# Inferring the Mechanical Properties of Glacier Beds Using Time-Dependent Surface Velocity Observations


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Earth, Atmospheric and Planetary Sciences

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CliMA Workshop, Caltech
November 28, 2018

# Introduction

- **How can we use** the extraordinary amount of recently available remotely sensed **surface velocity observations to address outstanding fundamental questions in glacier dynamics**?

- Directly address workshop questions:

    - **How can we integrate observations with models?**

    - **What additional observations would help improve models?**

- Indirectly address:

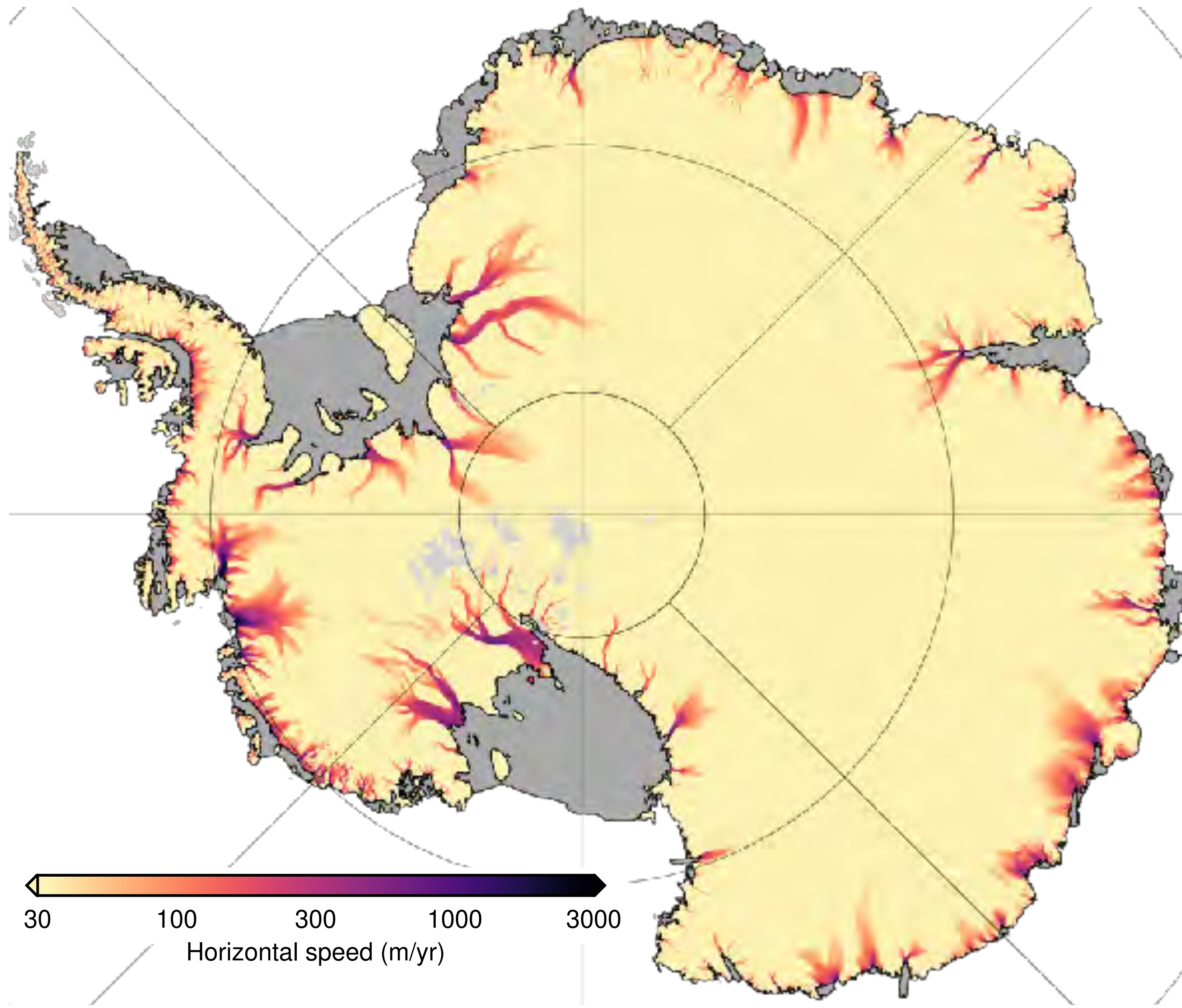
    - **How should we design a climate model to obtain better predictions of polar climates on timescales of decades?**

    - By highlighting and addressing key dynamical questions using time-dependent surface velocity observations

# Introduction — Big Qs in glacier dynamics

- Understanding the dynamic response of ice sheets to changing climate and depends on understanding
  - Viscosity of ice (esp. in shear zones)
  - Mechanics of the bed
- Why the mechanics of the bed?
  - *Essential for predictive models*
  - Rapid ice flow facilitated by rapid slip at the bed
  - Basal drag is the primary resistance to flow, in general
- **Key question: How is basal drag related to the rate of slip and other processes at the bed?**

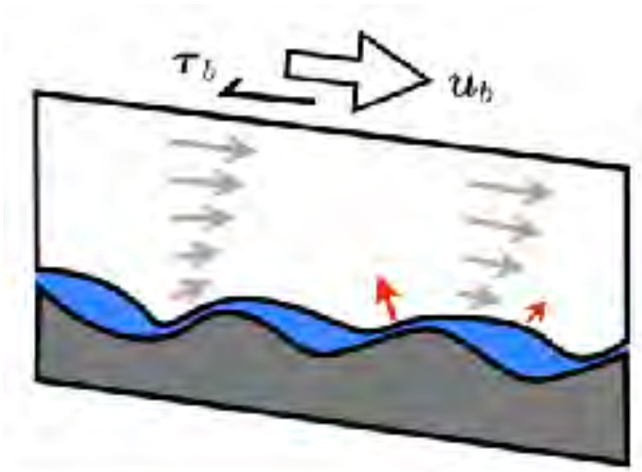
Observed ice flow speed in the grounded Antarctic Ice Sheet




contains data from: Gardner et al., 2018, Mouginot et al., 2017, and Fretwell et al., 2013

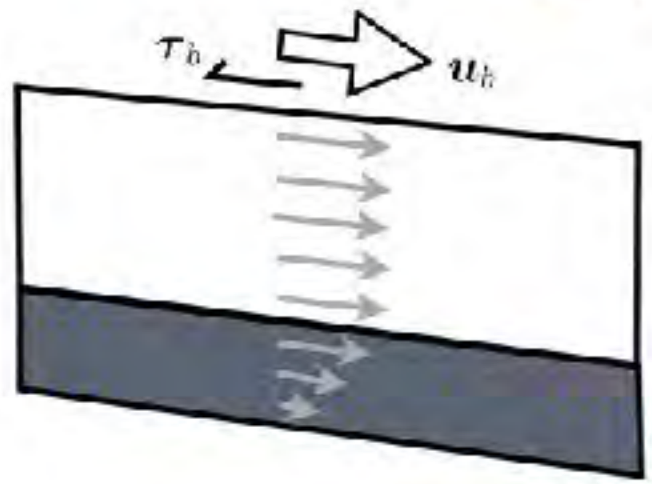
# Sliding law — Key mechanical basal boundary condition

- Has been the subject of decades of active research
- Numerous models have been proposed; most models fit into one of three groups



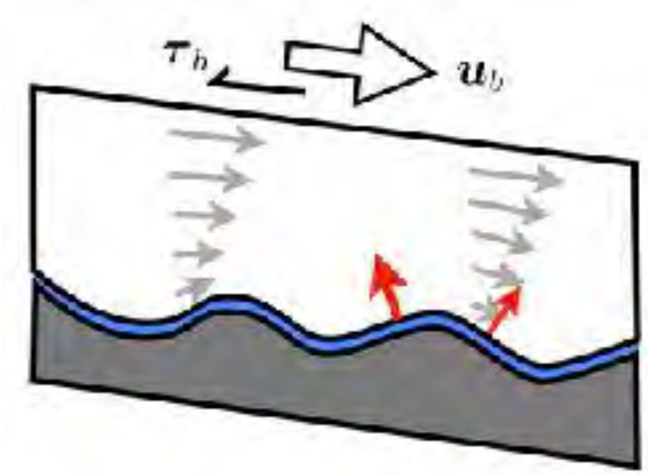

Viscous flow past roughness (with cavitation)

**Rate-weakening**




Bed deformation

**Plastic**

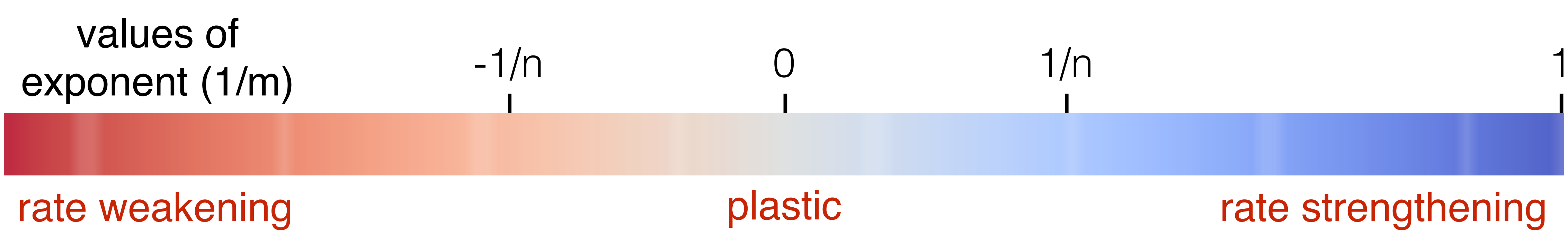



Viscous flow past roughness (no cavitation)

**Rate-strengthening**

- For fast-flow and sufficiently small changes in velocity, most models can be represented as a power law

$$\tau_b = c_b u_b^{1/m}$$





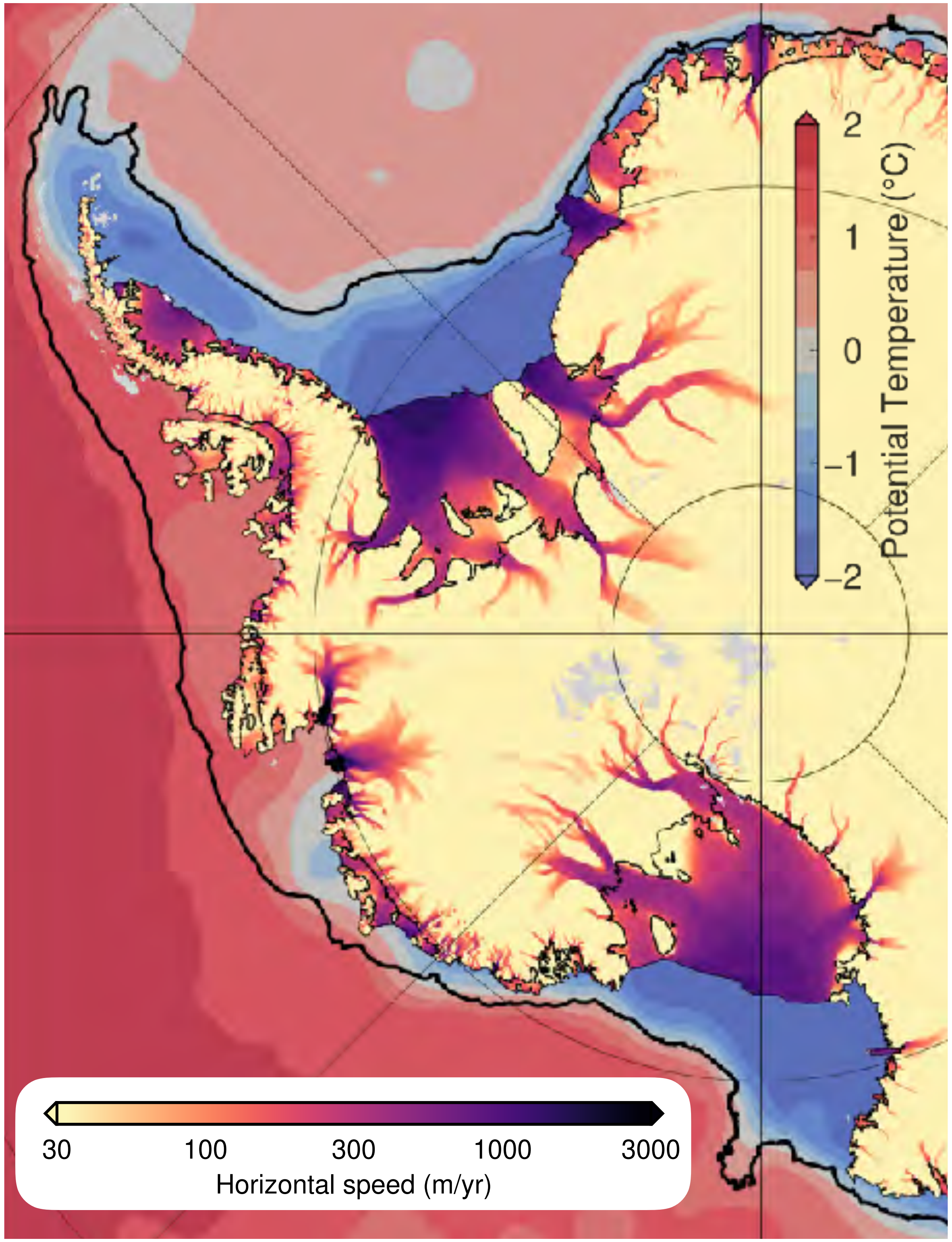

cartoons: I. Hewitt

# Sliding law in prognostic models

- **First workshop question:** How should we design a climate model to obtain better predictions of polar climates on timescales of decades?
- Most common approach to prognostic ice-flow modeling:
  - Treat ice as incompressible, non-Newtonian viscous fluid
  - **Employ Weertman-type (power-law) sliding law (basal BC), assuming a value for the exponent**

