Seasonal ice flow of Ross Ice Shelf reconciling model and observations

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Introduction

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ARTICLES

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Ross Ice Shelf response to climate driven by the tectonic imprint on seafloor bathymetry

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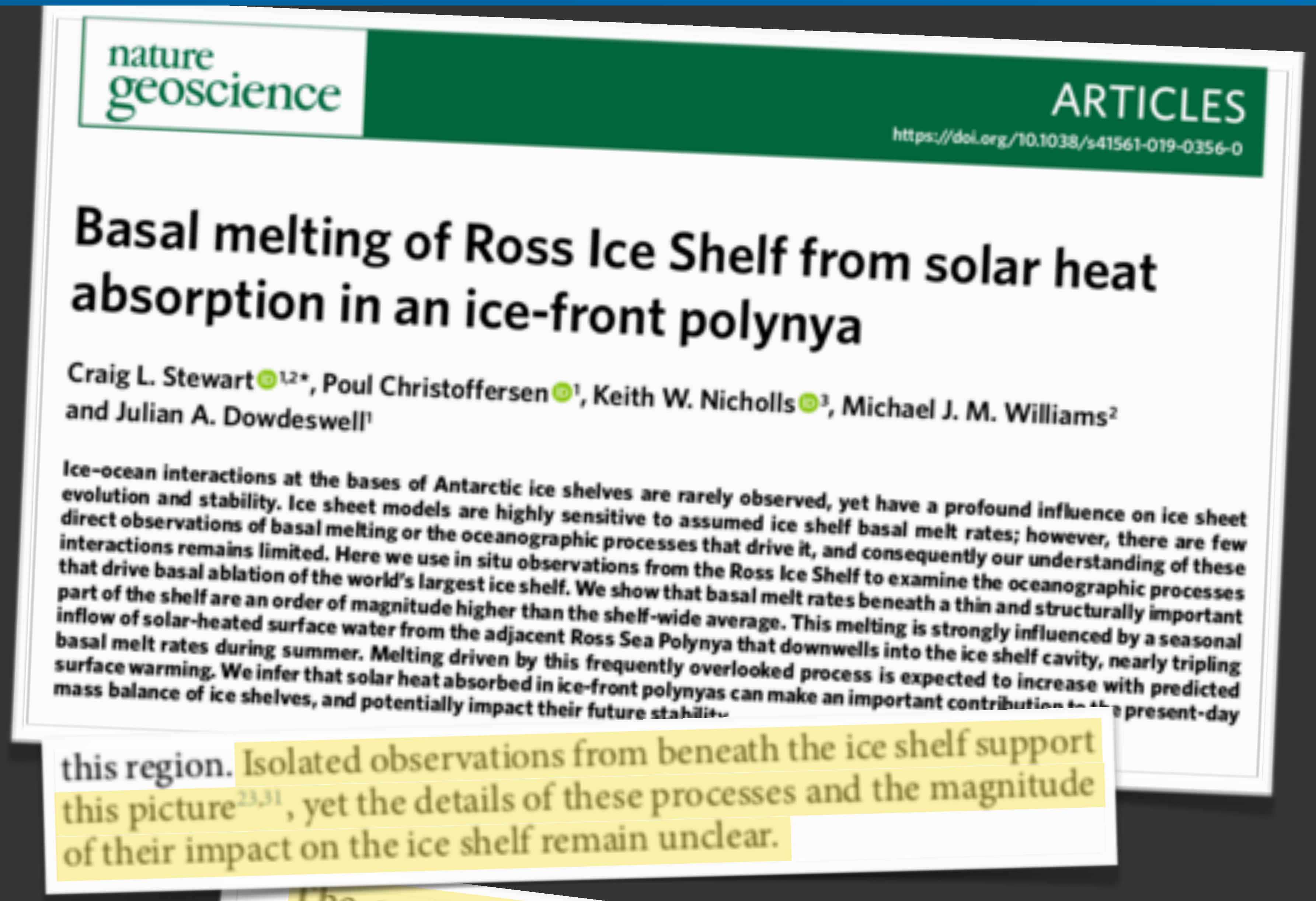
Ocean melting has thinned Antarctica's ice shelves at an increasing rate over the past two decades, leading to loss of grounded
ice. The Ross Ice Shelf is currently close to steady state but geological records indicate that it can disintegrate rapidly, which
would accelerate grounded ice loss from catchments equivalent to 11.6 m of global sea level rise. Here, we use data from the
ROSETTA-Ice airborne survey and ocean simulations to identify the principal threats to Ross Ice Shelf stability. We locate the
tectonic boundary between East and West Antarctica from magnetic anomalies and use gravity data to generate a new high-
resolution map of sub-ice-shelf bathymetry. The tectonic imprint on the bathymetry constrains sub-ice-shelf ocean circulation,
protecting grounding line from moderate changes in global ocean heat content. In contrast, local, seasonal pro-
duction of the ice front drives rapid ice shelf melting east of Ross Island, where thinning would
lead to fa West Antarctic ice sheets. We confirm high modelled melt rates in this
region us ificance of both the tectonic framework and local ocean-
atmosph ctic Ice Sheet.

the influence of global ocean heat. We have identified that the greatest vulnerability of both the East and West Antarctic ice sheets in the Ross Sea sector is to local, seasonal, upper-ocean warming and deepening of the surface layer at a key region of the ice front, near Ross Island. This finding highlights the need to incorporate the ice shelf response to local climate processes in large-scale predictions of ice sheet behaviour in the broader tectonic framework.



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ARTICLES

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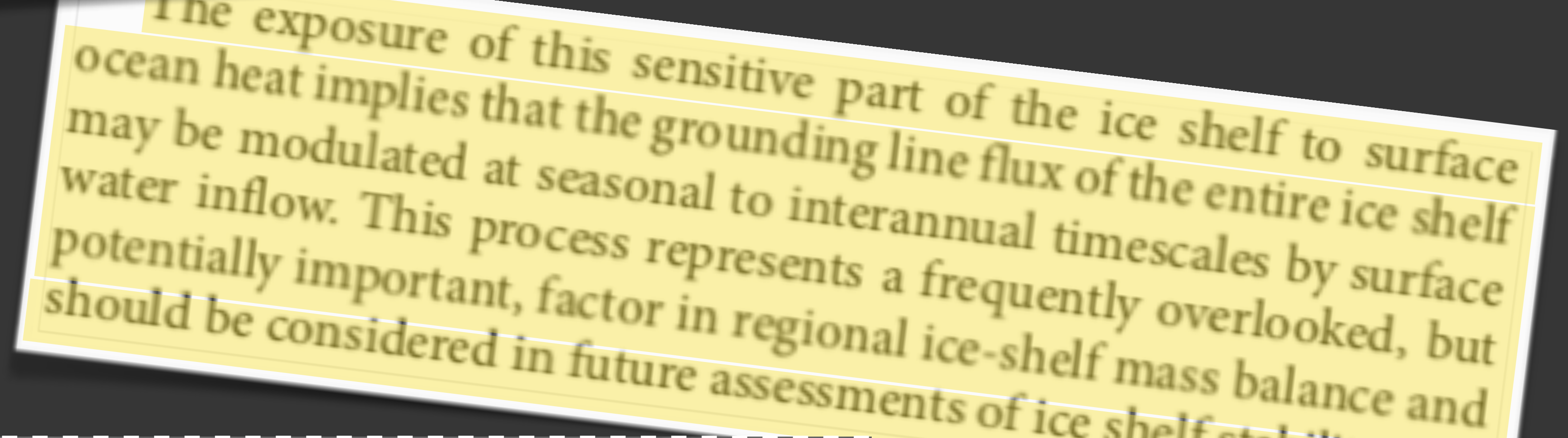
Basal melting of Ross Ice Shelf from solar heat absorption in an ice-front polynya

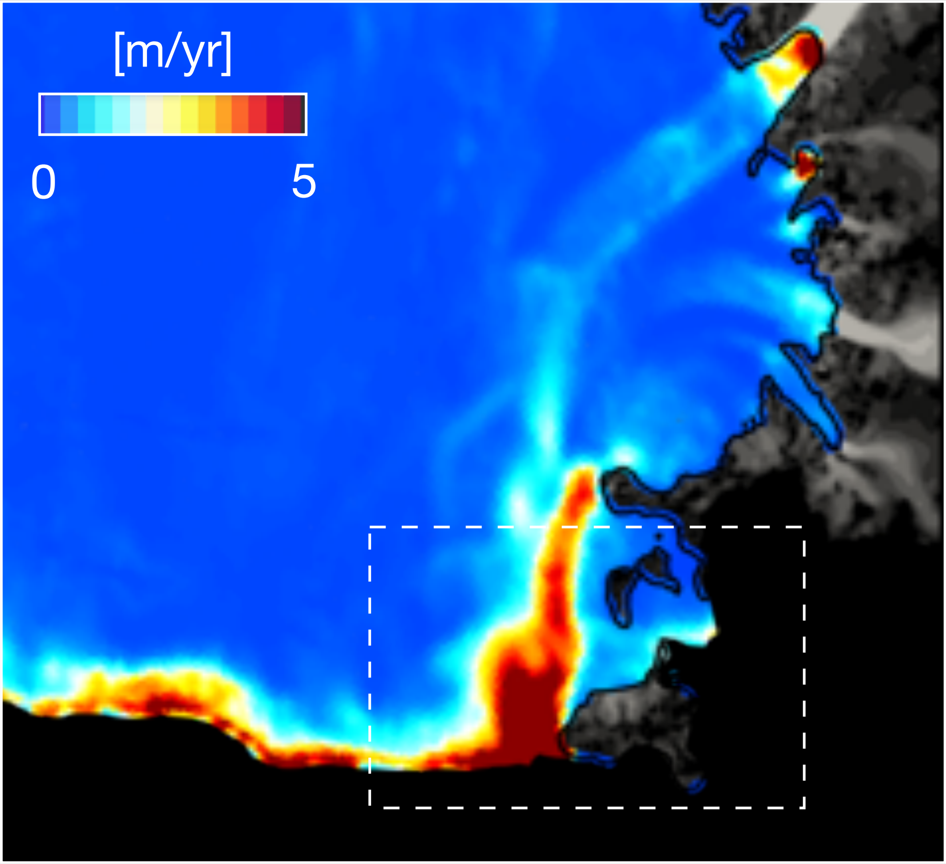
Craig L. Stewart[1,2*], Poul Christoffersen[1], Keith W. Nicholls[3], Michael J. M. Williams[2] and Julian A. Dowdeswell[1]

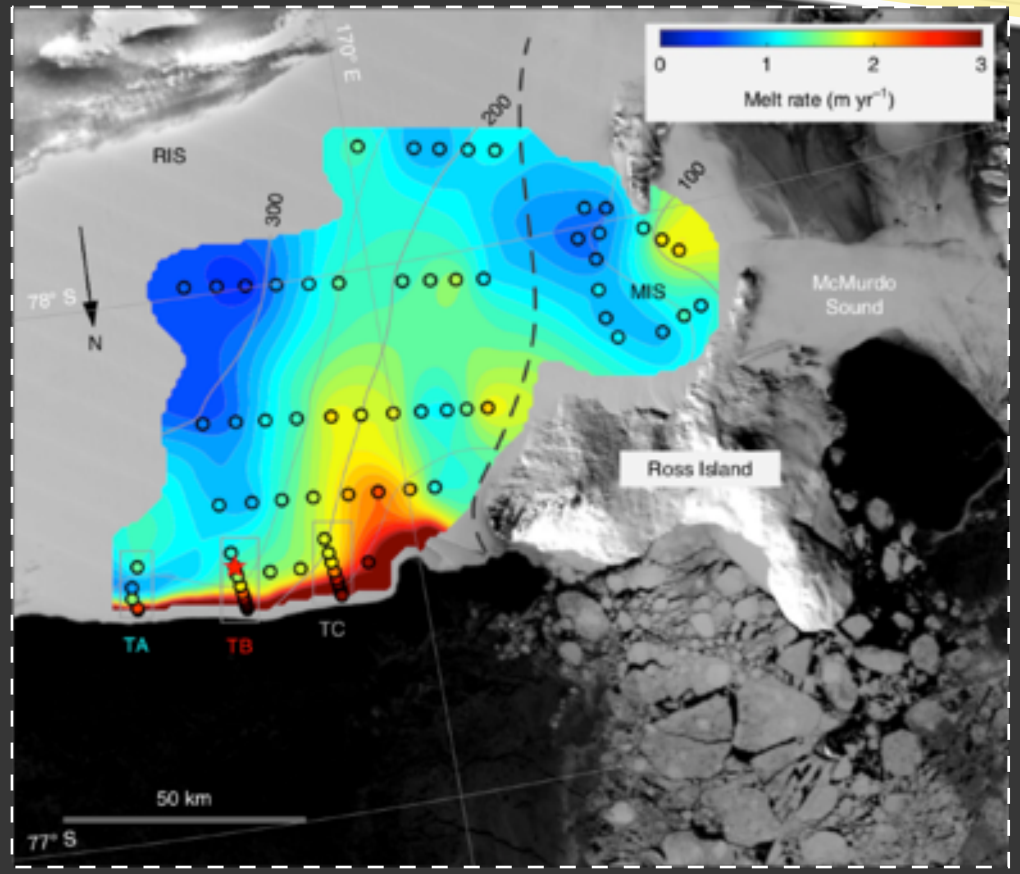
Ice–ocean interactions at the bases of Antarctic ice shelves are rarely observed, yet have a profound influence on ice sheet
evolution and stability. Ice sheet models are highly sensitive to assumed ice shelf basal melt rates; however, there are few
direct observations of basal melting or the oceanographic processes that drive it, and consequently our understanding of these
interactions remains limited. Here we use in situ observations from the Ross Ice Shelf to examine the oceanographic processes
that drive basal ablation of the world's largest ice shelf. We show that basal melt rates beneath a thin and structurally important
part of the shelf are an order of magnitude higher than the shelf-wide average. This melting is strongly influenced by a seasonal
inflow of solar-heated surface water from the adjacent Ross Sea Polynya that downwells into the ice shelf cavity, nearly tripling
basal melt rates during summer. Melting driven by this frequently overlooked process is expected to increase with predicted
surface warming. We infer that solar heat absorbed in ice-front polynyas can make an important contribution to the present-day
mass balance of ice shelves, and potentially impact their future stability.

this region. Isolated observations from beneath the ice shelf support this picture[23,31], yet the details of these processes and the magnitude of their impact on the ice shelf remain unclear.

