

Physical Mechanisms of Upper Ocean Mixing in the Arctic

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U.S. DEPARTMENT OF
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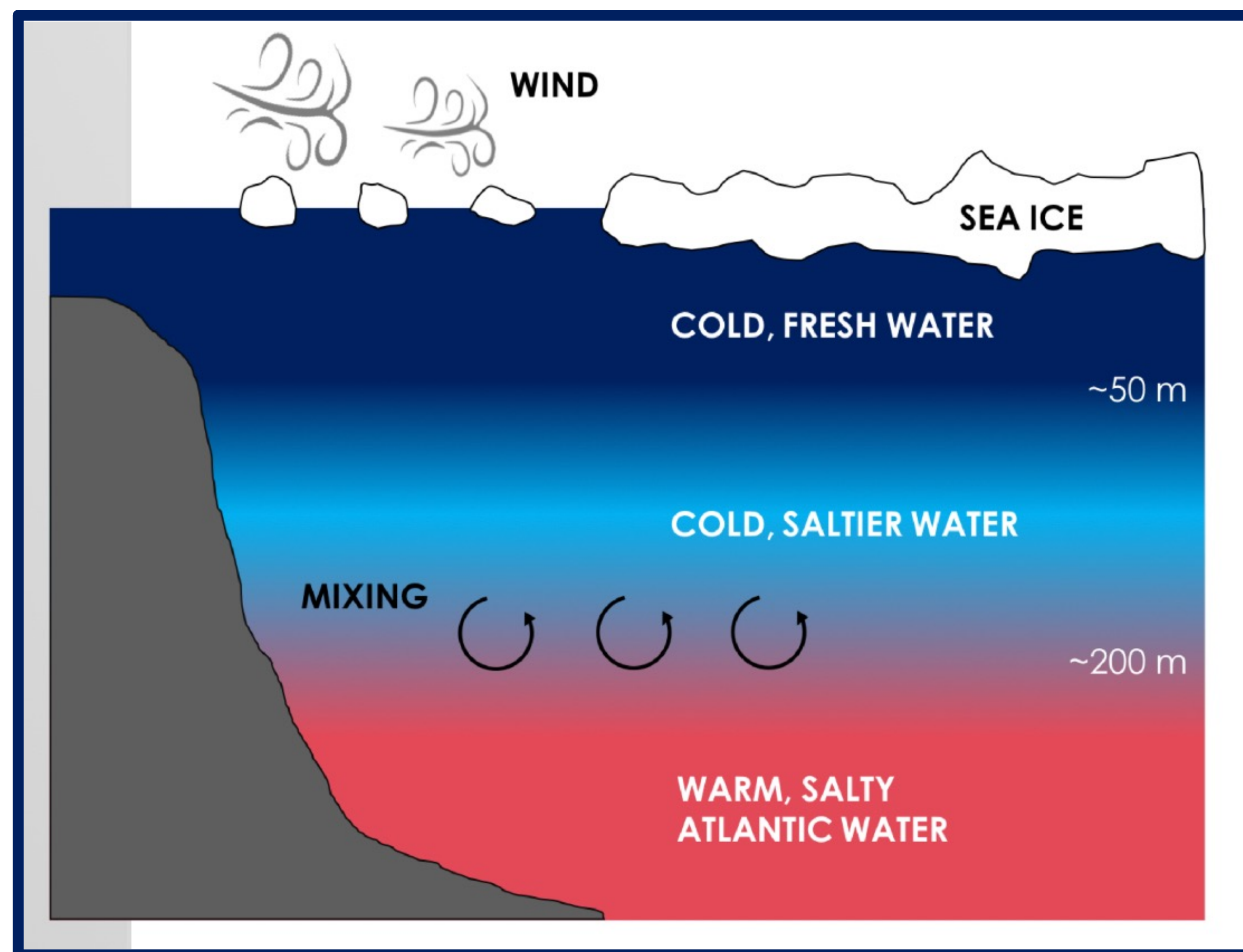


