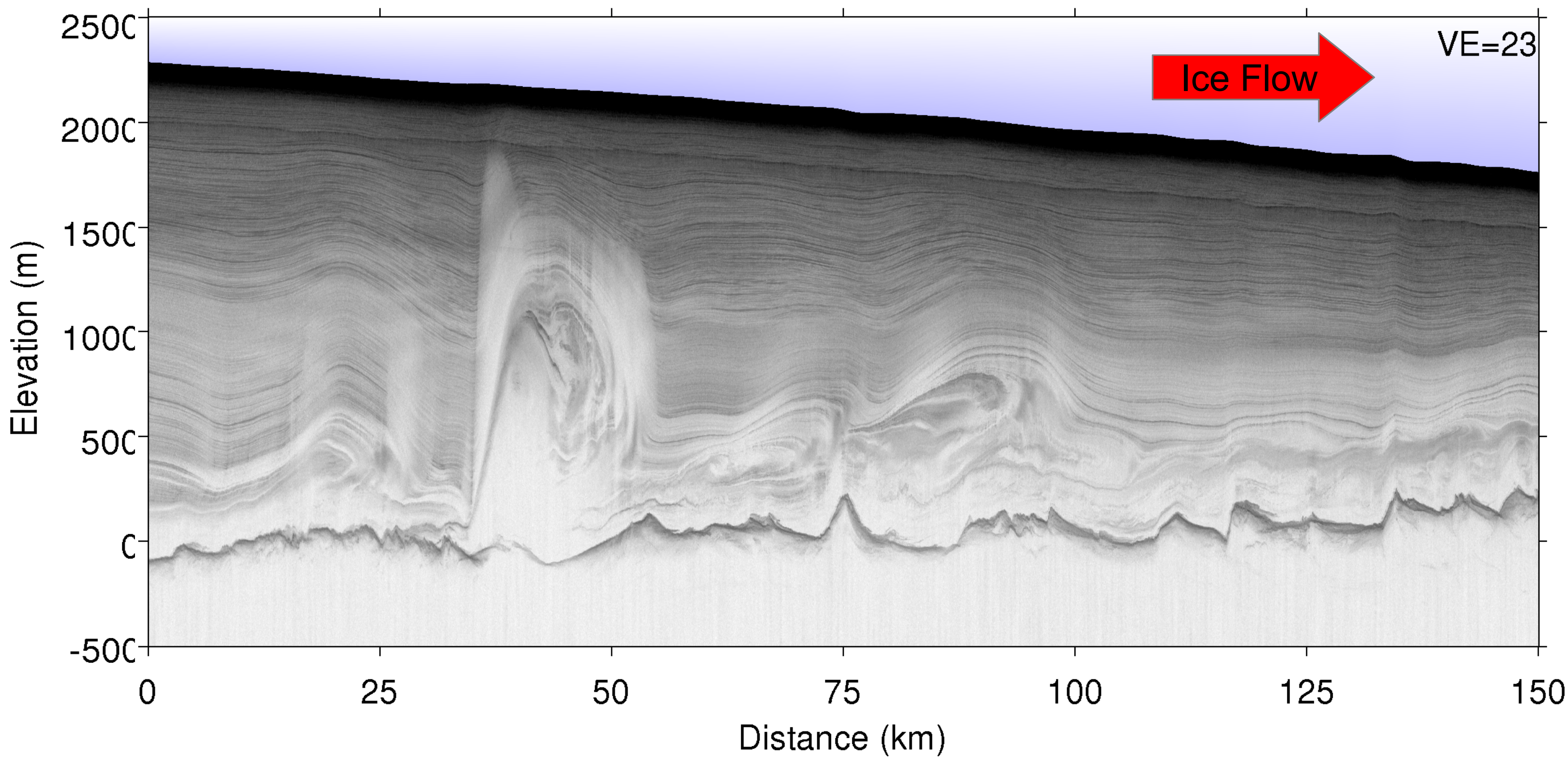
North Greenland



CReSIS, OIB
2011/2012

Observations

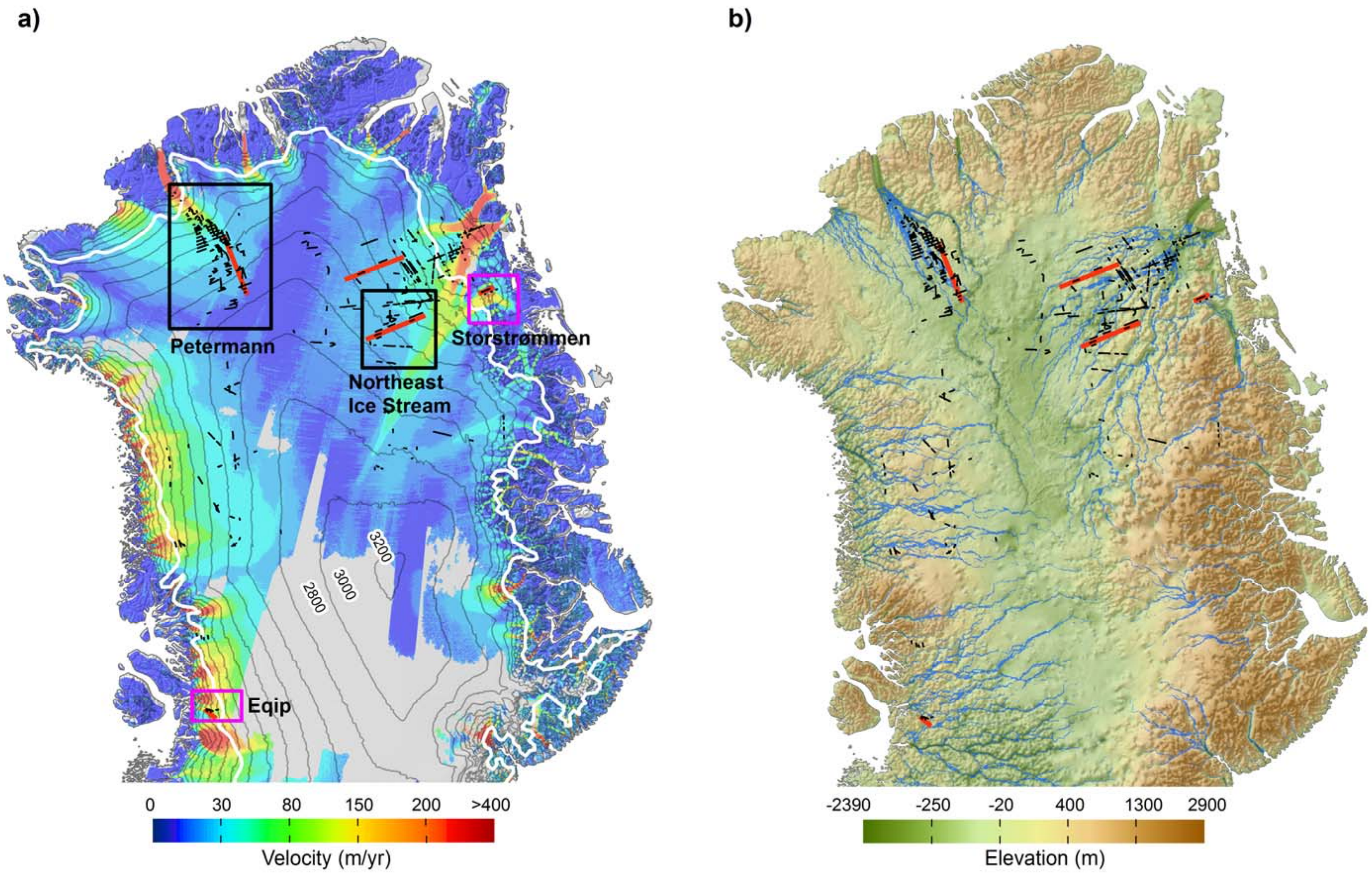
North Greenland



CReSIS, OIB
2011/2012

Observations

North Greenland

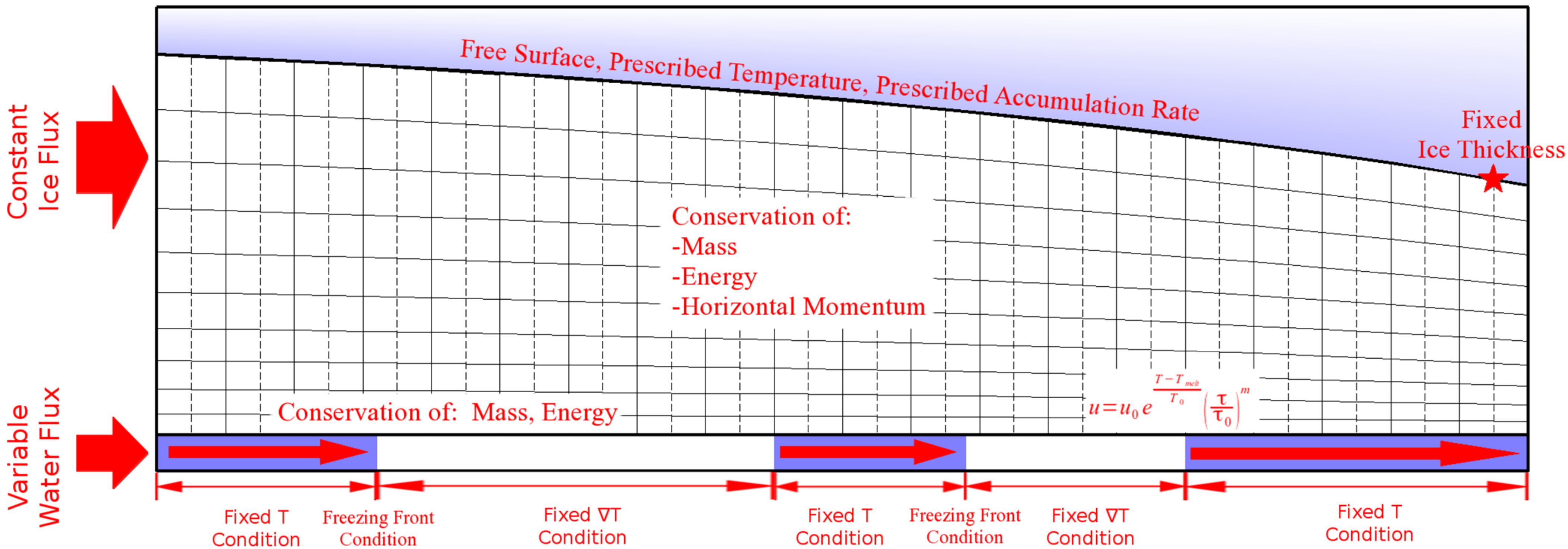


Bell et al., in prep

Model

2D higher-order flowline model

Model Domain and Boundary Conditions



Time-Variable

Wolovick et al., in review

Model

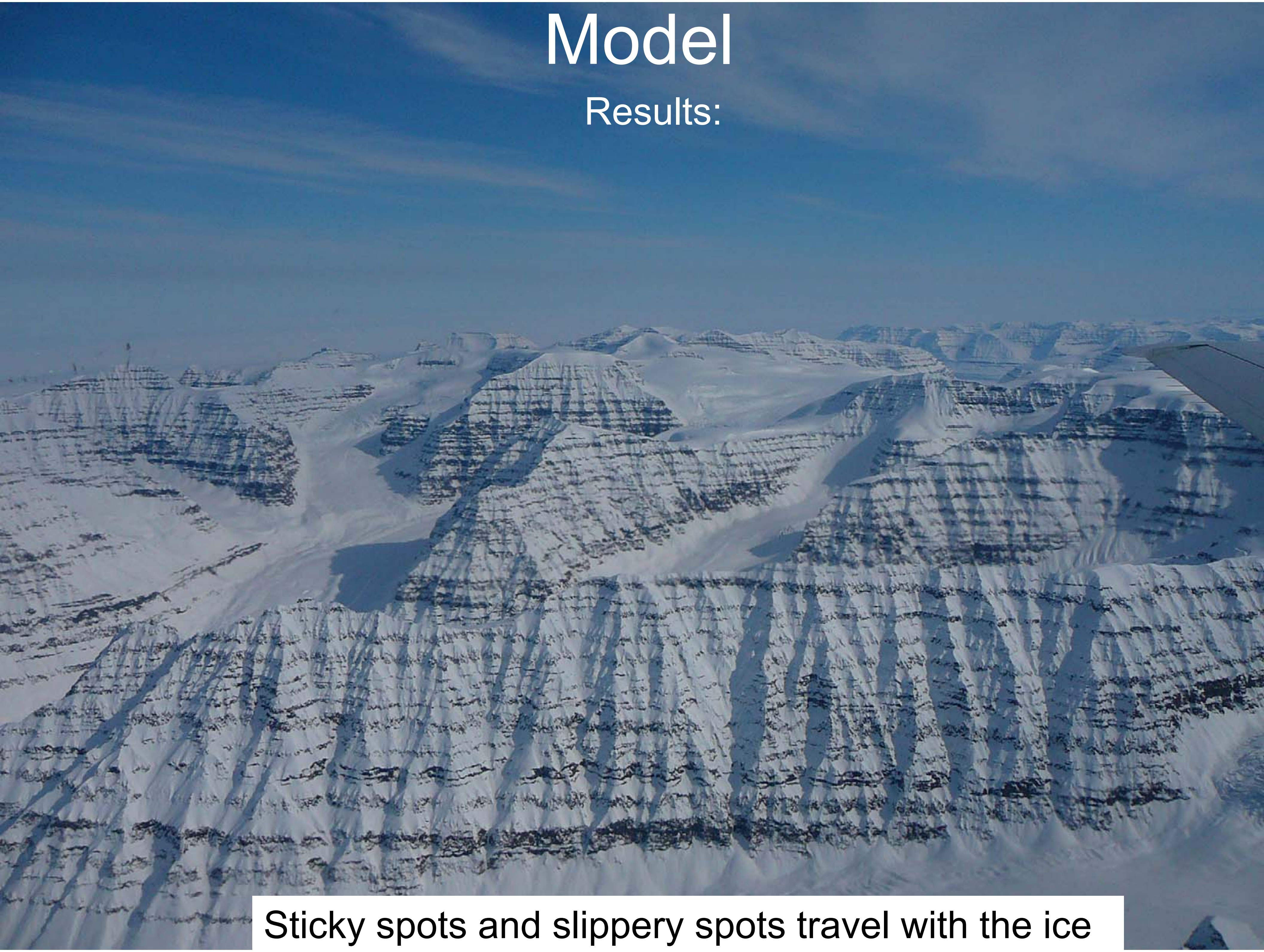
Model Equations:

Englacial Equations	Basal Equations	Boundary Conditions

Mass Conservation:
$\nabla \cdot \vec{u} = 0$
$\frac{\partial D}{\partial t} = \frac{-\partial}{\partial x}(Du) + a - m$
Energy Conservation:
$\rho_i c_p \left(\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T\right) = k \nabla^2 T + \boldsymbol{\sigma} \cdot \dot{\boldsymbol{\epsilon}}$
Momentum Conservation:
$\nabla \cdot \boldsymbol{\sigma} = -\rho_i g \frac{\partial S}{\partial x}$