$$\tau_b = c_b u_b^{1/m}$$

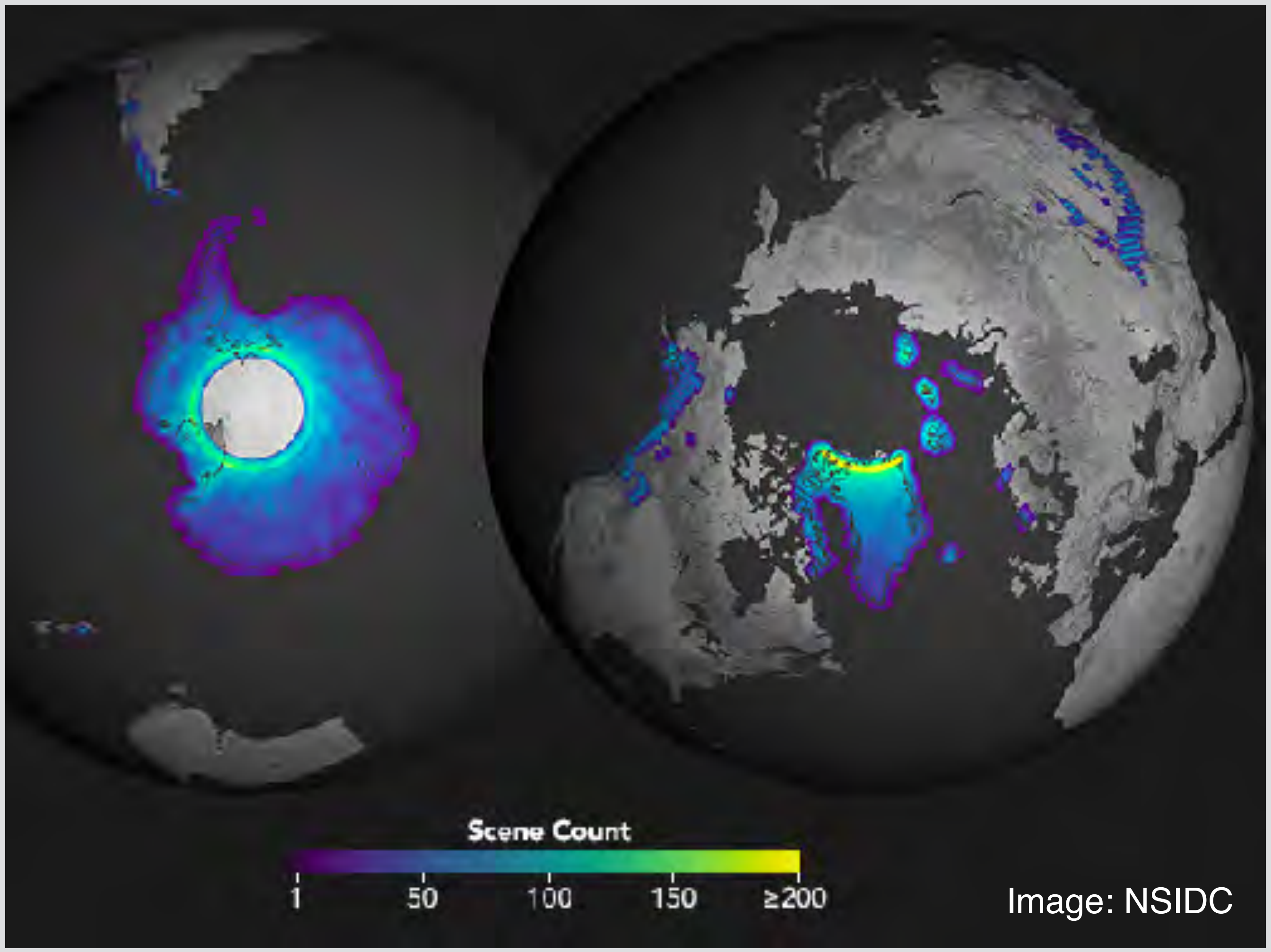
  - Use ice-flow models, constrained by observations, to infer basal slipperiness (or friction coefficient)
- Not ideal, but the best we can do up to now
- Ultimately, we want to be able to infer the exponent and prefactor from observations




data from: Gardner *et al.*, 2018, Mouginot *et al.*, 2017, Jenkins *et al.*, 2016, and Fretwell *et al.*, 2013

# Time-dependent surface velocity fields

## New data, new opportunities




### GoLIVE

- Landsat-8 derived 2-component displacement fields
- Dozens to hundreds per year
- Centralized processing and freely available near-real time data

### Sentinel-1

- Satellite constellation, 6-day repeat
- C-band InSAR
- Freely available data

NISAR
NASA - ISRO SAR Mission

- Scheduled to launch in 2020 or 2021
- L-band InSAR
- Centralized processing and freely available data

# Unprecedented quantity of data

- In the polar regions, more RS data (in terms of GB and spatial coverage) have been collected in the past few years than were collected in all previous years combined

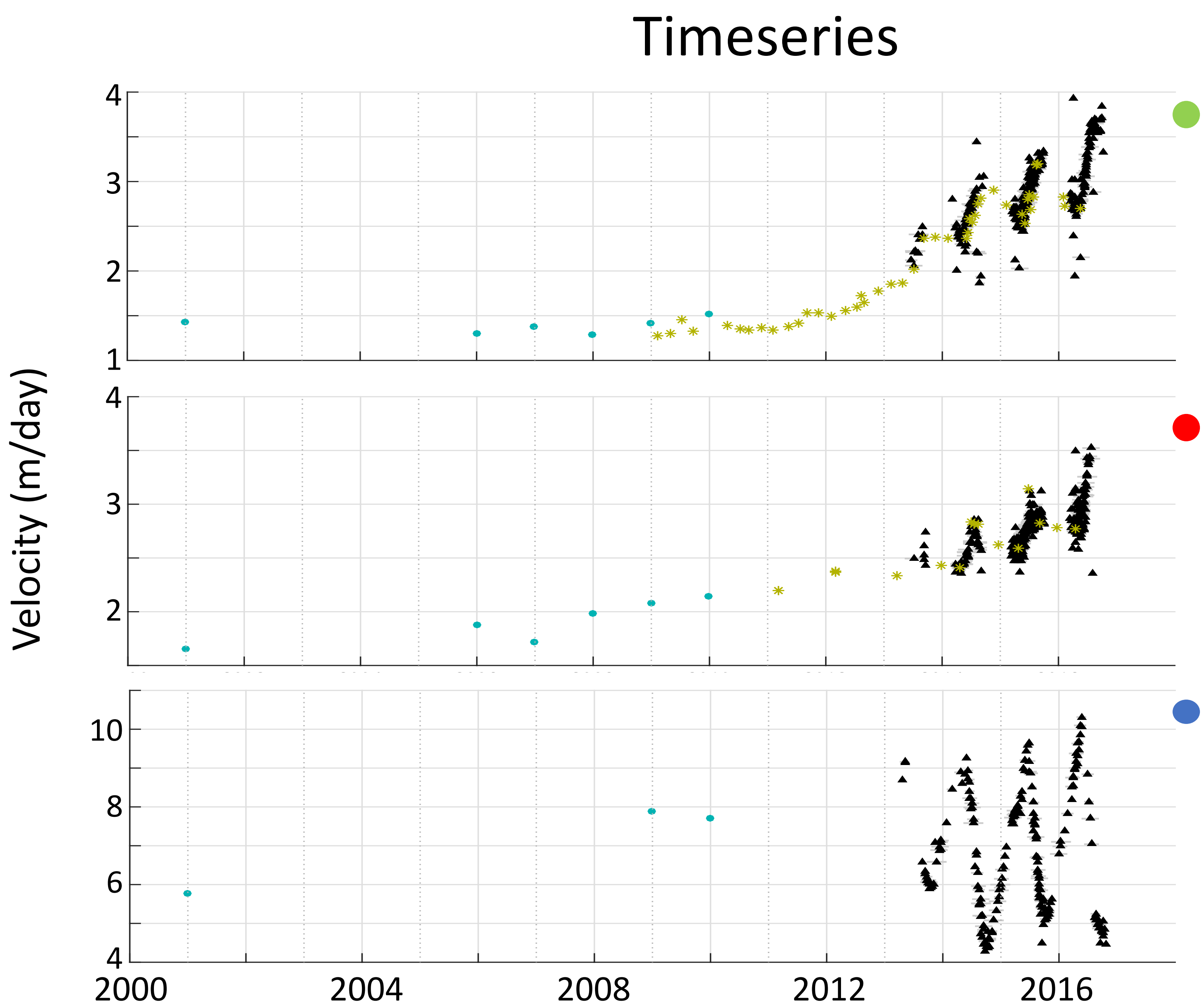
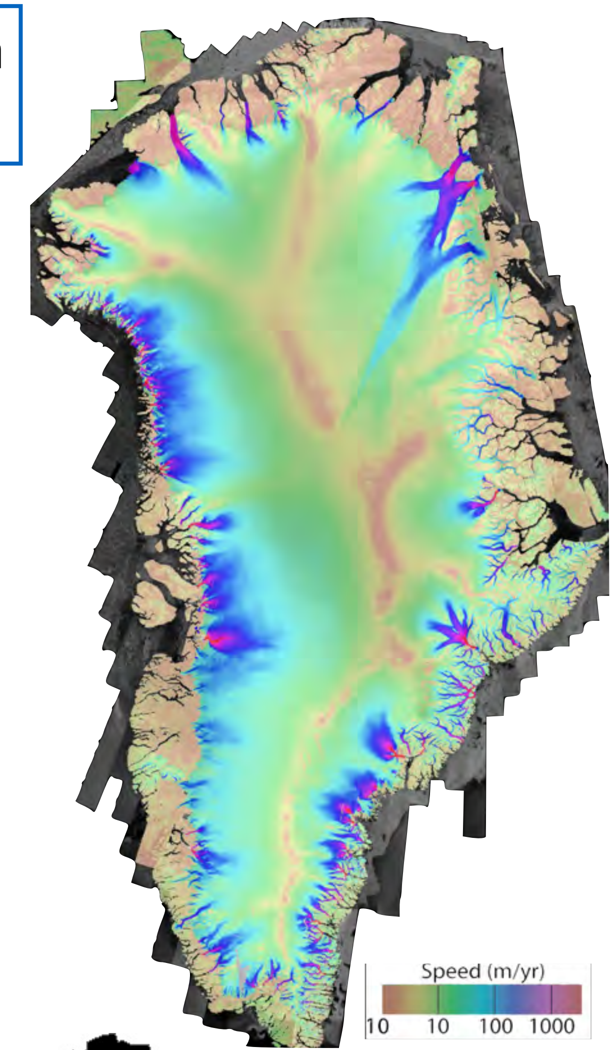
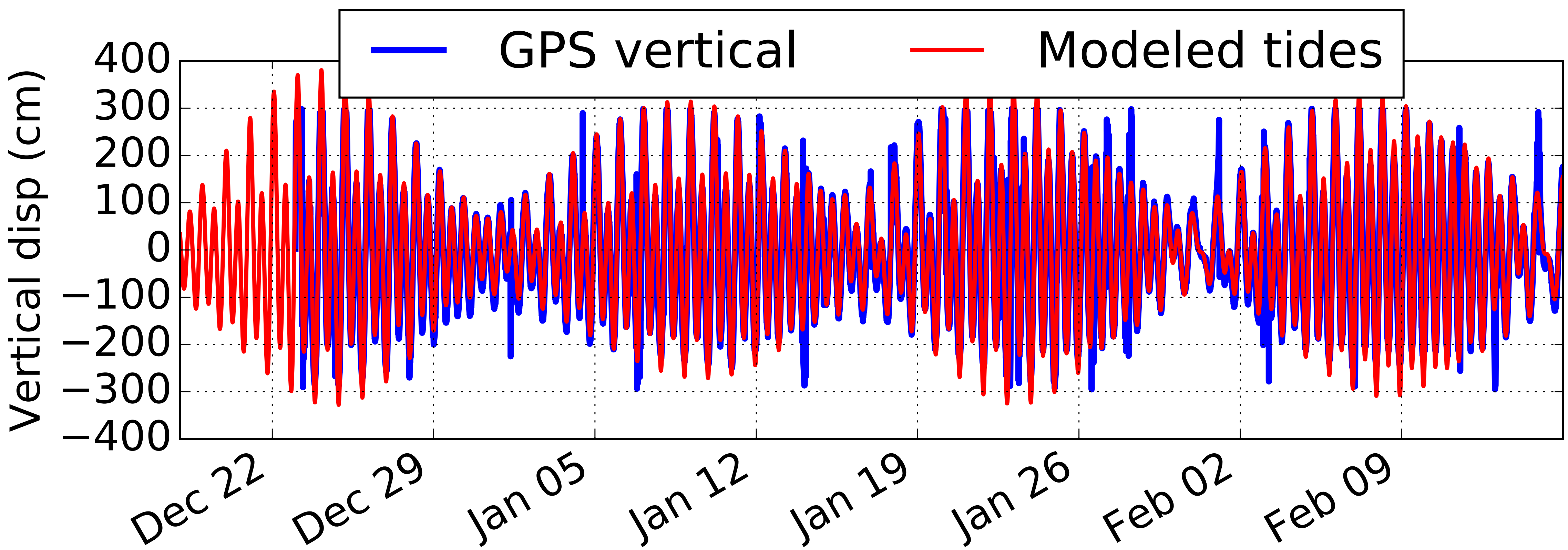



