Subglacial Hydrodynamics & Ice-Water Interactions

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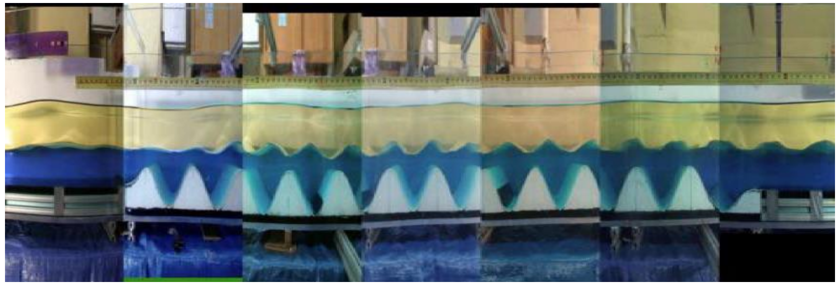
European Commission

MARIE CURIE ACTIONS

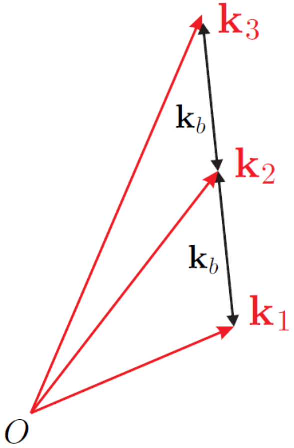
credit ©Pete Bucktrout

Fluid Mechanics Research

PhD @ UC Berkeley (Californie)
Postdoc @ IRPHE (Marseille) & British Antarctic Survey (Cambridge)
MC @ Lyon 1 & ENS



Wave Resonance



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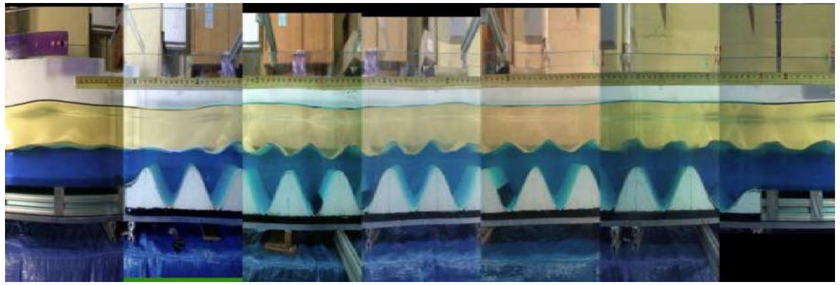

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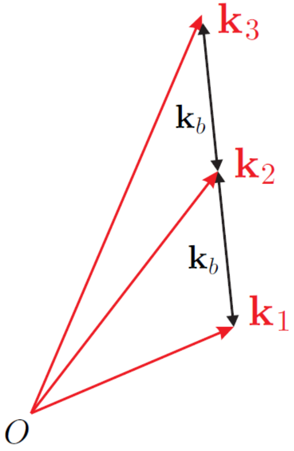

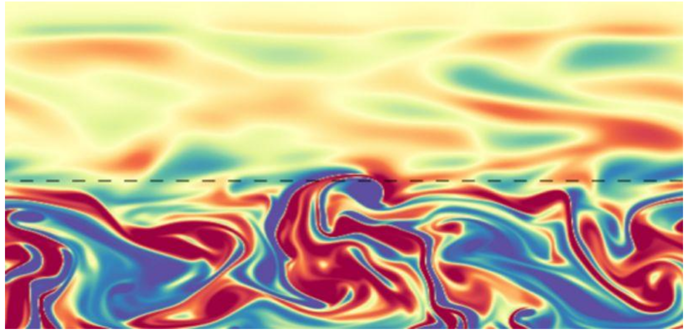

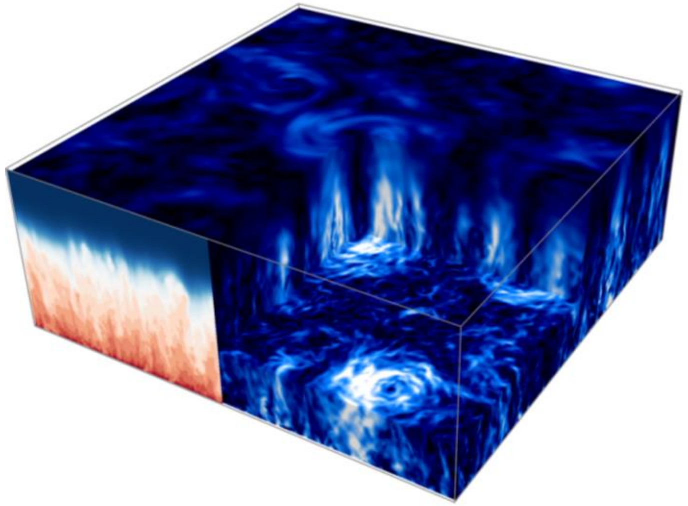

Turbulence & HPC

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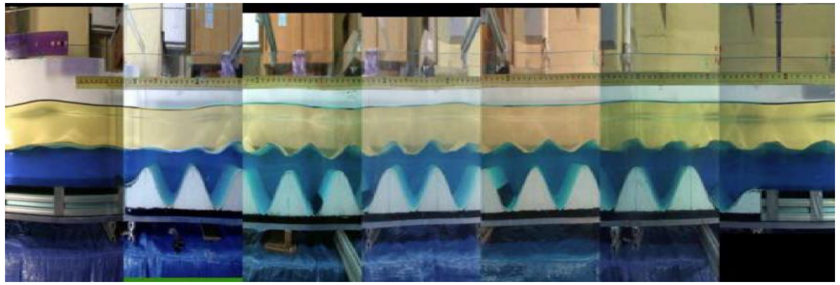

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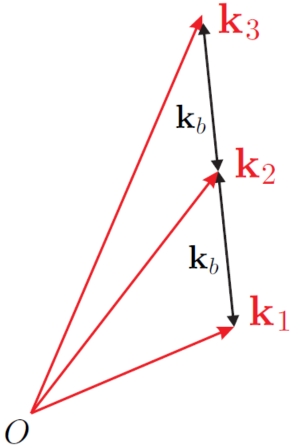
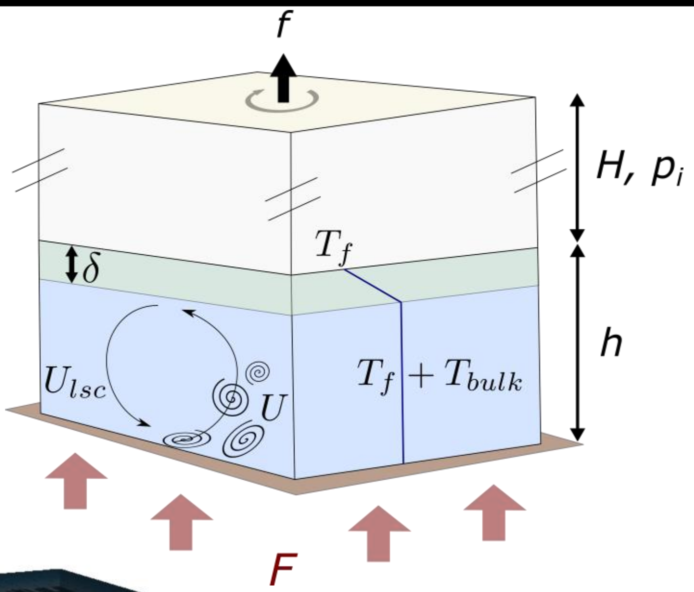
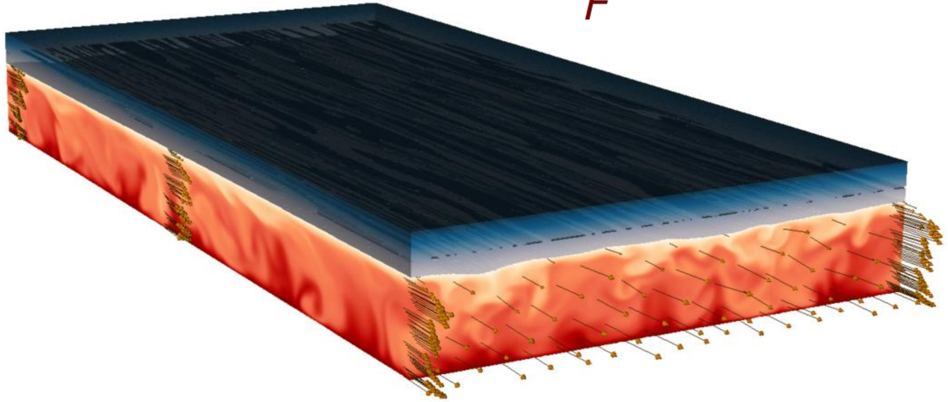
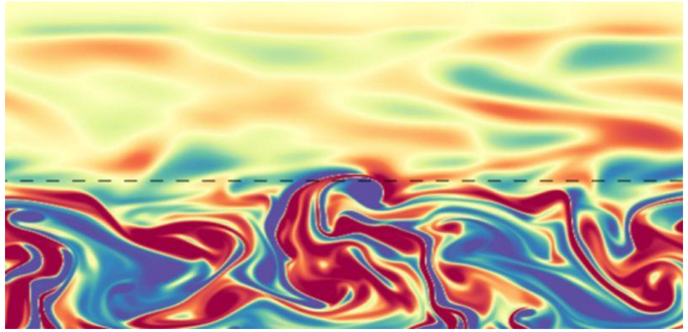
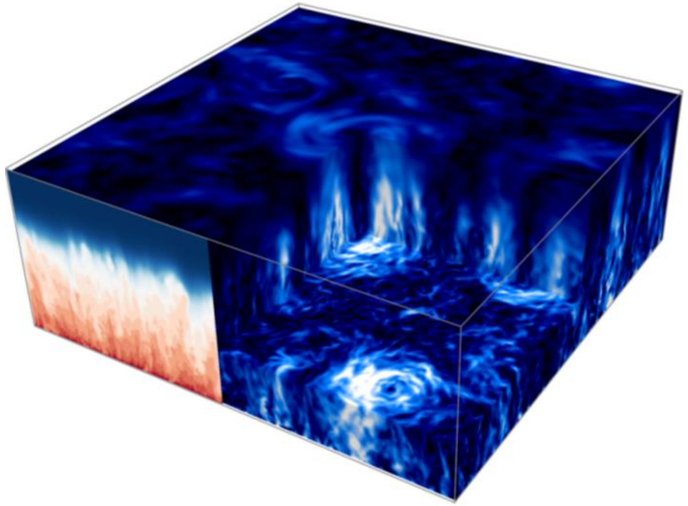


Ice-Water Systems

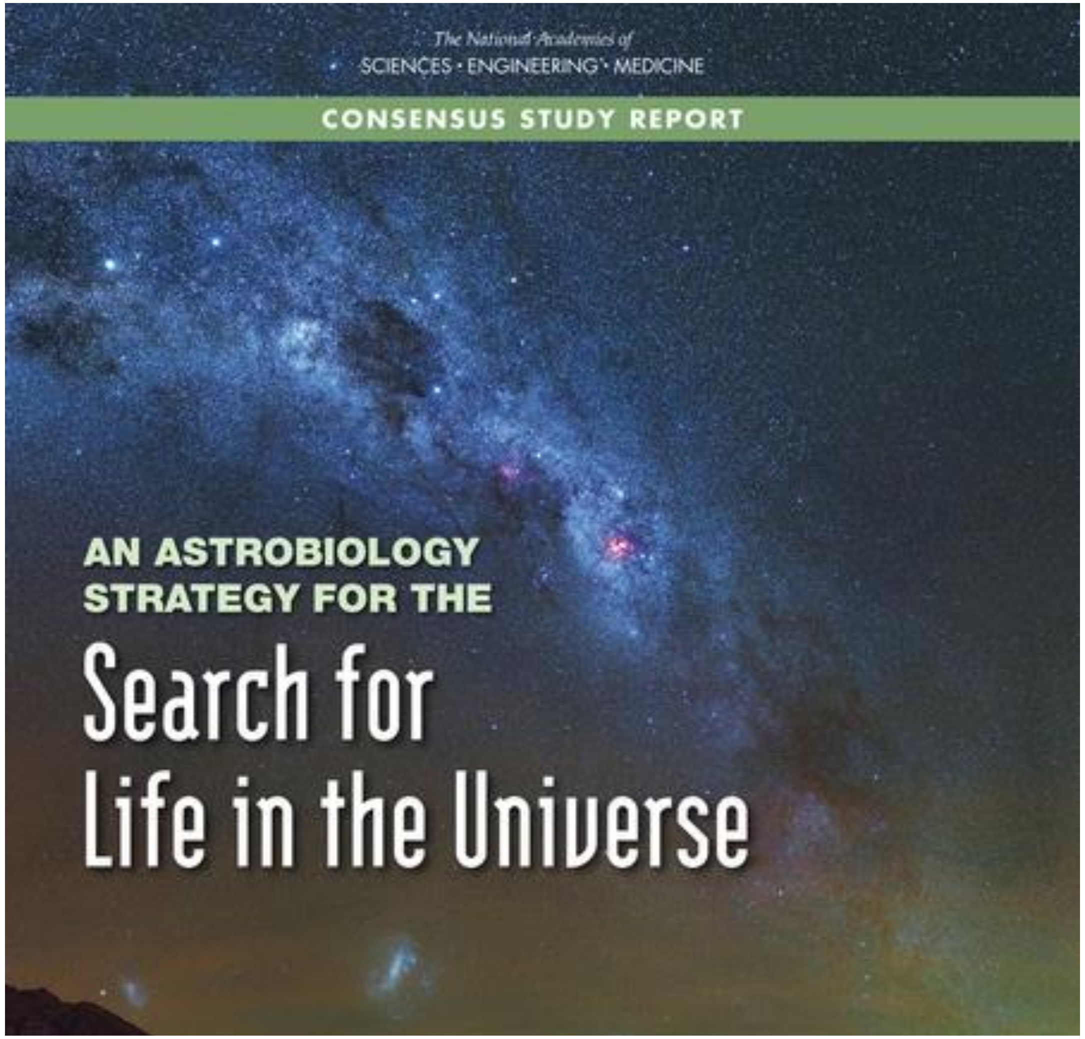








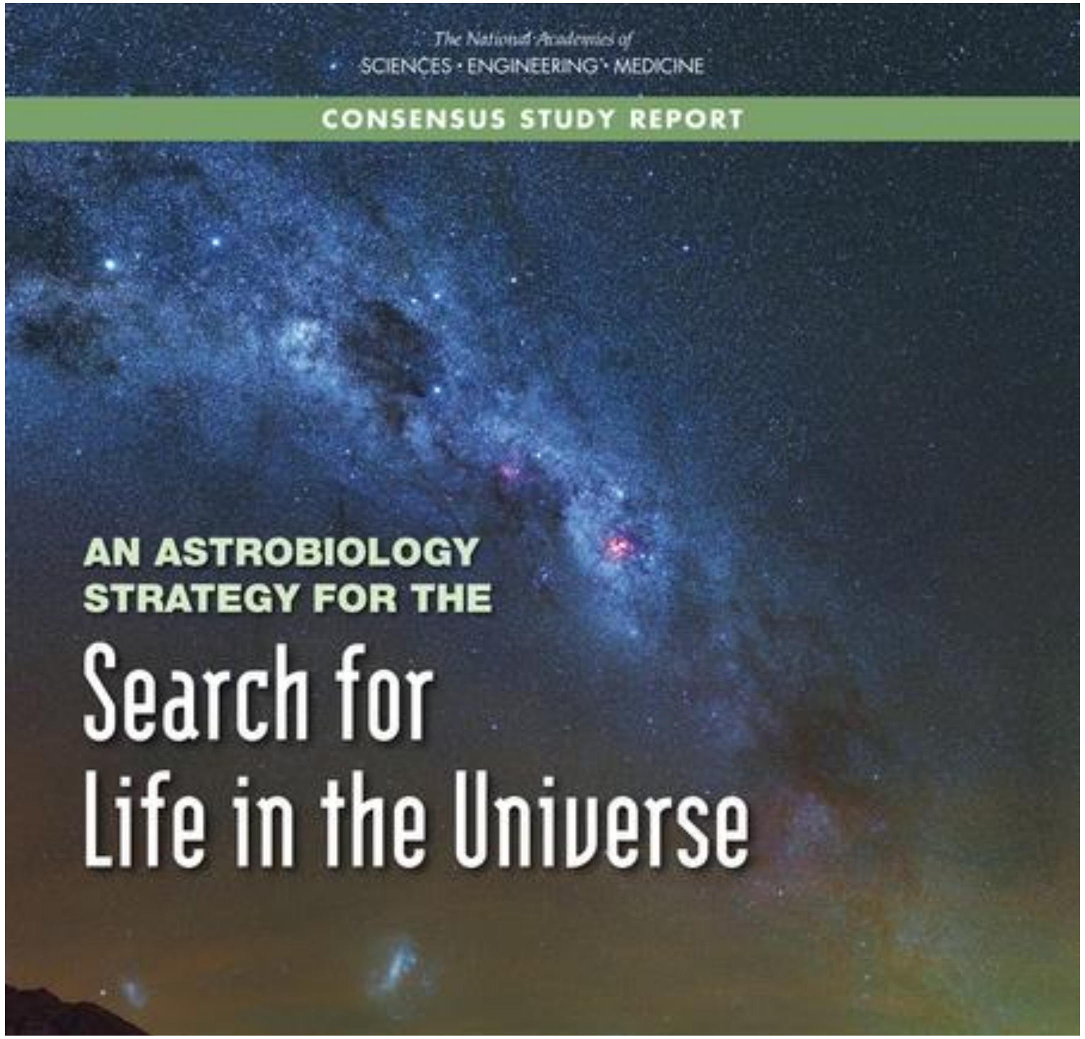
Turbulence & HPC

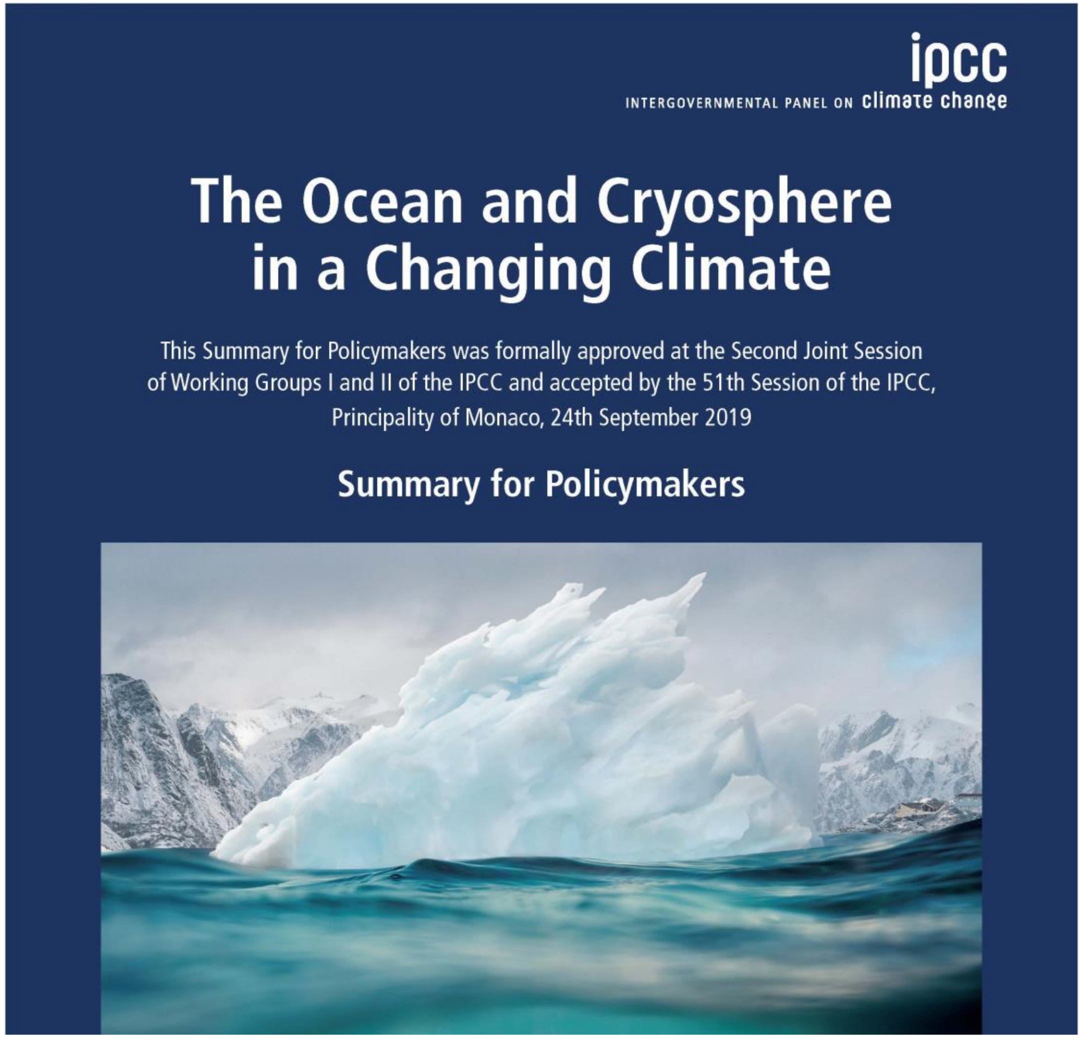


I. Astrobiology

Subglacial hydrodynamics

A. On Earth
B. On Icy Moons





I. Astrobiology

Subglacial hydrodynamics

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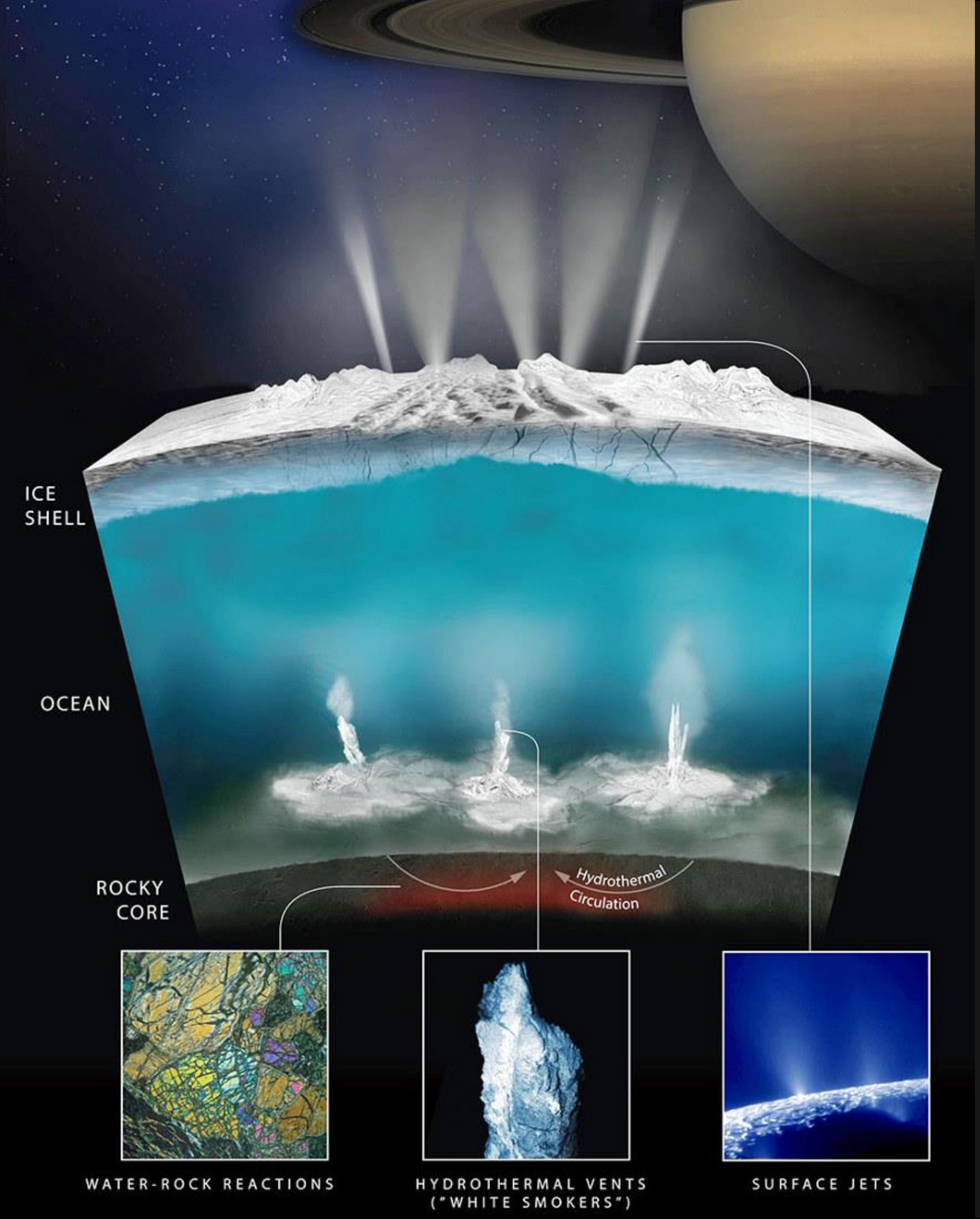
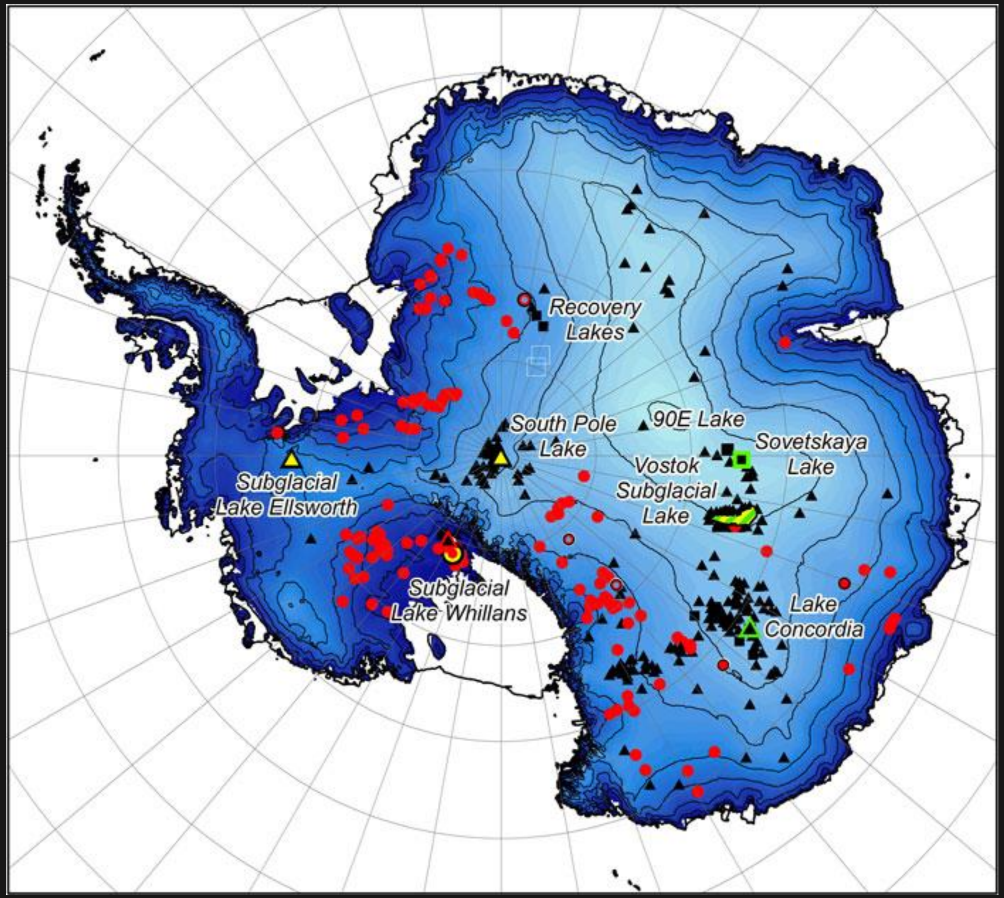
II. Climate change

Ice melting in polar oceans

A. Antarctica
B. Greenland

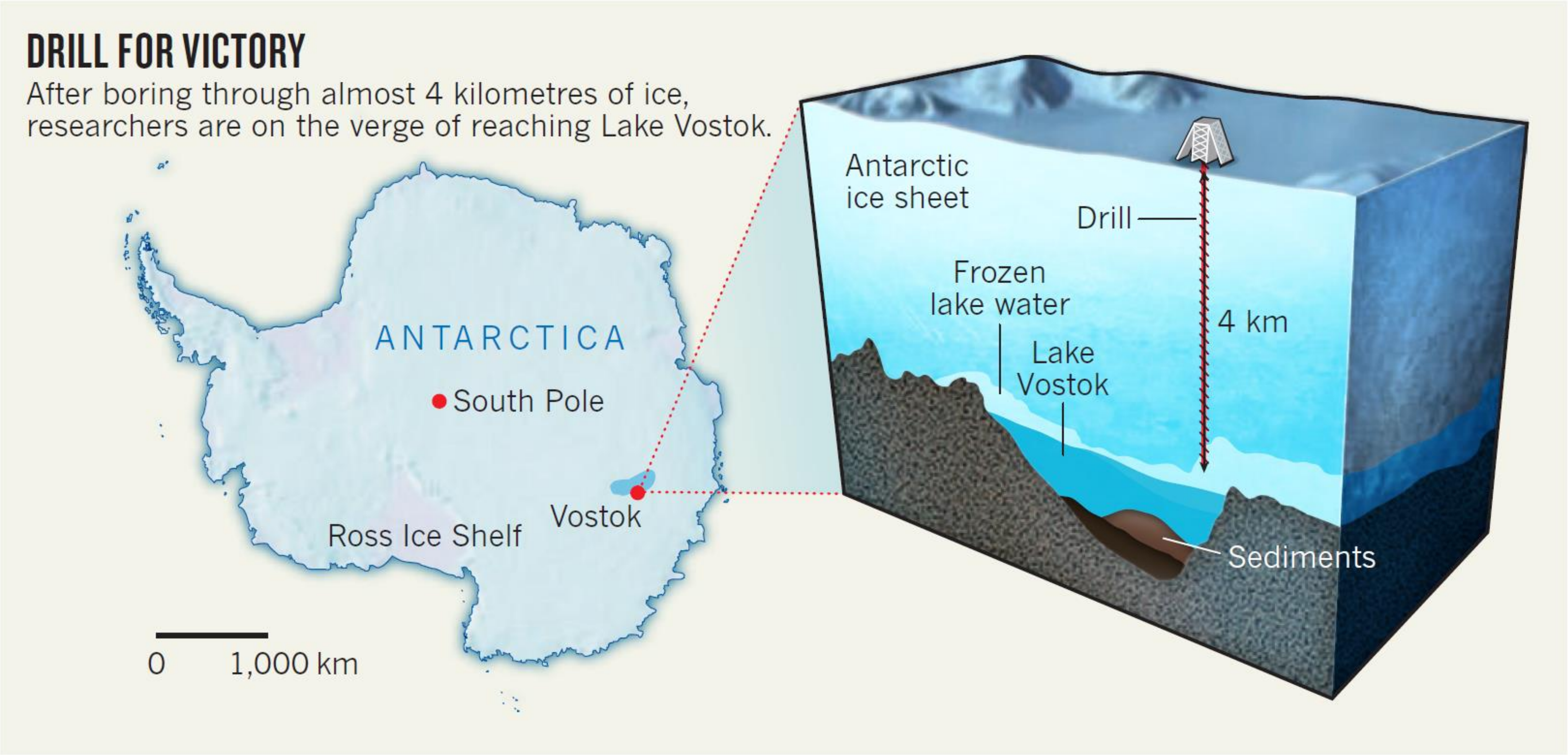




I.A. Sub. Hydro.: On Earth…

- Life in extreme conditions…
- Subglacial lakes as analogues of icy moons

I.A. Sub. Hydro.: On Earth. Subglacial lakes are within reach.



I.A. Sub. Hydro.: On Earth. Are subglacial lakes dynamic environments?

- No wind, nor solar radiations…

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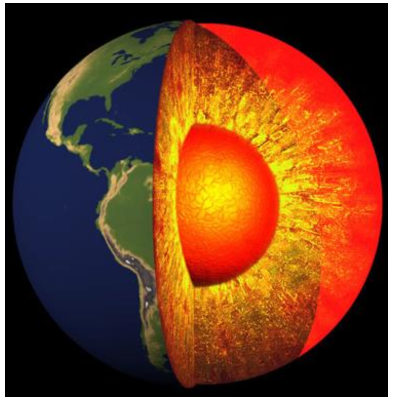
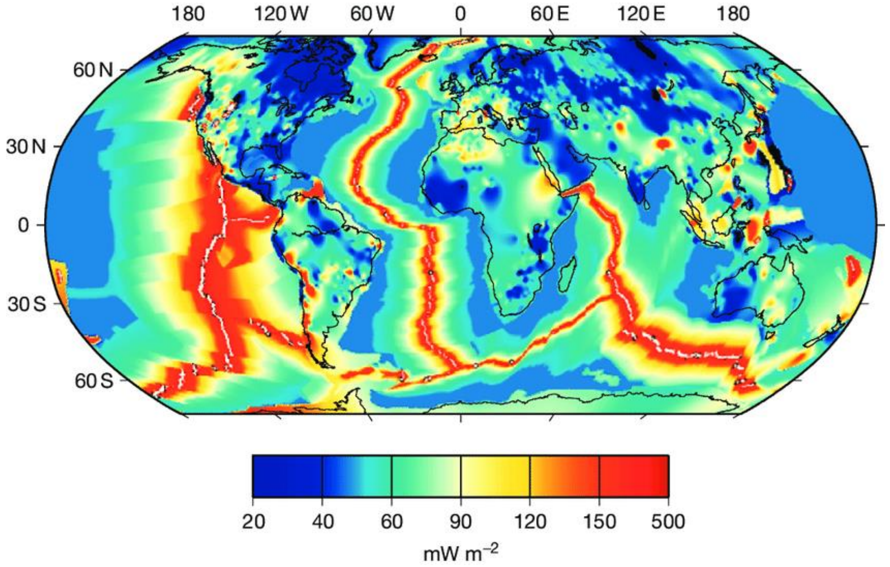
- No wind, nor solar radiations…

- But geothermal heating !





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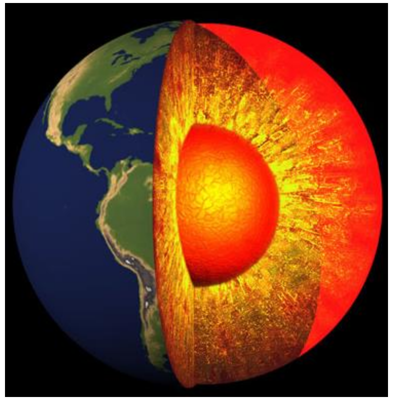
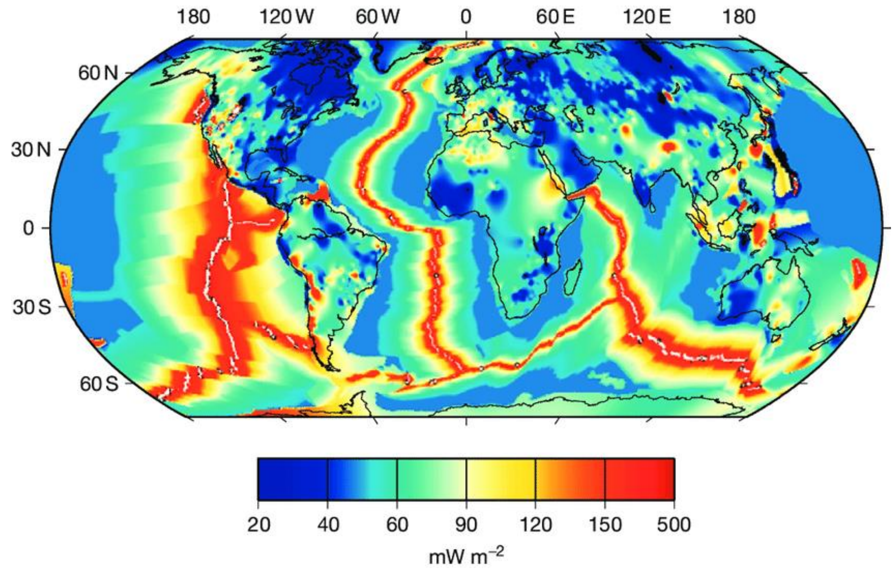
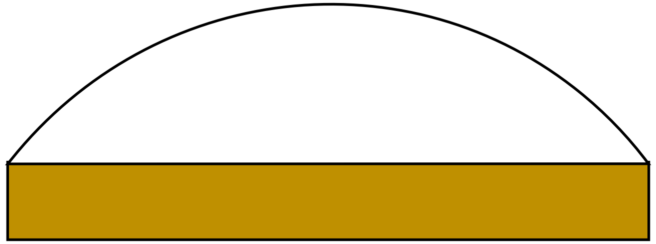
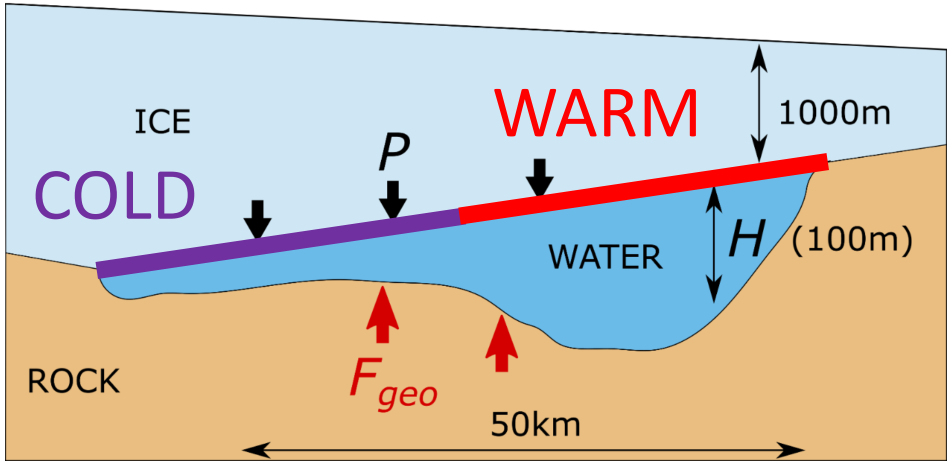




- And heterogeneous ice sheet… ⇒ horizontal temperature gradient !





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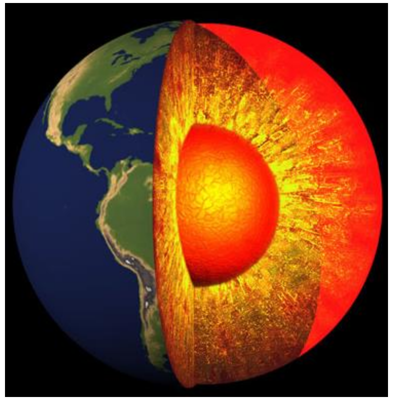

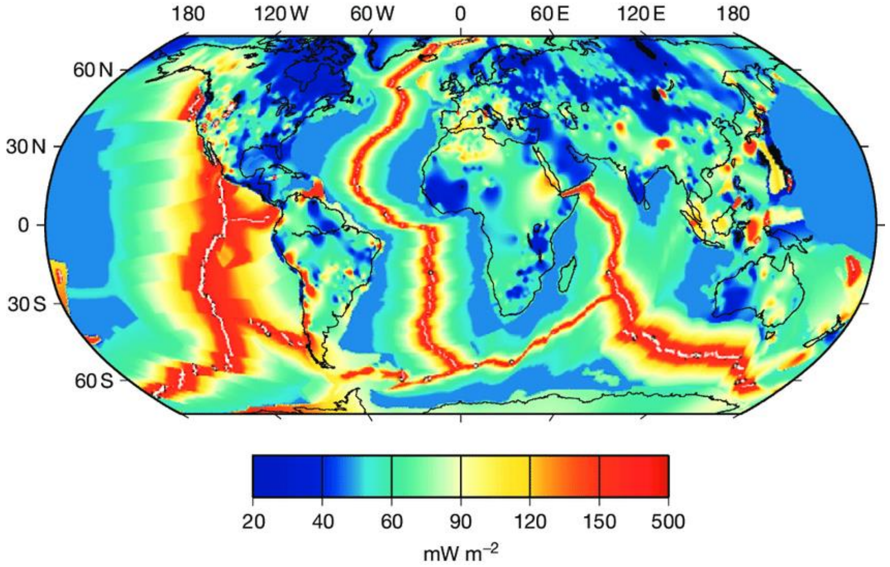

- But geothermal heating !

