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Title: Boundary layer turbulence below ice shelves in the shear-dominated regime

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Boundary layer turbulence below ice shelves in the shear-dominated regime

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Los Alamos National Laboratory

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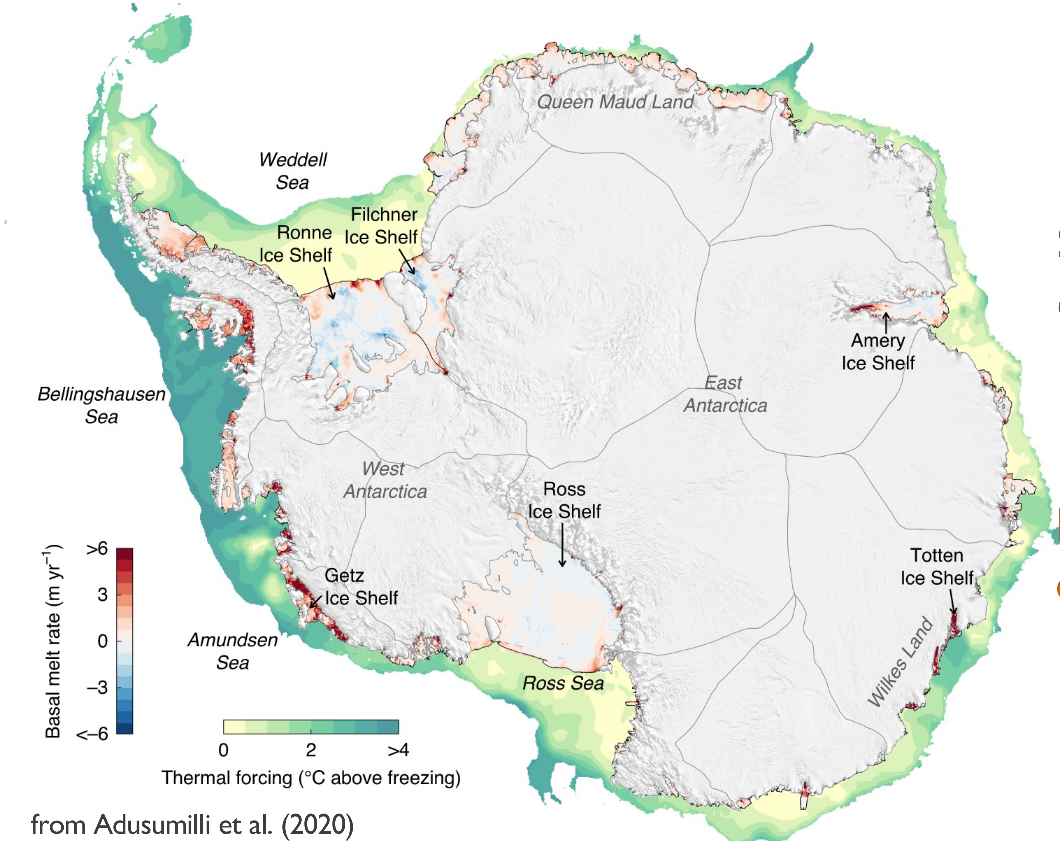
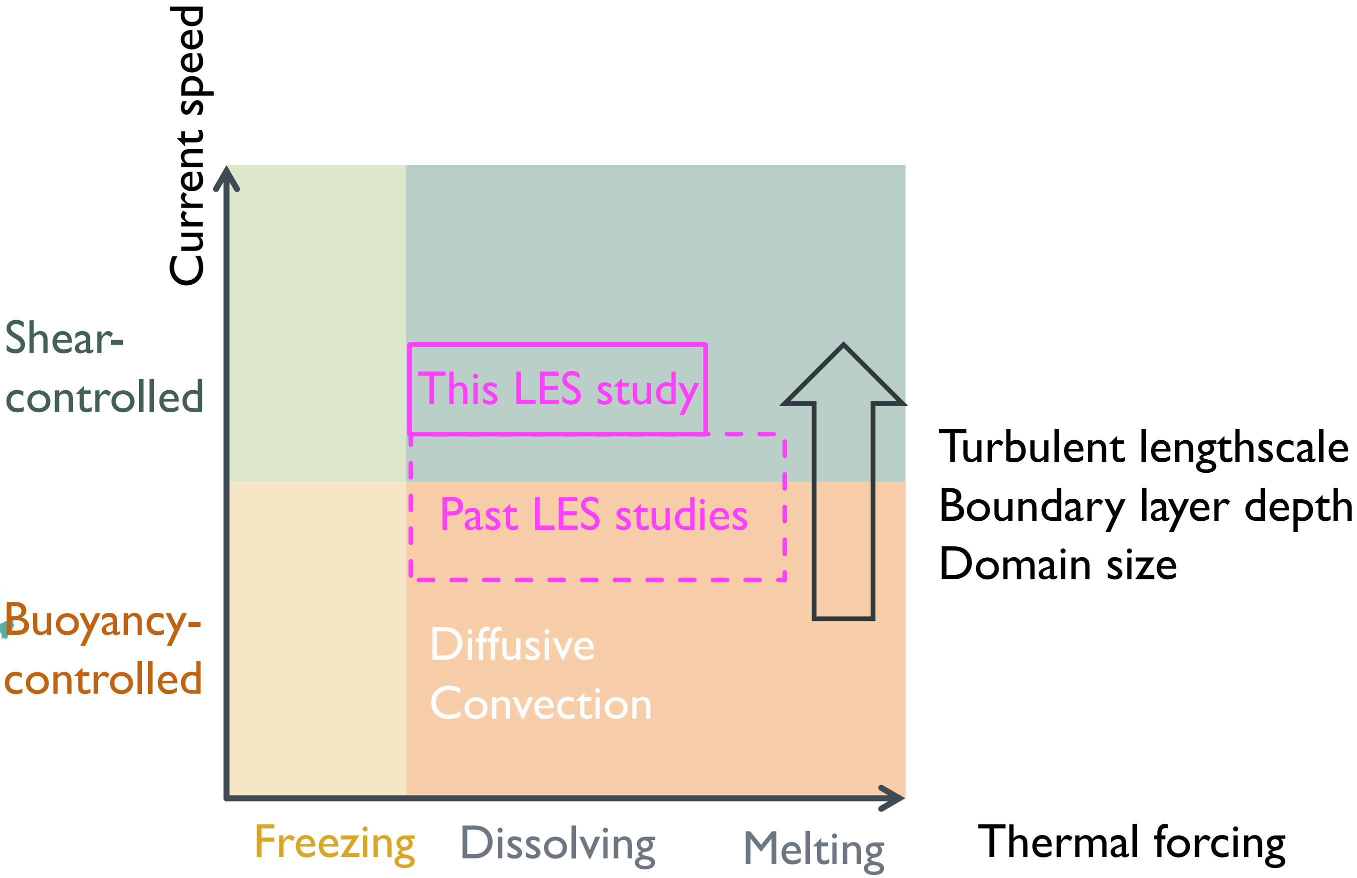
Antarctic melt regimes



from Adusumilli et al. (2020)



Current speed

Shear-controlled

Buoyancy-controlled

This LES study

Past LES studies

Diffusive Convection

Turbulent lengthscale
Boundary layer depth
Domain size

Freezing

Dissolving

Melting

Thermal forcing

After Malyarenko et al. (2020)

Key questions for this study

- To what extent does the standard ice-shelf melt parameterization characterize heat transfer at the meter-scale?

$$F_\Theta = \Gamma\, u_* (\Theta - \Theta_{freeze})$$

vertical heat flux at ice-ocean interface

thermal exchange coefficient

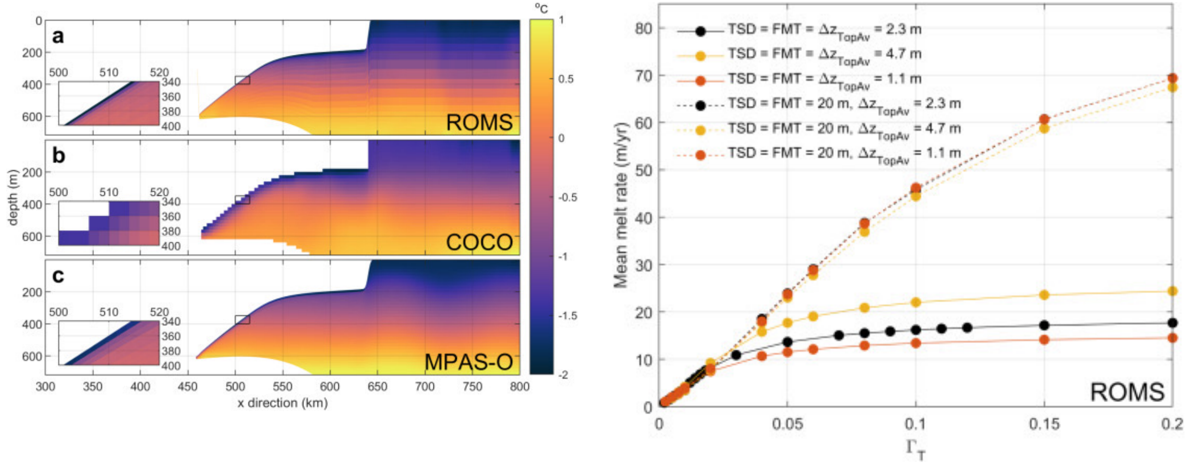
friction velocity ($c_d^{1/2} u$)

thermal driving at the boundary

- Does the thermal exchange coefficient Γ vary as a function of thermal driving or slope?

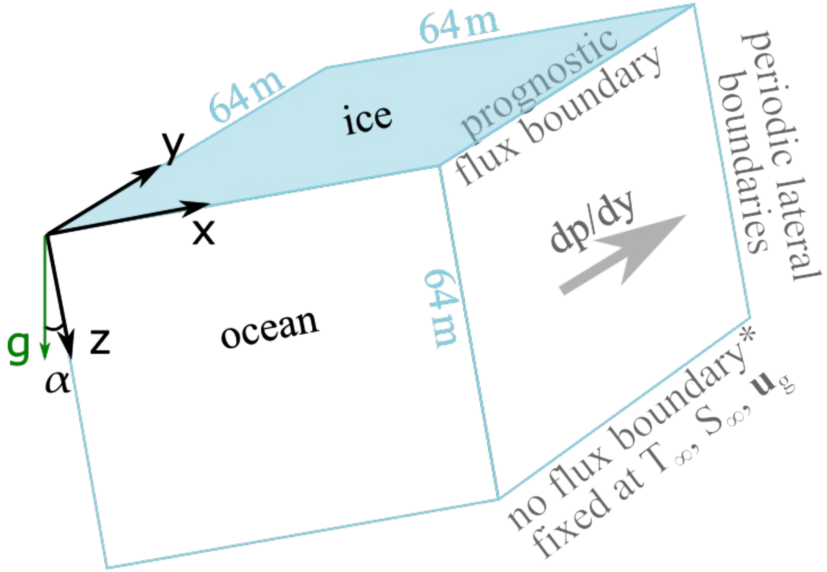
- Can we learn how vertical fluxes vary with distance from the ice boundary?

Melt rates are sensitive to vertical resolution and other discretization choices



Gwyther et al. (2020)

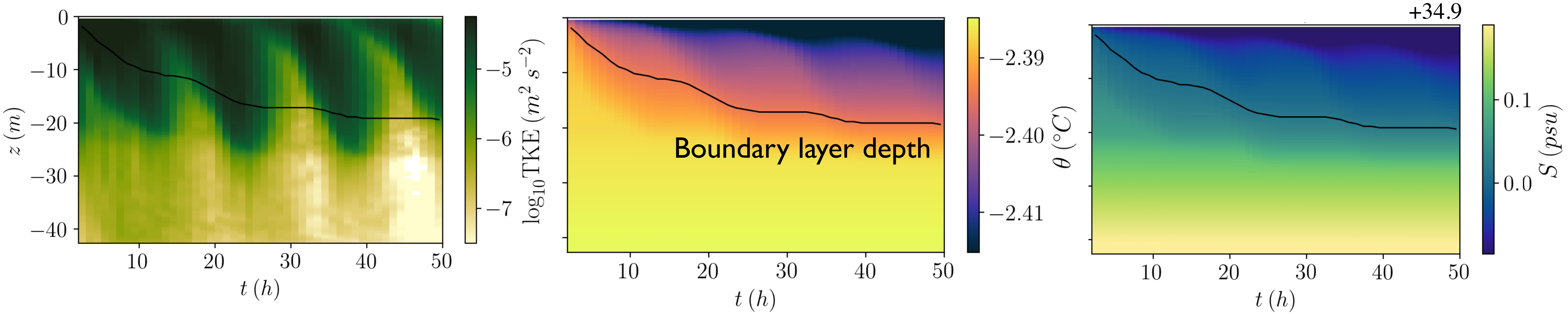
Large-eddy simulation set-up



- Resolution: $\Delta x, y = 0.5m, \Delta z = 0.25$m
- Strong shear: 20 cm/s far-field current
  - shear production of TKE >> buoyancy production of TKE

- **Stability-dependent** flux parameterizations at ice boundary
- Base case: 0.15°C thermal driving, 1.0° slope
  - 3 additional thermal driving simulations at 1.0° slope 0.15°C - 0.60°C
  - 3 additional sloped simulations at 0.15°C thermal driving 0.01° - 1.0°
- Run for 4 inertial periods, averaged over last inertial period

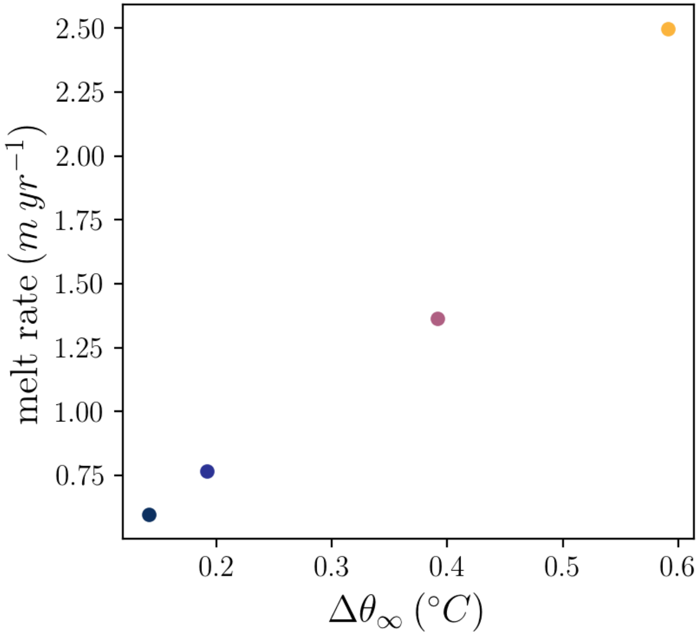
Simulations evolve toward boundary depths of ~20m with melt rates of ~1m/yr



