Tipping points in grounding zone melting via seawater intrusions

Alex Bradley and Ian Hewitt

@abraleey

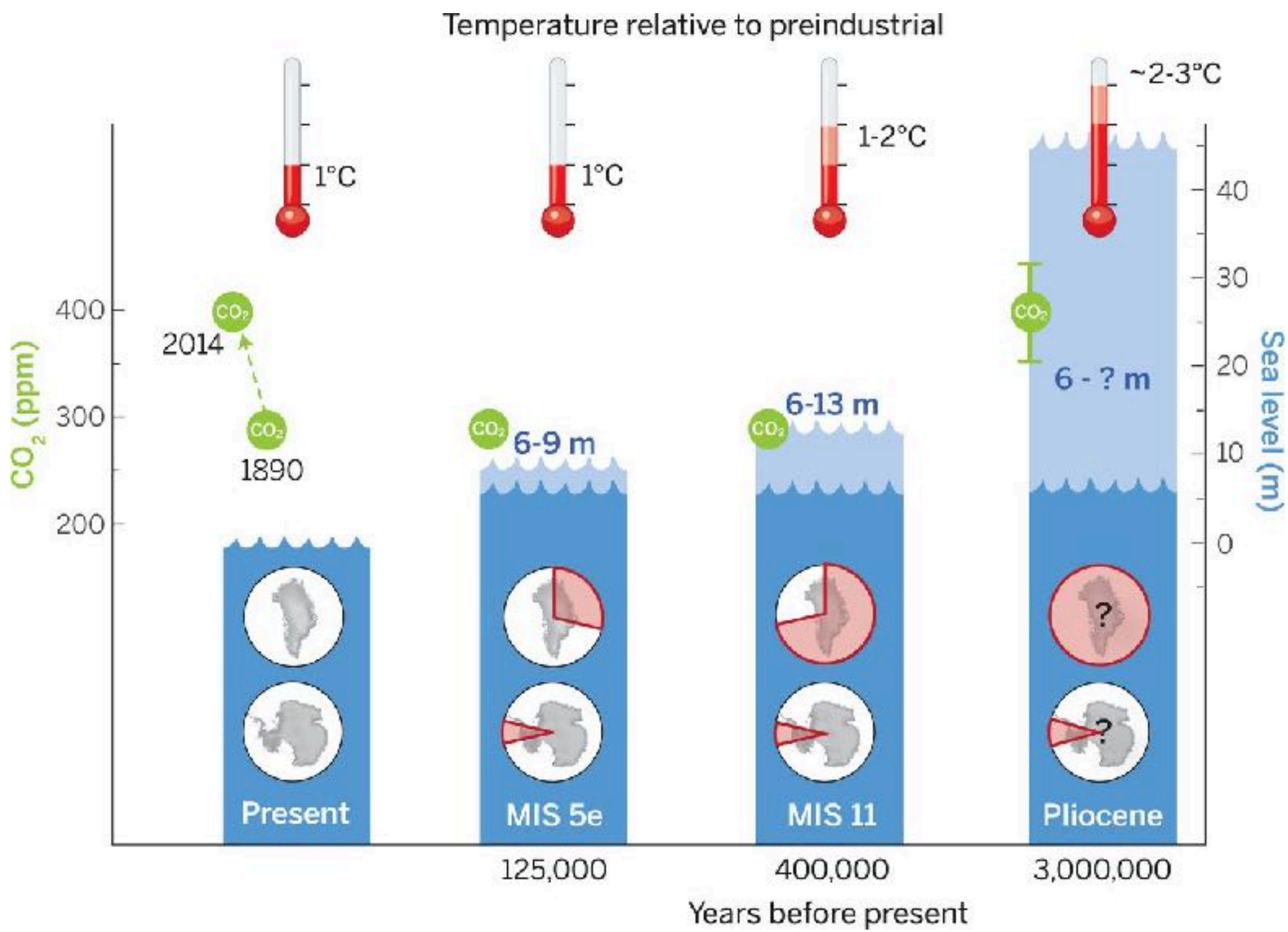
aleey@bas.ac.uk

UNIVERSITY OF OXFORD

UNIVERSITY OF CAMBRIDGE

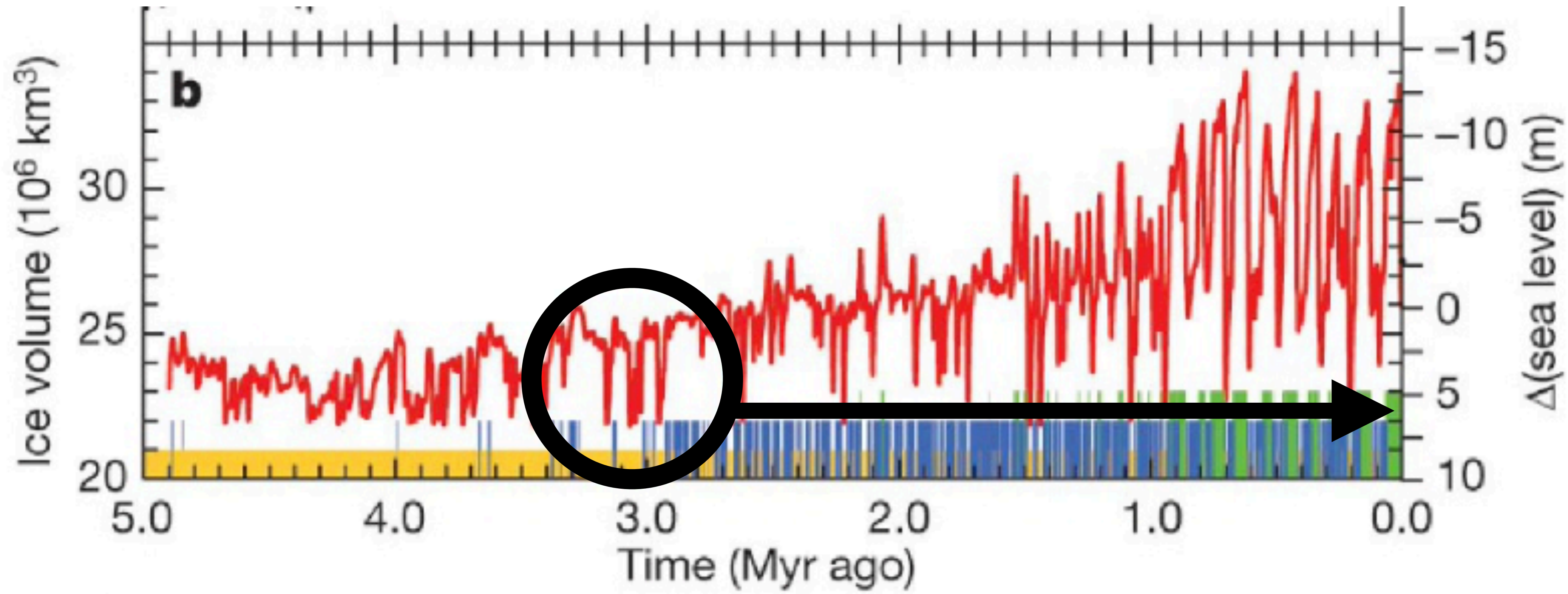
British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Sea levels have been much higher than today with similar CO2 and temperatures

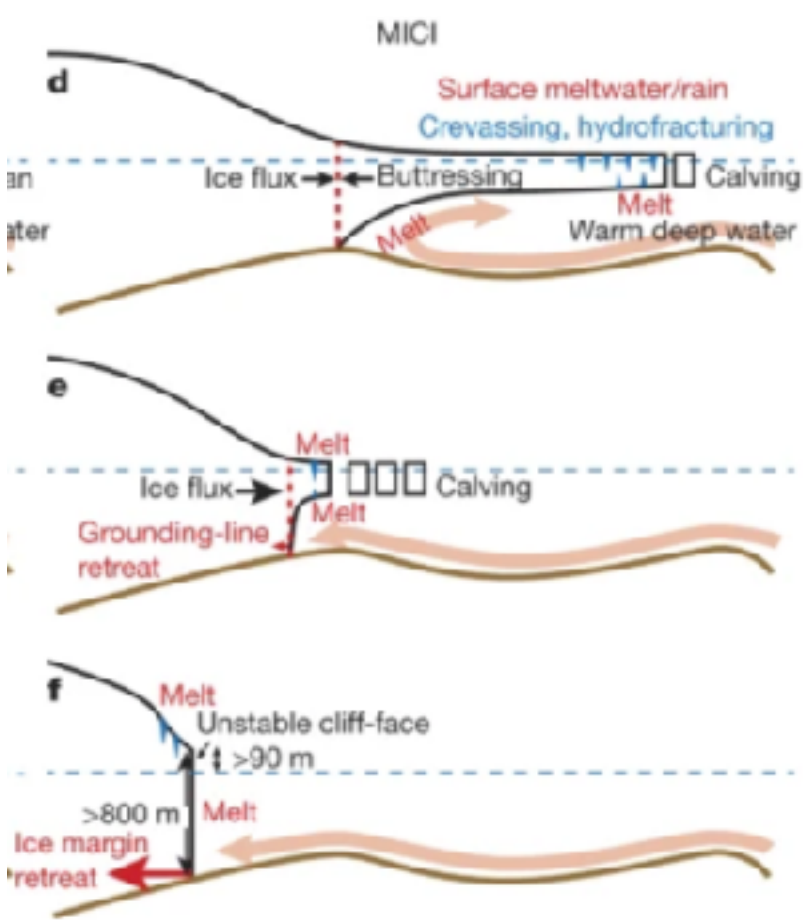


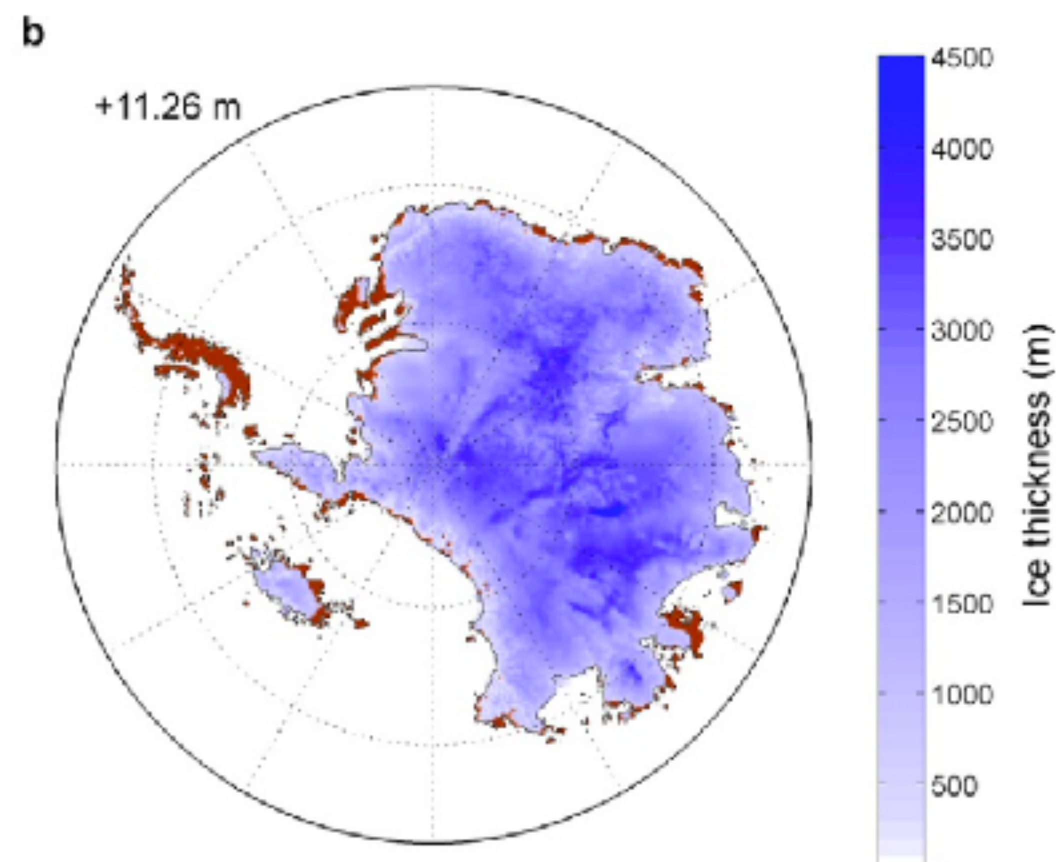
Models struggle to simulate this retreat