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ALASKA
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Background/Motivation

Arctic Stratification

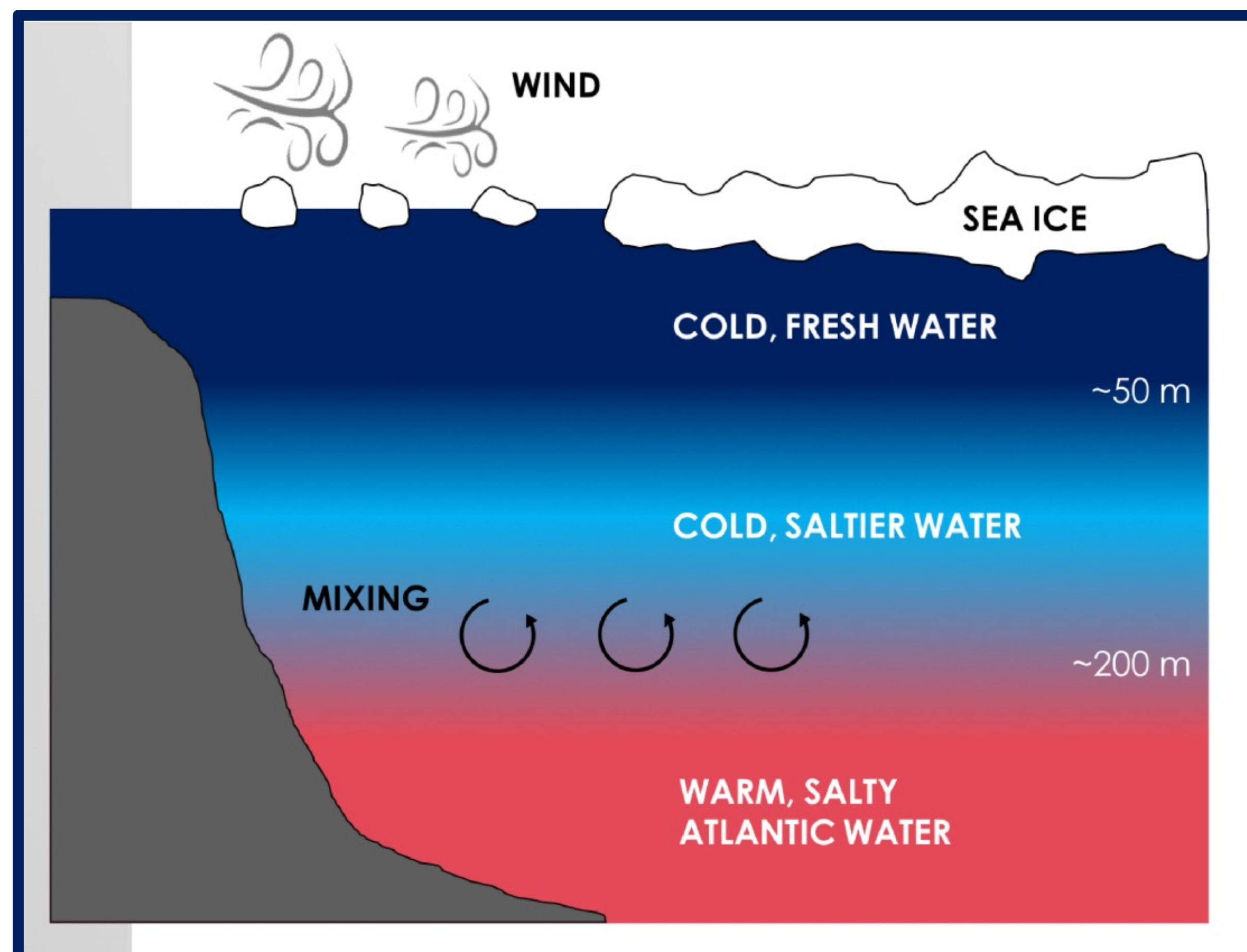


Chanona et al,
(poster)