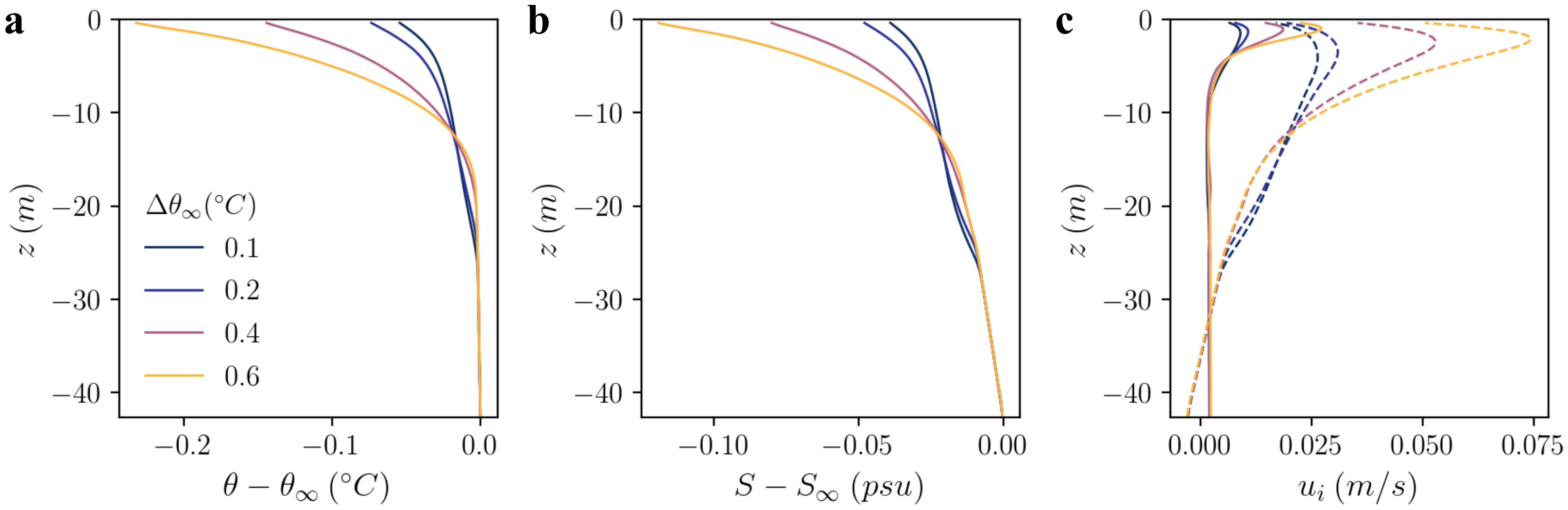
Boundary layer depth

As thermal driving increases…

- Melt rate increases



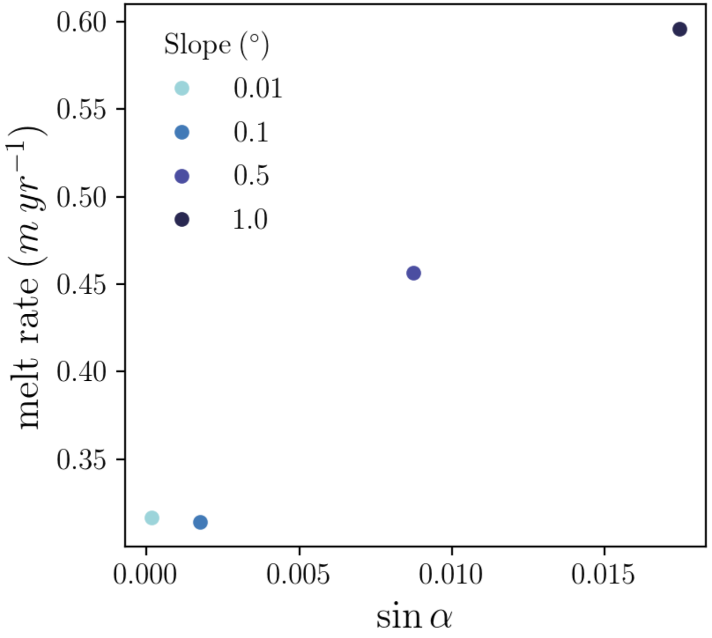
- Stratification increases
- Boundary layer depth decreases
- Boundary layer buoyancy and velocity increases



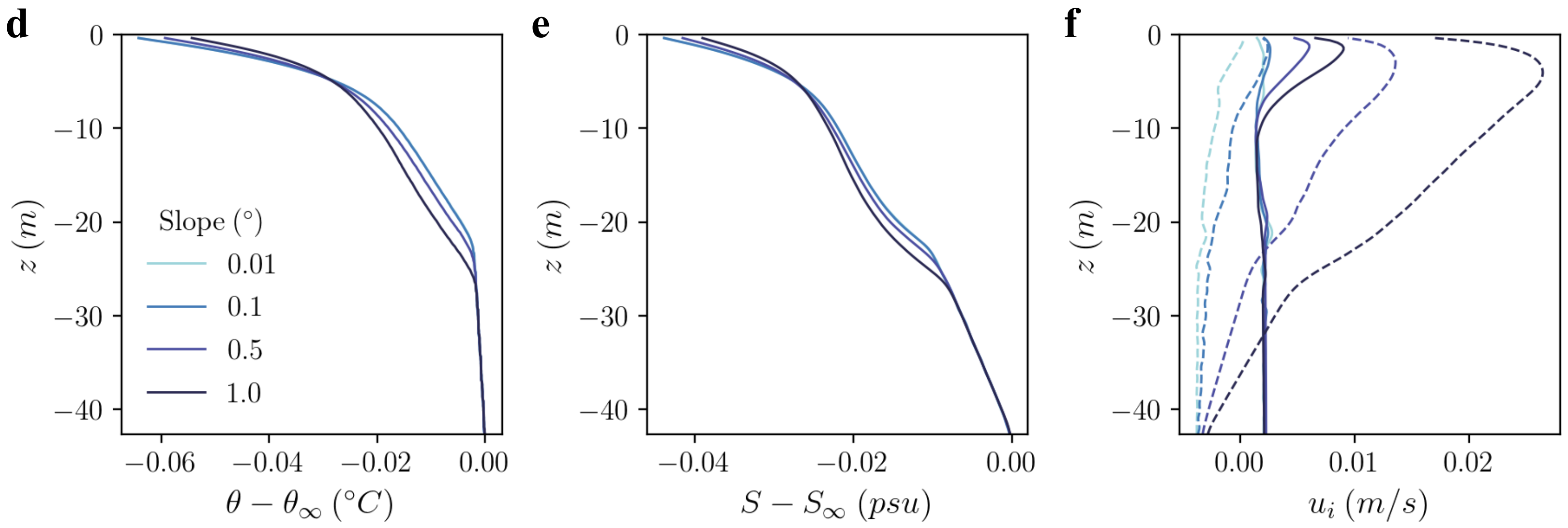
Solid = up-slope
Dashed = across-slope

As slope increases…

- Melt rate increases



- **Stratification decreases**
- **Boundary layer depth increases**
- Boundary layer buoyancy and velocity increases

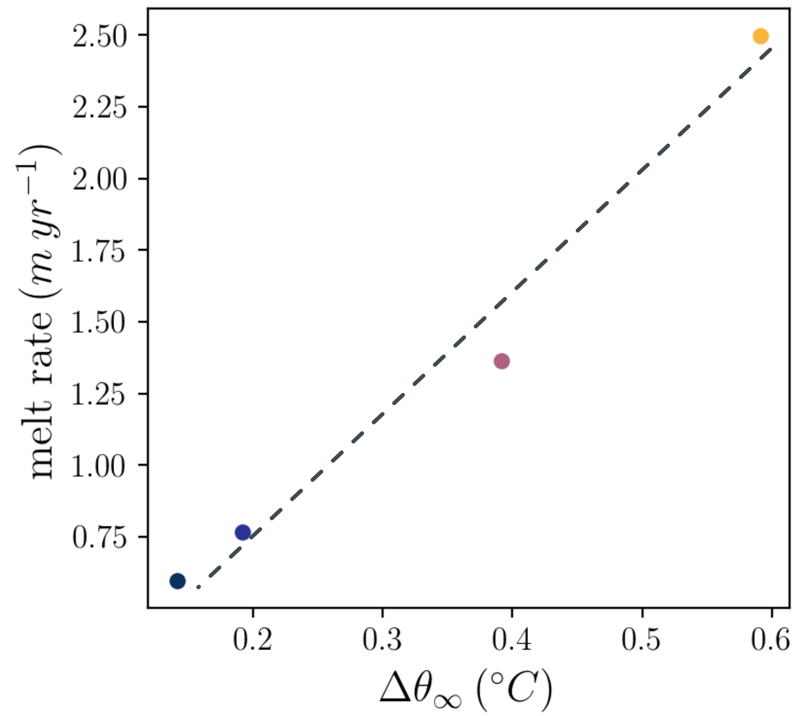


Solid = up-slope
Dashed = across-slope

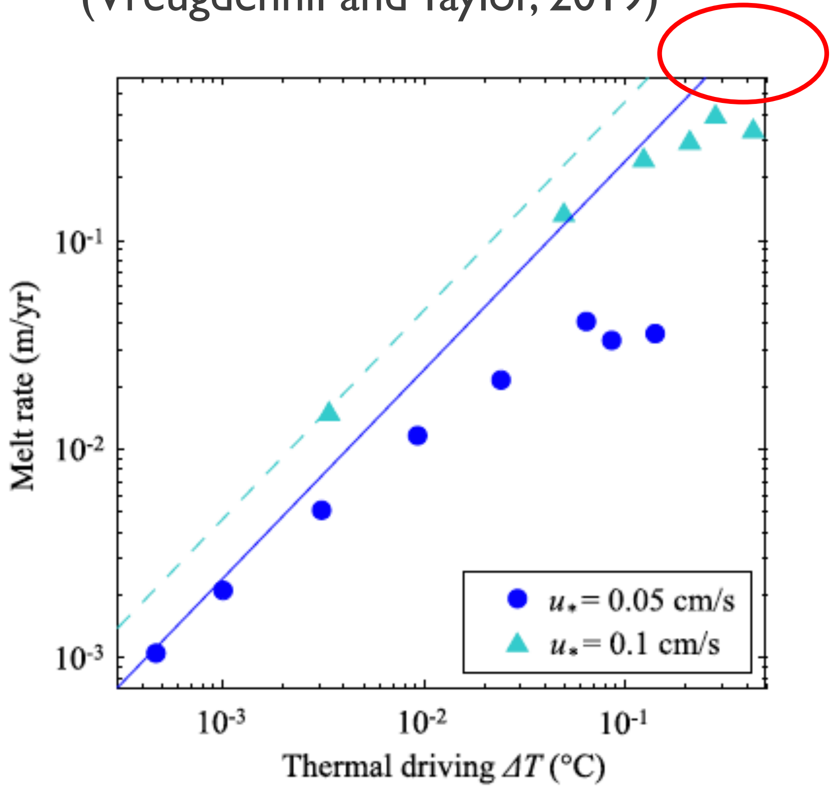
Melt rates increase roughly linearly with thermal driving

- Compatible with current parameterizations

$$F_{\Theta} = \Gamma\, u_{*}(\Theta - \Theta_{freeze})$$



- Recent LES support linear scaling (Vreugdenhil and Taylor, 2019)



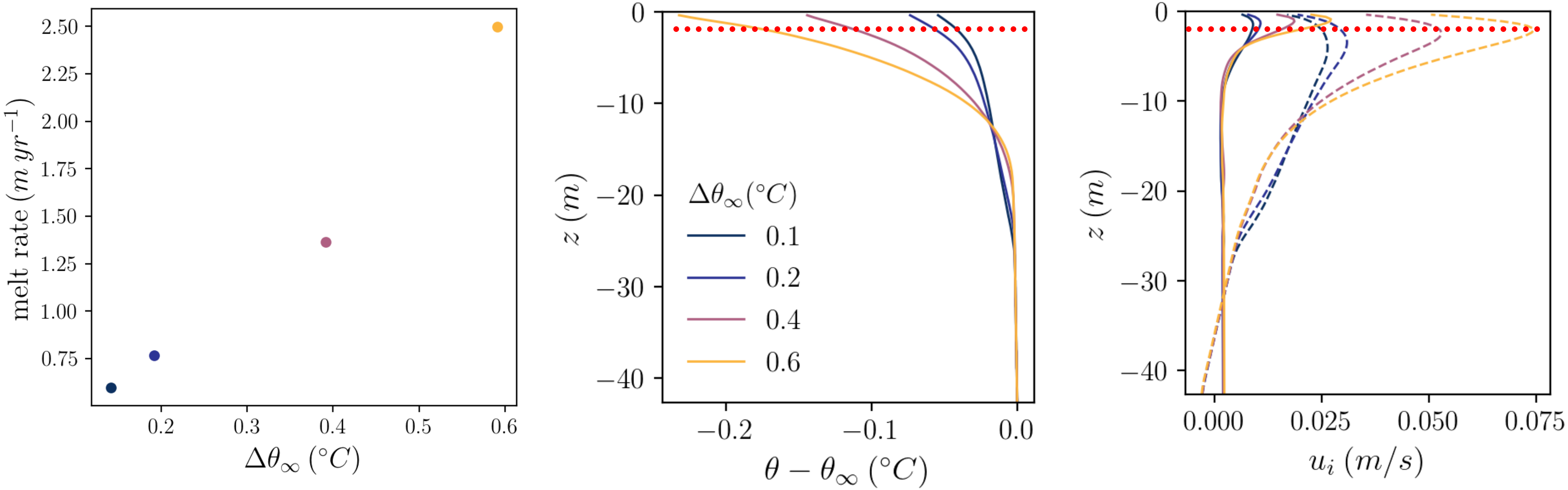
This study

FIG. 4. Melt rate against thermal driving for all runs in Table 1. The passive scalar $g = 0$ cases with $u_{*} = 0.05\ \mathrm{cm\,s^{-1}}$ (run 9; unbroken line) and $u_{*} = 0.1\ \mathrm{cm\,s^{-1}}$ (run 16; broken line) are also shown.