Pollard and DeConto, 2009

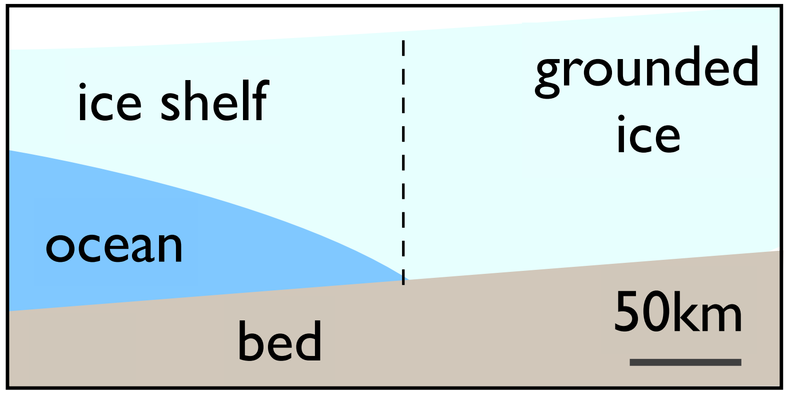


DeConto and Pollard, 2016

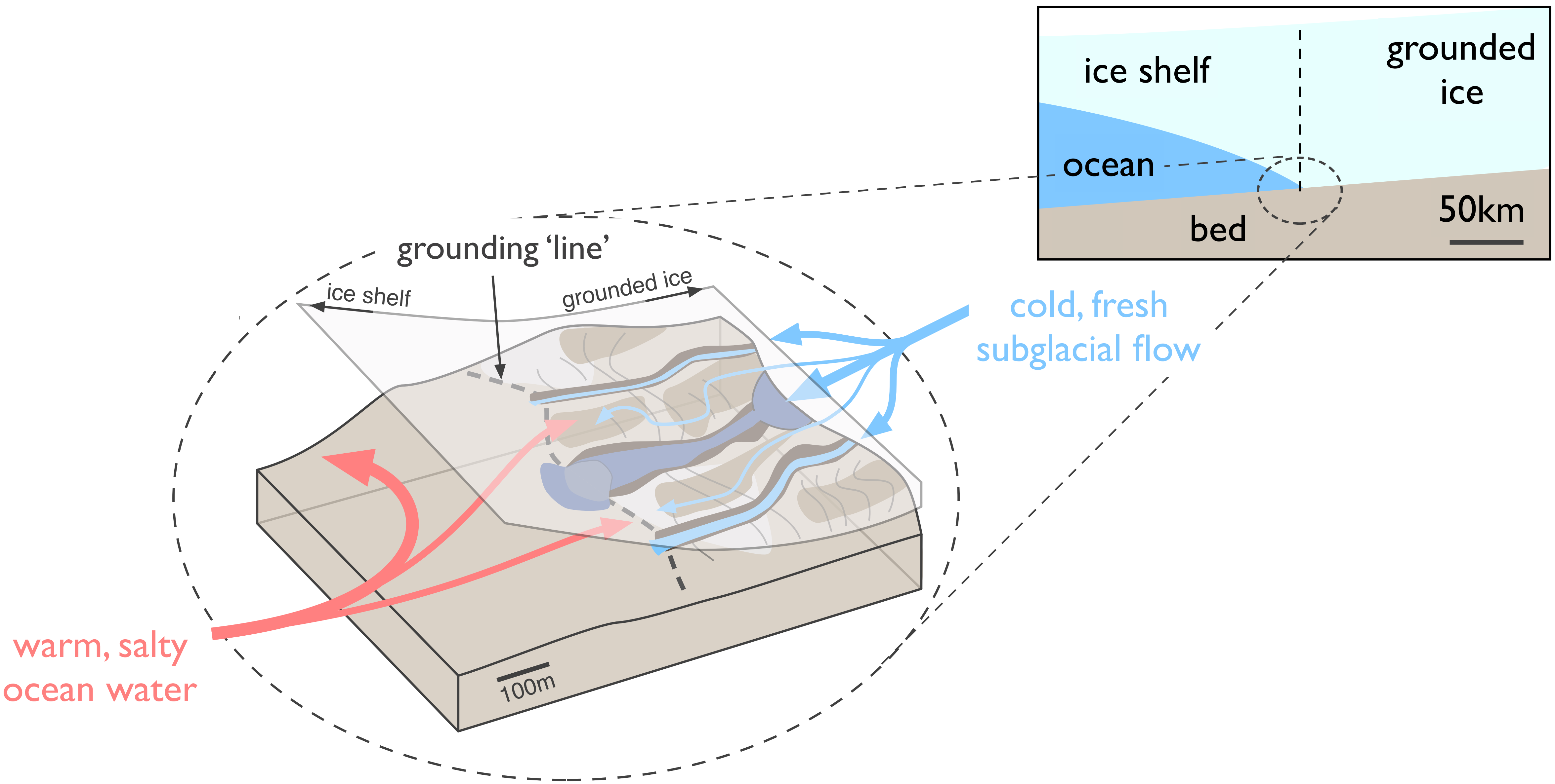




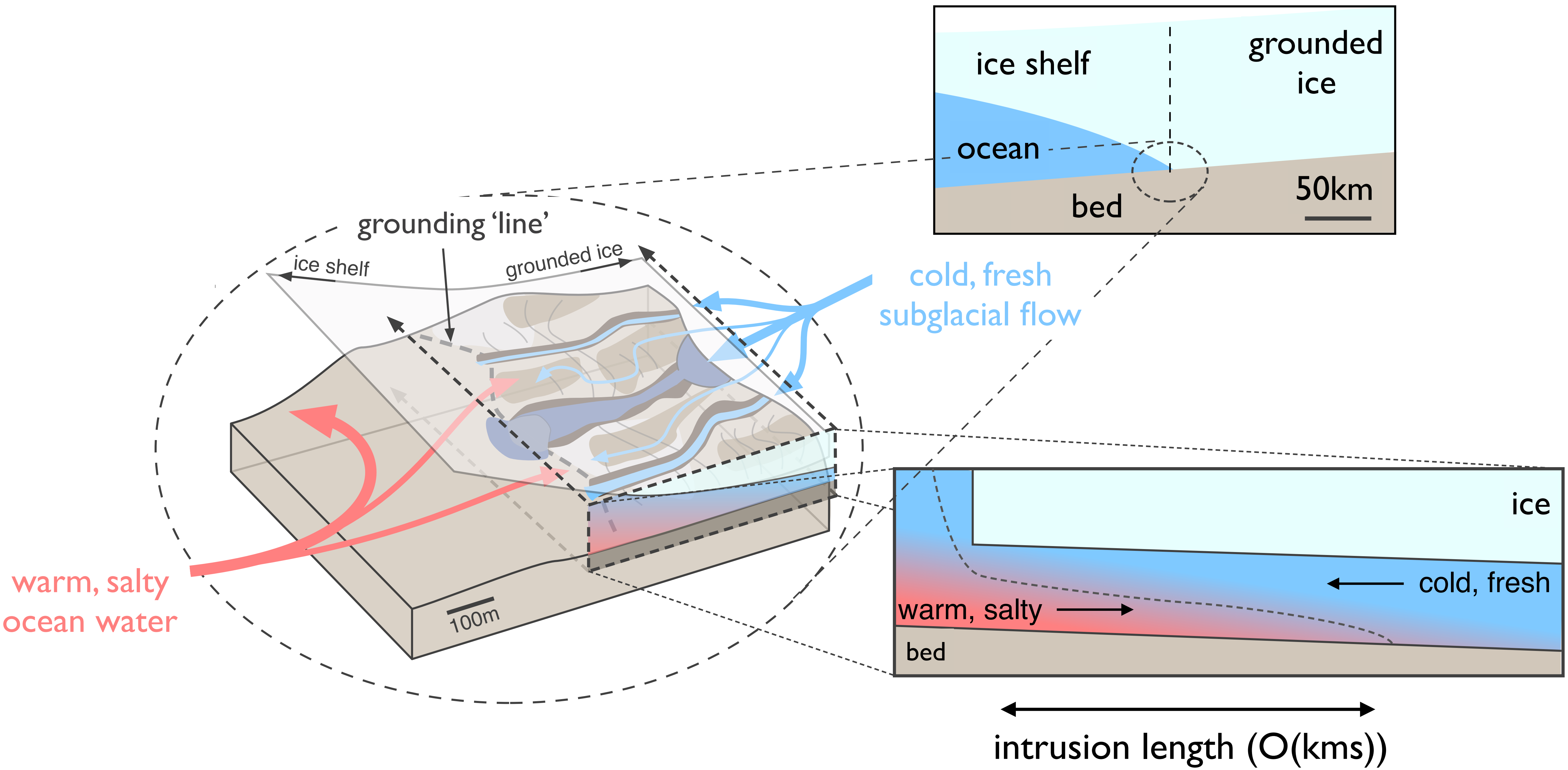
Grounding zone melt boosts ice sheet sensitivity