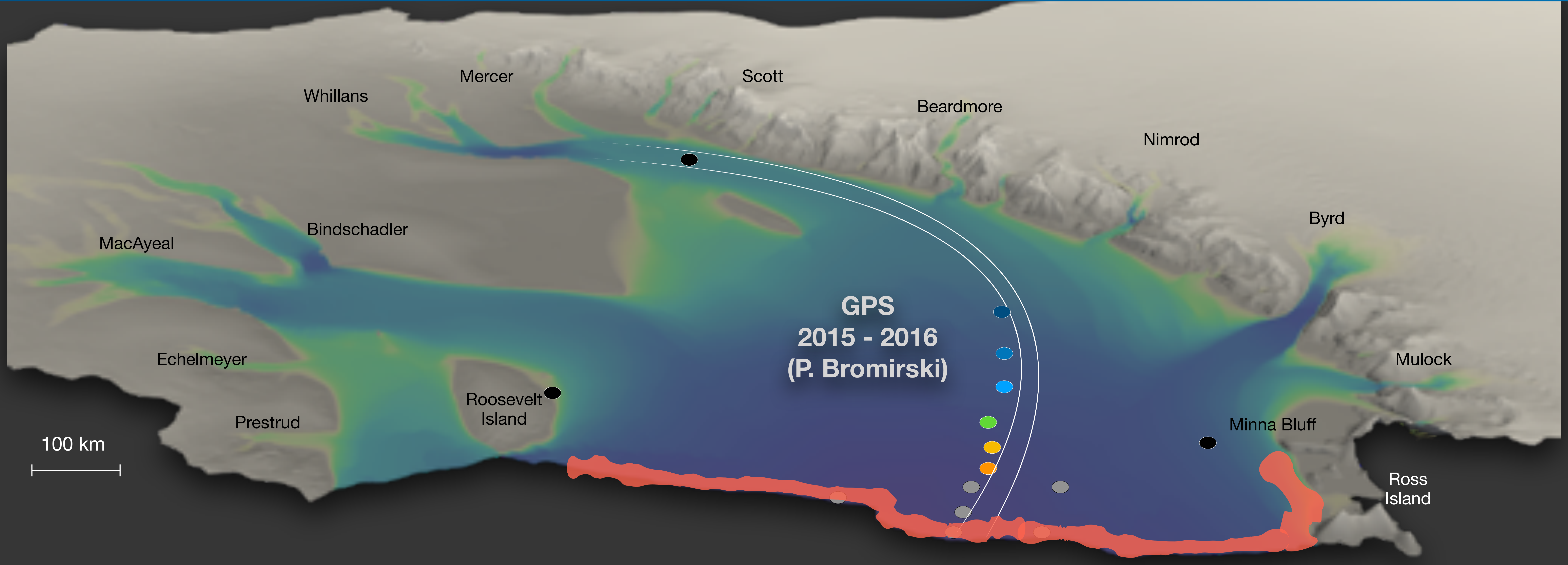


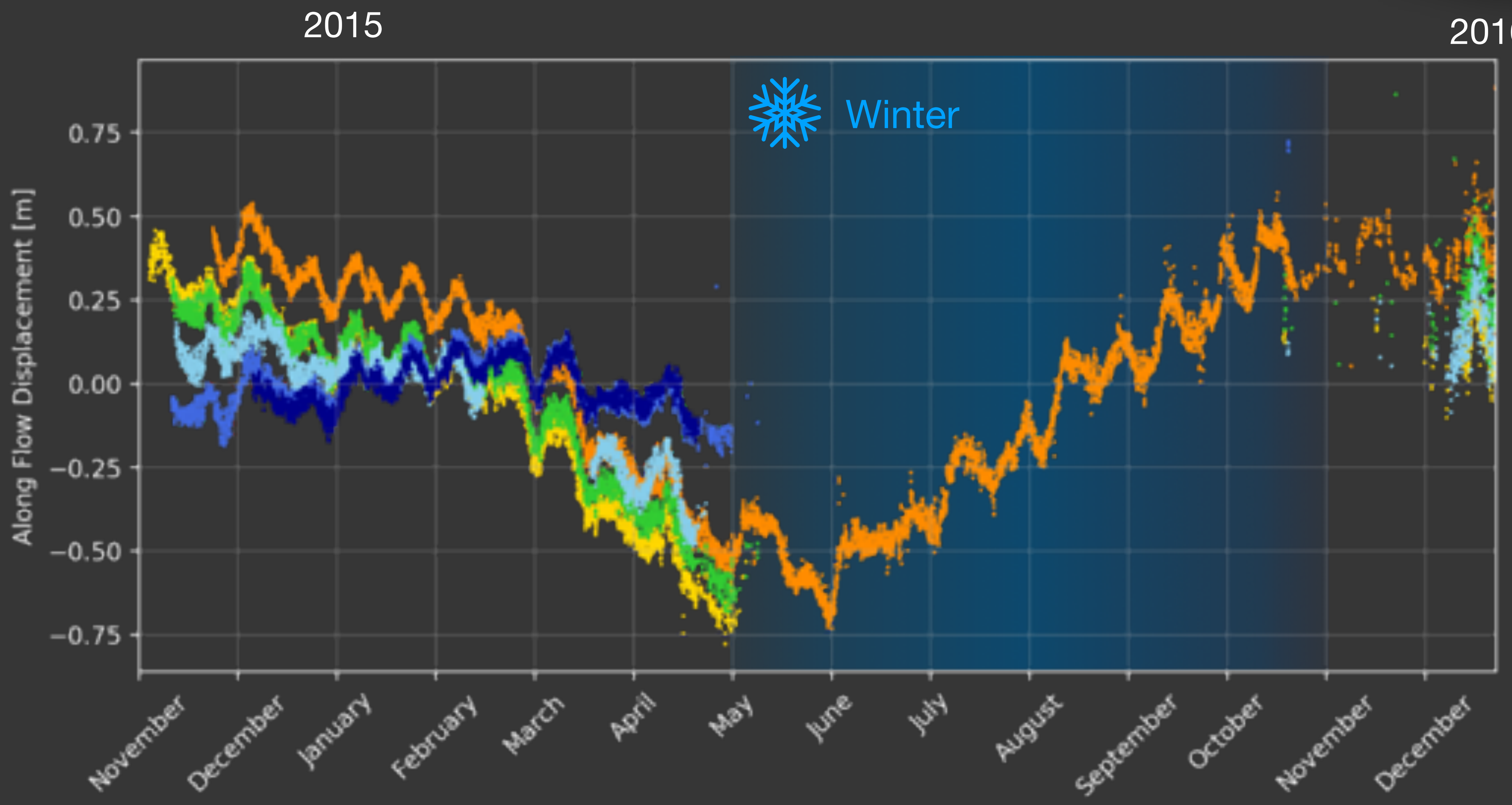
The exposure of this sensitive part of the ice shelf to surface ocean heat implies that the grounding line flux of the entire ice shelf may be modulated at seasonal to interannual timescales by surface water inflow. This process represents a frequently overlooked, but potentially important, factor in regional ice-shelf mass balance and should be considered in future assessments of ice shelf stability.

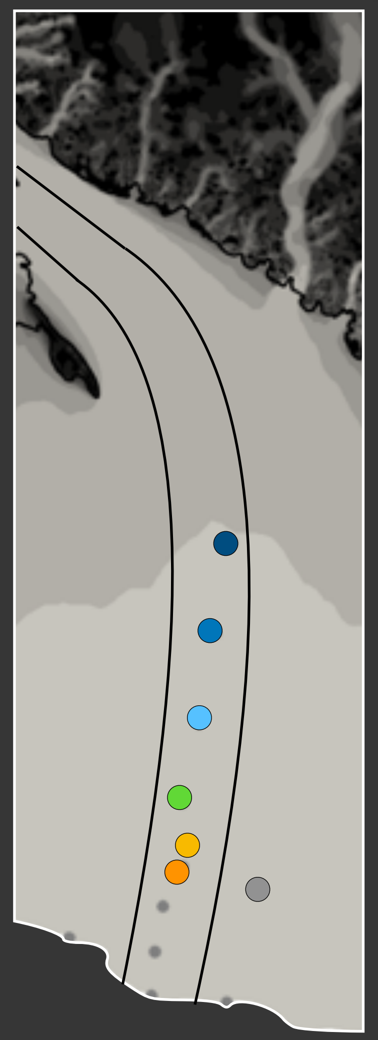




Introduction







What is the cause of this ?

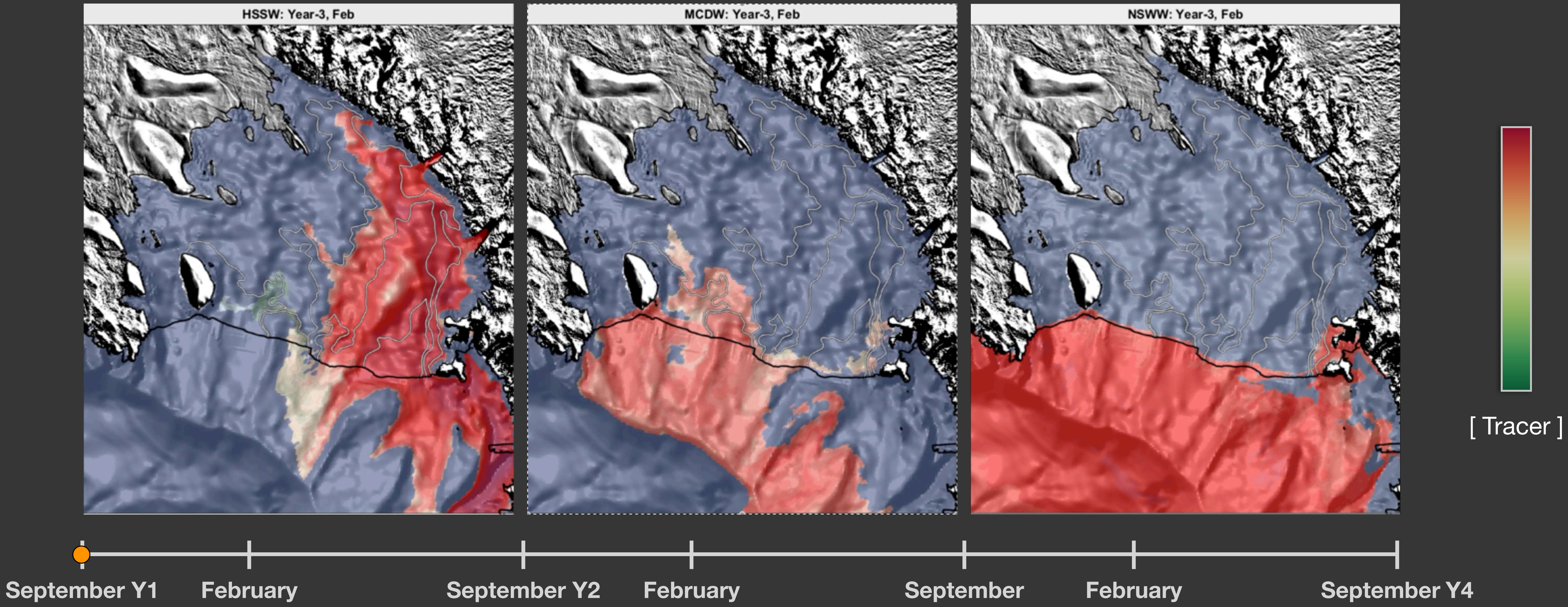
Melting ?

Introduction

High Salinity Shelf Water

Modified Circumpolar Deep Water

Antarctic Surface Warm Water



(Tinto et al., 2019)

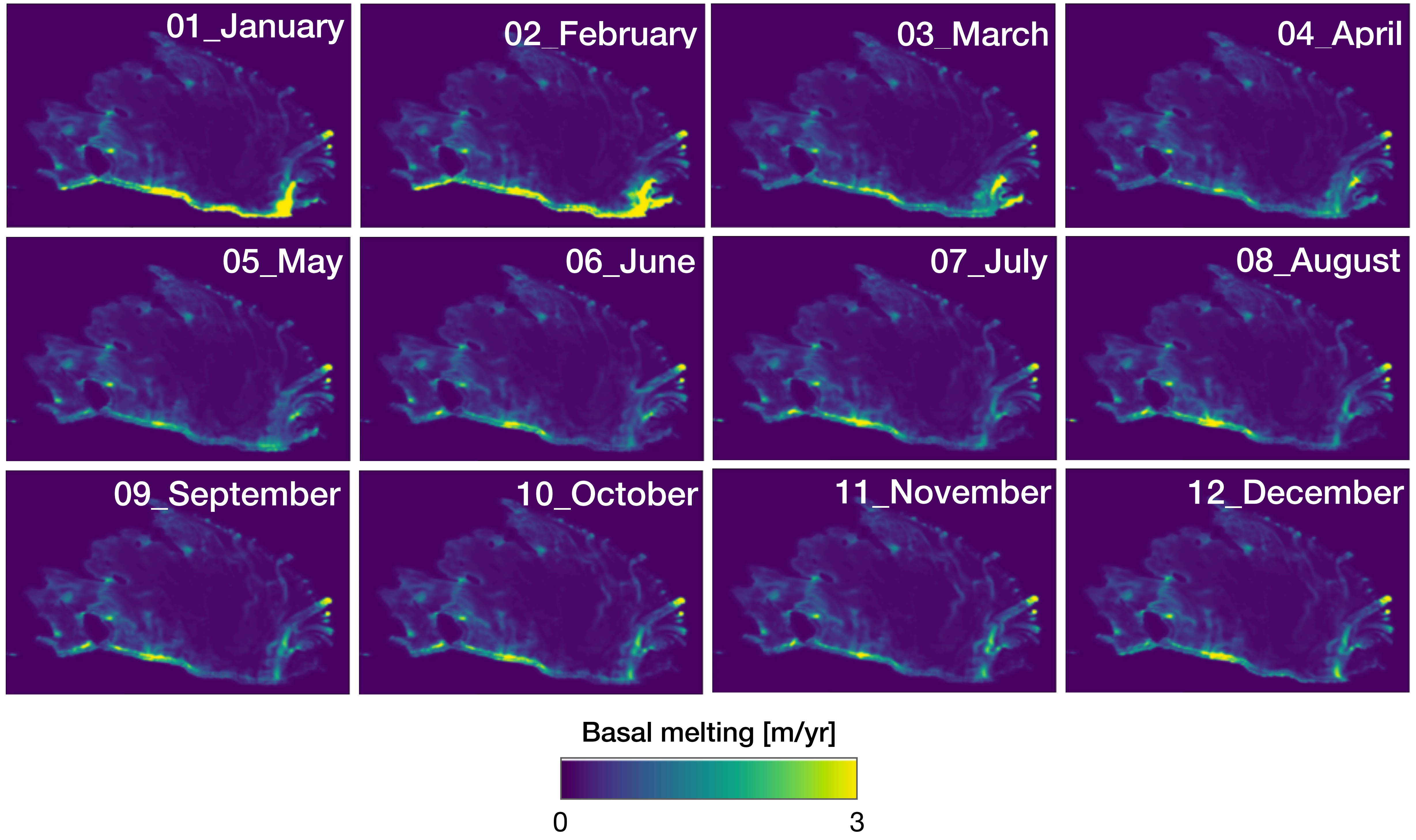
Seasonal melt forcing

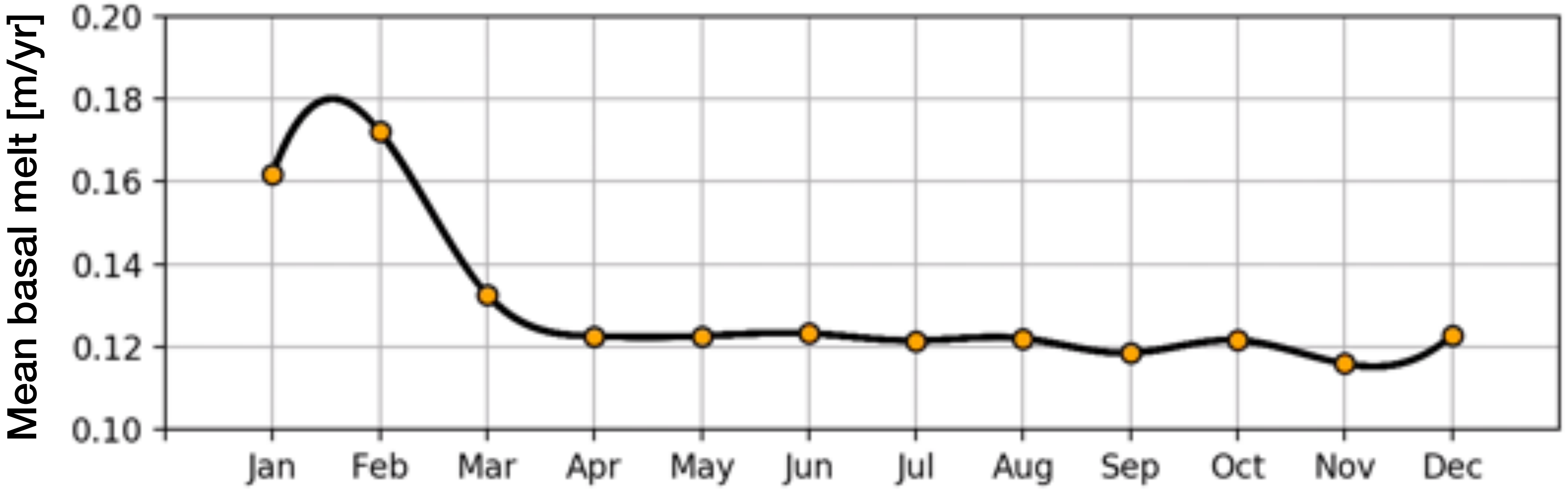
An important **increase in basal melting occurs over the summer period**, mostly in reason of an important basal melting event in Ross Island area

The rest of the year shows a more stable melting pattern with some small variations