Evaluating the thermal exchange coefficient Γ

Given $F_\Theta = \Gamma\, u_* \left(\Theta - \Theta_{freeze}\right)$, simulated melt rates, and temperature and velocity 2m from the boundary, derive the thermal exchange coefficient $\Gamma_{T,der}$

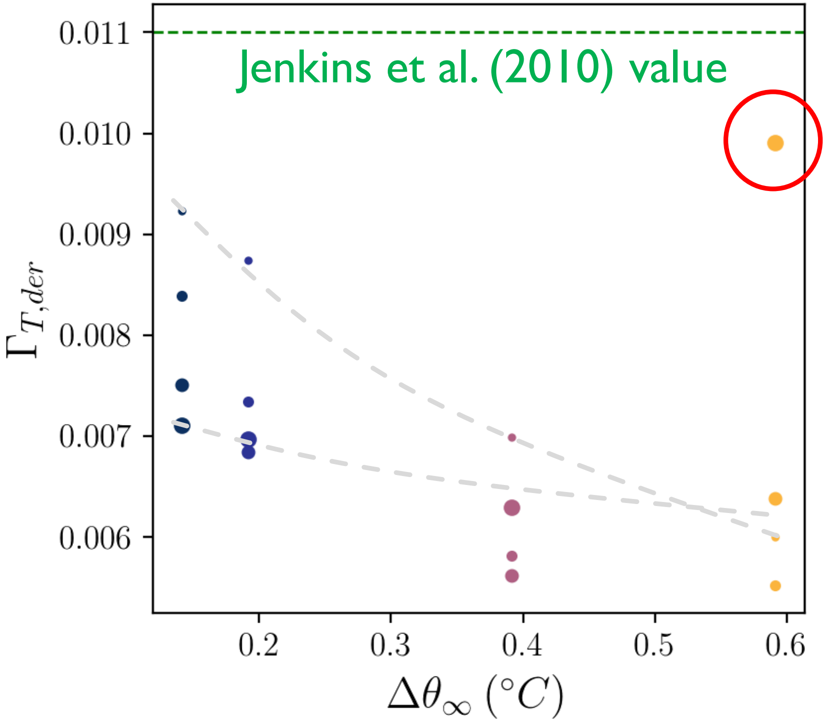
Inputs:



Evaluating the thermal exchange coefficient Γ

Given $F_{\Theta} = \Gamma\, u_{*}\left(\Theta - \Theta_{freeze}\right)$, simulated melt rates, and temperature and velocity 2m from the boundary, derive the thermal exchange coefficient $\Gamma_{T,der}$

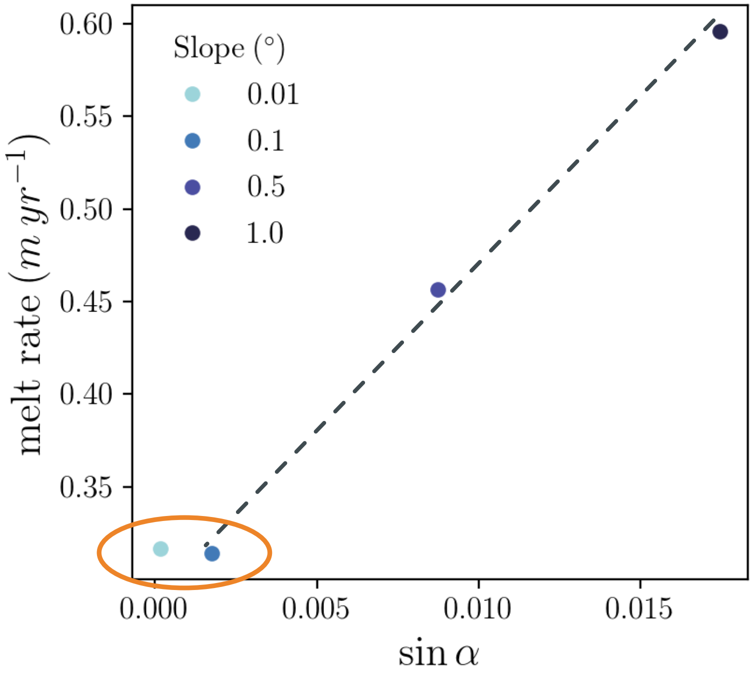
Heat transport near the ice boundary becomes *slightly* less efficient at higher thermal driving



Anomalous value: intermittent turbulence

Points increase in size with each inertial cycle

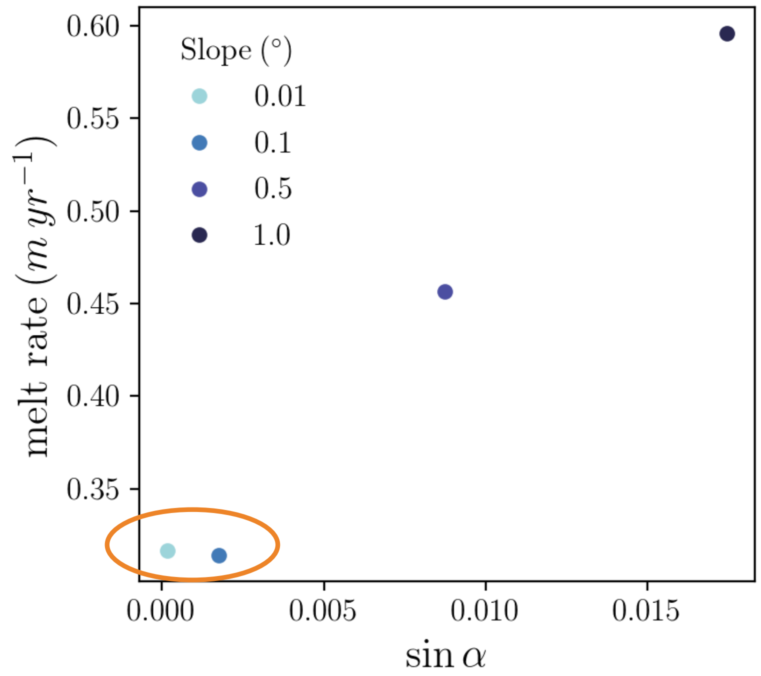
Melt rate increases linearly with sin(slope)

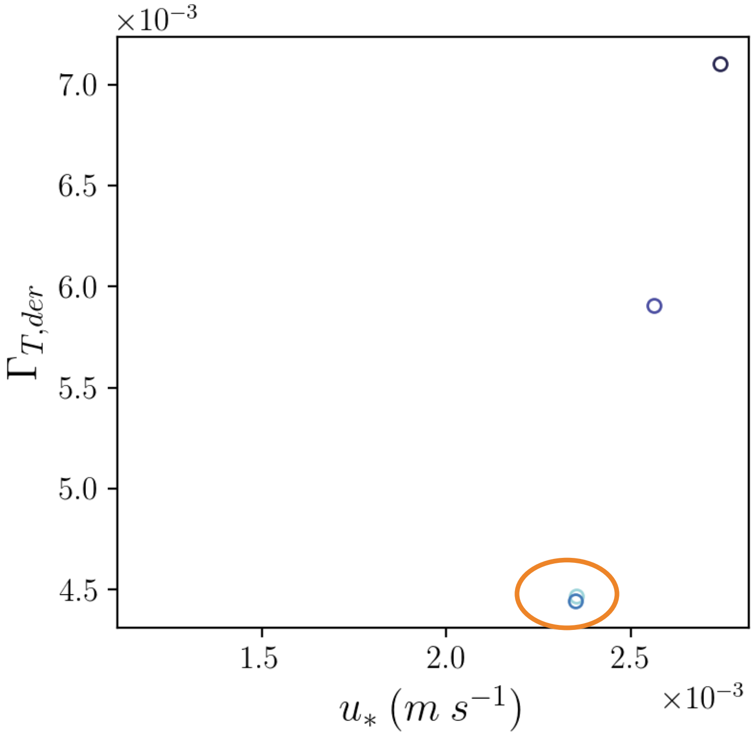


- Some disagreement in the literature about the exponent n, $m \propto (\sin\alpha)^n$
  - $n = 3/2$ scaling analysis (Magorrian and Wells 2016)
  - $n = 0$ no sensitivity at low slope (Vreugdenhil and Taylor 2019)
  - **$n = 1$ this study**
- At low slope, melt rate is constant

Heat transport near ice boundary becomes more efficient at higher slopes

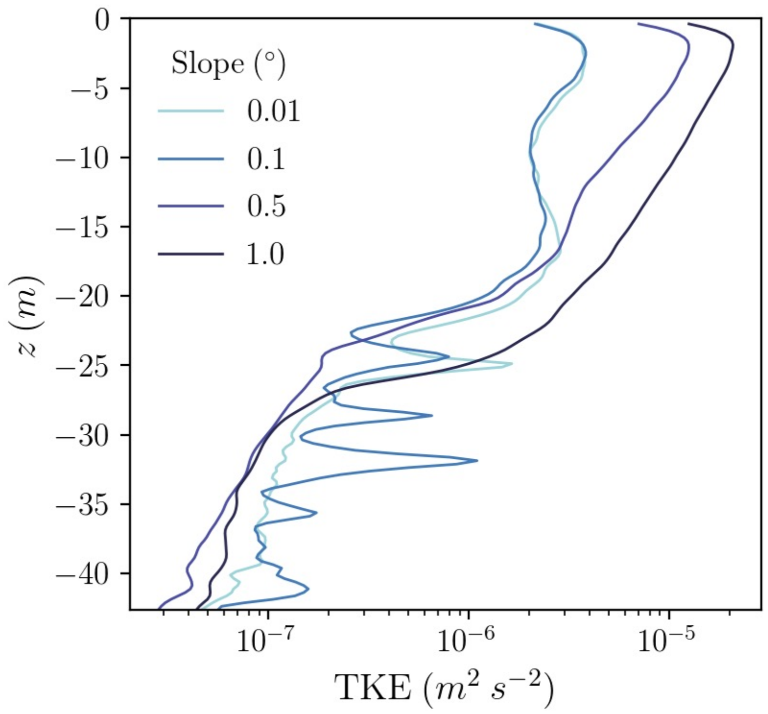
- The linear increase in melt rate with sin(slope) arises from acceleration of the BL *and* an increase in mixing efficiency, Γ