Grounding zone melt boosts ice sheet sensitivity

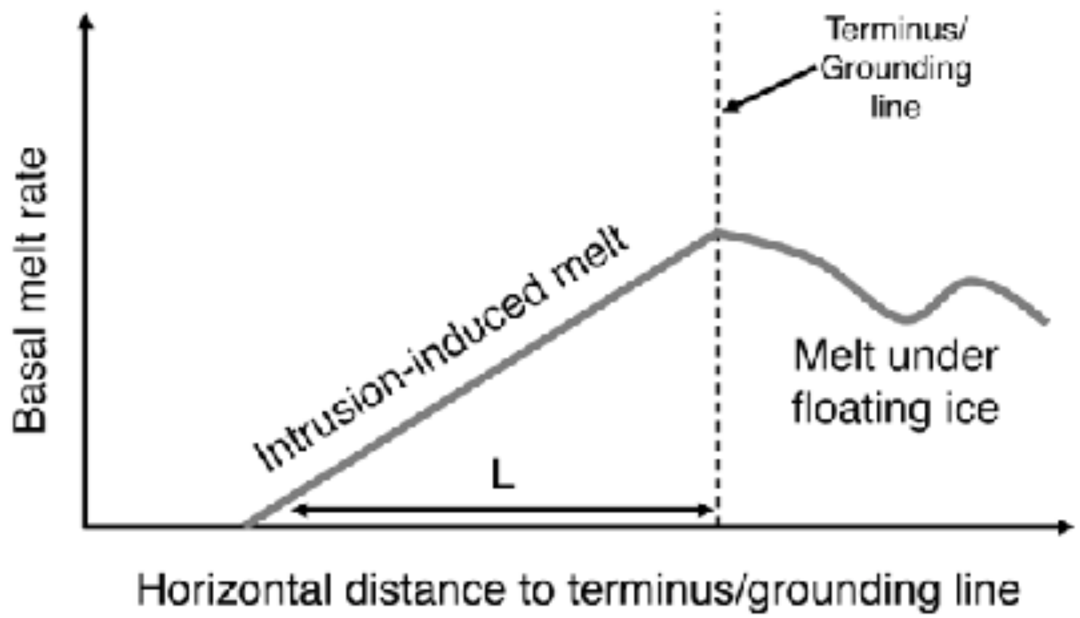


Grounding zone melt boosts ice sheet sensitivity

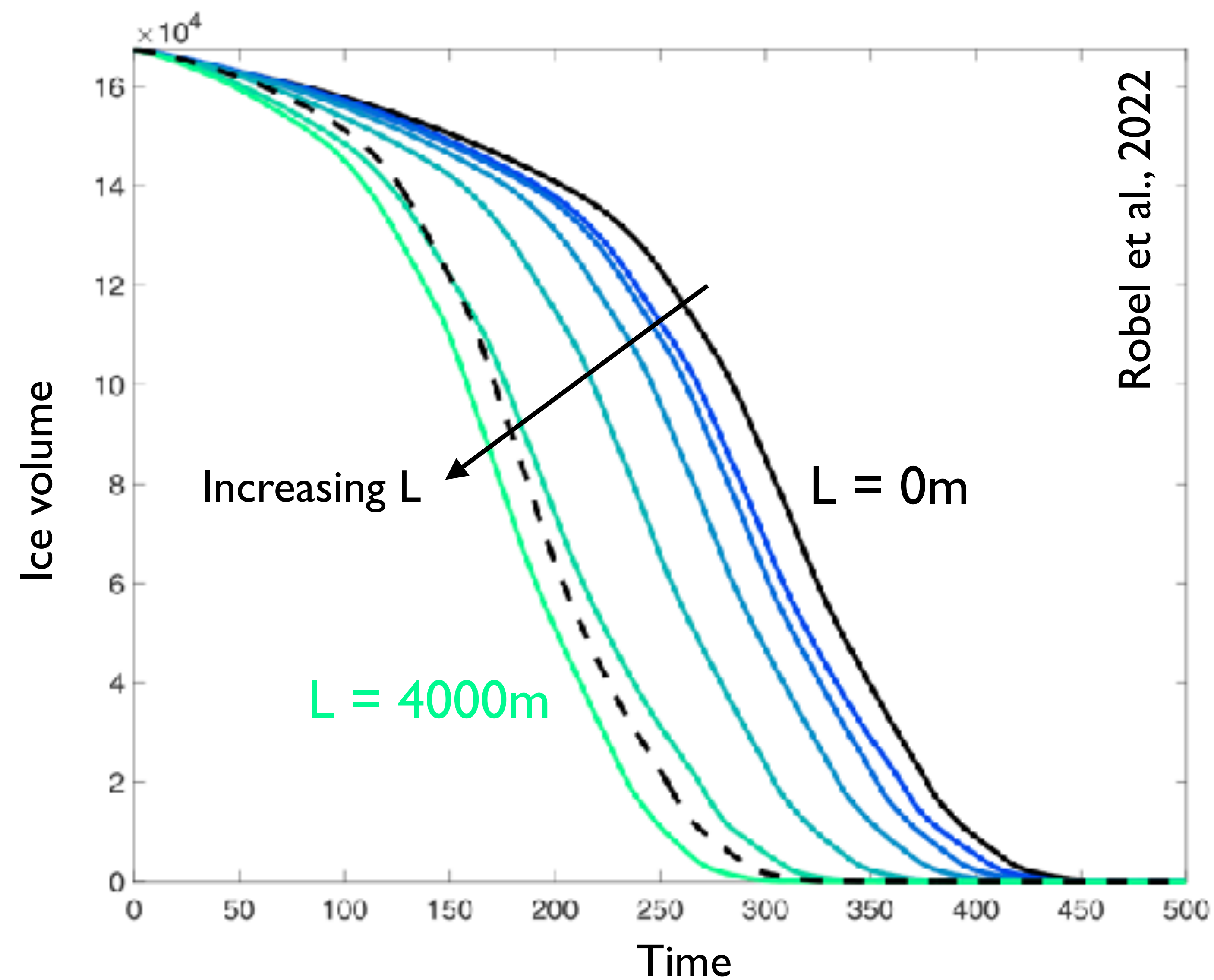


Robel et al., 2022, Wilson et al. 2020

Grounding zone melt boosts ice sheet sensitivity



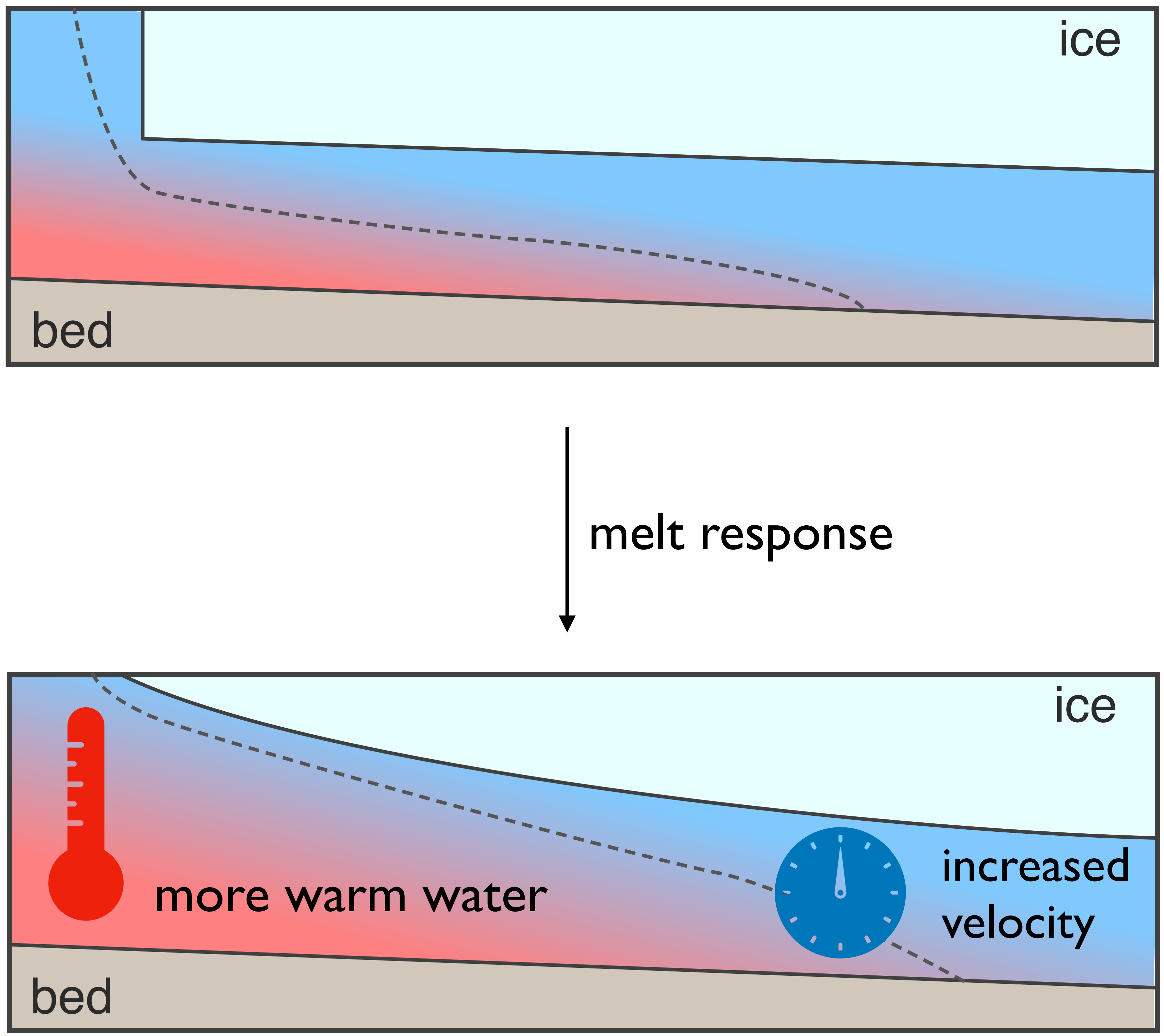
Robel et al., 2022

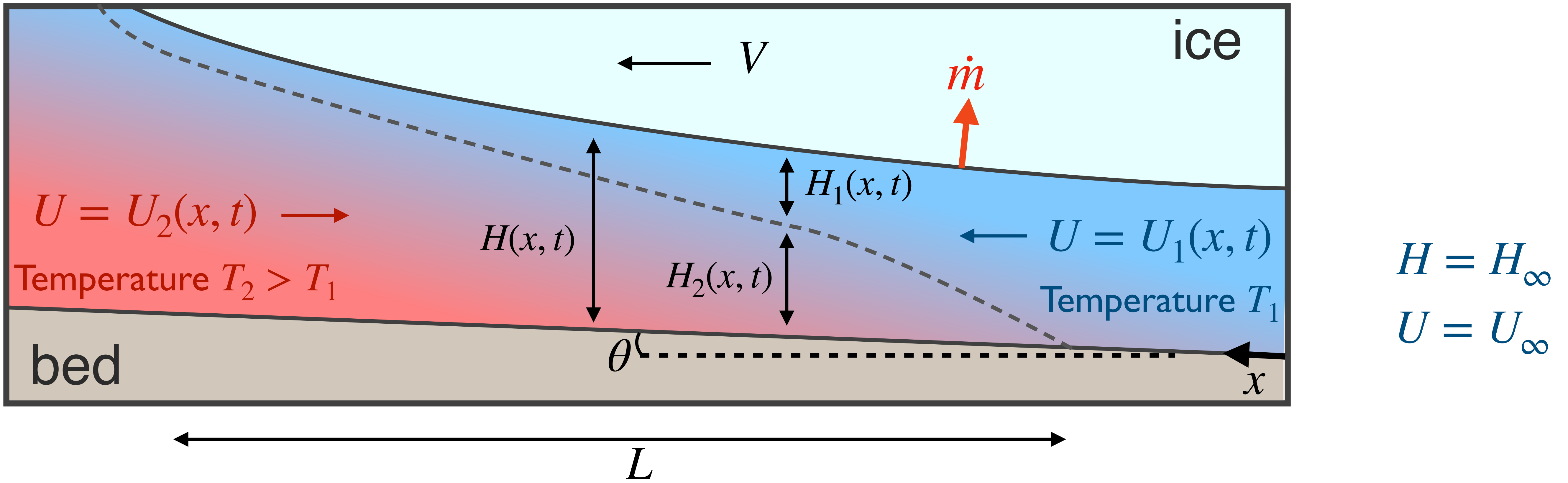


Robel et al., 2022

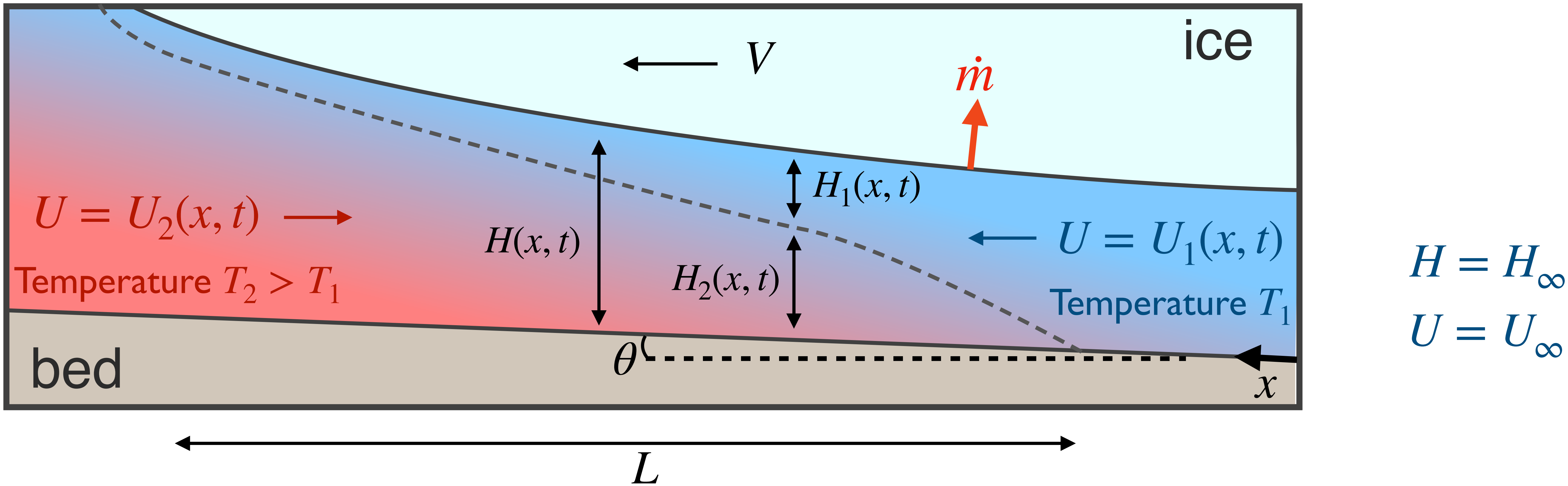
Significant seawater intrusion has dramatic consequences for ice dynamics

Melt feedbacks on seawater intrusions





ice
V
$\dot{m}$
$H_1(x,t)$
$U = U_2(x,t)$
$H(x,t)$
$U = U_1(x,t)$
Temperature $T_2 > T_1$
$H_2(x,t)$
Temperature T_1
$H = H_\infty$
$U = U_\infty$
bed
θ
x
L

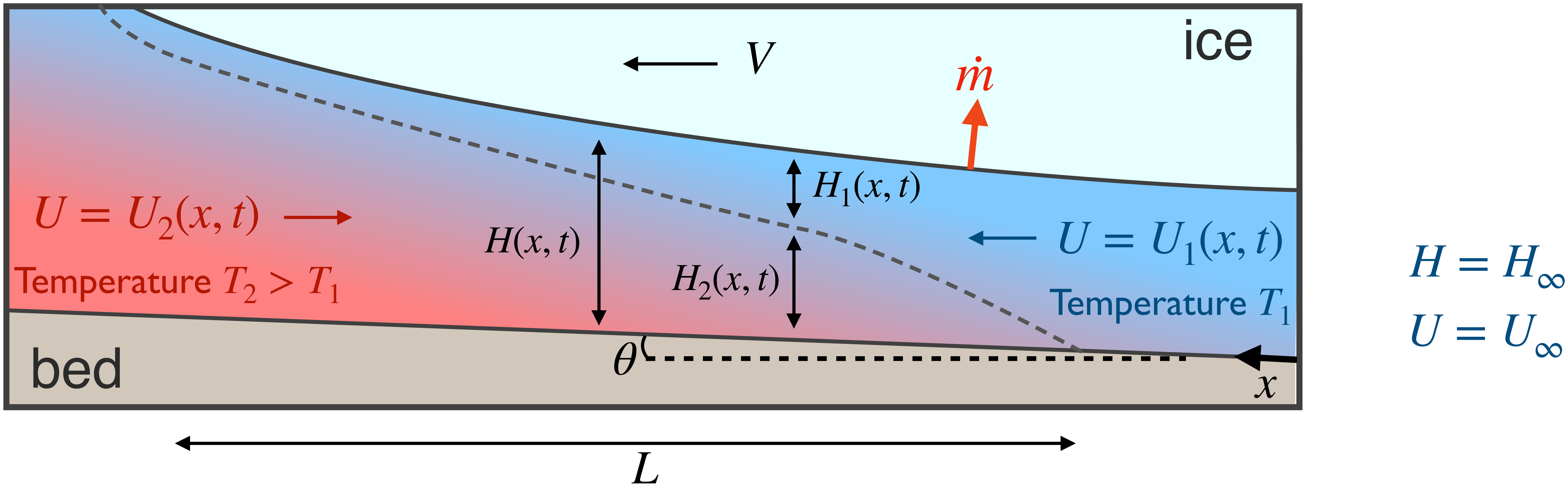


Momentum Conservation:

inertia | barotropic pressure gradient | interfacial drag | wall drag | gravitational driving

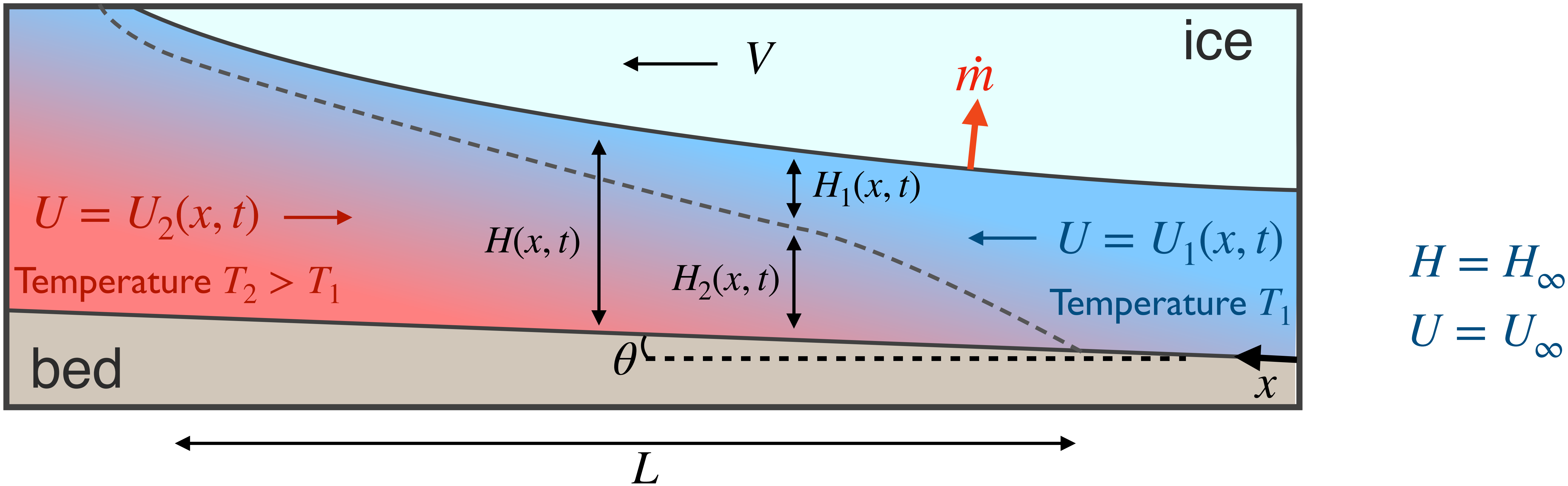