figure courtesy of T. Moon




# Example: the response of ice flow to ocean tides

Rutford Ice Stream, West Antarctica




Gudmundsson, 2006 (reproduced in Minchew et al., 2017)

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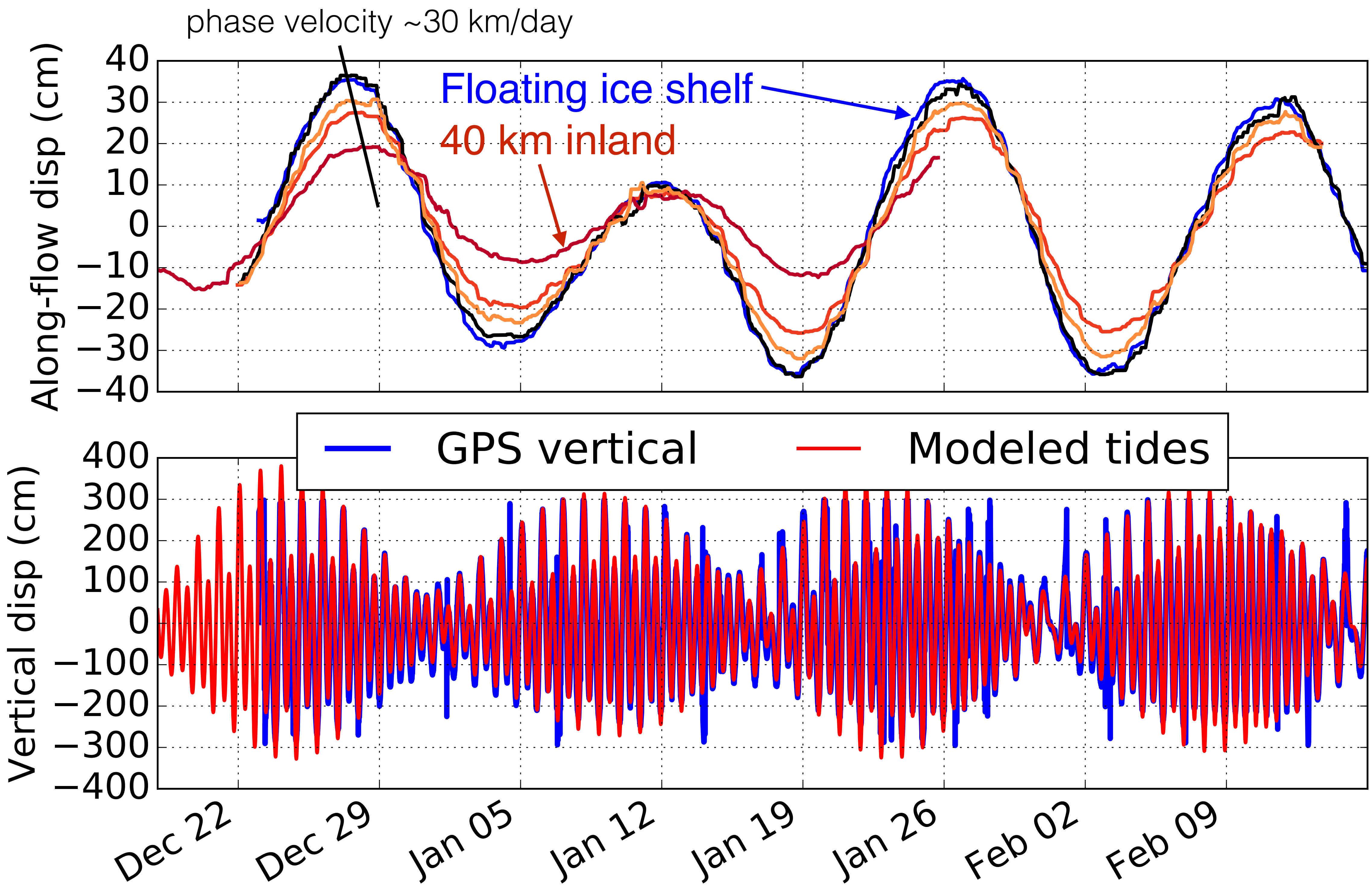


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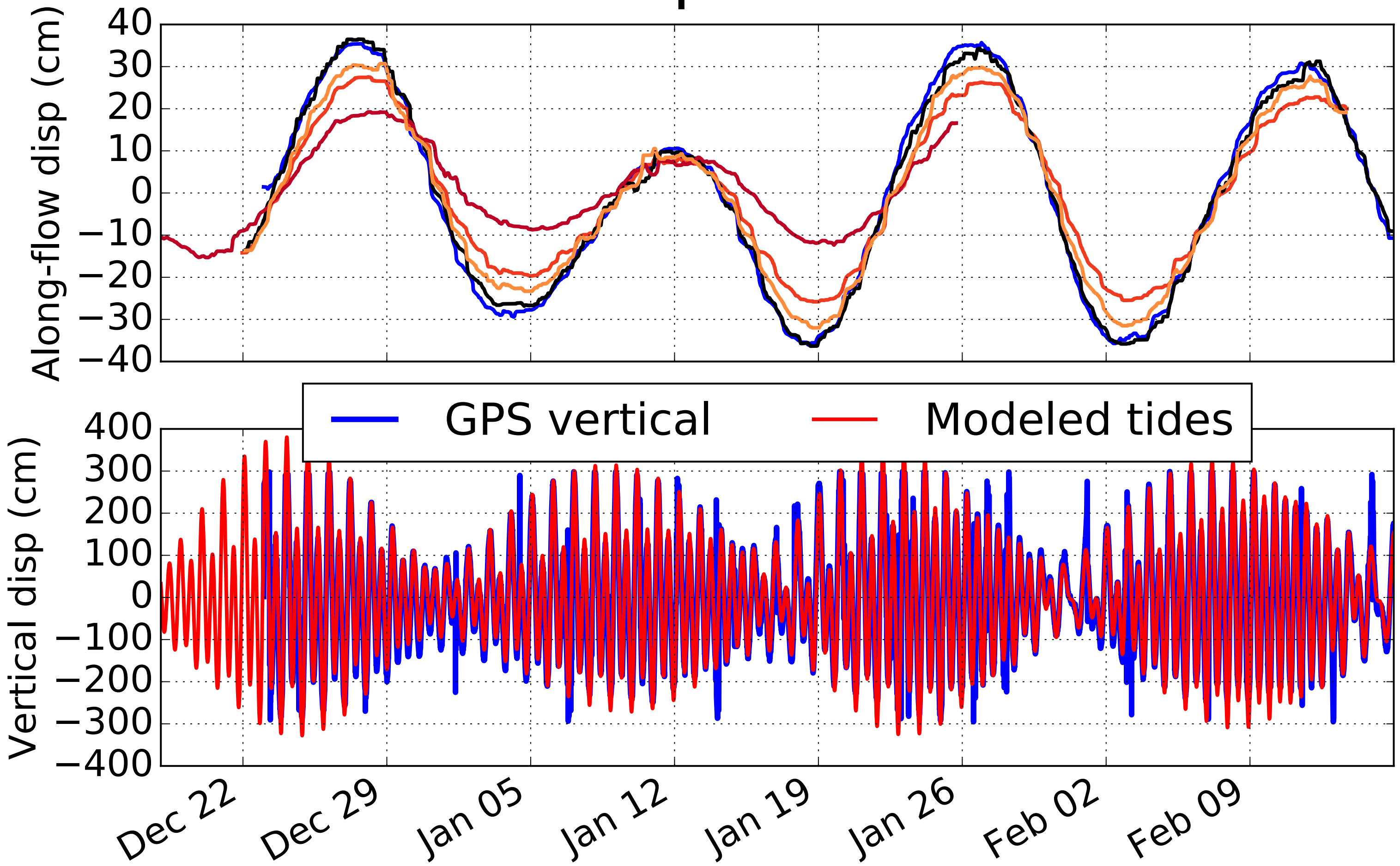
# Ocean tides and ice flow

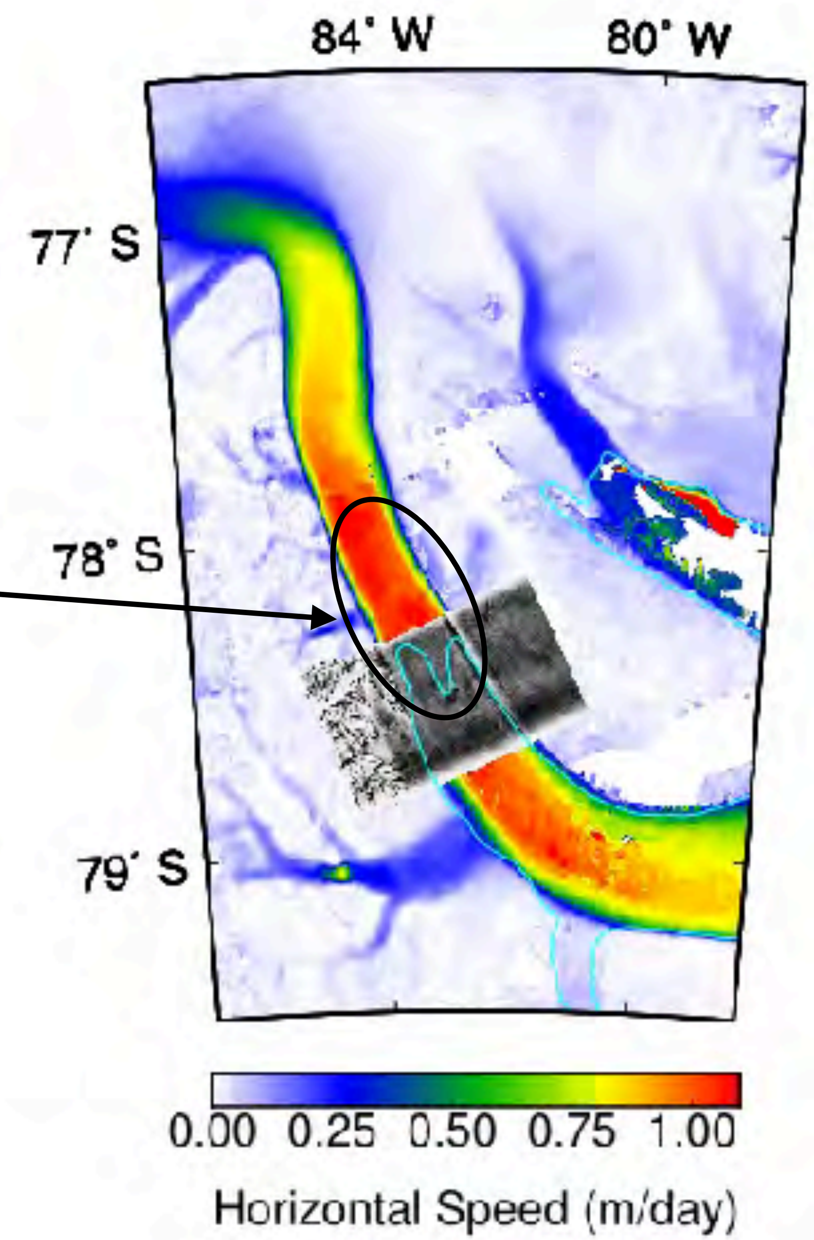
- Want broader spatial coverage and better spatial and temporal resolution
- Developed a new way to look at the problem utilizing spatially and temporally dense SAR observations