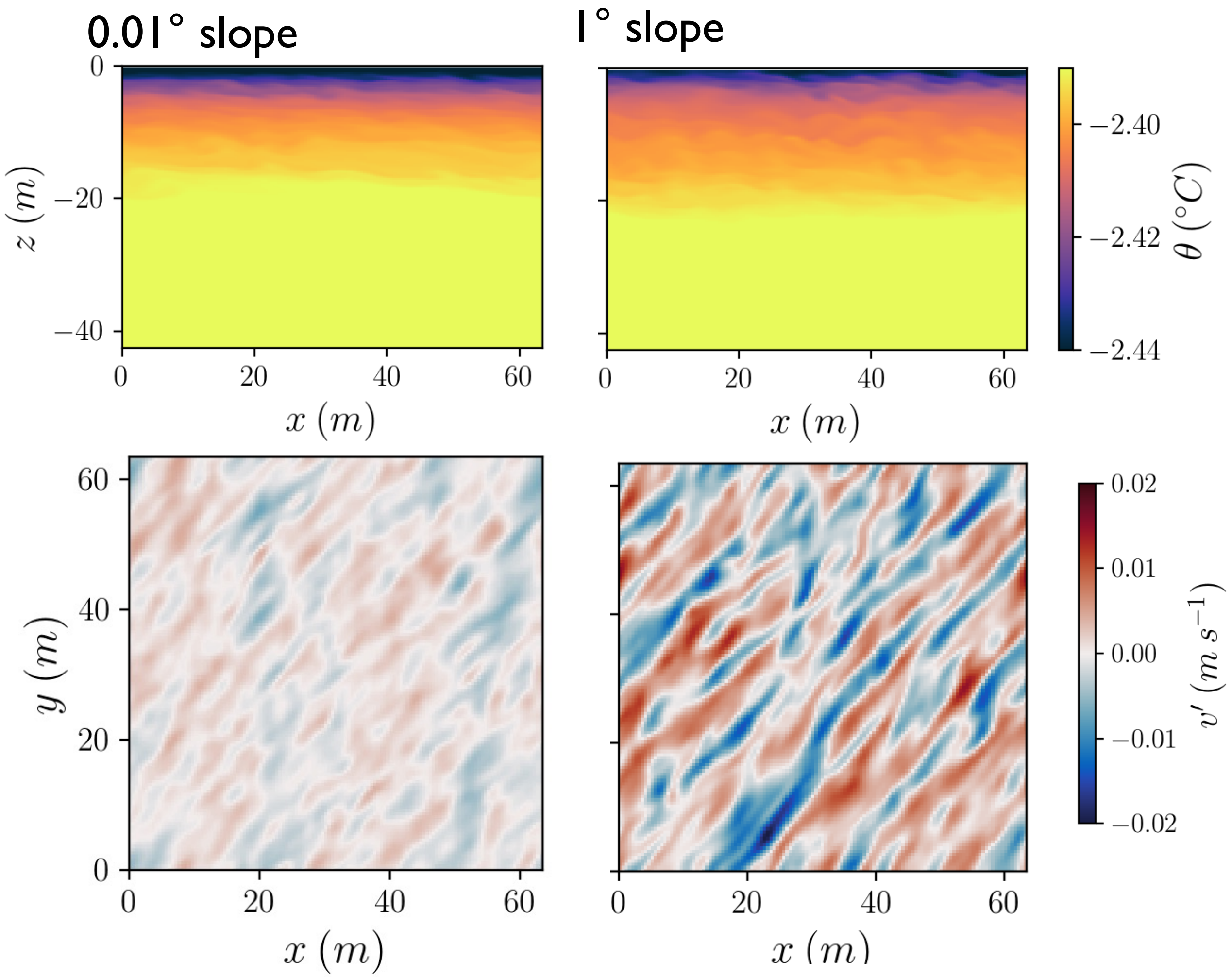




At low slope, velocity 2m from the boundary is constant

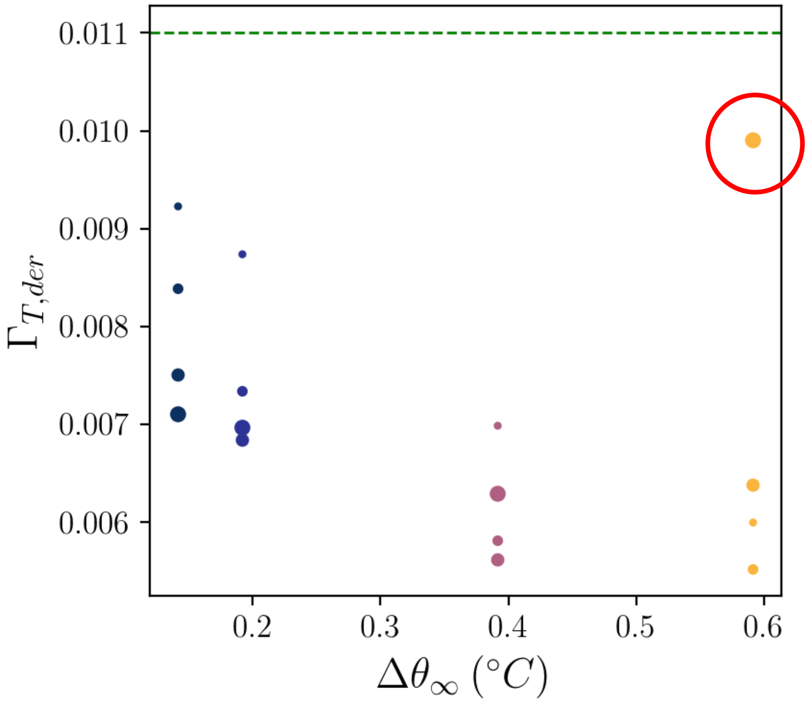
TKE increases as a function of slope



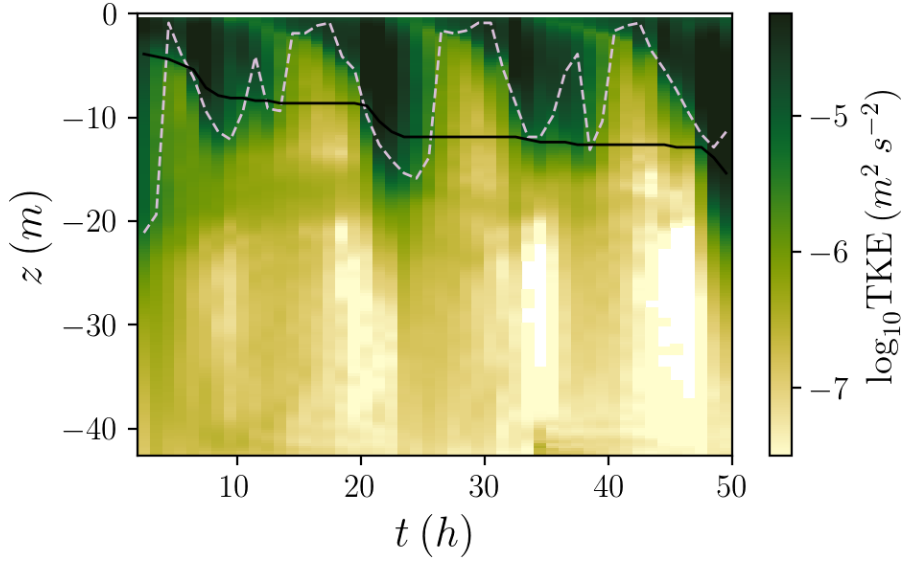

0.01° slope

1° slope

Turbulence intermittency for highly stratified simulations



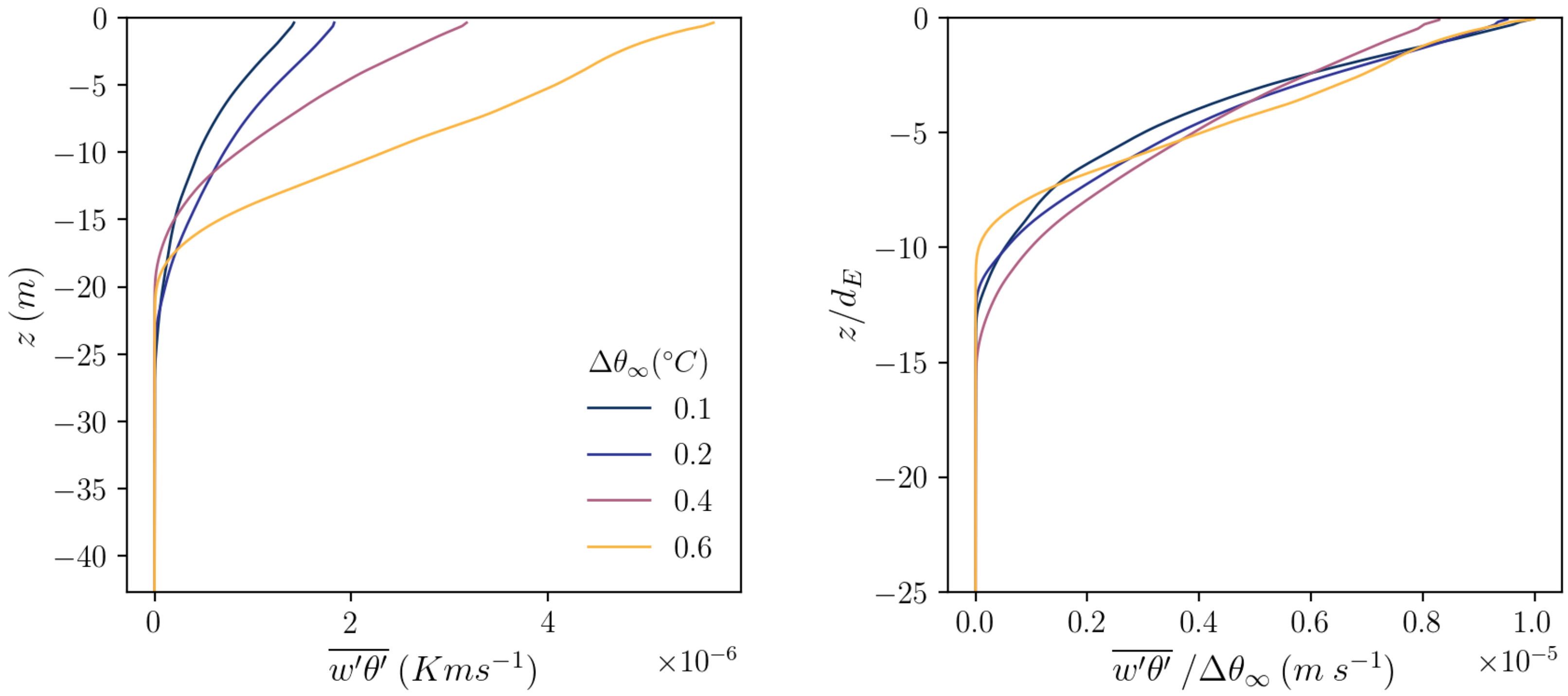
The most stratified case is that with the highest thermal driving: 0.6°C, 1.0° slope



Dashed line = depth of the mixing layer

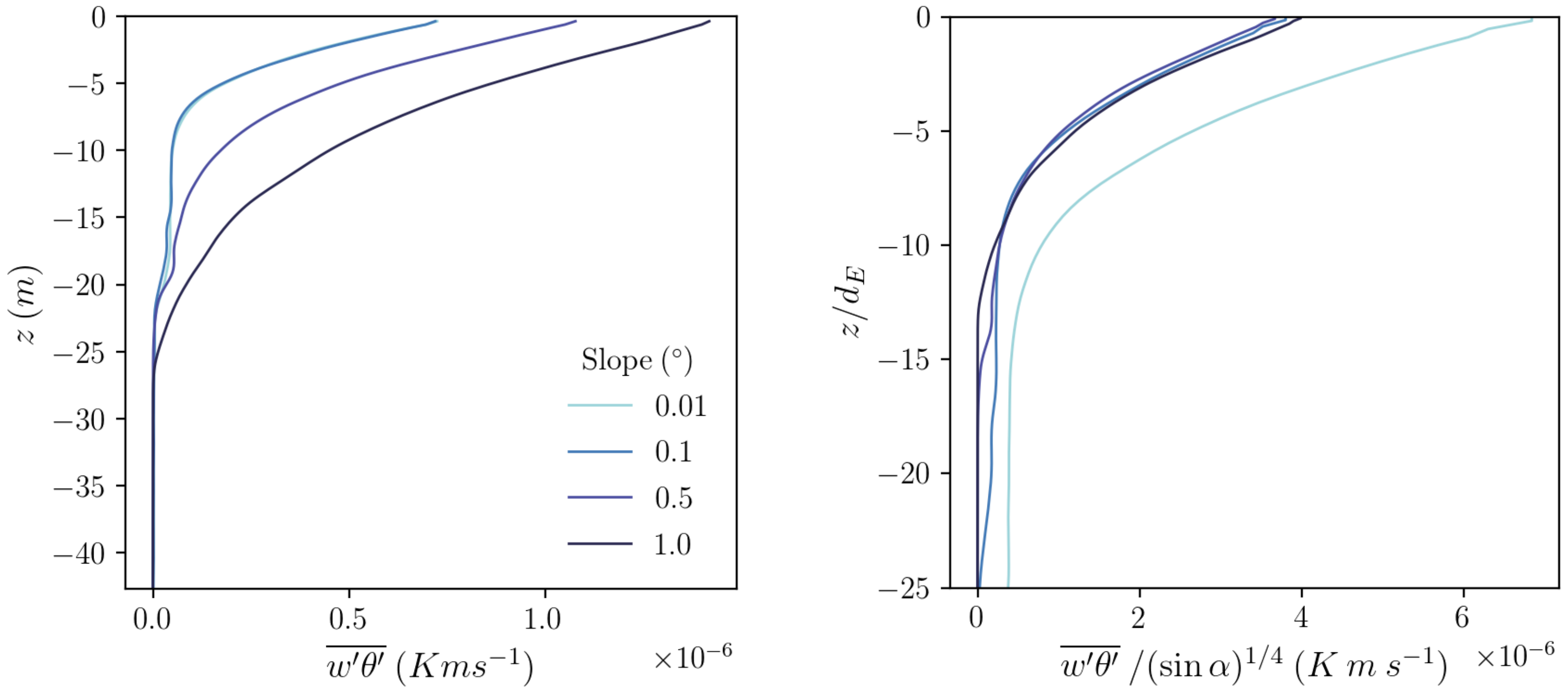
Solid line = depth of the mixed layer

Parameterizing vertical fluxes as a function of distance from ice boundary



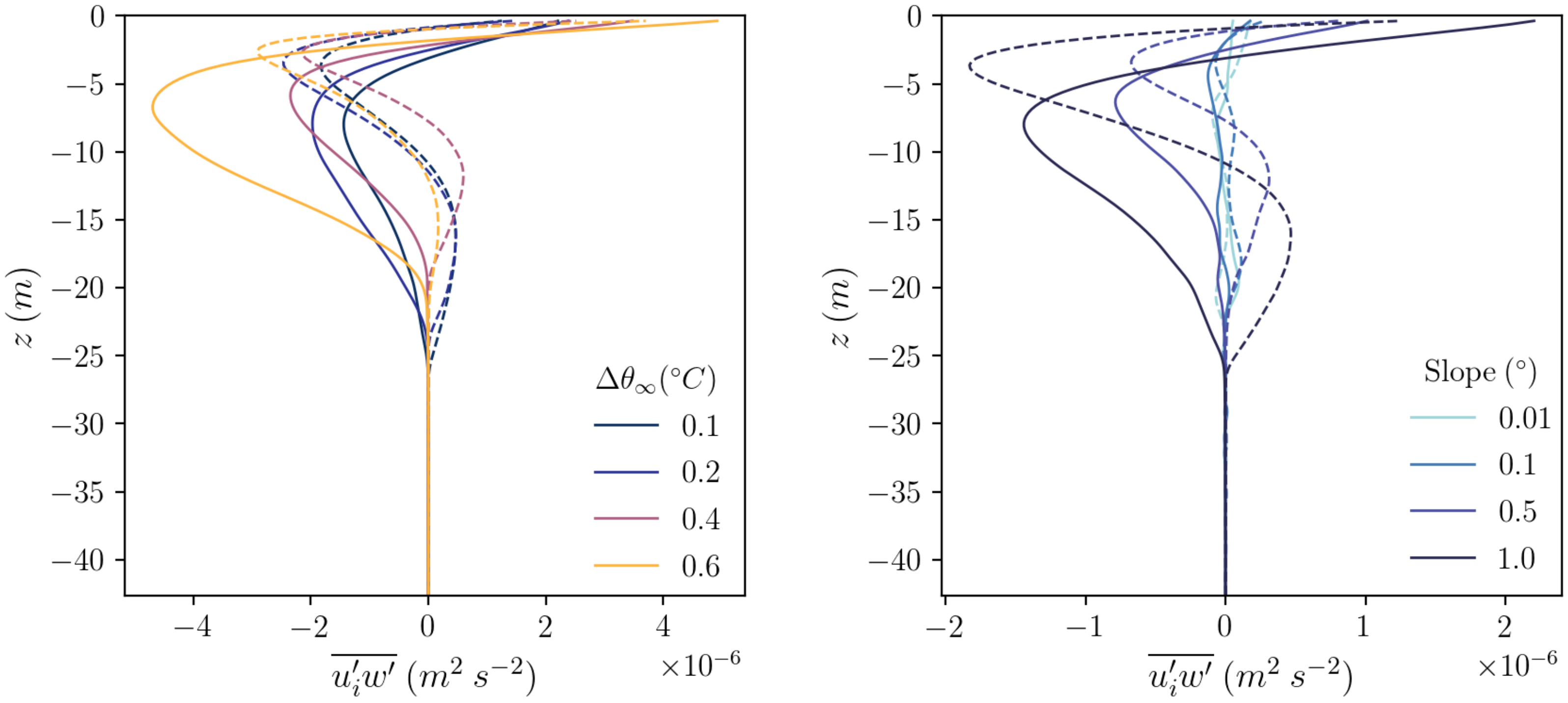
- Curves don’t collapse neatly but linear scaling of vertical fluxes with thermal driving works fairly well throughout the BL

Parameterizing vertical fluxes as a function of distance from ice boundary



- Curves do collapse neatly with weak dependence on sin(slope) and threshold behavior at low slopes

Parameterizing vertical fluxes as a function of distance from ice boundary



- High momentum gradients near the boundary
- Depending on the degree to which the BL is resolved, momentum fluxes can be positive or negative