$$\begin{cases} \dfrac{\partial U_1}{\partial t} + U_1 \dfrac{\partial U_1}{\partial x} + \dfrac{1}{\rho}\dfrac{\partial P}{\partial x} + \dfrac{C_i |U_1 - U_2|(U_1 - U_2)}{H_1} + \dfrac{C_d U_1^2}{H_1} = 0 \\ \dfrac{\partial U_2}{\partial t} + U_2 \dfrac{\partial U_2}{\partial x} + \dfrac{1}{\rho}\dfrac{\partial P}{\partial x} - \dfrac{C_i |U_1 - U_2|(U_1 - U_2)}{H_2} + \dfrac{C_d U_2^2}{H_2} + g'\left(\dfrac{\partial H_2}{\partial x} + \tan\theta\right) = 0 \end{cases}$$

$$(\mathrm{Fr}^2 - 1)\frac{\partial H_1}{\partial x} = \mathrm{Fr}^2\left(C_d + C_i \frac{H}{H - H_1}\right) - \left(\tan\theta + \frac{\partial H}{\partial x}\right)$$



<u>Momentum Conservation:</u>

$$(\mathrm{Fr}^2 - 1)\frac{\partial H_1}{\partial x} = \mathrm{Fr}^2\left(C_d + C_i\frac{H}{H - H_1}\right) - \left(\tan\theta + \frac{\partial H}{\partial x}\right)$$



Momentum Conservation:

$$(\mathrm{Fr}^2 - 1)\frac{\partial H_1}{\partial x} = \mathrm{Fr}^2\left(C_d + C_i\frac{H}{H - H_1}\right) - \left(\tan\theta + \frac{\partial H}{\partial x}\right)$$