- Sea ice has historically buffered the Arctic Ocean's surface layer, influencing sea-ice melt rates

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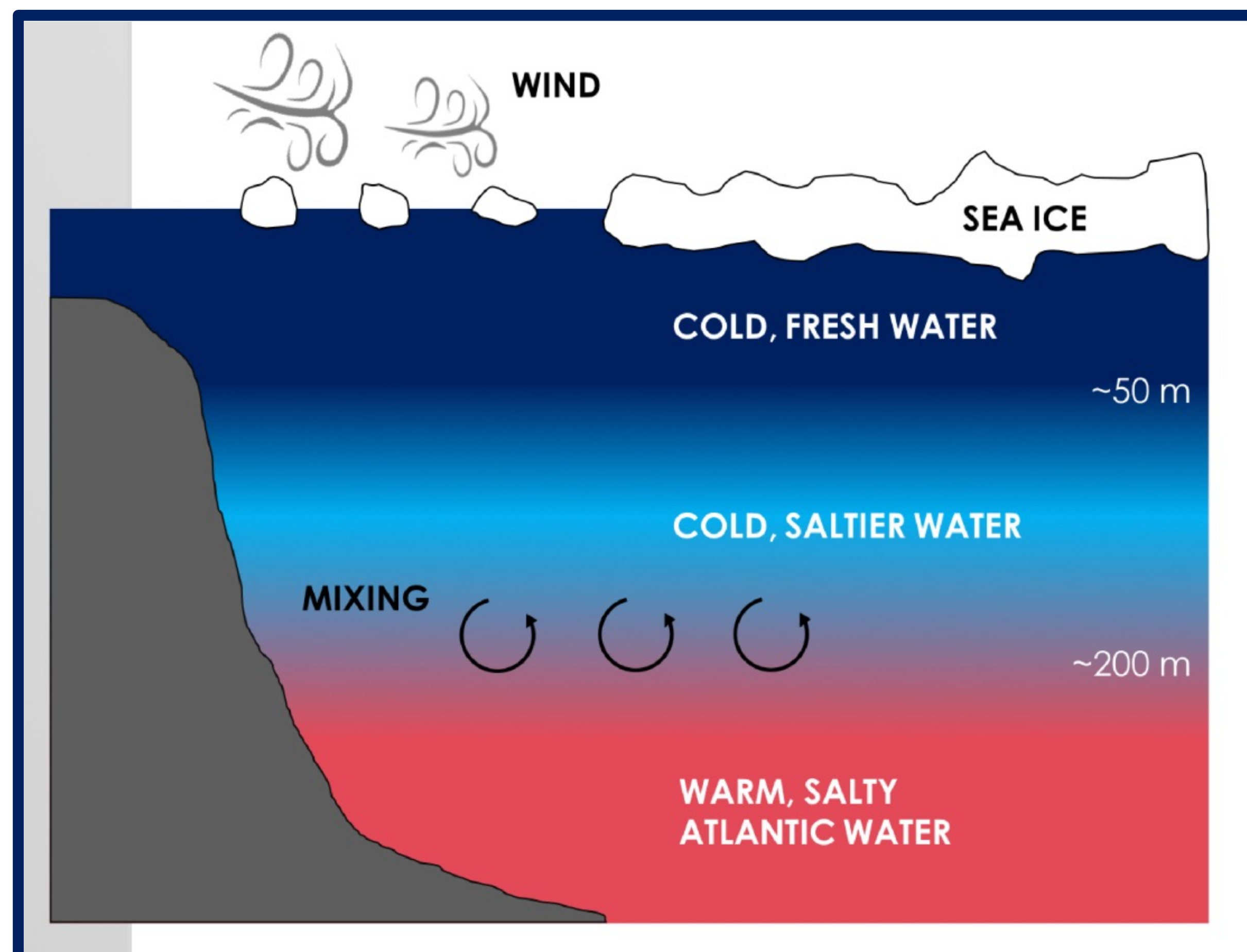