Overview

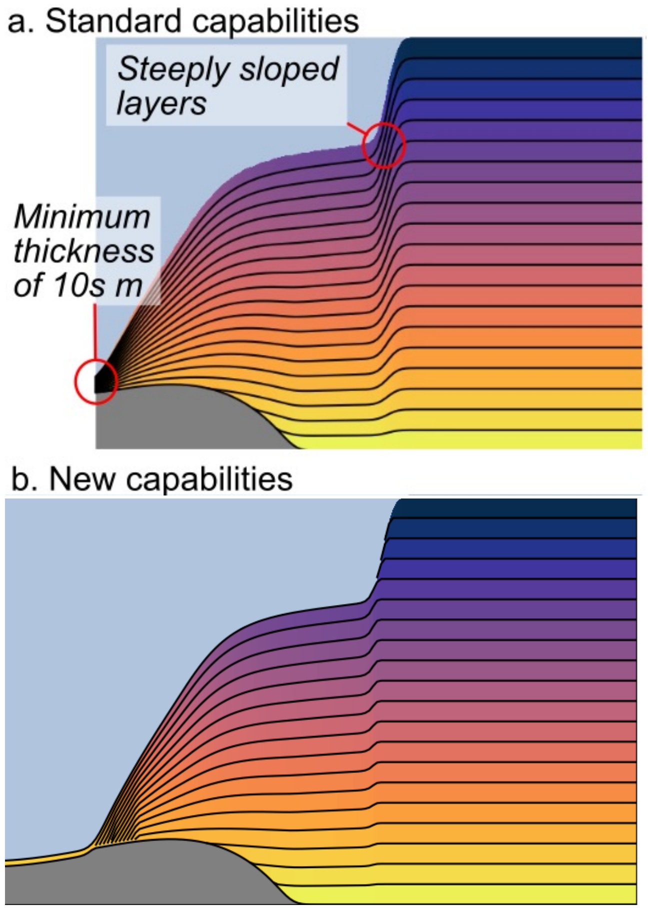
- We conducted large-eddy simulations to test a higher shear regime than previously explored
- Linear relationship between thermal driving and temperature continues across low and high shear regimes
- Even low ice shelf slopes do impact the melt rate and change the thermal exchange coefficient
- Gradients in velocity and scalars are high near the boundary
    - Poses a challenge for coarse-resolution ocean models and eddy-diffusivity schemes
- We make some progress toward a depth-dependent shape function for vertical fluxes
    - But we need simulations that span a wider regime space and a prognostic for boundary layer depth
- Caveat: These simulations don't have tides and could have less TKE than real ice shelf settings

Begeman, C. B., Asay-Davis, X., & Van Roekel, L. (2022). Ice-shelf ocean boundary layer dynamics from large-eddy simulations. *The Cryosphere*, *16*(1), 277–295. https://doi.org/10.5194/tc-16-277-2022

Considerations for ocean modeling of the ice-shelf ocean boundary layer

Some strategies for capturing boundary layer structure:

- Reducing spurious mixing
    - We implemented vertical Lagrangian-remapping (Griffies et al. 2020)
- Optimizing grid
    - Vertical Lagrangian-remapping allows us to increase vertical resolution near the ice base
    - We added hybrid grid capabilities so we can follow the terrain of the ice shelf base and have terminating layers at the ice front
- Learning how to account for resolution effects in turbulence closure



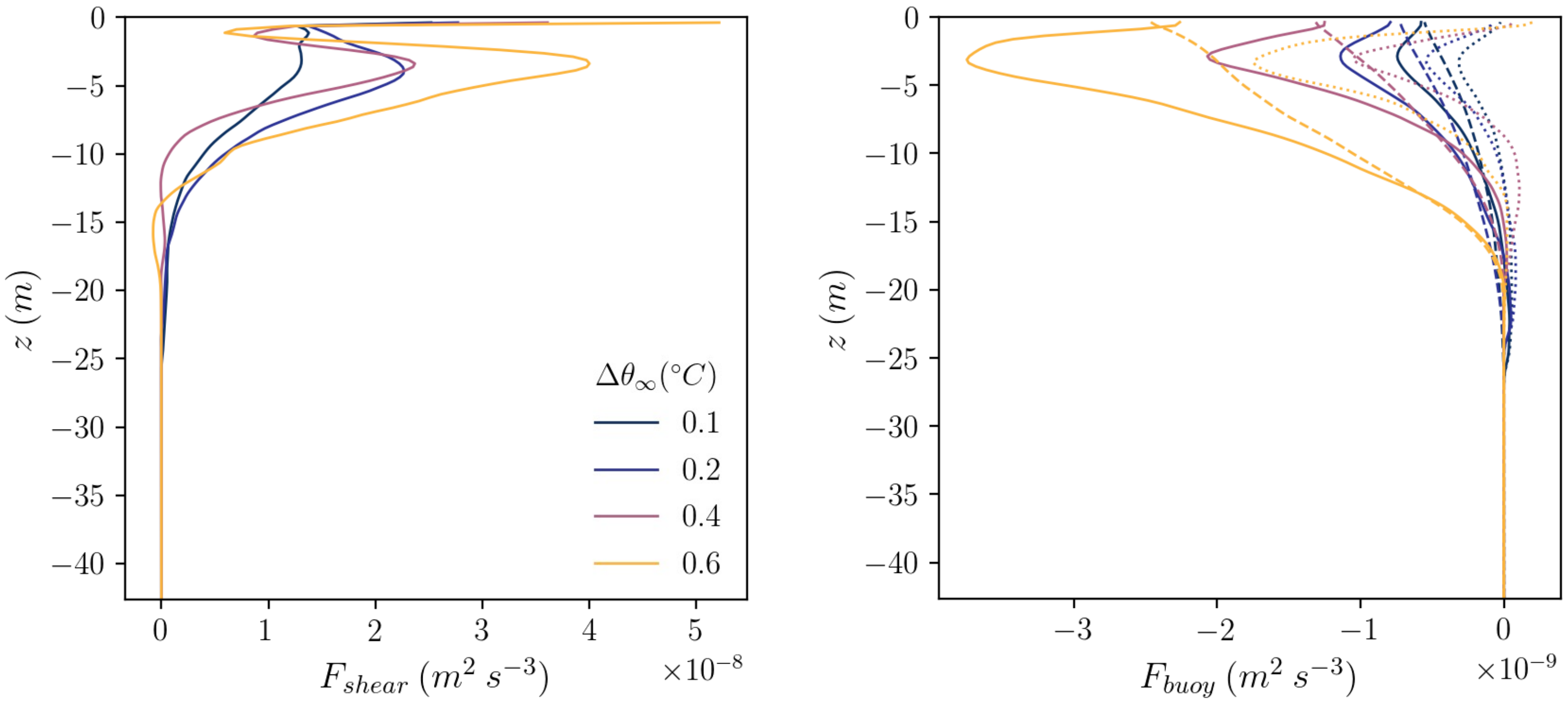
Q&A

Thanks for your attention!

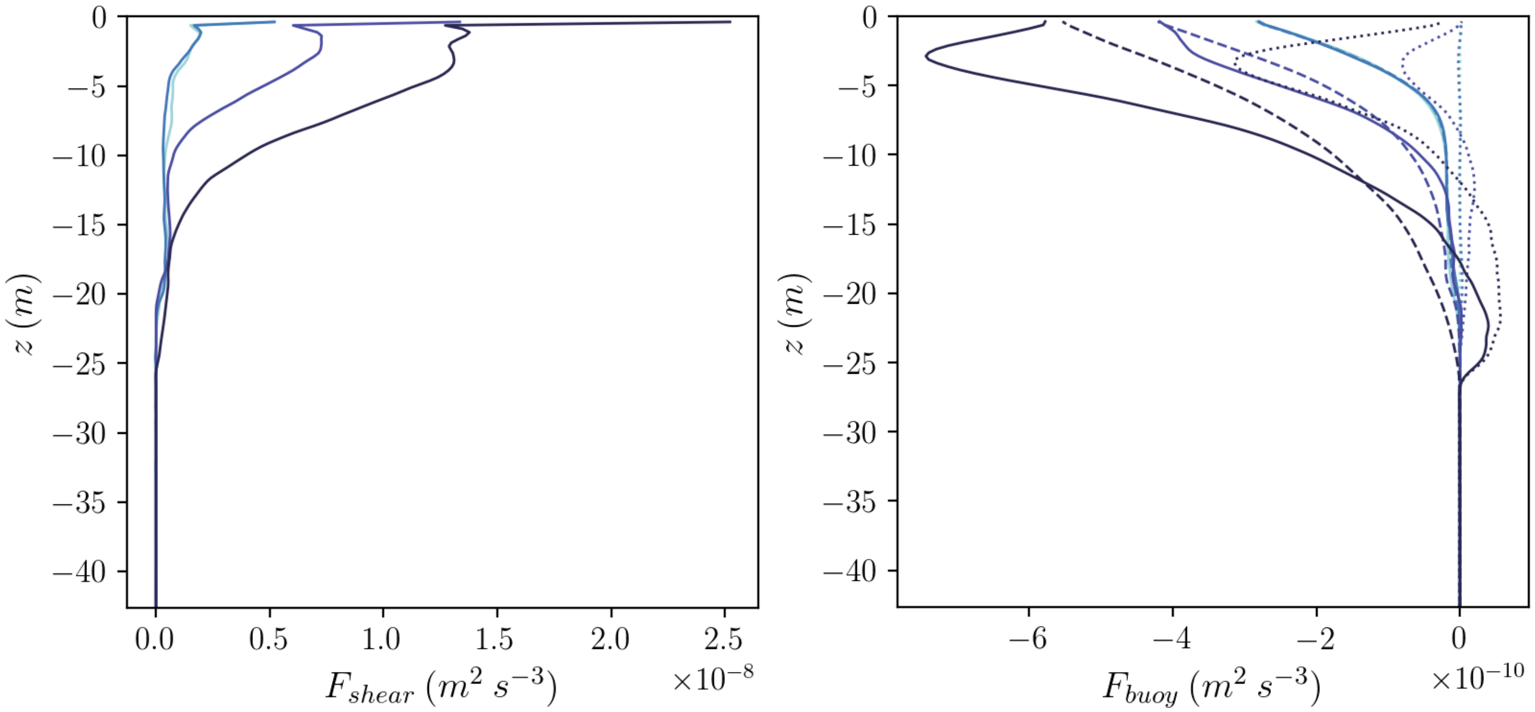
SUPPLEMENTAL SLIDES

- Shear production of TKE dominates in all simulations (dT)
- Shear production of TKE dominates in all simulations (slope)
- TKE hovmoller plots
- Melt, Gamma
- Timeseries for all simulations
- Snapshots within inertial cycle
- Vertical temperature flux profiles through the simulation
- Vertical flux profiles
- TKE budget, slope cases
- TKE budgets, thermal driving cases
- Resolution test
- Salt flux profiles
- Effective diffusivity (for computation of Ekman depth)
- Ratio of horizontal to vertical velocity variance
- Subgrid diffusivities
- Melt rate dependence over course of simulation

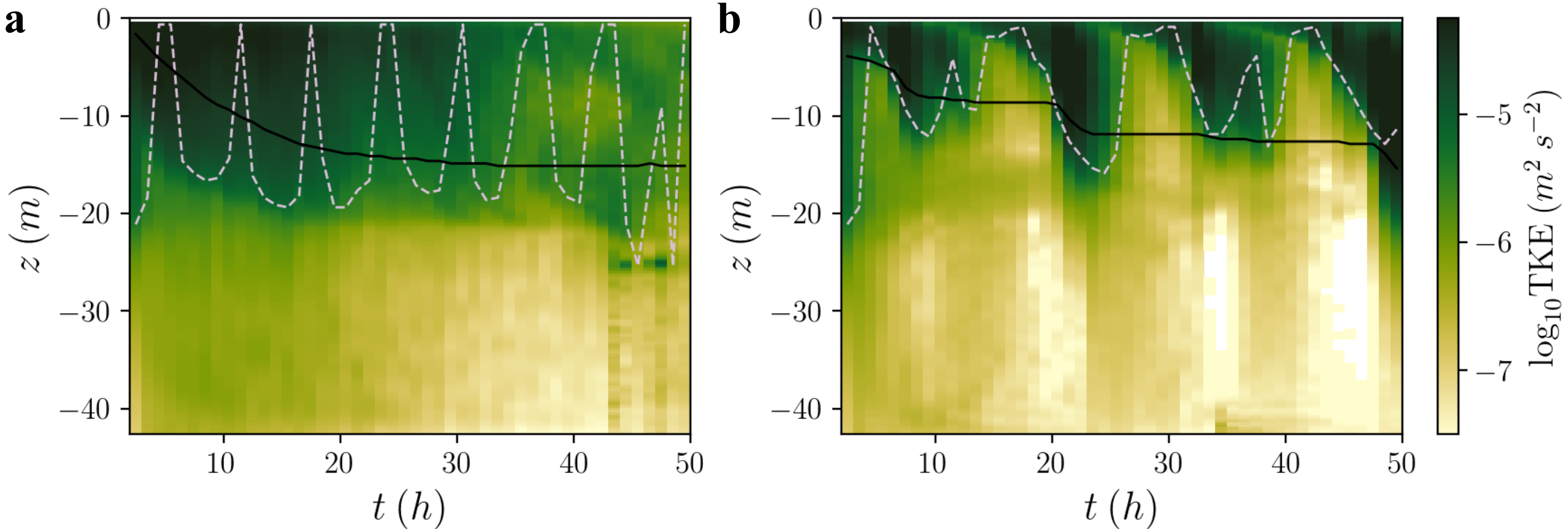
Shear production of TKE dominates in all simulations (dT)



Shear production of TKE dominates in all simulations (slope)