Melting:

$$\dot{m} = \frac{\mathrm{St}C}{L}u^*\Delta T$$

thermal driving

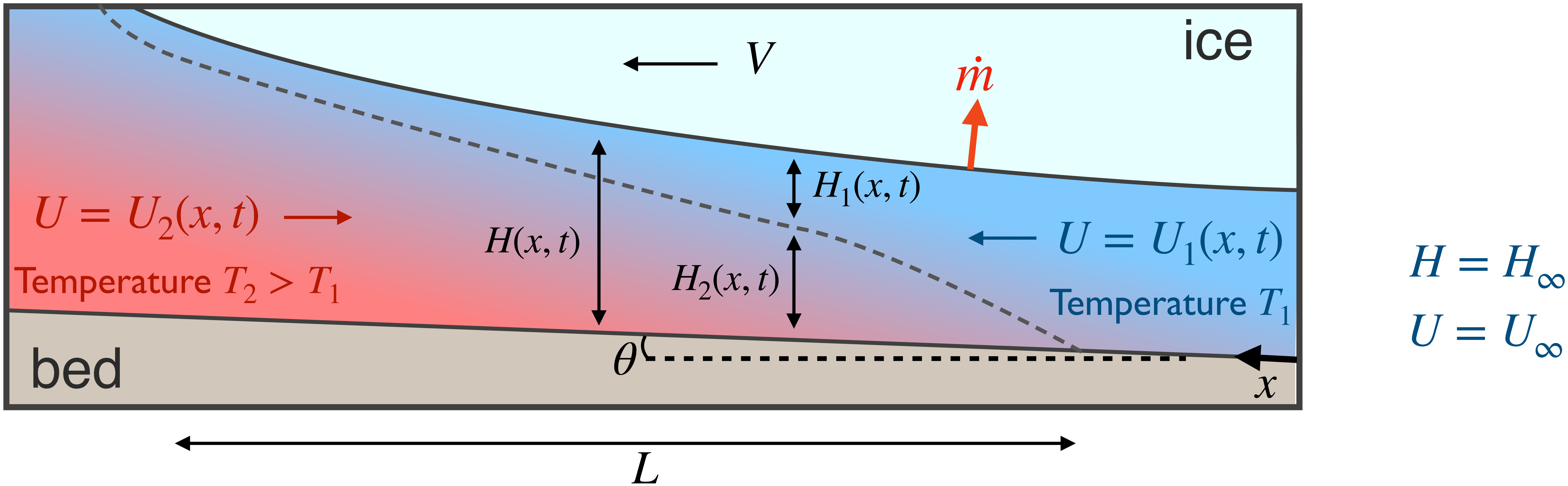
boundary layer velocity $u^* = U_1$

$$\Delta T = T - T_f$$

$$T = \frac{H_1}{H}T_1 + \left(1 - \frac{H_1}{H}\right)T_2$$

T_f : local freezing point

$$\dot{m} = \frac{\mathrm{St}C}{L}U_1\left[\frac{H_1}{H}T_1 + \left(1 - \frac{H_1}{H}\right)\right]$$

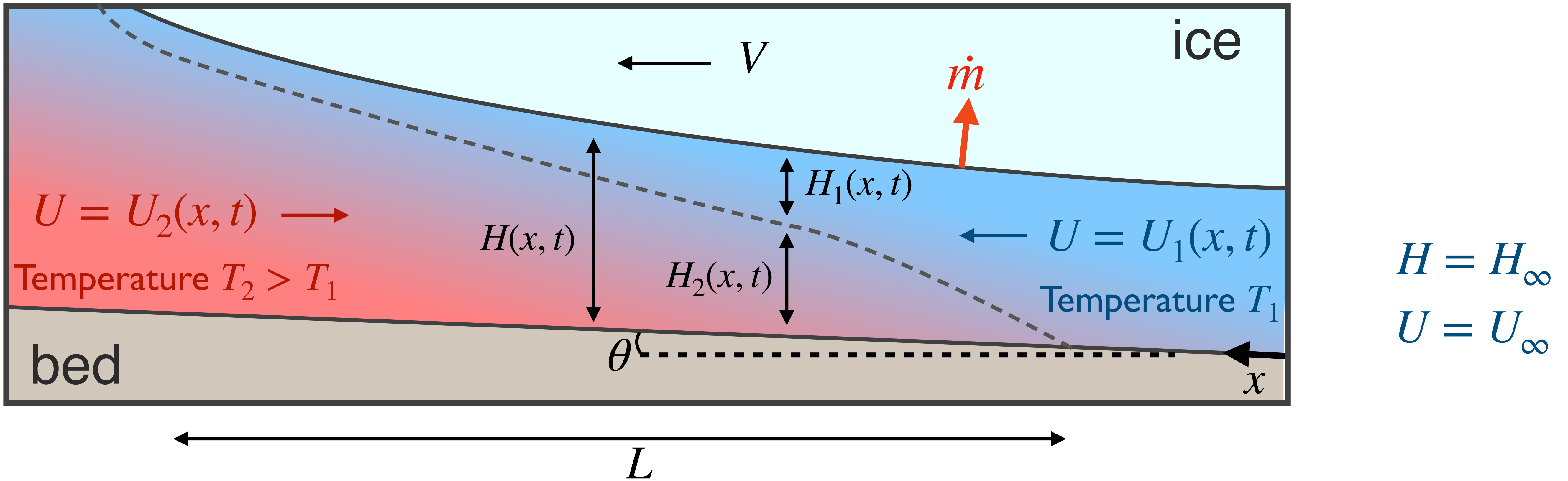


Momentum Conservation:

$$(\mathrm{Fr}^2 - 1)\frac{\partial H_1}{\partial x} = \mathrm{Fr}^2\left(C_d + C_i\frac{H}{H - H_1}\right) - \left(\tan\theta + \frac{\partial H}{\partial x}\right)$$

Melting:

$$\dot{m} = \frac{\mathrm{St}C}{L}U_1\left[\frac{H_1}{H}T_1 + \left(1 - \frac{H_1}{H}\right)\right]$$



Momentum Conservation:

$$(\mathrm{Fr}^2 - 1)\frac{\partial H_1}{\partial x} = \mathrm{Fr}^2\left(C_d + C_i\frac{H}{H - H_1}\right) - \left(\tan\theta + \frac{\partial H}{\partial x}\right)$$

Melting:

$$\dot{m} = \frac{\mathrm{St}C}{L}U_1\left[\frac{H_1}{H}T_1 + \left(1 - \frac{H_1}{H}\right)\right]$$

Kinematic Condition:

$$\frac{\partial H}{\partial t} + V\frac{\partial H}{\partial x} = \dot{m}$$

Momentum conservation:

$$\left(\frac{\mathrm{F}^2}{h_1^3} - 1\right)\frac{\partial h_1}{\partial x} = \frac{\mathrm{F}^2}{h_1^3}\left(1 + C\frac{h}{h - h_1}\right) - \left(S + \frac{\partial h}{\partial x}\right)$$

Melting + kinematic:

$$\frac{\partial h}{\partial t} + \frac{1}{M}\frac{\partial h}{\partial x} = \frac{1}{h_1}\left(1 - \frac{h_1}{h}\right)$$

$$S = \frac{\tan\theta}{C_d}$$

dimensionless bed slope

$$F = \frac{U_\infty}{\sqrt{g' H_\infty}}$$

upstream Froude number

$$C = \frac{C_i}{C_d}$$

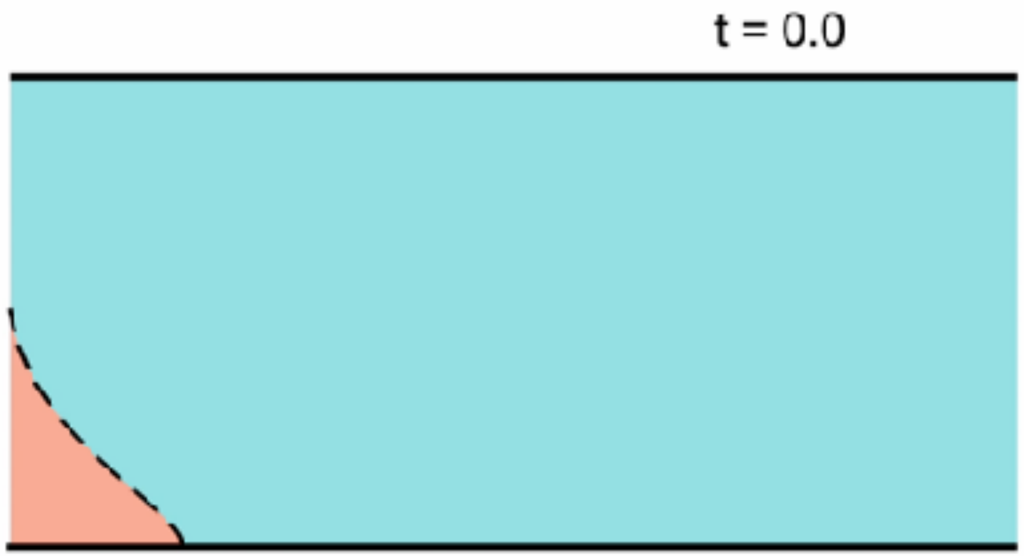
dimensionless drag

$$M = \frac{u_\infty}{V}\frac{\mathrm{St}}{c_d}\frac{T_2 - T_1}{L/c}$$

dimensionless melt

+ boundary condition: $h_1^{3/2} = \mathrm{F}^{2/3}$ at $x = 0$

$T_2 = 1.9^{\circ}C \quad (M = 0.38)$



70m (no melt feedback, Robel et al. 2020)

110m with melt feedback

‘bounded intrusion’