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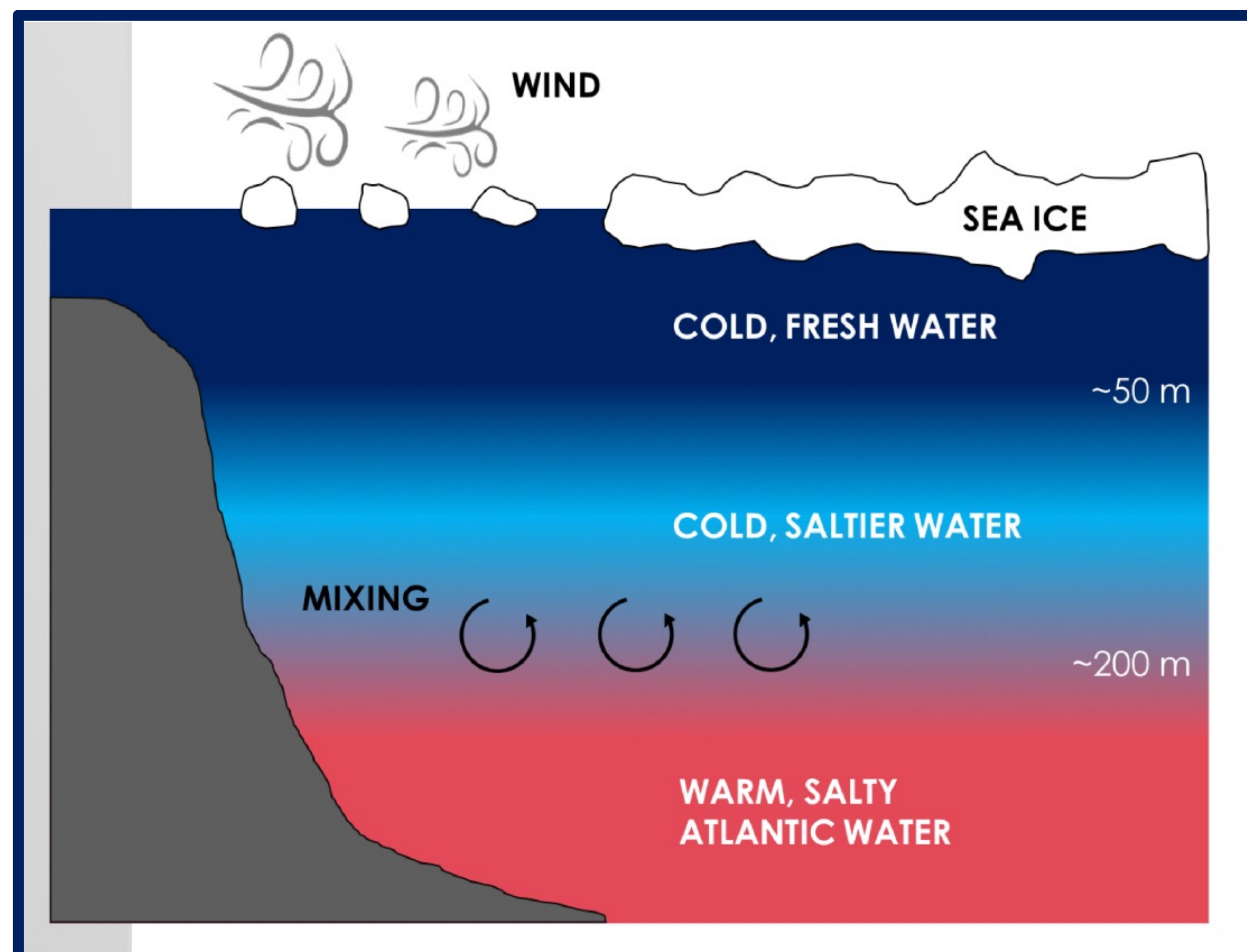