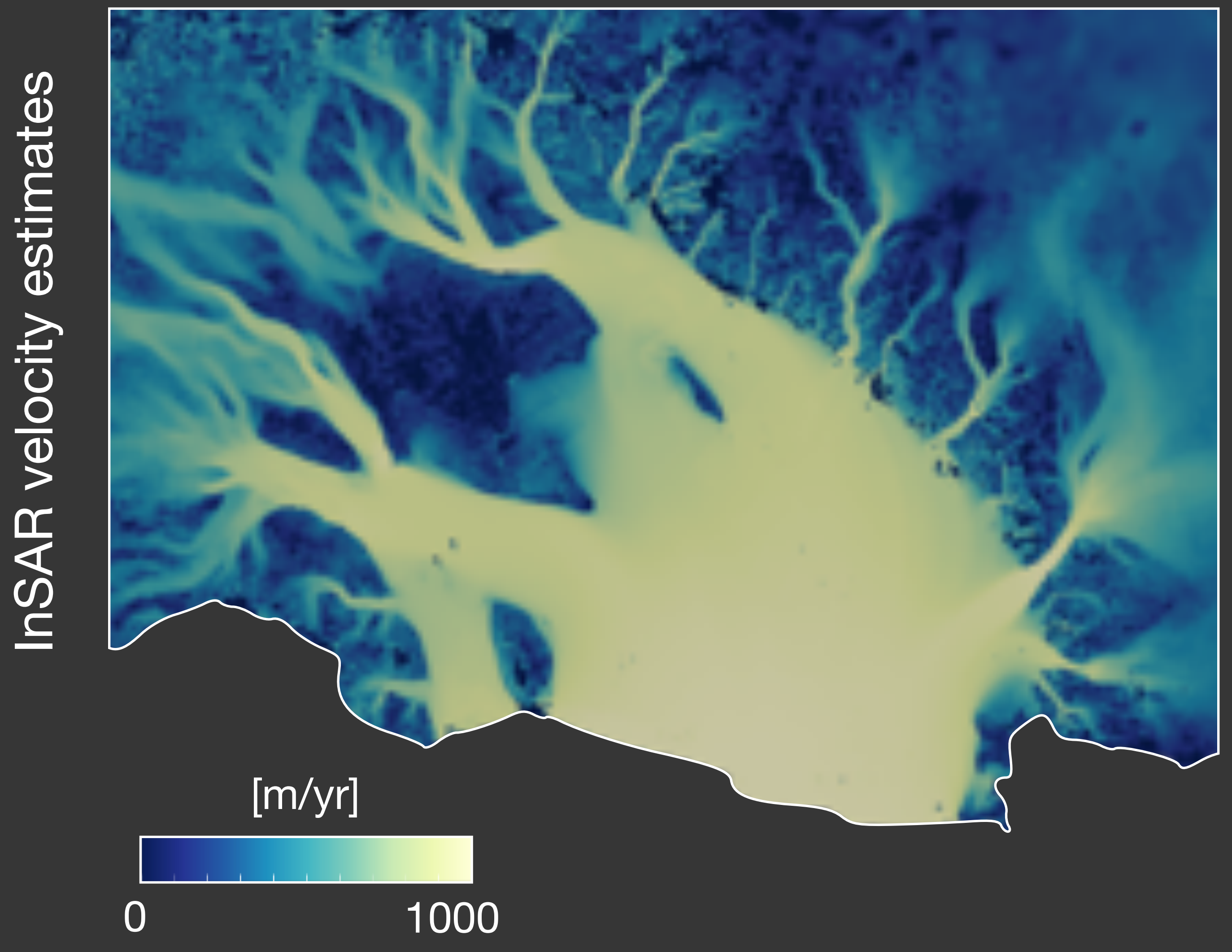
Each **basal melting snapshot** is taken on the first day of each month and is then used **to force the ice sheet model over a month period**.

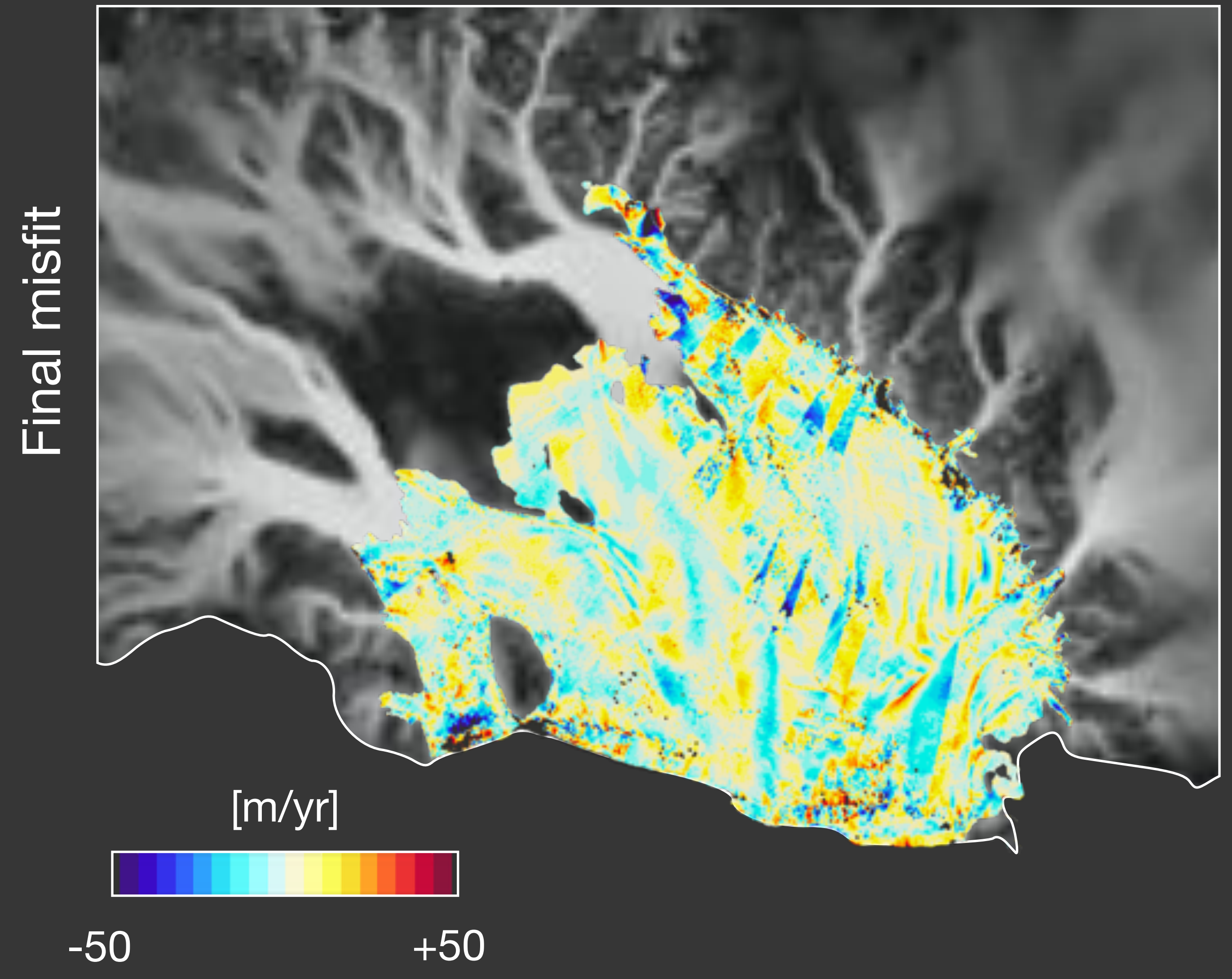
ROMS Model (S. Springer)

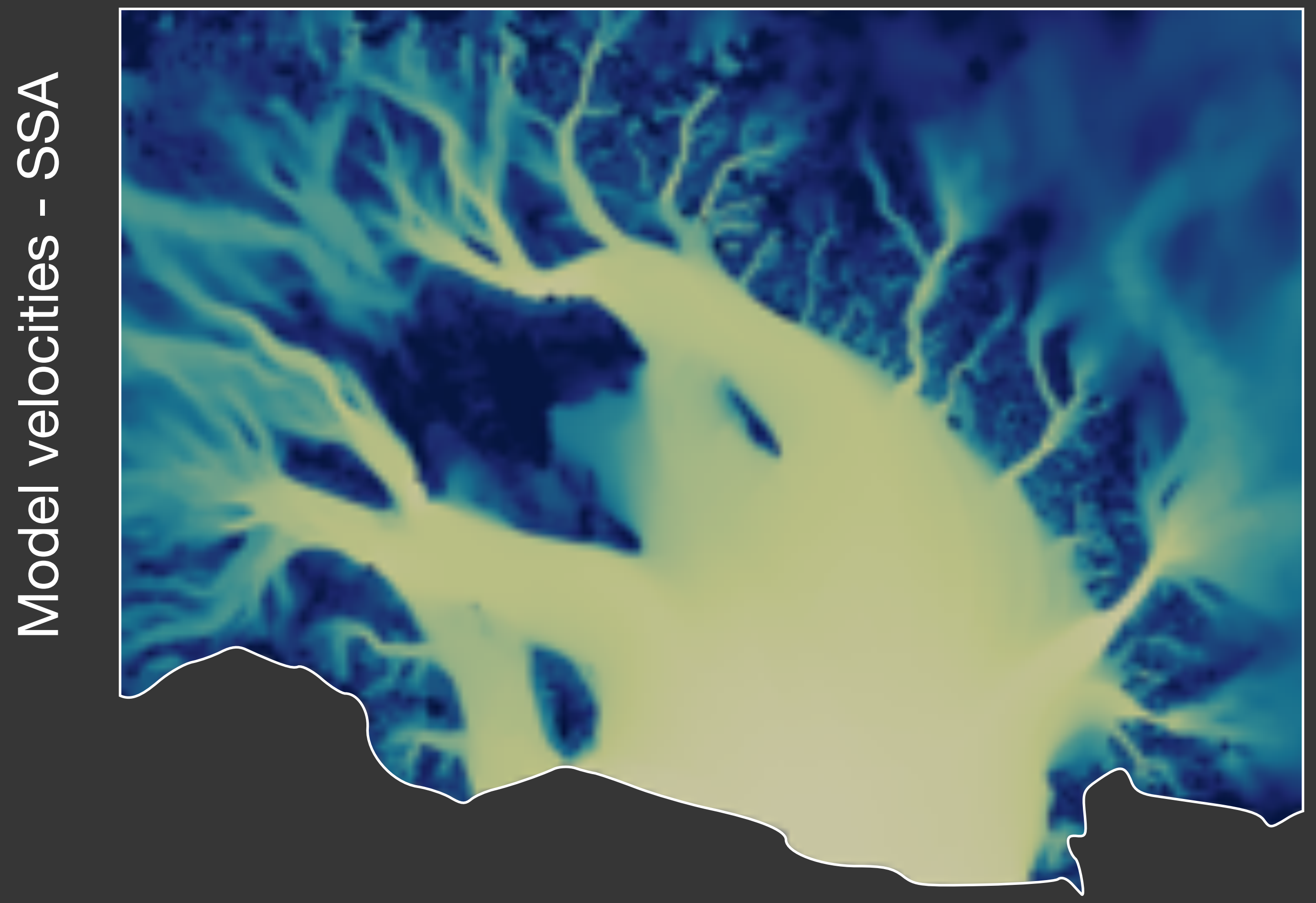


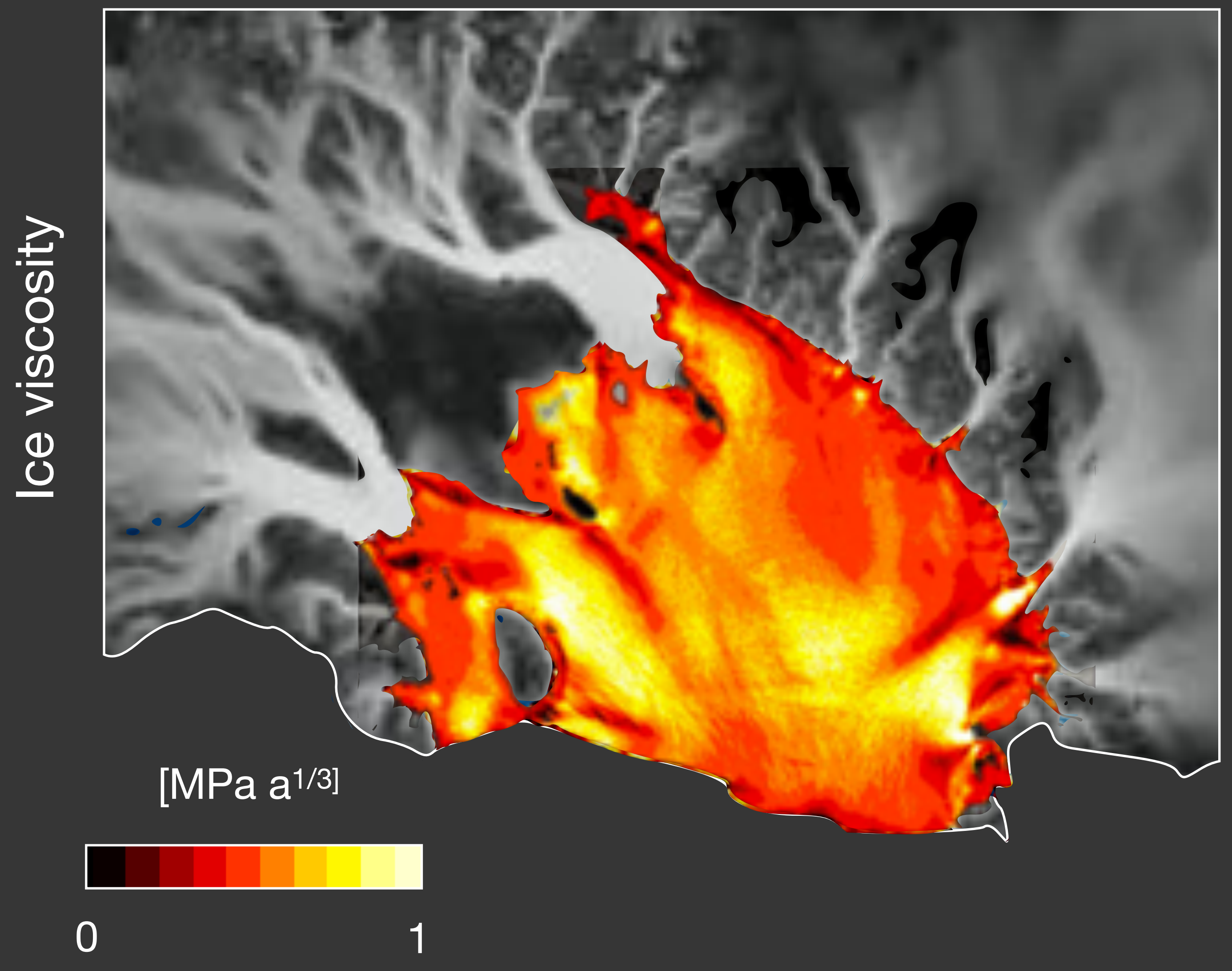


Model SSA and Initialization


InSAR velocity estimates


Final misfit


Model velocities - SSA


Ice viscosity

$$J = J_v + \lambda_{\frac{dh}{dt}} J_{\frac{dh}{dt}} + \lambda_\beta J_\beta + \lambda_{\eta_0} J_{\eta_0}$$