$M < M_c$

$T_2 = 2^{\circ}C \quad (M = 0.4)$

70m

$L \to \infty$

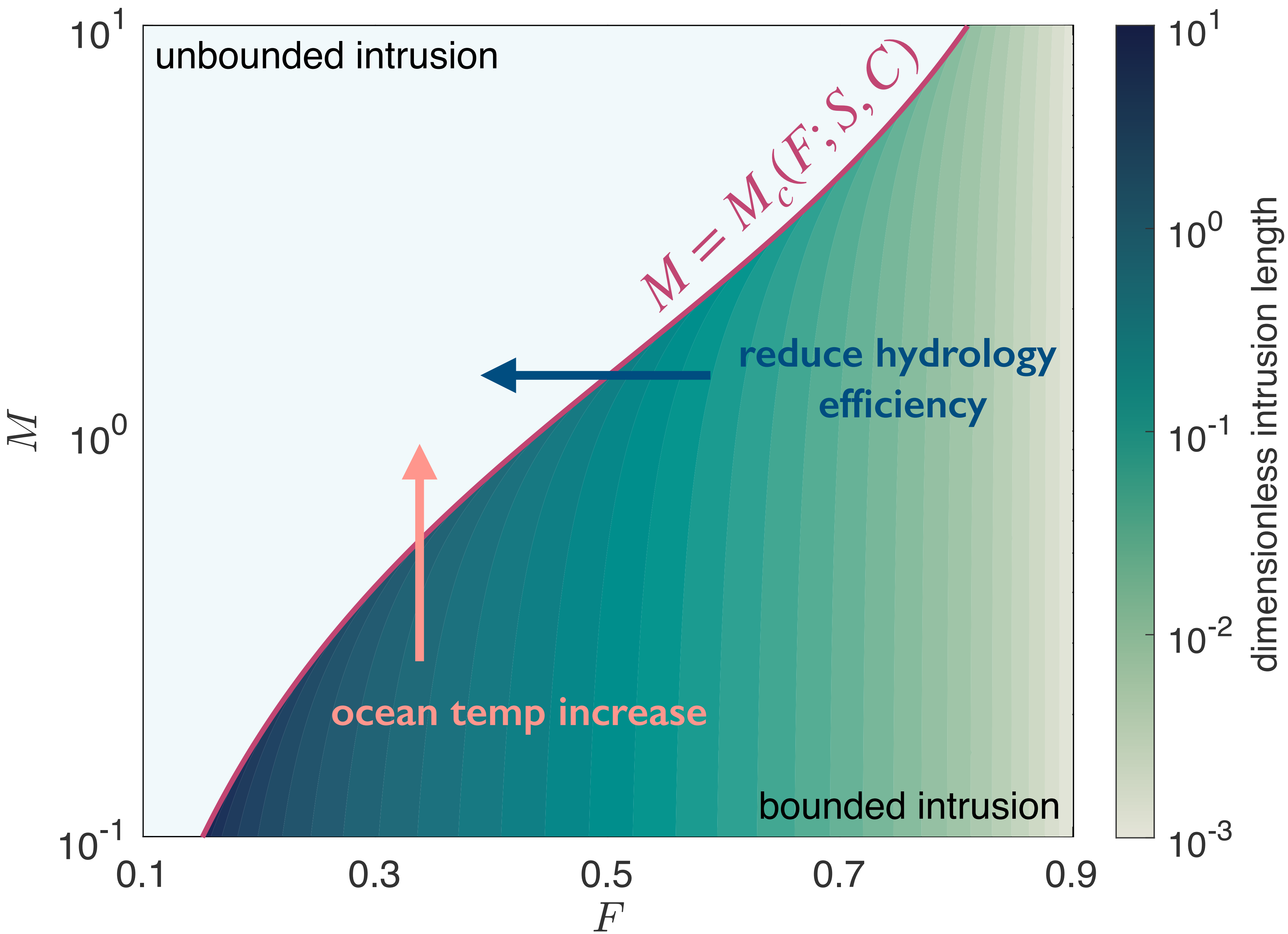
‘unbounded intrusion’

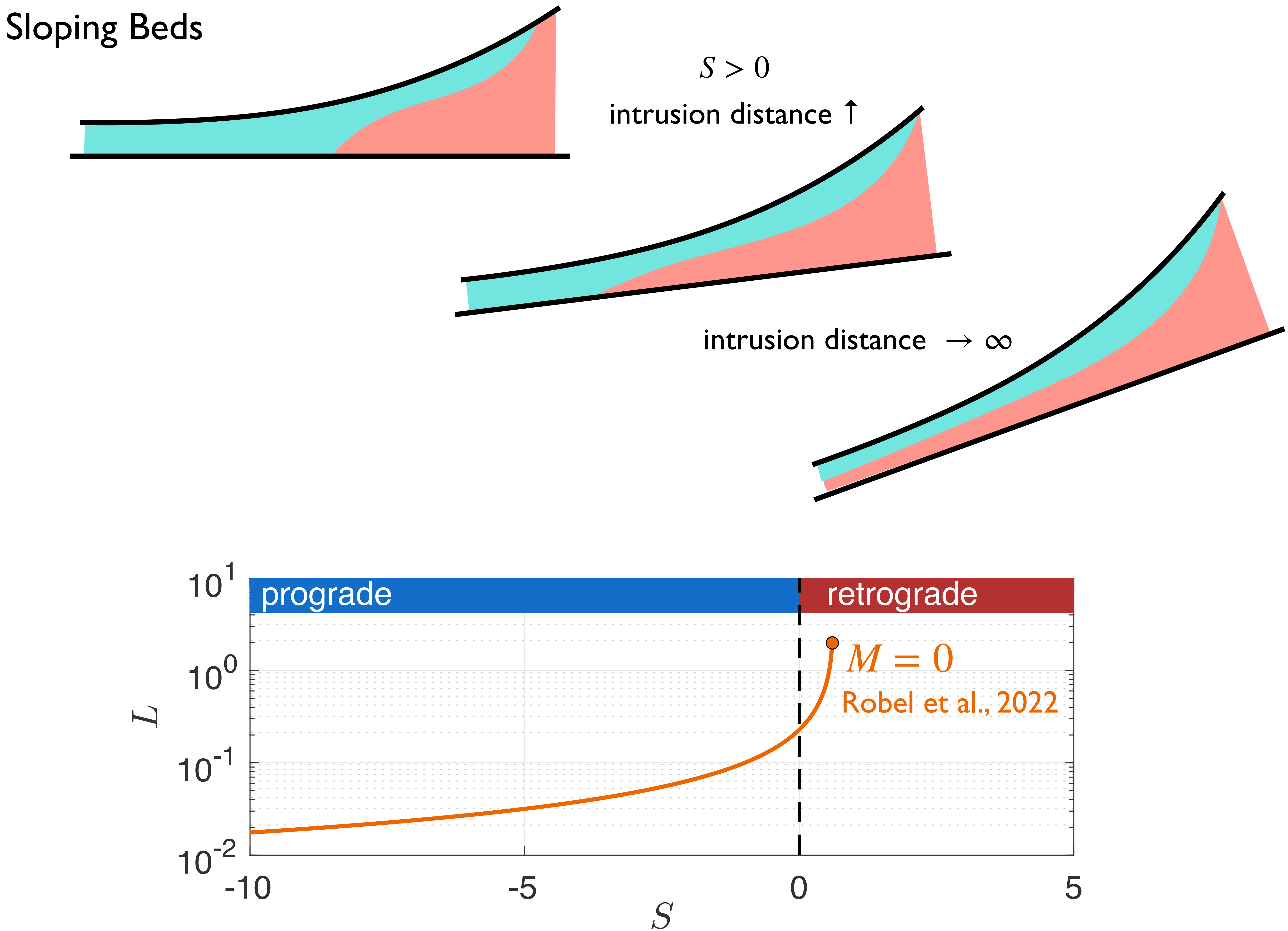
$M > M_c$

A **small change** in **ocean temperature** leads to a **large response** in **grounding zone melting,** with significant **implications for ice dynamics**

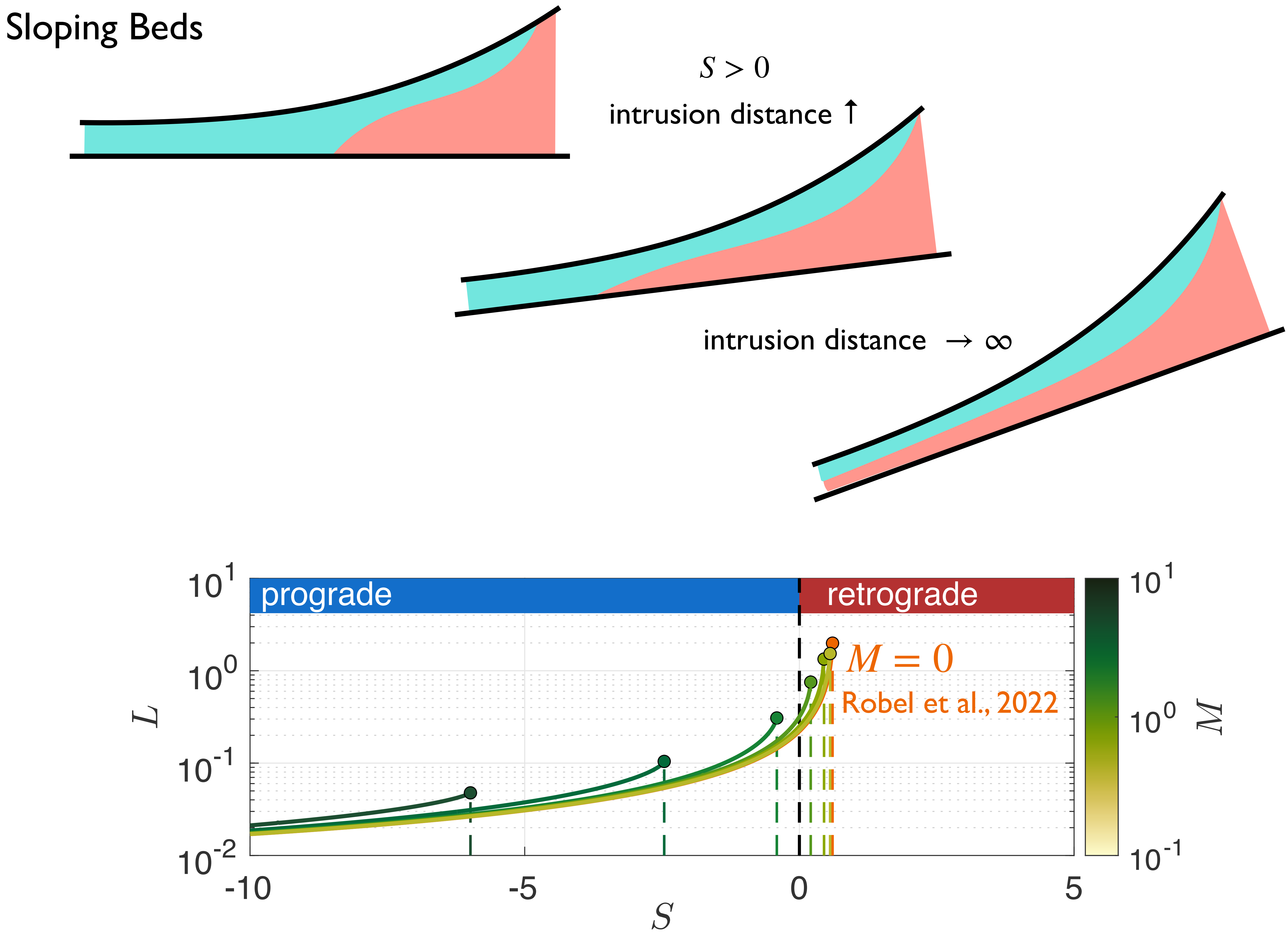
$$M = \frac{u_\infty}{V} \frac{\mathrm{St}}{c_d} \frac{T_2 - T_1}{L/c}$$