$\dot{\boldsymbol{\epsilon}} = A \boldsymbol{\sigma}^n$
Only the horizontal component of momentum is considered
	Mass Conservation:
	$\frac{\partial W}{\partial x} = \left(\frac{\rho_i}{\rho_w}\right) m$
	Energy Conservation:
	$-k \left(\frac{\partial T}{\partial z}\right)_{z=B} + \rho_i L m = G + \tau u + Q_w$
	$T \leqslant T_m$
	Sliding Rule:
	$u_b = u_0 \left(\frac{\tau}{\tau_0}\right)^m$
	$u_0 = u_m e^{\frac{T - T_m}{T_0}}$
	Exponential falloff below the melting point
		Bottom:
		• Geothermal flux
		• Power-law sliding
		Sides:
		• Influx on left (ice and water)
		• Thickness on right
		• 1D steady T profiles
		Top:
		• Free slip
		• Surface temperature
		  • -25-30 ºC
		• Surface accumulation
		  • 30 cma^{-1}

Model

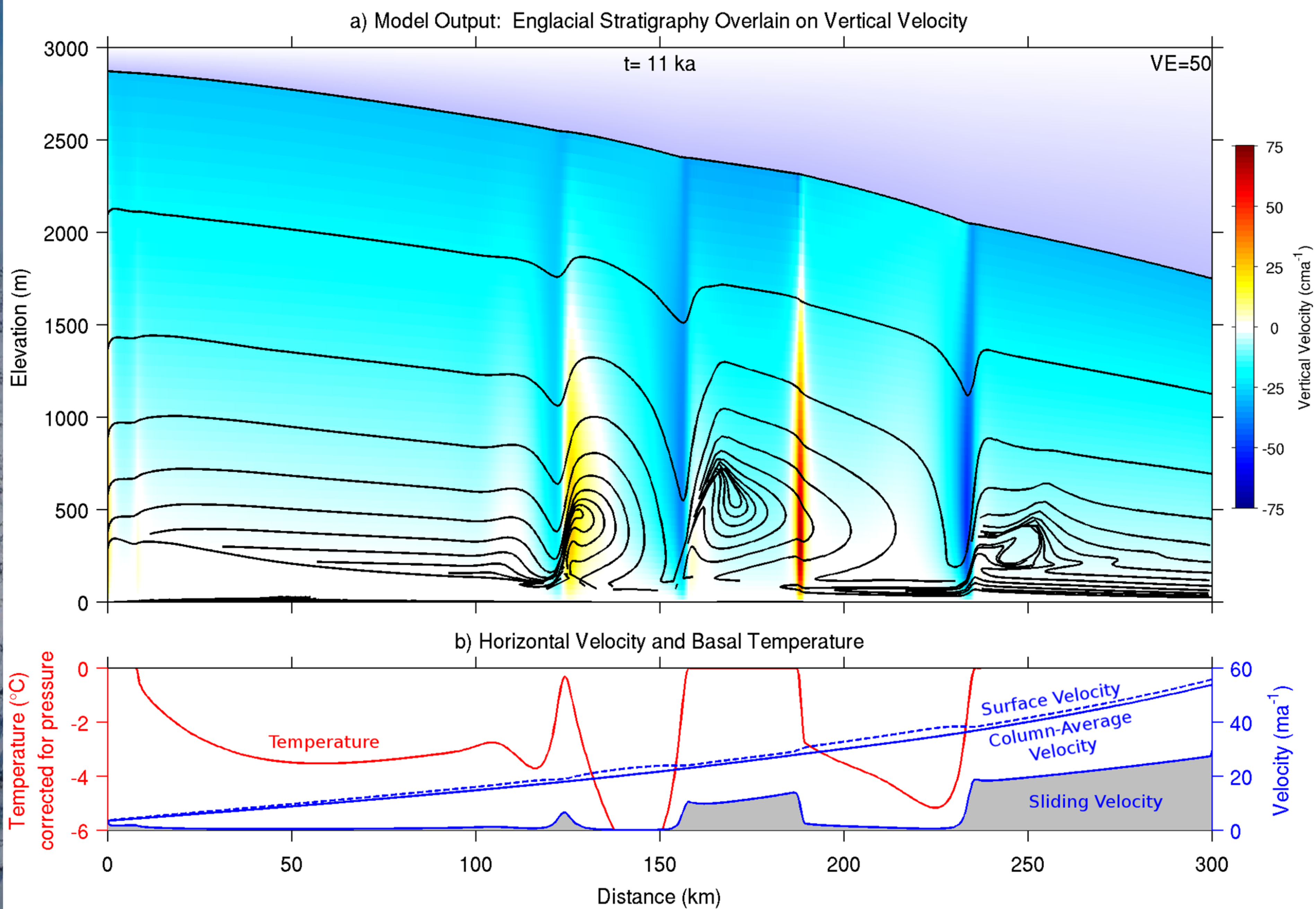
Results:



Sticky spots and slippery spots travel with the ice

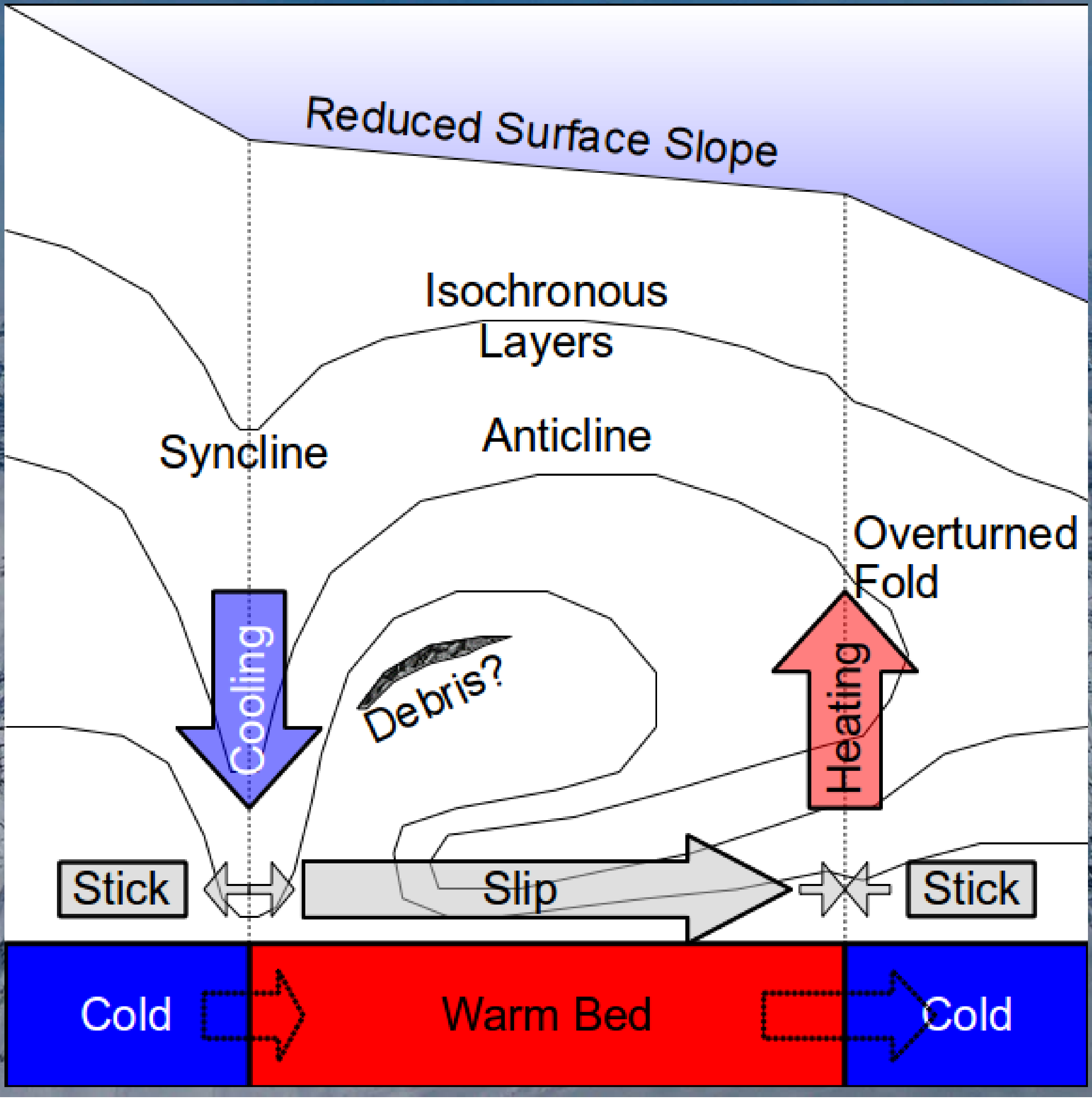
Model

Results:



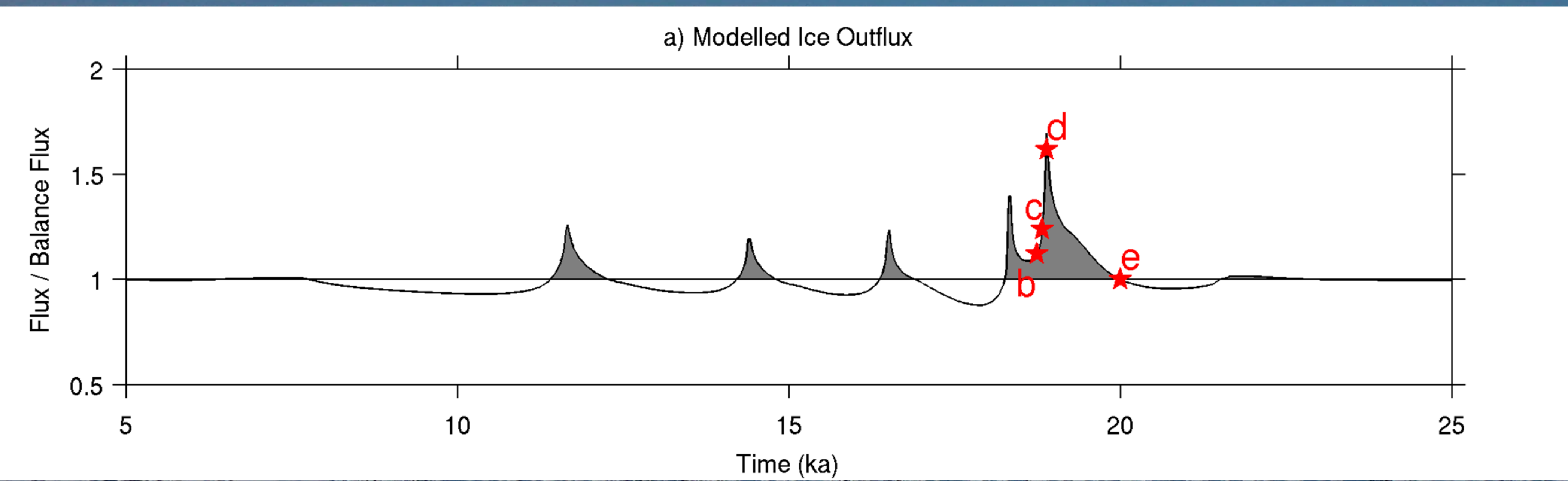
Model

Cartoon Summary



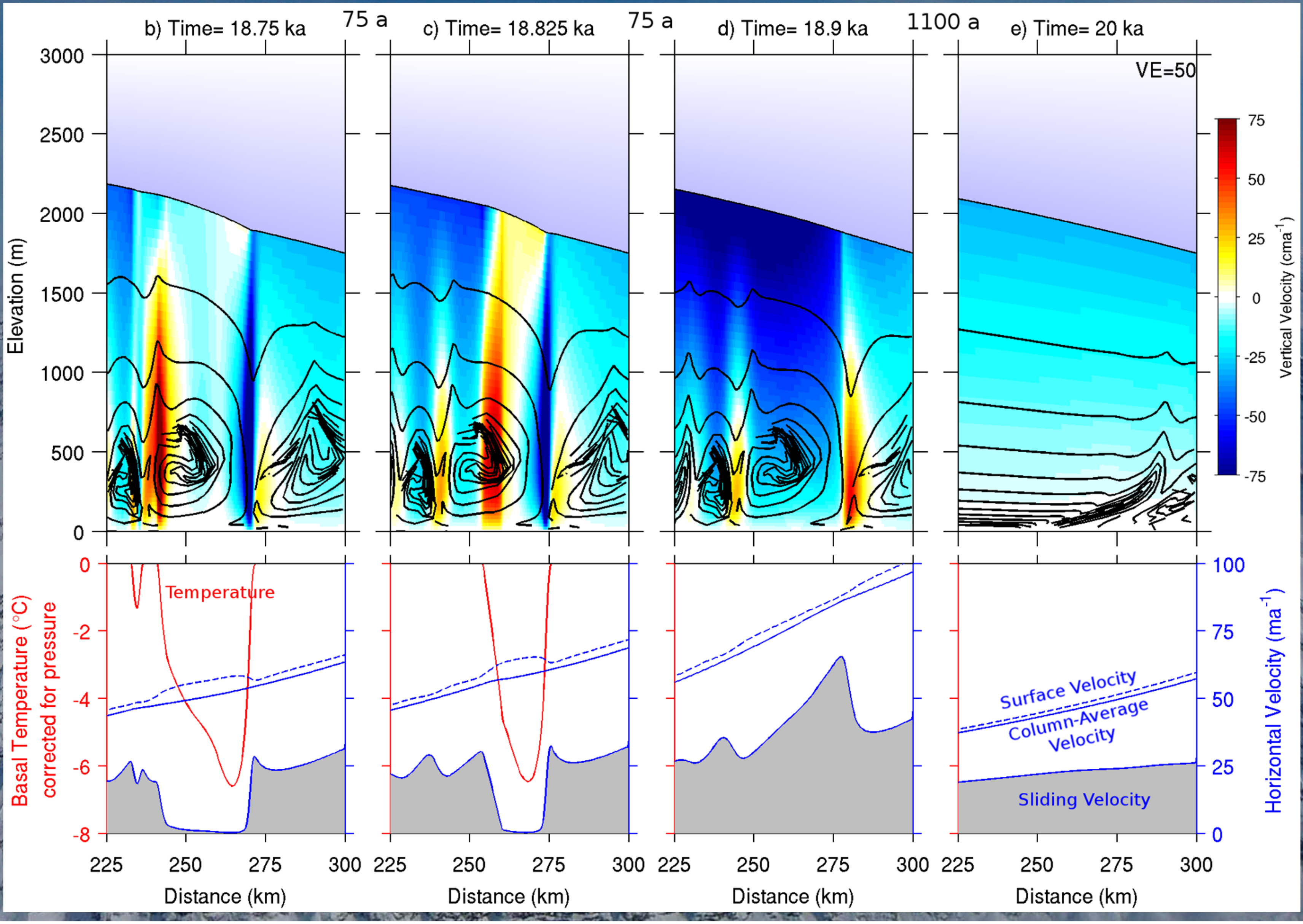
Model

Ice Flux



Model

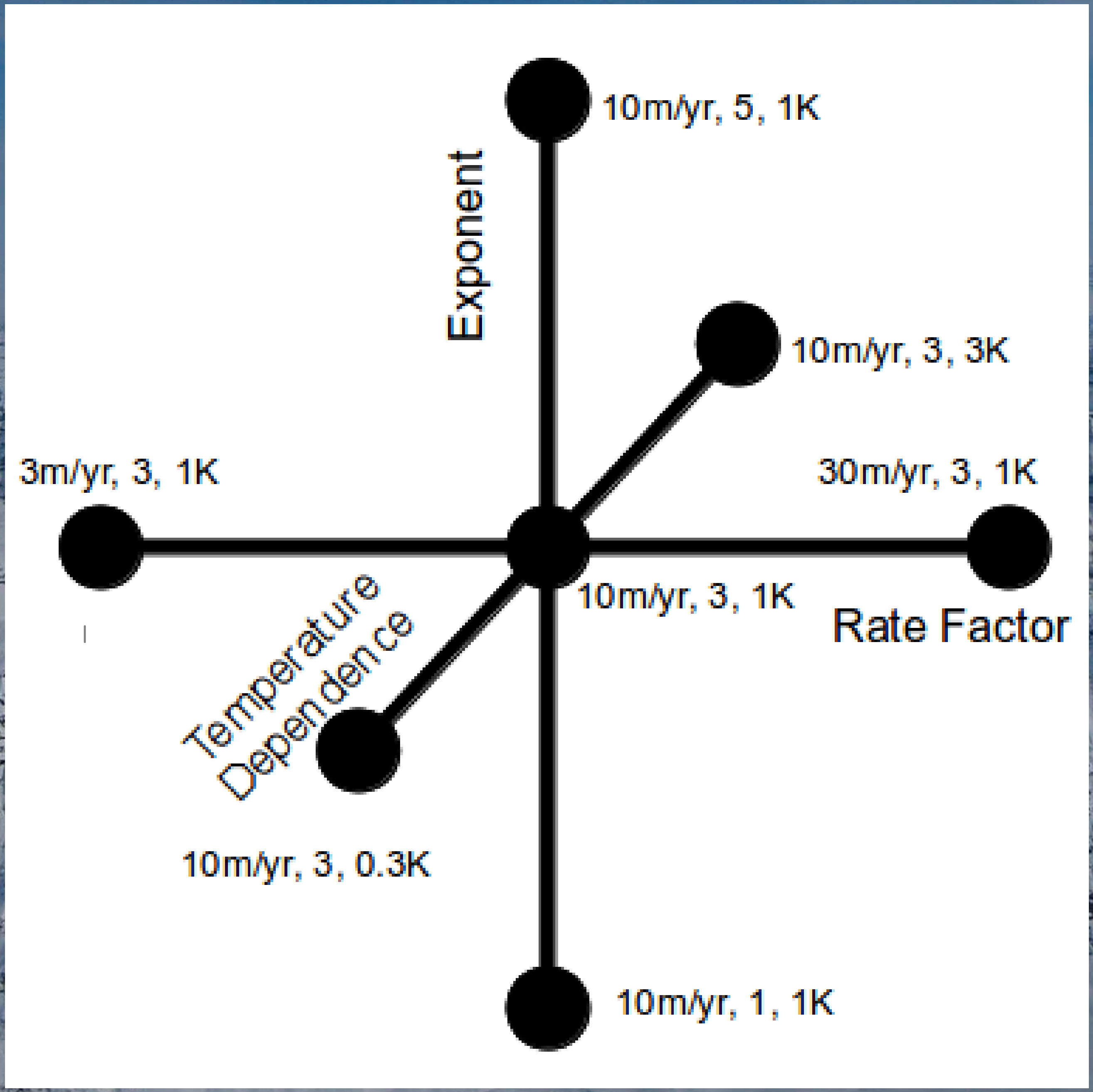
Ice Flux



Convergent fronts overtake divergent fronts, warm the cold spots, and cause the ice sheet to accelerate