TKE hovmoller plots

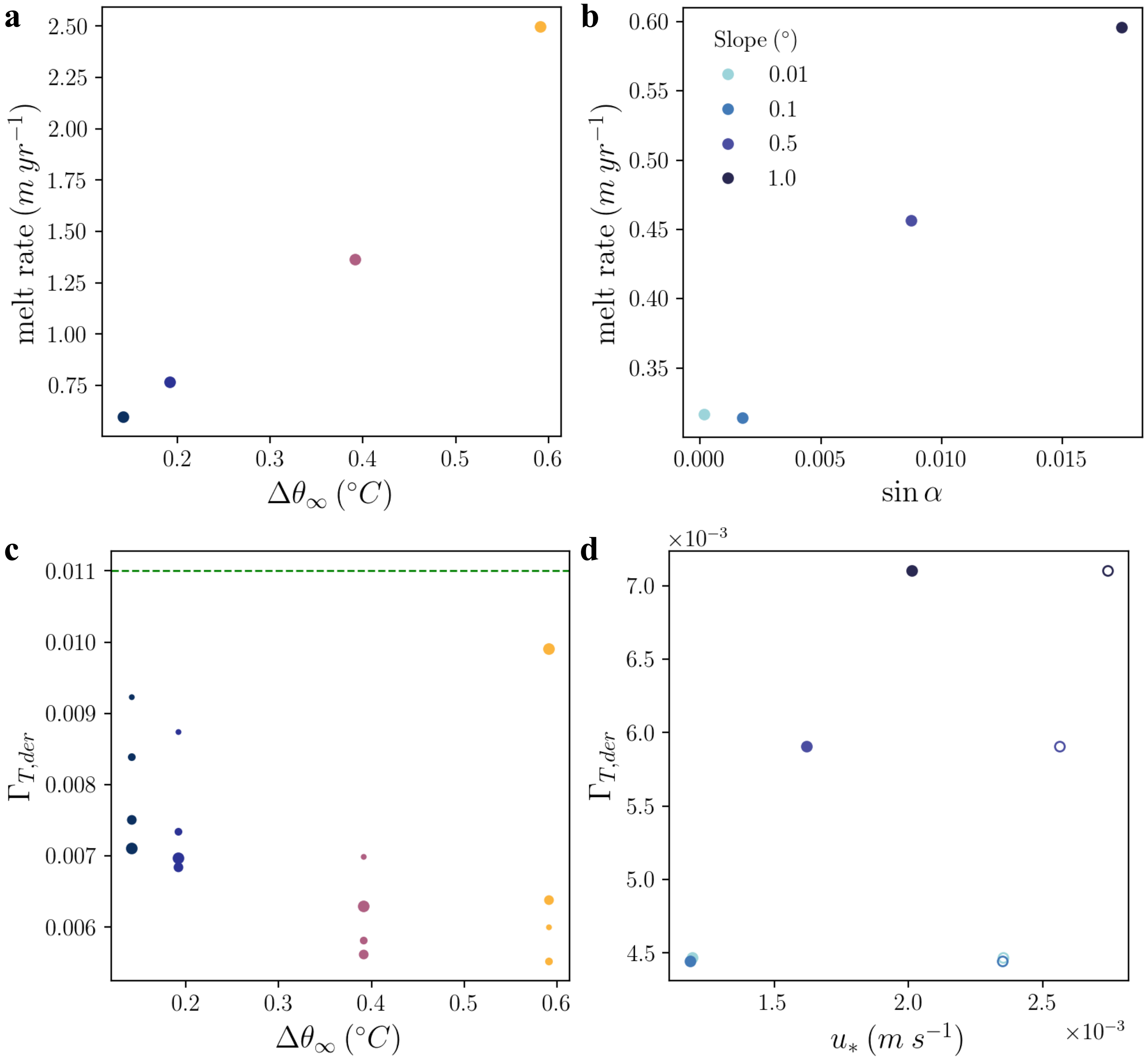


0.15°C, 0.01° slope

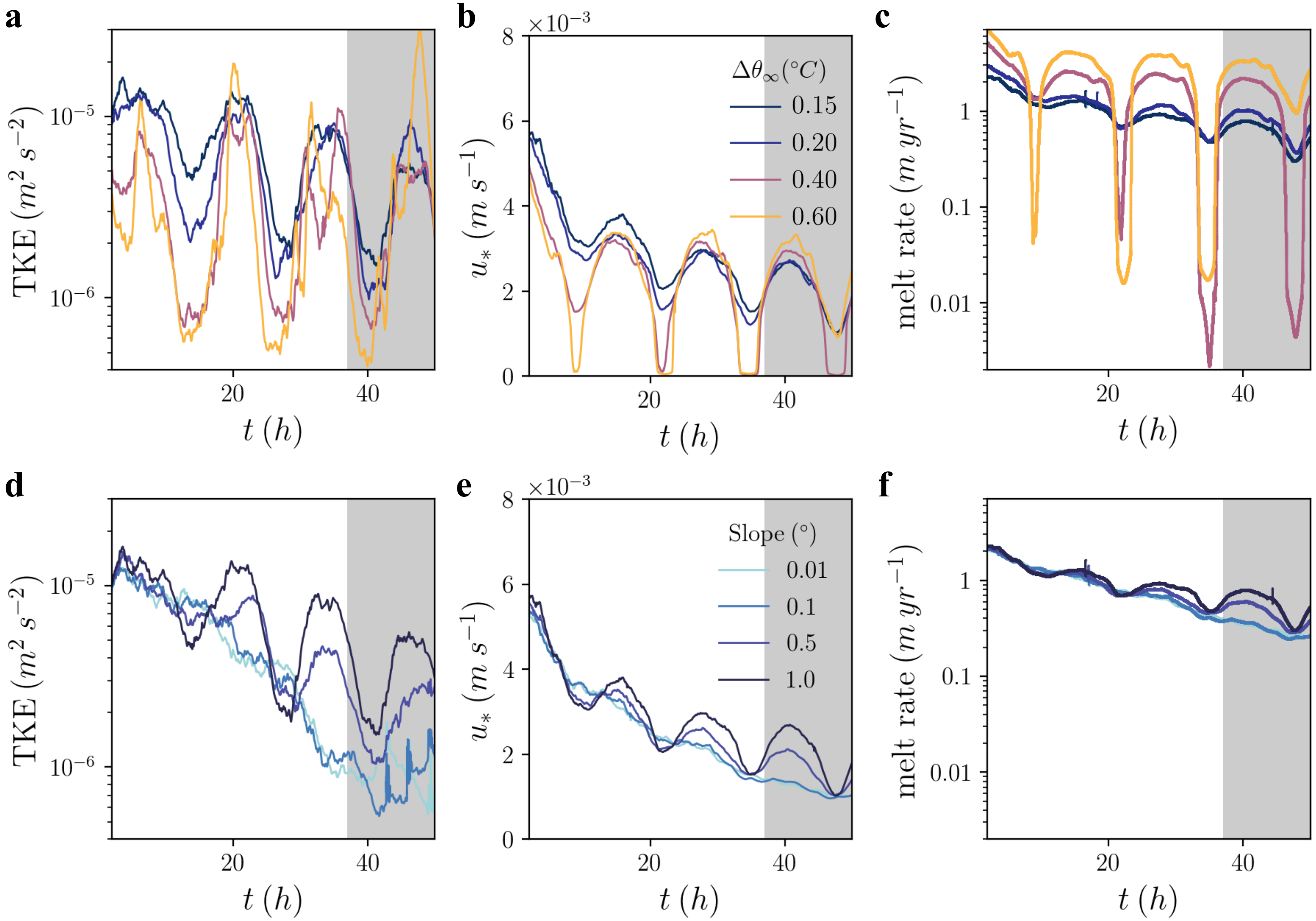
0.6°C, 1.0° slope

Dashed line = depth of the mixing layer
Solid line = depth of the surface layer

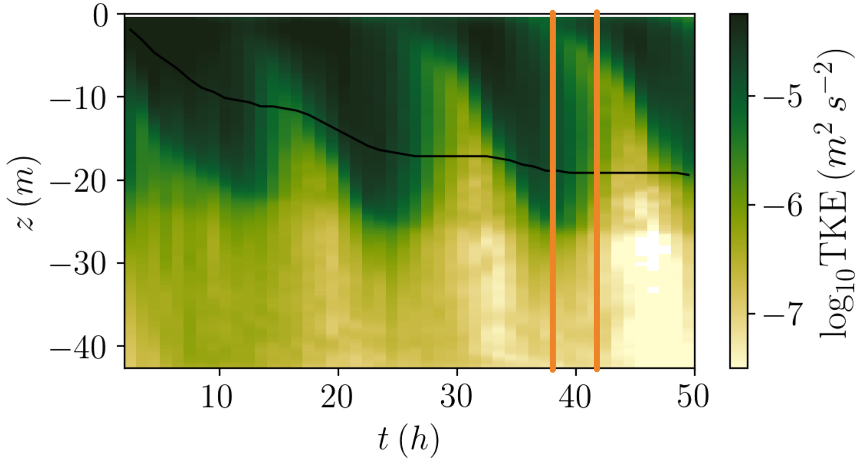
MELT, GAMMA

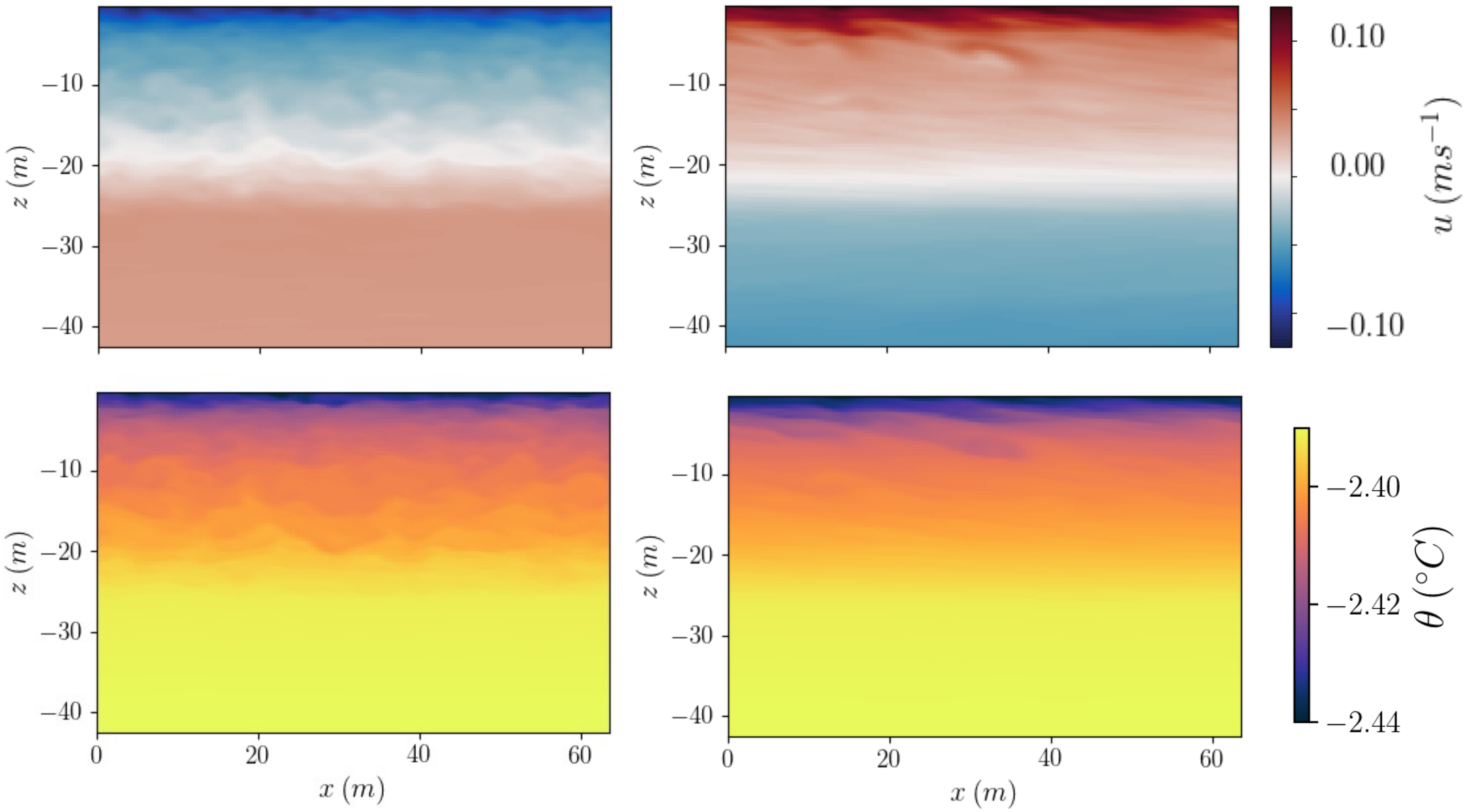

a
melt rate $(m\,yr^{-1})$
2.50
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.2
0.3
0.4
0.5
0.6
$\Delta\theta_\infty\ (^\circ C)$
b
melt rate $(m\,yr^{-1})$
0.60
0.55
0.50
0.45
0.40
0.35
0.000
0.005
0.010
0.015
$\sin\alpha$
Slope (°)
0.01
0.1
0.5
1.0
c
$\Gamma_{T,der}$
0.011
0.010
0.009
0.008
0.007
0.006
0.2
0.3
0.4
0.5
0.6
$\Delta\theta_\infty\ (^\circ C)$
d
$\times10^{-3}$
$\Gamma_{T,der}$
7.0
6.5
6.0
5.5
5.0
4.5
1.5
2.0
2.5
$\times10^{-3}$
$u_*\ (m\,s^{-1})$