V: ice velocity
u_∞: upstream meltwater velocity
$T_2 - T_1$: ocean forcing



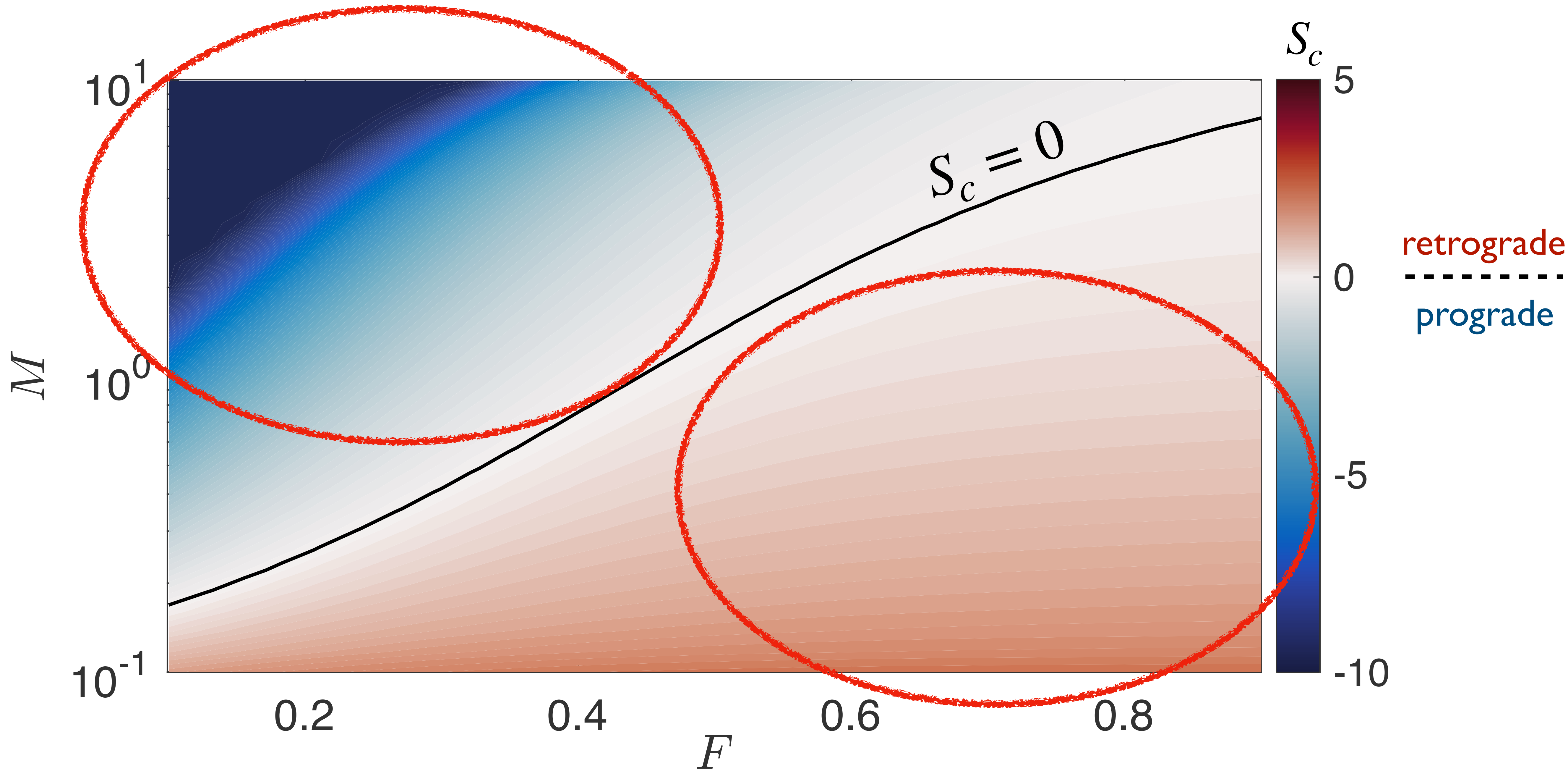


Sloping Beds
$S > 0$
intrusion distance ↑
intrusion distance → ∞
prograde
retrograde
$M = 0$
Robel et al., 2022
10^{1}
10^{0}
10^{-1}
10^{-2}
-10
-5
0
5
L
S



Sloping Beds
$S > 0$
intrusion distance ↑
intrusion distance → ∞
prograde
retrograde
$M = 0$
Robel et al., 2022
10^1
10^0
10^{-1}
10^{-2}
L
-10
-5
0
5
S
10^1
10^0
10^{-1}
M

prograde bedslopes can also have **unbounded intrusion - less stable than we think?**



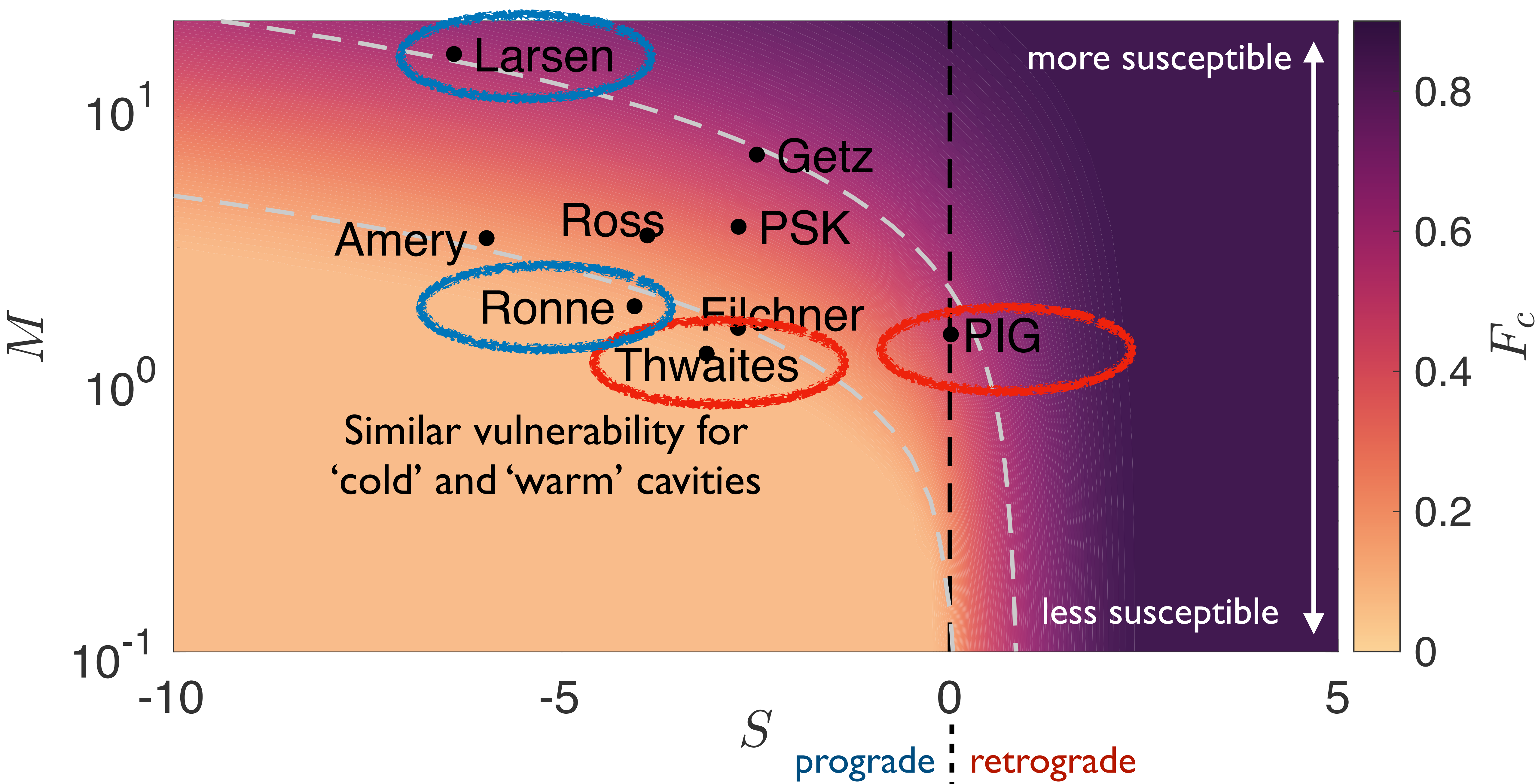
melt feedback makes **unbounded intrusion easier** on **retrograde** bedslopes - **candidate mechanism** to explain warm period retreat?

F is poorly constrained, plot as a function of M, S

$$S = \frac{\tan\theta}{C_d}$$
dimensionless bed slope

$$F = \frac{U_\infty}{\sqrt{g' H_\infty}}$$
upstream Froude number

$$M = \frac{u_\infty}{V}\frac{\mathrm{St}}{c_d}\frac{T_2 - T_1}{L/c}$$
dimensionless melt