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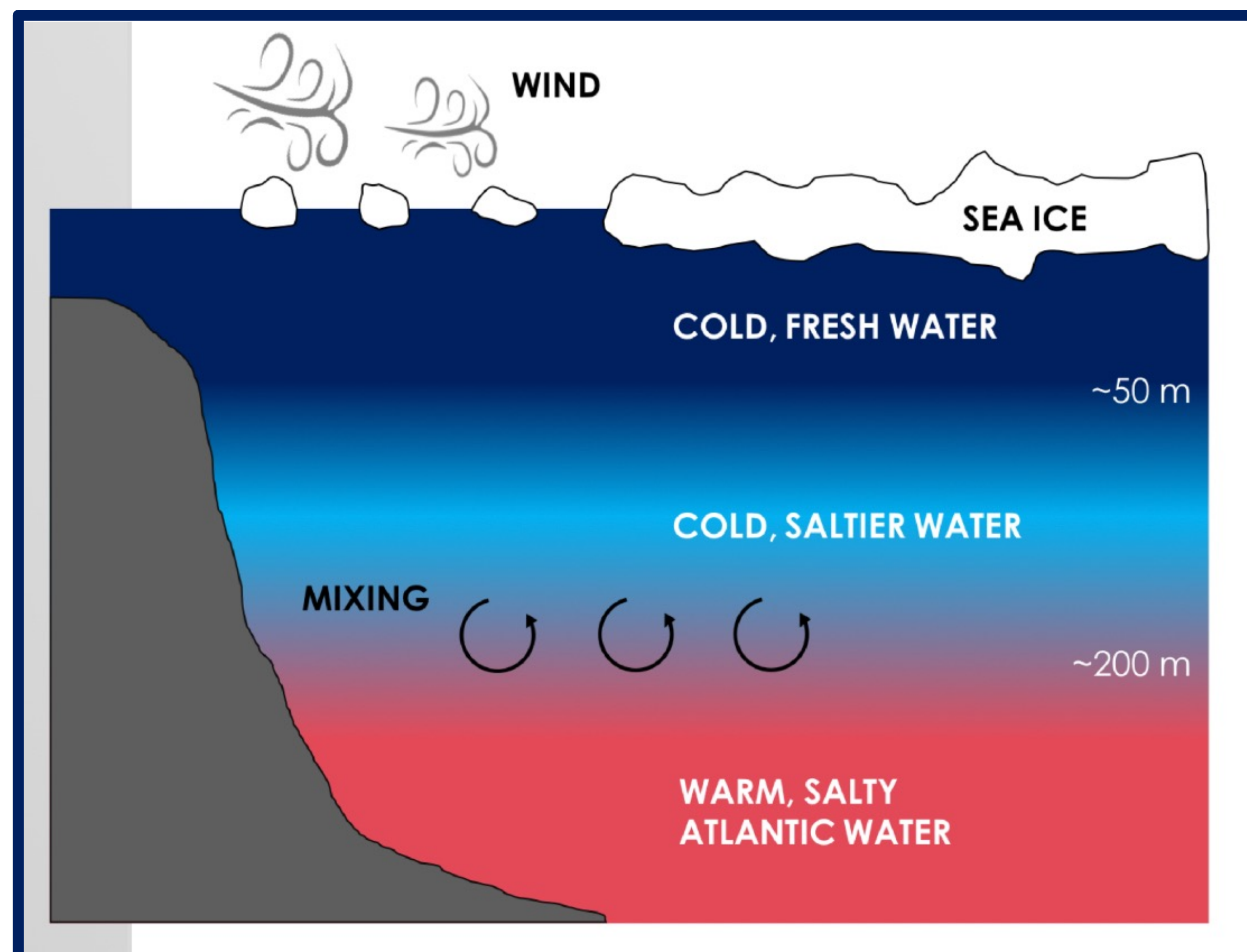