$$\min_{\beta,\eta_0} J$$

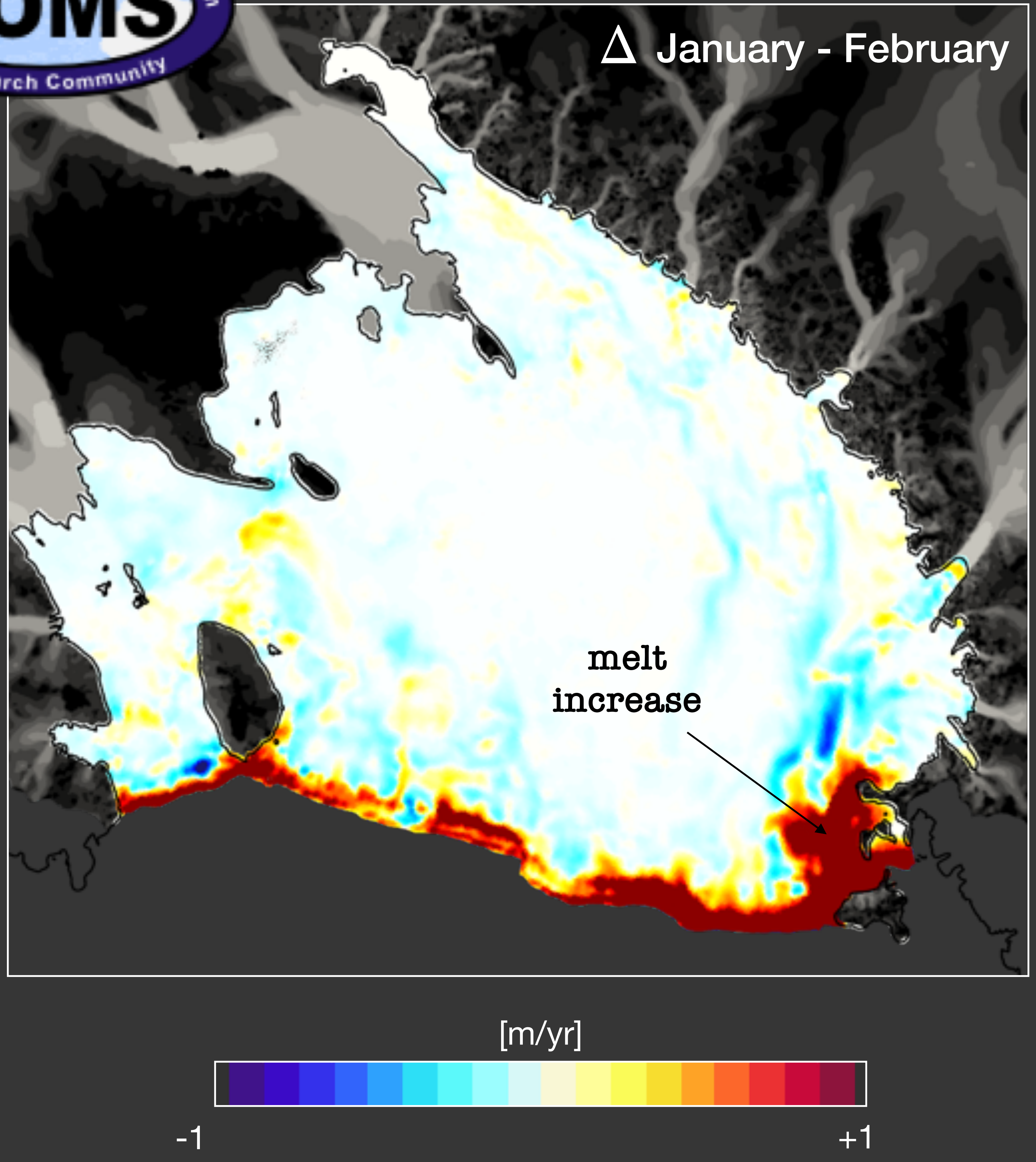
$$\downarrow$$

250-year relaxation

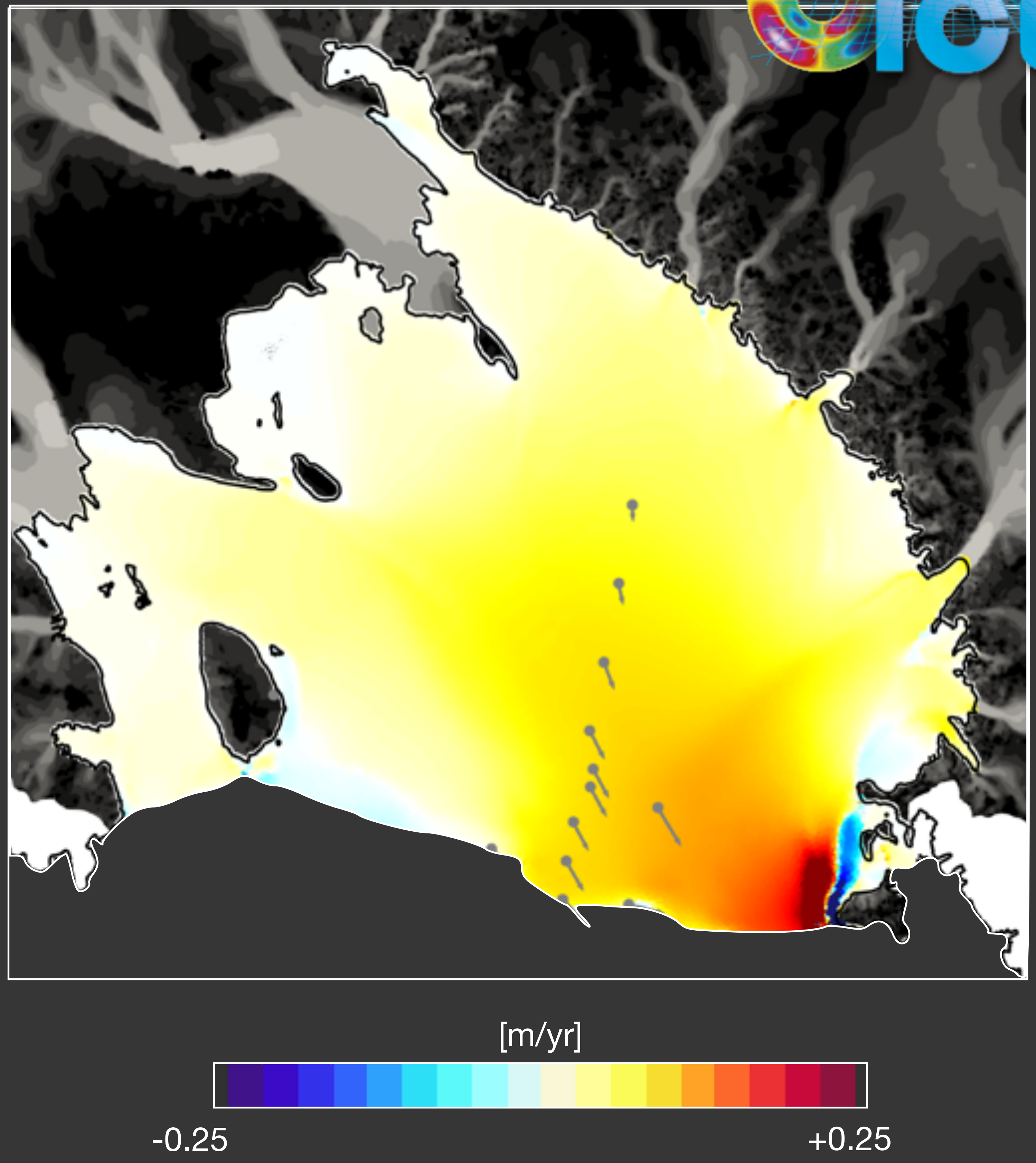
InSAR velocities (Rignot et al., 2016)
Geometry from Bedmap2 (Fretwell et al., 2013)
Surface mass balance from MAR (Agosta et al., 2019)

Ice Flow Response

Summer acceleration



Melt change

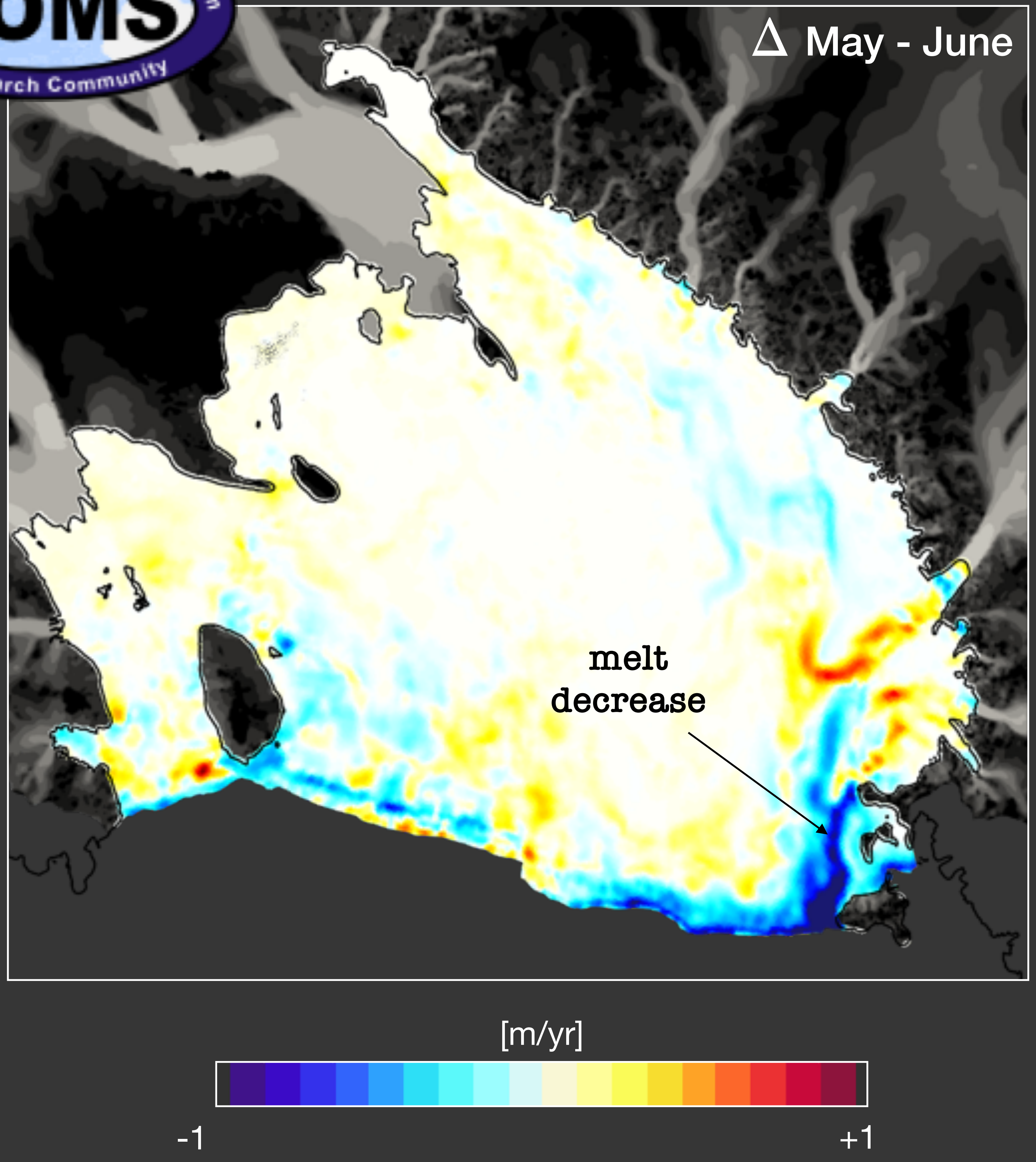


Velocity change

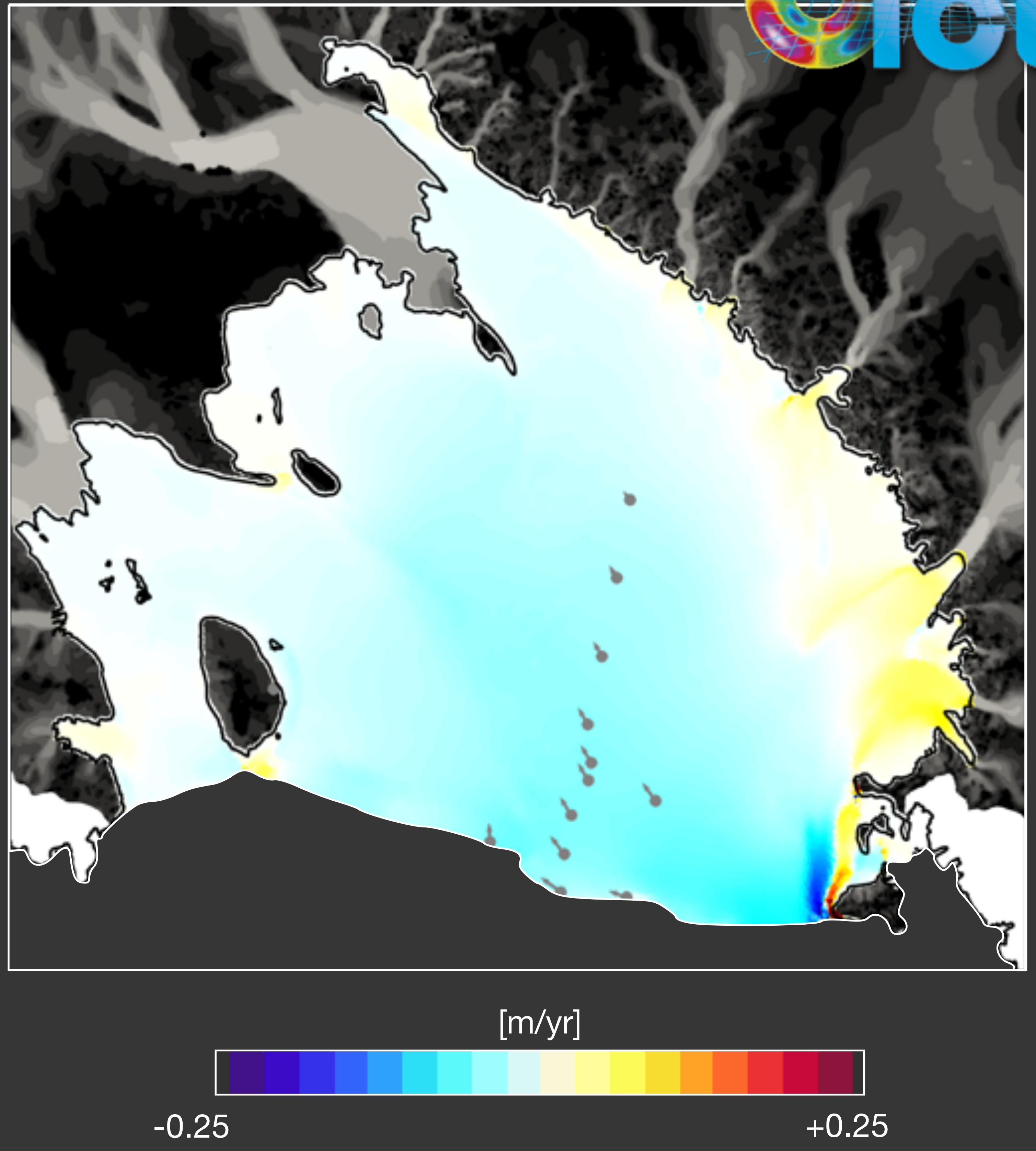
The model allows to compute monthly acceleration ...