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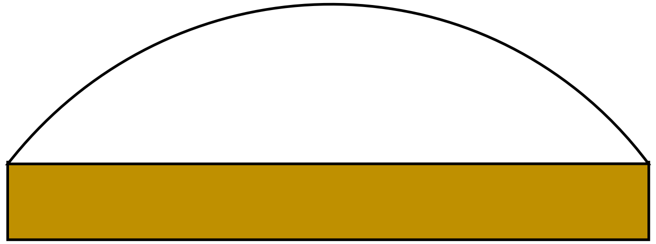
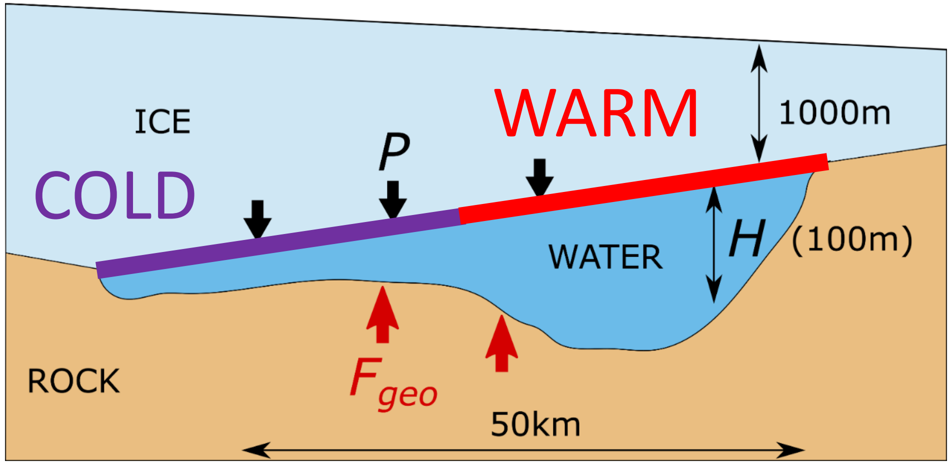
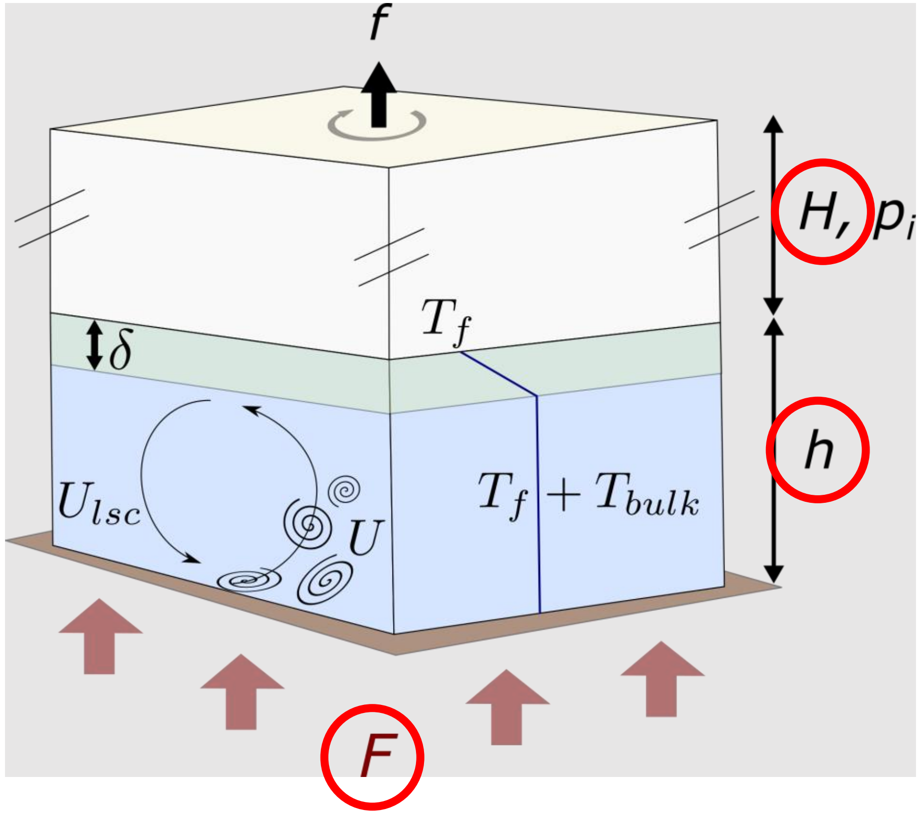


$T_f \approx -10^{-3}(°\mathrm{C/dbar})P$

$\rightarrow$ 1°C/km vertical drop



I.A. Sub. Hydro.: On Earth. Circulation due to geothermal heating.



Science Advances 7.8 (2021): eabc3972. *Journal of Fluid Mechanics* 915 (2021).

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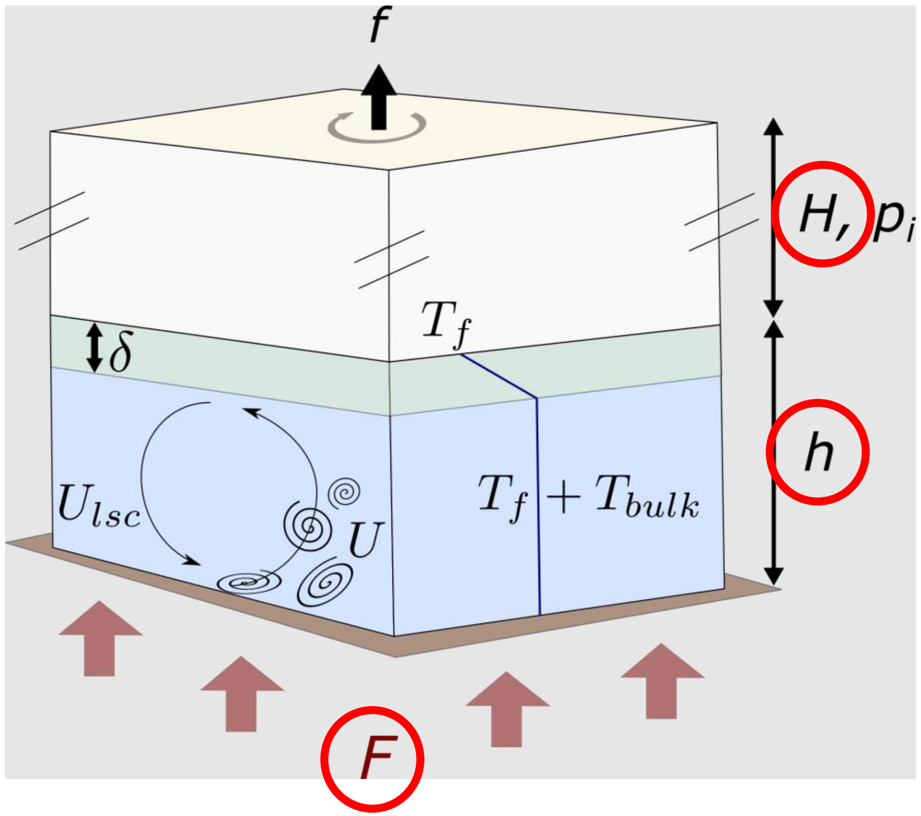
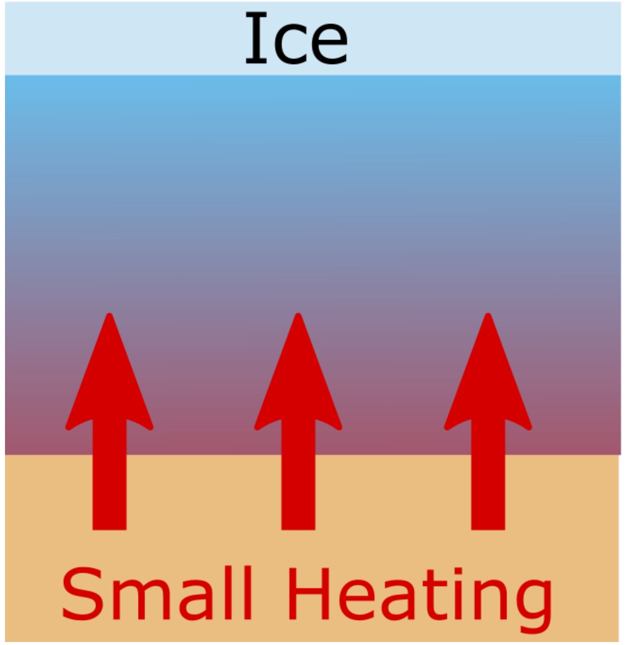
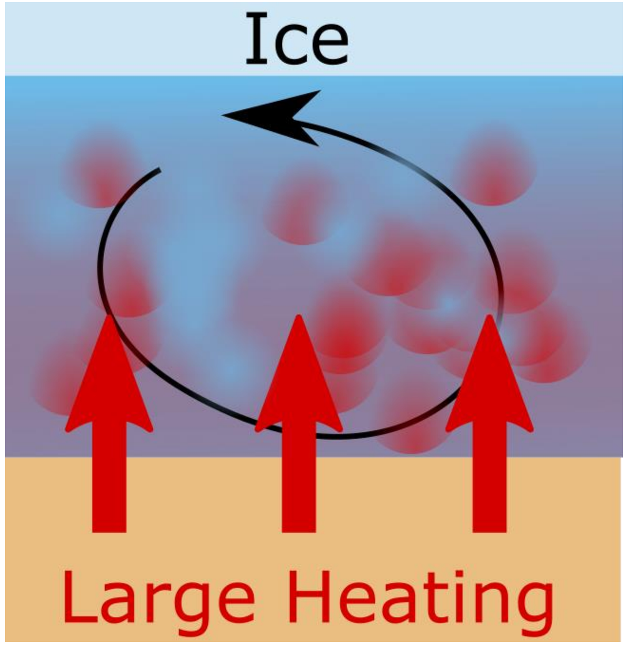


Stable diffusive state. No motion.



Unstable diffusive state. Circulation.



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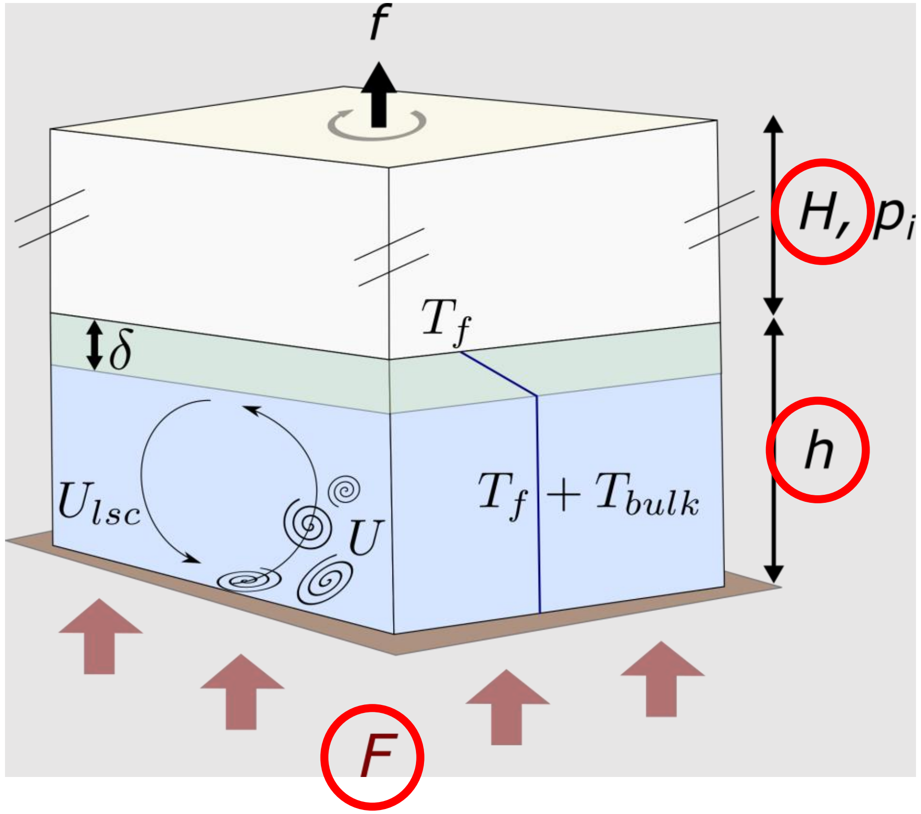
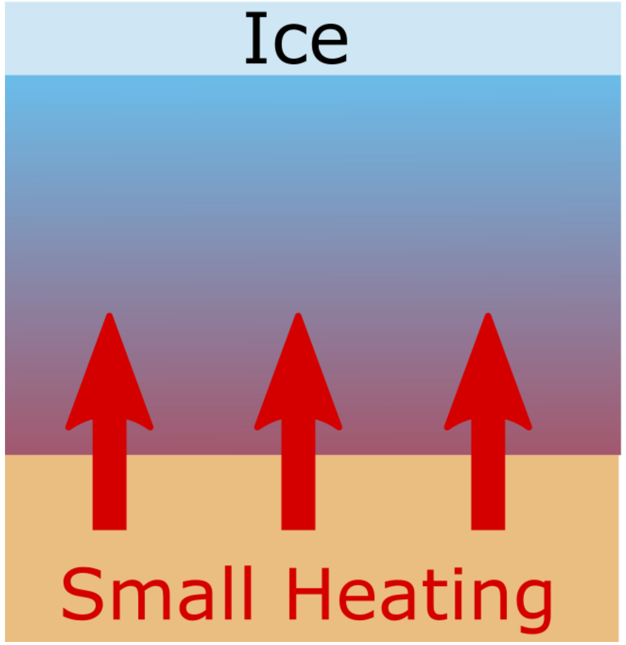


Control Parameter
Rayleigh Number

$$Ra = \frac{g\alpha h^4 F}{\nu\kappa k}$$

Stable diffusive state. No motion.



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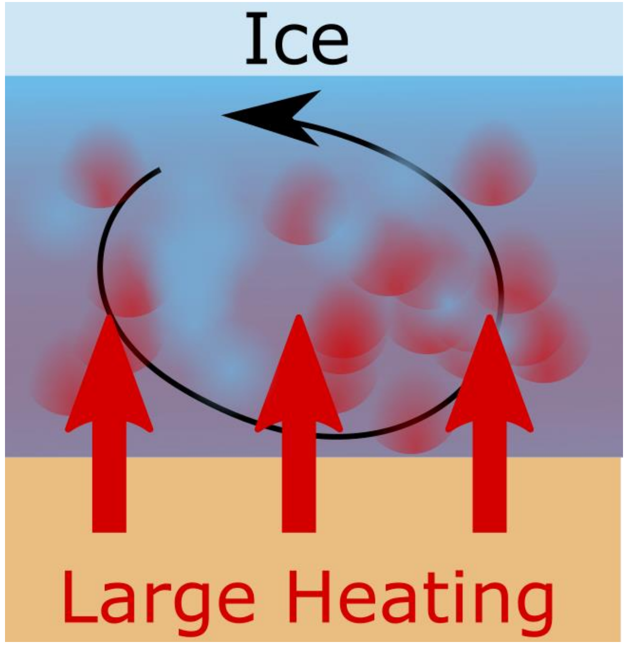

Unstable when $Ra > Ra_C = O(1000)$

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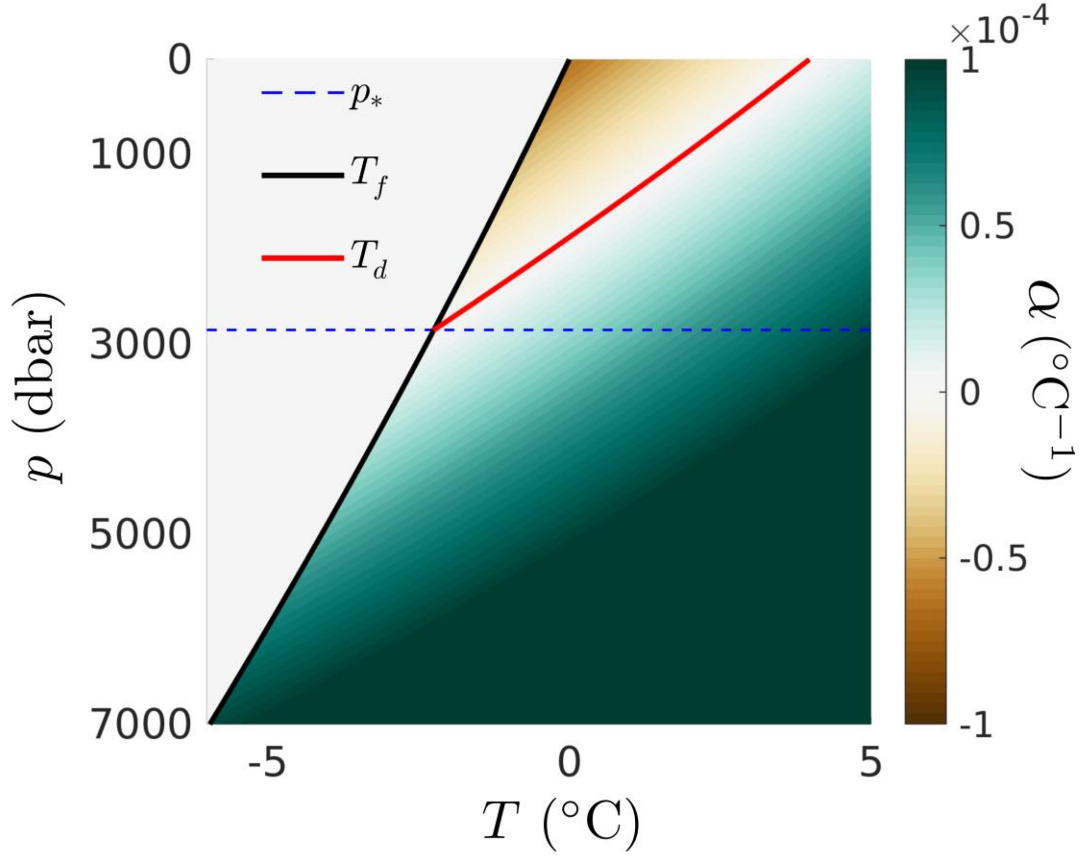
I.A. Sub. Hydro.: On Earth. Stability ? Water has a nonlinear equation of state.



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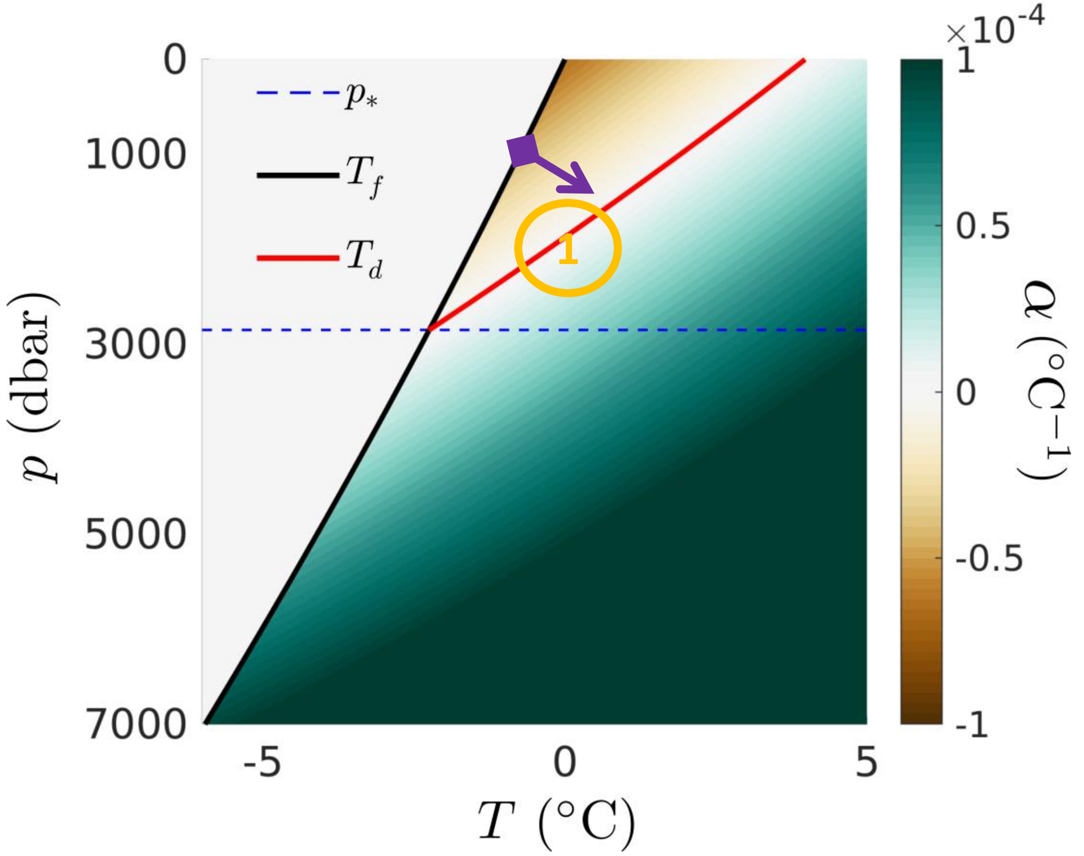
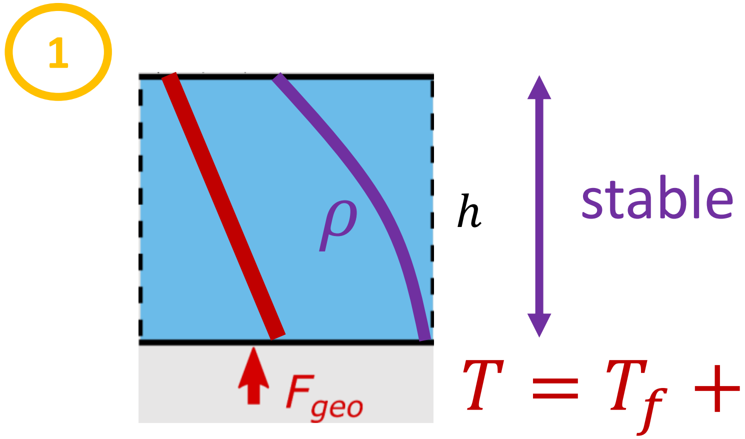
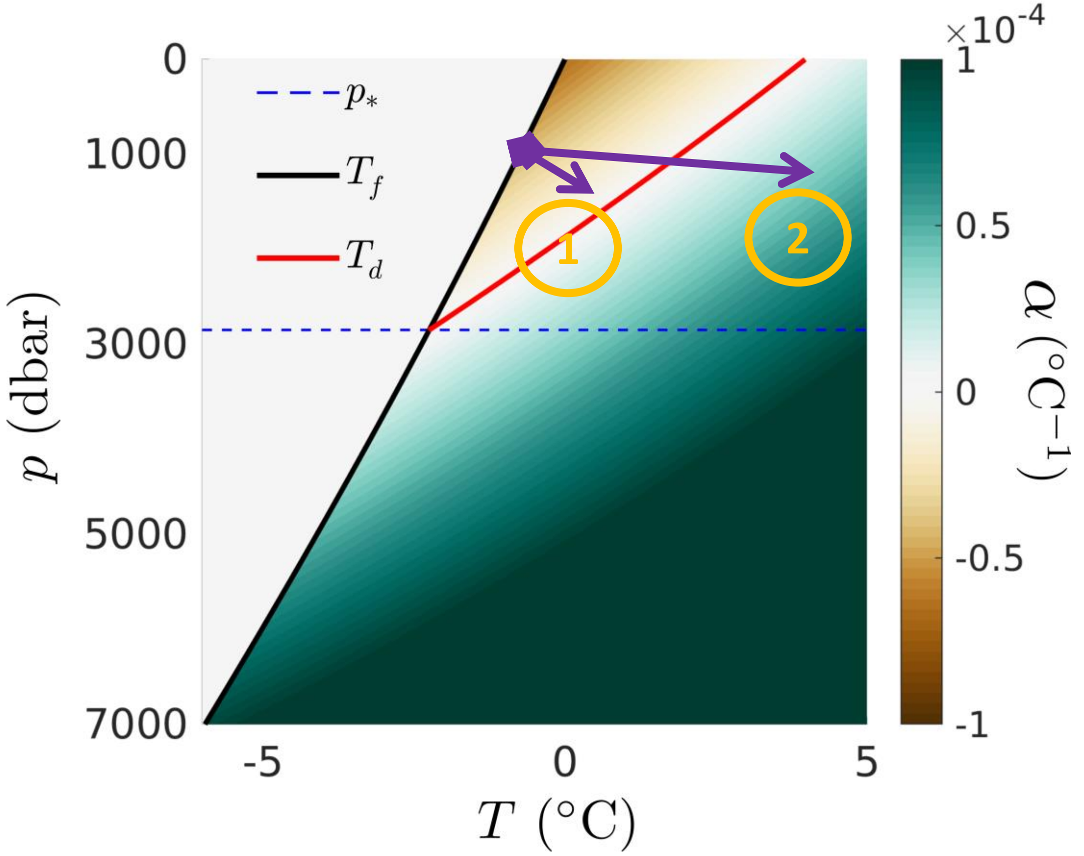
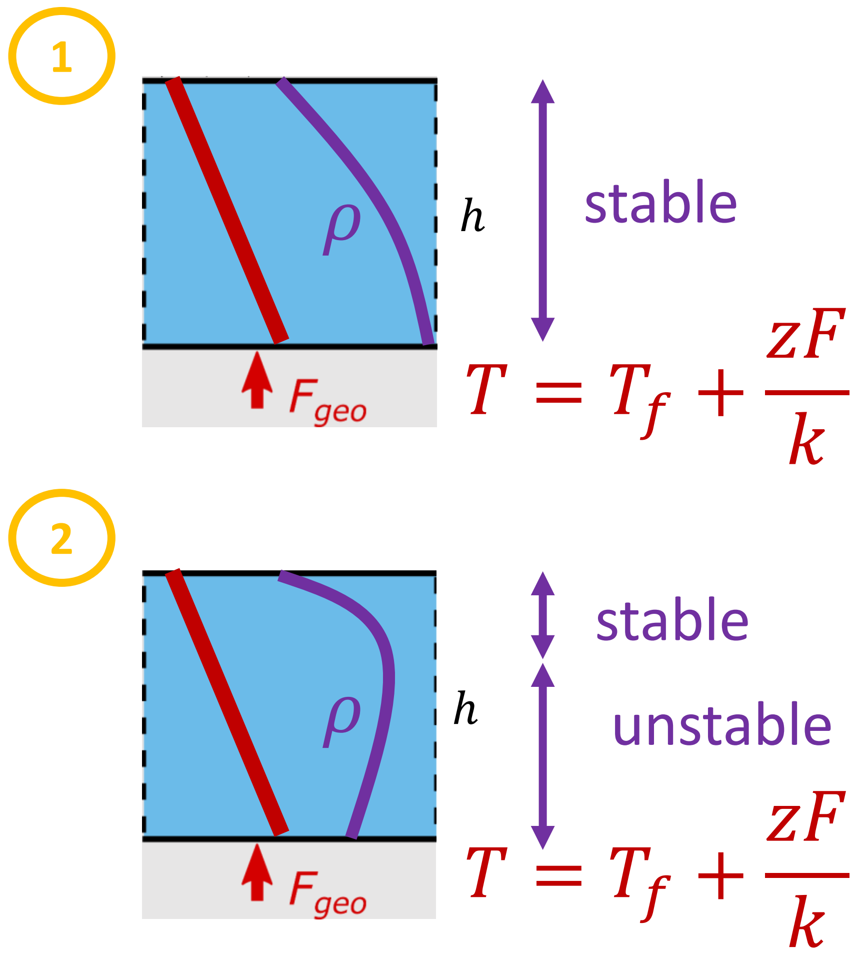




$$T = T_f + \frac{zF}{k}$$

I.A. Sub. Hydro.: On Earth. Stability ? Water has a nonlinear equation of state.





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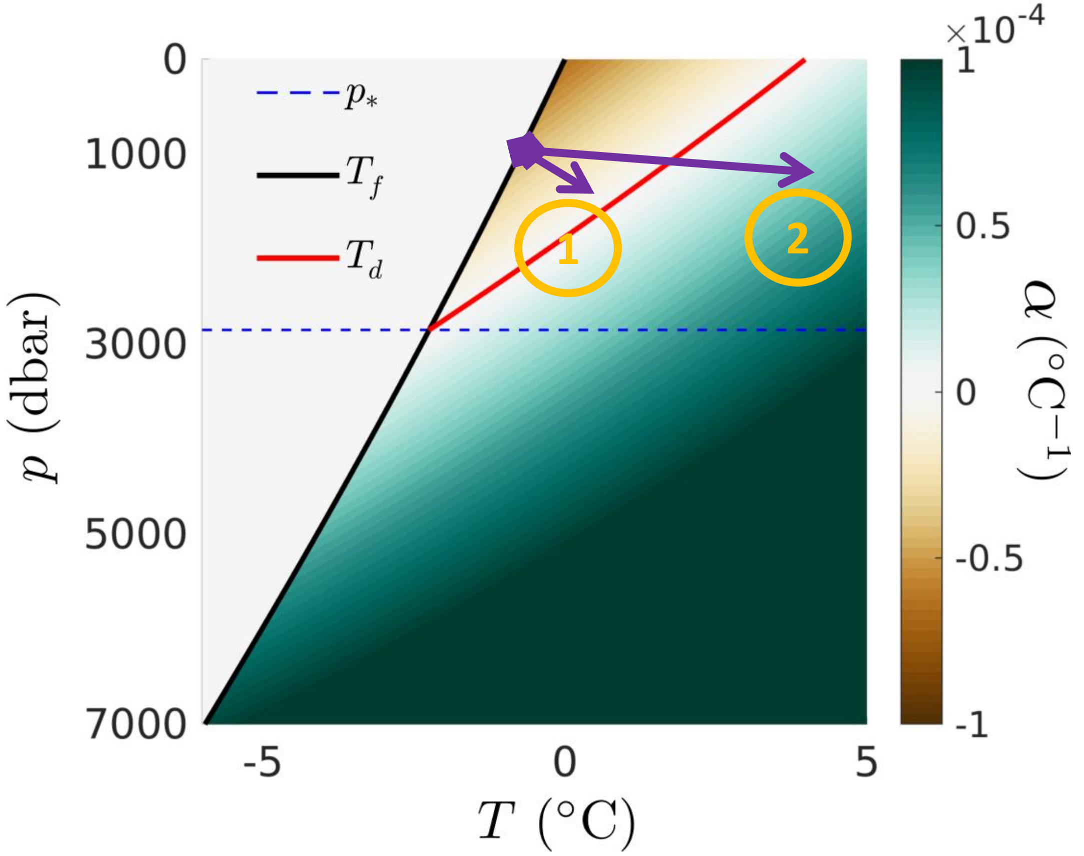
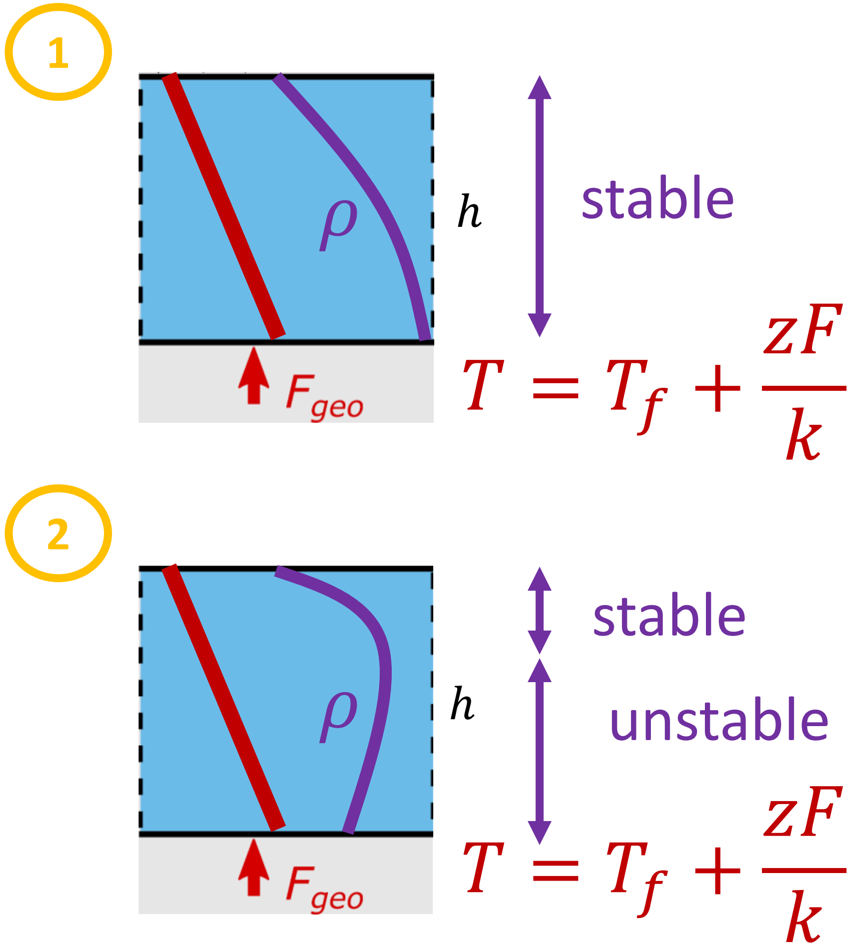
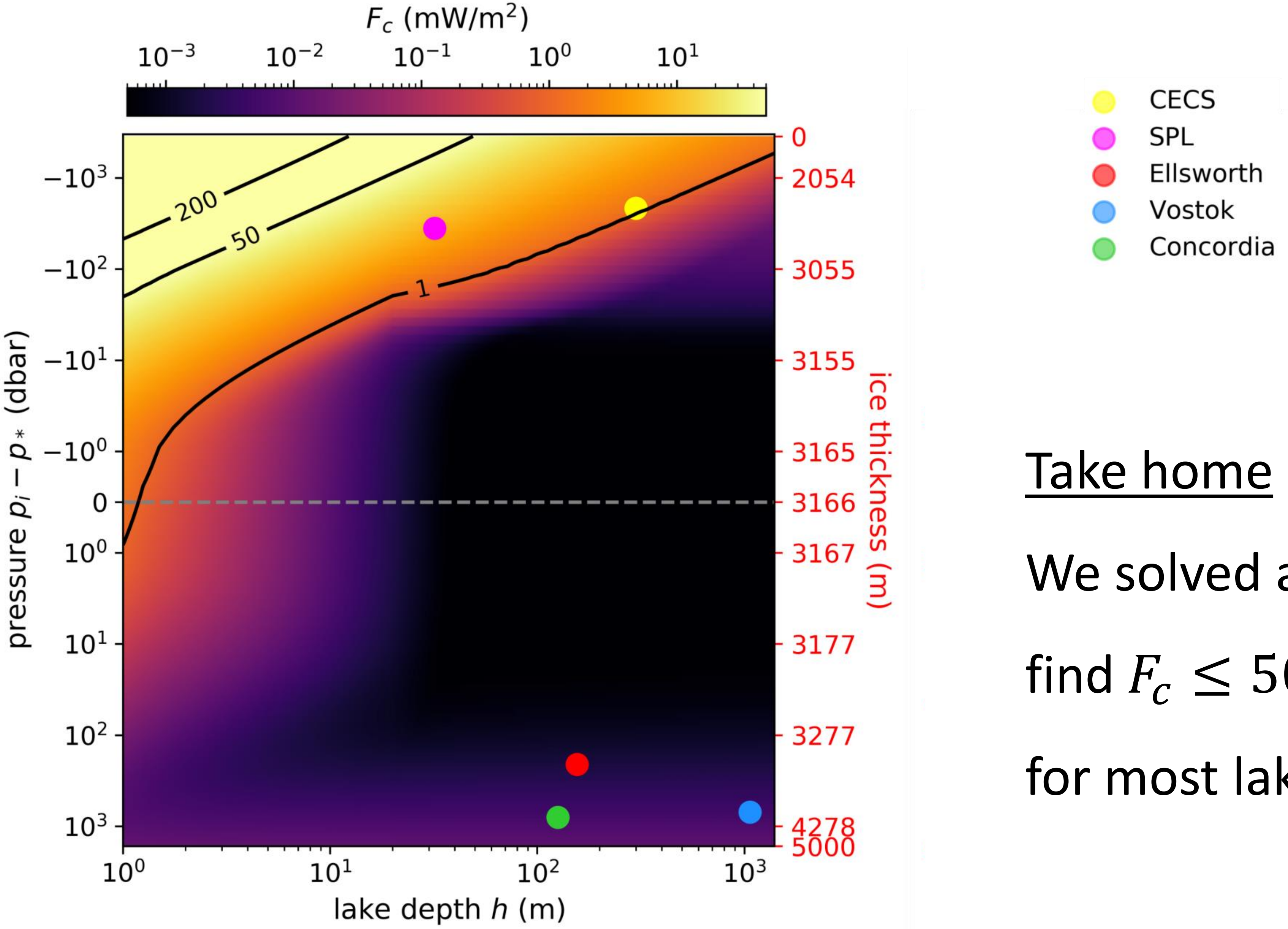




Instability: $\alpha_{bot} > 0$ + Ra large (forcing overcomes dissipation)
+ $F > F_{ad}$ (compressibility effects)

I.A. Sub. Hydro.: On Earth. Critical geothermal heat flux.

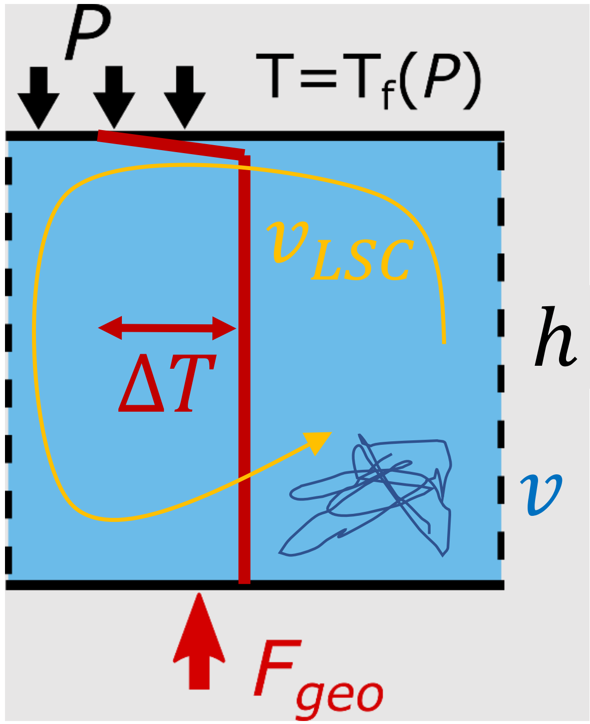


Take home

We solved an EVP to find $F_c \leq 50\ mW/m^2$ for most lakes.

We want to know…

- Turbulence
- Circulation
- Mean temperature



I.A. Sub. Hydro.: On Earth. Circulation due to geothermal heating.