GPS: Temporal resolution




Gudmundsson, 2006; Minchew et al., 2017

Remote sensing:
Spatial coverage/resolution




Velocity data: Rignot *et al.*, 2011
GL data: Bedmap2

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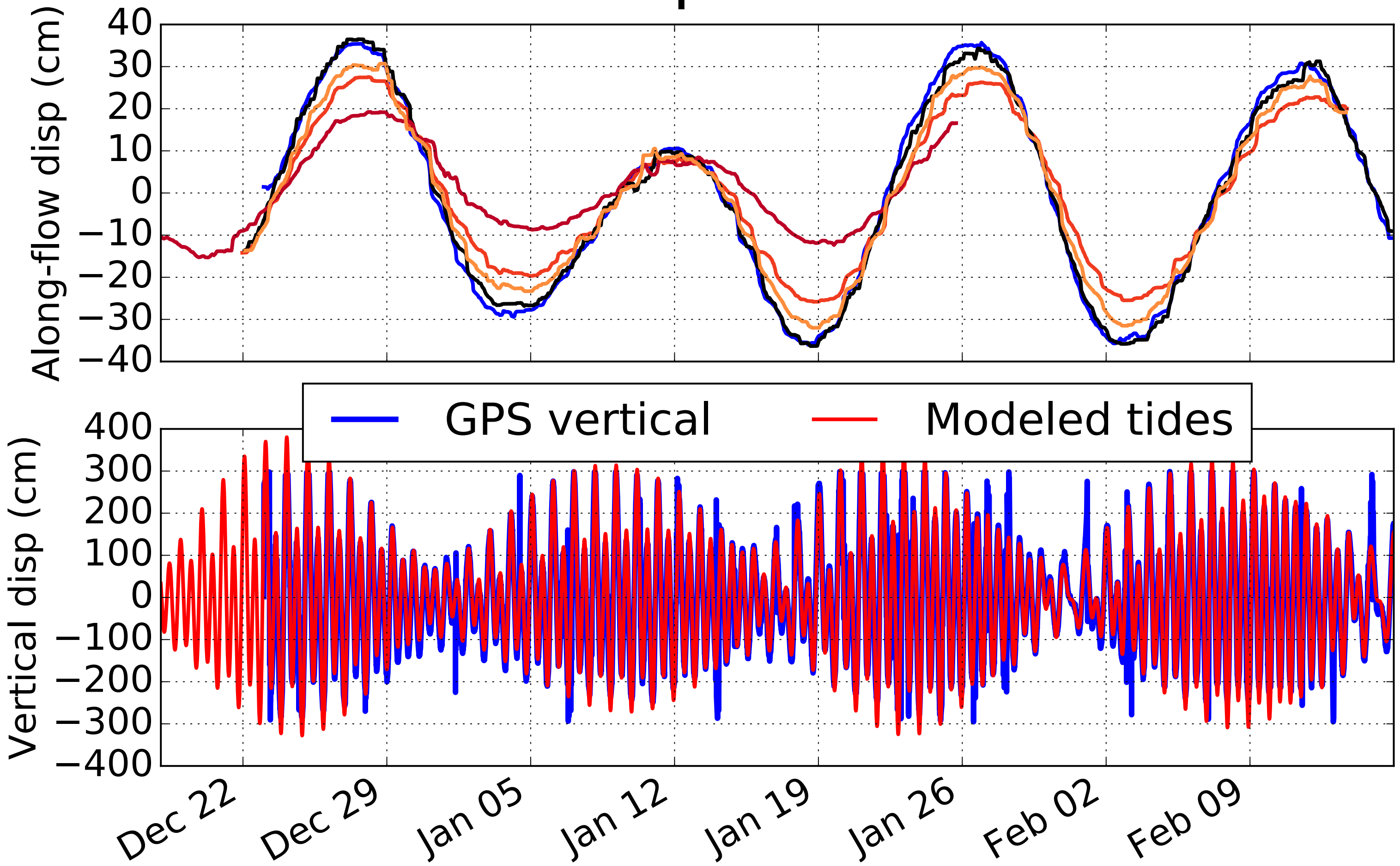


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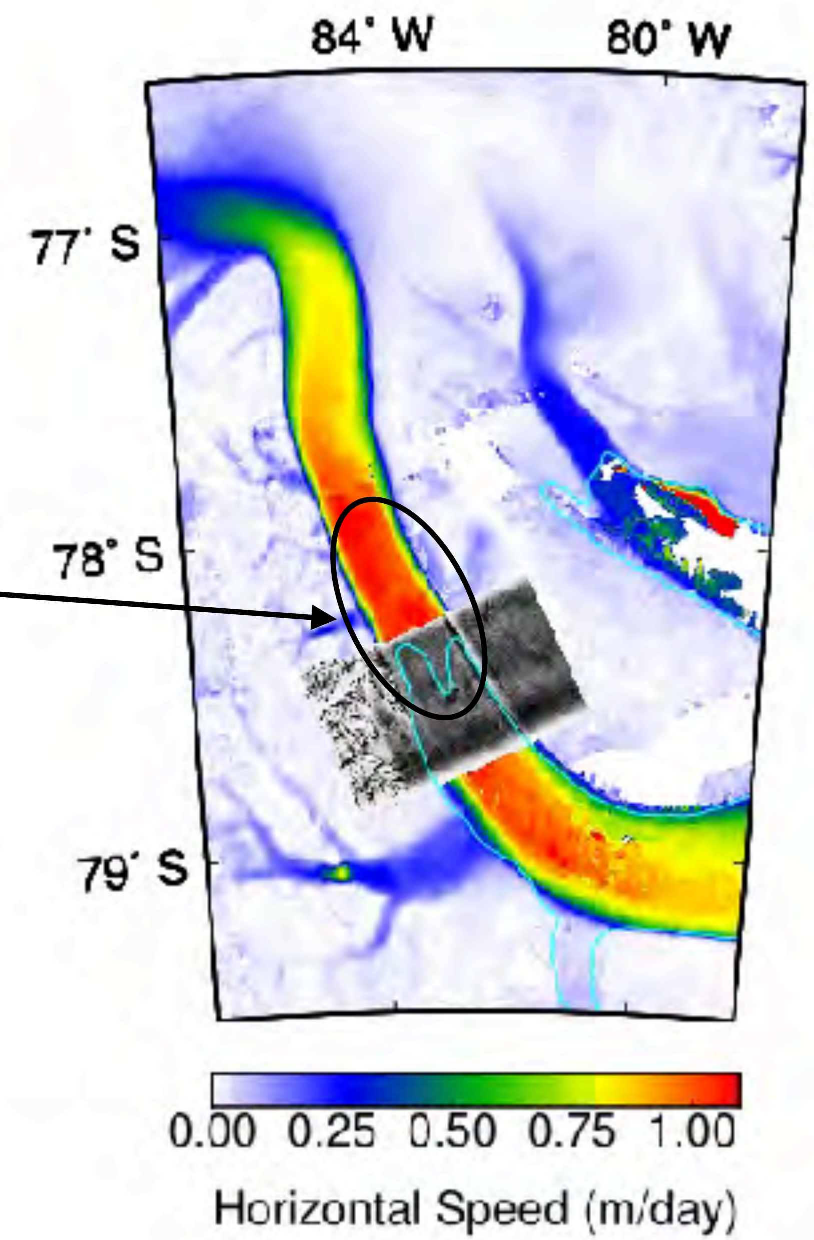


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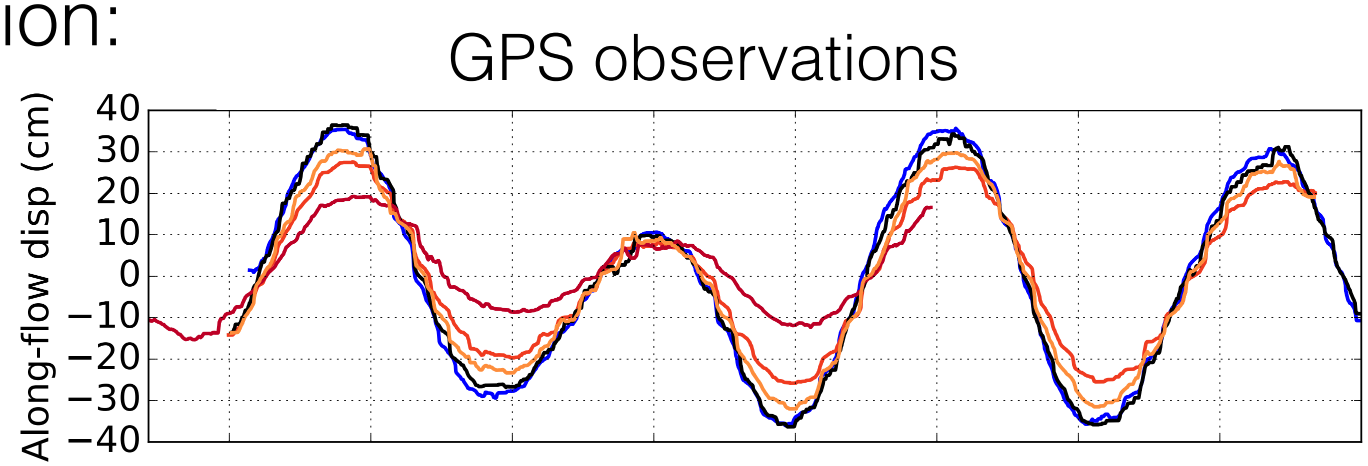
# 3-D, time-dependent velocity fields

- Prior information:




- Instantaneous displacement at position $\mathbf{r}$ and time $t$:

$$\mathbf{u}(\mathbf{r},t) = \begin{bmatrix} v^e \\ v^n \\ v^u \end{bmatrix} t + \sum_{i=1}^{k} \begin{bmatrix} a_i^e \sin\left(\omega_i t + \phi_i^e\right) \\ a_i^n \sin\left(\omega_i t + \phi_i^n\right) \\ a_i^u \sin\left(\omega_i t + \phi_i^u\right) \end{bmatrix}$$