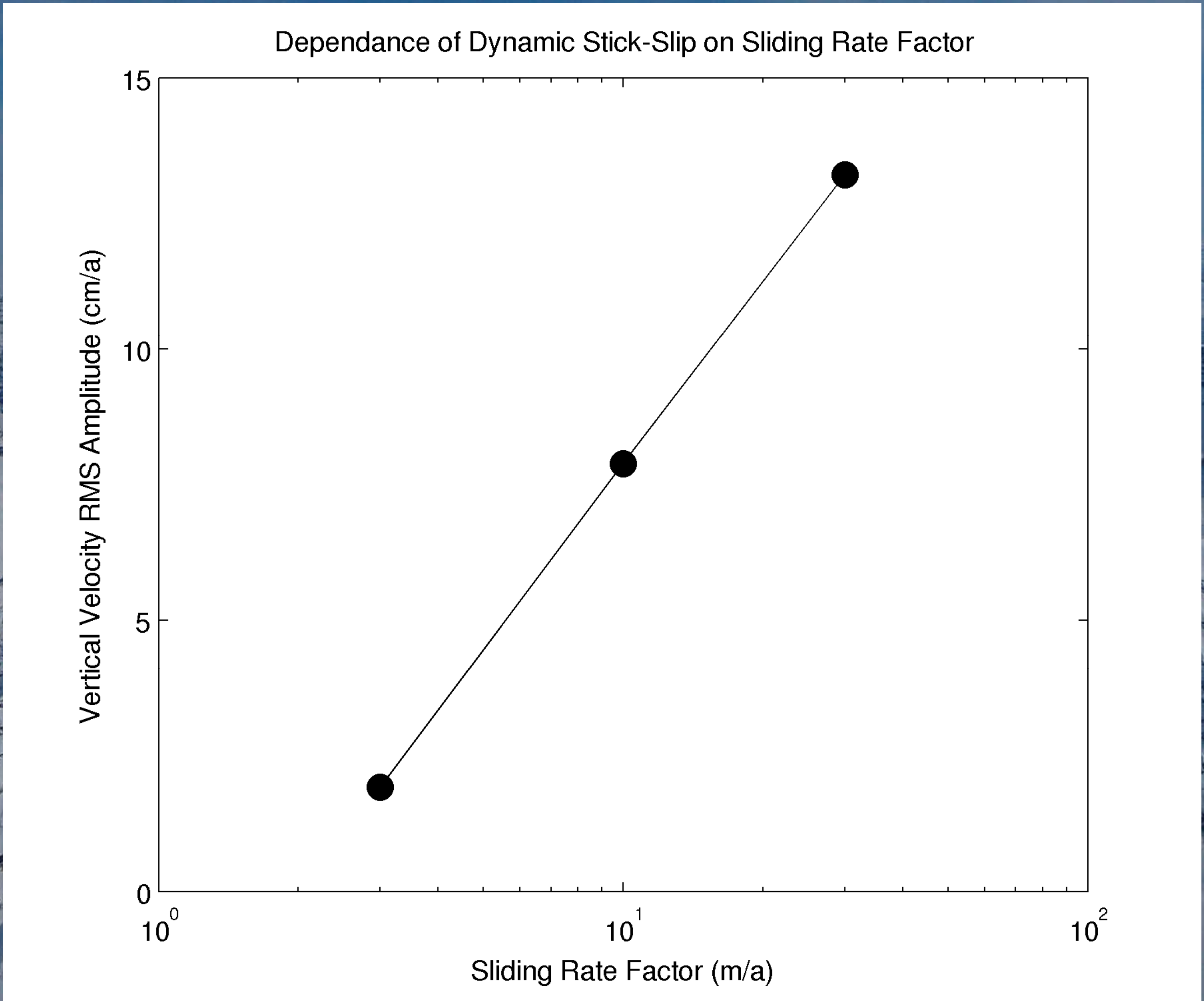
Parameter Tests

Sliding Parameters Explored:



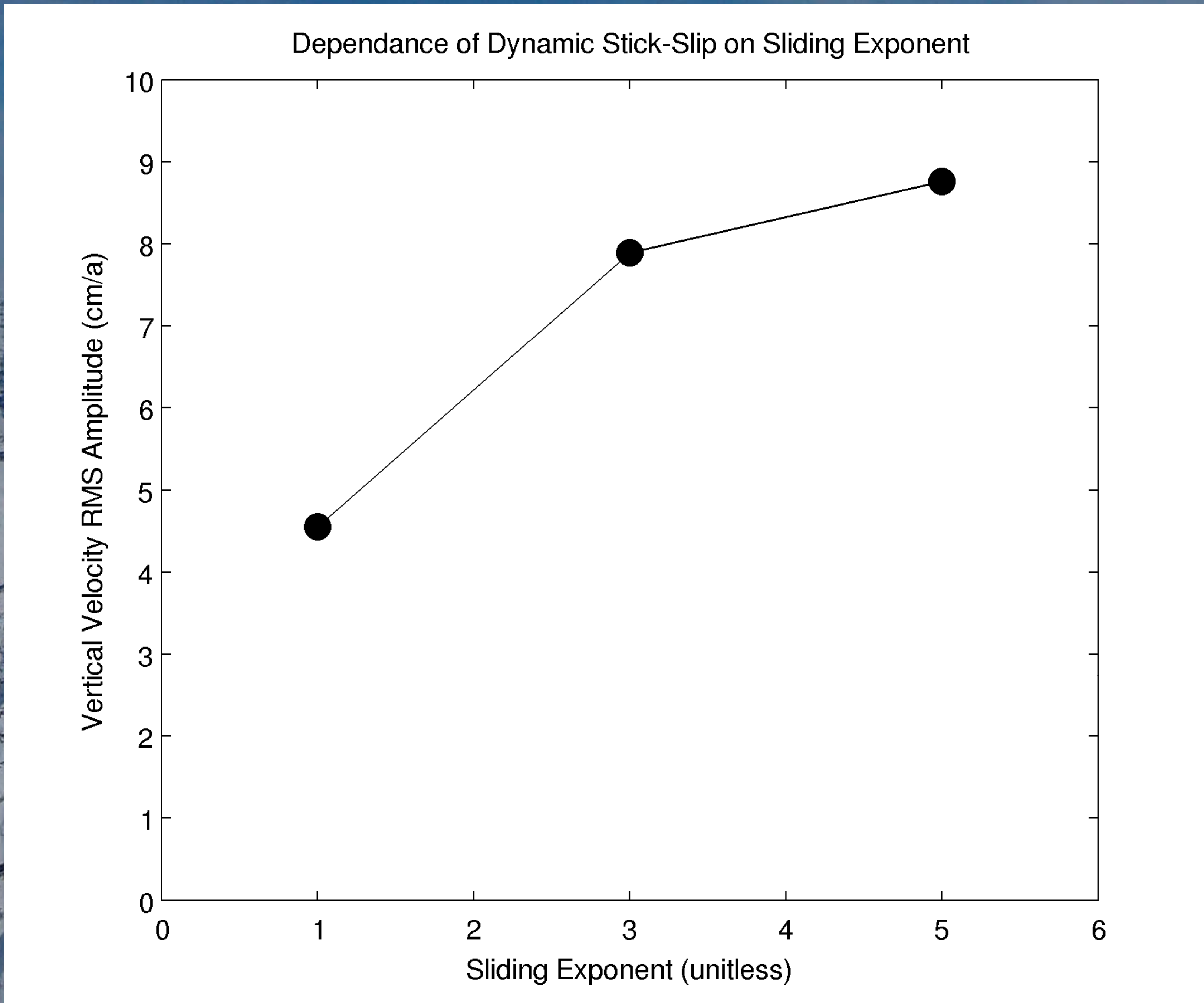
Parameter Tests

Rate Factor:



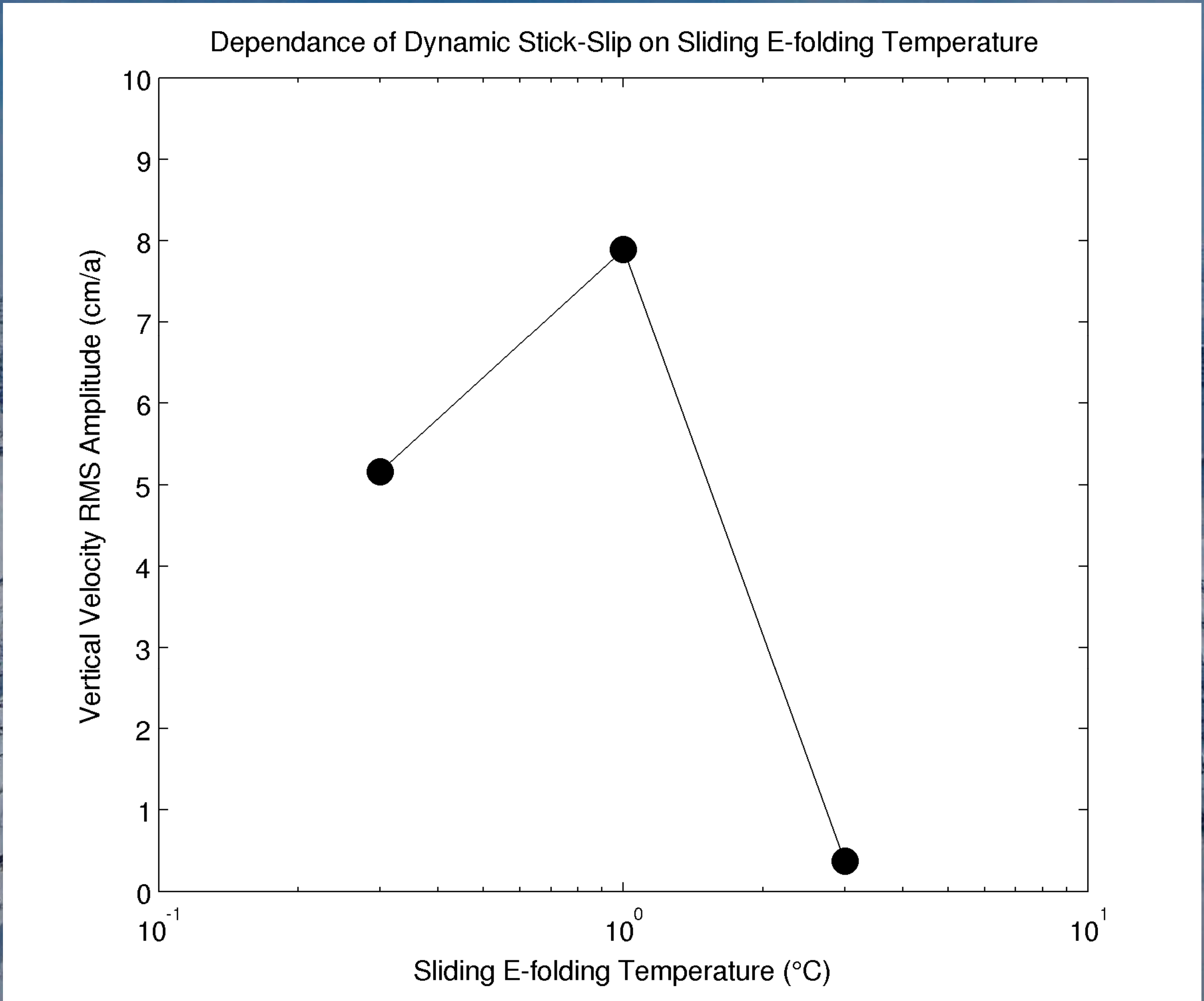
Parameter Tests

Exponent:



Parameter Tests

Temperature Dependence:



Parameter Tests

New Behavior at Strong Temperature Dependence?