<u>We want to know…</u>

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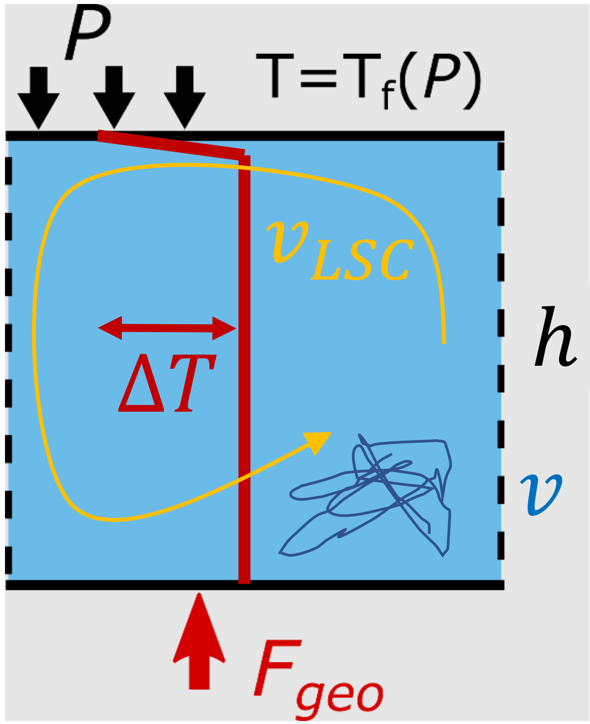
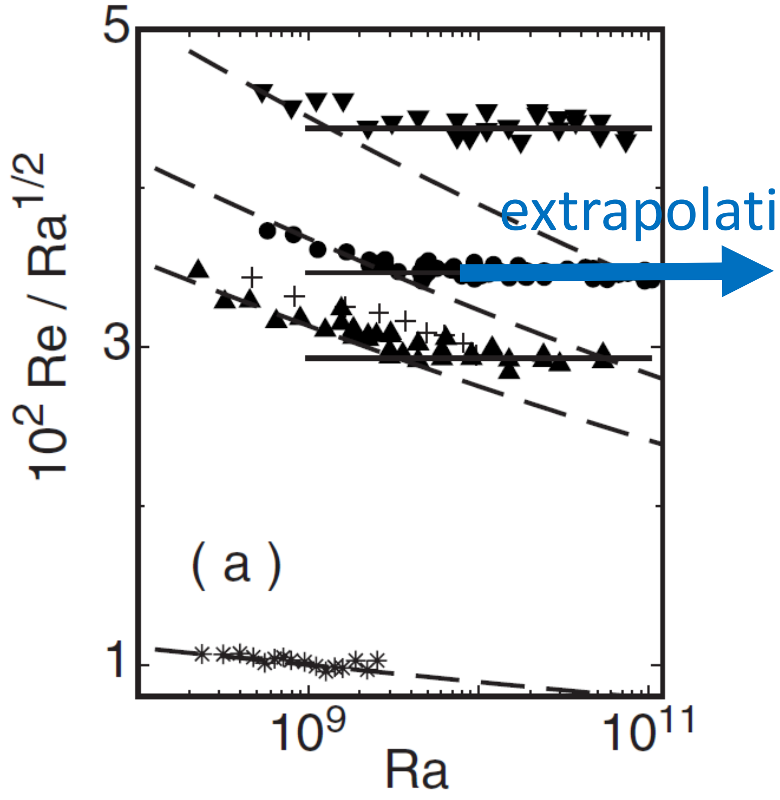
Reynolds number

$$Re = \frac{vh}{\nu} \approx 0.03 Ra^{\frac{1}{2}}$$





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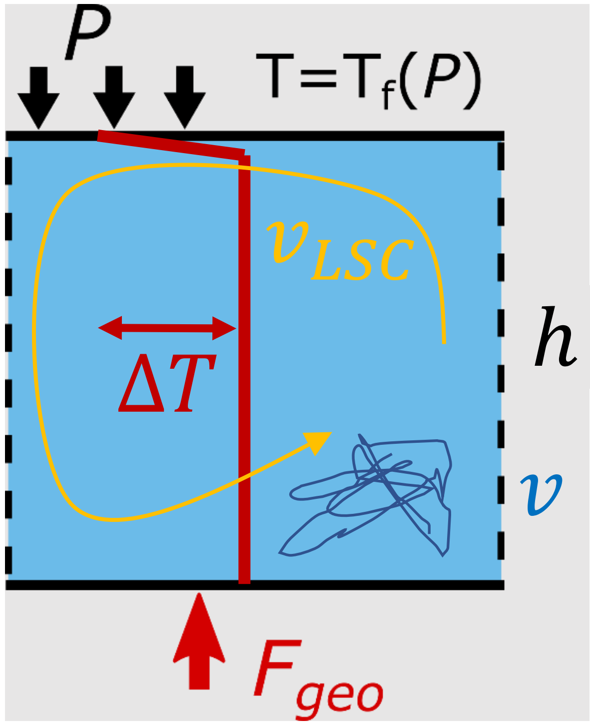

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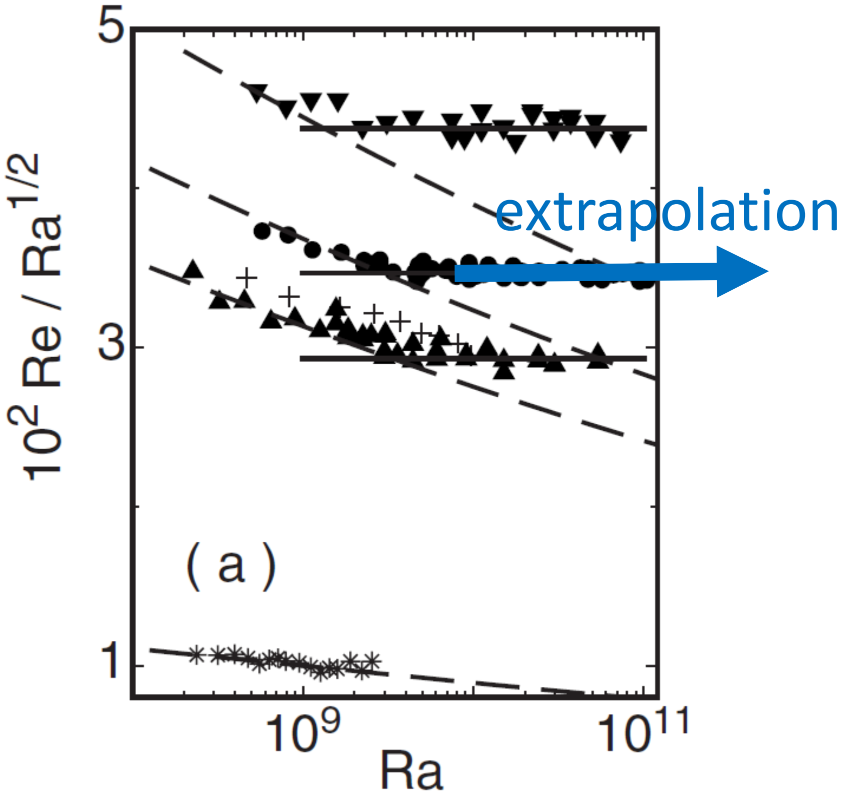
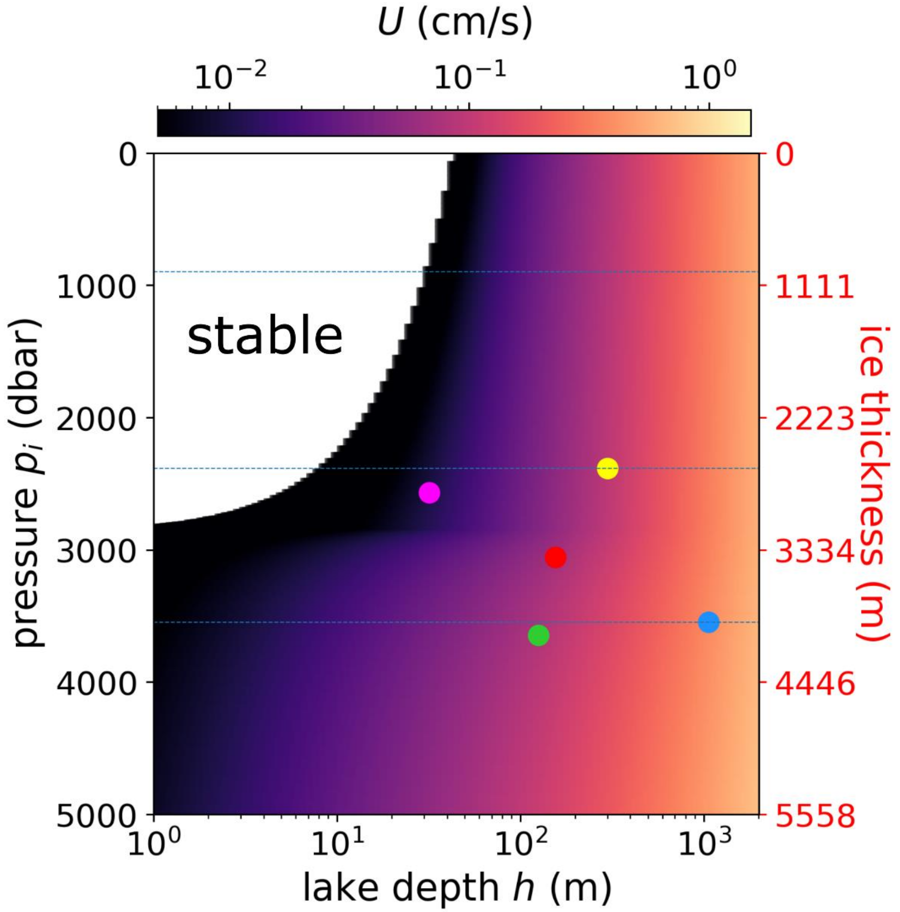


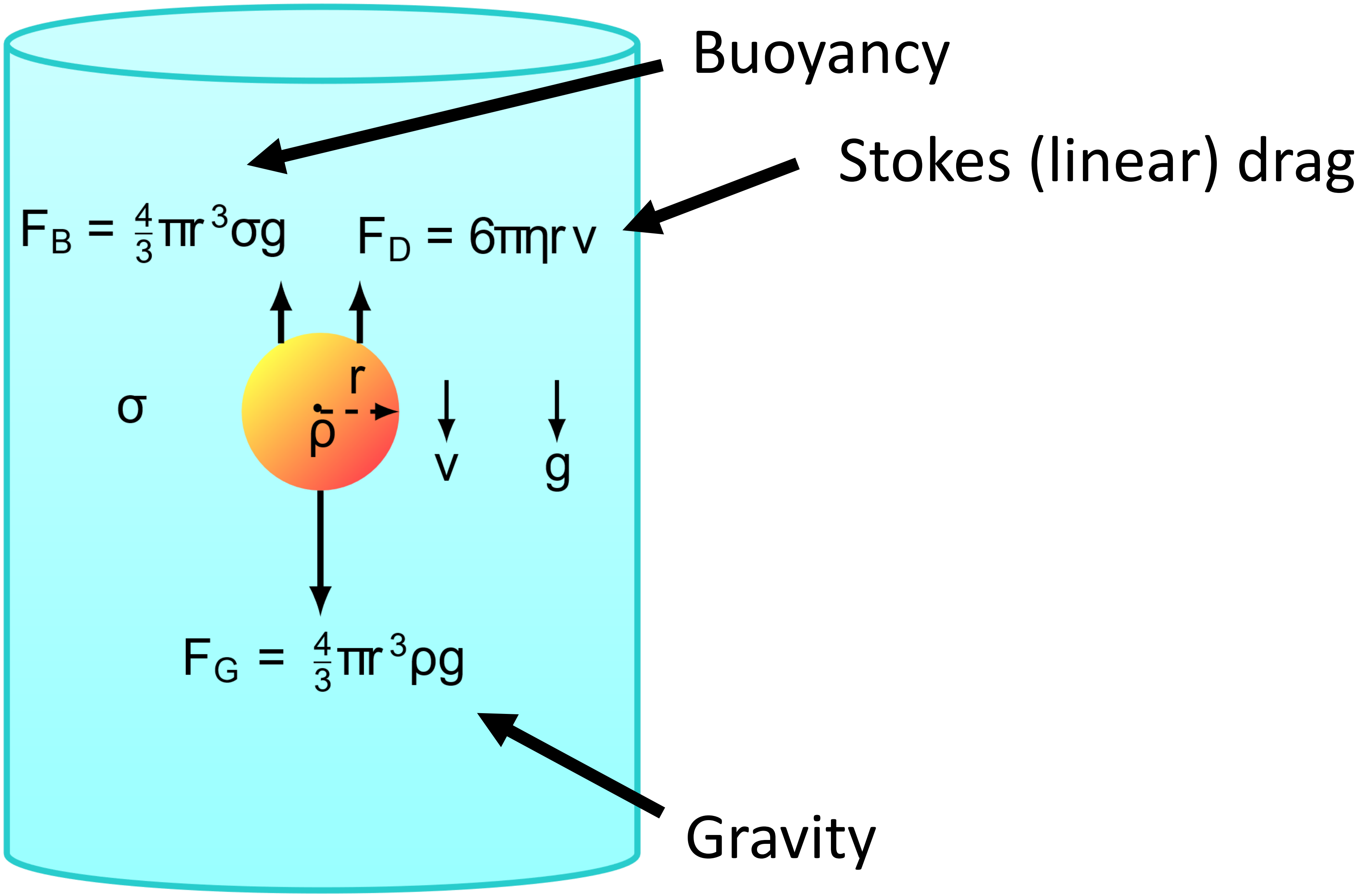
Take home

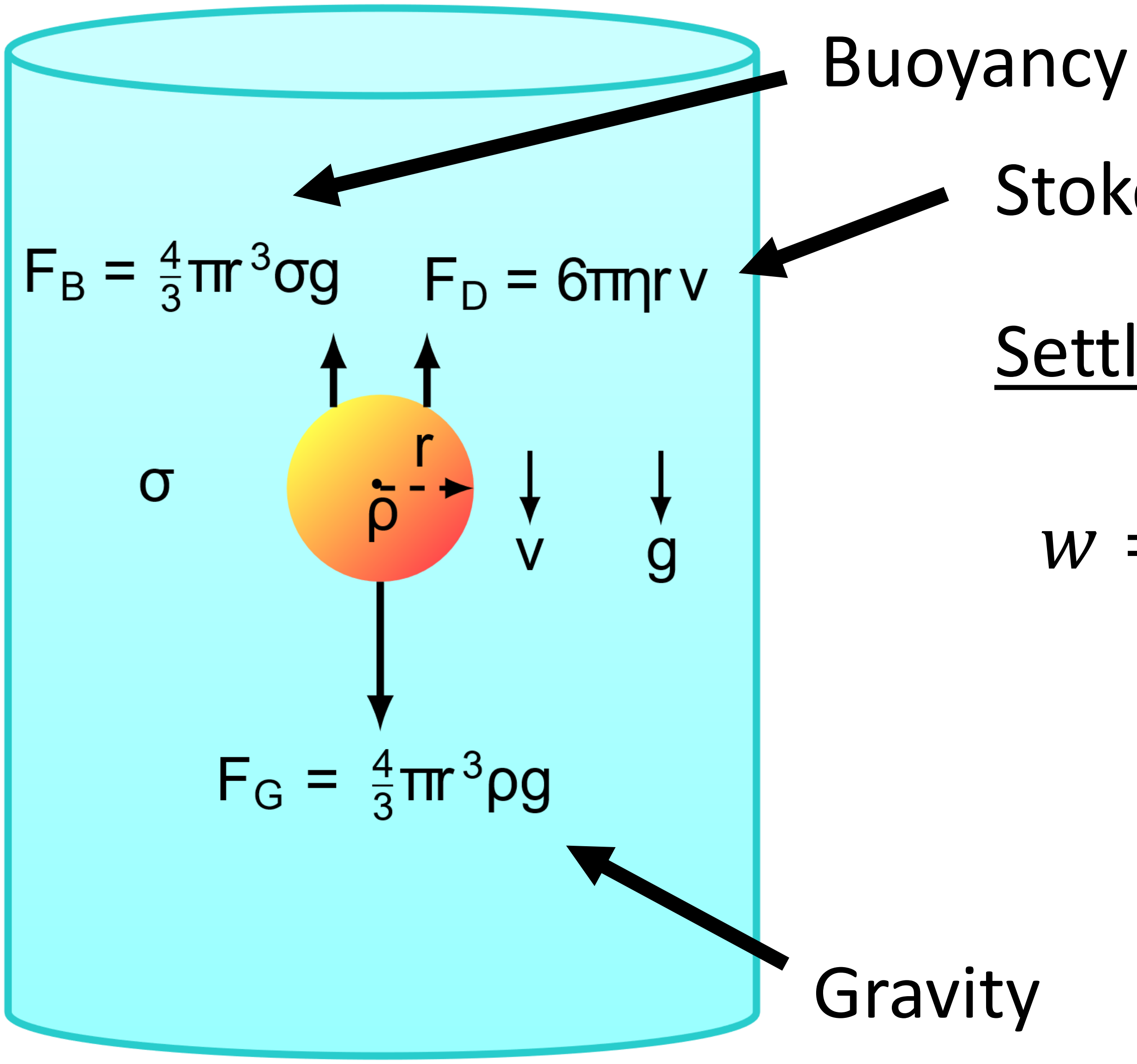
v up to few mm/s

v increases with h



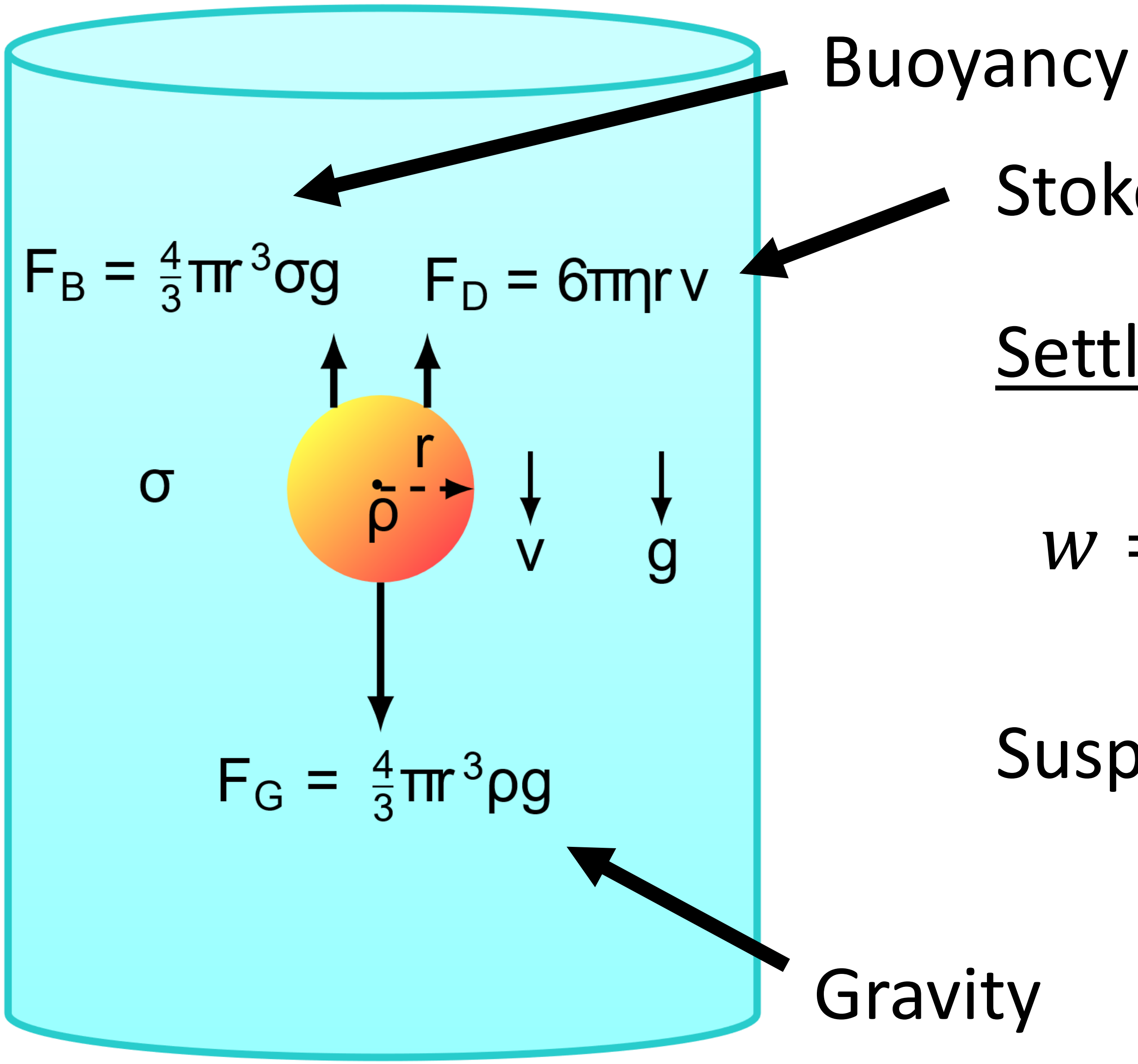
I.A. Sub. Hydro.: On Earth. Convective transport of particles.





Settling/sedimentation velocity

$$w = \frac{2g(\rho_w - \rho_p)r^2}{9\eta}$$



Settling/sedimentation velocity

$$w = \frac{2g(\rho_w - \rho_p) r^2}{9\eta}$$

Suspended if $v > w \;\rightarrow r_{max}$

I.A. Sub. Hydro.: On Earth. Convective transport of particles.

	Ice thickness (m)	Water depth (m)	U (mm/s)	U_{lsc} (mm/s)	$2r_{max}$ (µm)
CECs	2653	300	0.97	0.32	22
SPL	2857	32	0.10	0.04	7.8
Ellsworth	3400	156	0.69	0.26	20
Vostok	3945	1067	3.80	0.85	36
Concordia	4055	126	0.83	0.31	22

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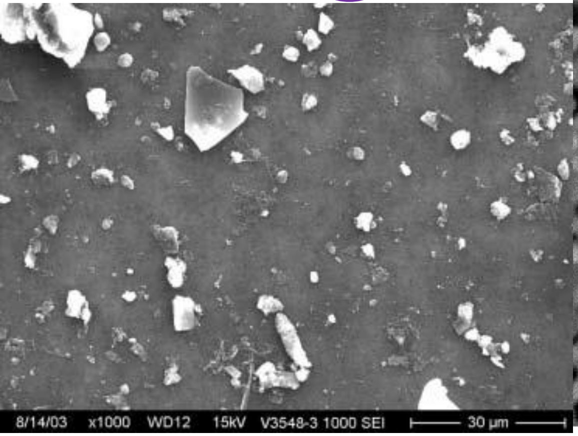
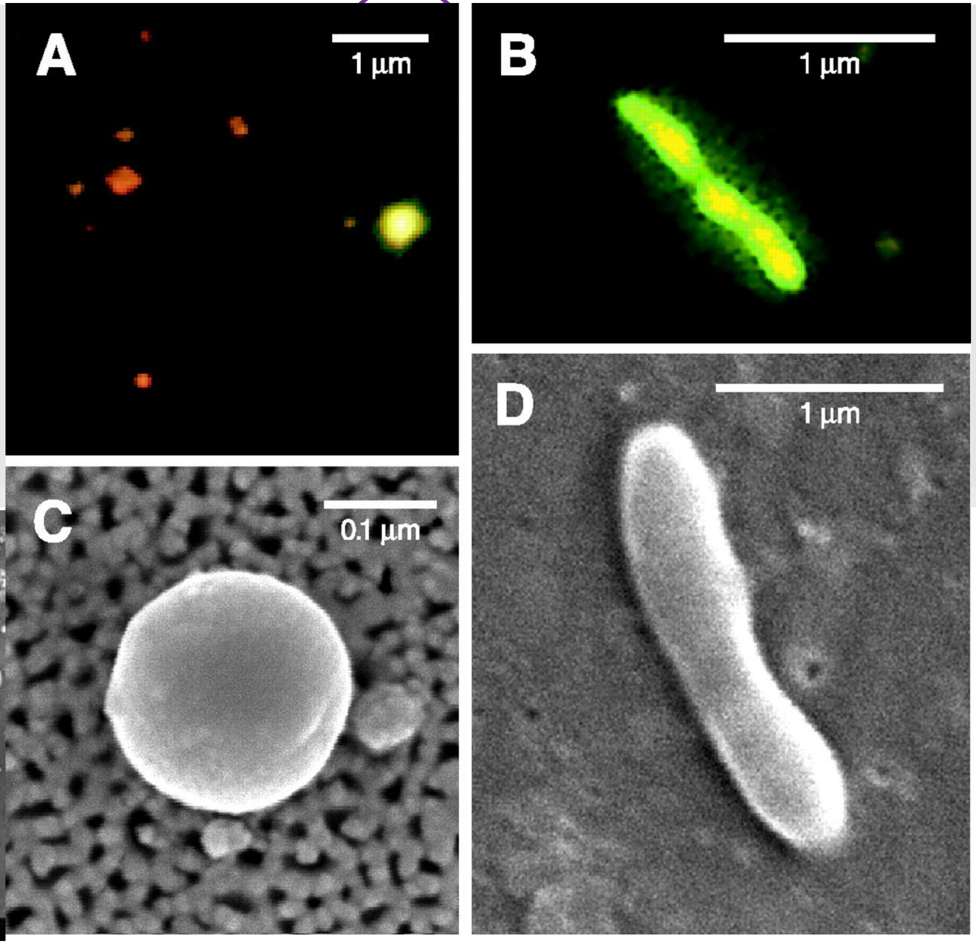
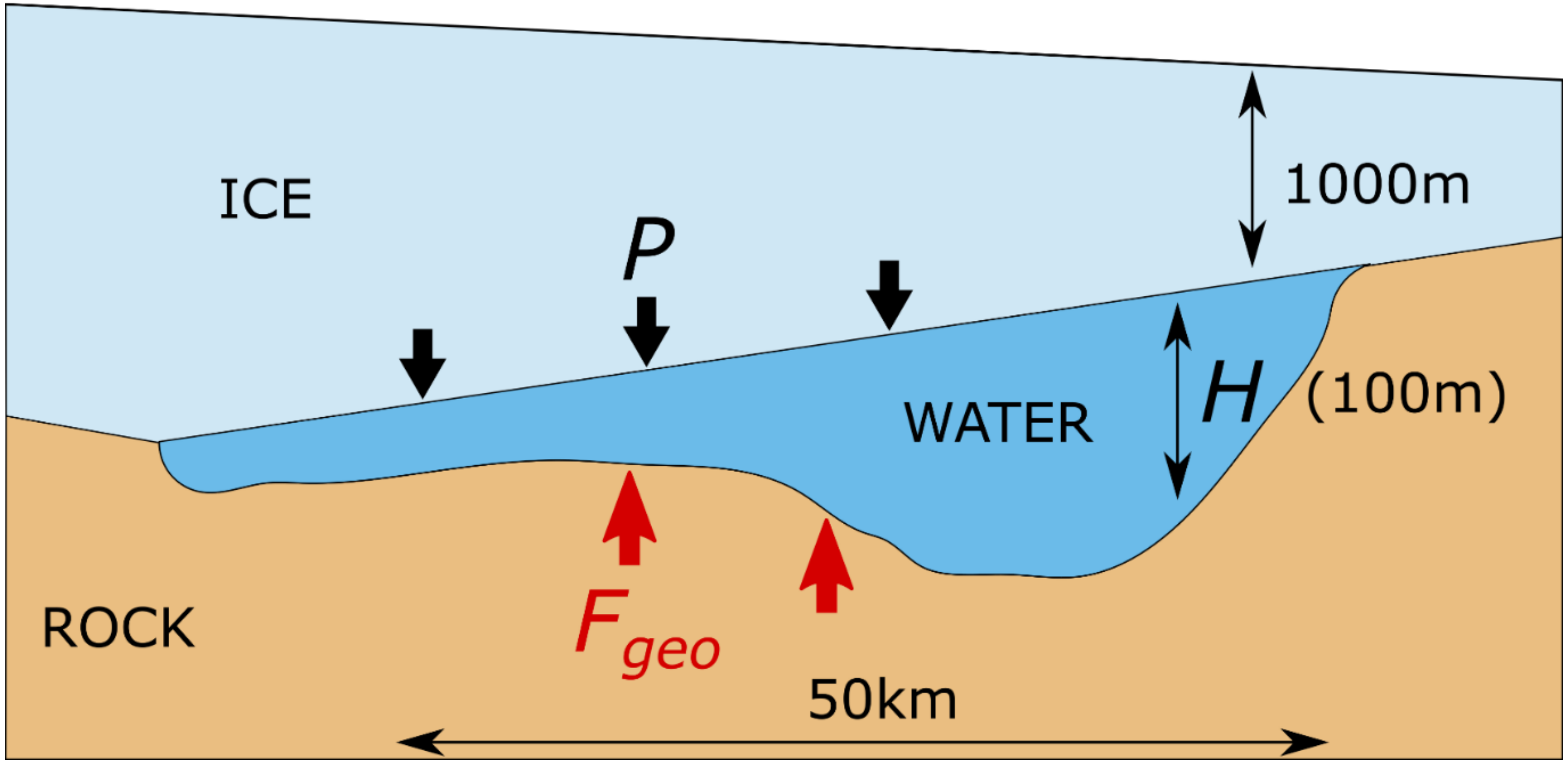




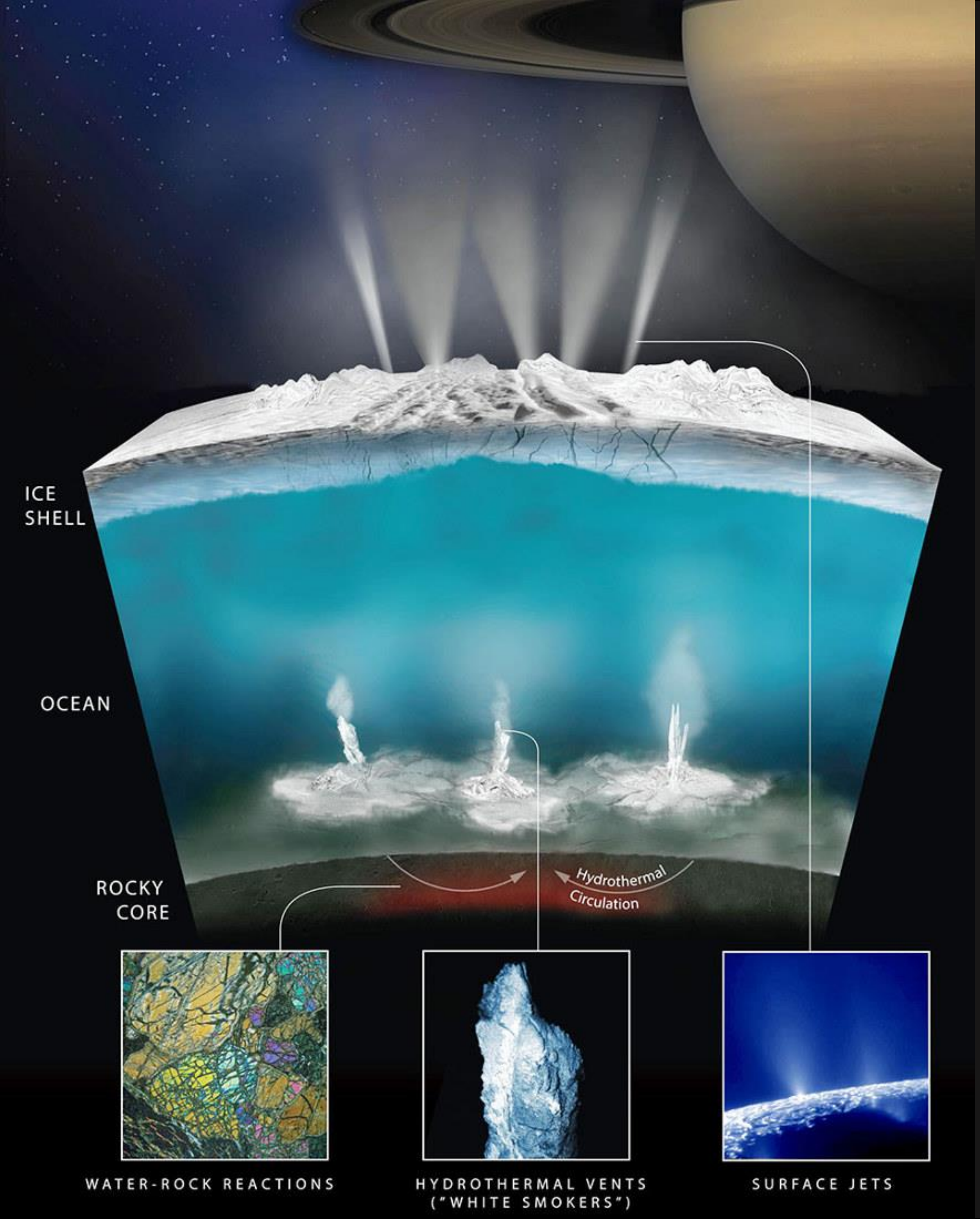
Take home

Microorganisms & dust aggregates can be suspended and encapsulated within the ice through freezing → good news for accreted ice analysis.

- Horizontal temperature gradient*
- Advanced particle transport model
- Lake CECs**



*ongoing project (J. Nandaha M2 internship)
**in collaboration with CECs (Chile) and BAS (UK)



credit ©C. Michaut *J.Geophys. Res. Planets*, *119*, 550–573, 2014

I.B. Sub. Hydro.: On Icy Moons

- ~~Global oceans~~; near-surface, small-scale water pockets lurking beneath crustal topography.

I.B. Sub. Hydro.: On Icy Moons. Crustal dynamics following intrusion.

What about the water dynamics?

Icarus 286 (2017) 261–269

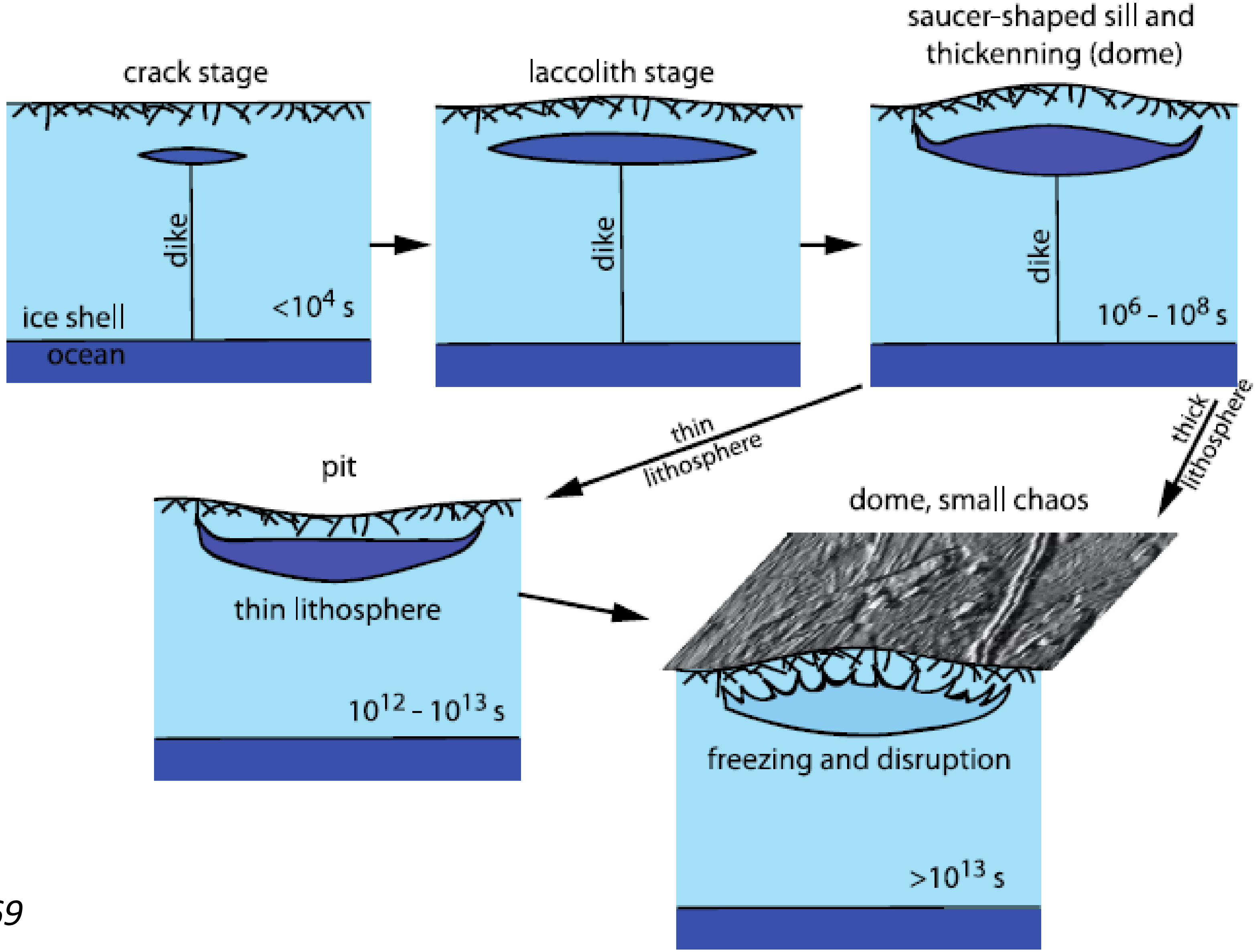


Fig. 3. Schematic illustration of the evolution of a saucer-shaped sill and its surface expression to create pits, domes or small chaos. The upward-pointing parts of the frozen sill represent intrusions produced by freezing and lead to surface disruption, or extrusion to make spots. Not to scale.

I.B. Sub. Hydro.: On Icy Moons. Longevity and cryovolcanism.