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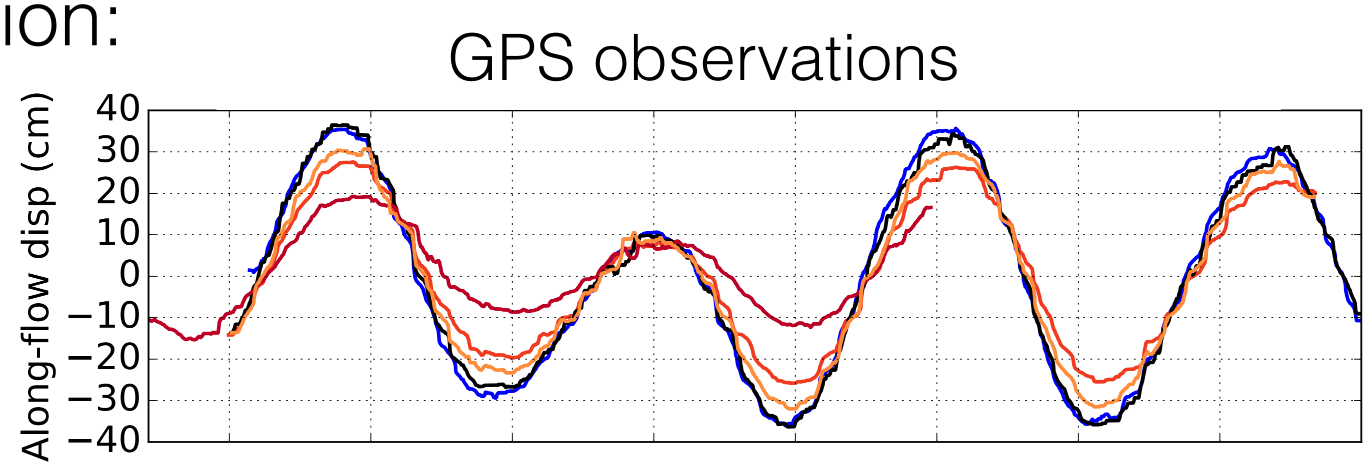


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- Observed displacements:

$$d_i = \hat{\boldsymbol{\ell}} \cdot \left(\mathbf{u}(\mathbf{r},t_a) - \mathbf{u}(\mathbf{r},t_b)\right)$$

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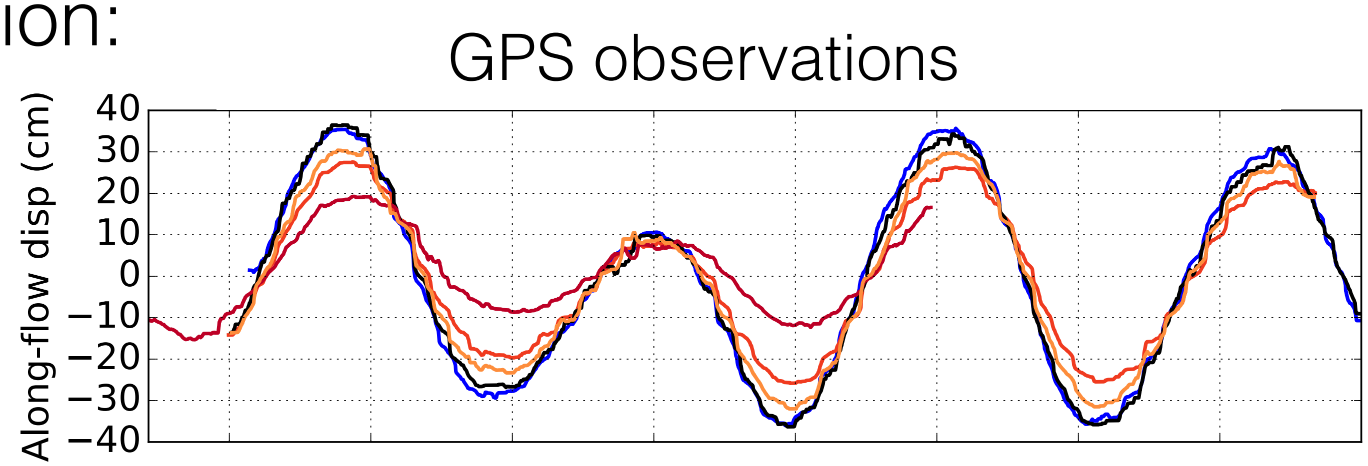


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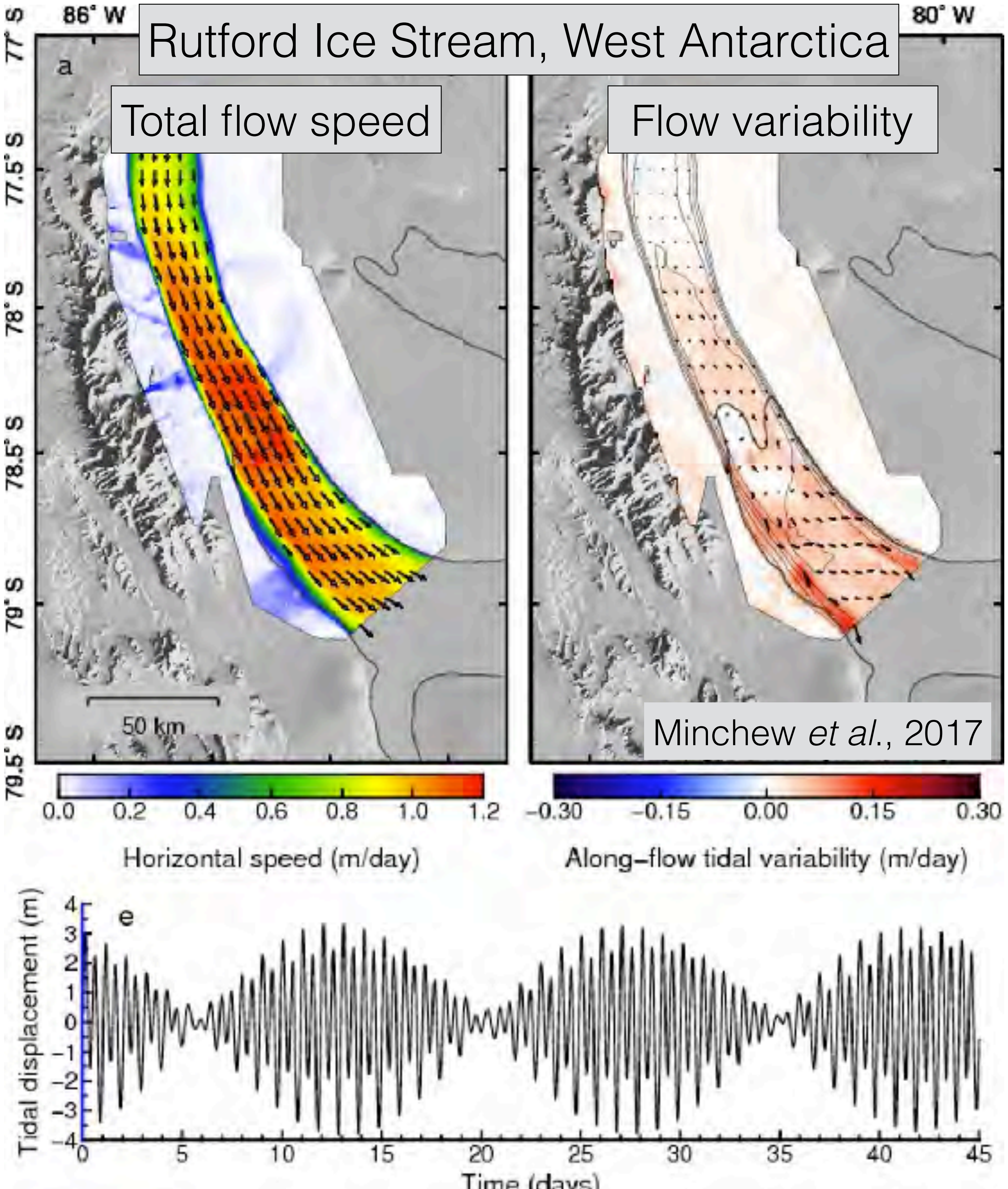
- System of equations:

$$\mathbf{G}\mathbf{m} = \mathbf{d}$$

- Details in Minchew et al., 2015, 2016b, 2017

# Observations: Time-dependent surface velocity fields




Takeaways:

- Upstream propagation of signal: Originates on ice shelf and propagates ~90 km inland in 3 days
- Changes in buttressing stresses from the ice-shelf are likely to be the driver of flow variability

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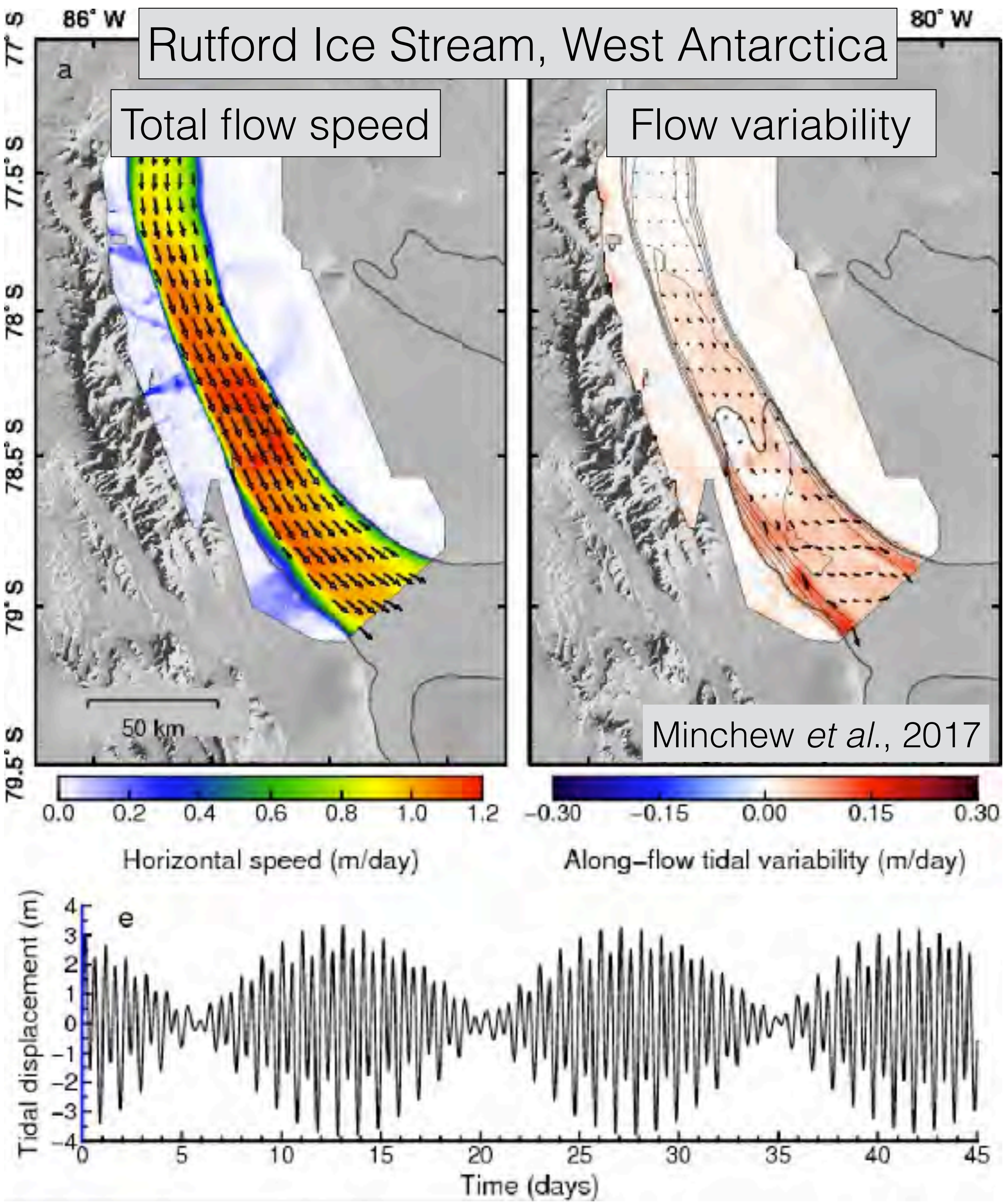