Timeseries for all simulations



Snapshots within inertial cycle

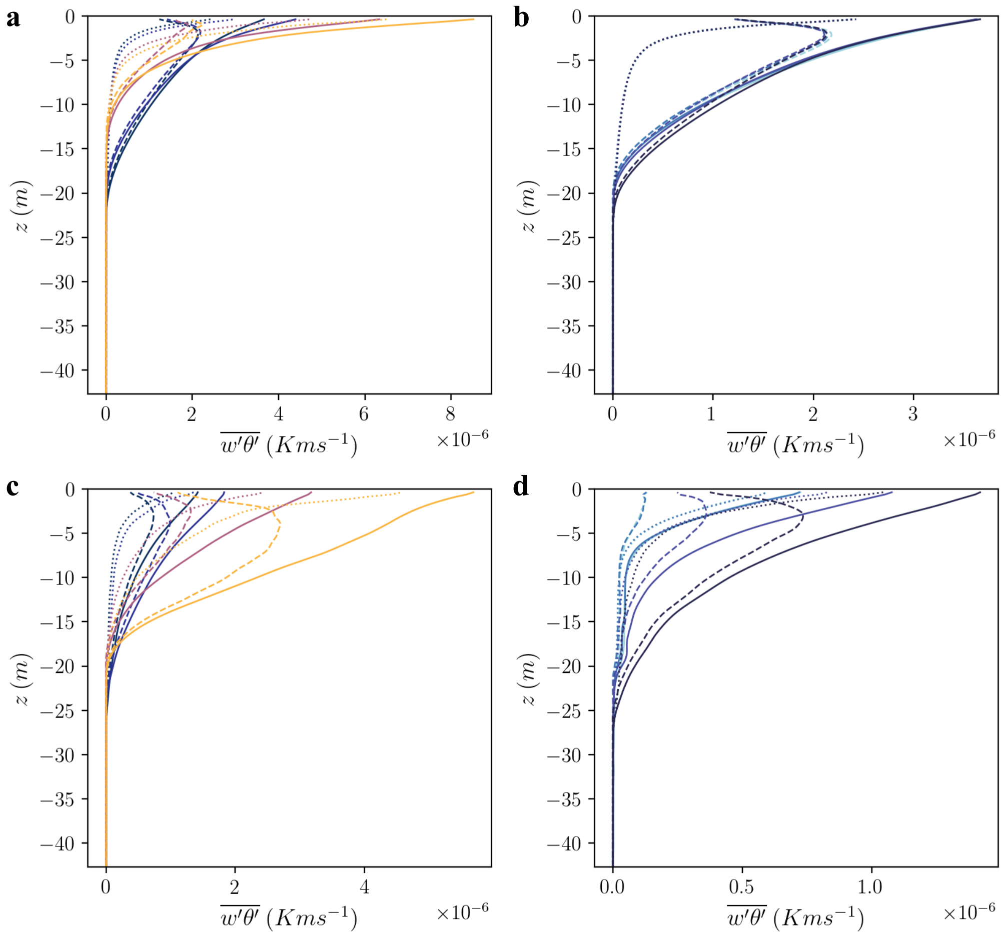




Vertical temperature flux profiles through the simulation

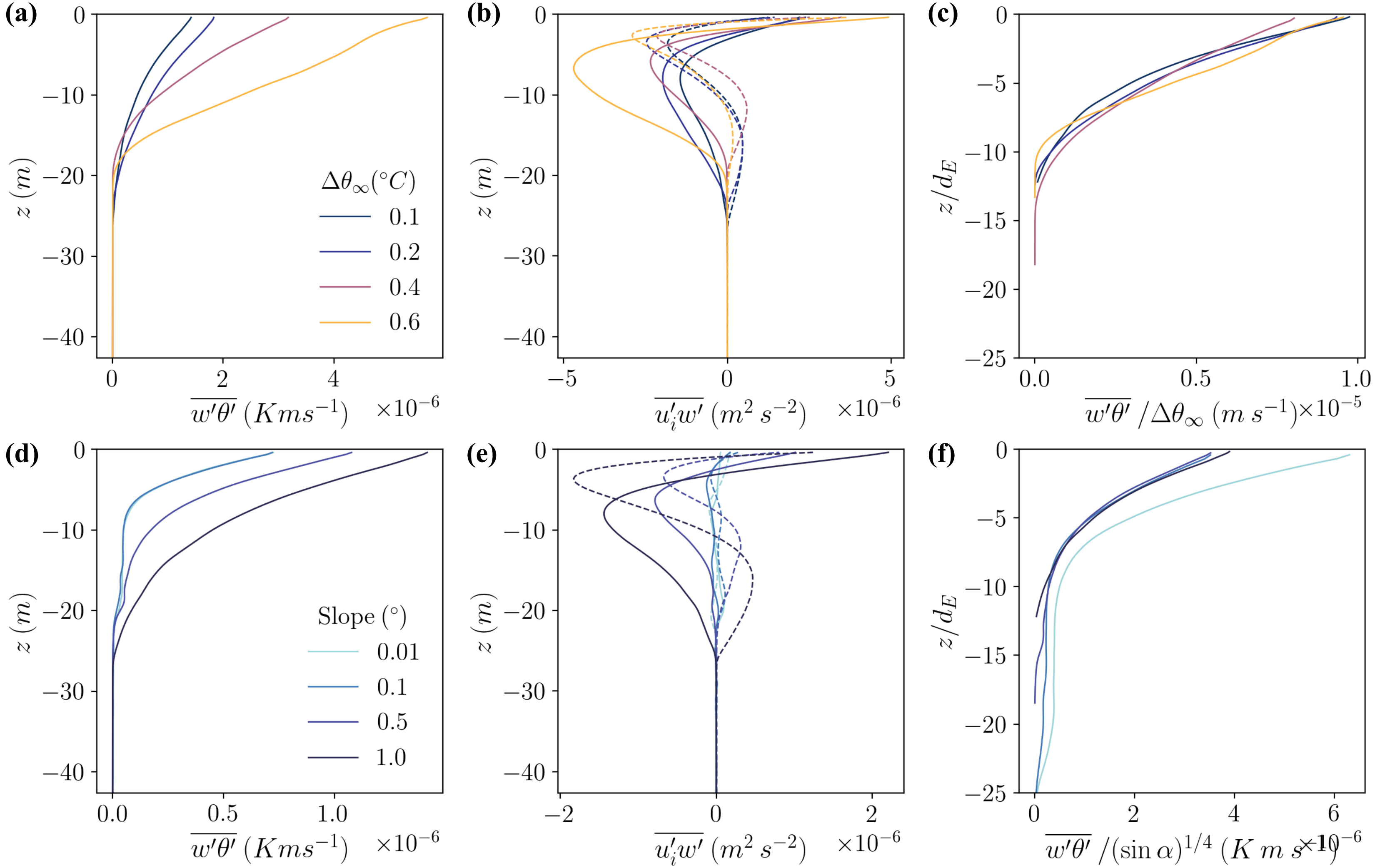
First inertial period

Fourth inertial period

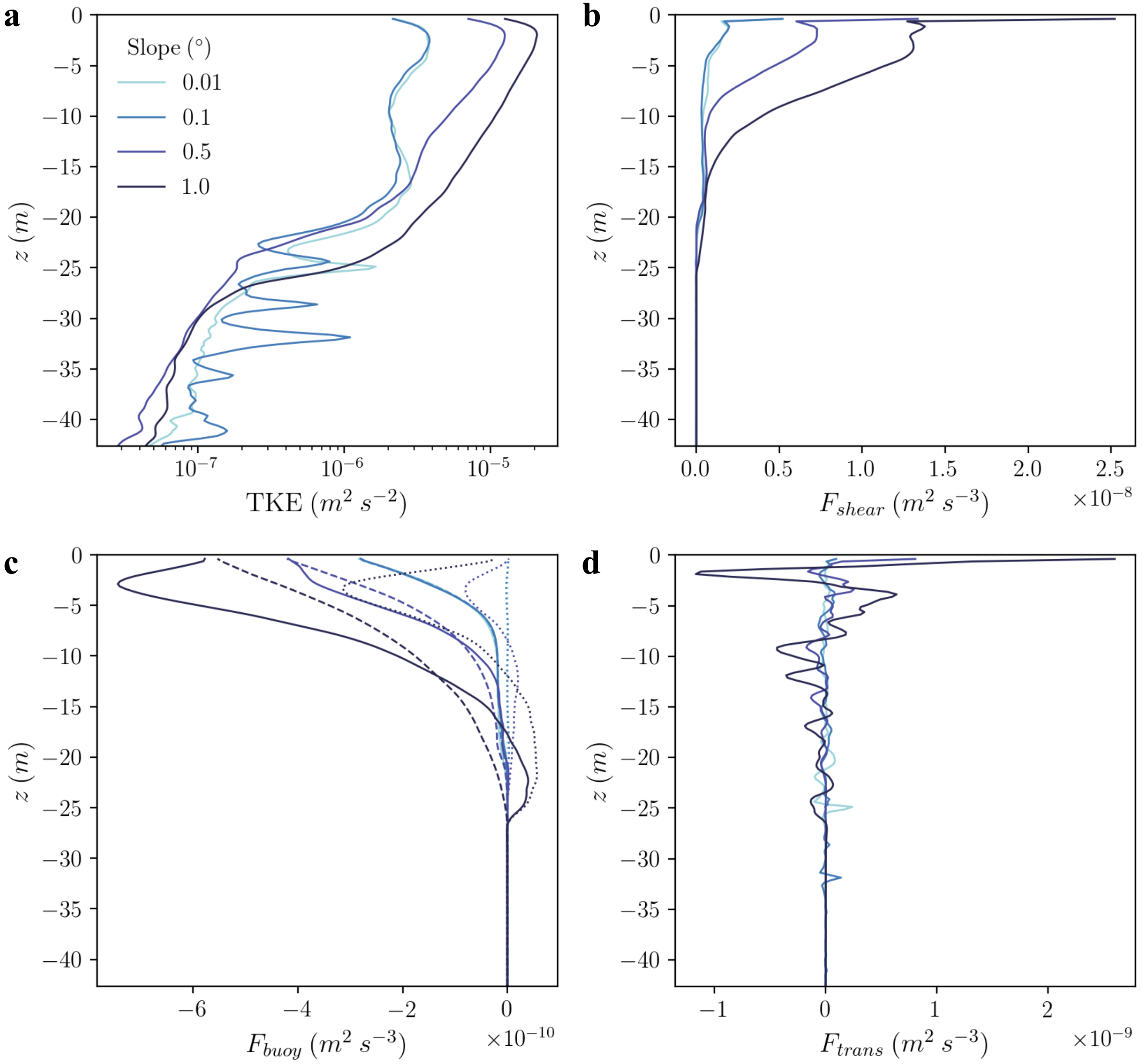


Dotted=subgrid
Dashed=resolved

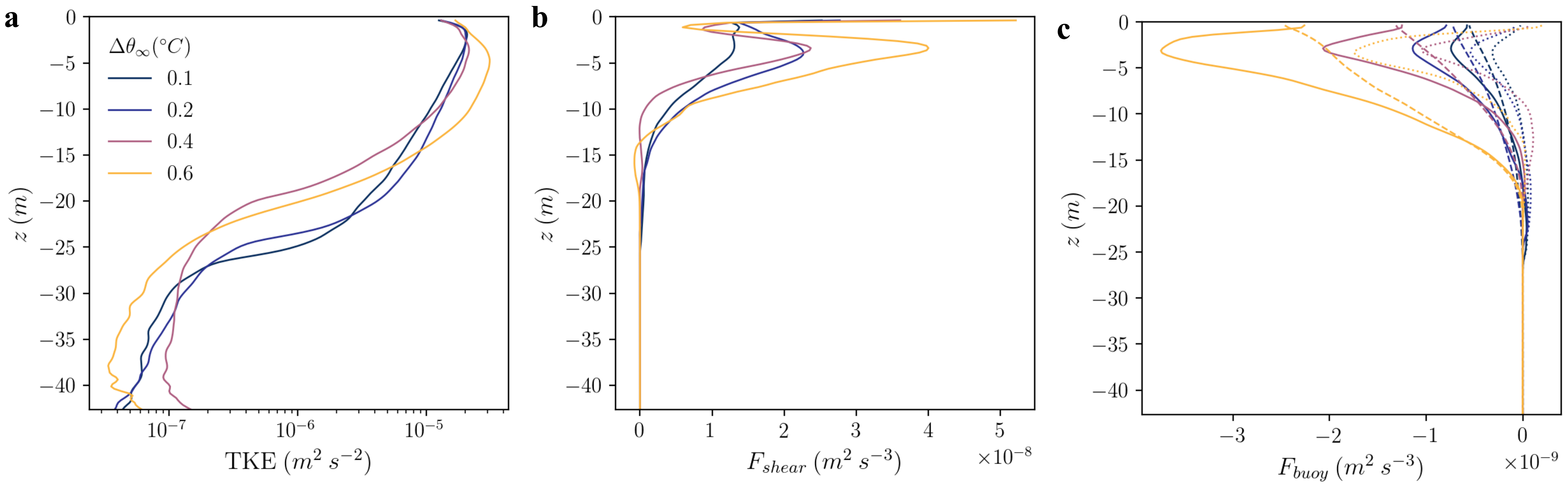
Vertical flux profiles



TKE budget, slope cases

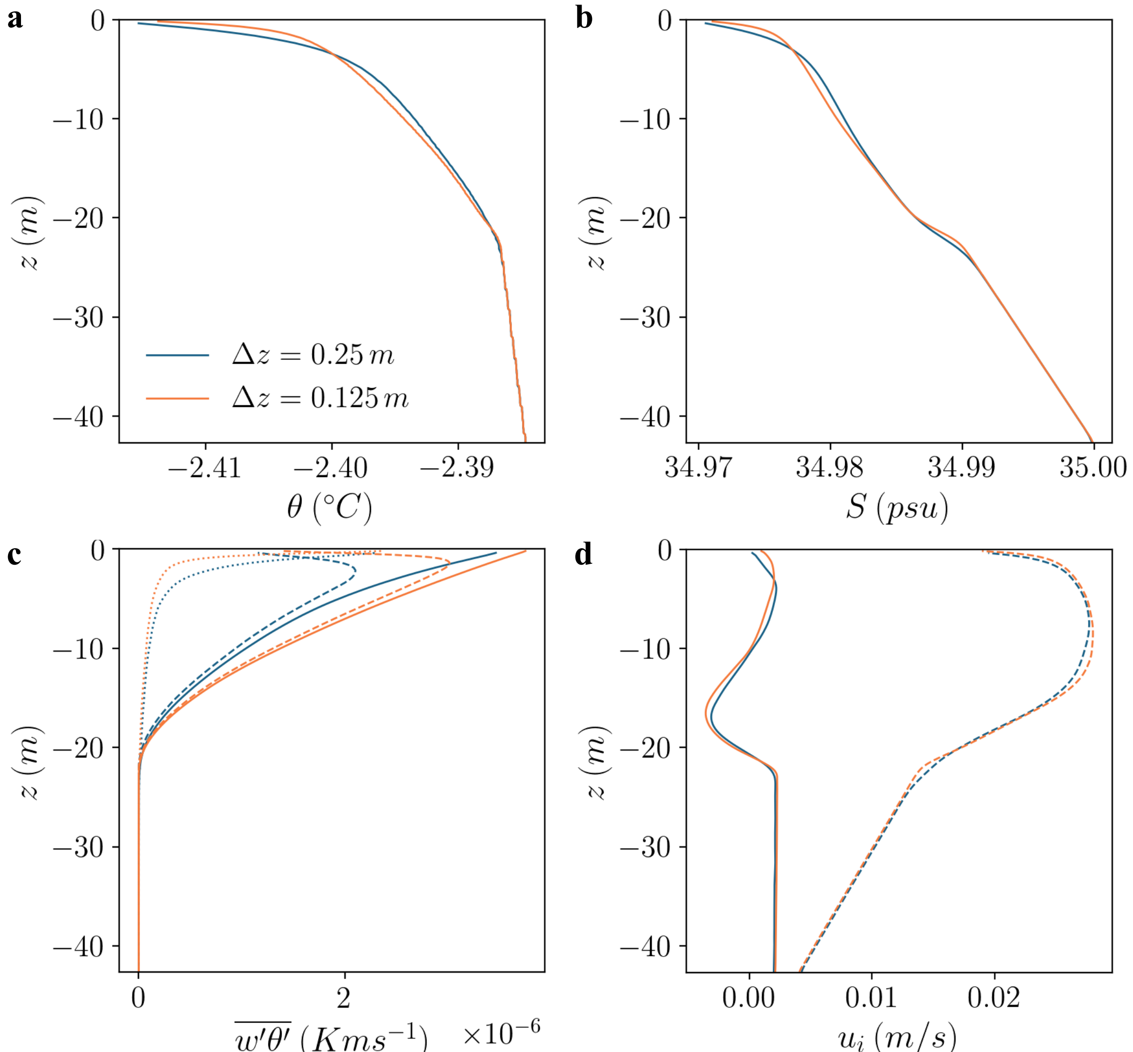


TKE budgets, thermal driving cases