Ice Flow Response

Winter deceleration



Melt change

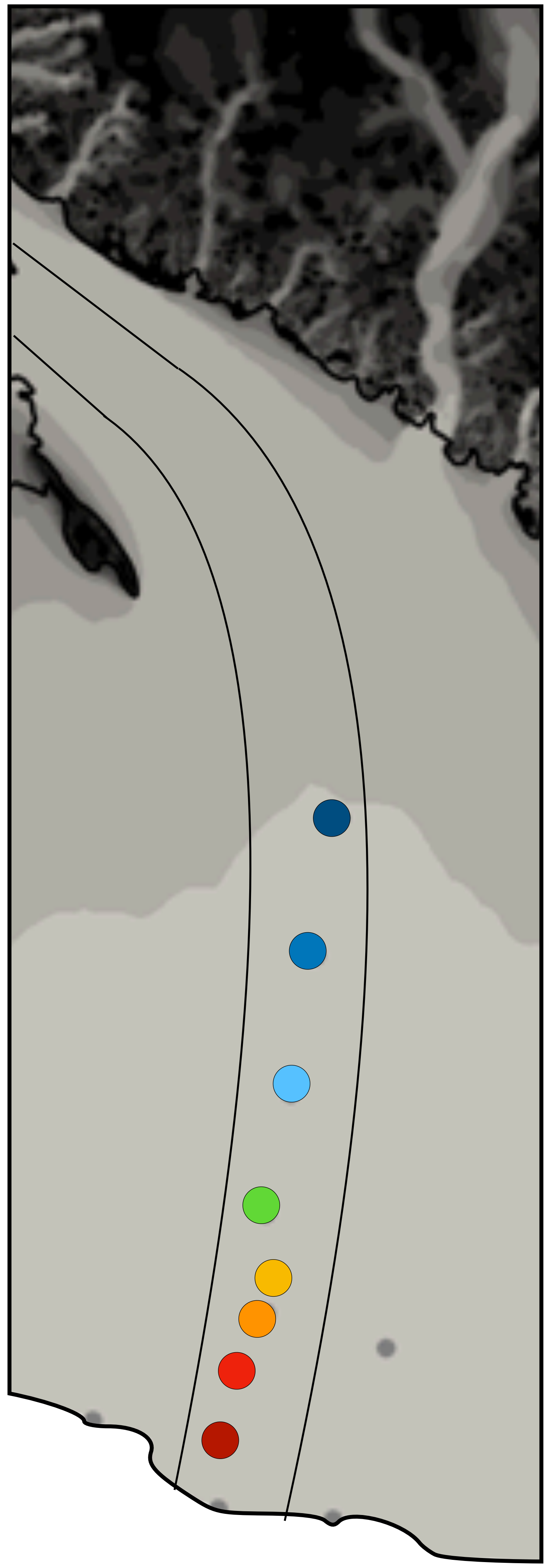


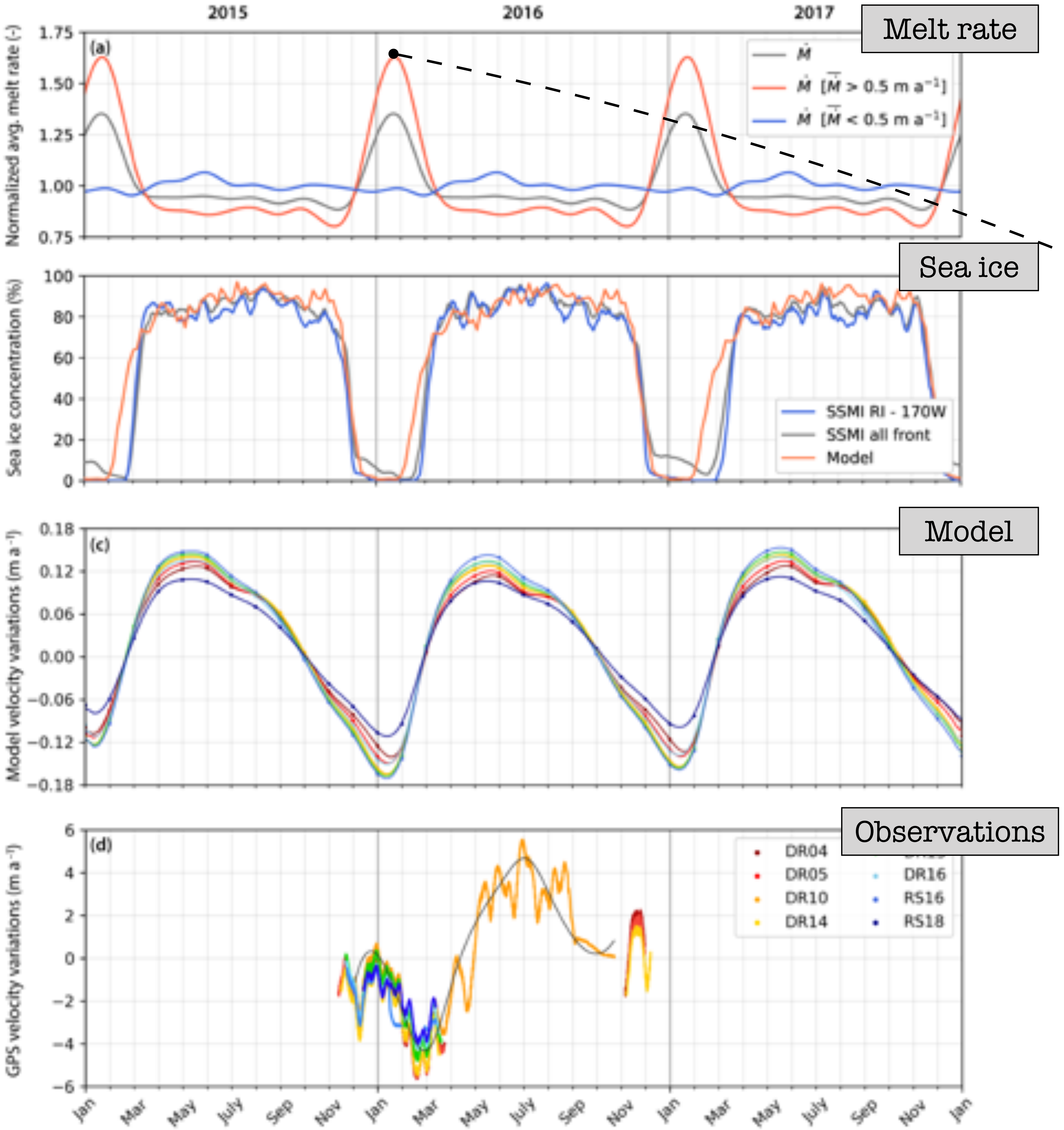
Velocity change

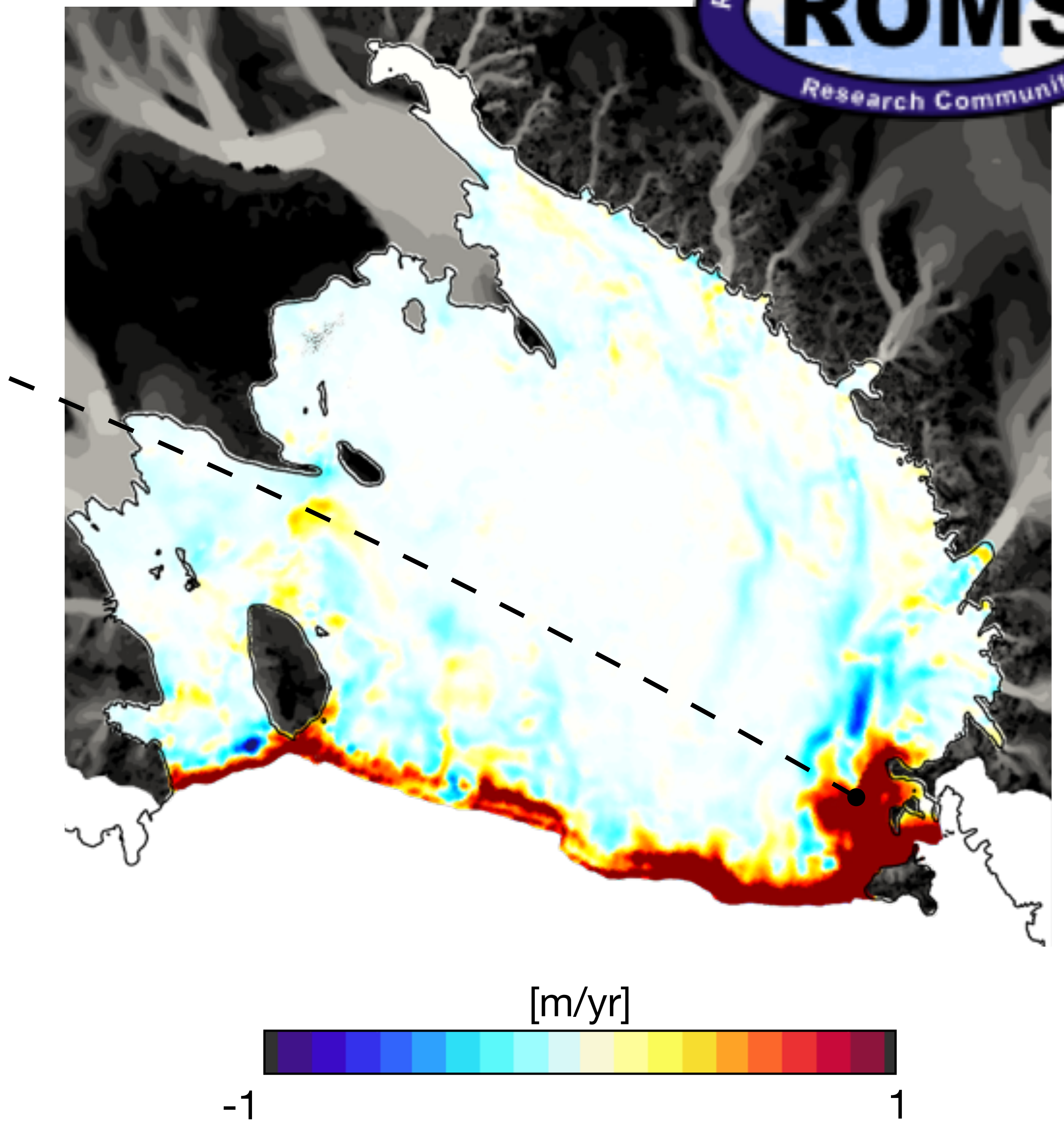
The model allows to compute monthly acceleration and deceleration

Ice Flow Response

Klein E*, Mosbeux C*, Bromirski PB, Padman L, Bock Y, Springer SR, and Fricker HA (2020).
Annual cycle in flow of Ross Ice Shelf, Antarctica: contribution of variable basal melting, JoG



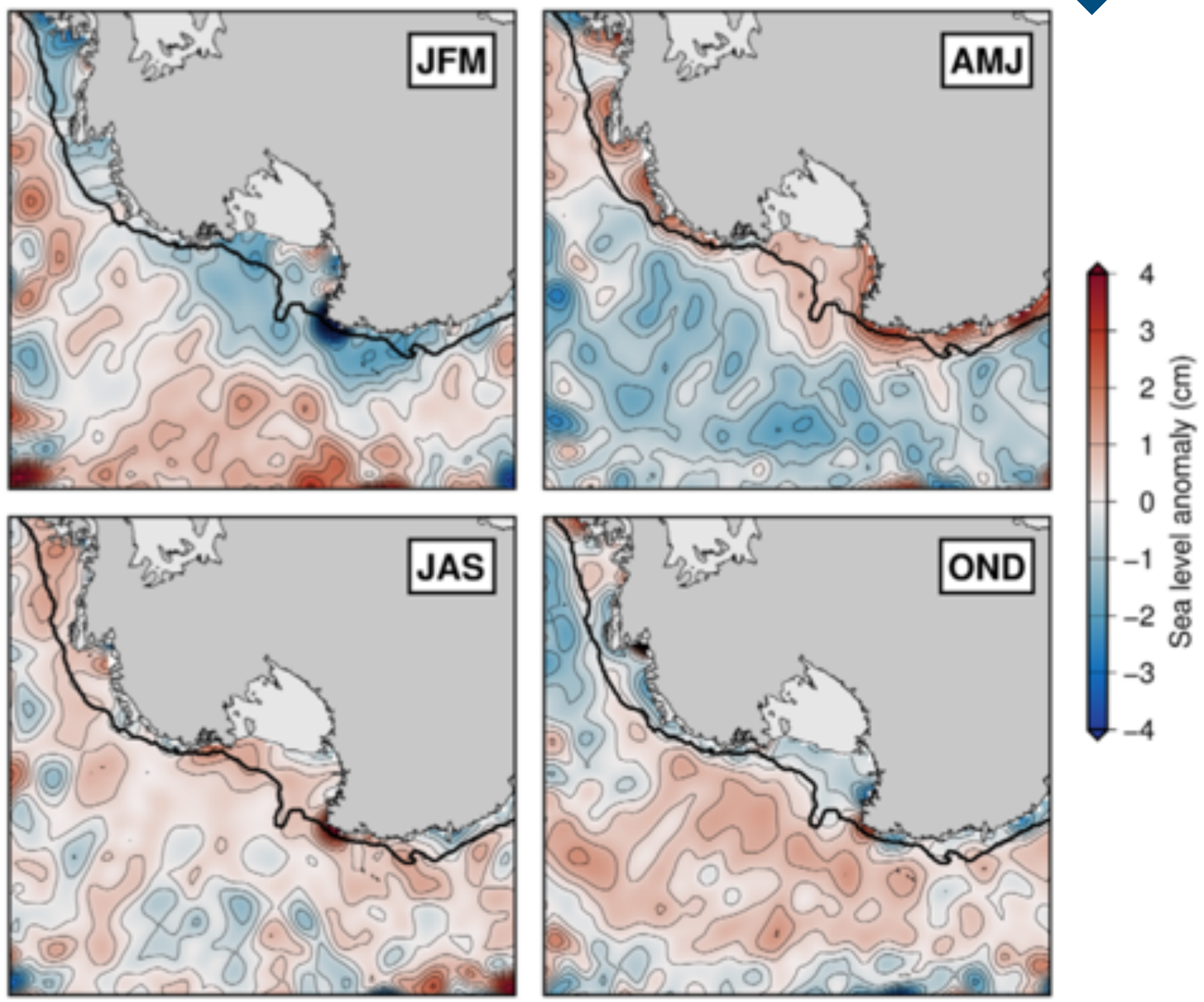




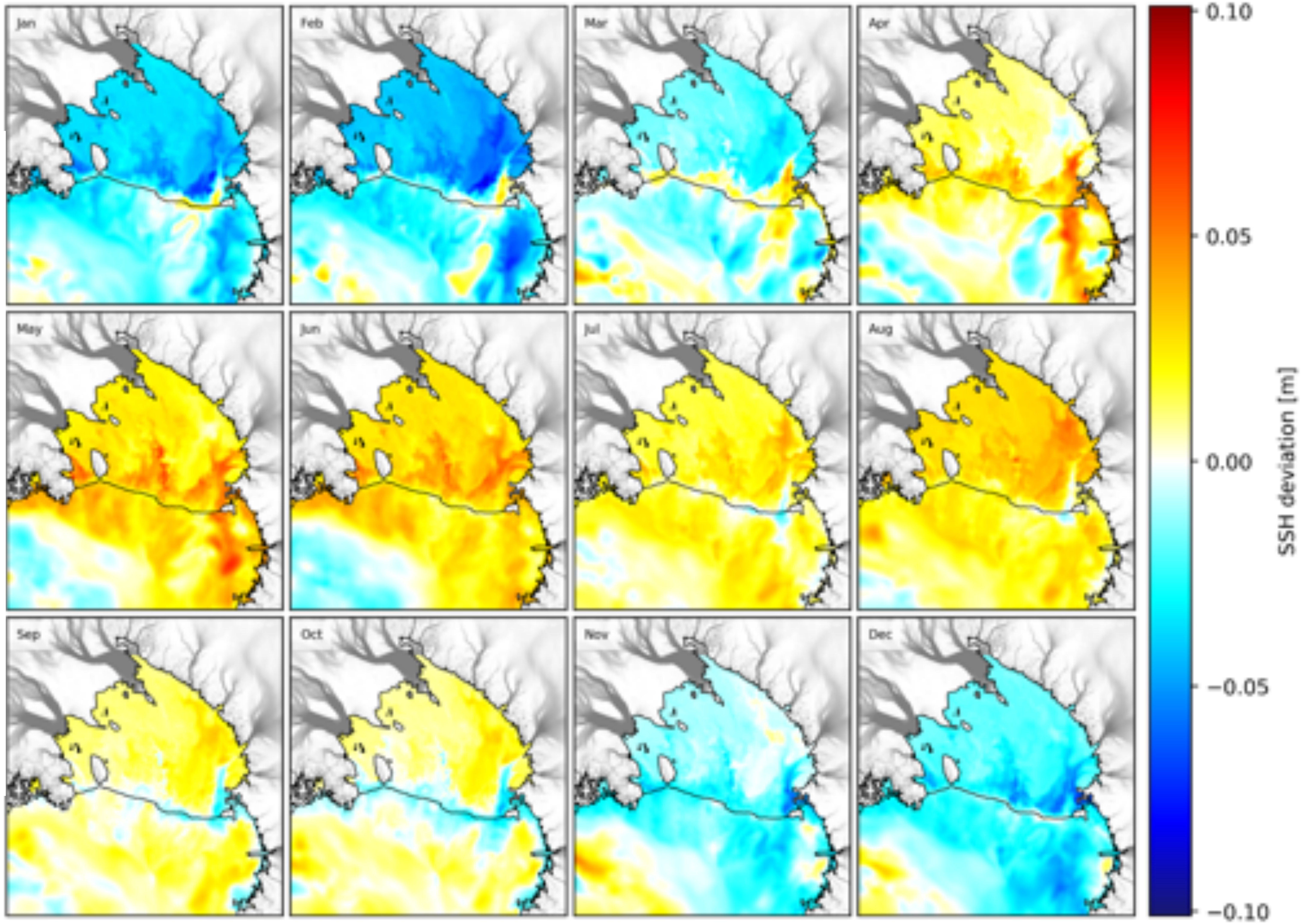
So melt is a factor but not enough... What could cause such seasonality?