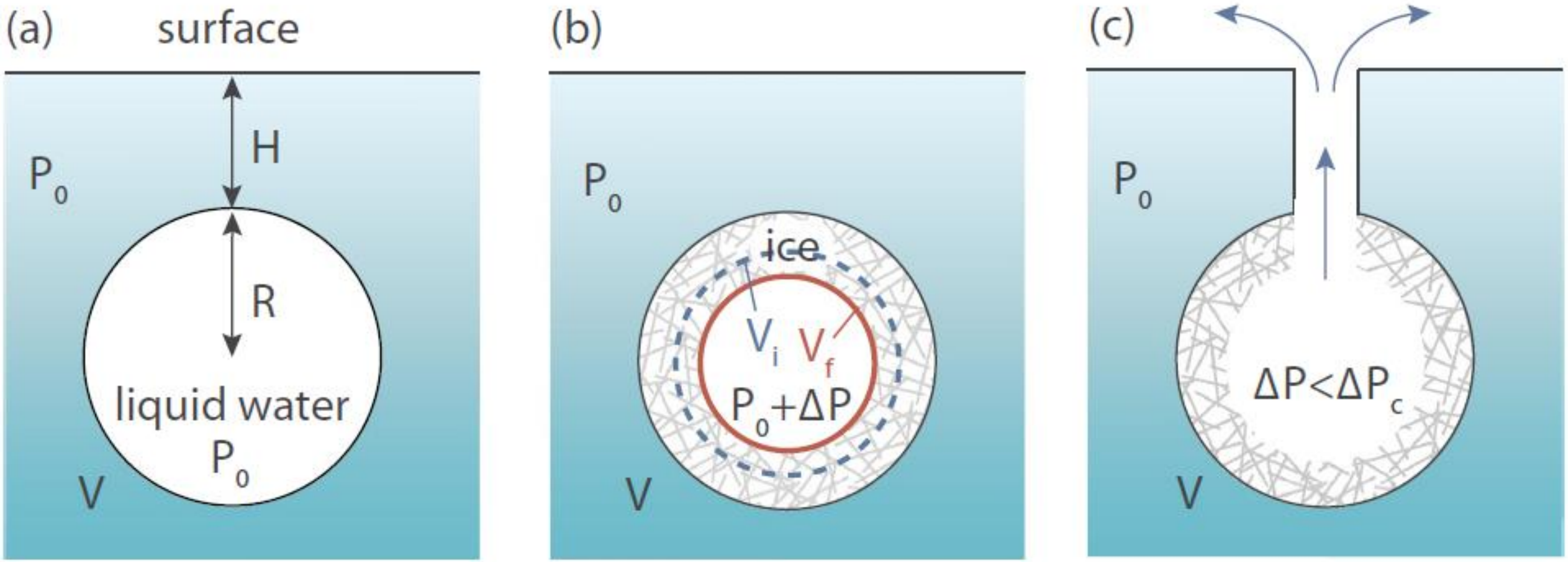
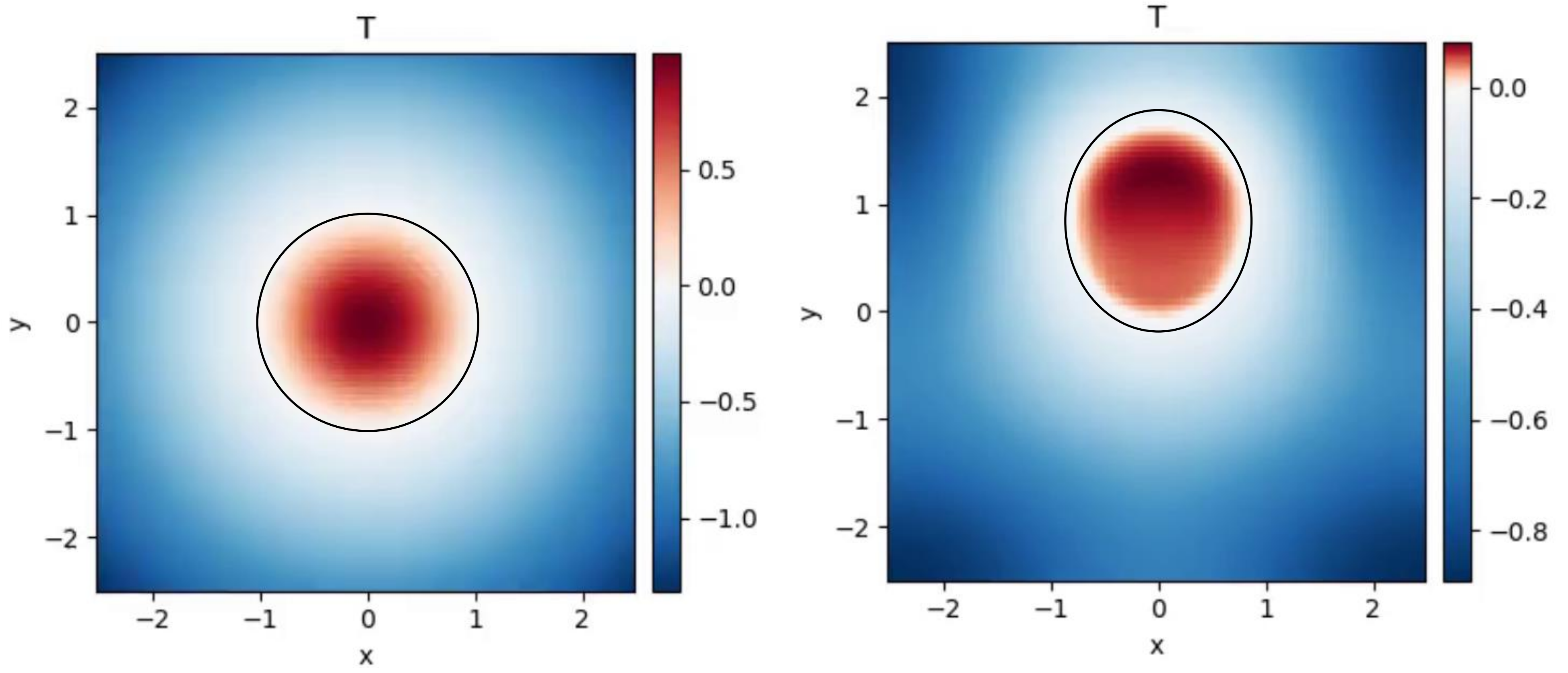


Fig. 2. Schematic representation of a cryomagma reservoir of volume V and radius R, located at depth H under the surface. Liquid cryomagma is represented in white whereas frozen cryomagma is hatched in grey. (a) The reservoir is filled with pure or briny liquid water at isostatic pressure P_0. (b) An initial liquid volume V_i freezes and becomes a volume V_f of ice, inducing an overpressure ΔP in the reservoir (see Section 2.2). (c) When the pressure reaches a critical value ΔP_c, the wall fractures and the pressurized liquid rises to the surface through a H long fracture (see Section 2.3).

Icarus 335 (2020) 113369

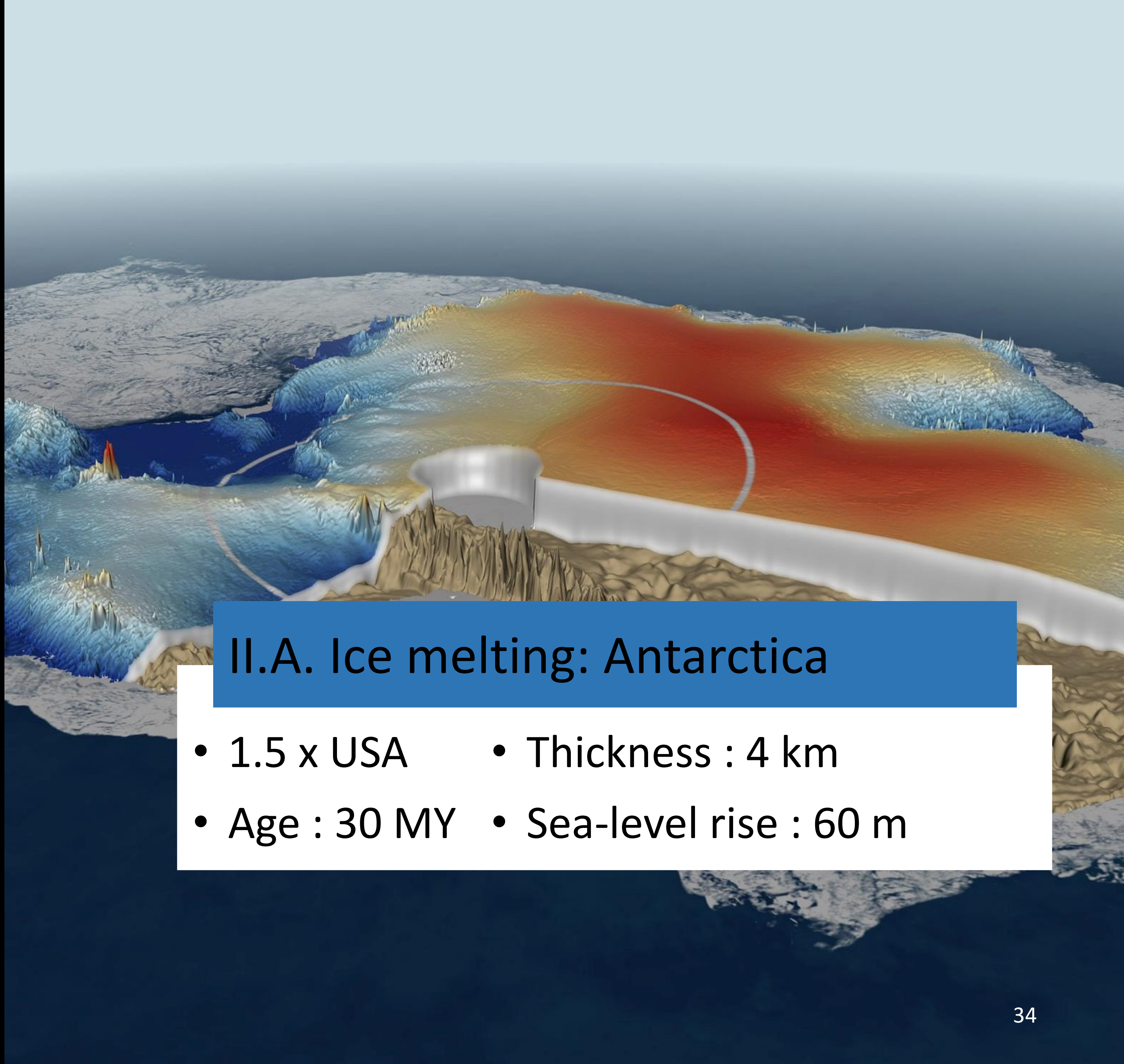
Is melting truly homogeneous ?

I.B. Sub. Hydro.: On Icy Moons. Preliminary results (C. De La Salle M2 internship).



Stronger melting in the cavity upper half.

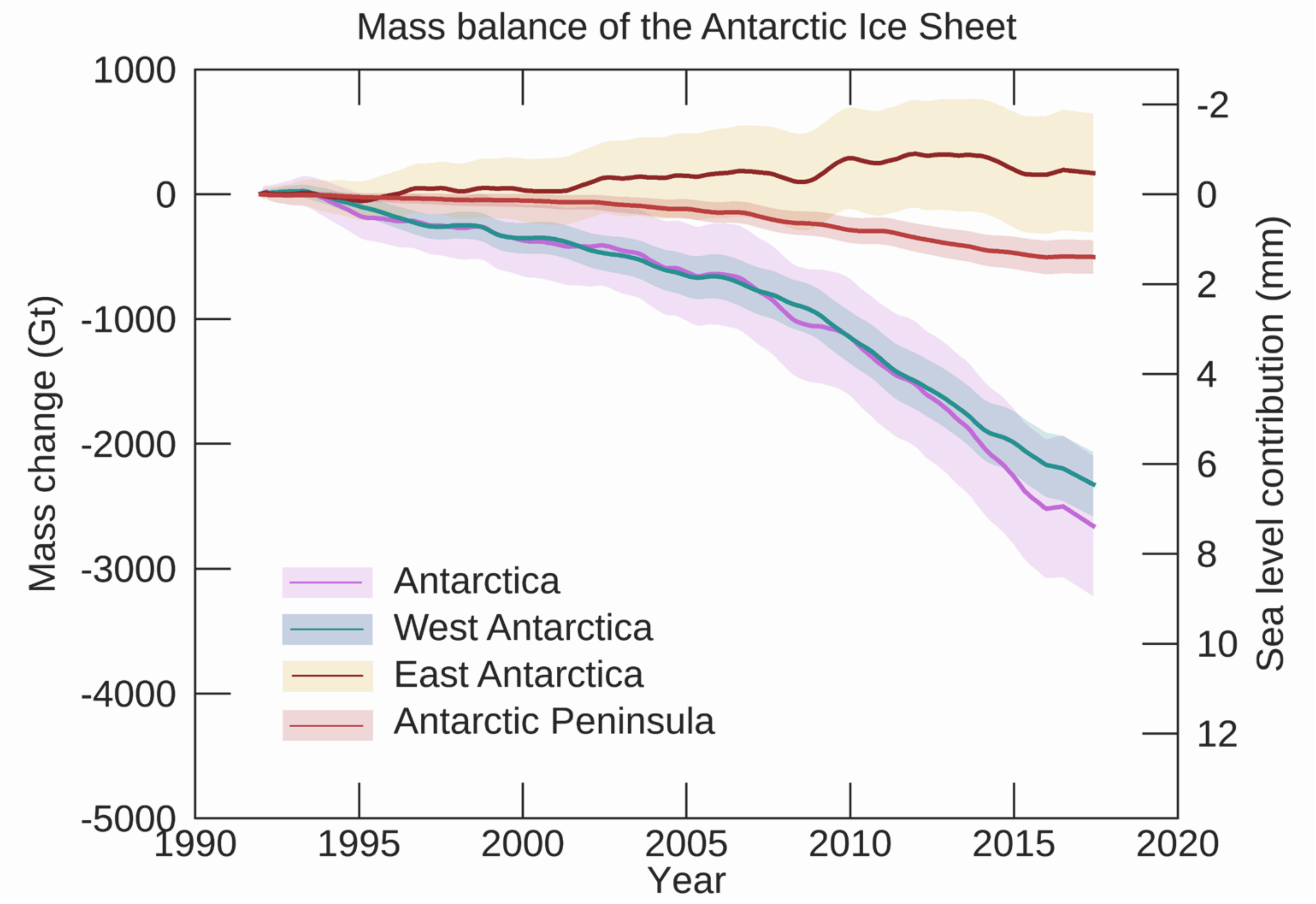
- Heterogeneous melting drives translation and deforms the initial shape.
- How does this affect longevity and crustal stability/fracturing ?



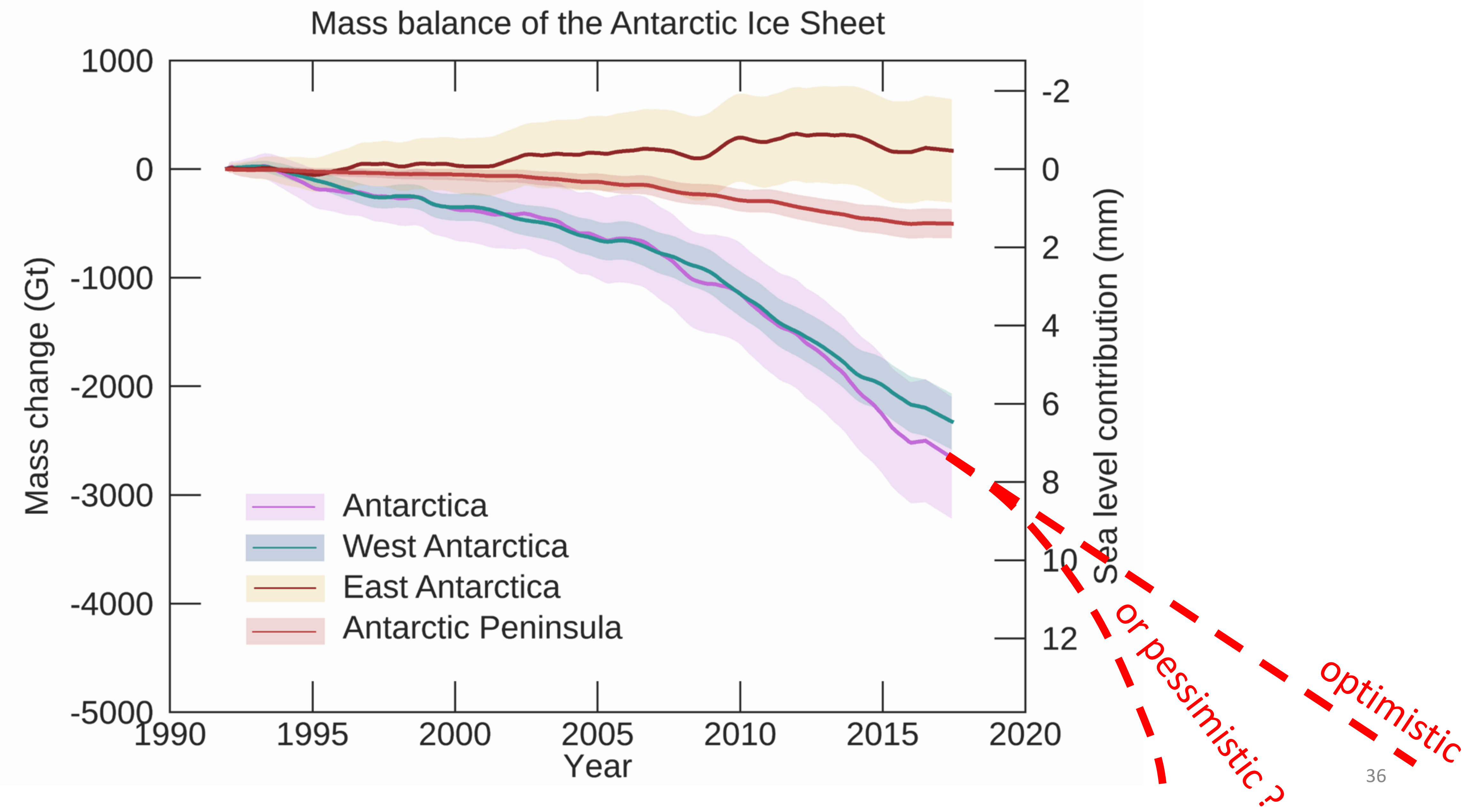
II.A. Ice melting: Antarctica

- 1.5 x USA
- Age : 30 MY
- Thickness : 4 km
- Sea-level rise : 60 m

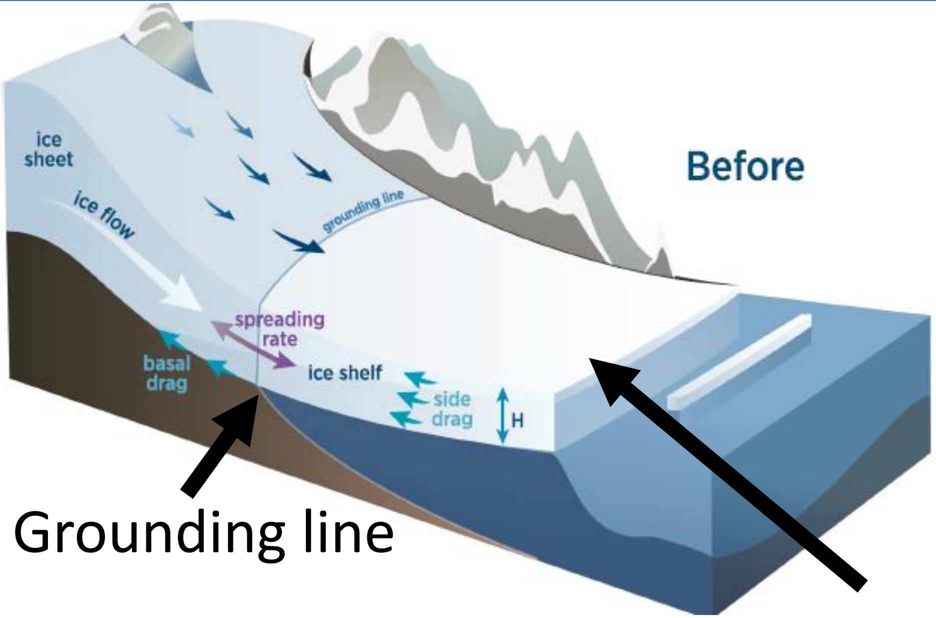
II.A. Ice melting: Antarctica.



II.A. Ice melting: Antarctica.

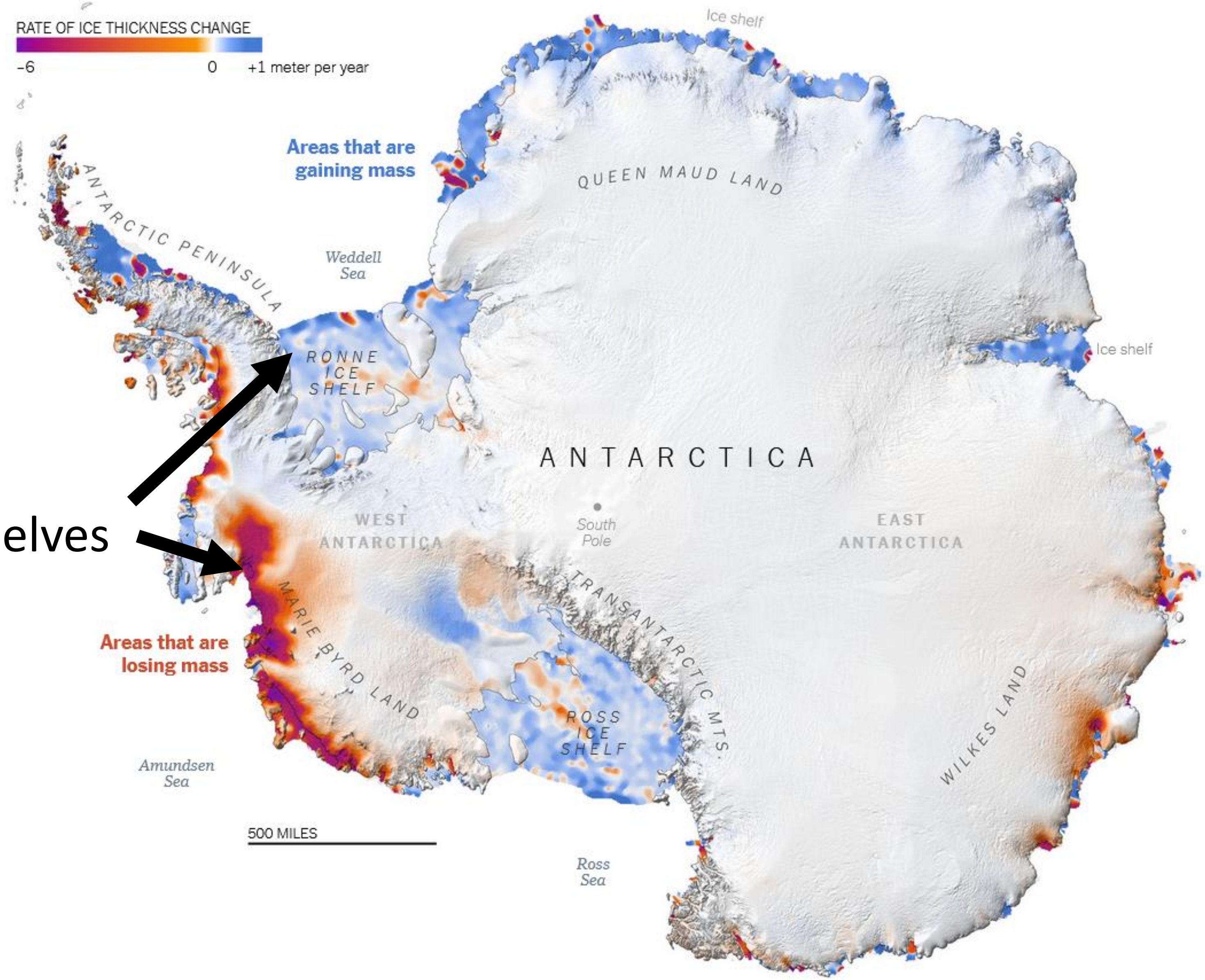


II.A. Ice melting: Antarctica. Observations; large-scale mechanism.



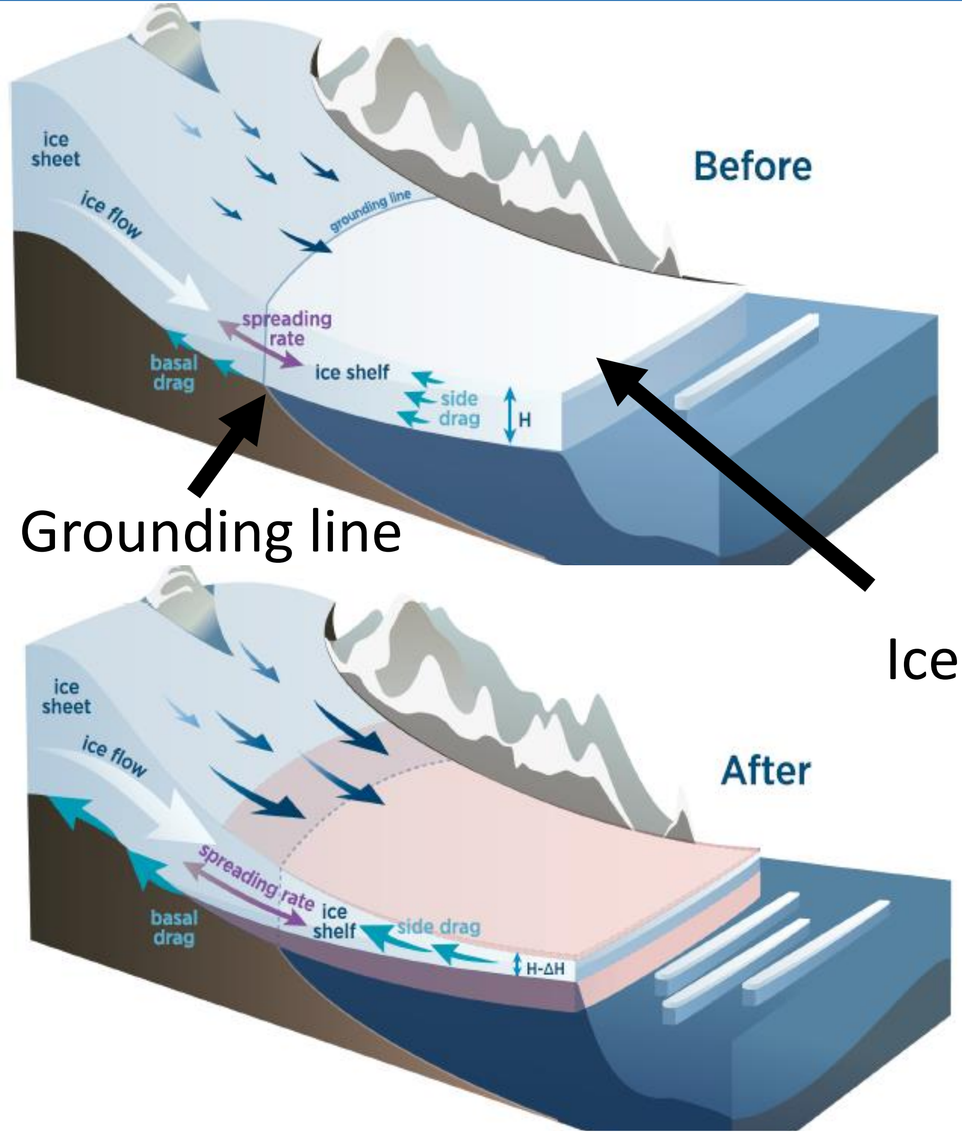
Grounding line

Ice shelves



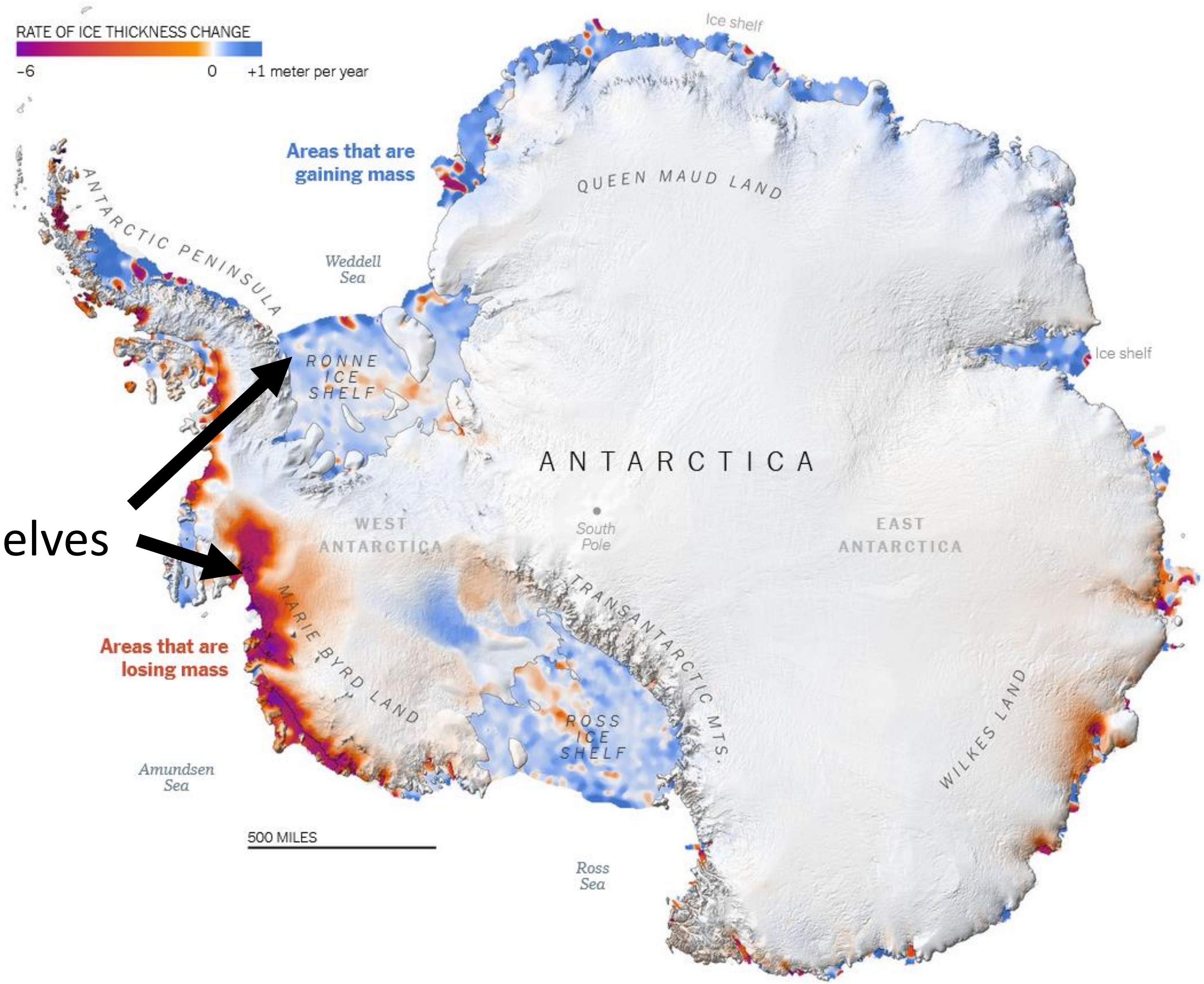
NASA, Gudmundson et al. (2019), Smith et al. (2020)/NYT

II.A. Ice melting: Antarctica. Observations; large-scale mechanism.



Grounding line

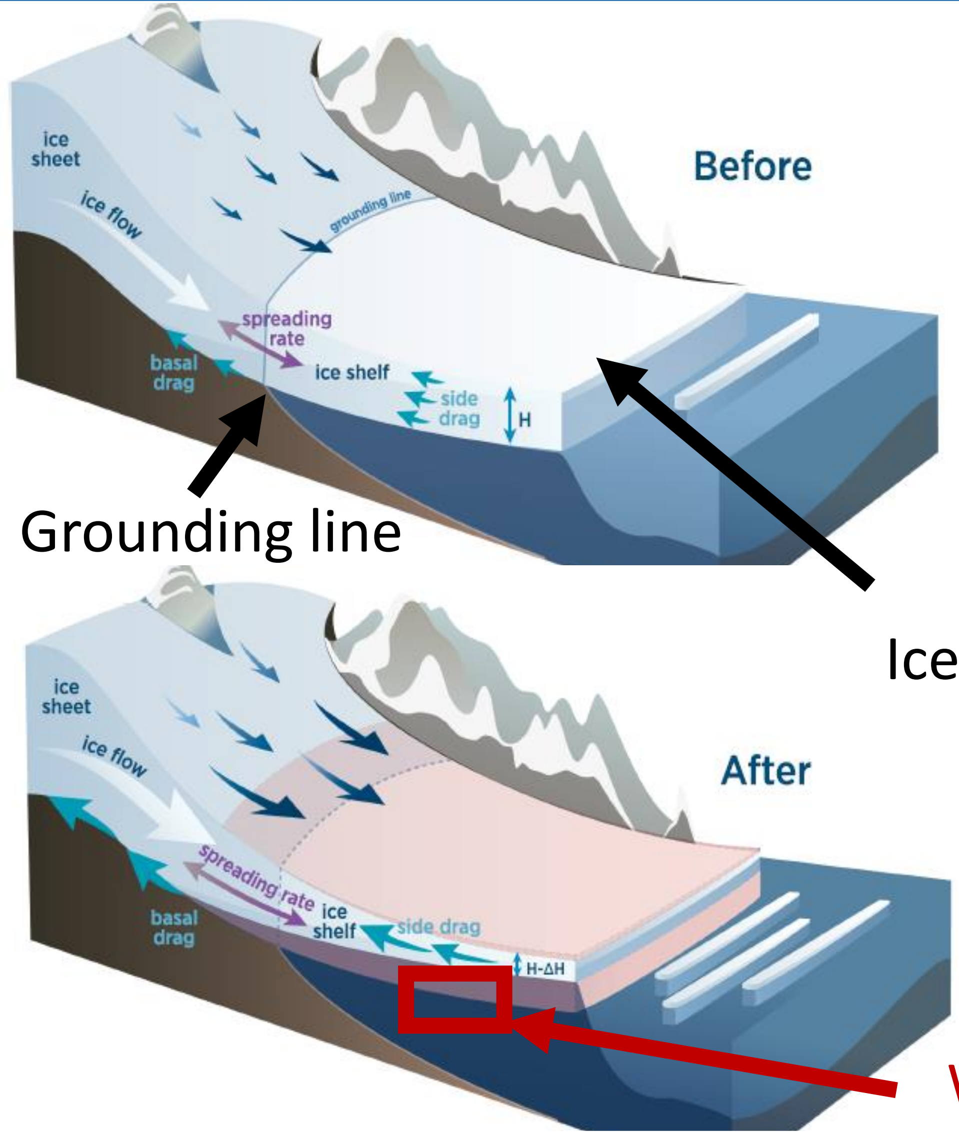
Ice shelves



⇒ <u>Basal</u> melting is key

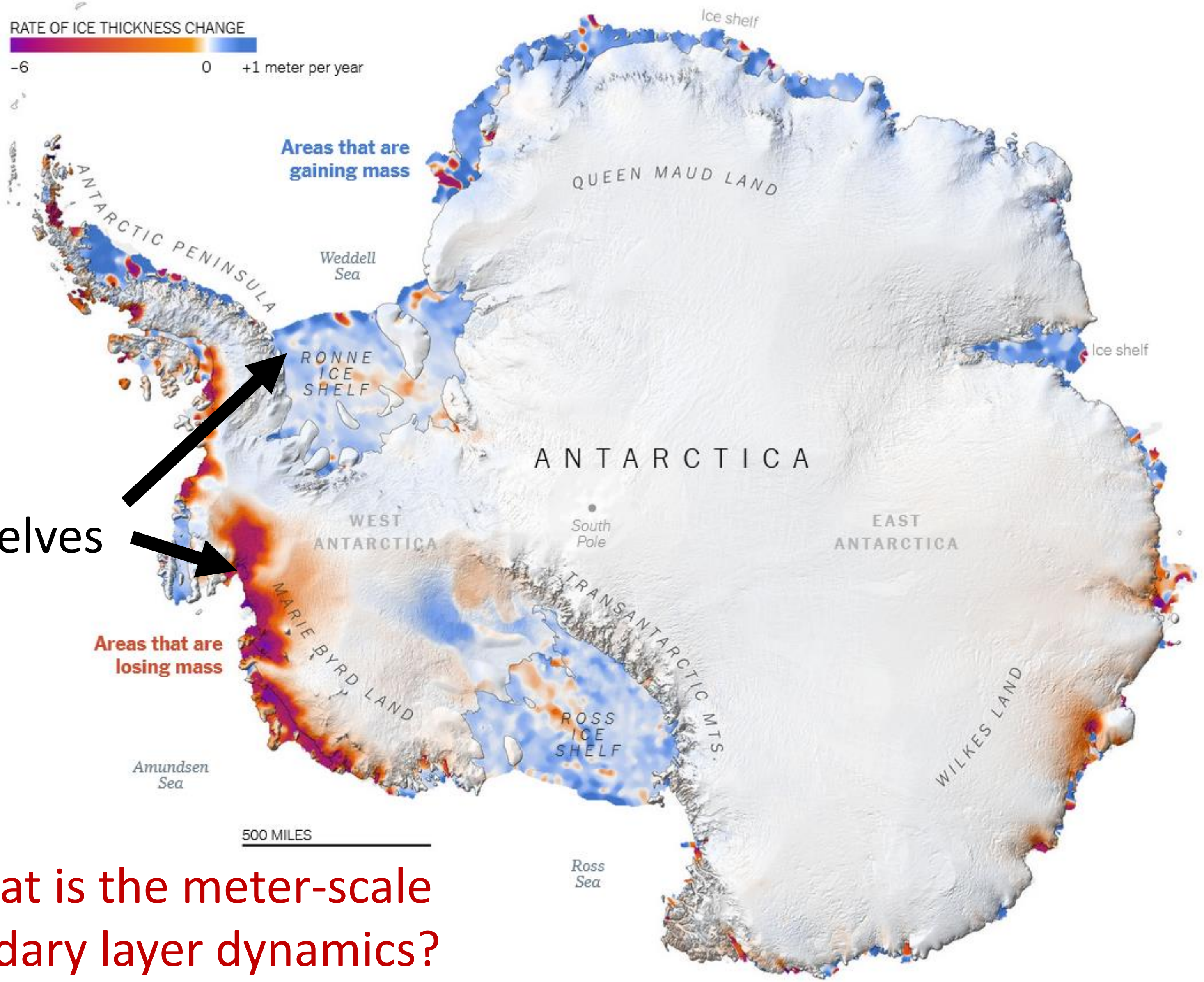
NASA, Gudmundson et al. (2019), Smith et al. (2020)/NYT

II.A. Ice melting: Antarctica. Observations; large-scale mechanism.



Grounding line

Ice shelves

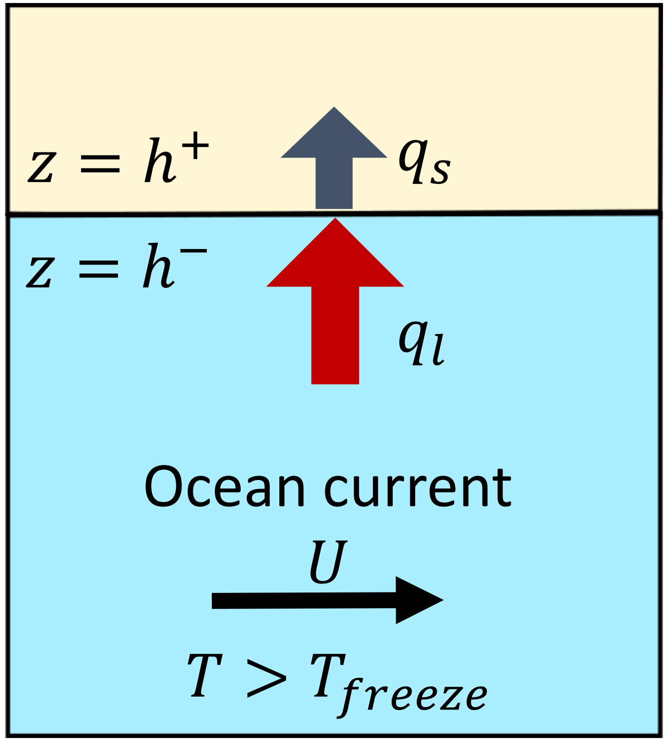


What is the meter-scale boundary layer dynamics?

⇒ <u>Basal</u> melting is key

NASA, Gudmundson et al. (2019), Smith et al. (2020)/NYT

II.A. Ice melting: Antarctica. Boundary layer thermodynamics.



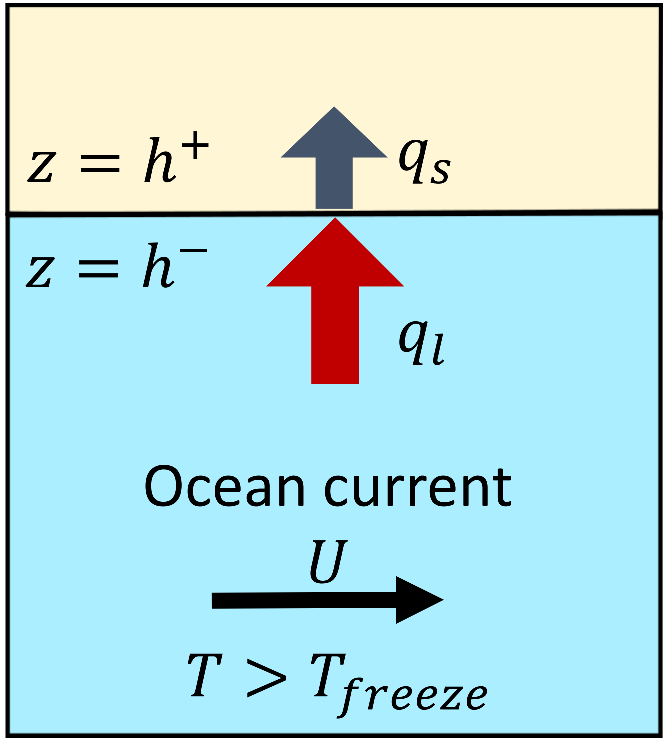
<u>Stefan Problem</u>

$$St\partial_t h = q_l - q_s$$

$$\begin{cases} q_l = -\partial_z T, & z = h^-, \\ q_s = -\partial_z T, & z = h^+, \\ St = \dfrac{L}{c_p\left(T - T_{freeze}\right)} & \end{cases}$$

Latent heat

Sensible heat



Stefan Problem

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Latent heat

Sensible heat

Observation

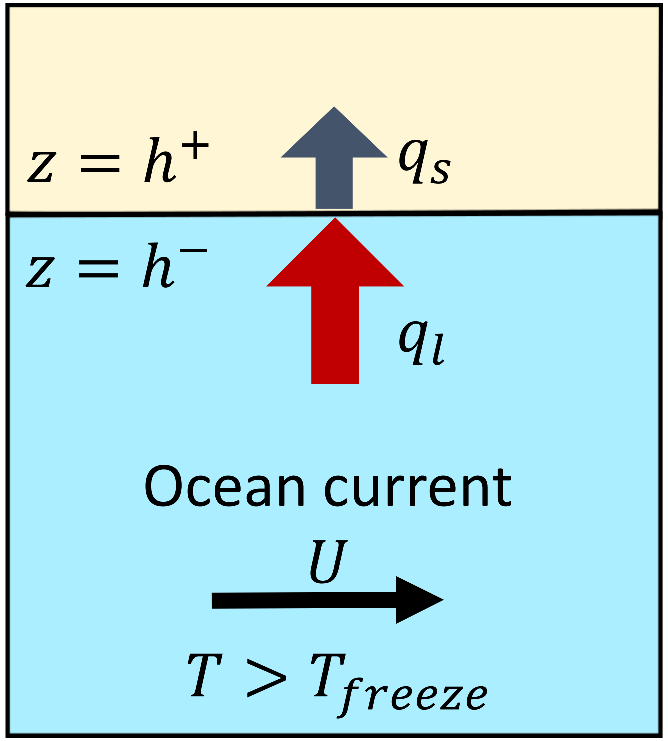
$q_l, q_s \equiv$ fluxes within a turbulent boundary layer $\sim O(1)cm$

Conclusion

→ parametrized in ocean models $\sim O(10)m$

$q_s = 0, \qquad q_l = C_d^{1/2}\Gamma_T U\left(T - T_{freeze}\right)$ (eq 1)

II.A. Ice melting: Antarctica. Boundary layer thermodynamics.