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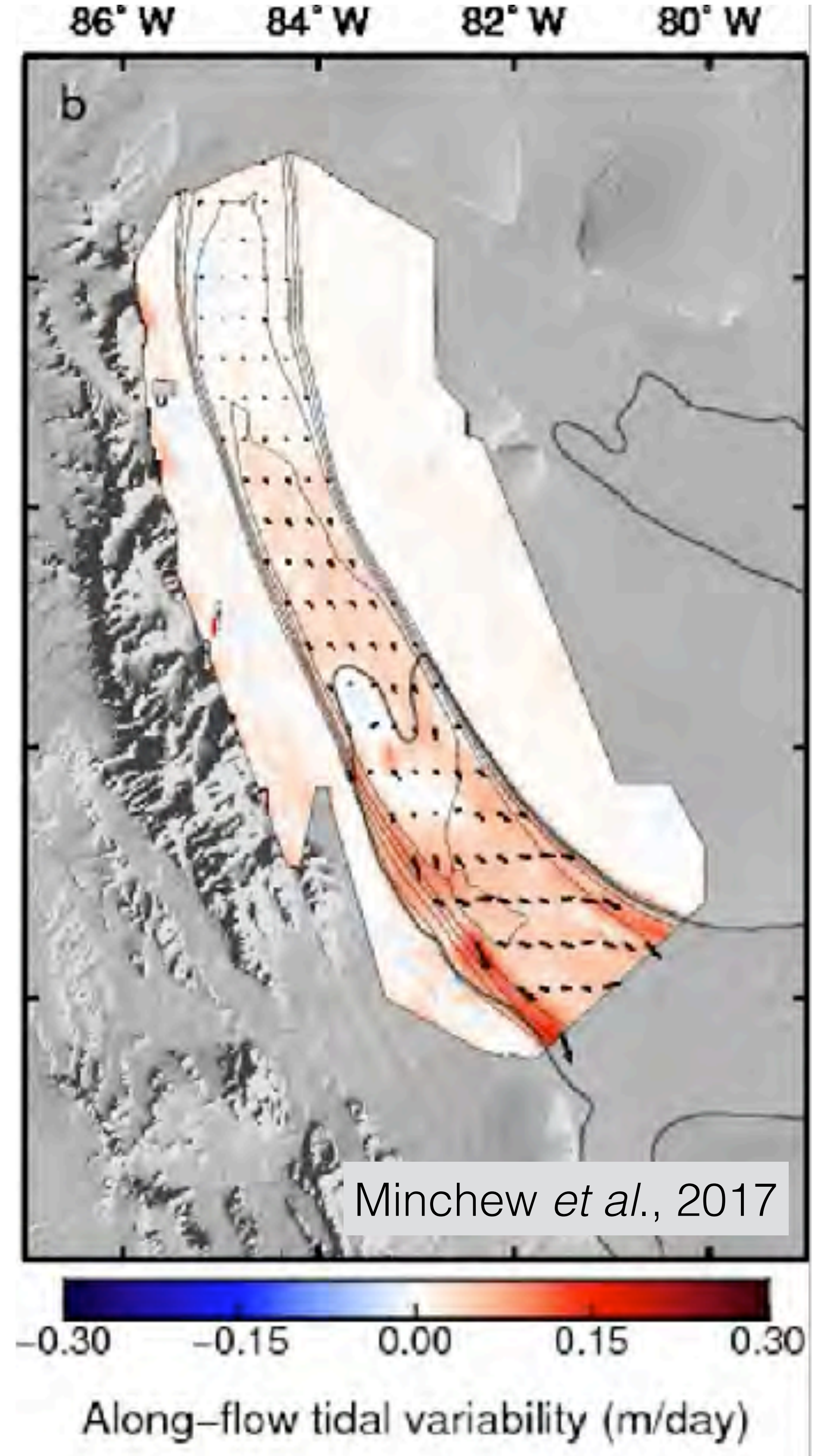
# Time-dependent surface velocity fields

Key observables:

- Secular (time-invariant) velocity
  - Similar to velocity snapshots and compilations that have been available for a while
  - Used successfully to study spatial variations in bed mechanics
  - E.g., work by Mathieu, Helene, Olga, Hilmar, et al.
- Time-varying velocity gives more information
  - Decay distance: amplitude decreases by 1/e; ~ 45 km
  - Propagation speed (phase velocity); ~ 30 km/day




Minchew *et al.*, 2017

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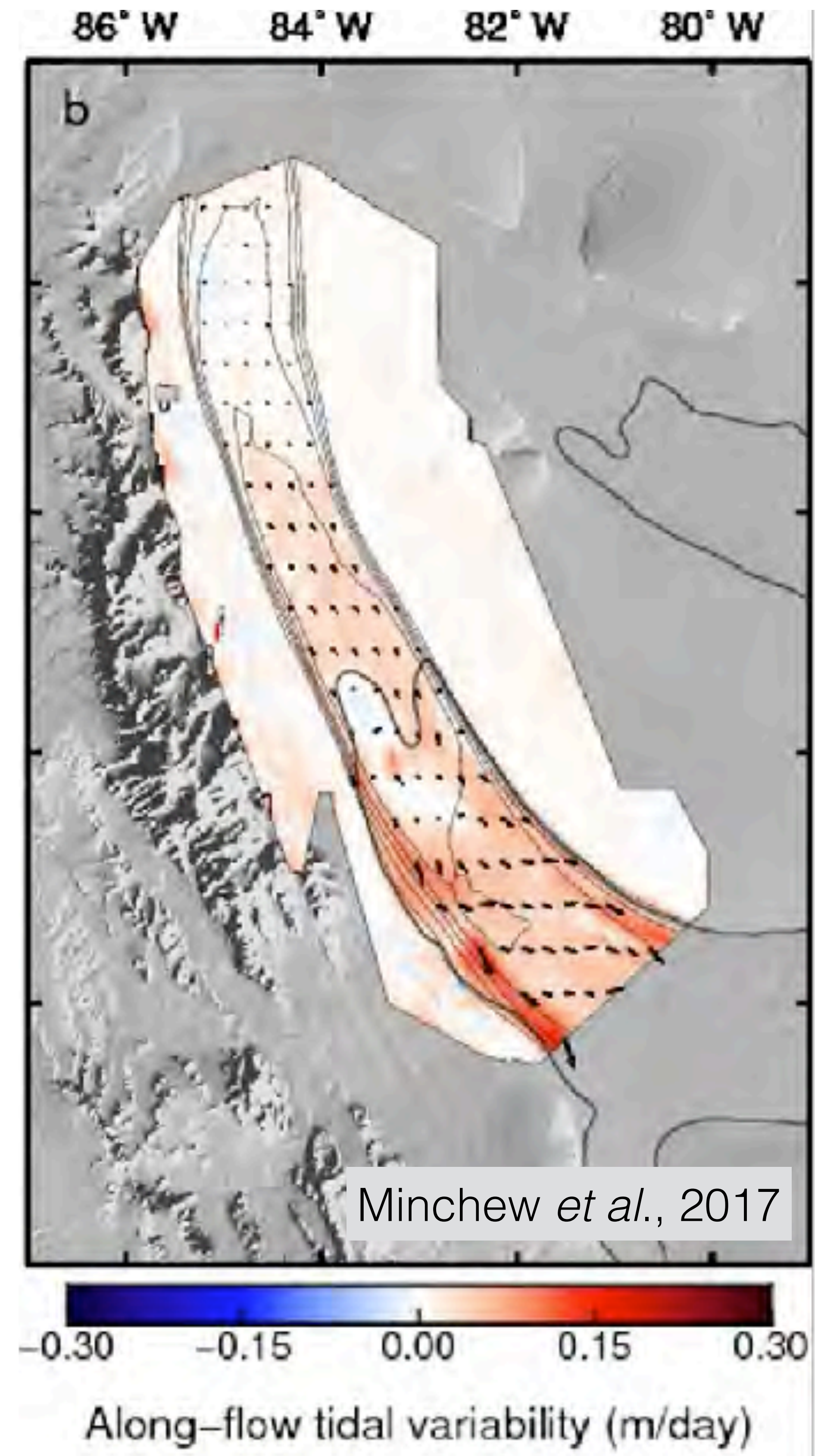
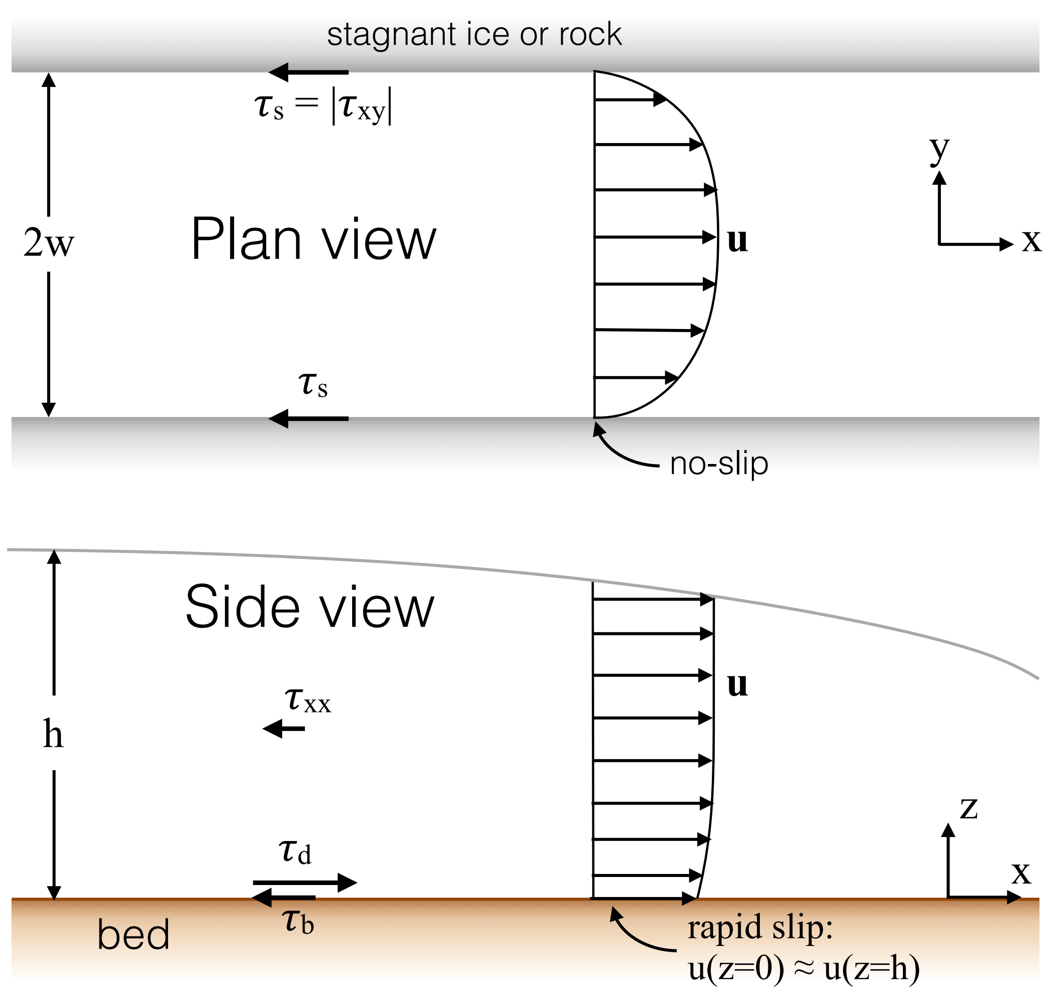
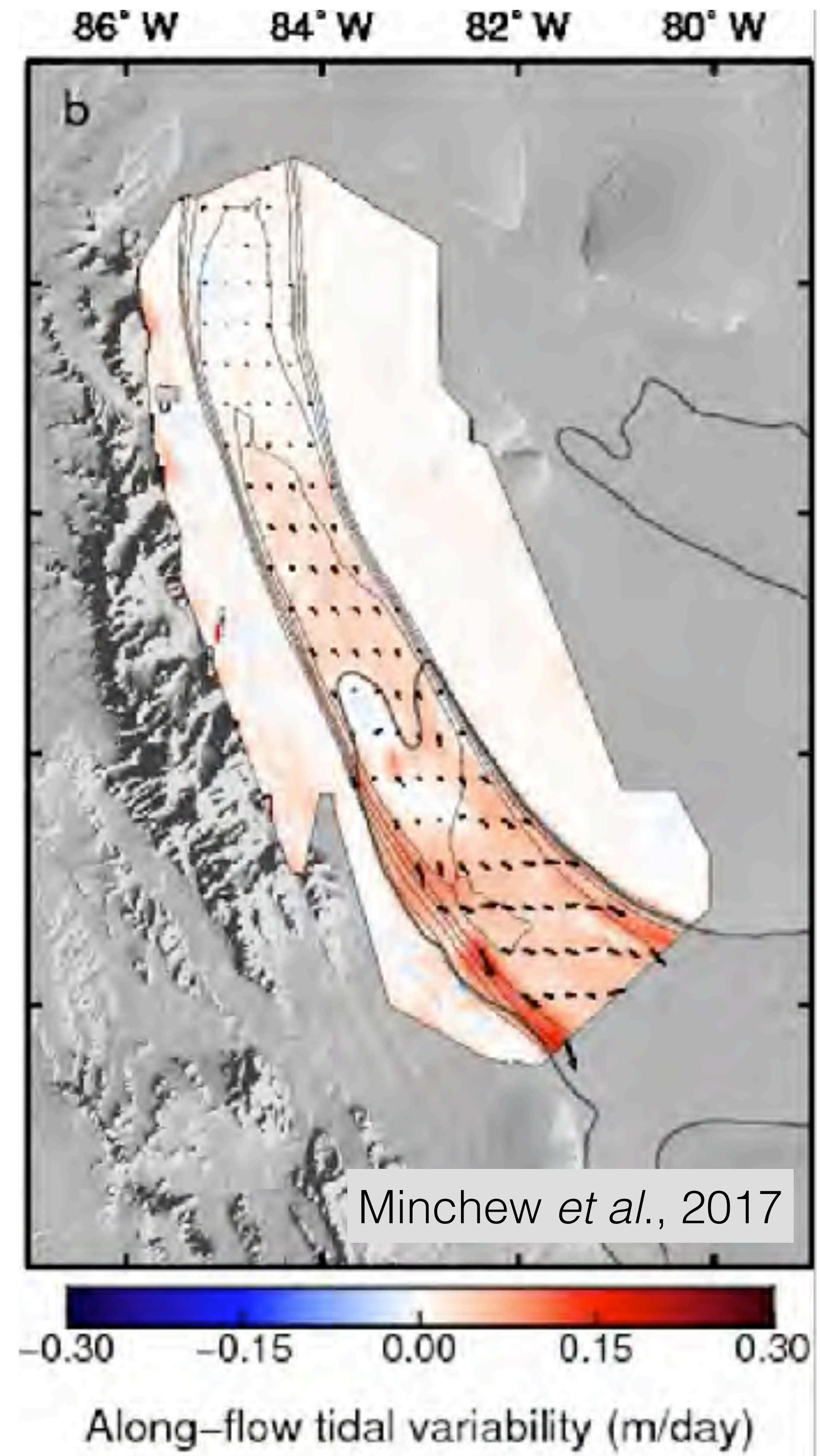