(Klein et al., 2018)

SSH : Method



(Armitage et al., 2018)



(Model outputs)

SSH : Method

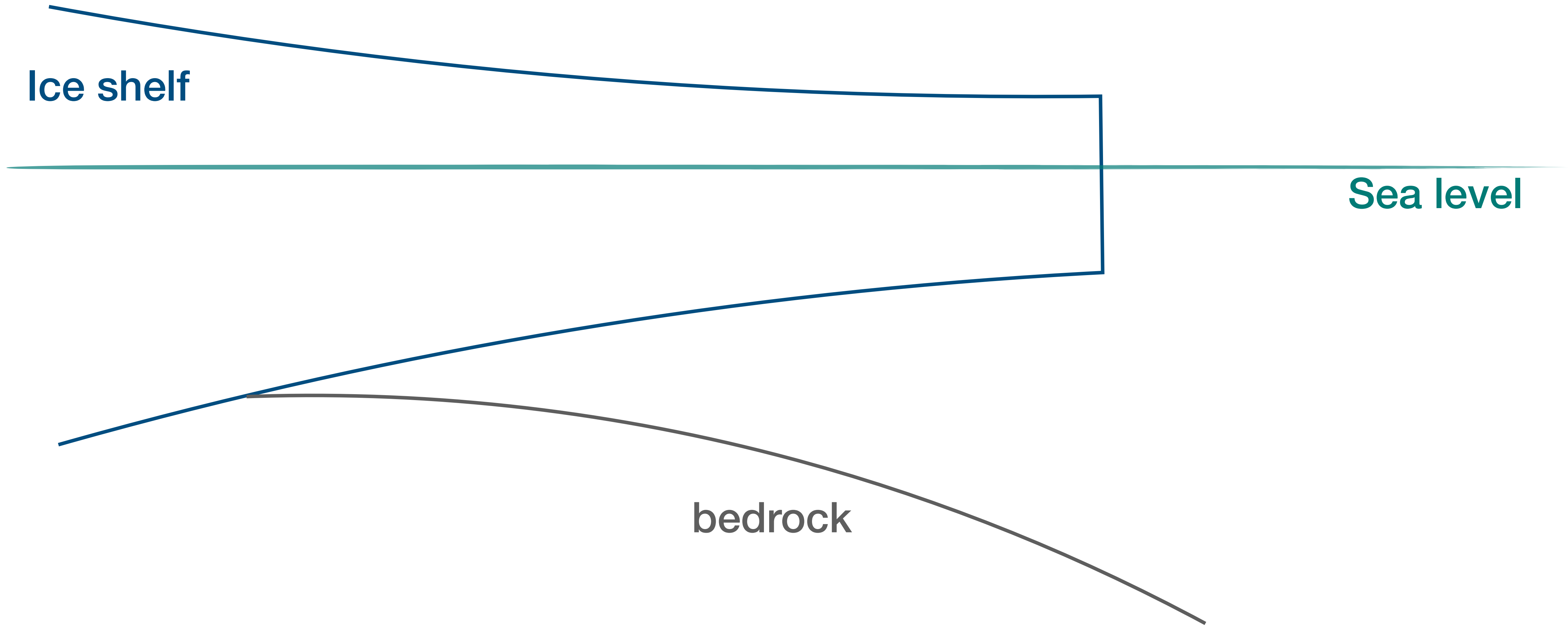
SSA

Non-linear differential

Driving stress

$$f(u) - \tau_b = \sigma_g$$

Basal drag



SSH : Method

SSA

Non-linear differential — Driving stress

$$\underbrace{f(u)}_{\text{Non-linear differential}} - \underbrace{\tau_b}_{\text{Basal drag}} = \underbrace{\sigma_g}_{\text{Driving stress}}$$

Basal drag

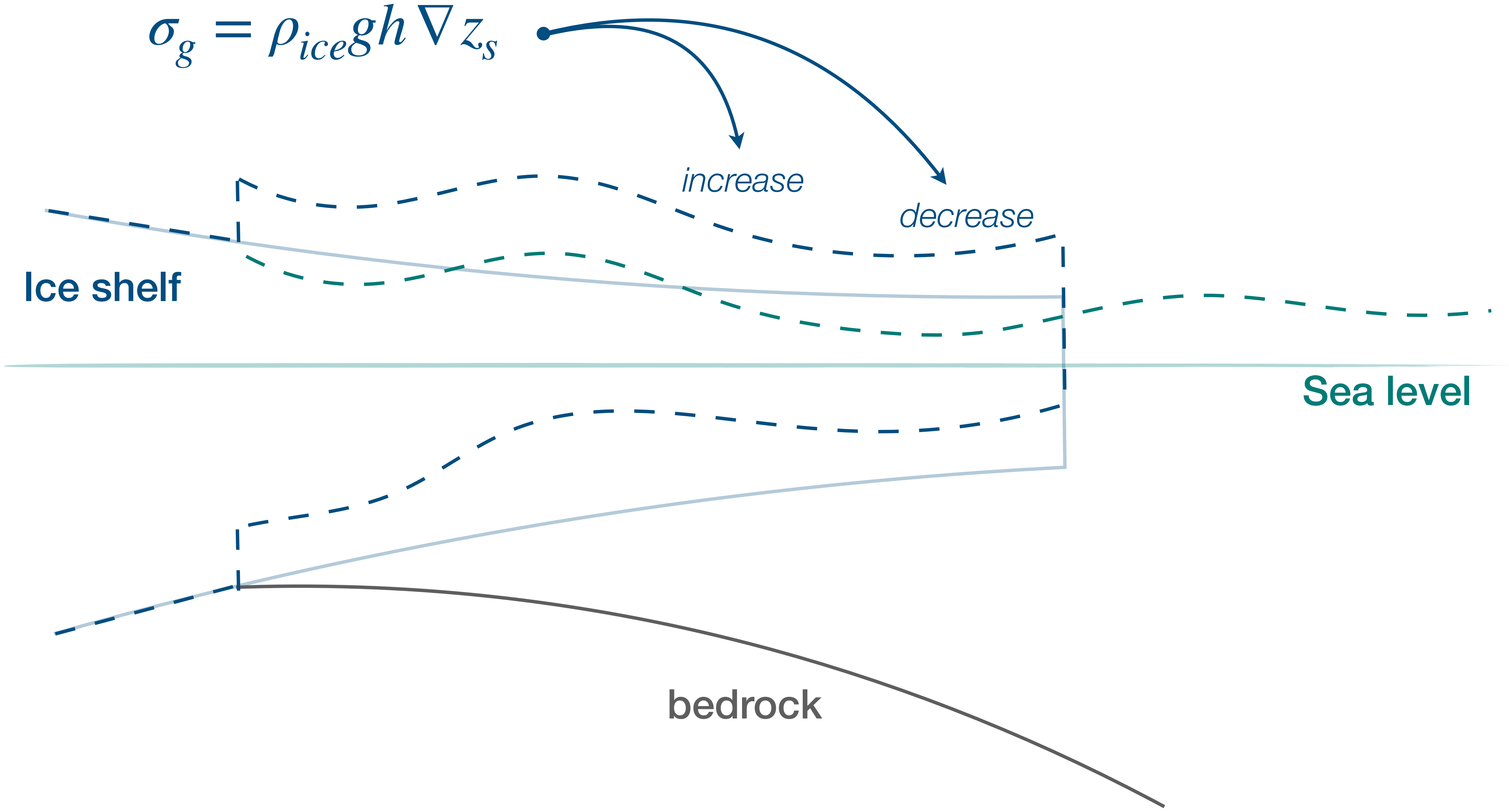
Sea surface height evolves over the year with an amplitude (m):

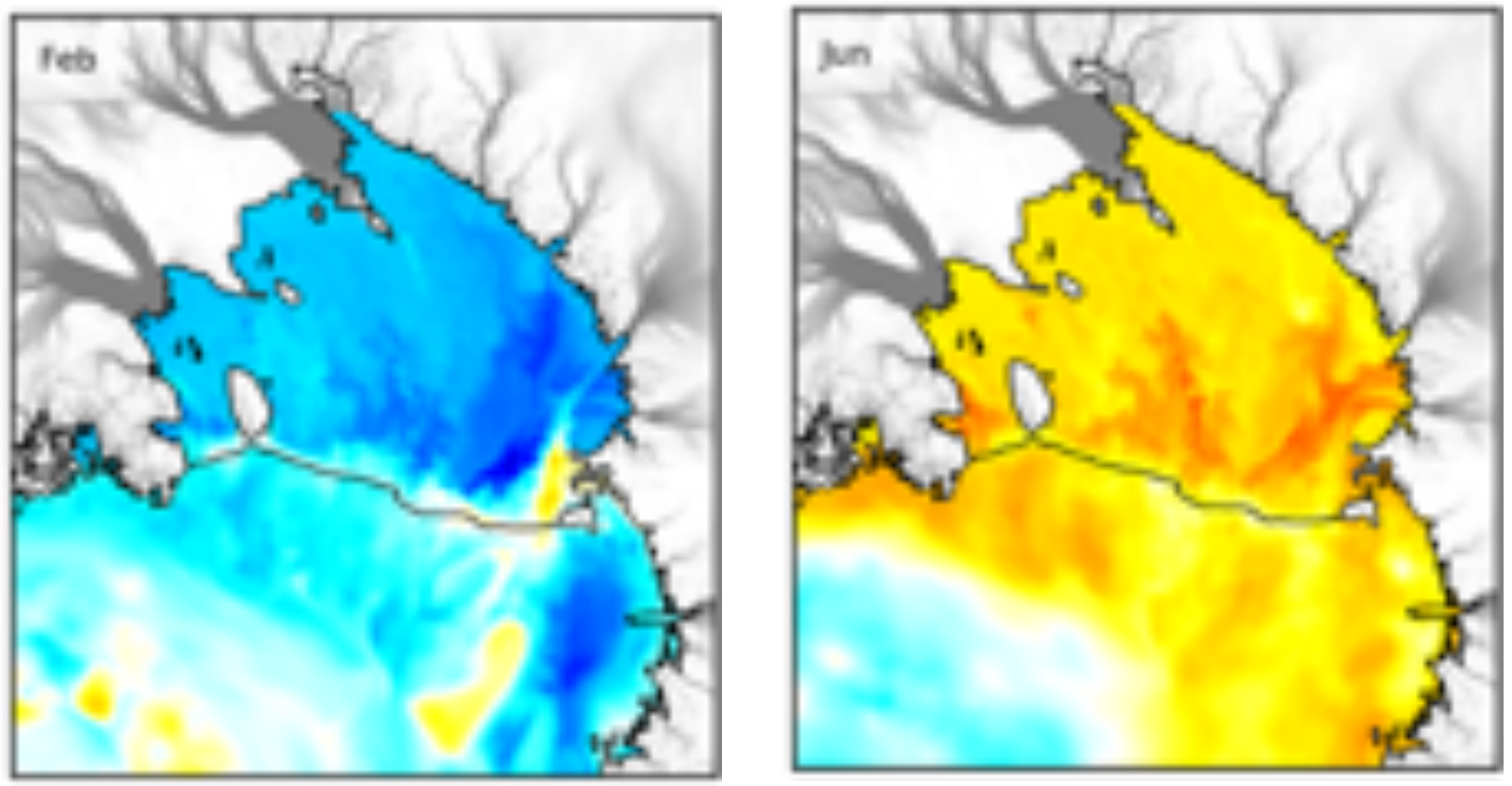
$$\overline{SSH} \pm \Delta SSH \sim \overline{SSH} \pm 0.1$$

It changes…

1. Surface gradient
   - winter — higher front — slowdown
   - summer — lower front — speedup

$$\sigma_g = \rho_{ice} g h \nabla z_s$$





SSH : Surface gradient and driving stress change

SSA

Non-linear differential Driving stress

$$f(u) - \tau_b = \sigma_g$$

Basal drag

Sea surface height evolves over the year with an amplitude (m):

$$\overline{SSH} \pm \Delta SSH \sim \overline{SSH} \pm 0.1$$

It changes...