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Latent heat

Sensible heat

Observation

$q_l, q_s \equiv$ fluxes within a turbulent boundary layer $\sim O(1)cm$

Conclusion

$\rightarrow$ parametrized in ocean models $\sim O(10)m$

$q_s = 0, \qquad q_l = C_d^{1/2}\Gamma_T U\left(T - T_{freeze}\right)$ (eq 1)

Questions

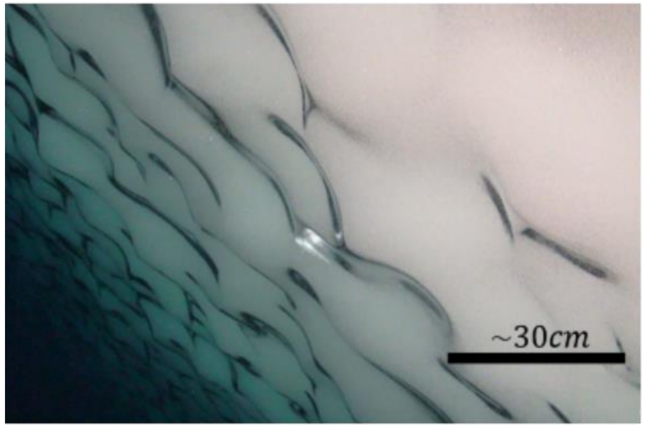
Is (eq 1) reasonable ?

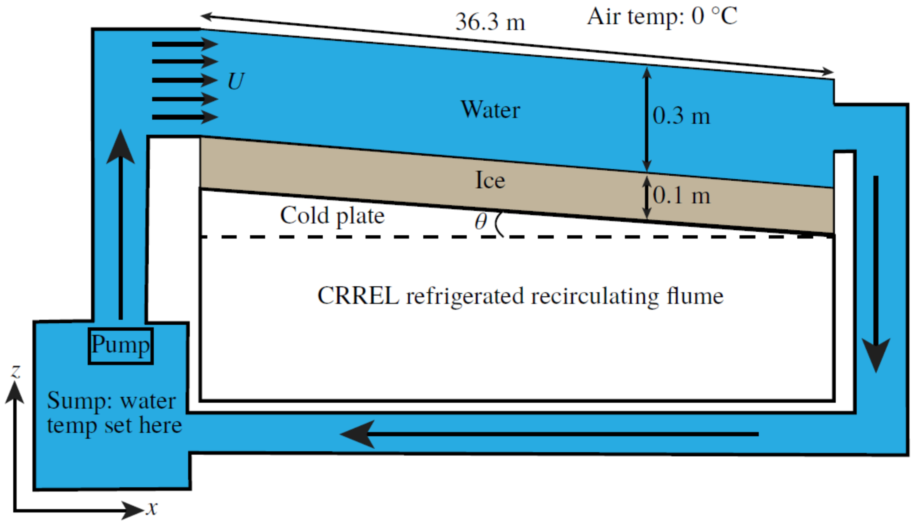
How do the problem parameters influence C_d et Γ_T?

U, T, local slope, …

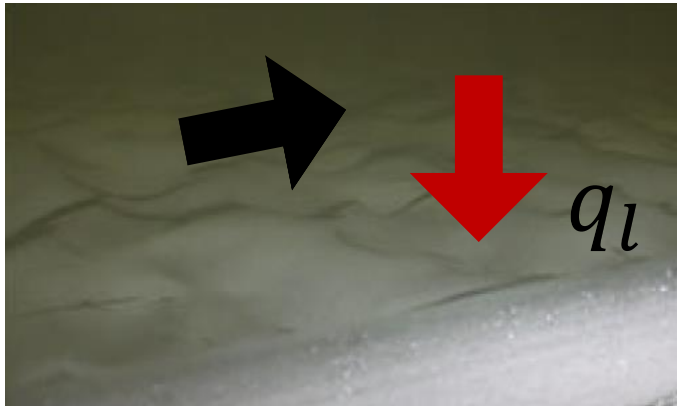
Are hydraulically-smooth ice surfaces morphologically stable ?

"Scallops"

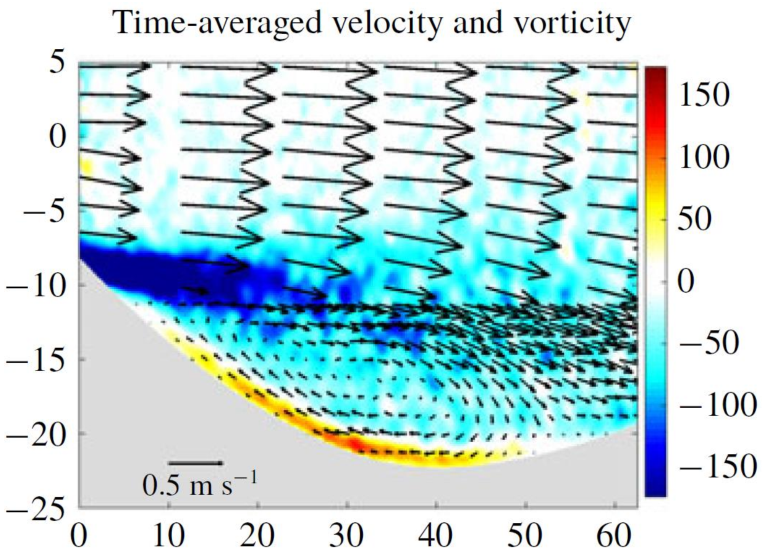




Bushuk et al. (2019)

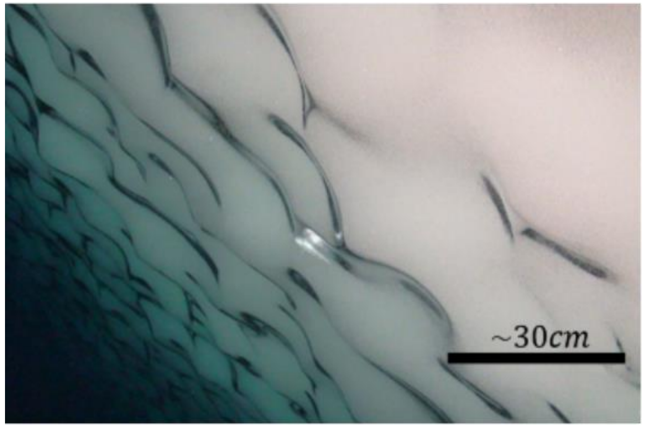


Melting ← × 2



II.A. Ice melting: Antarctica. Smooth to rough ice surfaces.

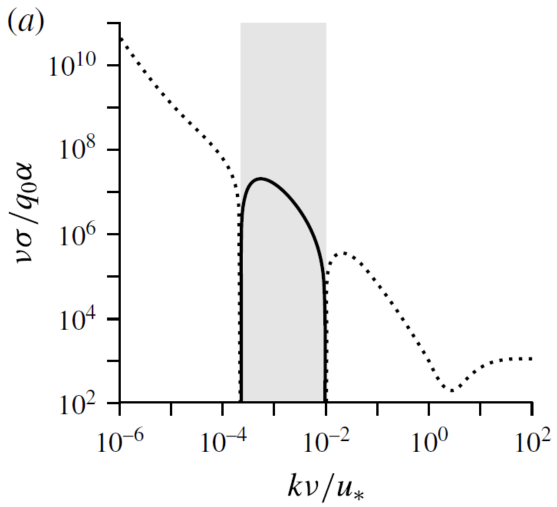
"Scallops"

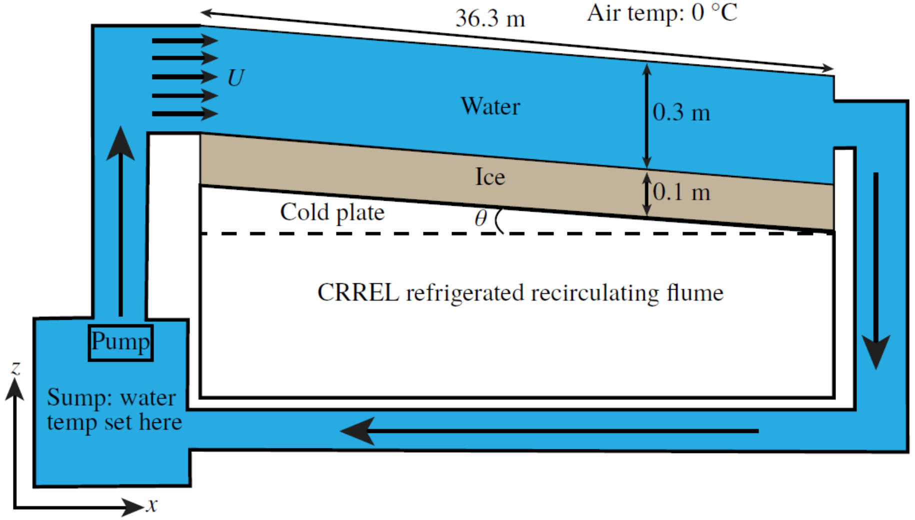


<u>Statistical approach:</u>

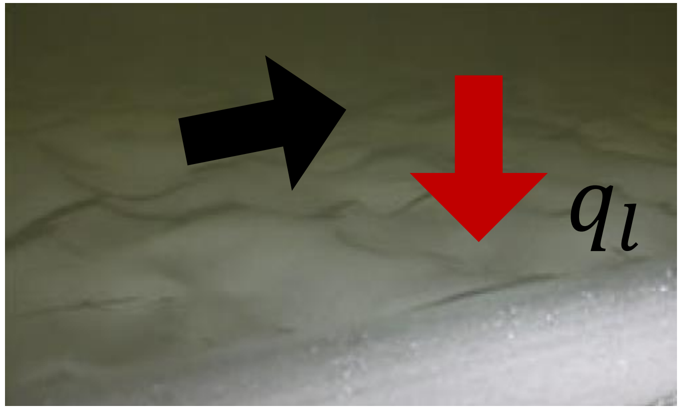
q_l and h out-of-phase such that max(q_l) lies within a trough.

Claudin et al. (2017)

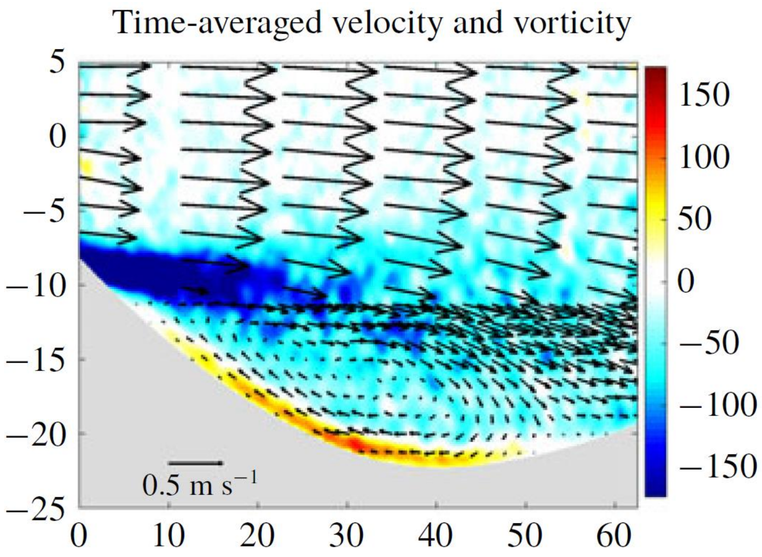




Bushuk et al. (2019)



Melting ← × 2



II.A. Ice melting: Antarctica. Modelling strategy; first objectives.

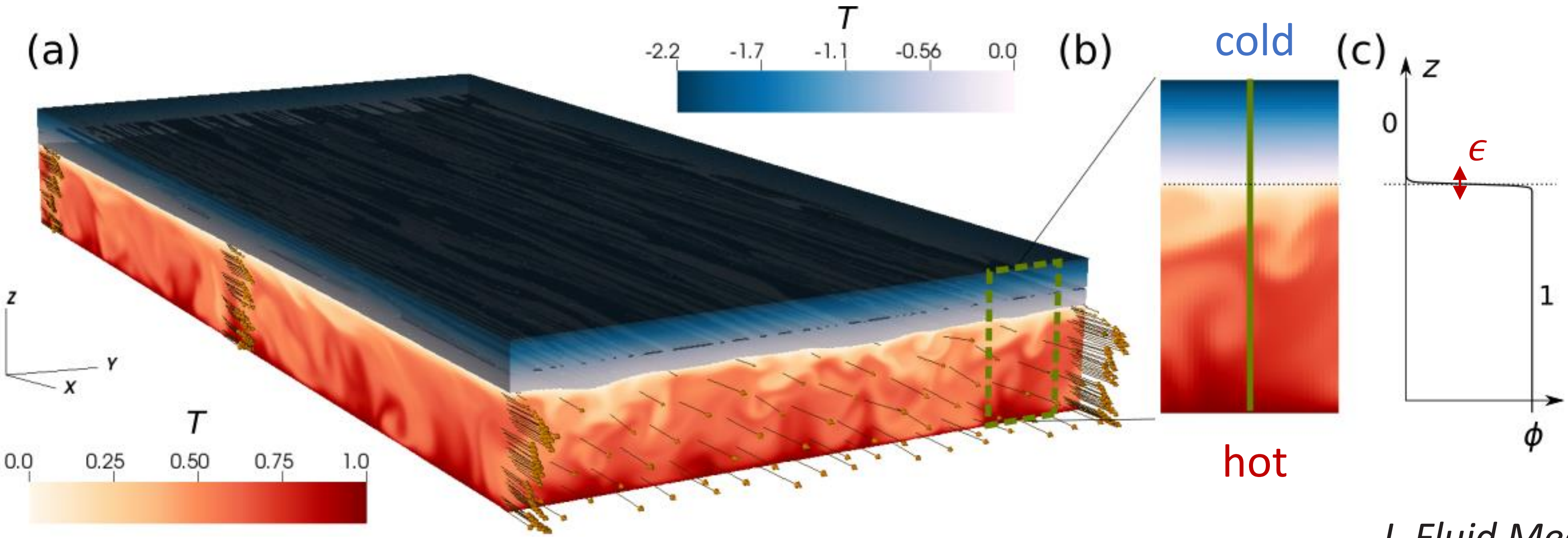
2 discontinuous domains

$$\partial_t T_s = \nabla^2 T_s$$ solid

liquid

$$D_t T_l = \nabla^2 T_l$$
$$\nabla \cdot \vec{u}_l = 0$$
$$D_t \vec{u}_l = Pr \nabla^2 \vec{u}_l - \nabla p_l - Pr Ri T_l \hat{z} + 2\, Pr^2 Re\, \hat{x}$$

$$T_l = T_s = T_{freeze}$$
$$St \partial_t h = \partial_z T_s - \partial_z T_l$$ interface



J. Fluid Mech. (2021), *vol.* 911, A44

II.A. Ice melting: Antarctica. Modelling strategy; first objectives.

2 discontinuous domains

solid:

$$\partial_t T_s = \nabla^2 T_s$$

liquid:

$$D_t T_l = \nabla^2 T_l$$
$$\nabla \cdot \vec{u}_l = 0$$
$$D_t \vec{u}_l = Pr\nabla^2 \vec{u}_l - \nabla p_l - PrRiT_l \hat{z} + 2\, Pr^2 Re\, \hat{x}$$

interface:

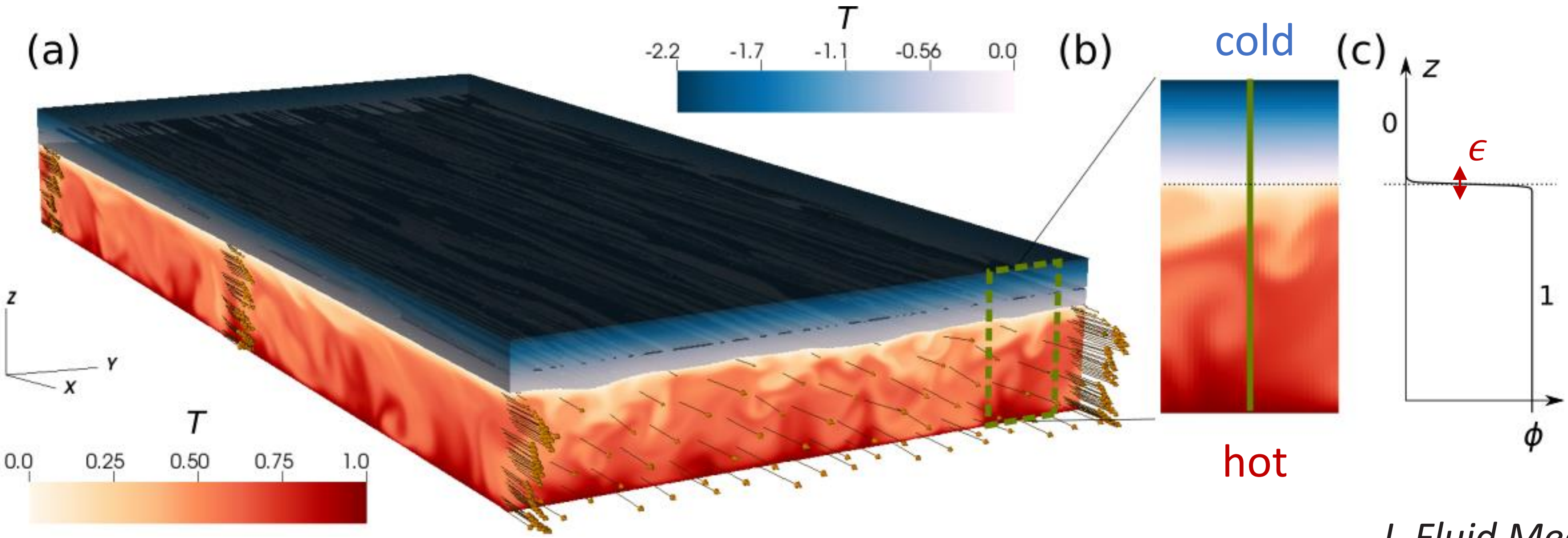
$$T_l = T_s = T_{freeze}$$
$$St\partial_t h = \partial_z T_s - \partial_z T_l$$

1 diffuse 2-phase (porous) domain

solid & liquid

$$D_t T = \nabla^2 T - St\partial_t \phi$$
$$\nabla \cdot \vec{u} = 0$$
$$D_t \vec{u} = Pr\nabla^2 \vec{u} - \nabla p - PrRiT\hat{z} + 2\, Pr^2 Re\, \hat{x} - Pr\frac{(1-\phi)}{\Gamma(\epsilon)}\vec{u}$$

$$\partial_t \phi = A(\epsilon)\nabla^2 \phi + g(\phi)$$ Gov. eq. for phase var. ϕ



J. Fluid Mech. (2021), *vol.* 911, A44

II.A. Ice melting: Antarctica. Modelling strategy; first objectives.

2 discontinuous domains

$\partial_t T_s = \nabla^2 T_s$ solid

liquid

$D_t T_l = \nabla^2 T_l$

$\nabla \cdot \vec{u}_l = 0$

$D_t \vec{u}_l = Pr\nabla^2 \vec{u}_l - \nabla p_l - PrRiT_l \hat{z} + 2\,Pr^2 Re\,\hat{x}$

$T_l = T_s = T_{freeze}$

$St\partial_t h = \partial_z T_s - \partial_z T_l$ interface

1 diffuse 2-phase (porous) domain

solid & liquid

$D_t T = \nabla^2 T - St\partial_t \phi$

$\nabla \cdot \vec{u} = 0$

$D_t \vec{u} = Pr\nabla^2 \vec{u} - \nabla p - PrRiT\hat{z} + 2\,Pr^2 Re\,\hat{x} - Pr\frac{(1-\phi)}{\Gamma(\epsilon)}\vec{u}$

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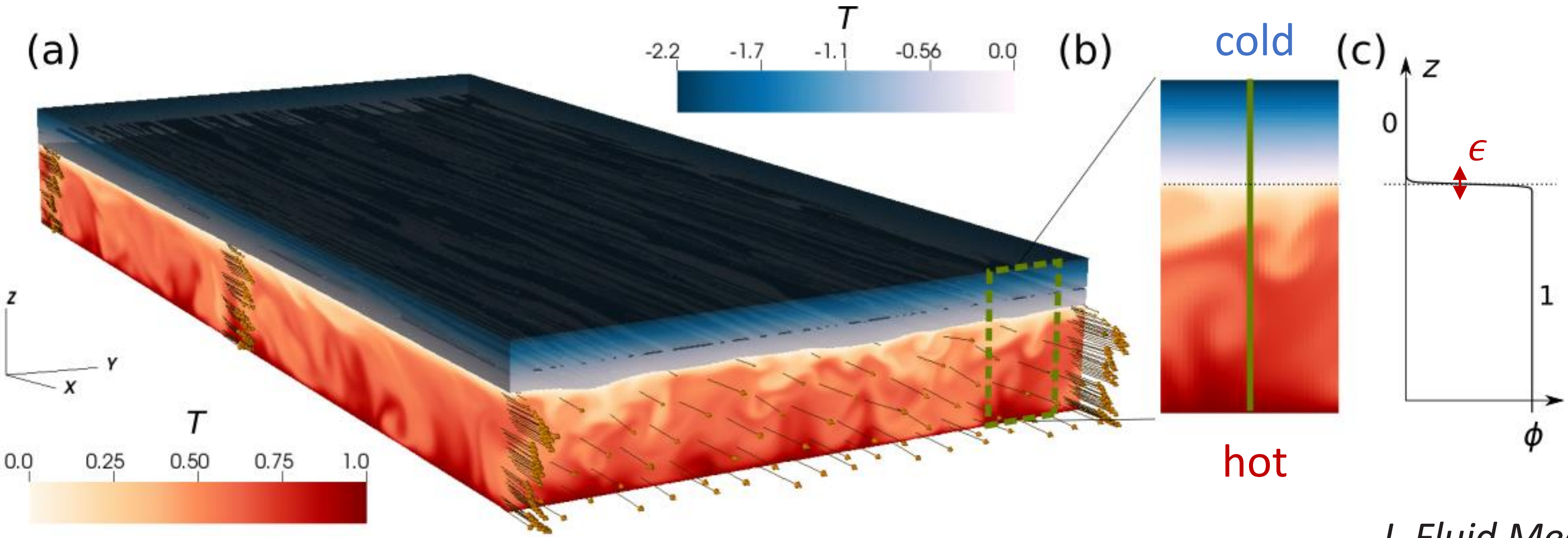


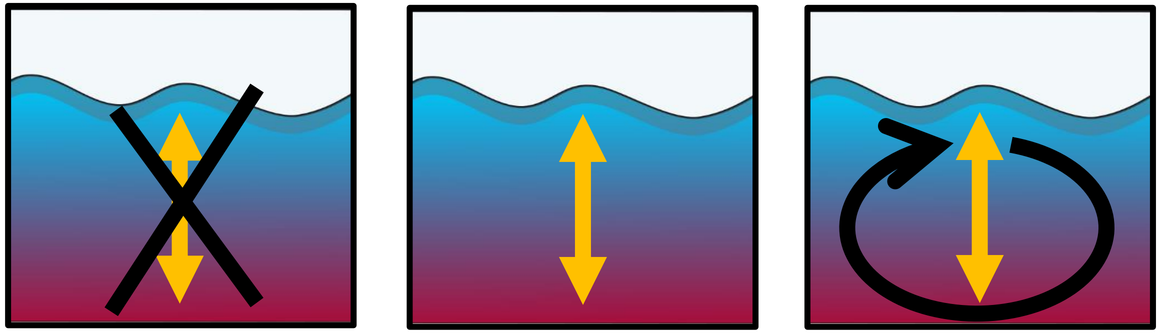
Obj.: Effect of ~~current~~ and stratification

J. Fluid Mech. (2021), *vol.* 911, A44

II.A. Ice melting: Antarctica. Modelling strategy; first objectives.

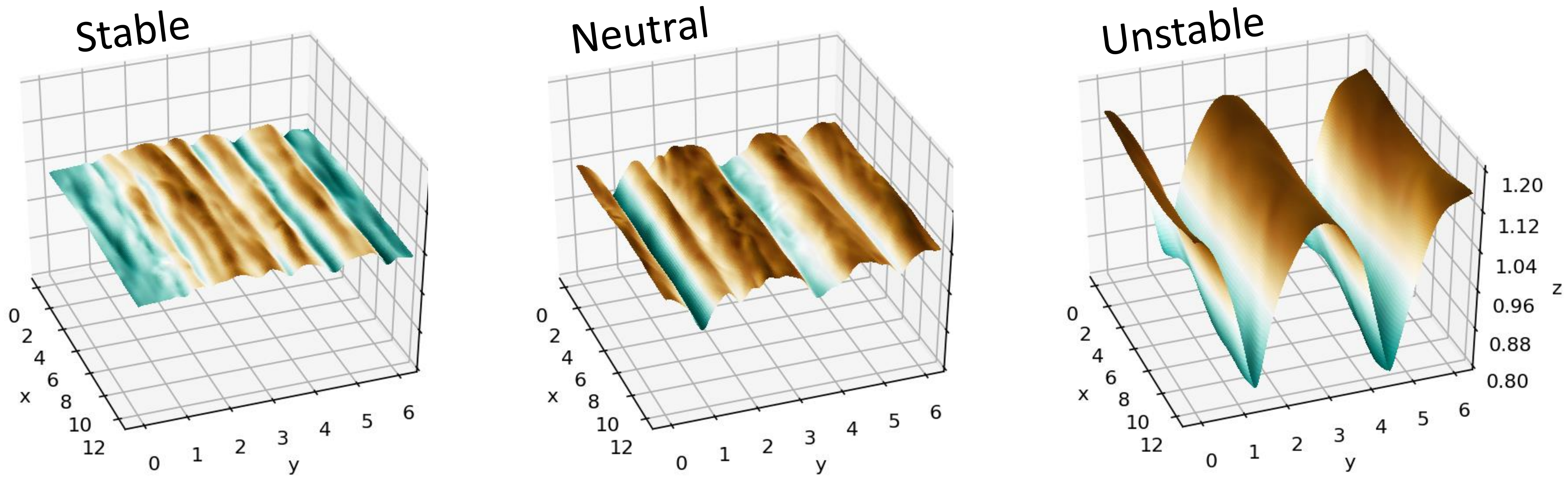
Stratification effects

$Ri = 4.5\ 10^5$ $(Ri_* = 40)$ | $Ri = 0$ | $Ri = -4.5\ 10^5$ $(Ra = 4.5\ 10^5)$



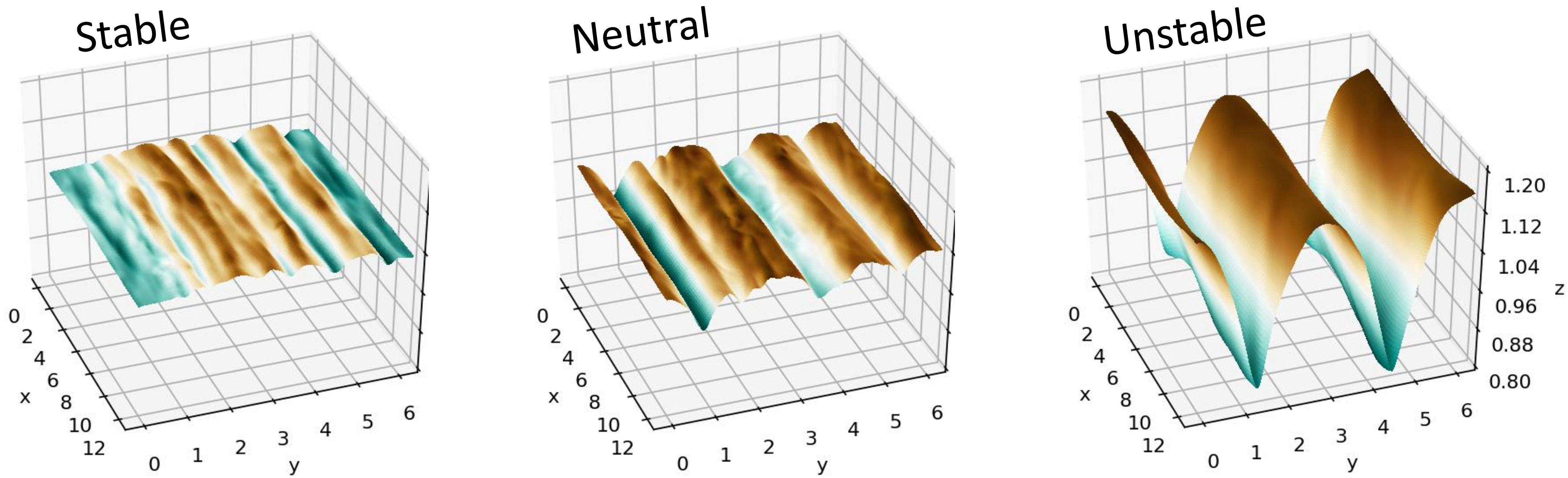
stable | neutral | unstable

II.A. Ice melting: Antarctica. First results: streamwise channels and keels.

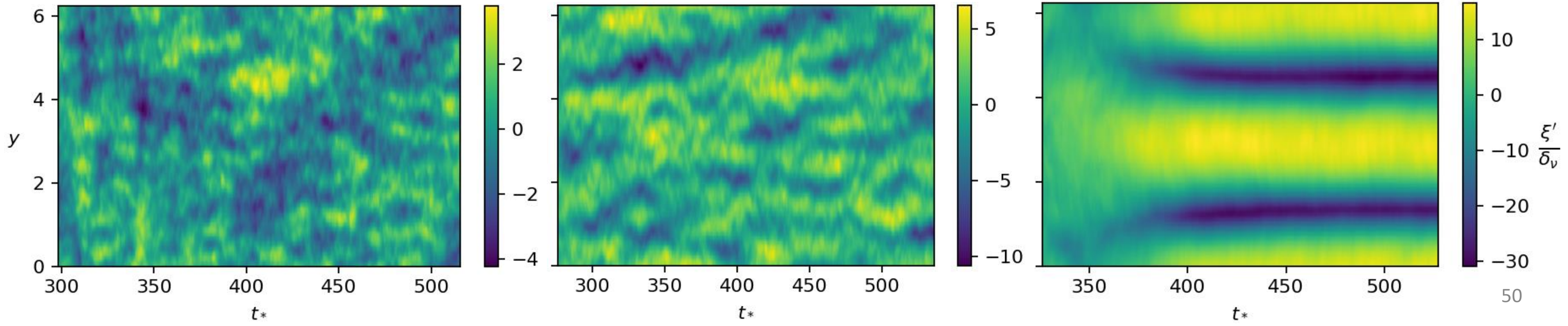


Carving from BL-attached streamwise vortices to domain-scale Rayleigh-Benard rolls.

II.A. Ice melting: Antarctica. First results: streamwise channels and keels.



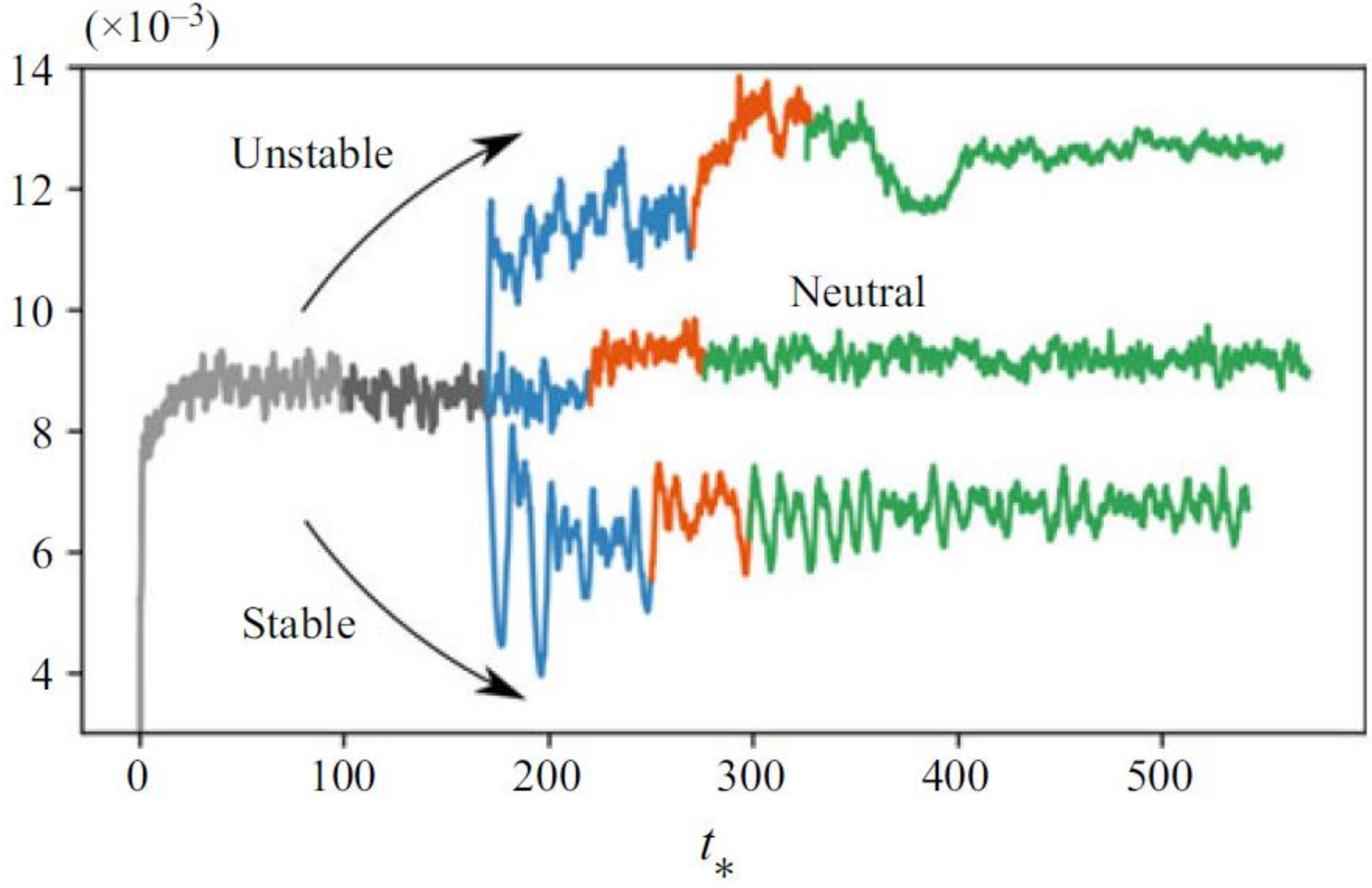
Carving from BL-attached streamwise vortices to domain-scale Rayleigh-Benard rolls.



Streamwise averages

II.A. Ice melting: Antarctica. First results: no clear effect on C_d.

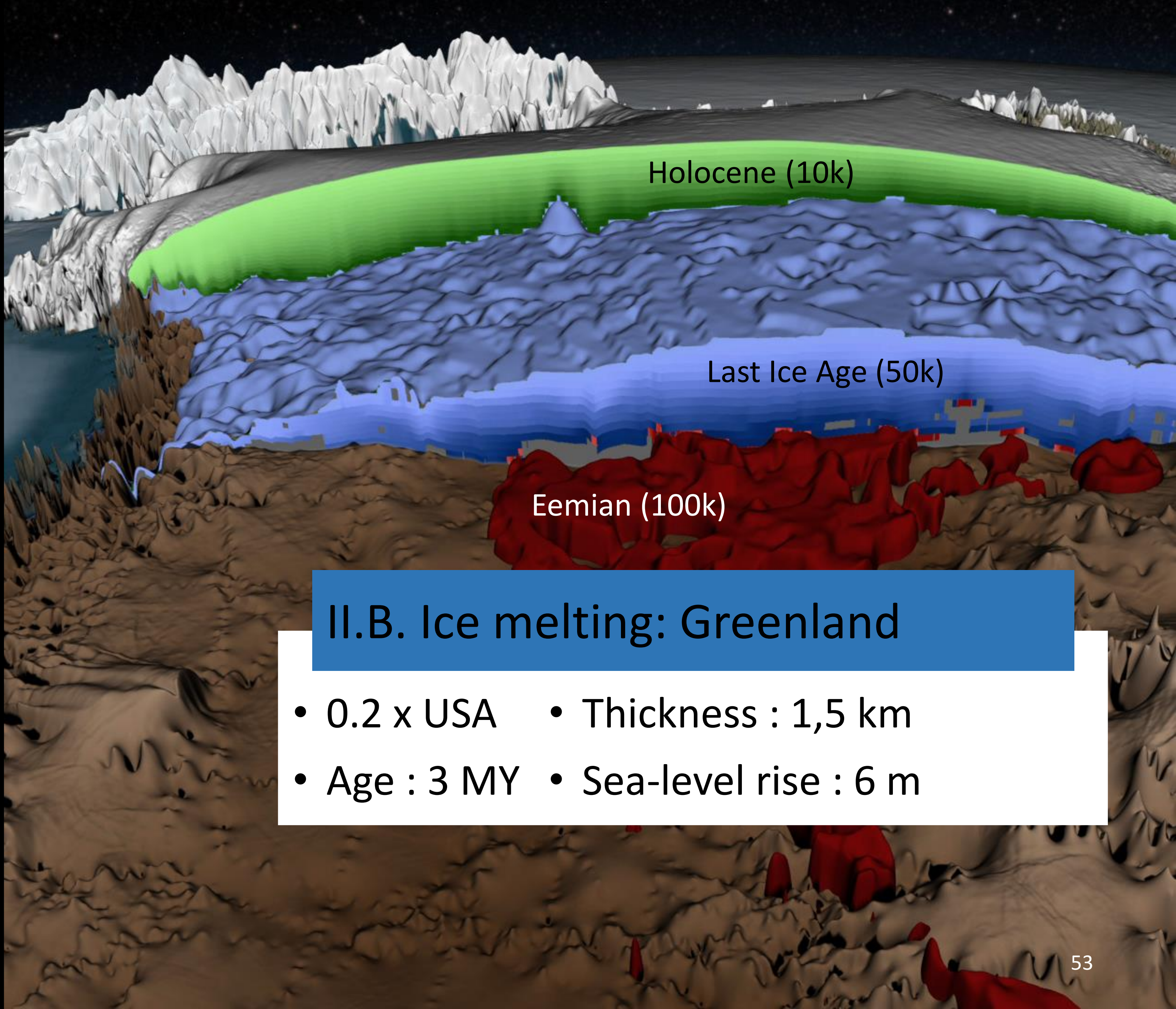
$$C_d = 2\left(\frac{u_*}{u_b}\right)^2$$



II.A. Ice melting: Antarctica. Perspectives.

→ consider stronger currents to *get* to « scallops ».