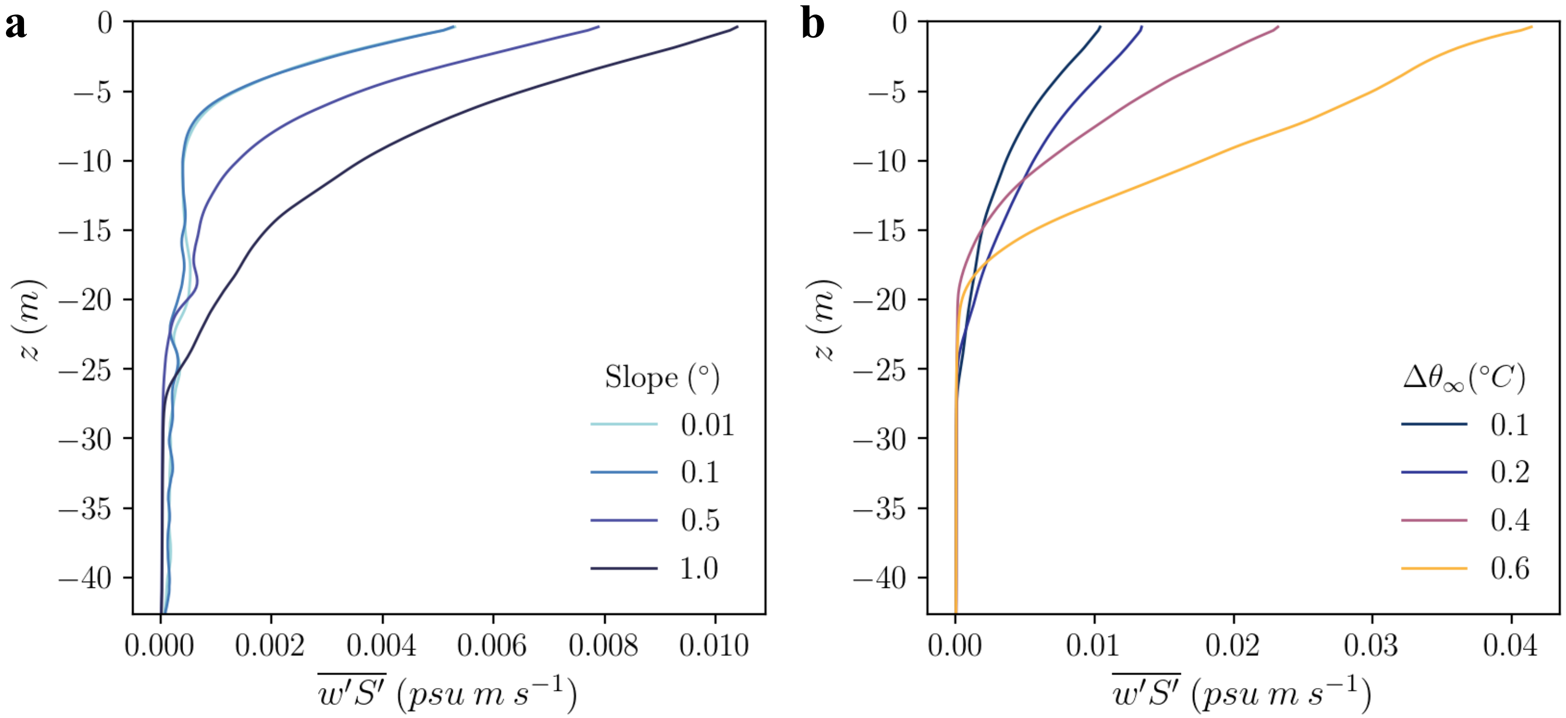


Dashed = vertical
Dotted = horizontal

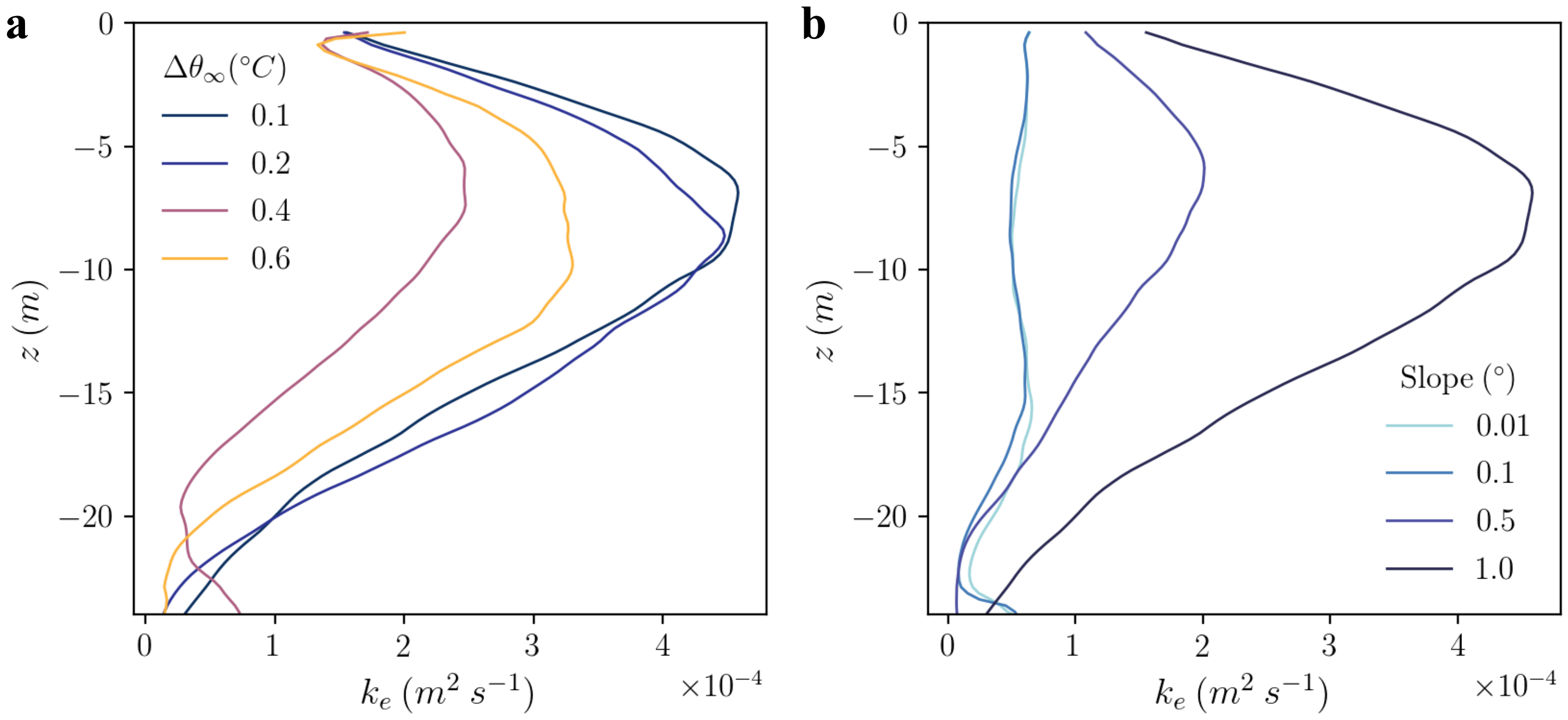
Resolution test



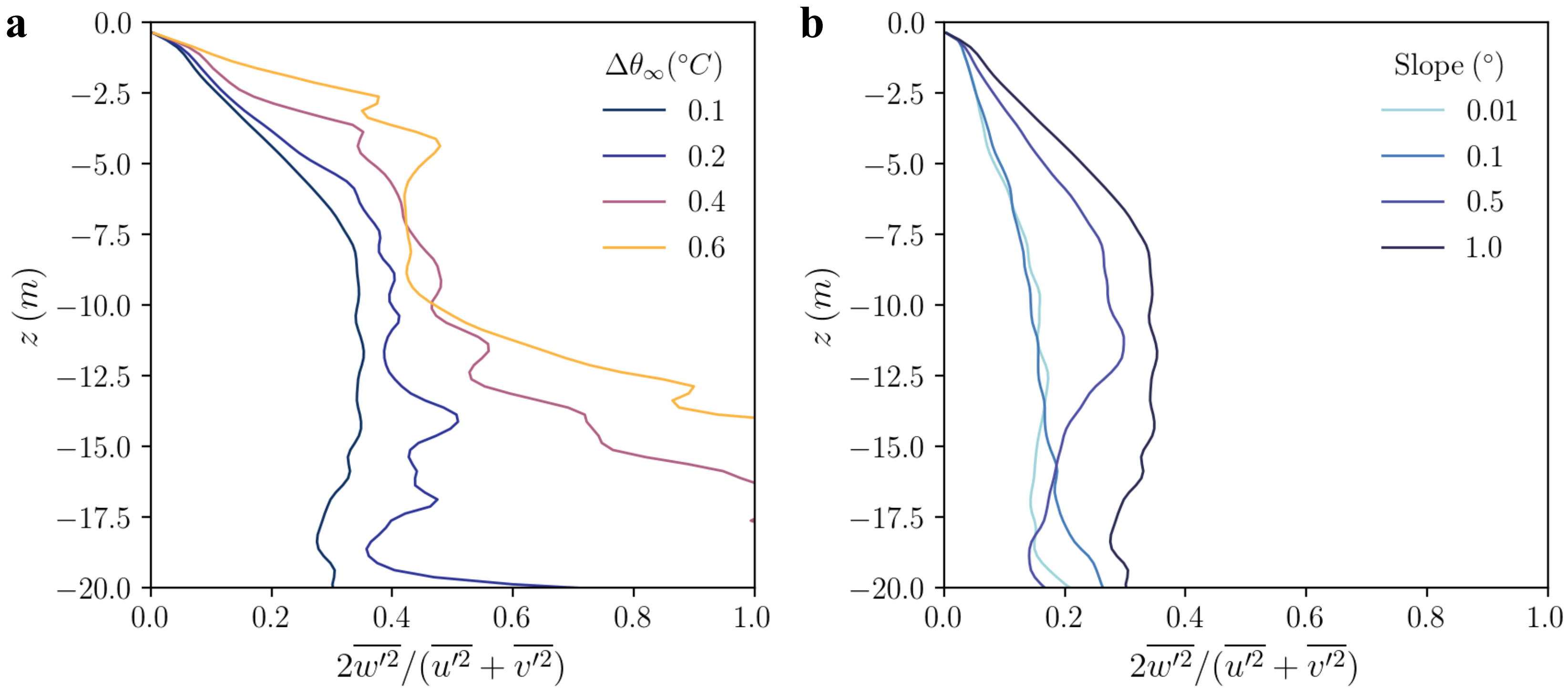
Salt flux profiles



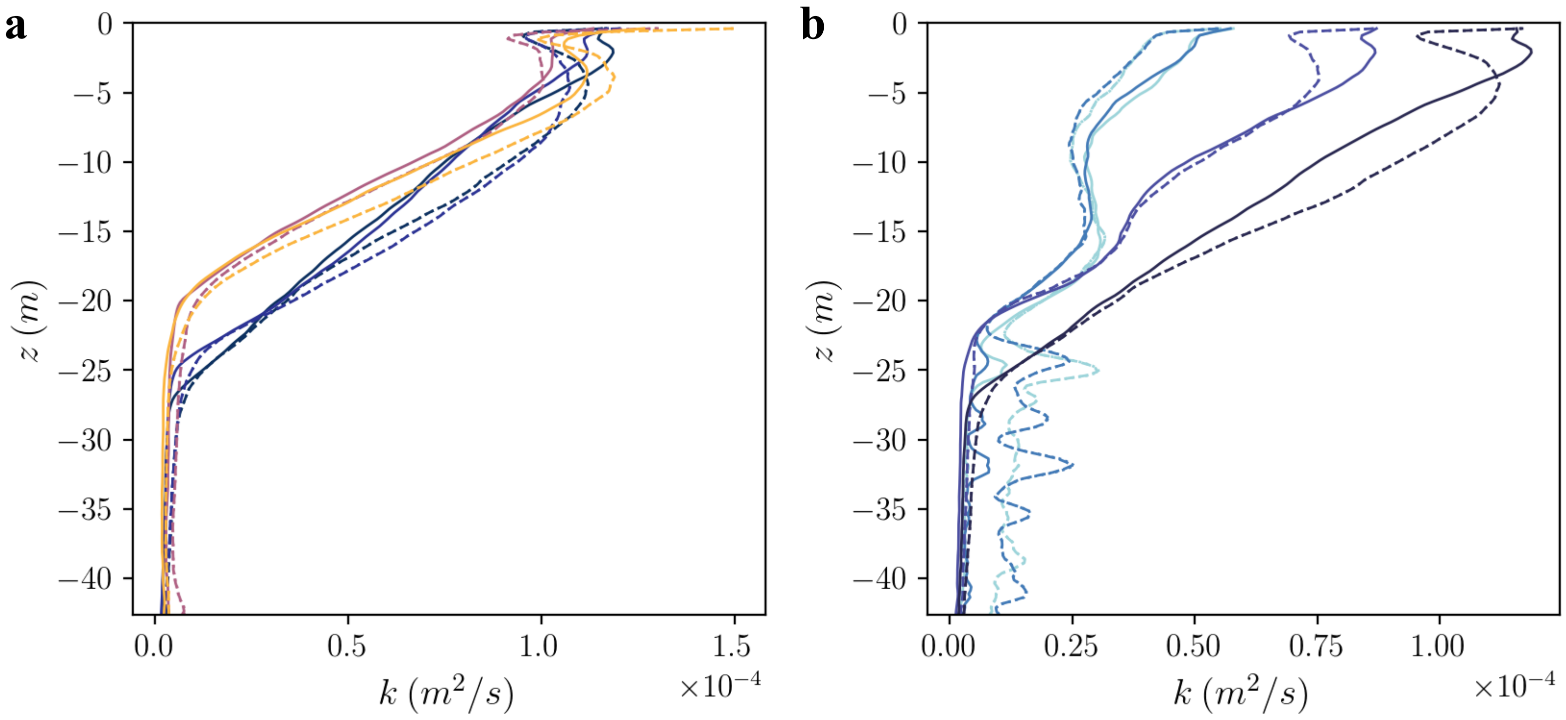
Effective diffusivity (for computation of Ekman depth)



Ratio of horizontal to vertical velocity variance



Subgrid diffusivities (solid=viscosity, dashed=scalar diffusivity)



Melt rate dependence over course of simulation