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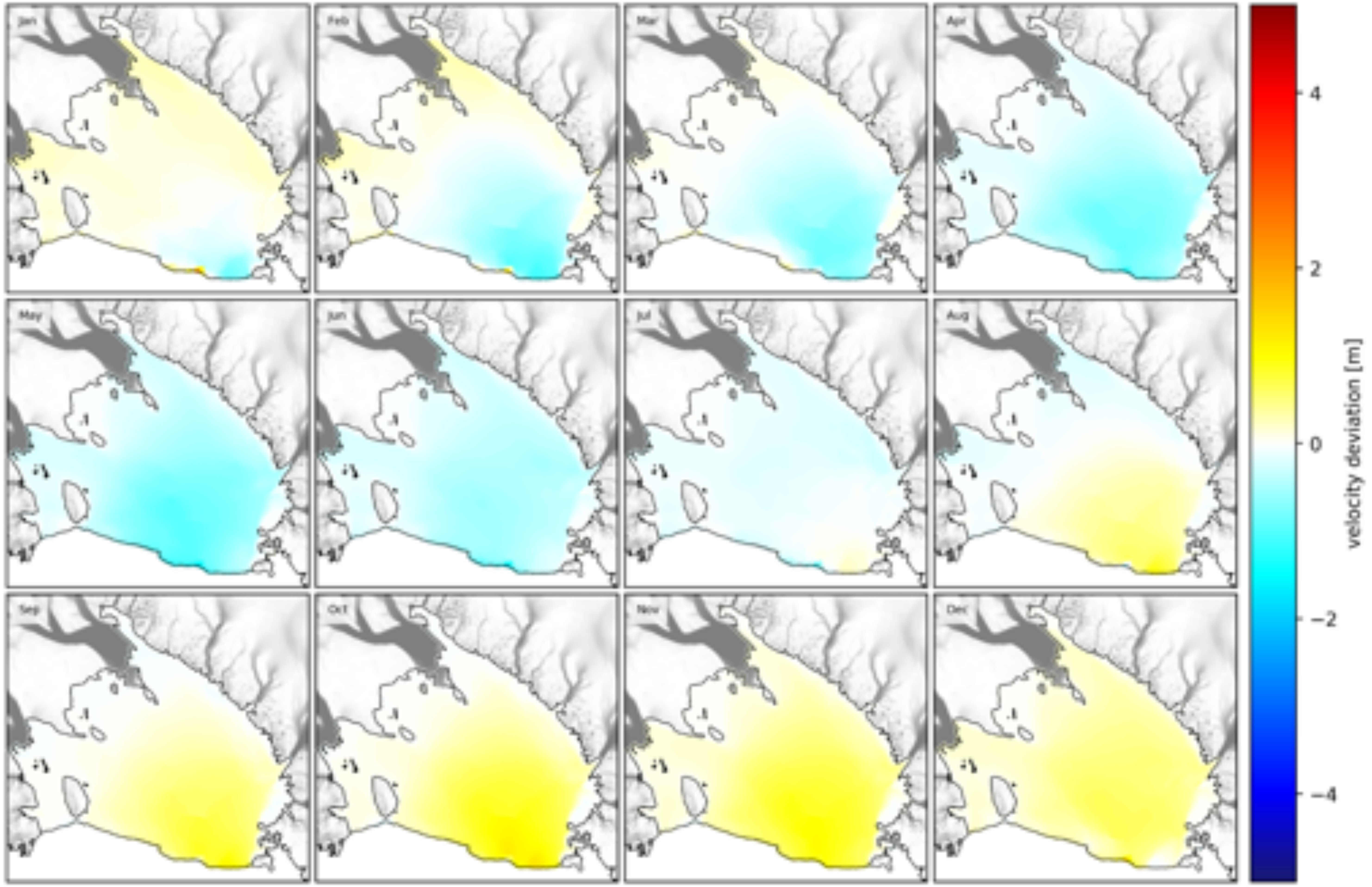
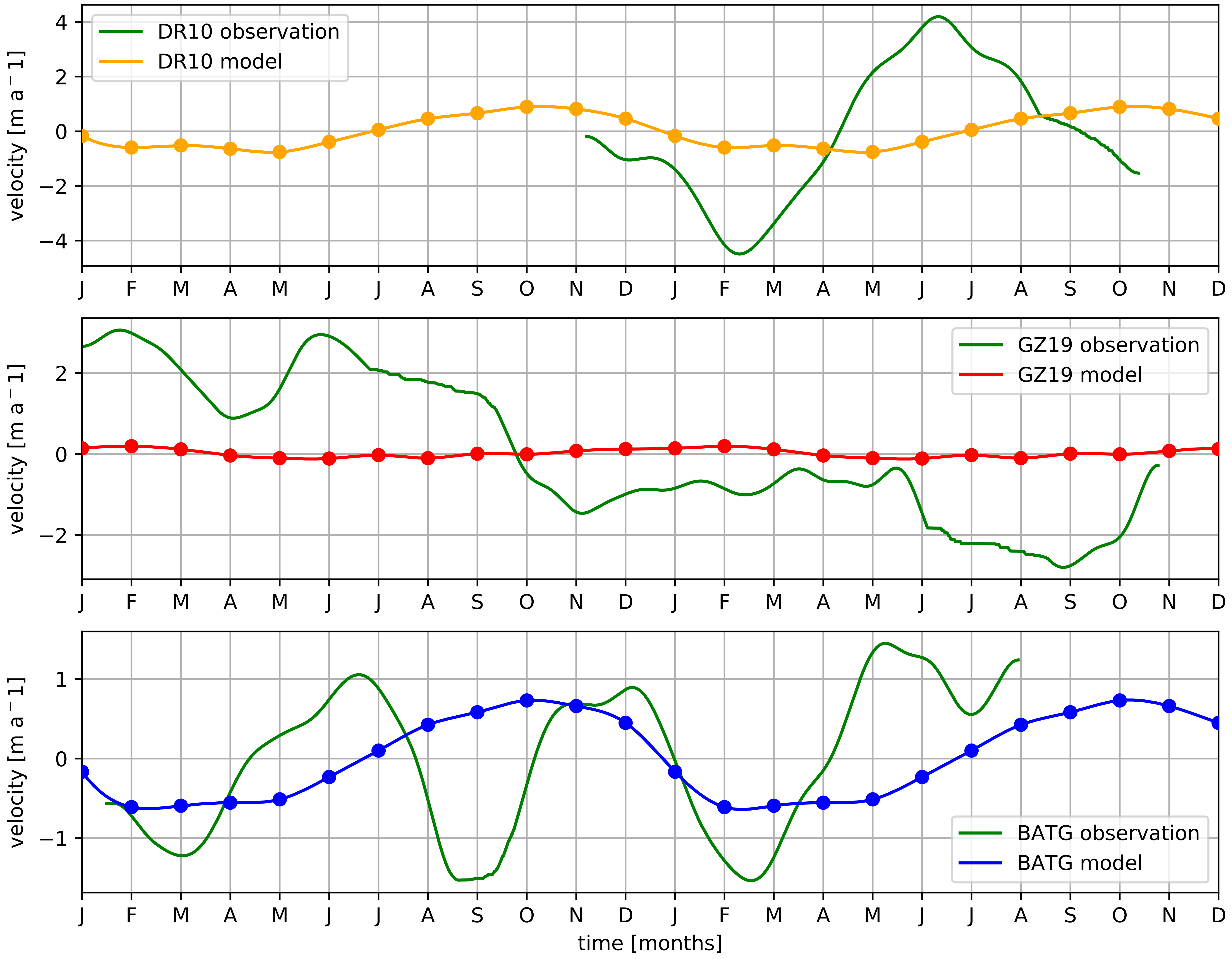
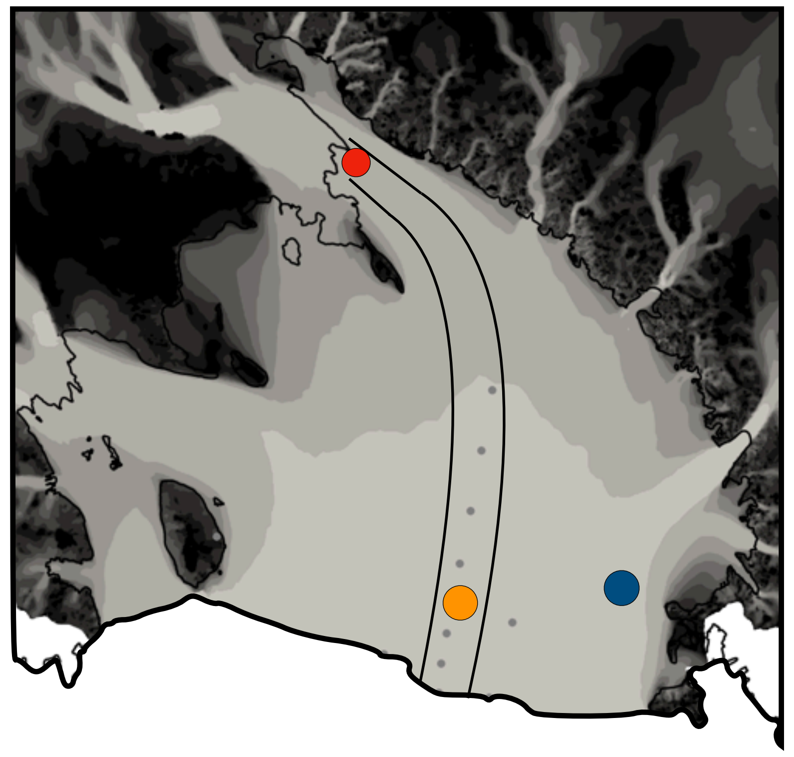


SSH : Surface gradient and driving stress change





The amplitude is better than with melting but not the phase

To be precise…
It is not in phase

SSH : Method

SSA

Non-linear differential   Driving stress

$$f(u) - \tau_b = \sigma_g$$

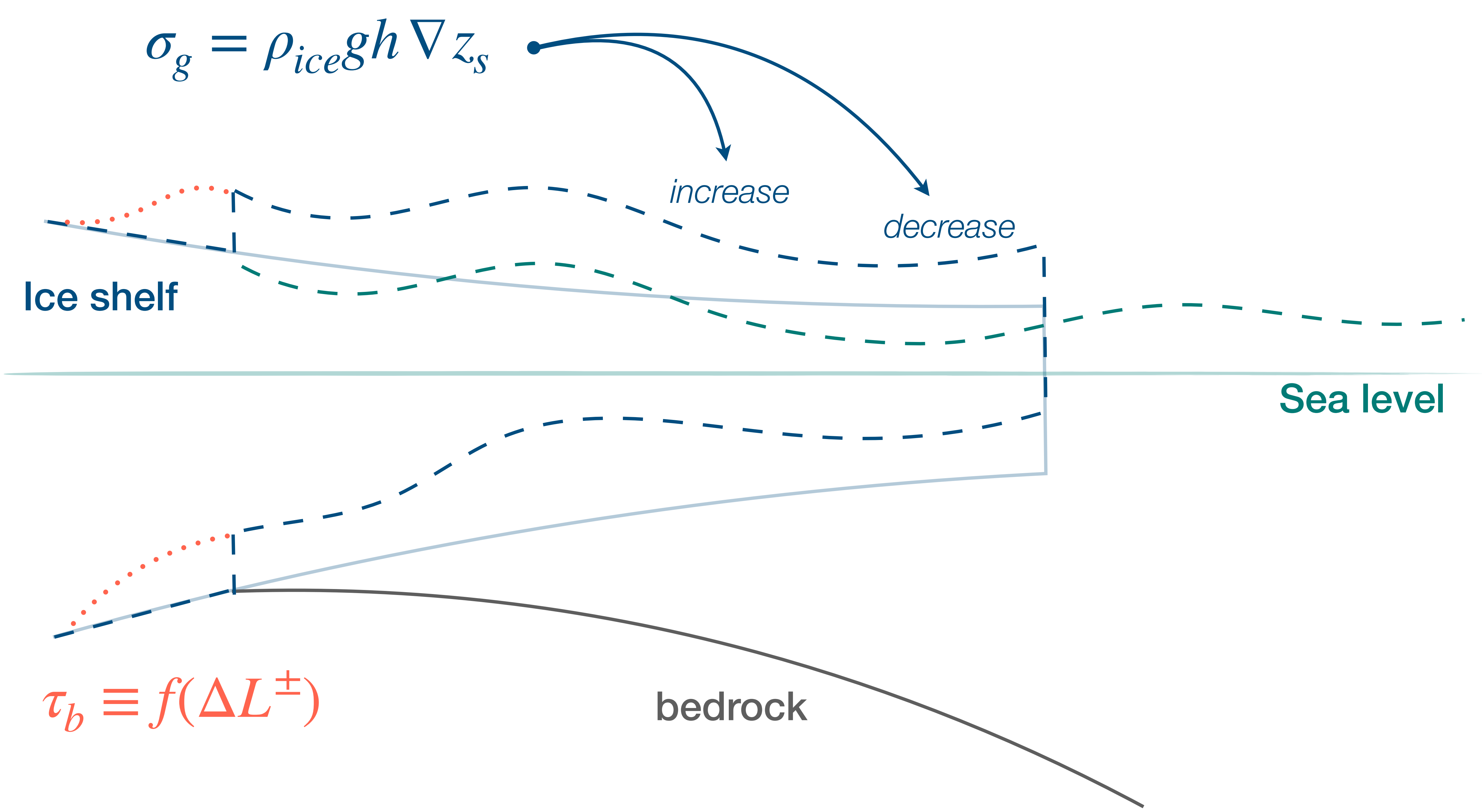
Basal drag

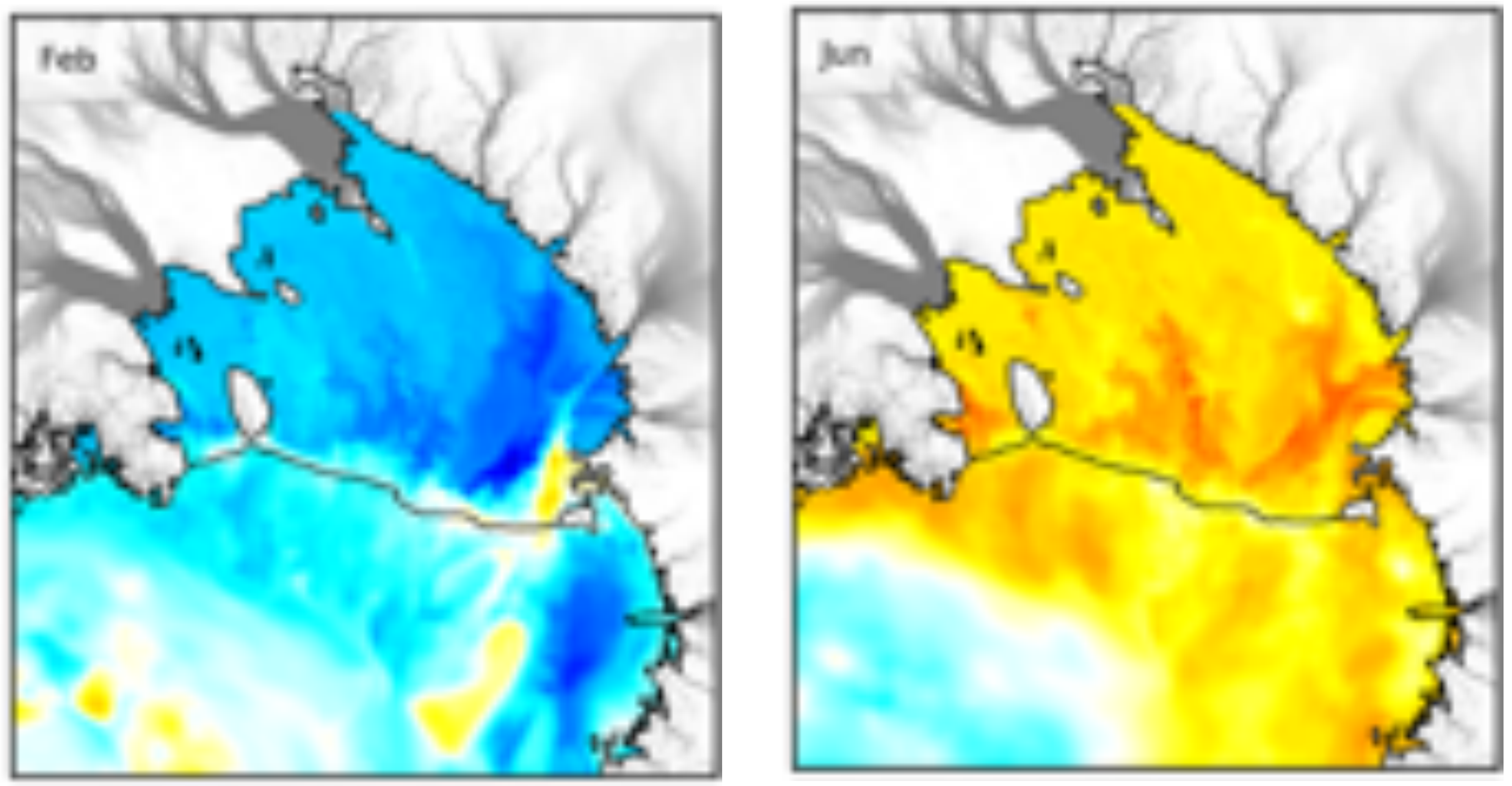
Sea surface height evolves over the year with an amplitude (m):

$$\overline{SSH} \pm \Delta SSH = \overline{SSH} \pm 0.1$$

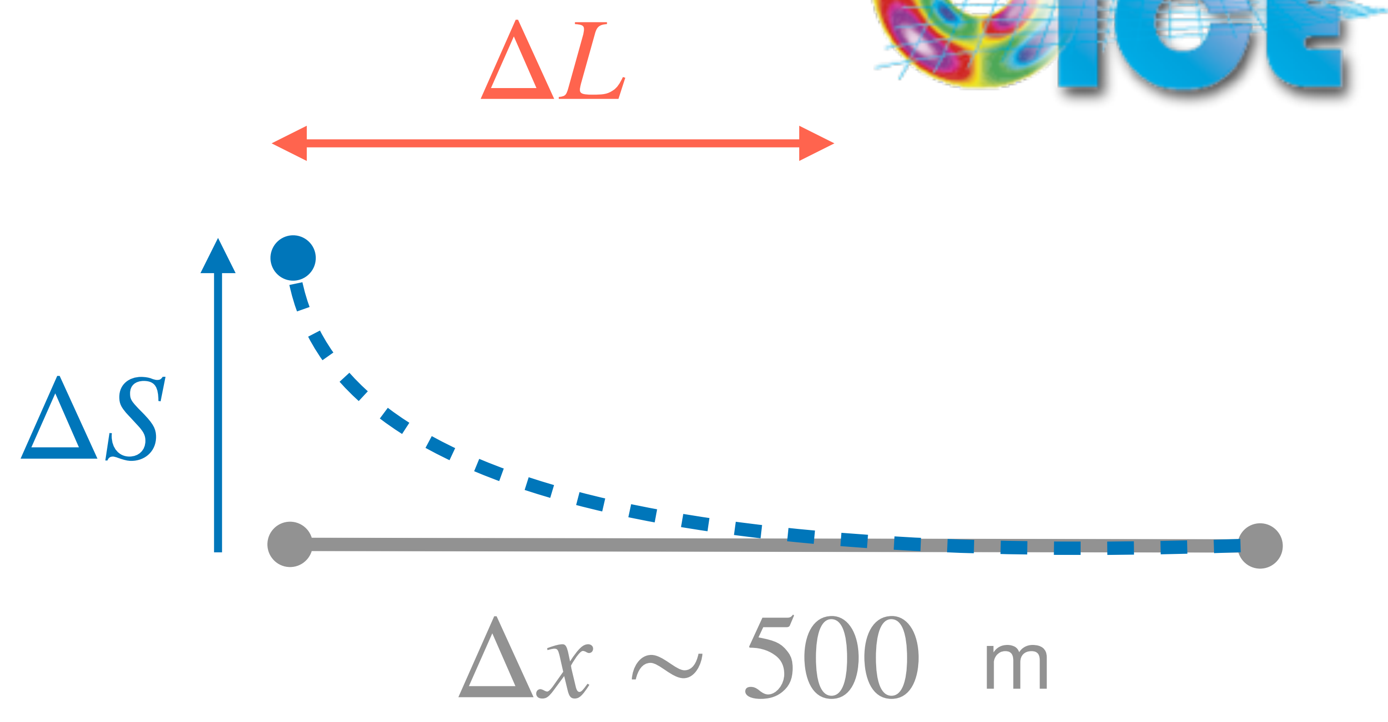
It changes…

1. Surface gradient
   - summer — higher front — slowdown
   - winter— lower front — speedup
2. Grounding line migration
   - summer — ΔL^- — slowdown
   - winter — ΔL^+ — speedup





SSH: Sensitivity to GL migration



Grounding line migration (Tsai and Gudmundsson, 2015)

$$\Delta L^{\pm} = \frac{\Delta S^{\pm}}{\gamma^{\pm}}$$

with

$$\gamma^{+} = \beta + \frac{\rho_i}{\rho_w}(\alpha - \beta) \quad \text{and} \quad \gamma^{-} = \frac{\gamma^{+}}{1 - \rho_i/\rho_w}$$

and α the surface and β the bed slope.