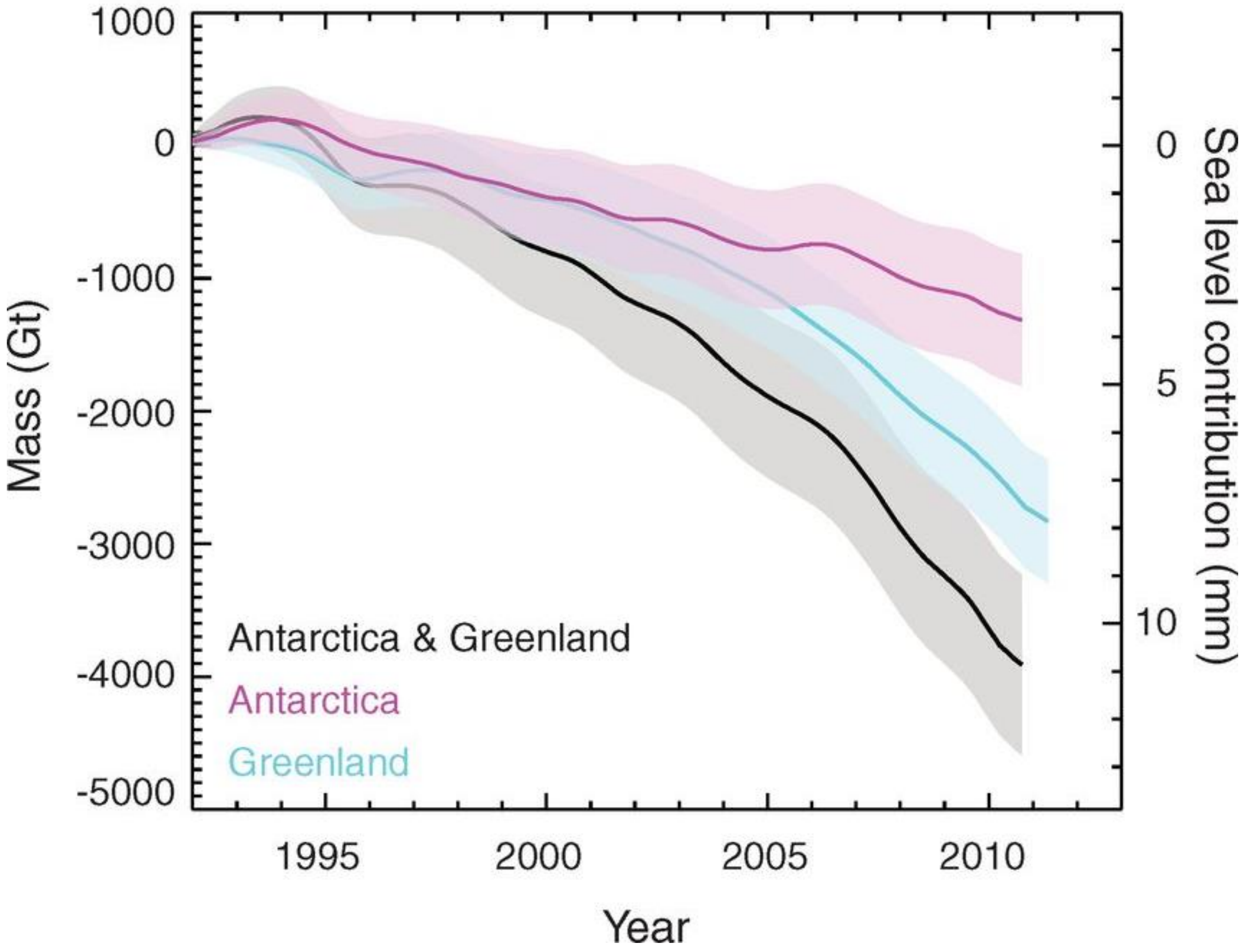
→ consider ice melting in saltwater (numerical and experimental work possible).



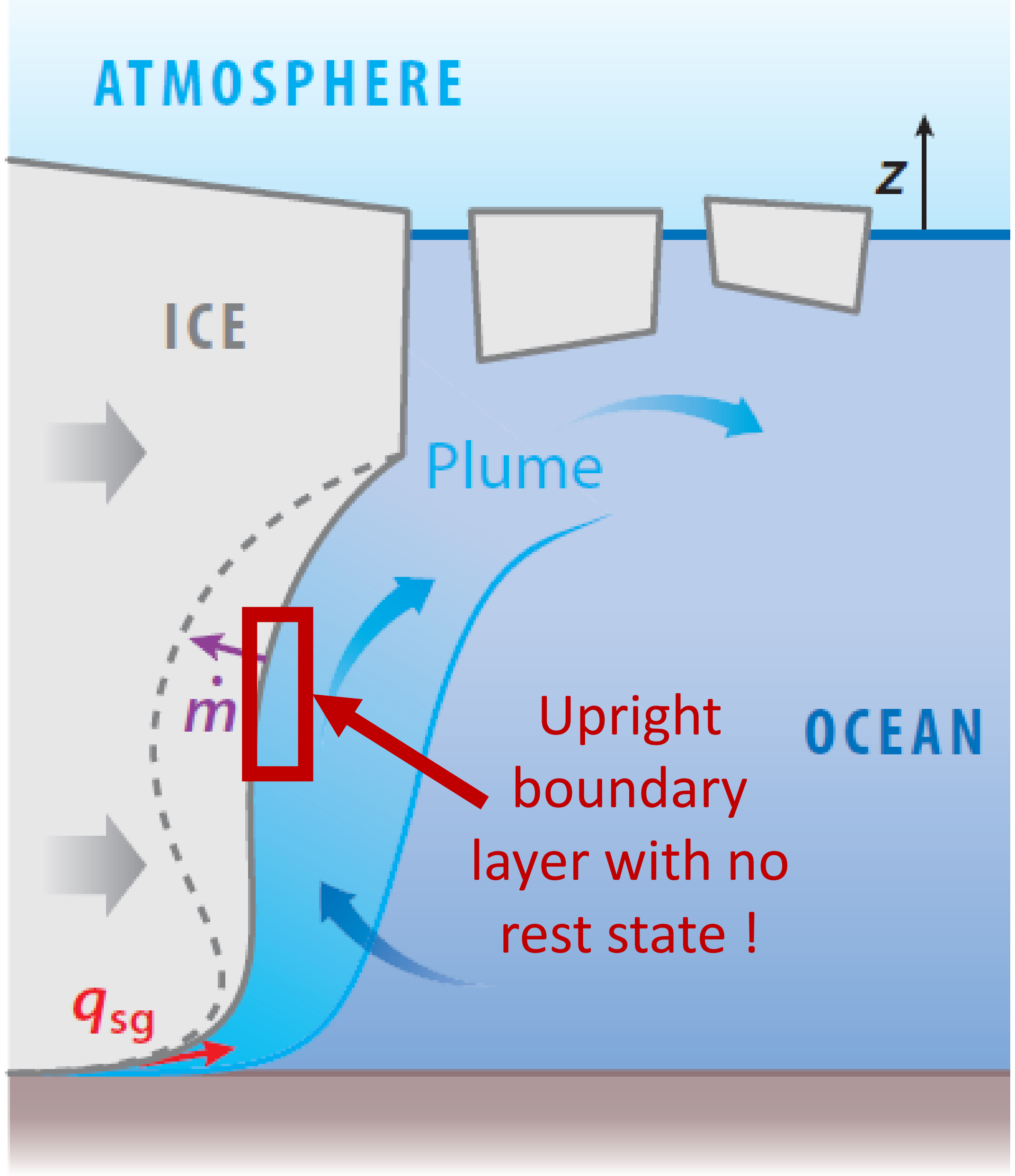
II.B. Ice melting: Greenland

- 0.2 x USA
- Age : 3 MY
- Thickness : 1,5 km
- Sea-level rise : 6 m

II.B. Ice melting: Greenland.



II.B. Ice melting: Greenland. New set-up, similar questions.



The need for a grand parameterization.

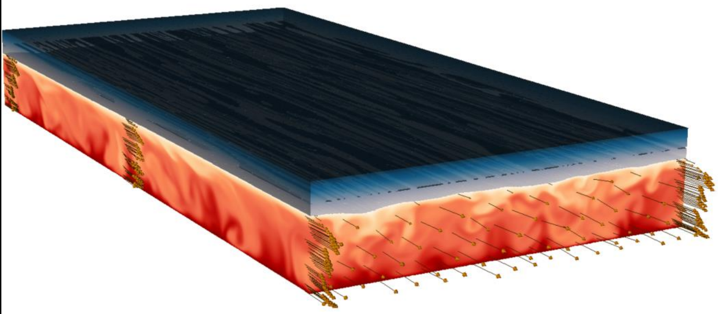
→ current parameterization predicts only 1% observed melt rate!

→ because buoyancy-controlled melting (not shear)

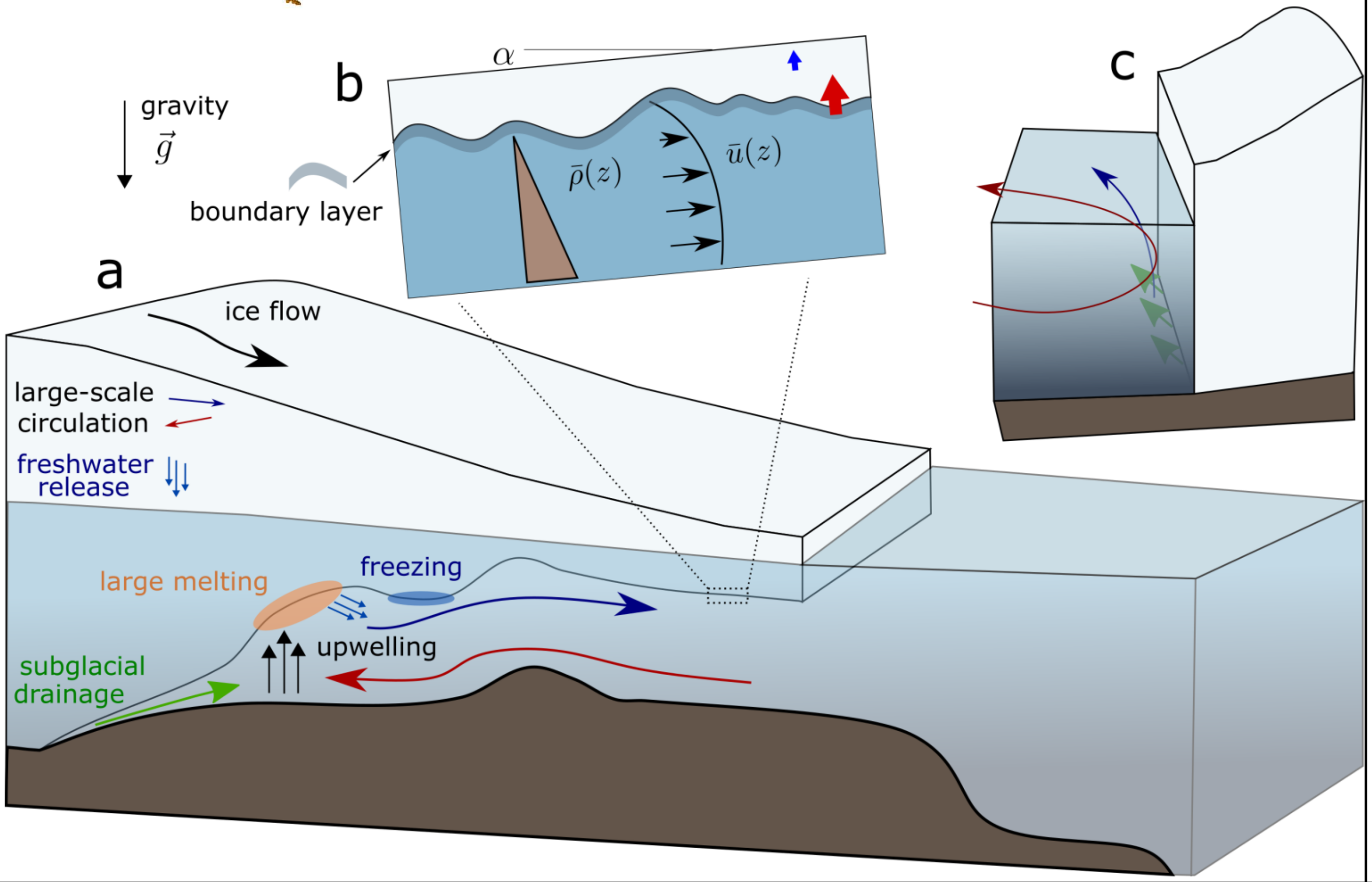
→ horizontal circulation in the "fjord" could play an important role.

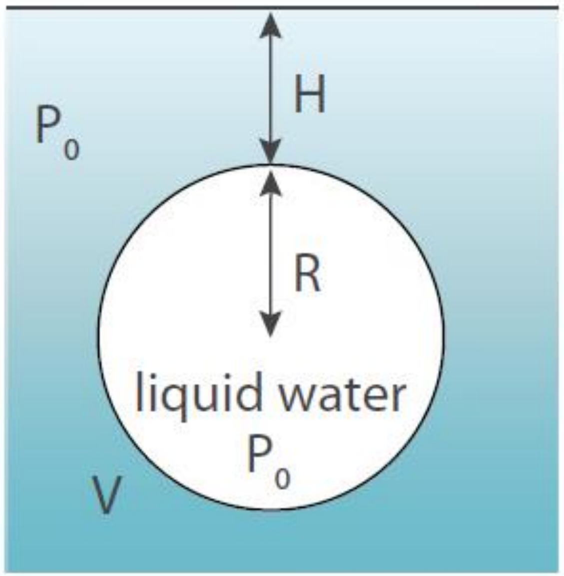
Combined sims & experiments approach with R. Volk and S. Joubaud in preparation!

Conclusions

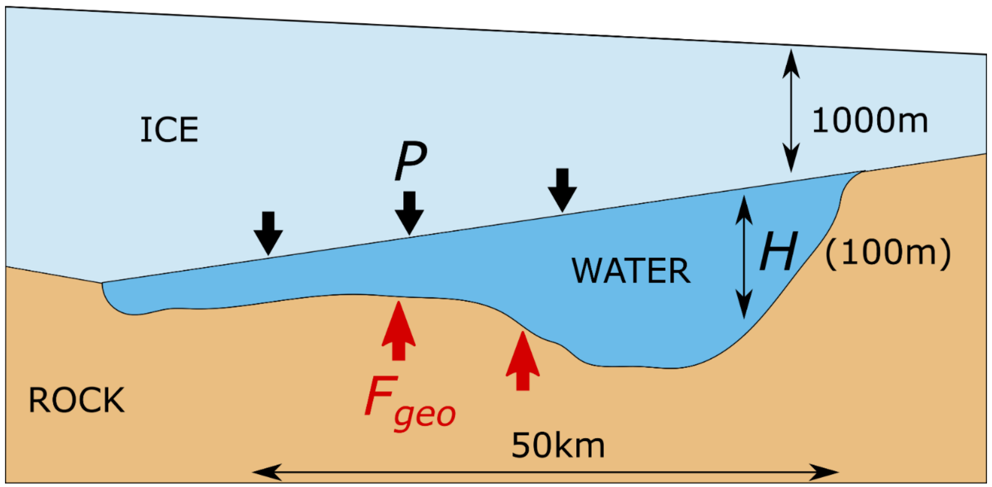


Ice melting and morphological stability using phase field models.



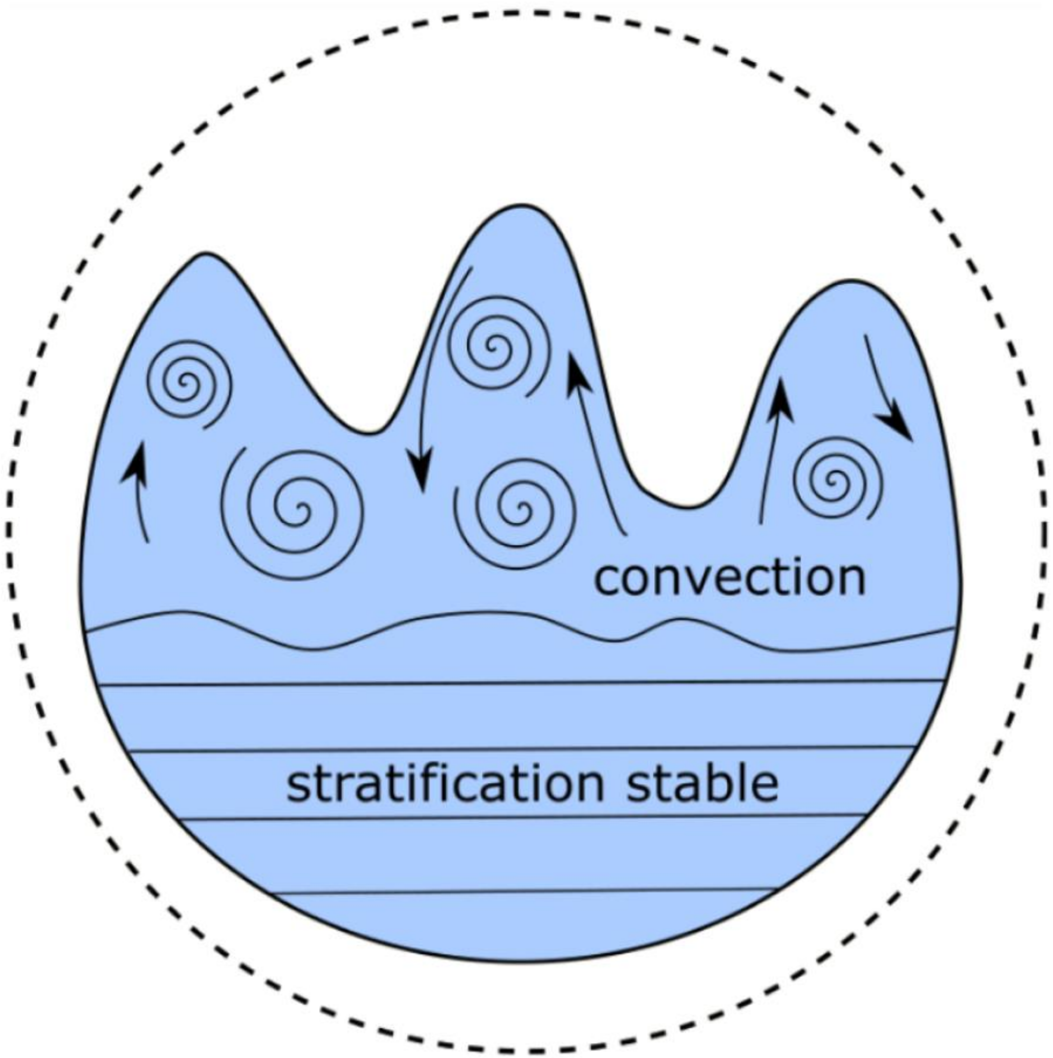


Subglacial hydrodynamics (buoyancy driven) on Earth and Icy Moons.

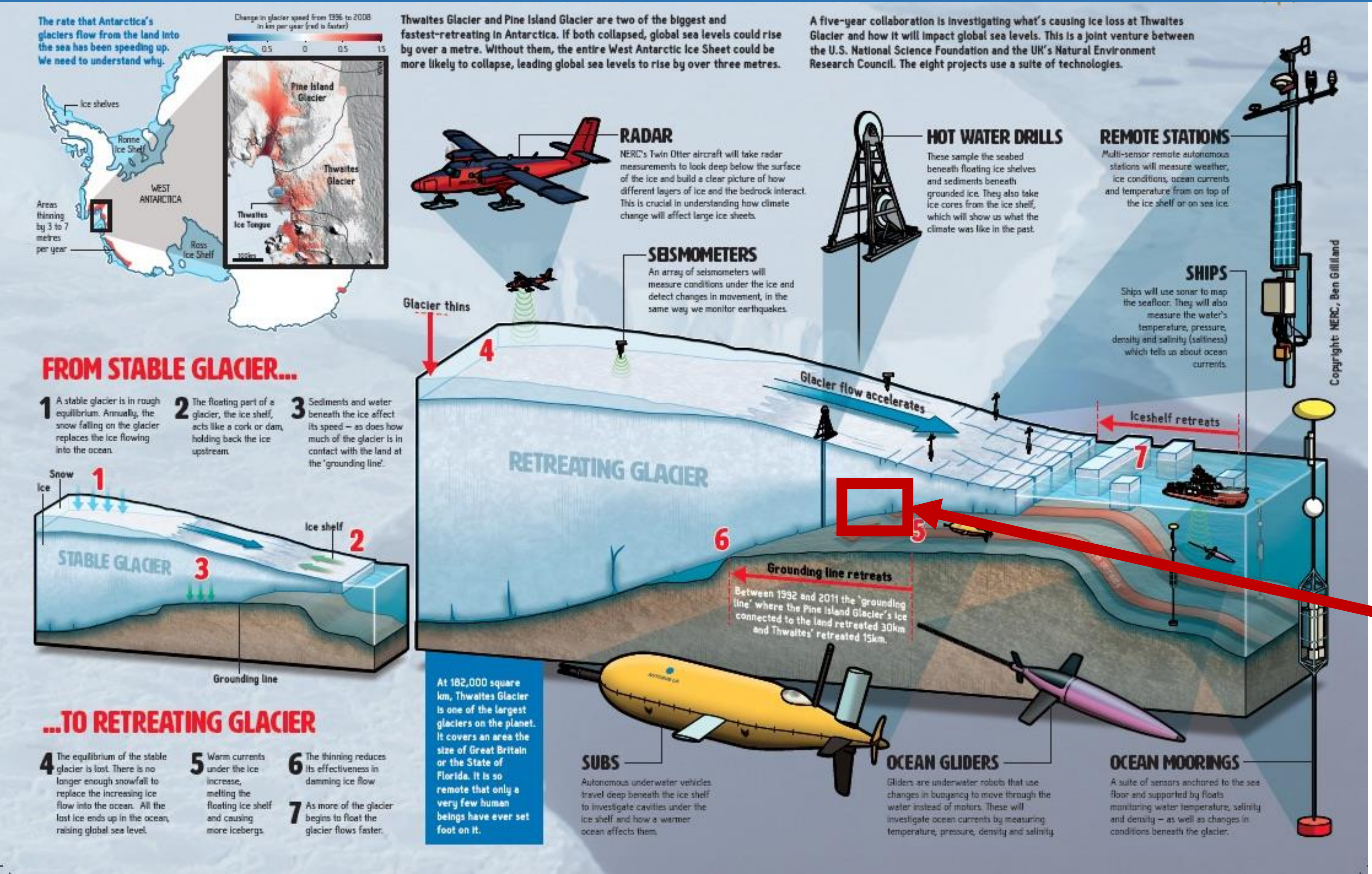


APPENDICES

I.B. Sub. Hydro.: On Icy Moons. Expected dynamics is heterogeneous.



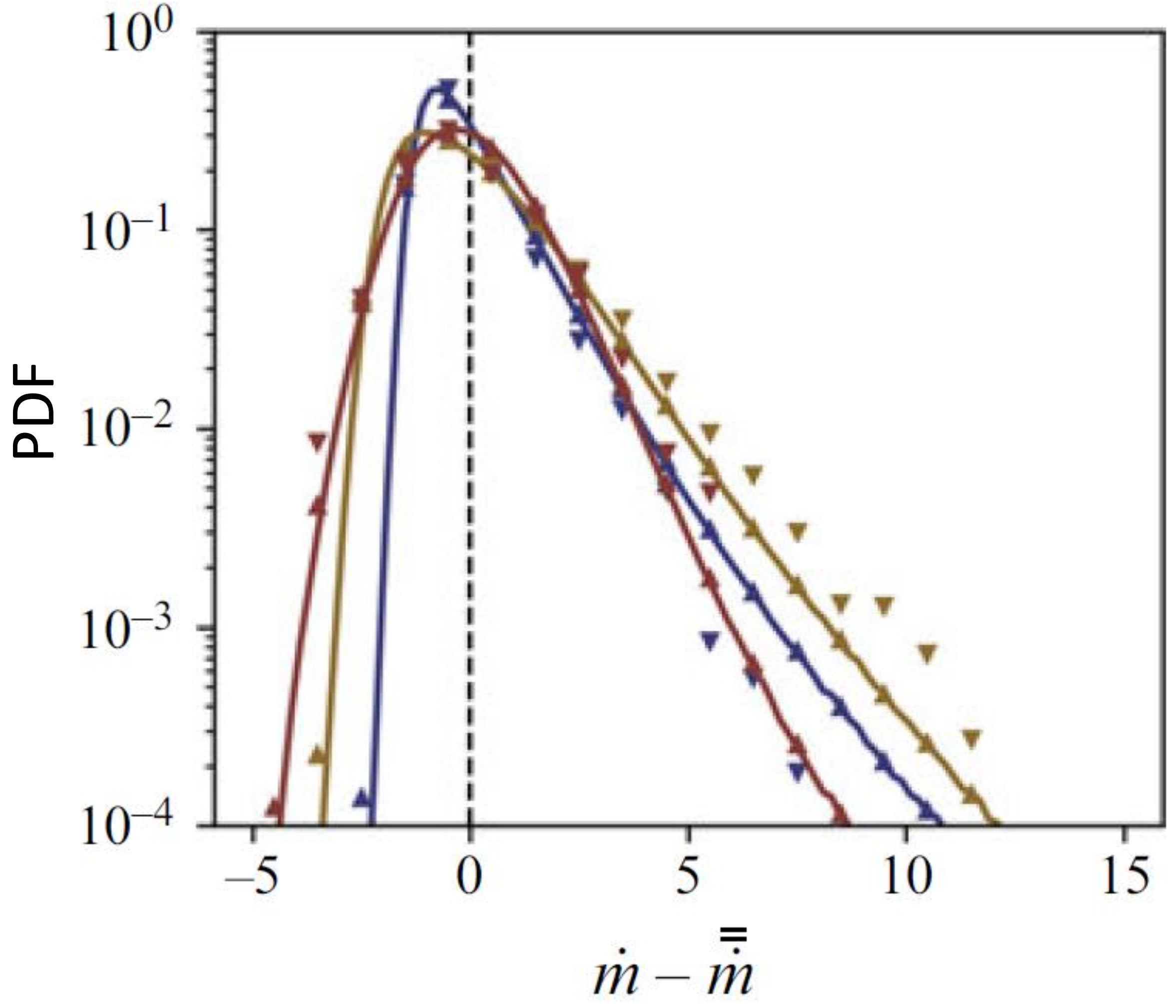
II.A. Ice melting: Antarctica. Observation of Thwaites glacier and cavity.



+ simulations with $O(1)km$ horizontal -- $O(10)m$ vertical resolution

What is the $O(1)cm$ boundary layer dynamic ???

I.A. Ice melting: Antarctica. First results: asymmetric melt-rate PDF!



However, no phase-change origin…
Same asymmetry exists for the heat flux at a smooth boundary.

→Not due to coupling… but an intrinsic property of wall-bounded flows.

Upwellings (hot) have a high probability of being intense, while downwellings (cold) are always weak.

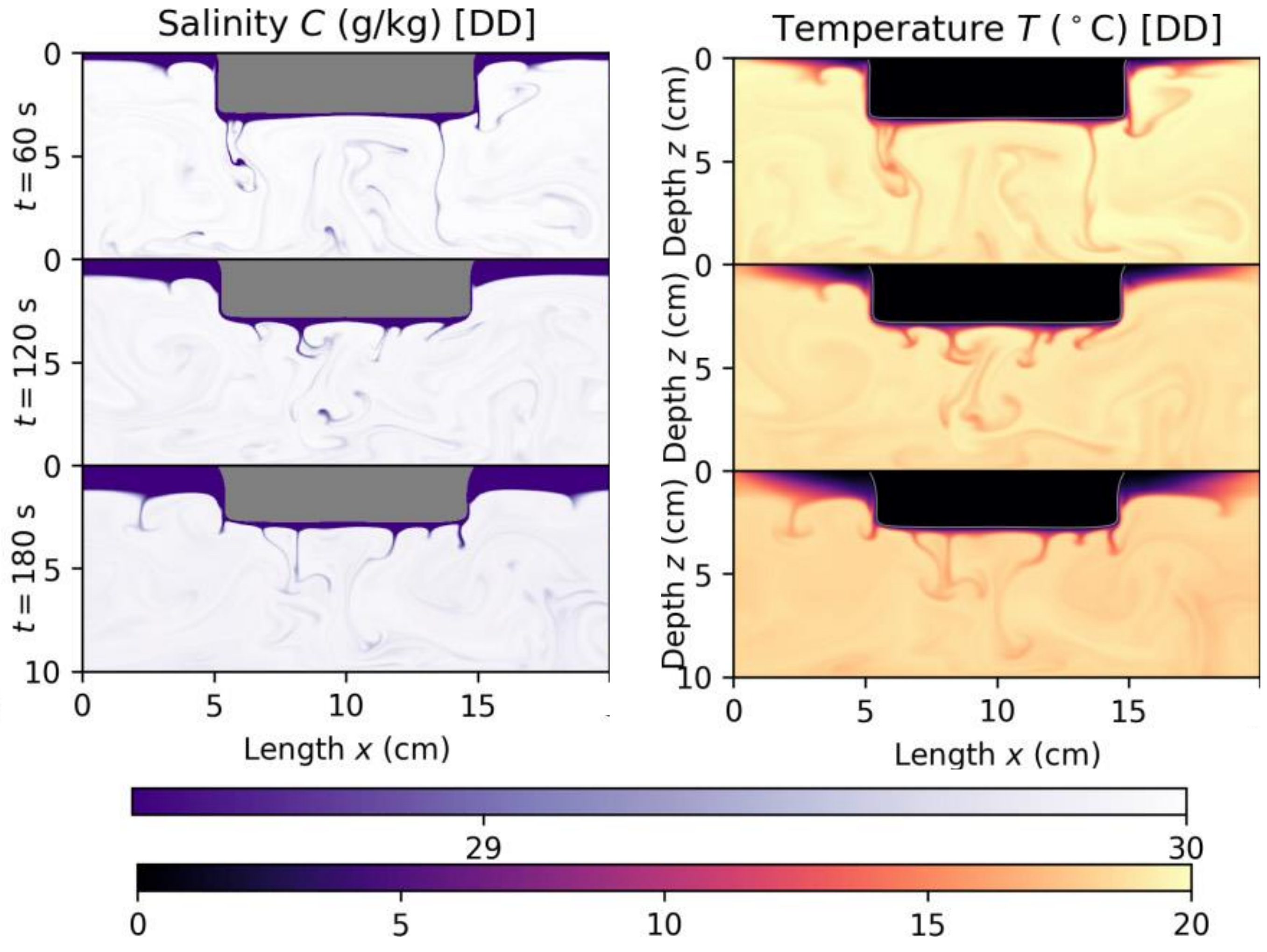
I.A. Ice melting: Antarctica. Perspectives.

→ consider stronger currents to *get* to « scallops ».

→ consider ice melting in an ambiant at rest but stratified in temperature and salt.

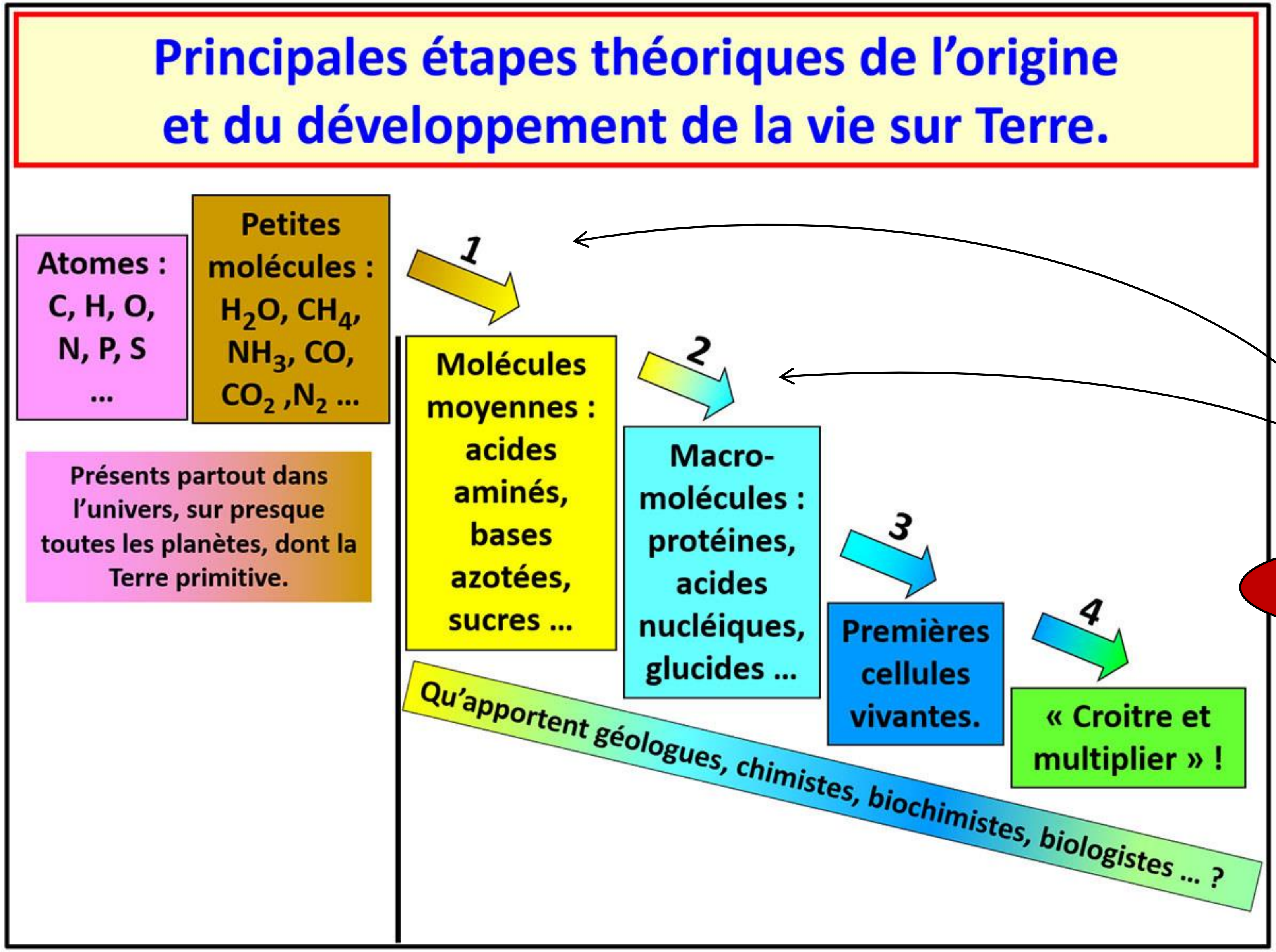
→ go back to 2-domain approach.

*interested? Send me an email! louis.couston@ens-lyon.fr



Physical Review Fluids 6.2 (2021): 023802.

II.A. Astrobiologie: Sur Terre.



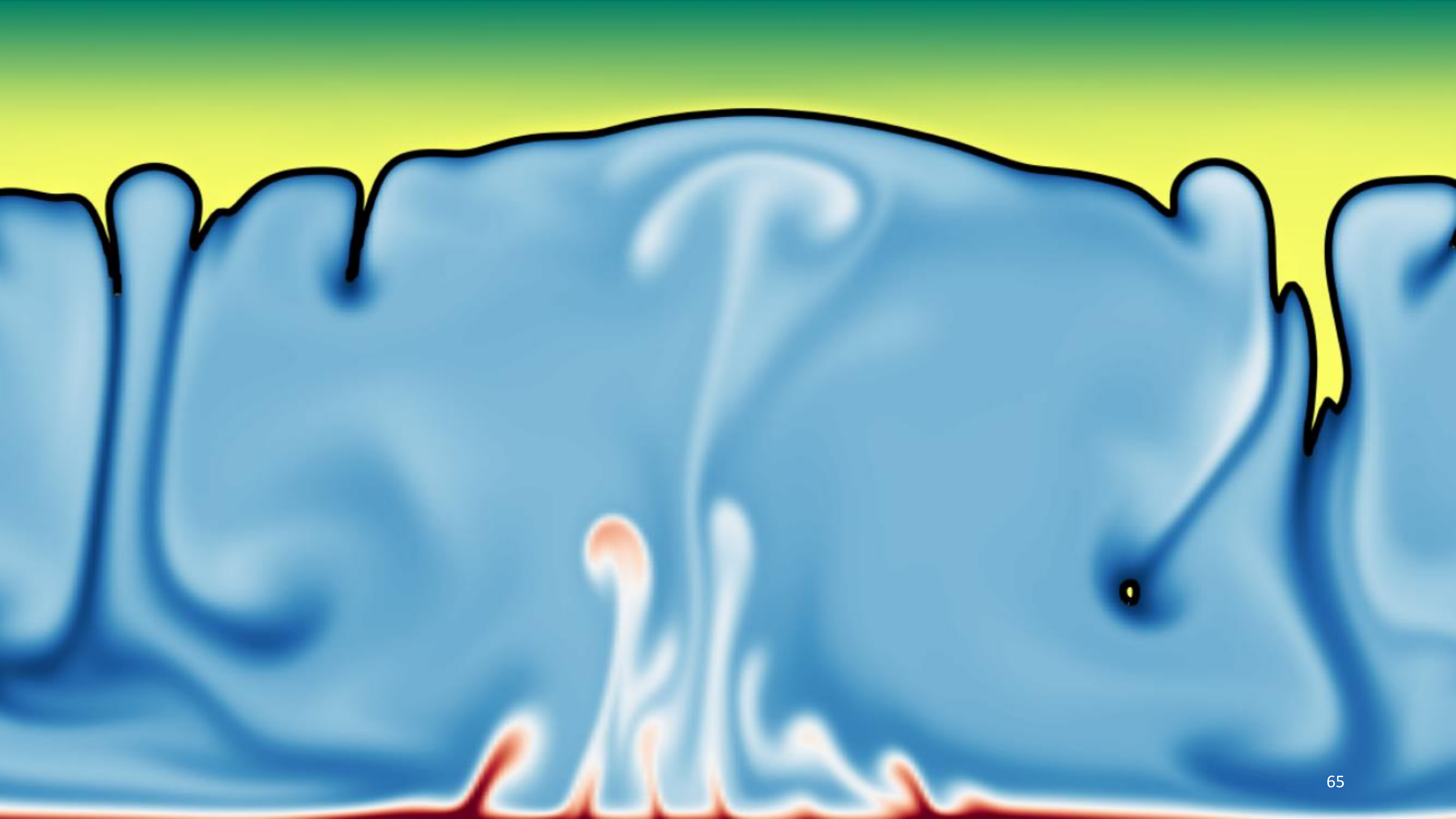
credit ©Pierre Thomas

Ressources

Physique du transport

cellules

Occuper l'espace.