Conclusions

Take-Home Messages:

1) Northern Greenland is *filled* with uplifted basal structures
2) Dynamic stick-slip patches coupled to basal temperature can explain these structures
3) Dynamic stick-slip patches can (with aid) uplift basal ice into the middle of the ice sheet

Conclusions

Implications:

1) Dynamic stick-slip patches can create “surges” in ice flux and modify ice stream onset
2) Ice sheet interiors contain dynamic processes and instabilities, in addition to the margins
3) Dynamic stick-slip patches can produce overturned stratigraphy and complex age-depth scales (NEEM)

Conclusions

Parameter Dependence:

1) Stronger sliding → stronger process
2) Nonlinear sliding → stronger process, with a limit?
3) Stronger temperature dependence → more instability, new behavior.

Acknowledgements

- <u>People:</u>

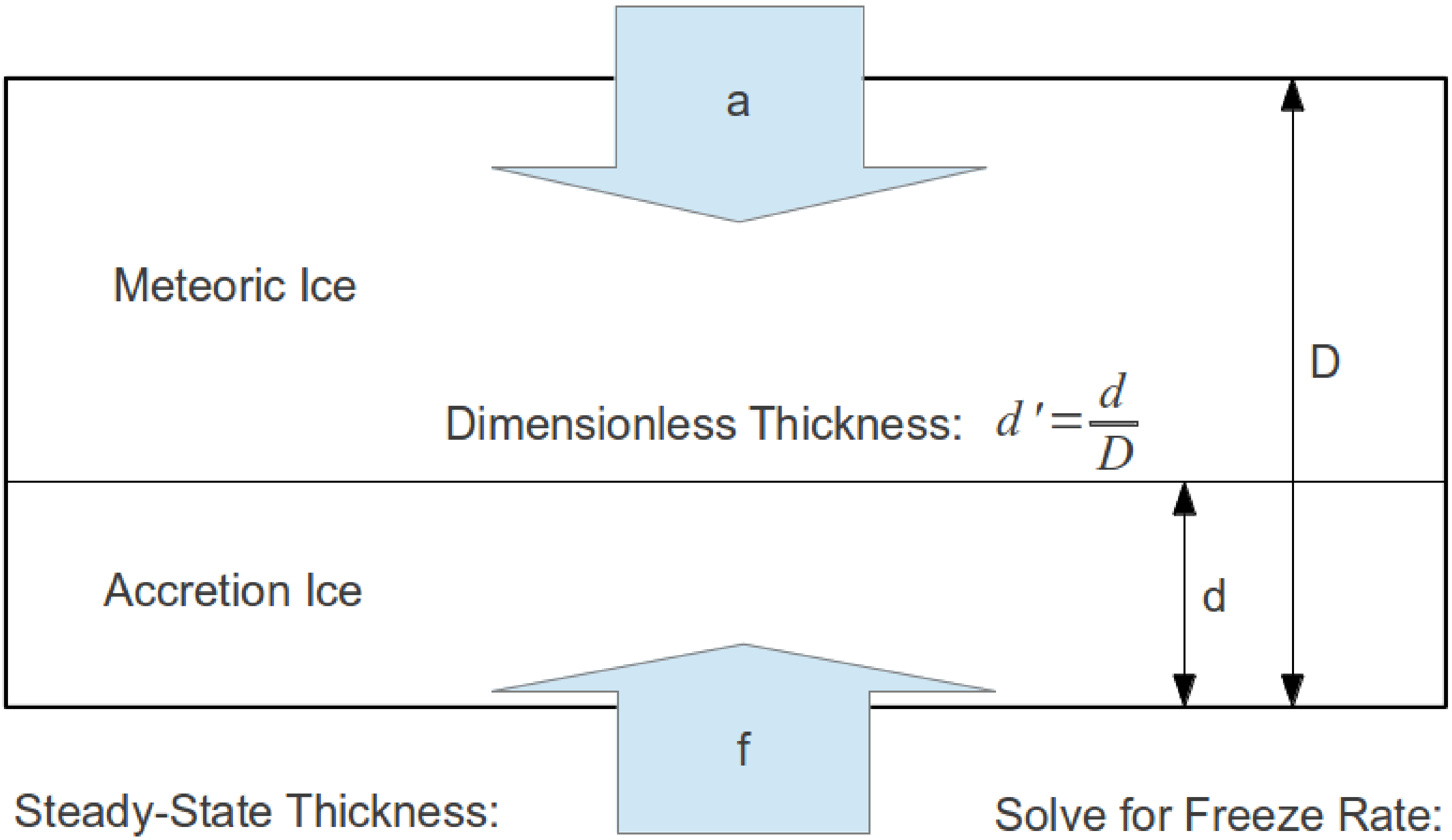
Robin Bell, Roger Buck, Tim Creyts, Nick Frearson, Hakim Abdi, Indrani Das, Kirsty Tinto, Kirsty Langley, Winnie Chu, Alex Boghosian, Dave Porter, Marc Spiegelman, Kenni Dinesen Petersen, John Paden

- <u>Projects/Organizations:</u>

Polar Geophysics Group
Antarctica's Gamburtsev Province
Operation IceBridge
National Science Foundation OPP

Order-of-Magnitude Estimates

Generous Approximation:
large horizontal extent, constant longitudinal stretching



Steady-State Thickness:

$$d' = \frac{f}{a+f}$$

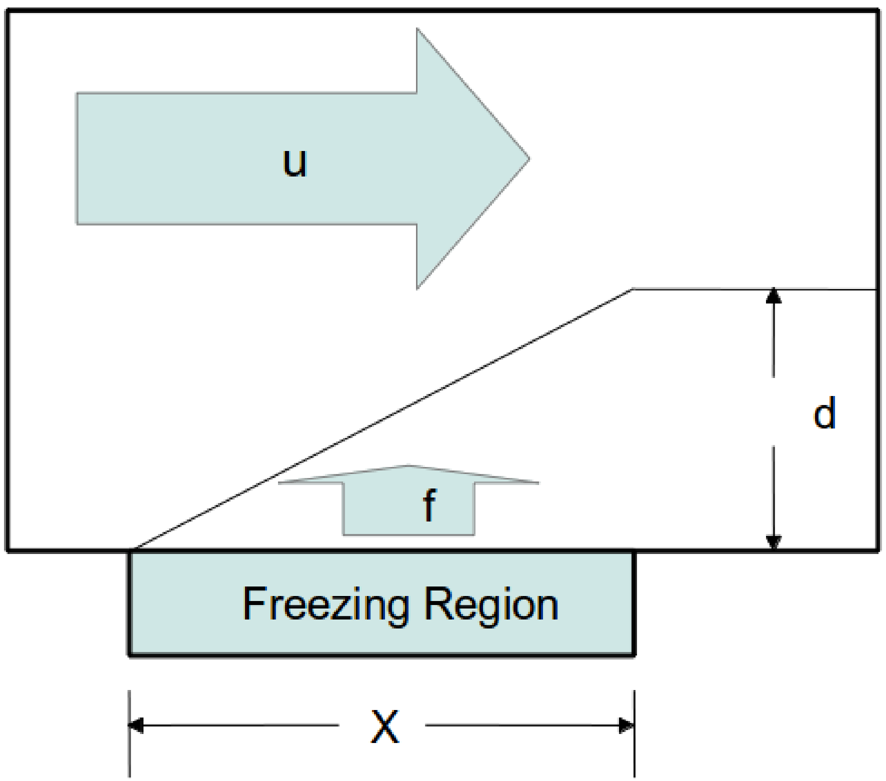
Solve for Freeze Rate:

$$f = \frac{d'a}{1-d'}$$

Accretion rate scales by accumulation rate

Order-of-Magnitude Estimates

Demanding Approximation:
small horizontal extent, no longitudinal stretching



Time Spent over Freezing Region:

$$t = \frac{X}{u}$$

Thickness of Freeze-on Package:

$$d = ft = \frac{f}{u} X$$

Solve for Freeze Rate:

$$f = \frac{d}{X} u$$

Accretion rate scales by horizontal velocity

Order-of-Magnitude Estimates

$Q = \rho_i L f$

$Q \sim 10f$
(Wm^{-2} and ma^{-1})

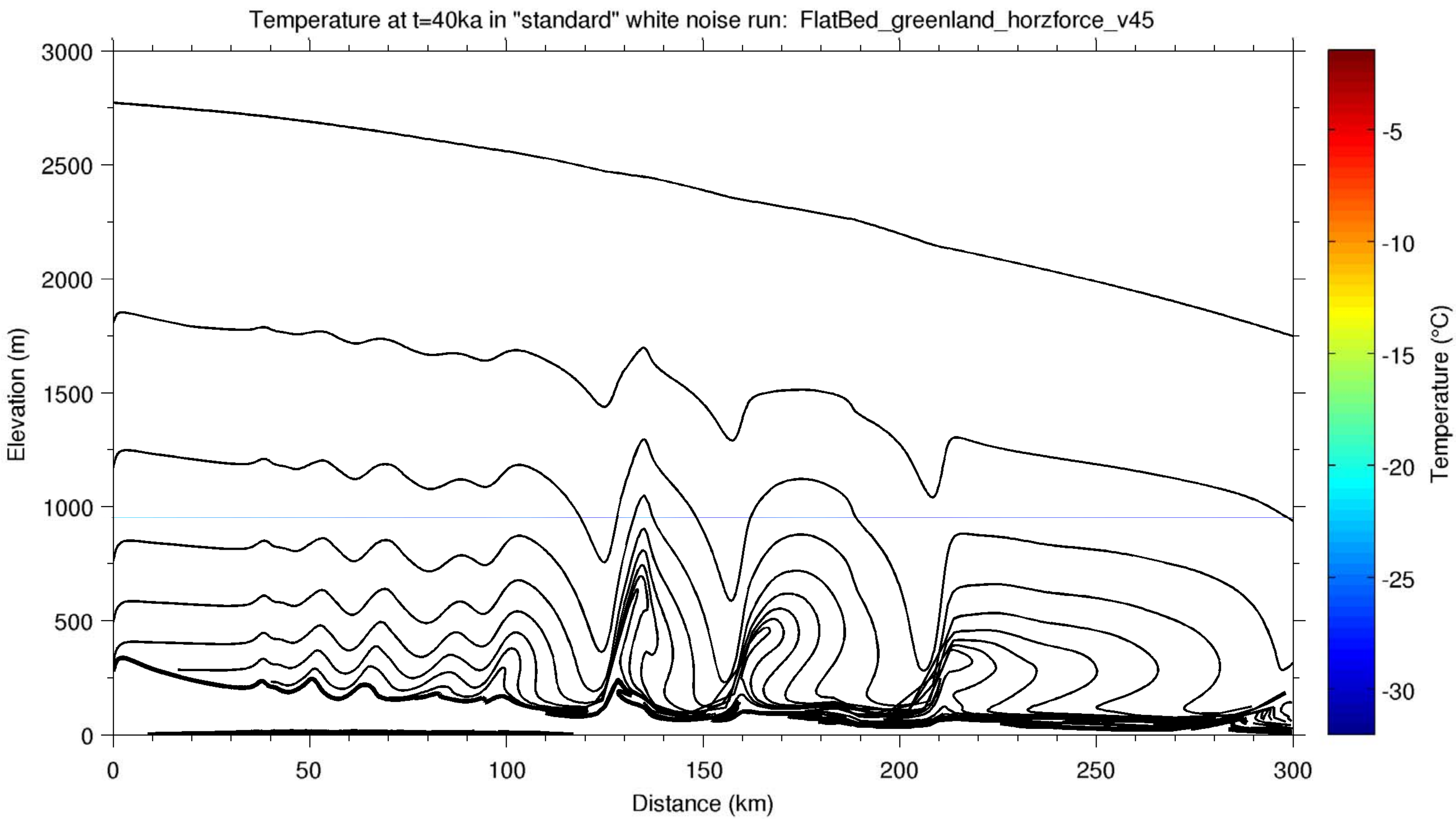
Plug in Numbers to Simple Approximations:

	Greenland	East Antarctica
Generous Approximation	freeze rate: $f \sim$ 10-20 cma^{-1} heat flux: $Q \sim$ 1-2 Wm^{-2} supercooling water flux: $W \sim 2.5\text{-}5 \times 10^6\ m^2a^{-1}$	$f \sim$ 0.2-2 cma^{-1} $Q \sim$ 0.02-0.2 Wm^{-2} $W \sim 0.05\text{-}0.5 \times 10^6\ m^2a^{-1}$
Demanding Approximation	freeze rate: $f \sim$ 50-100 cma^{-1} heat flux: $Q \sim$ 5-10 Wm^{-2} supercooling water flux: $W \sim 13\text{-}26 \times 10^6\ m^2a^{-1}$	$f \sim$ 4-20 cma^{-1} $Q \sim$ 0.4-2.0 Wm^{-2} $W \sim 1\text{-}5 \times 10^6\ m^2a^{-1}$

*water flux calculations assume surface slope of 10^{-3} and bed/surface slope ratio of -5

Model

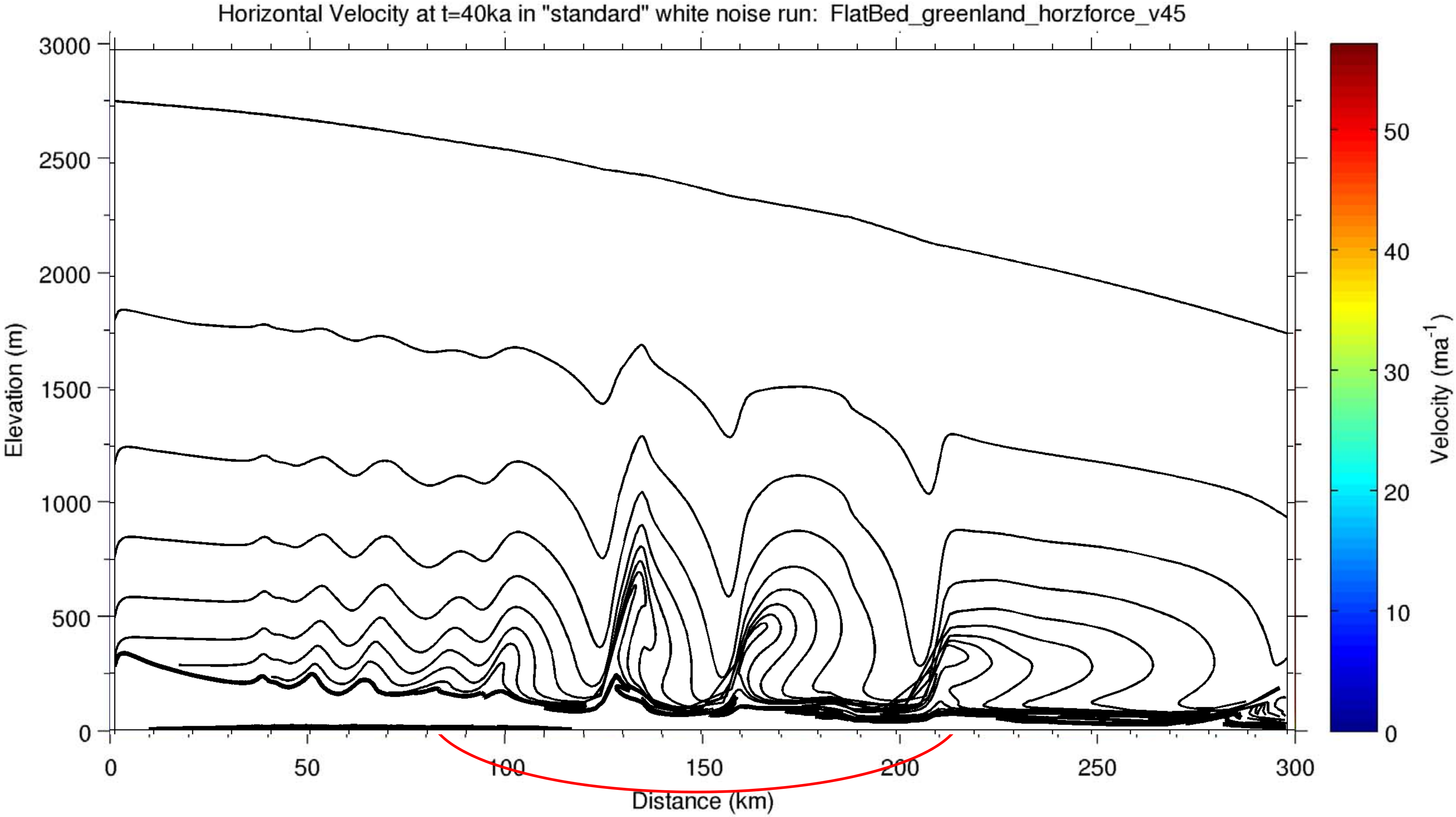
Results:



Uplifted areas are warm, drawdown areas are cold

Model

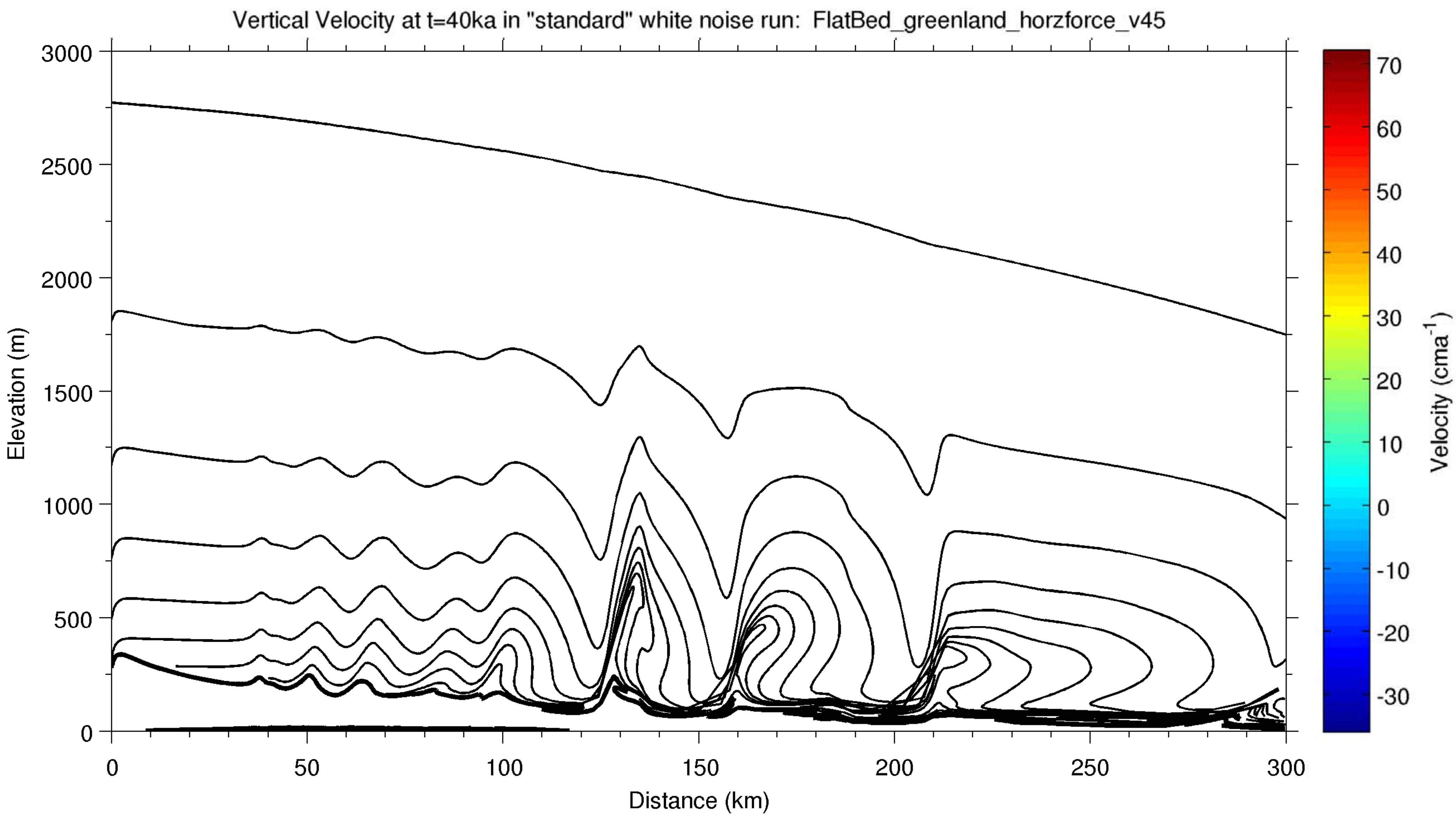
Results:



Basal temperature produces sticky spots and slippery spots

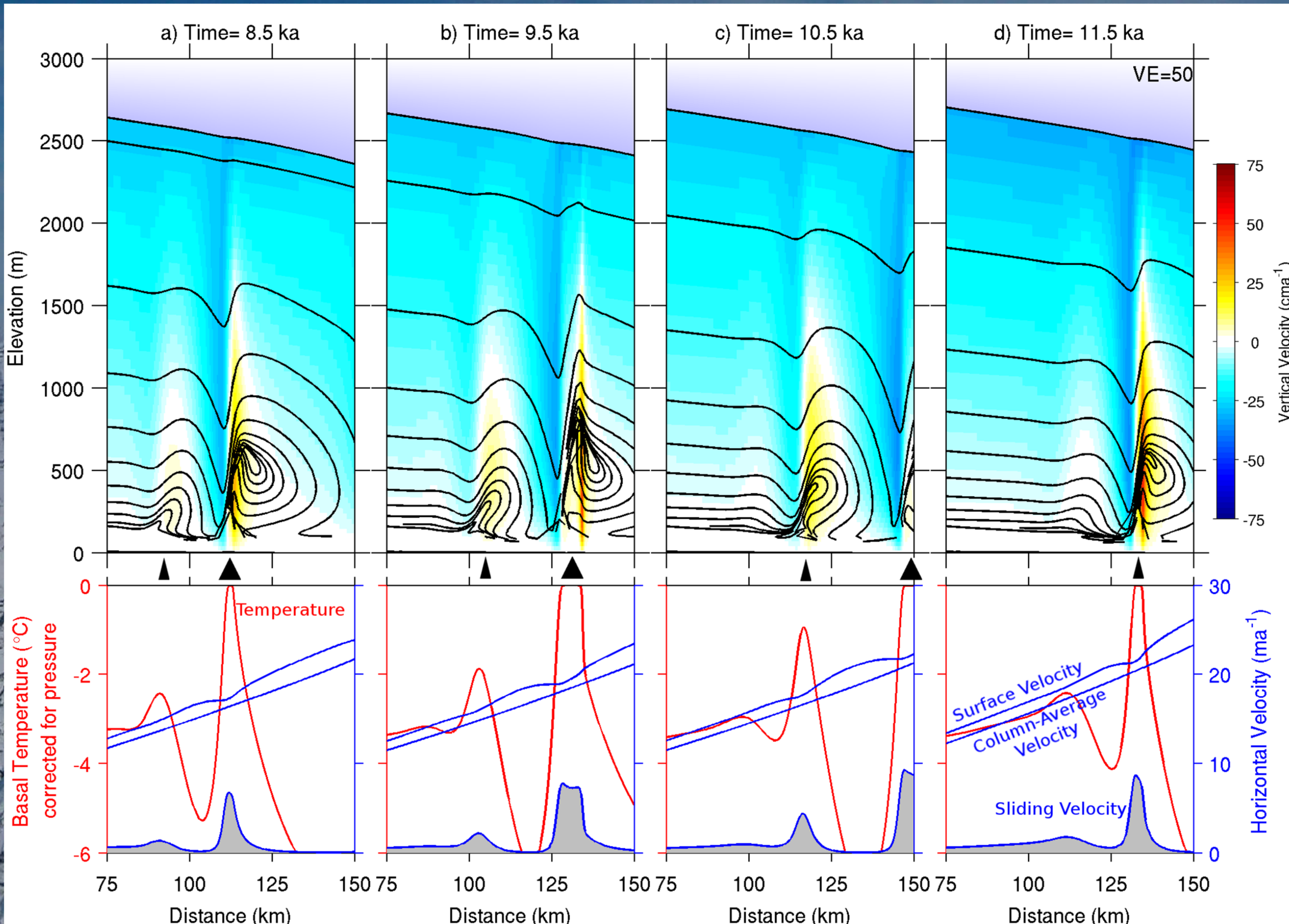
Model

Results:



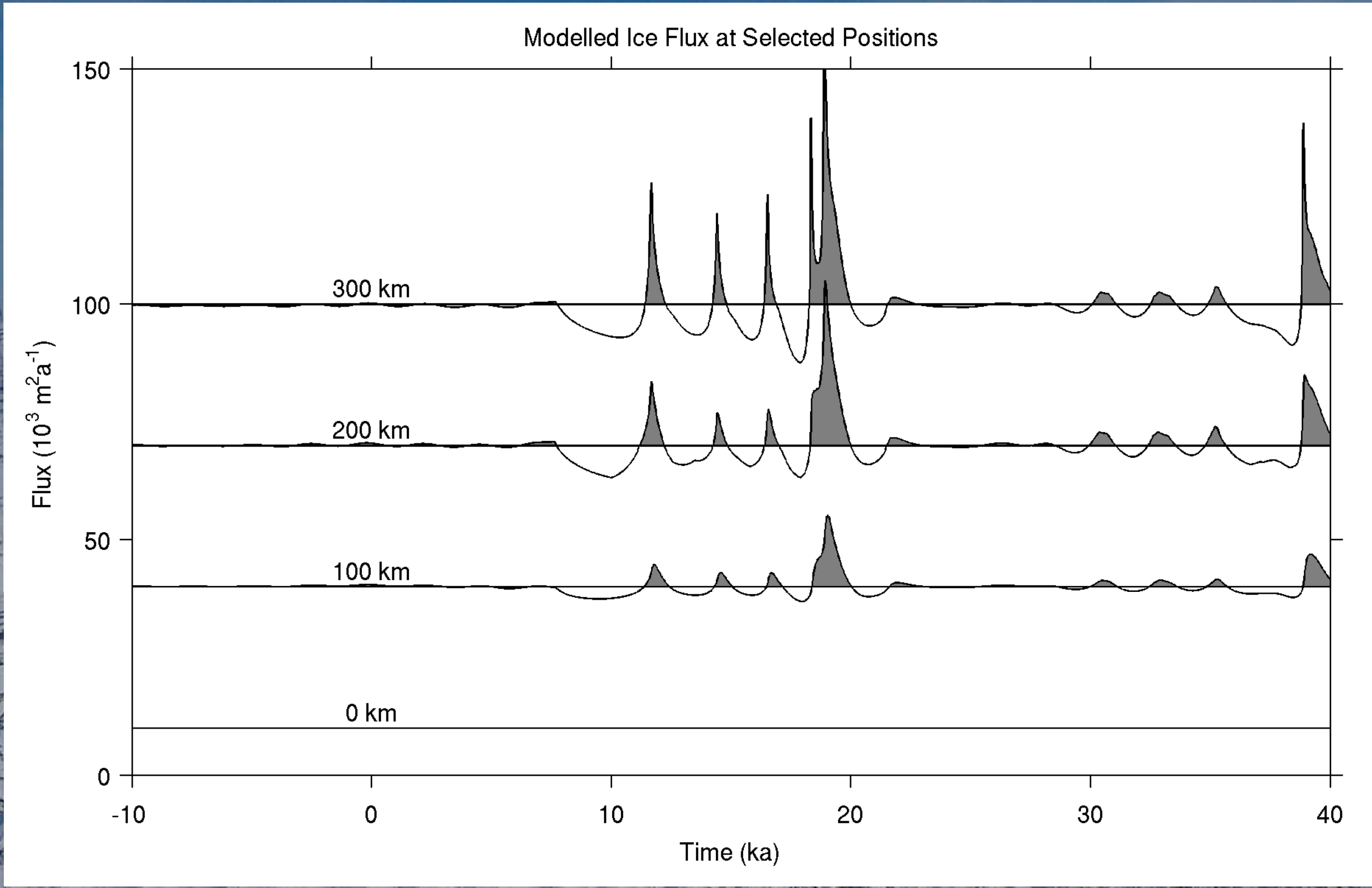
Variations in sliding velocity produce vertical velocities

Discussion



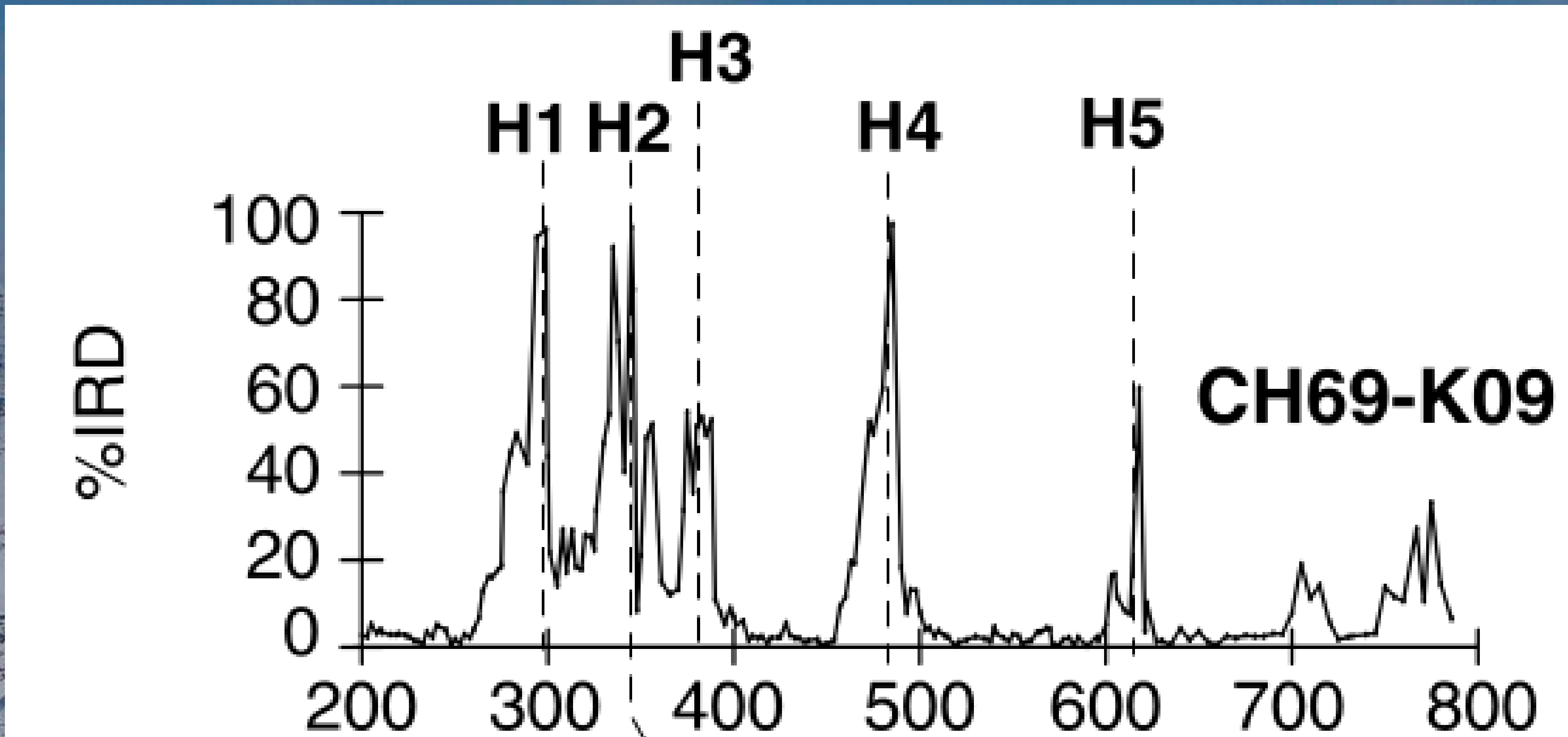
New slippery spots are generated in the wake of an old slippery spot

Discussion



Model experiences periodic 'surges' in output flux:
~20-70% above background, ~100-1000 yr duration