F is poorly constrained, plot as a function of M, S

$$S = \frac{\tan\theta}{C_d}$$

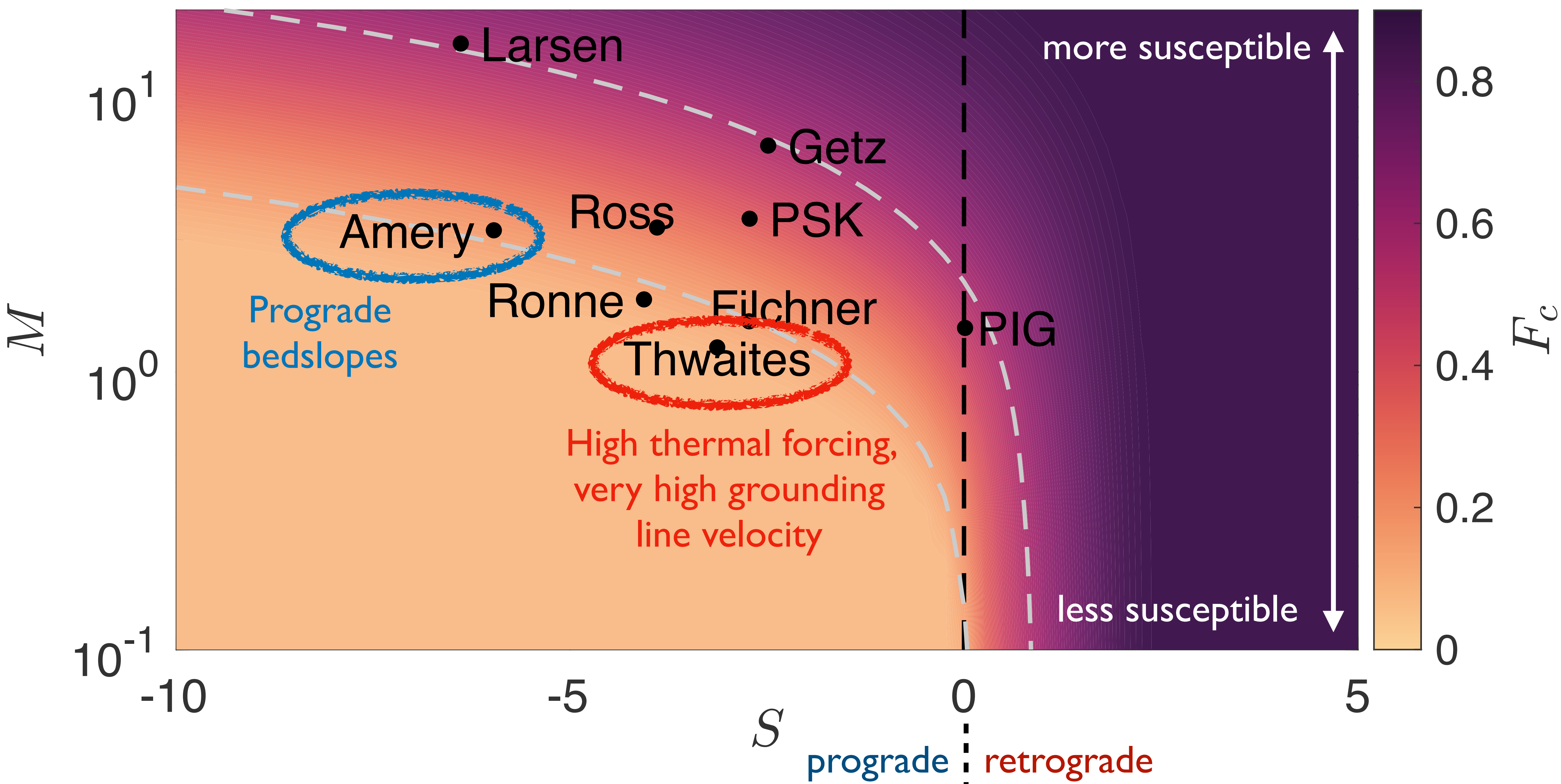
dimensionless bed slope

$$F = \frac{U_\infty}{\sqrt{g' H_\infty}}$$

upstream Froude number

$$M = \frac{u_\infty}{V} \frac{\mathrm{St}}{c_d} \frac{T_2 - T_1}{L/c}$$

dimensionless melt



F is poorly constrained, plot as a function of M, S

$$S = \frac{\tan\theta}{C_d}$$

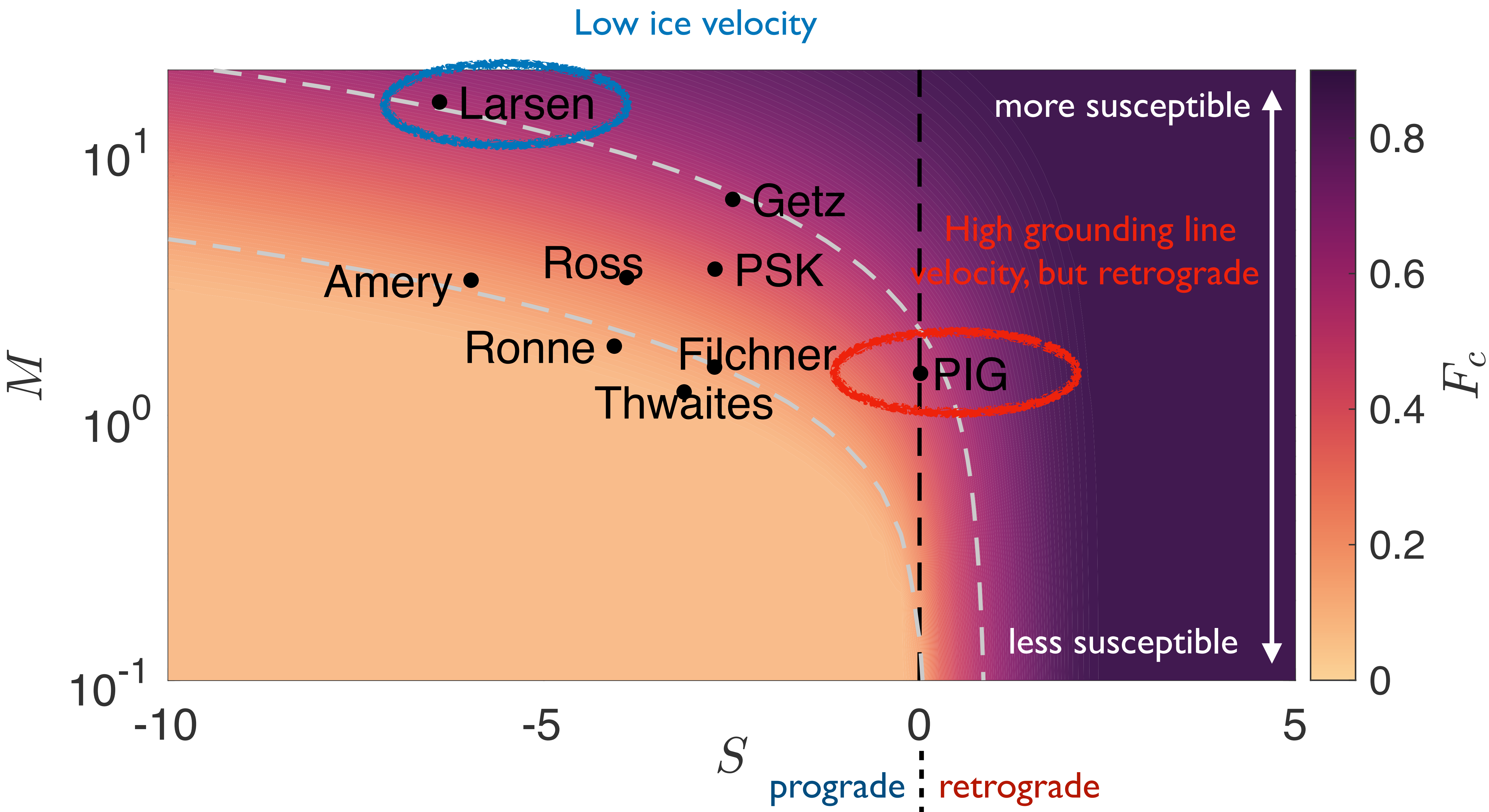
dimensionless bed slope

$$F = \frac{U_\infty}{\sqrt{g' H_\infty}}$$

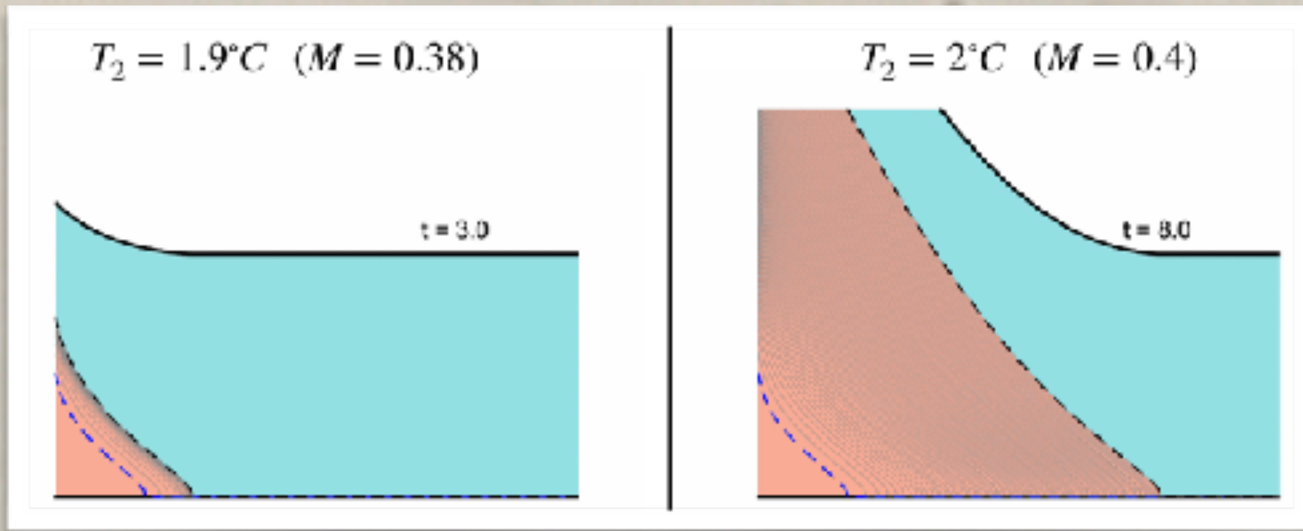
upstream Froude number

$$M = \frac{u_\infty}{V} \frac{\mathrm{St}}{c_d} \frac{T_2 - T_1}{L/c}$$

dimensionless melt

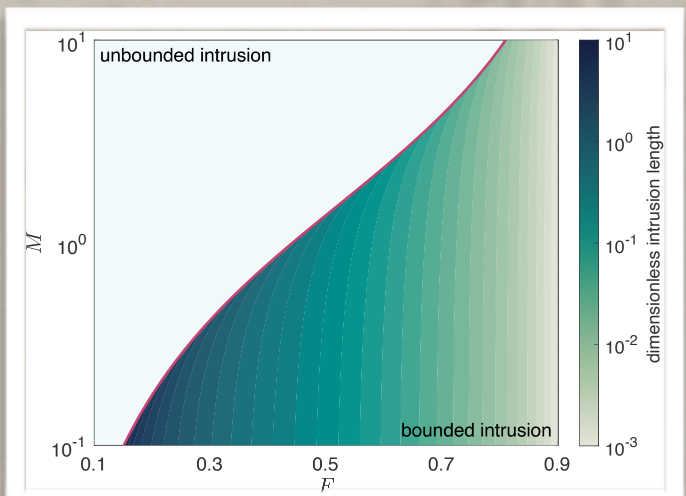


Melt feedback result in grounding zone tipping points

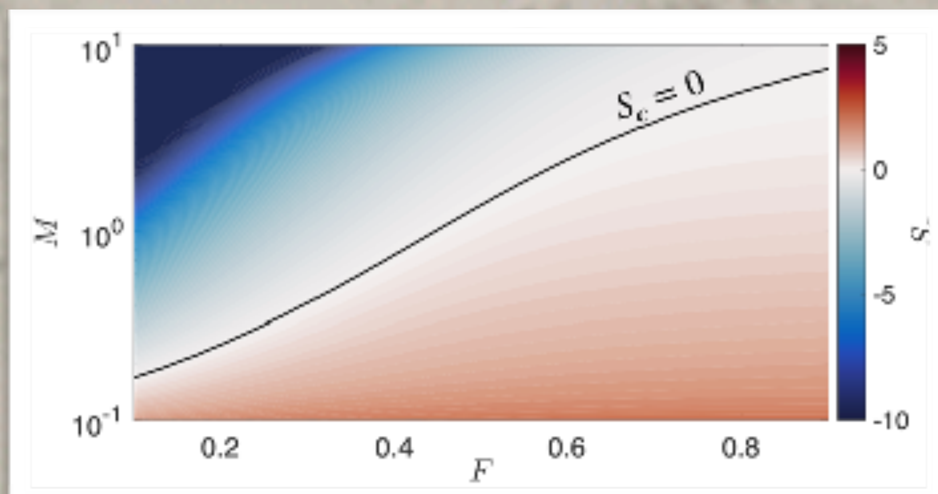


@abraleey
aleey@bas.ac.uk

Tipping point is 'generic'



Prograde slopes vulnerable, retrograde enhanced



Cold and warm cavity shelves susceptible