On aimerait savoir…

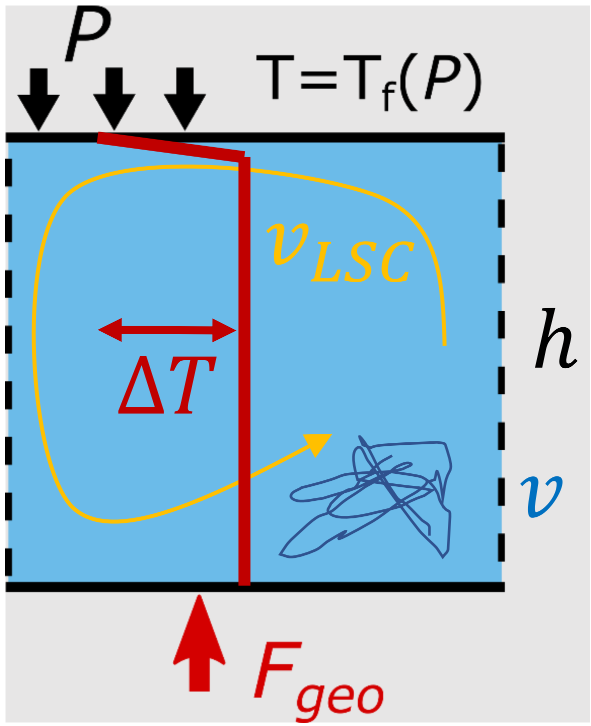
- Intensité de la turbulence
- Vitesses grandes échelles
- Température moyenne

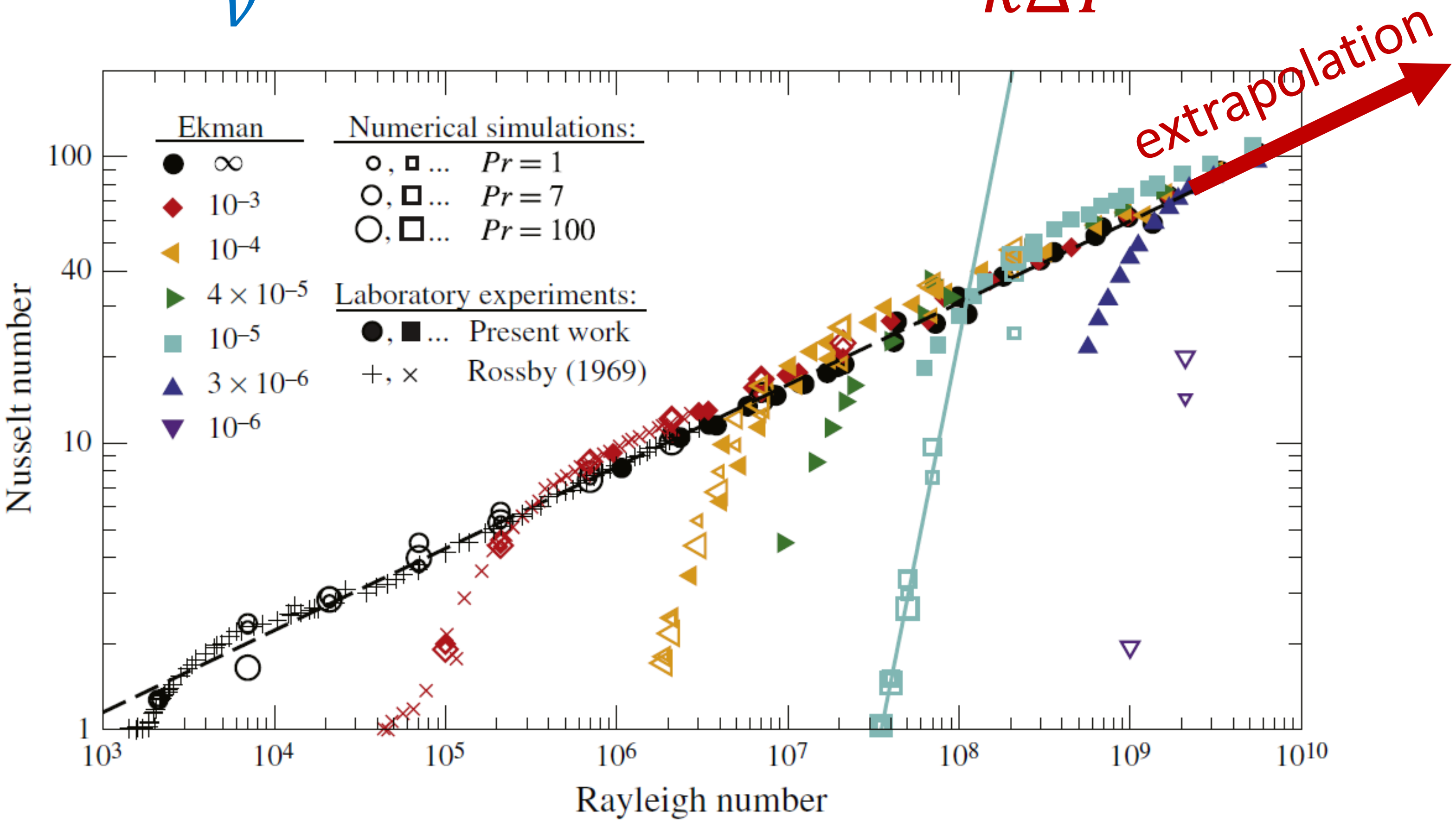
Nombre de Reynolds

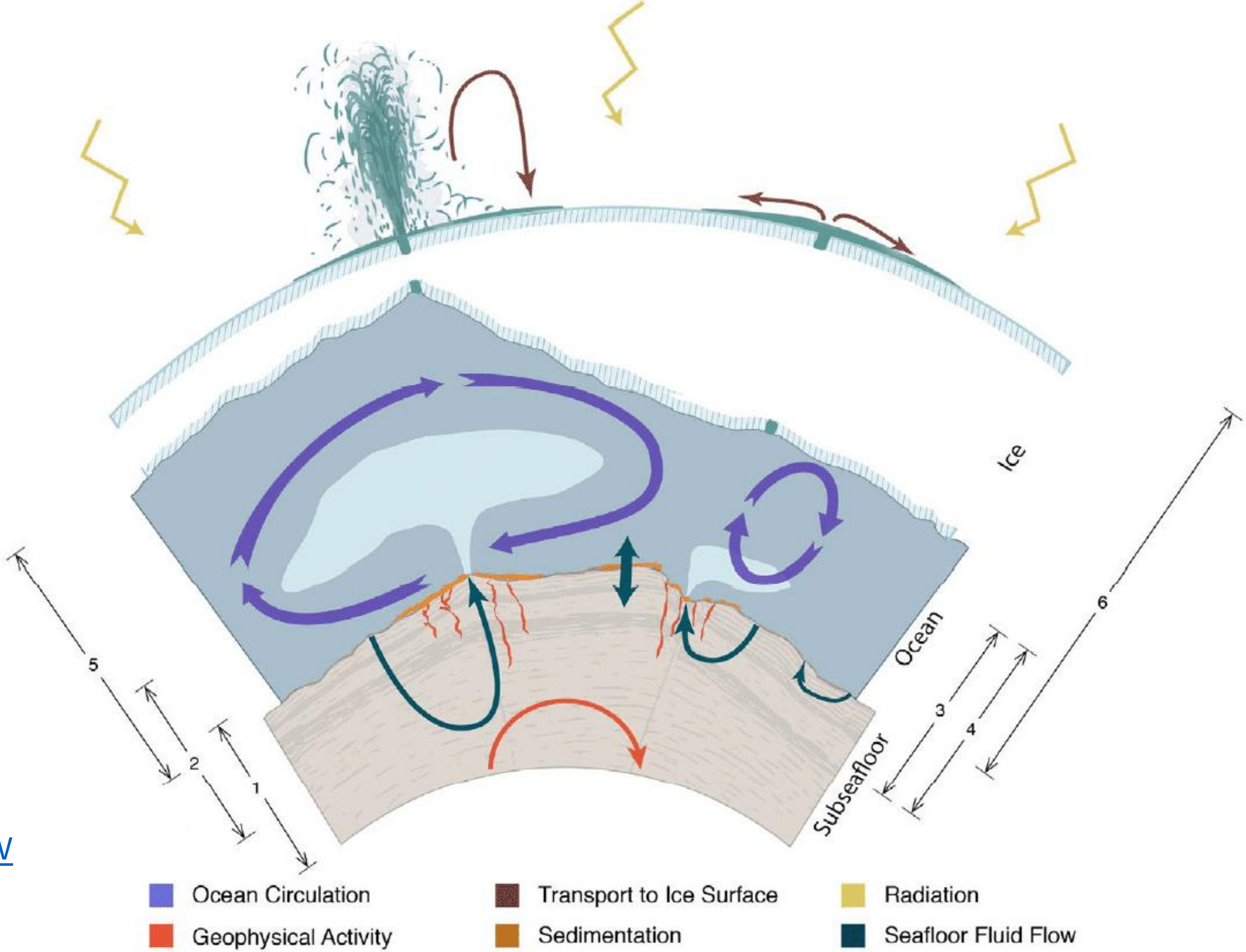
$$Re = \frac{vh}{\nu} \approx 0.03 Ra^{\frac{1}{2}}$$

Nombre de Nusselt

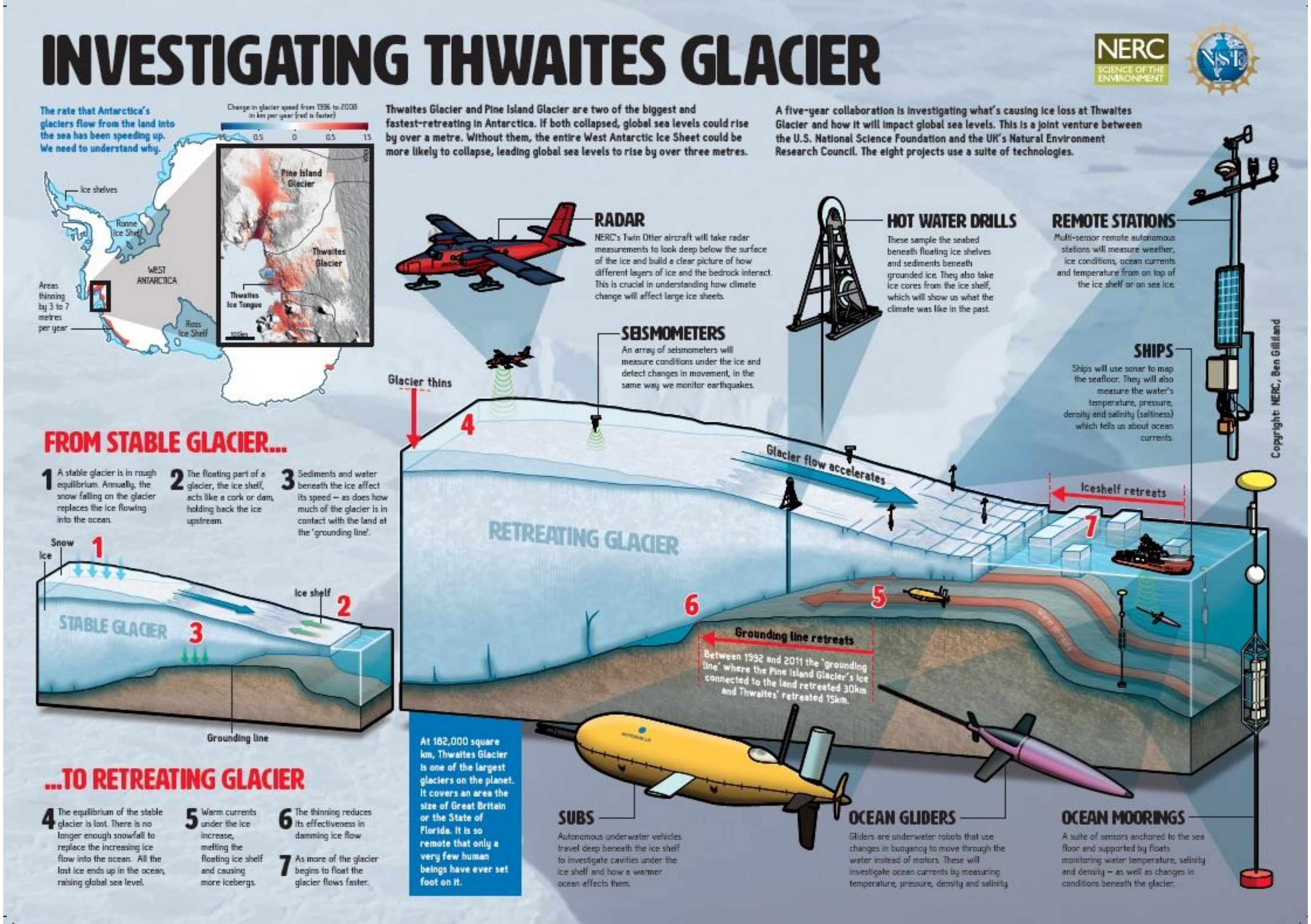
$$Nu = \frac{Fh}{k\Delta T} \approx 0.2 Ra^{\frac{2}{7}}$$






Ice
Ocean
Subseafloor
1
2
3
4
5
6
Ocean Circulation
Geophysical Activity
Transport to Ice Surface
Sedimentation
Radiation
Seafloor Fluid Flow

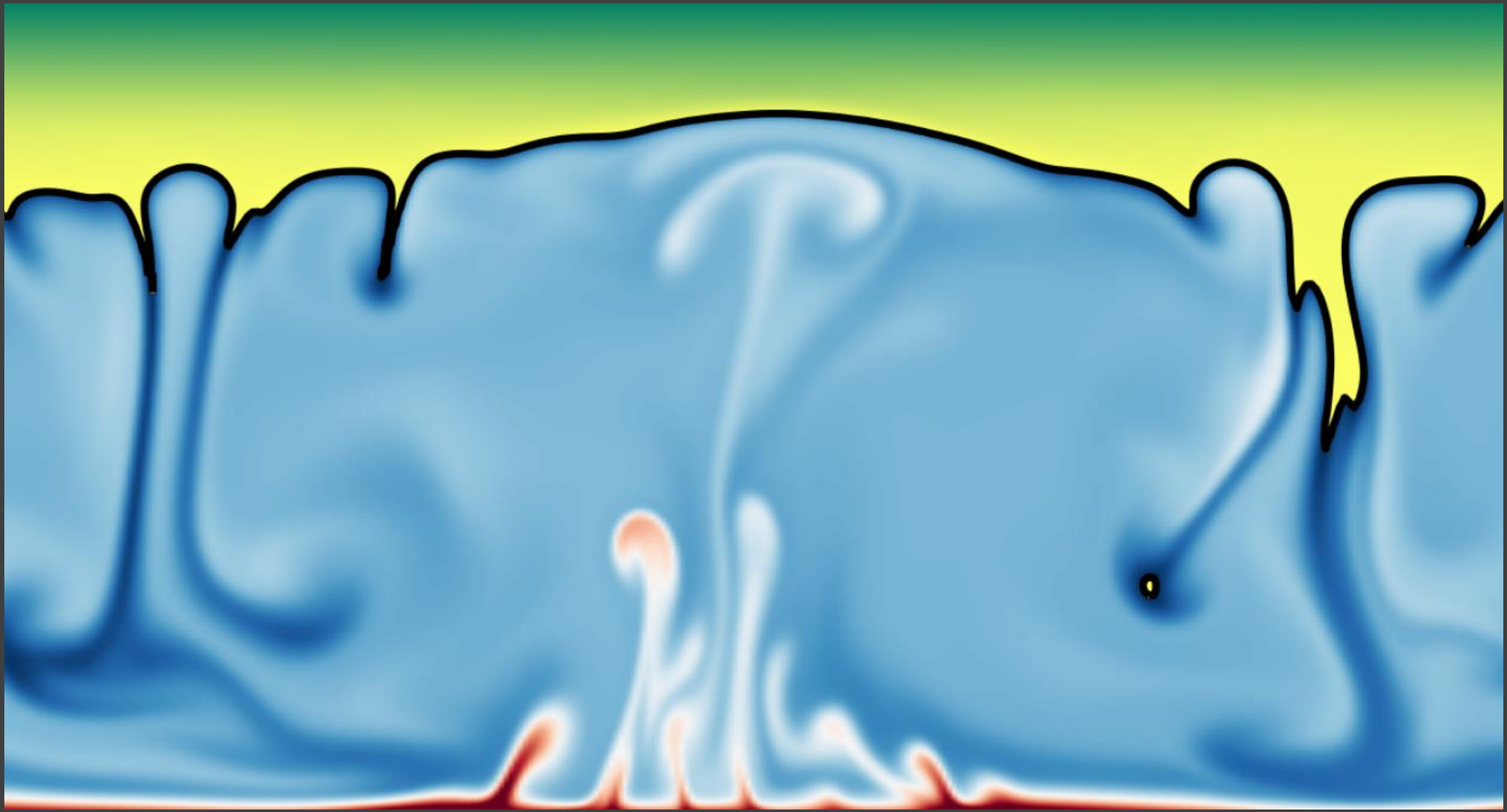
credit ExOW



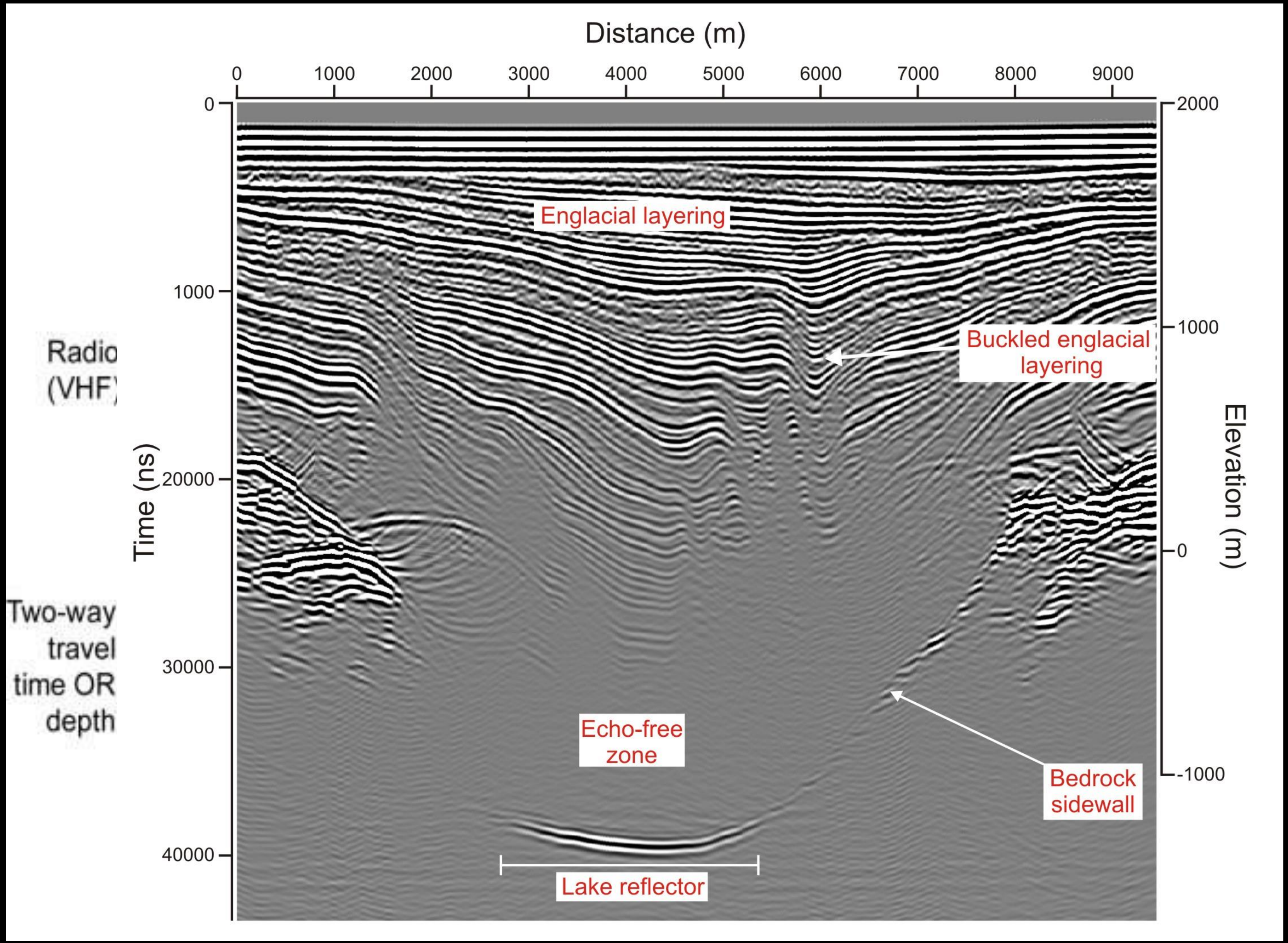
INVESTIGATING THWAITES GLACIER
NERC SCIENCE OF THE ENVIRONMENT
NSF
The rate that Antarctica's glaciers flow from the land into the sea has been speeding up. We need to understand why.
Change in glacier speed from 1996 to 2008 in km per year (red is faster)
Ice shelves
Ronne Ice Shelf
WEST ANTARCTICA
Areas thinning by 3 to 7 metres per year
Ross Ice Shelf
Pine Island Glacier
Thwaites Glacier
Thwaites Ice Tongue
Thwaites Glacier and Pine Island Glacier are two of the biggest and fastest-retreating in Antarctica. If both collapsed, global sea levels could rise by over a metre. Without them, the entire West Antarctic Ice Sheet could be more likely to collapse, leading global sea levels to rise by over three metres.
A five-year collaboration is investigating what's causing ice loss at Thwaites Glacier and how it will impact global sea levels. This is a joint venture between the U.S. National Science Foundation and the UK's Natural Environment Research Council. The eight projects use a suite of technologies.
RADAR
NERC's Twin Otter aircraft will take radar measurements to look deep below the surface of the ice and build a clear picture of how different layers of ice and the bedrock interact. This is crucial in understanding how climate change will affect large ice sheets.
HOT WATER DRILLS
These sample the seabed beneath floating ice shelves and sediments beneath grounded ice. They also take ice cores from the ice shelf, which will show us what the climate was like in the past.
REMOTE STATIONS
Multi-sensor remote autonomous stations will measure weather, ice conditions, ocean currents and temperature from on top of the ice shelf or on sea ice.
SEISMOMETERS
An array of seismometers will measure conditions under the ice and detect changes in movement, in the same way we monitor earthquakes.
SHIPS
Ships will use sonar to map the seafloor. They will also measure the water's temperature, pressure, density and salinity (saltiness) which tells us about ocean currents.
Copyright: NERC, Ben Gilliland
Glacier thins
Glacier flow accelerates
Iceshelf retreats
RETREATING GLACIER
Grounding line retreats
Between 1992 and 2011 the 'grounding line' where the Pine Island Glacier's ice connected to the land retreated 30km and Thwaites' retreated 15km.
FROM STABLE GLACIER...
1 A stable glacier is in rough equilibrium. Annually, the snow falling on the glacier replaces the ice flowing into the ocean.
2 The floating part of a glacier, the ice shelf, acts like a cork or dam, holding back the ice upstream.
3 Sediments and water beneath the ice affect its speed – as does how much of the glacier is in contact with the land at the 'grounding line'.
Snow
Ice
Ice shelf
STABLE GLACIER
Grounding line
...TO RETREATING GLACIER
4 The equilibrium of the stable glacier is lost. There is no longer enough snowfall to replace the increasing ice flow into the ocean. All the lost ice ends up in the ocean, raising global sea level.
5 Warm currents under the ice increase, melting the floating ice shelf and causing more icebergs.
6 The thinning reduces its effectiveness in damming ice flow
7 As more of the glacier begins to float the glacier flows faster.
At 182,000 square km, Thwaites Glacier is one of the largest glaciers on the planet. It covers an area the size of Great Britain or the State of Florida. It is so remote that only a very few human beings have ever set foot on it.
SUBS
Autonomous underwater vehicles travel deep beneath the ice shelf to investigate cavities under the ice shelf and how a warmer ocean affects them.
OCEAN GLIDERS
Gliders are underwater robots that use changes in buoyancy to move through the water instead of motors. These will investigate ocean currents by measuring temperature, pressure, density and salinity.
OCEAN MOORINGS
A suite of sensors anchored to the sea floor and supported by floats monitoring water temperature, salinity and density – as well as changes in conditions beneath the glacier.

- The Astrobiology Primer v2
- NASA roadmap to astrobiology
- IPCC’s special report on The Ocean and Cryosphere in a Changing Climate

- Christopher German Exploring Ocean Worlds (ExOW) project at WHOI
- Thwaites



Motivation: Extreme Antarctic subglacial lakes (ASL)



Seismic sounding
50s

Radar
Vehicles, then planes
60s

First detection
1970
unusually flat & bright
subglacial radio-echo surface

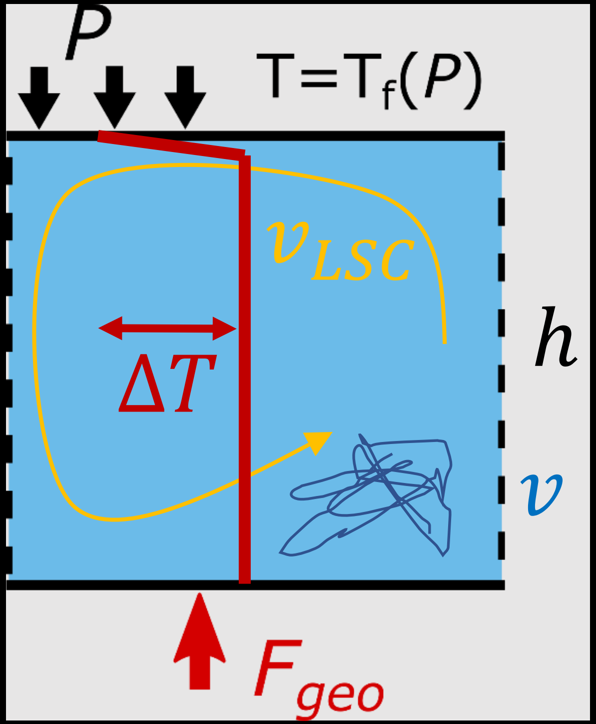
State-of-the-art: Heating or Rayleigh-Bénard convection

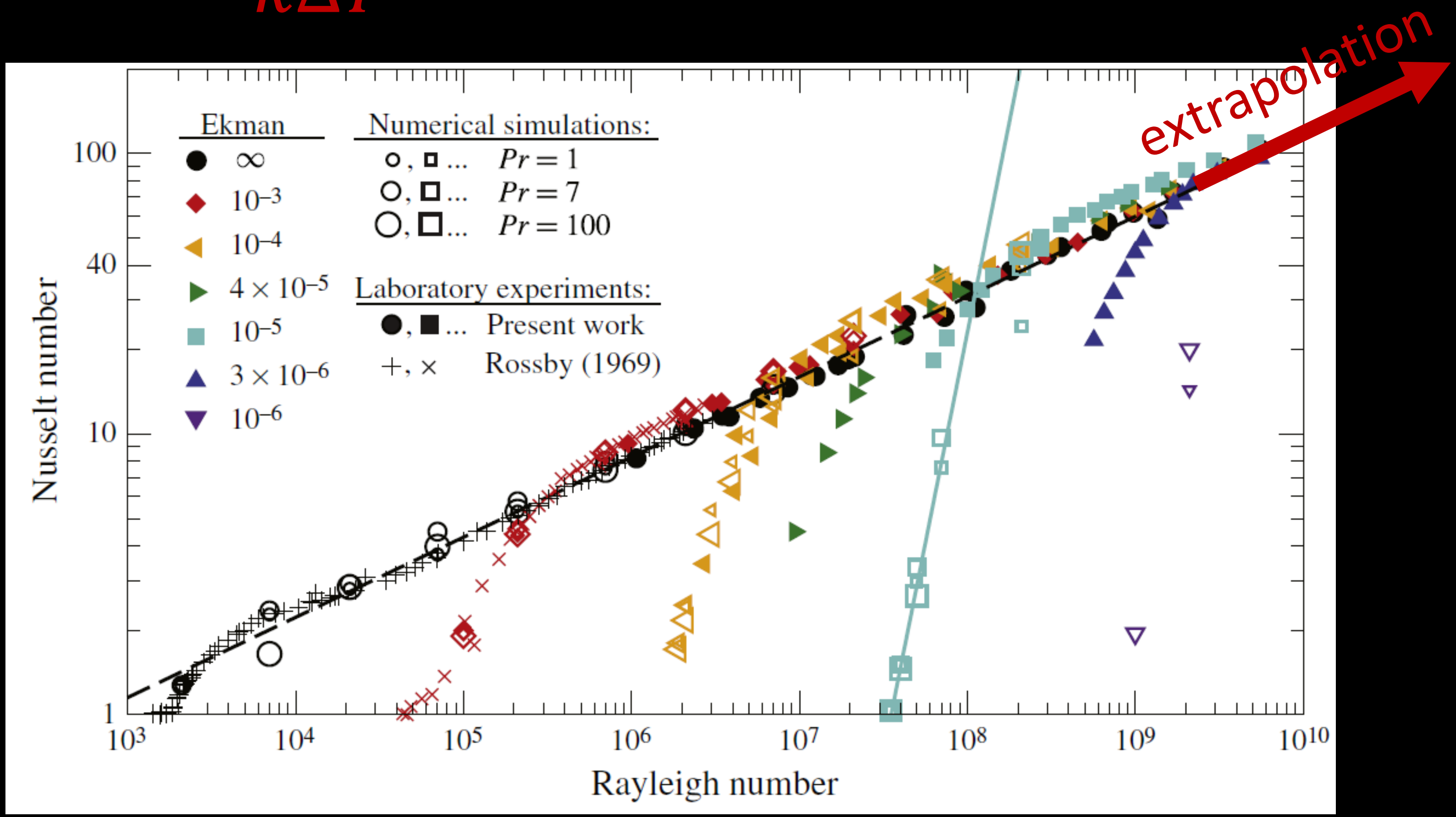
Nusselt number

$$Nu = \frac{Fh}{k\Delta T} \approx 0.2 Ra^{\frac{2}{7}}$$

<u>What we want to know</u>

- Thermal structure
- Turbulence intensity
- Speed of overturning



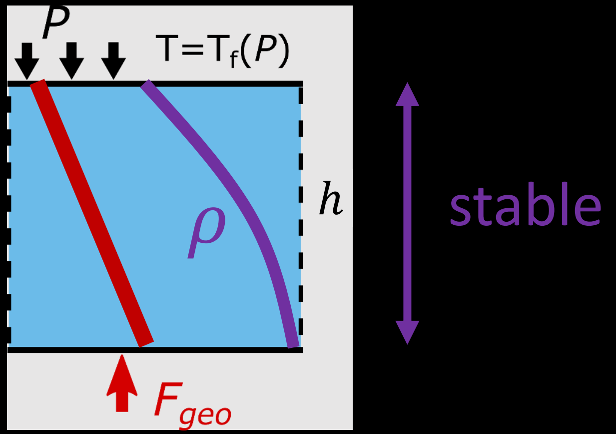


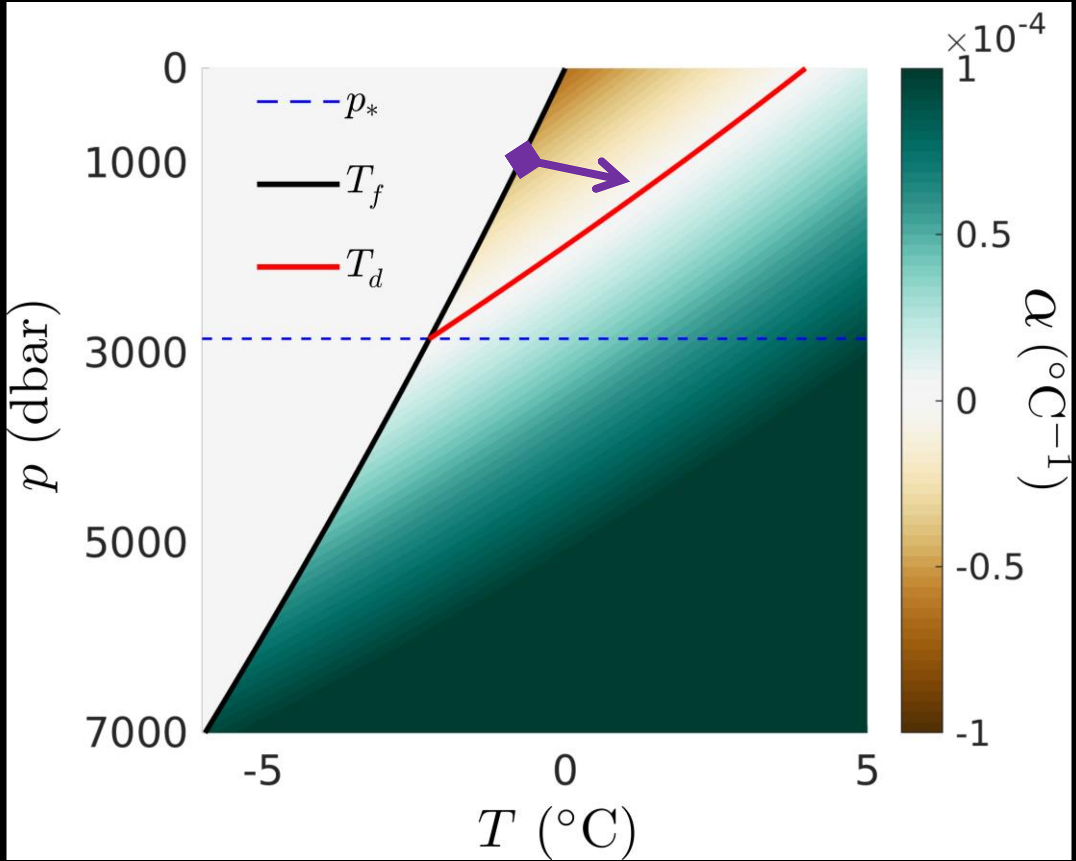
Result #1: Are ASL stable, or unstable?

RB instability for a simple fluid:
(overcome viscous/thermal dissipation)

$$Ra = \frac{g\alpha h^4 F}{\nu\kappa k} > O(1000)$$

$$T = T_f + \frac{zF}{k}$$





But…

- The equation of state for water is nonlinear

Result #1: Are ASL stable, or unstable?

RB instability for a simple fluid:
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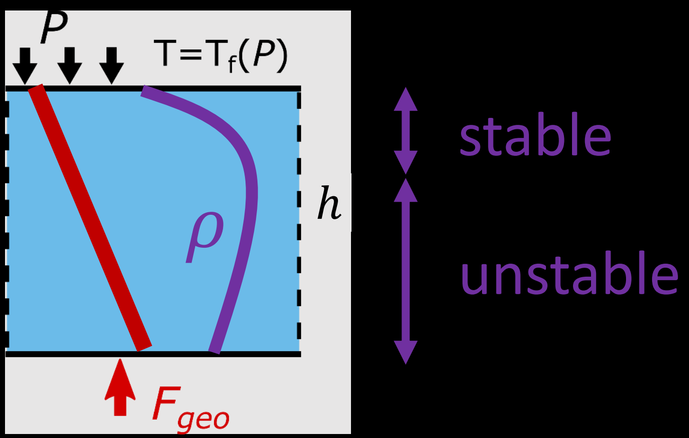
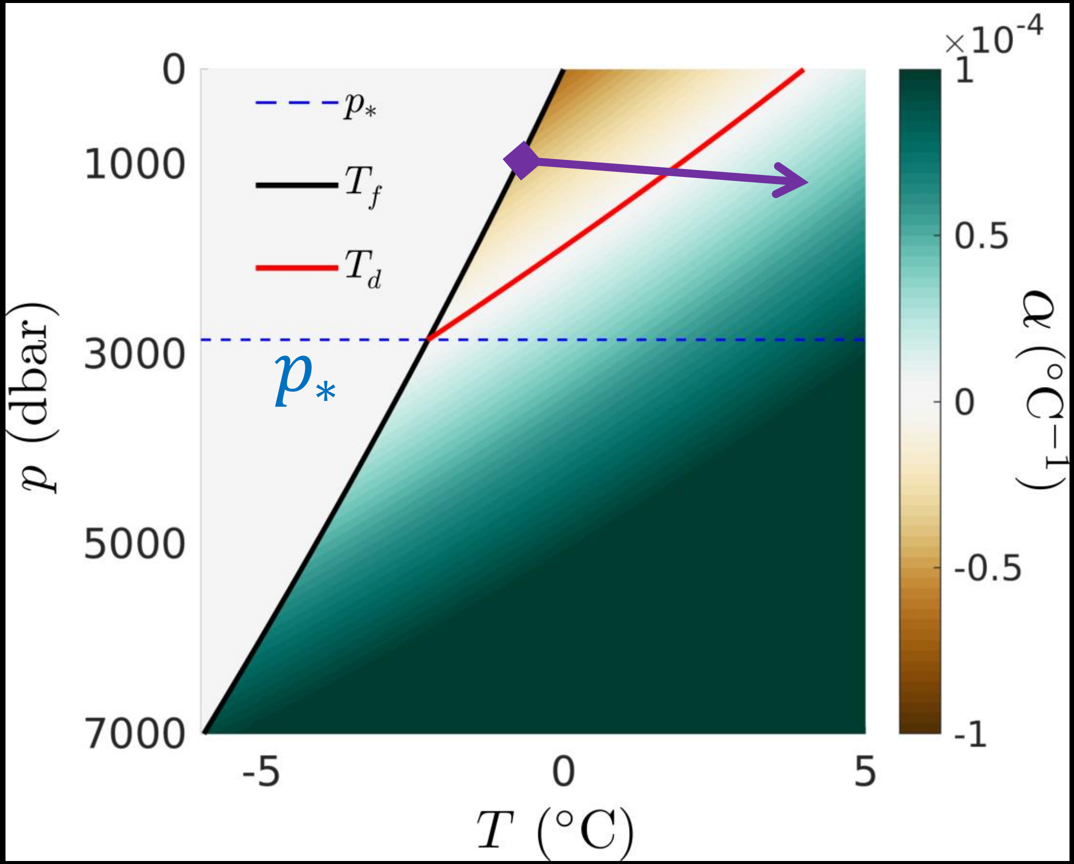


But…

- The equation of state for water is nonlinear



$\oplus$ $\alpha_{bot} > 0$ (thin ice)

Result #1: Are ASL stable, or unstable?

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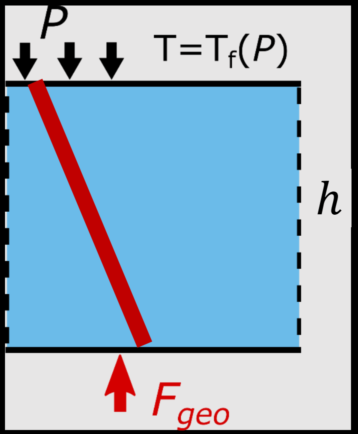


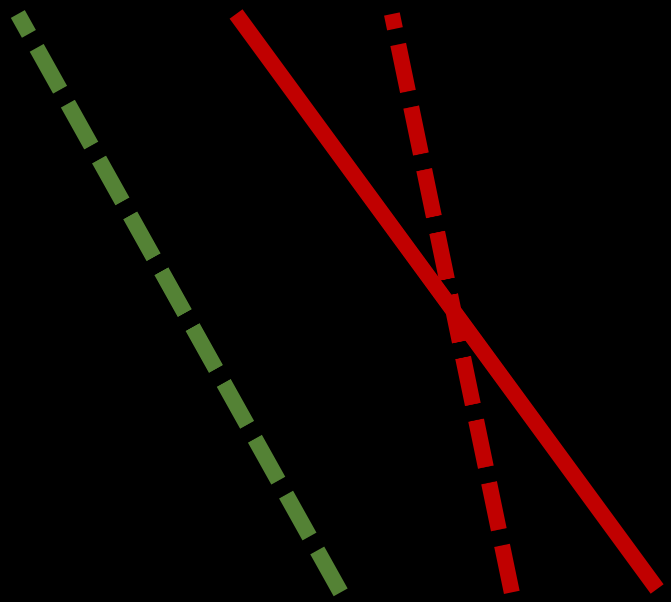
But…

- The equation of state for water is nonlinear
- ASL can be 1km deep and experience compressibility

$\oplus$ $\alpha_{bot} > 0$ (thin ice)

$\oplus$ $F > F_{ad}$ (thick ice)

Hydrostatic pressure P



Adiabatic temp. gradient F_{ad}

Result #1: Are ASL stable, or unstable?

RB instability for a simple fluid:
(overcome viscous/thermal dissipation)

$$Ra = \frac{g\alpha h^4 F}{\nu\kappa k} > O(1000)$$

But…

- The equation of state for water is nonlinear
- ASL can be 1km deep and experience compressibility

$\oplus\ \alpha_{bot} > 0$ (thin ice)

$\oplus\ F > F_{ad}$ (thick ice)

Recipe

- ❑ Compressible rotating Boussinesq equations
- ❑ Linear perturbations around the base hydrostatic/diffusive state
- ❑ Growth rate σ from the eigenvalue problem

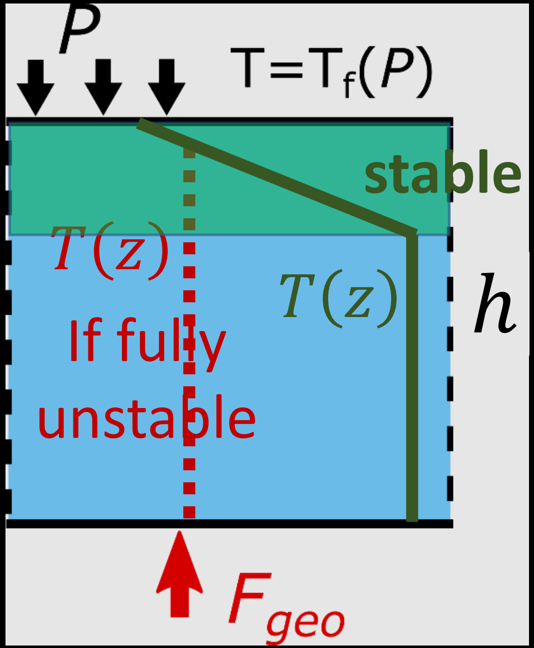
➢ We search for F_c such that $\sigma > 0$ for a bunch of ice pressures and water depths.