Which give us about:

$$\Delta L^{\pm}_{max} = \frac{\Delta S^{\pm}}{\gamma^{\pm}} \simeq \frac{0.1}{\gamma^{\pm}} \simeq 100^{+}/15^{-} \text{ m}$$

Solve for the change in β at the GL

$$F_i = \tau_i \, \Delta x = \beta_i u_i \, \Delta x$$

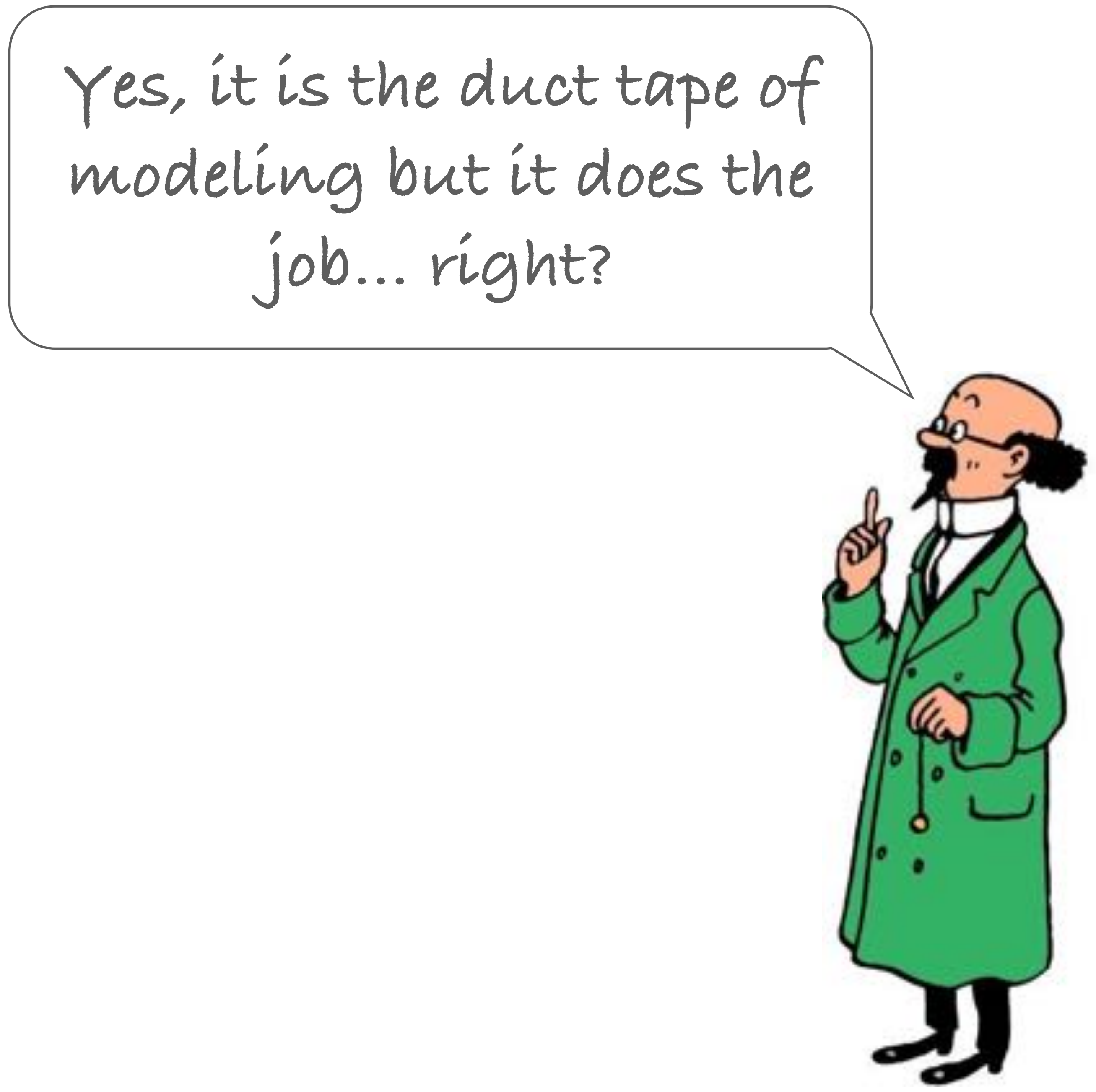
$$F_f = \tau_i \, (\Delta x - \Delta L) = \beta_i u_i \, (\Delta x - \Delta L)$$

Assuming that

$$F_f = \tau_f \Delta x = \beta_f u_f \Delta x \quad \text{and} \quad \frac{u_i}{u_f} \sim 1$$

Gives us....

$$\beta_f = \frac{\Delta x - \Delta L}{\Delta x} \beta_i \ \sim [0.9 - 1.1] \times \beta_i$$



SSH: Driving stress and GL migration

SSA

Non-linear differential Driving stress

$$f(u) - \tau_b = \sigma_g$$

Basal drag

Sea surface height evolves over the year with an amplitude (m):

$$\overline{SSH} \pm \Delta SSH = \overline{SSH} \pm 0.1$$

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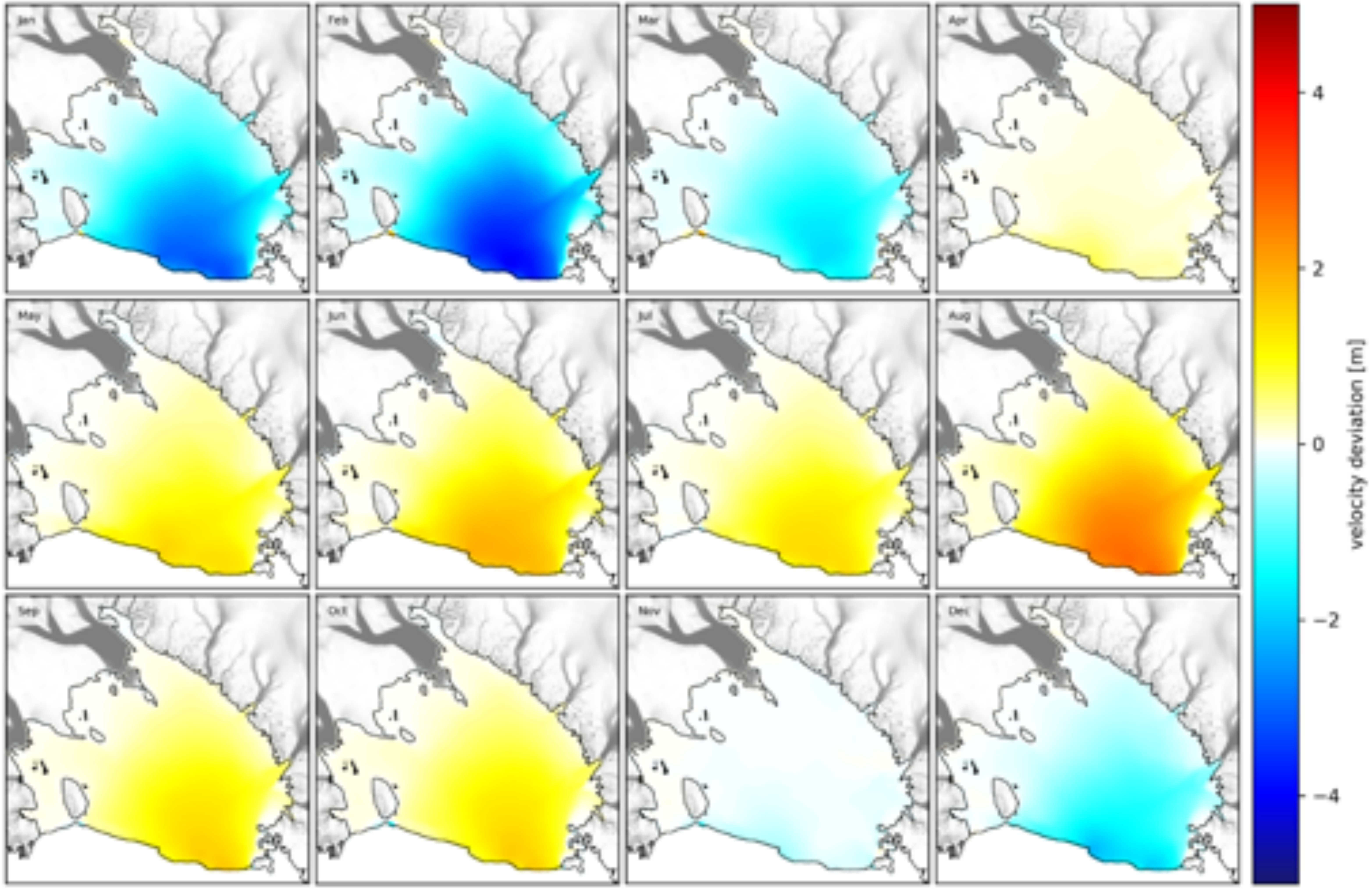
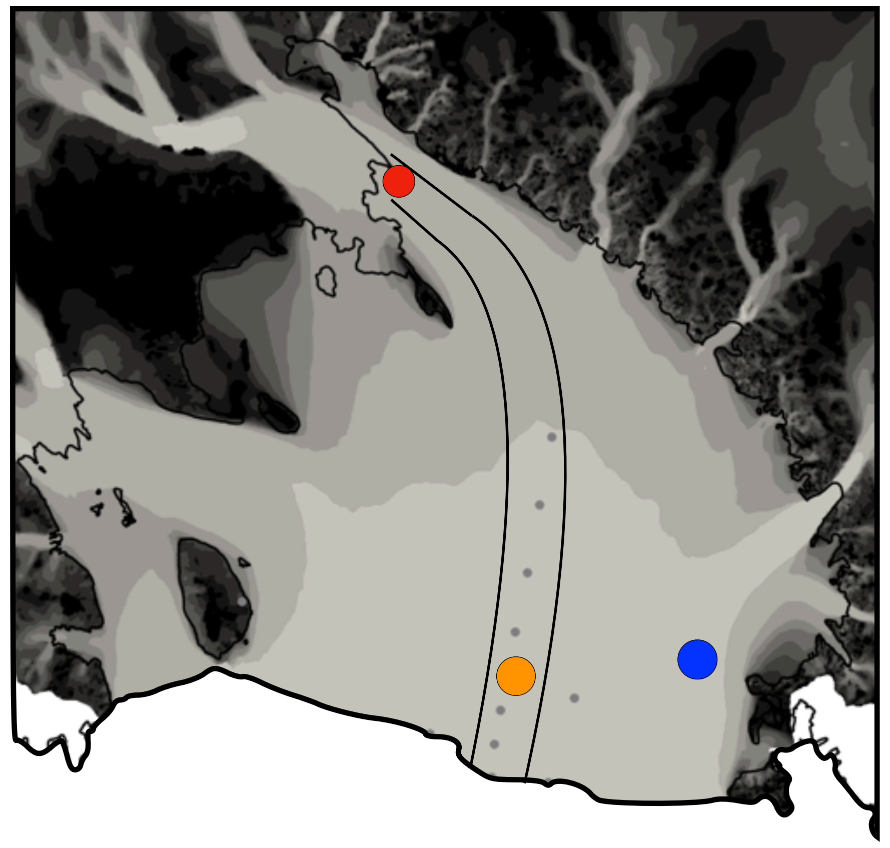
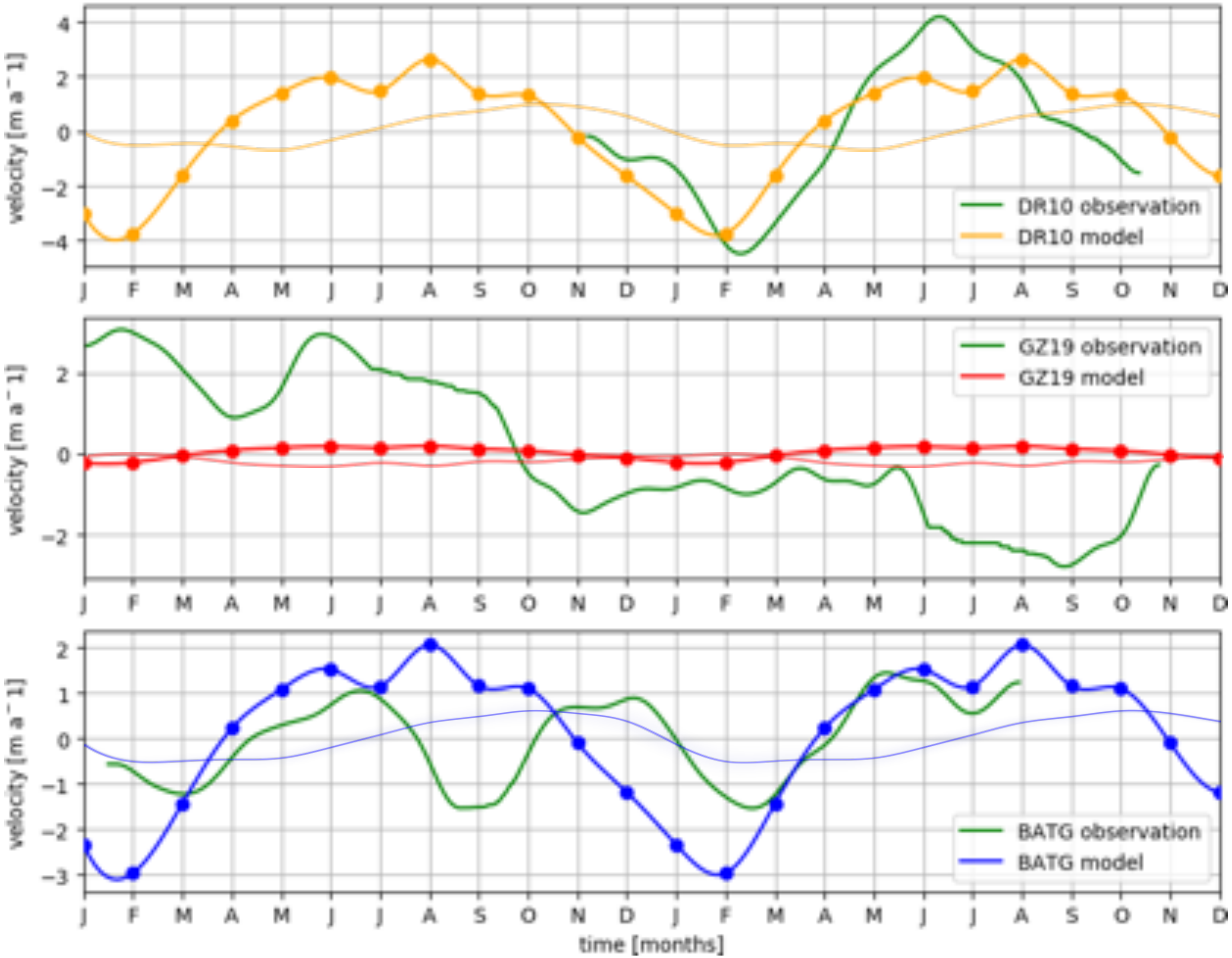


SSH: Driving stress and GL migration





Conclusion

- Seasonal melt changes affect the ice flow… But not enough to explain the seasonality observed in GPS data

- However, it reveals that an increase in summer melt rate and an “extended summer” could lead to significant changes in RIS flow

- SSH variations…

  - by locally changing the driving stress
  - by leading to alternated upstream and downstream migration of the GL

… could explain the seasonal flow we observe

- The migration mechanism and the effect of the ice rheology remain poorly known

  - Parametrization more adapted to tides : elastic (*Sayag and Worster, 2011 and 2013*) and elastic fracture (*Tsai and Gudmundsson, 2015*)