# A simple physical model

- Laterally confined glacier with well-lubricated bed
  - Shear stresses in the margins
  - Drag at the bed
- Assume that sliding law parameters are constant in time and space
- Maxwell viscoelastic ice rheology
- Forced by distal, short-timescale, periodic forcing



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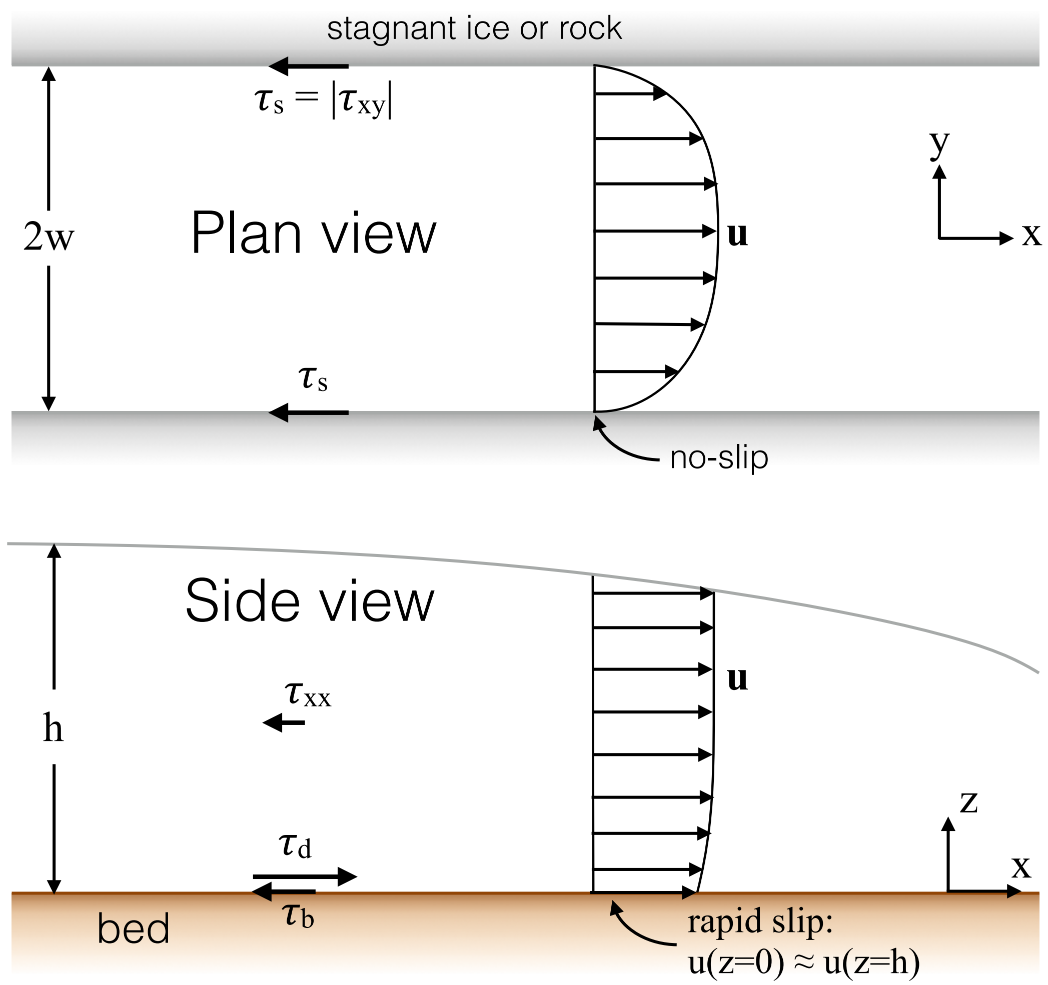
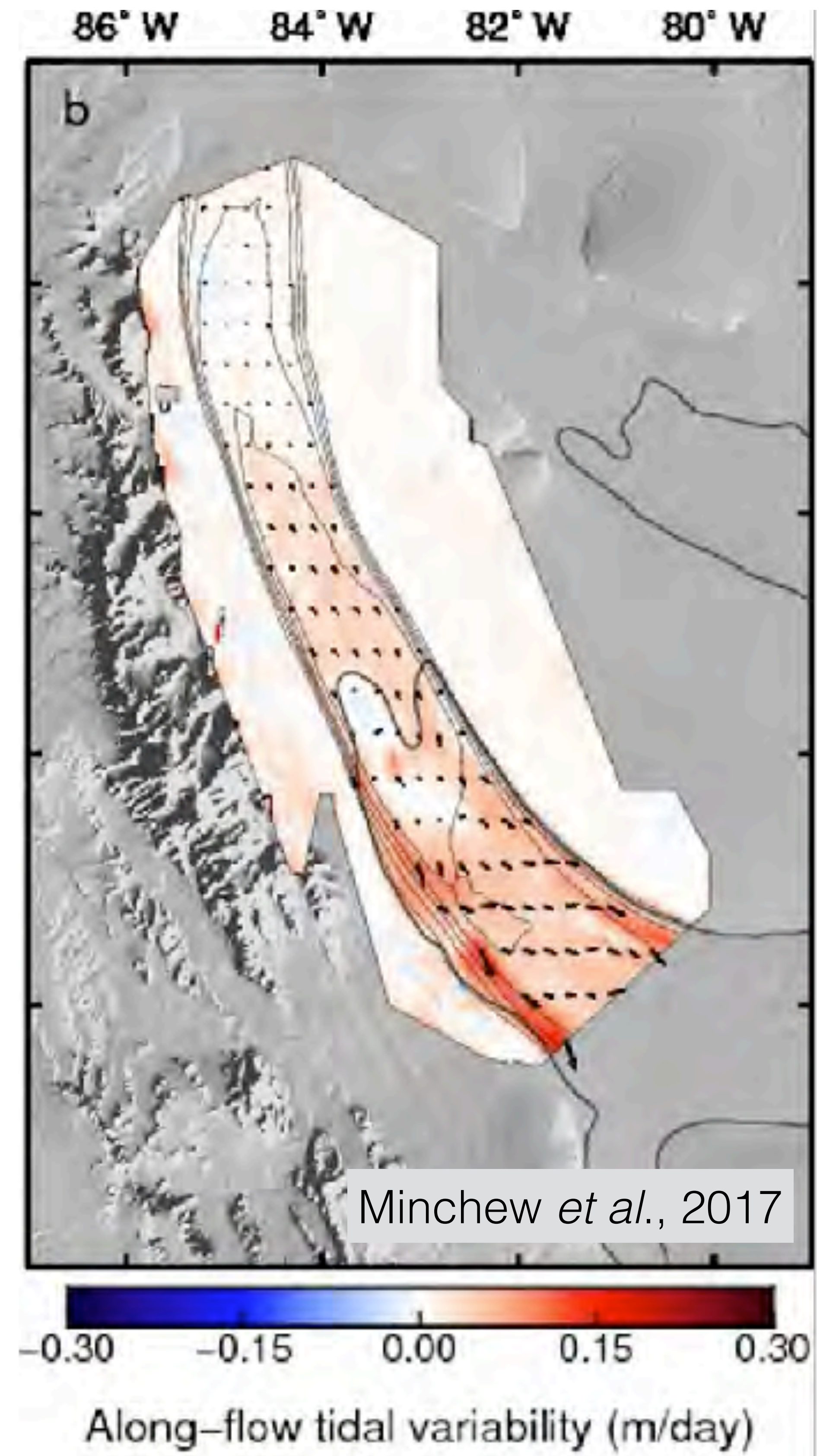


# An analytical solution for the sliding law exponent

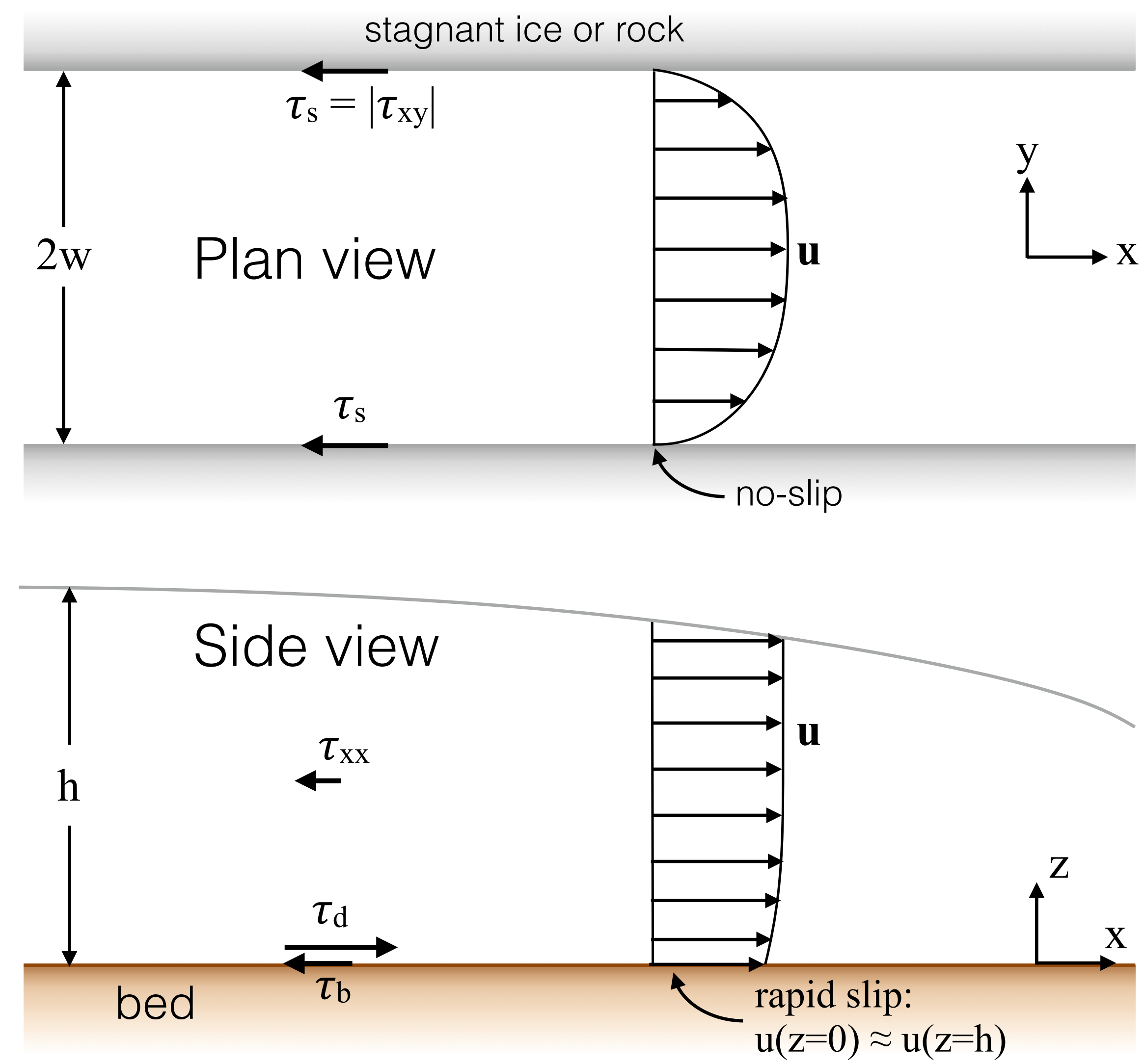
- After some manipulation

$$\boxed{\frac{n}{m} = 1 - \frac{\bar{\tau}_d}{\bar{\tau}_b}\Phi(\mathbf{v}_p, \ell, \bar{u}, h, A, \ldots)}$$