❖ We use the open-source pseudo-spectral code Dedalus with the eigentools package.

Implications for future lake exploration

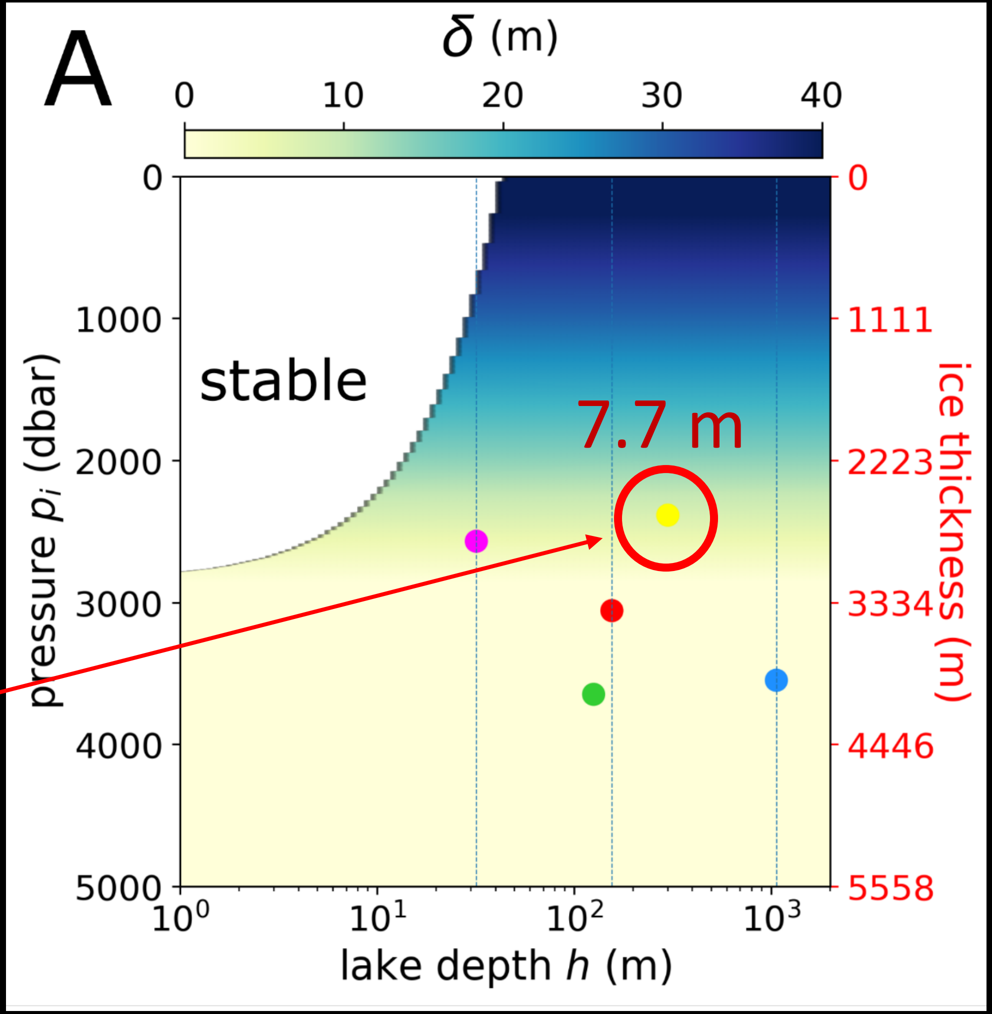
- Go for large water depth
- Upwelling is where there is melting
- Don't use accreted ice if you're sampling a lake with a thin ice cover

Remember the nonlinear equation of state…

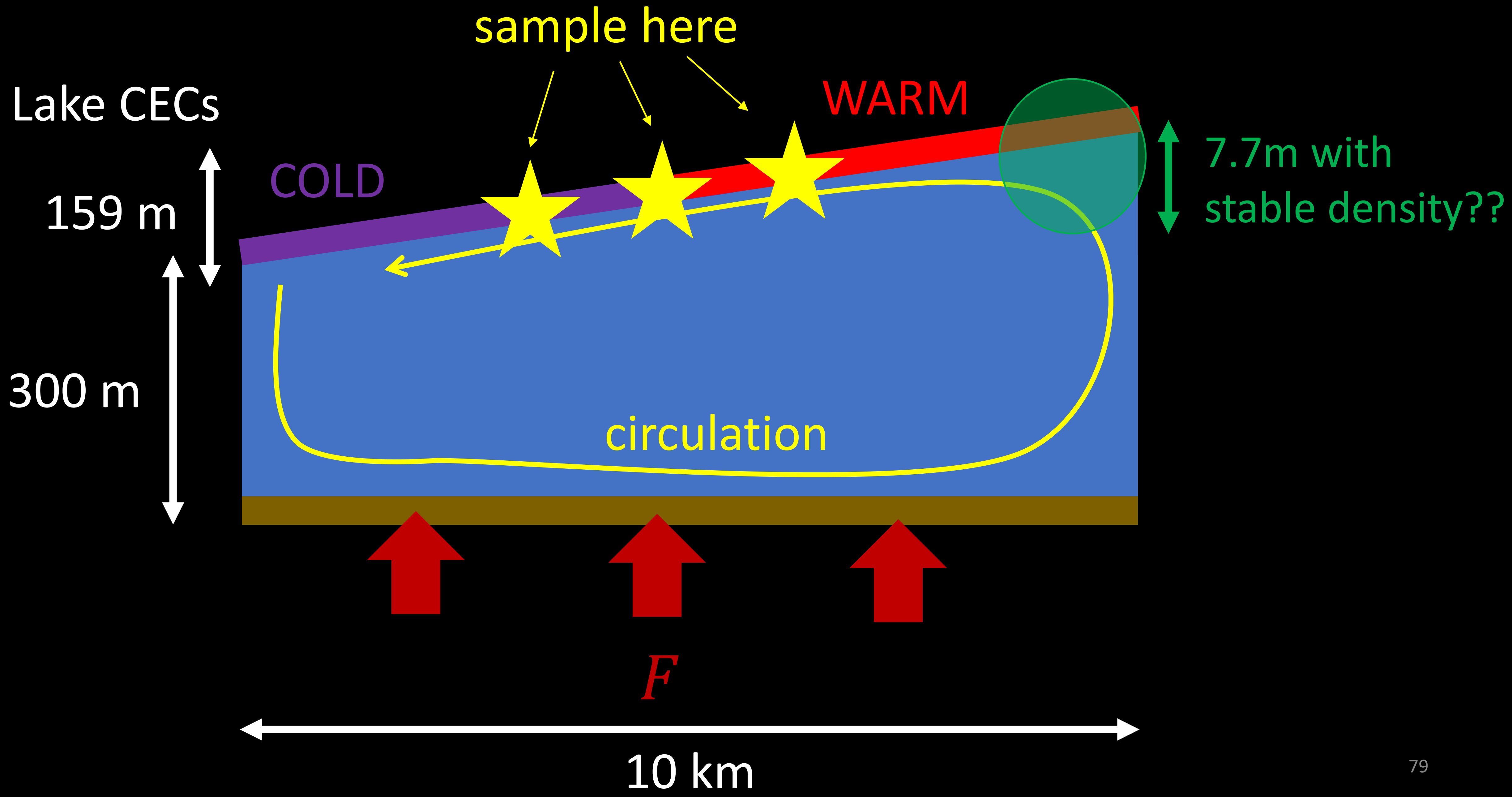


Lake CECs will be explored in 2023!
→ sample at least over 10 m (300 m deep)

Thickness of the stable layer

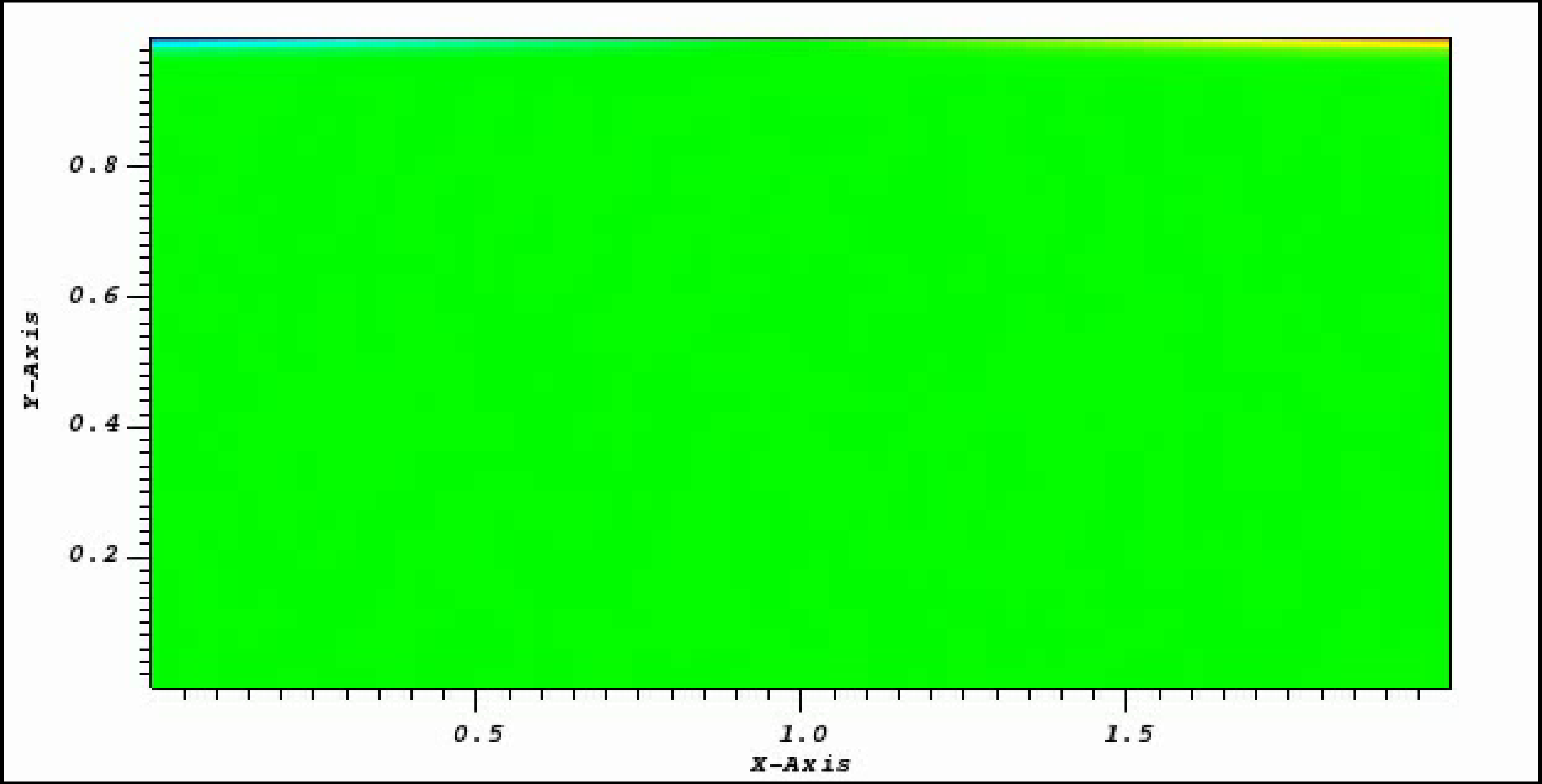


What’s next…



sample here
Lake CECs
WARM
COLD
159 m
7.7m with
stable density??
300 m
circulation
F
10 km

What's next…



What's next…

	Ice thickness (m)	Ice drop (m)	Lake length (km)	Water depth (m)	δ (m)	T_{bulk} (K)	ℓ (m)	U (mm/s)	U_{lsc} (mm/s)	V_{hc} (mm/s)	$2r_{max}$ (µm)
CECs	2653	159	10.35	300	7.7	0.69	1.6	0.97	0.32	0.041	22
SPL	2857	30	10	32	4.7	0.42	0.8	0.10	0.04	0.010	7.8
Ellsworth	3400	300	10	156	0.077	0.0069	1.2	0.69	0.26	0.066	20
Vostok	3945	600	280	1067	0.066	0.0059	2.3	3.80	0.85	0.066	36
Concordia	4055	168	45	126	0.063	0.0056	1.0	0.83	0.31	0.044	22

Take home

- Definitely worth considering variable freezing point for tilted roofs.
- However, the horizontal flow is likely weaker than the heat-flux induced vertical circulation.

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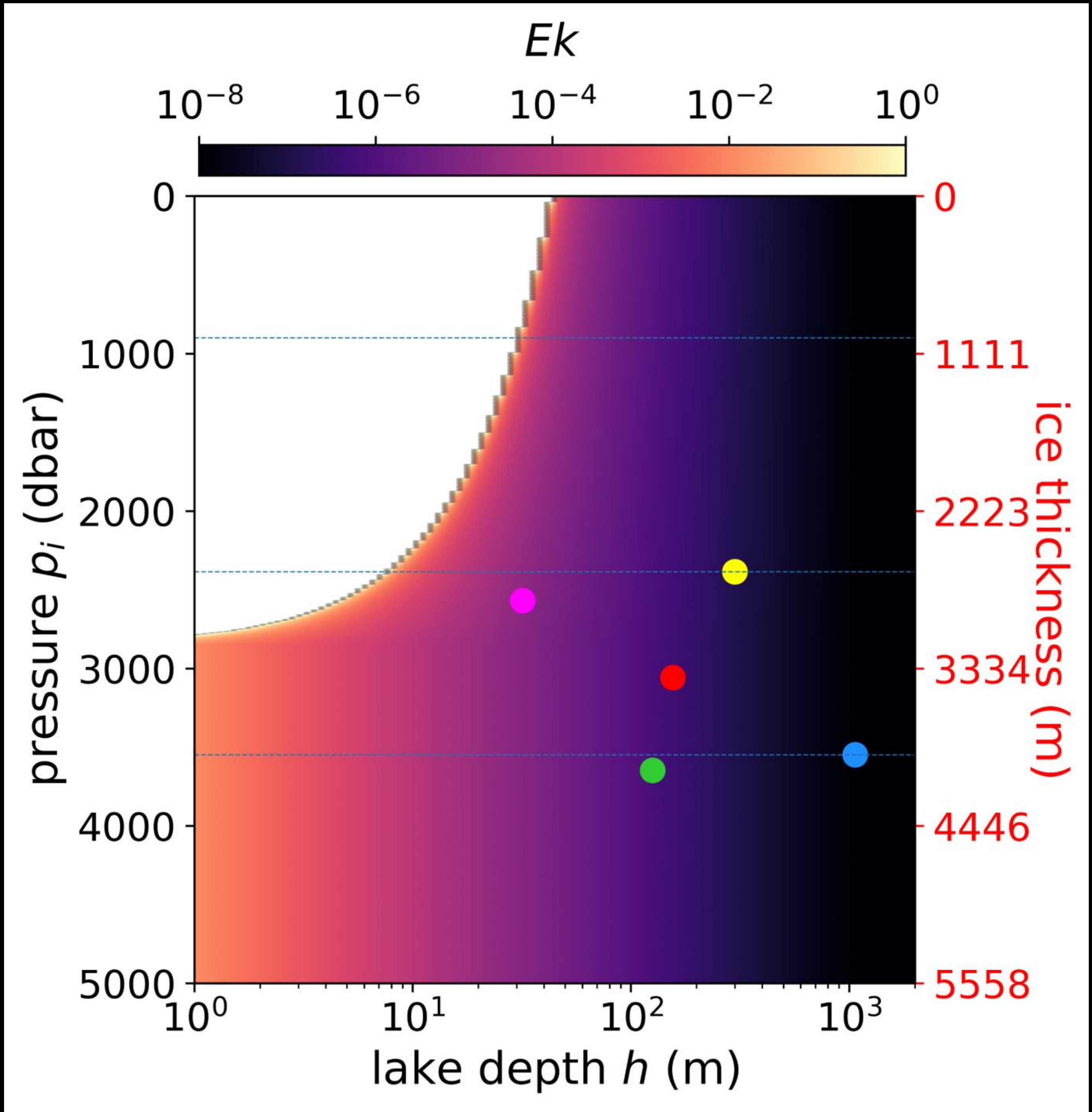
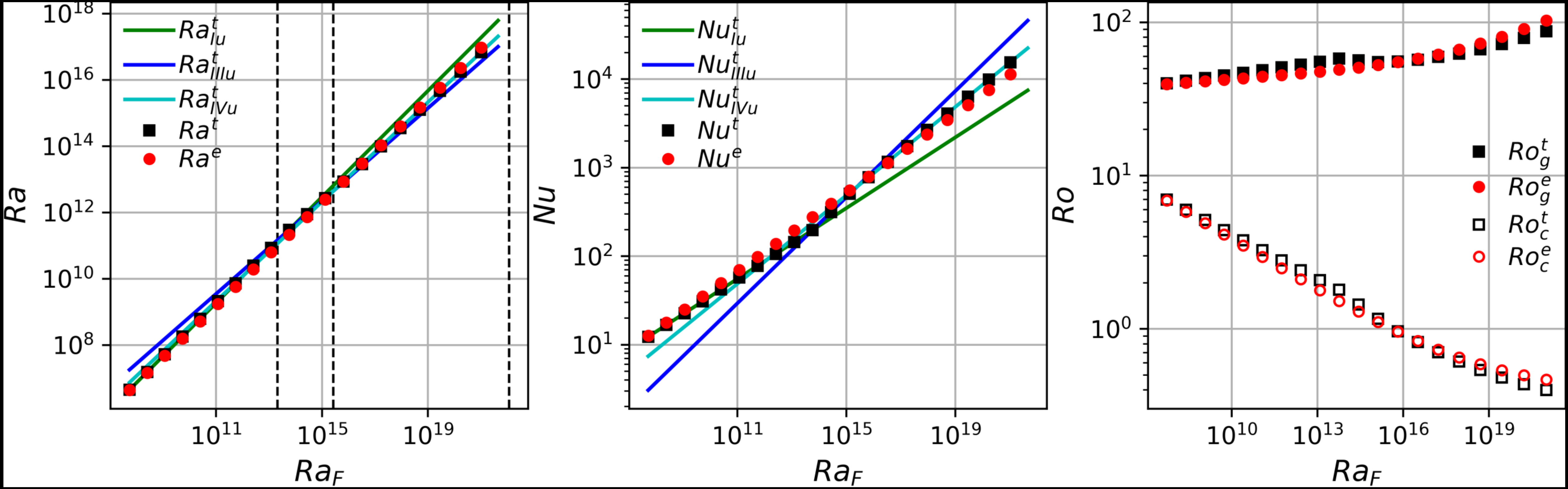
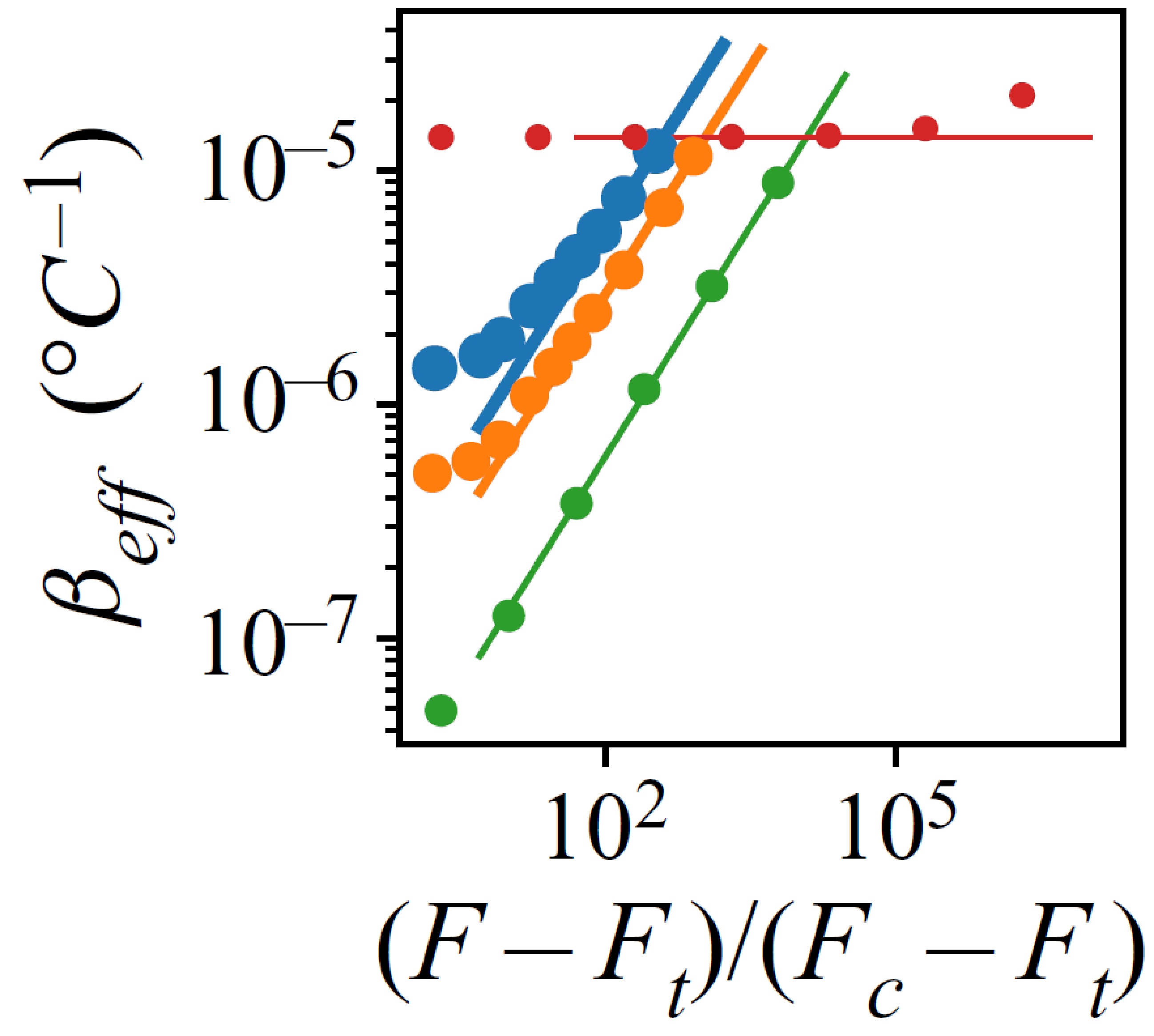
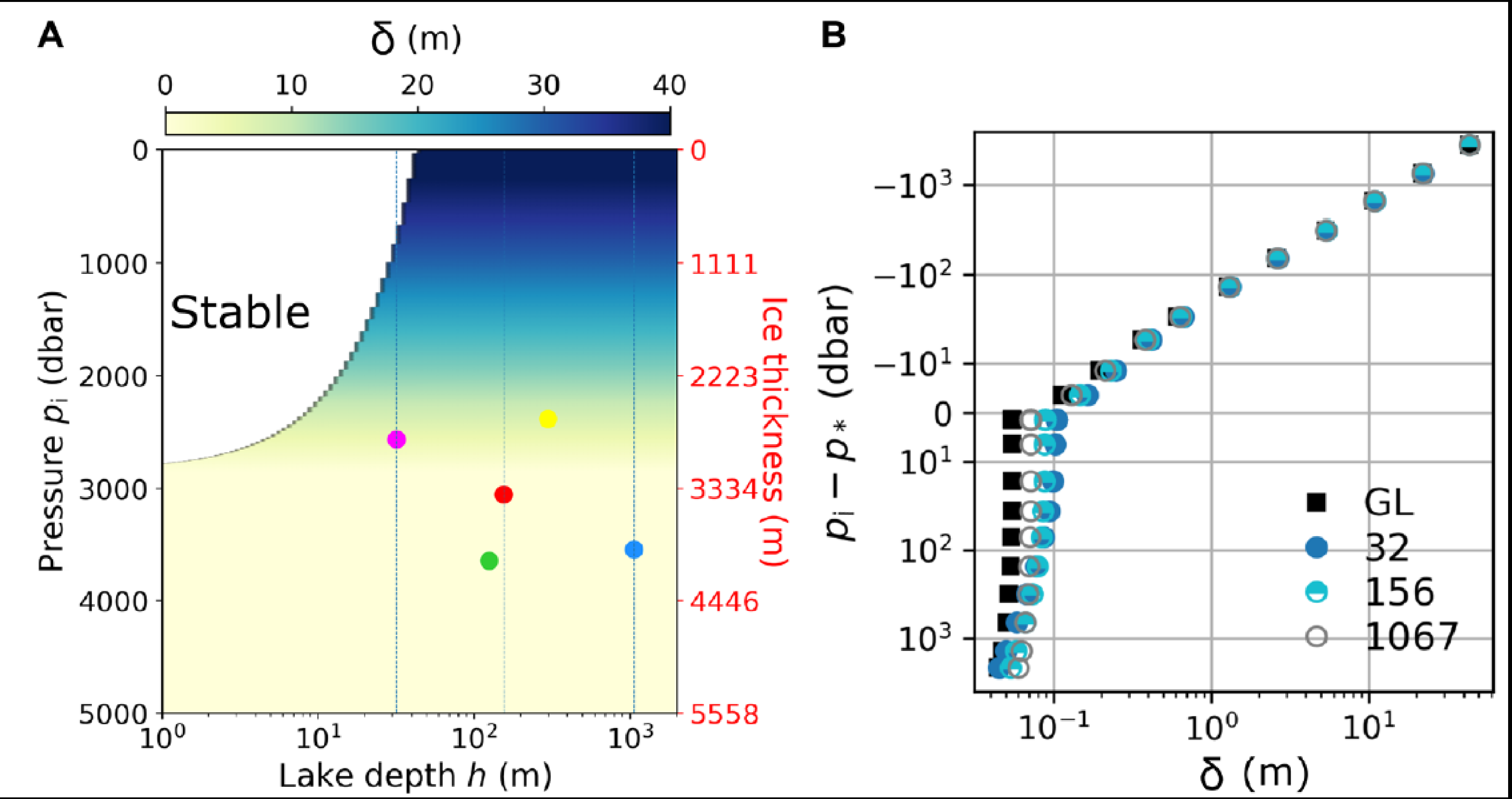


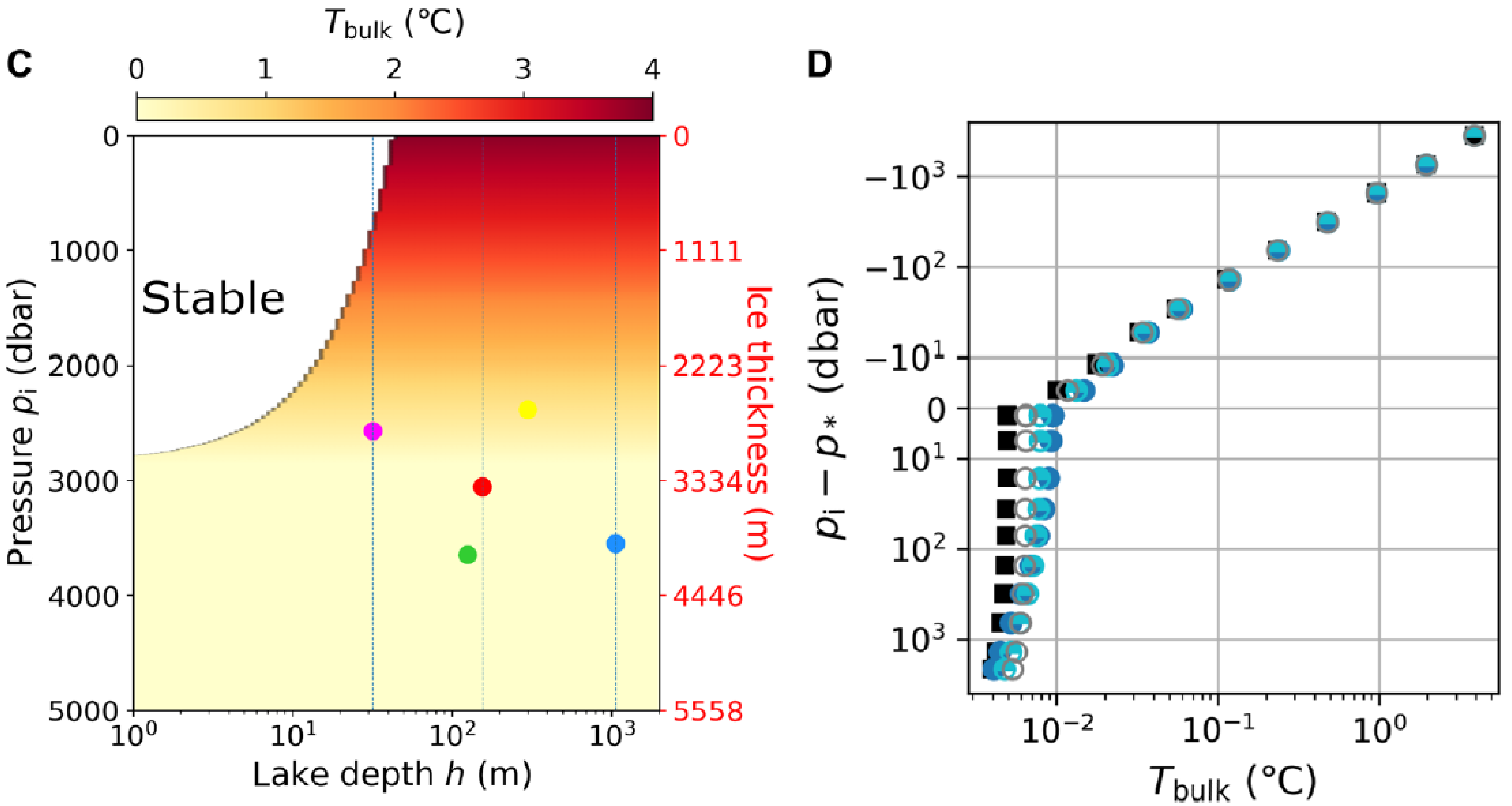
Ek
10−8
10−6
10−4
10−2
10^0
0
1000
2000
3000
4000
5000
pressure p_i (dbar)
0
1111
2223
3334
4446
5558
ice thickness (m)
10^0
10^1
10^2
10^3
lake depth h (m)



Ra^t_{Iu}
Ra^t_{IIIu}
Ra^t_{IVu}
Ra^t
Ra^e
Ra
Ra_F
Nu^t_{Iu}
Nu^t_{IIIu}
Nu^t_{IVu}
Nu^t
Nu^e
Nu
Ra_F
Ro^t_g
Ro^e_g
Ro^t_c
Ro^e_c
Ro
Ra_F

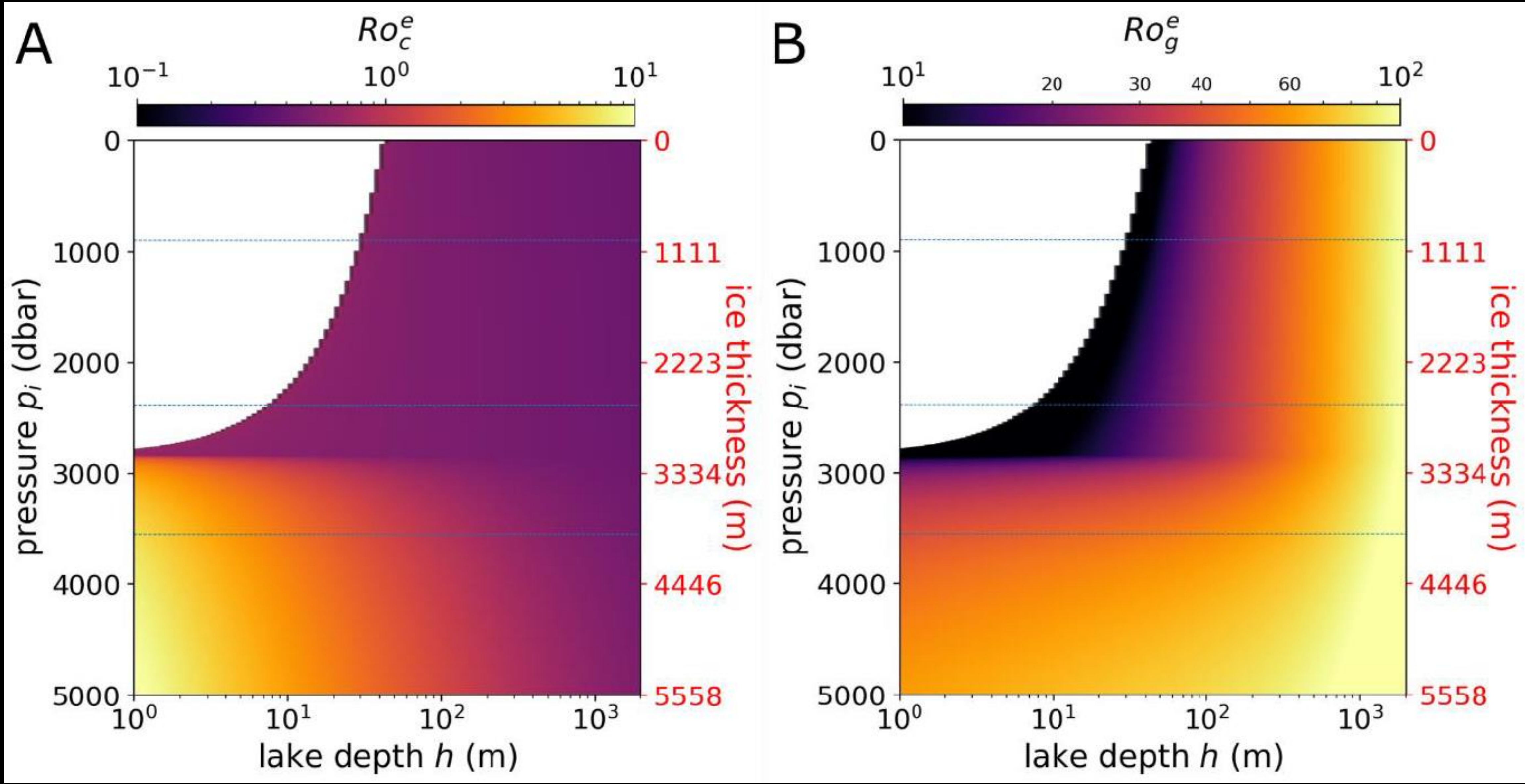

β_{eff} (°C^{-1})
10^{-5}
10^{-6}
10^{-7}
10^2
10^5
$(F-F_t)/(F_c-F_t)$

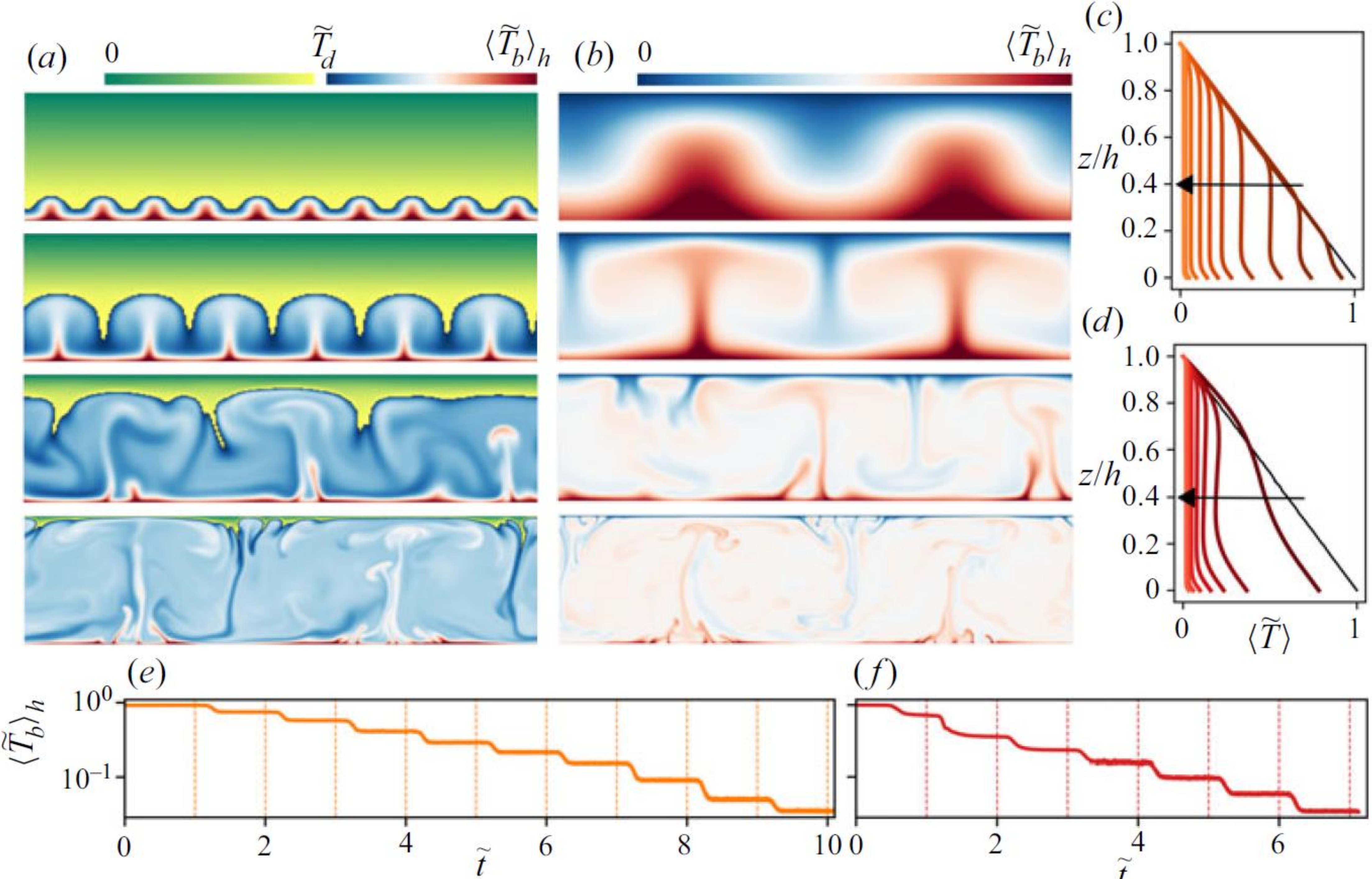

A
δ (m)
0
10
20
30
40
Stable
Pressure p_i (dbar)
0
1000
2000
3000
4000
5000
Ice thickness (m)
0
1111
2223
3334
4446
5558
10^0
10^1
10^2
10^3
Lake depth h (m)
B
$p_i - p_*$ (dbar)
-10^3
-10^2
-10^1
0
10^1
10^2
10^3
10^{-1}
10^0
10^1
δ (m)
GL
32
156
1067


C
T bulk (°C)
0
1
2
3
4
Stable
Pressure p i (dbar)
0
1000
2000
3000
4000
5000
Ice thickness (m)
0
1111
2223
3334
4446
5558
10^0
10^1
10^2
10^3
Lake depth h (m)
D
−10^3
−10^2
−10^1
0
10^1
10^2
10^3
p i − p * (dbar)
10^−2
10^−1
10^0
T bulk (°C)

$$Ro_c^e = \sqrt{RaEk^2/Pr}$$

$$Ro_g^e = \sqrt{RaEk^{1.5}/Pr^{0.5}}$$




(a)
0
$\widetilde{T}_d$
$\langle \widetilde{T}_b \rangle_h$
(b)
0
$\langle \widetilde{T}_b \rangle_h$
(c)
1.0
0.8
0.6
0.4
0.2
0
z/h
0
1
(d)
1.0
0.8
0.6
0.4
0.2
0
z/h
0
$\langle \widetilde{T} \rangle$
1
(e)
$\langle \widetilde{T}_b \rangle_h$
10^0
10^{-1}
0
2
4
6
8
10
$\tilde{t}$
(f)
0
2
4
6
$\tilde{t}$