Discussion

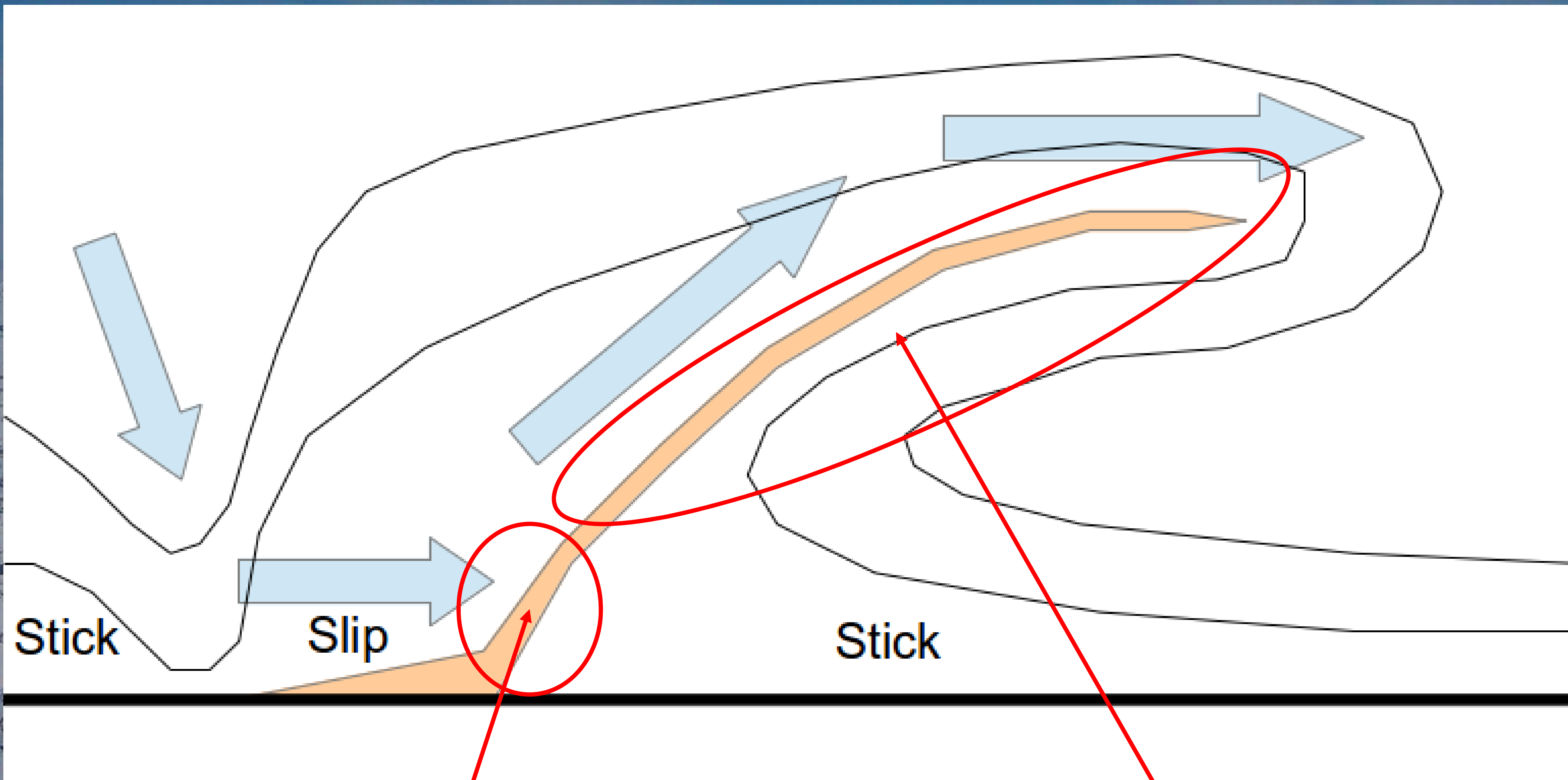


Hemming, 2004

Model 'surges' are reminiscent of Heinrich Events

Discussion

Cartoon Interpretation

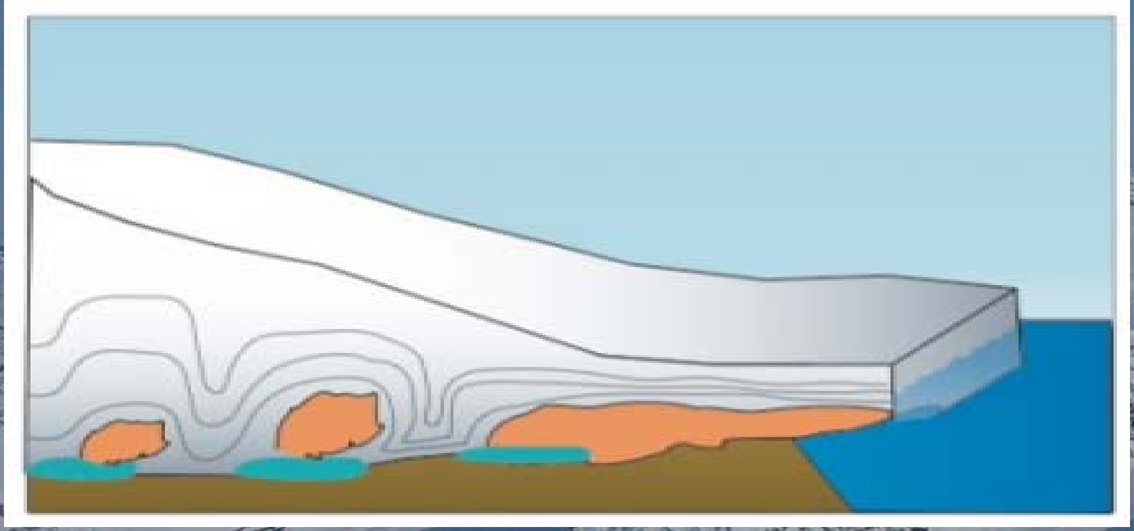


Fabric? Crystal size?
30 → 100 m

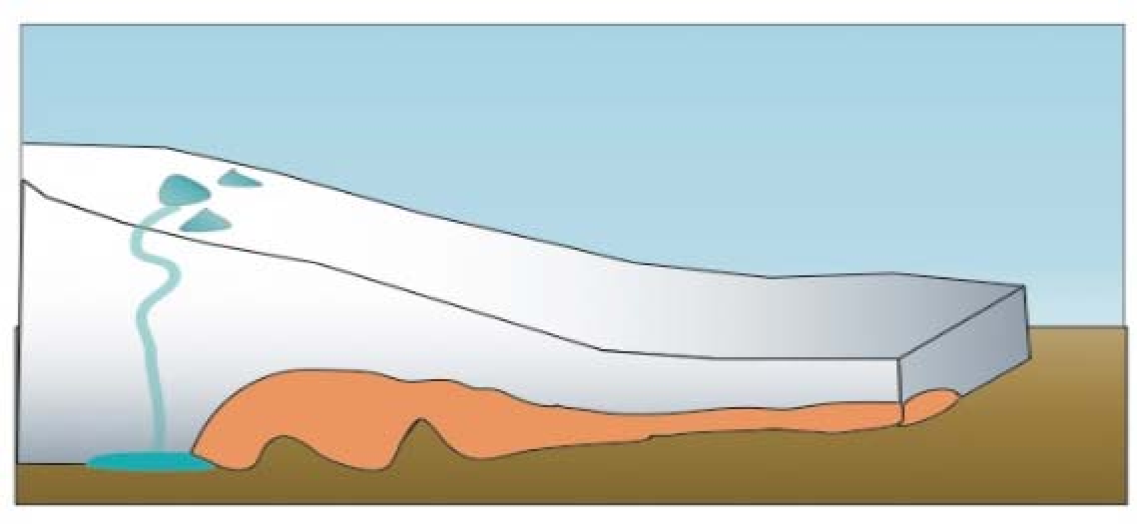
Convergence
100 → 1000 m

Discussion

Cartoon Interpretation



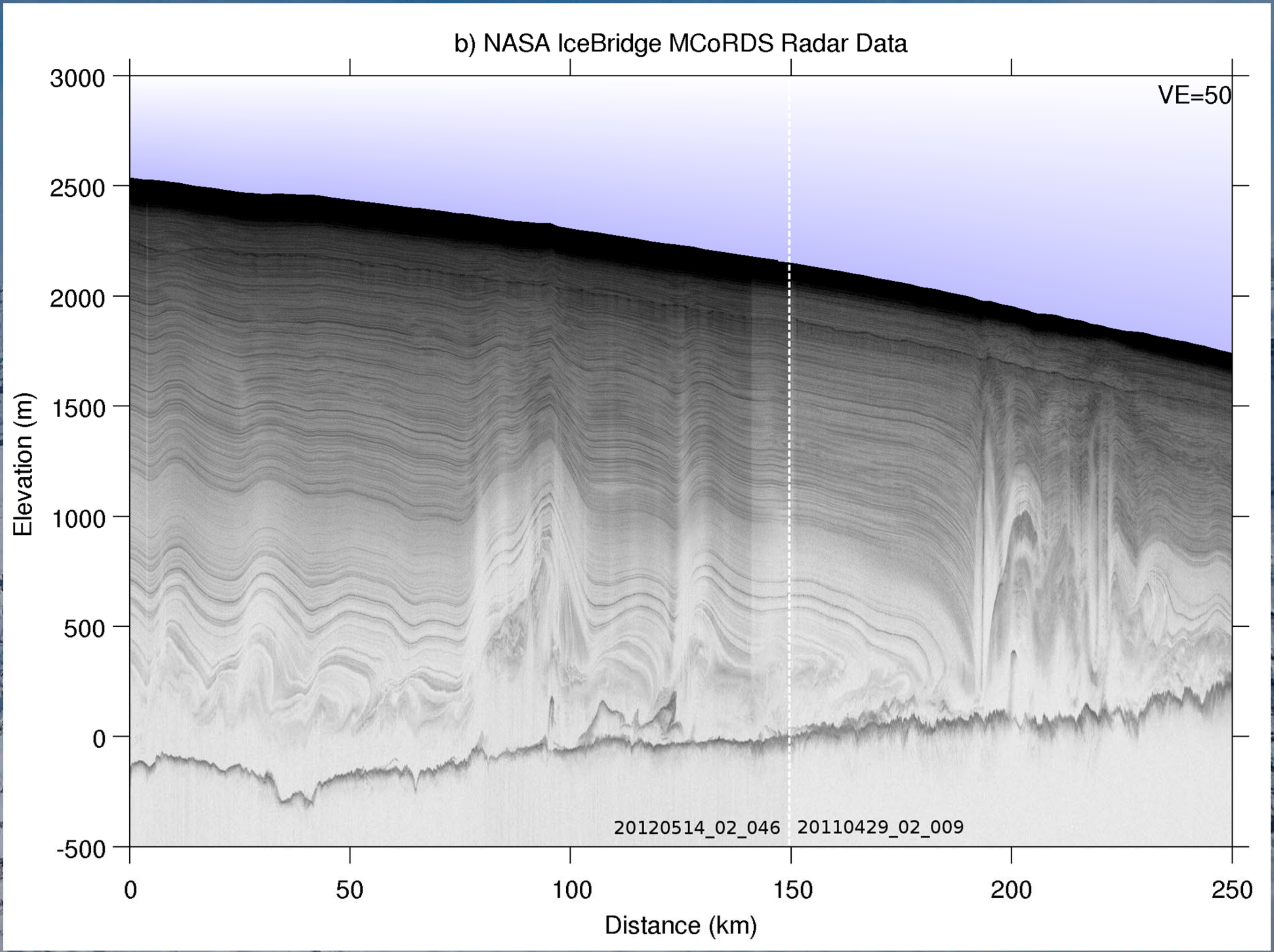
Train of traveling anomalies in the interior



Stationary supercooling sources of freeze-on near the margins

Discussion

Observational Comparison: North Greenland



OIB, CReSIS, 2011 and 2012