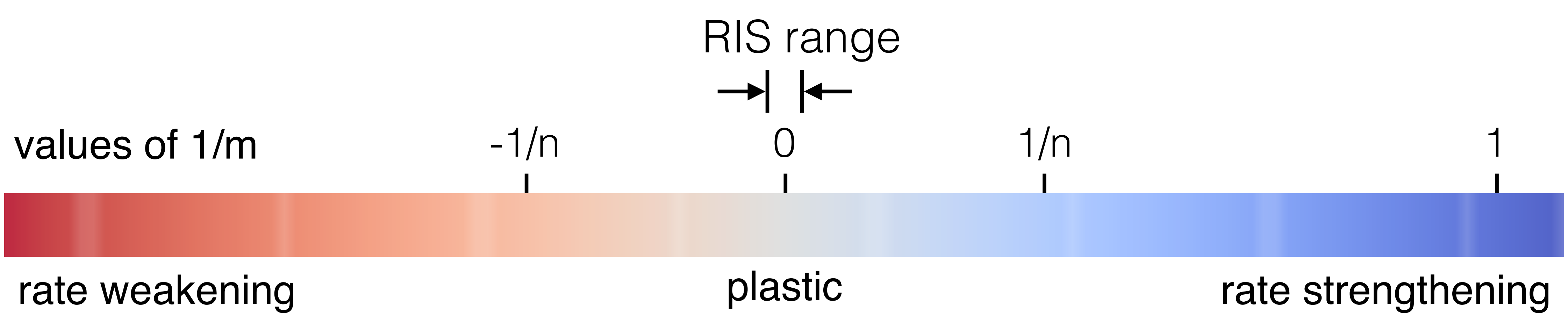
time-averaged basal drag

decay distance

phase velocity




- Plugging in representative values from Rutford IS gives a *preliminary* range what's very close to perfectly plastic ($|1/m| < 5 \times 10^{-2}$)



# Conclusions and closing thoughts

- Is the bed rate-weakening ($1/m < 0$), rate strengthening ($1/m > 0$), or plastic ($1/m \sim 0$)?

- We developed a method for using time-dependent surface velocity fields to infer the sliding law exponent (and prefactor, a straightforward extension)

  - Used time-dependent velocity fields to estimate phase velocity and decay distance of changes in ice-flow velocity caused changes in ice shelf buttressing

  - Constrained the rheology of ice within the shear margins

  - Derived a new, simple model relating the exponent to observable quantities

  - Results suggest that the bed beneath Rutford Ice Stream is plastic

- More generally: Basis for working strategies for processing the vast amount of surface velocity observations that will accumulate over the next few years

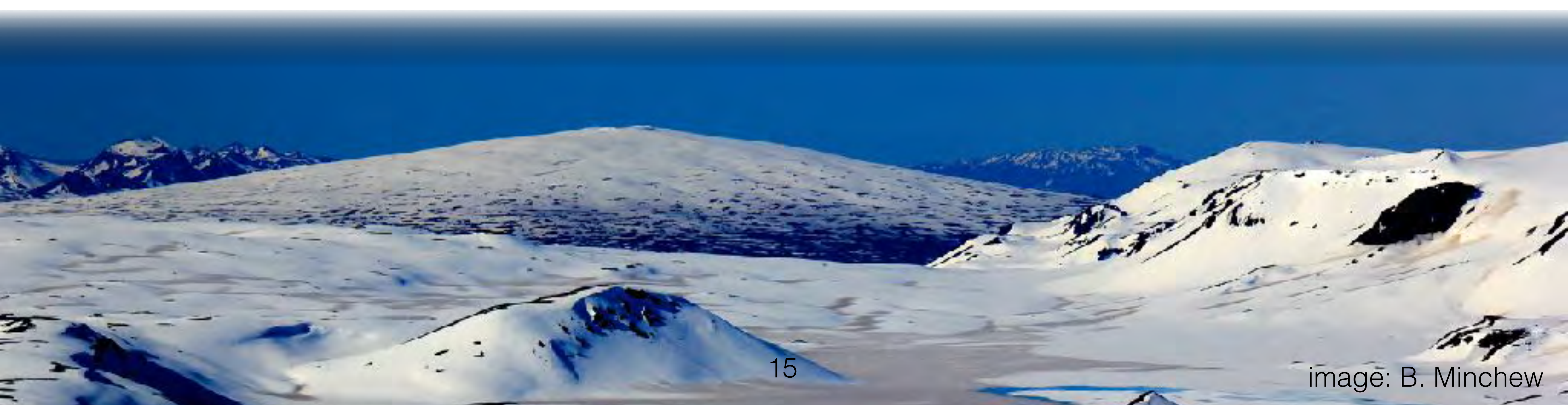


image: B. Minchew

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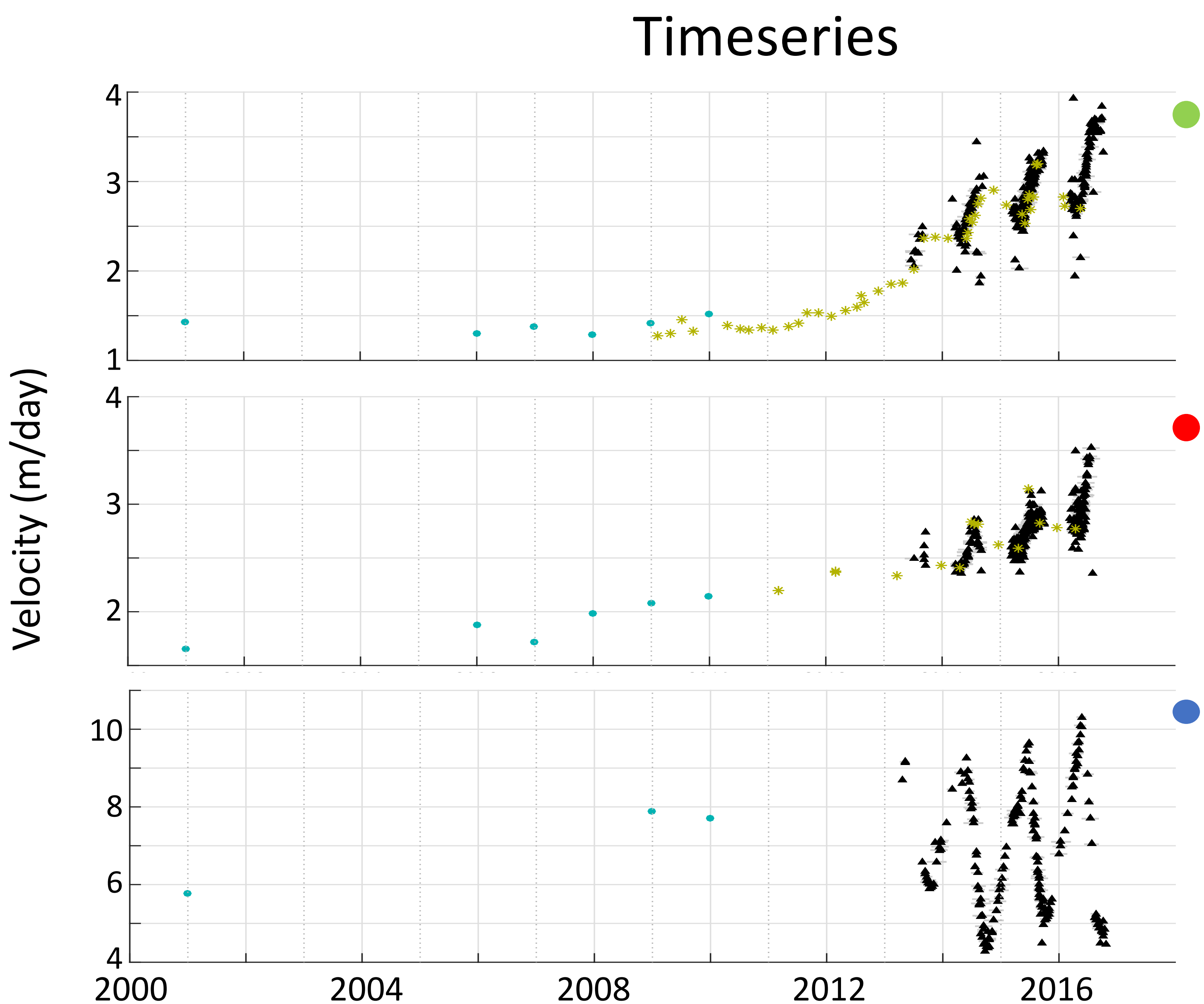


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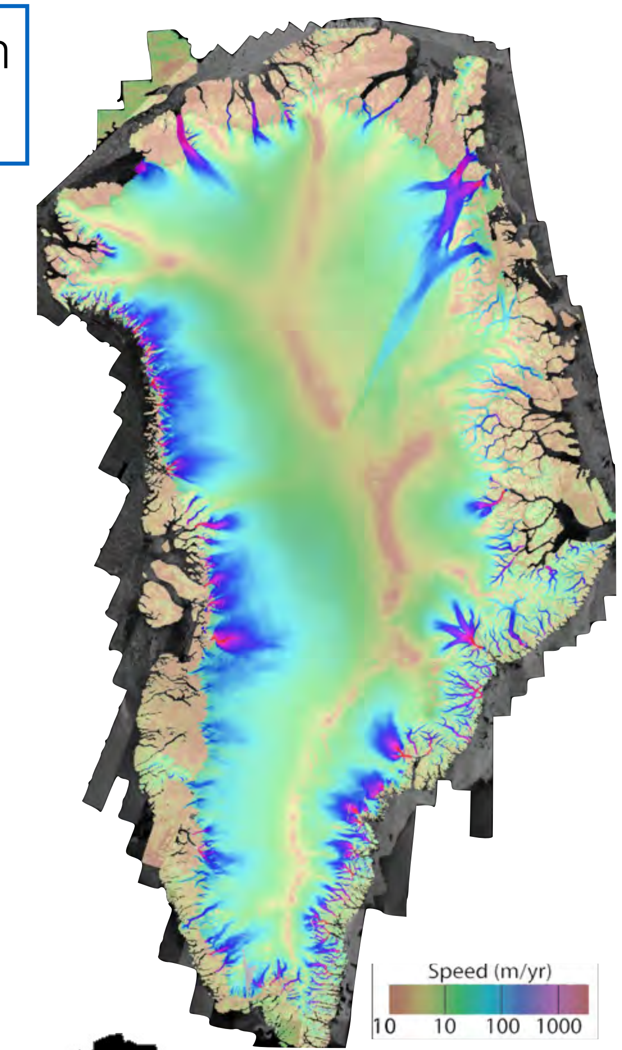


# Addressing the goals of the workshop

- Today’s example: Used new type of observation to address a fundamental, long-standing problem in glacier dynamics
- Limitations → opportunities for development:
  - One relatively small area → Similar signals exist elsewhere, need to explore further
  - Leveraged extraordinary dataset → need to deal with lower SNR and more sparse sampling
  - Relied on prior knowledge of the signal of interest → must relax this requirement
  - Simple physical model for inference of characteristic values → assimilate data in more sophisticated models
- Examples of current research
  - AI: Learning and quantifying spatiotemporal patterns (in surface velocity fields) from remote sensing time-series
  - Sophisticated and efficient data assimilation methods

image: B. Minchew