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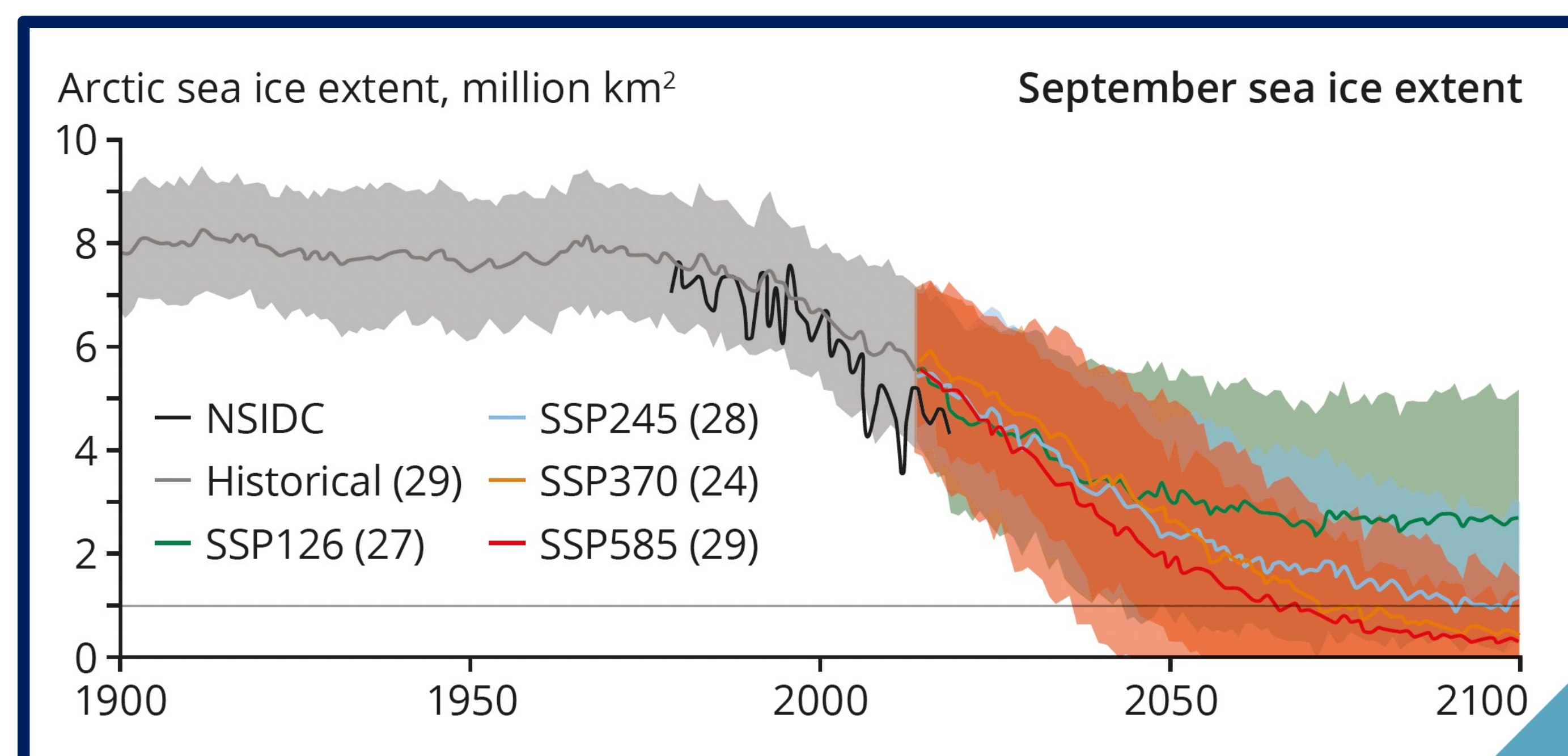
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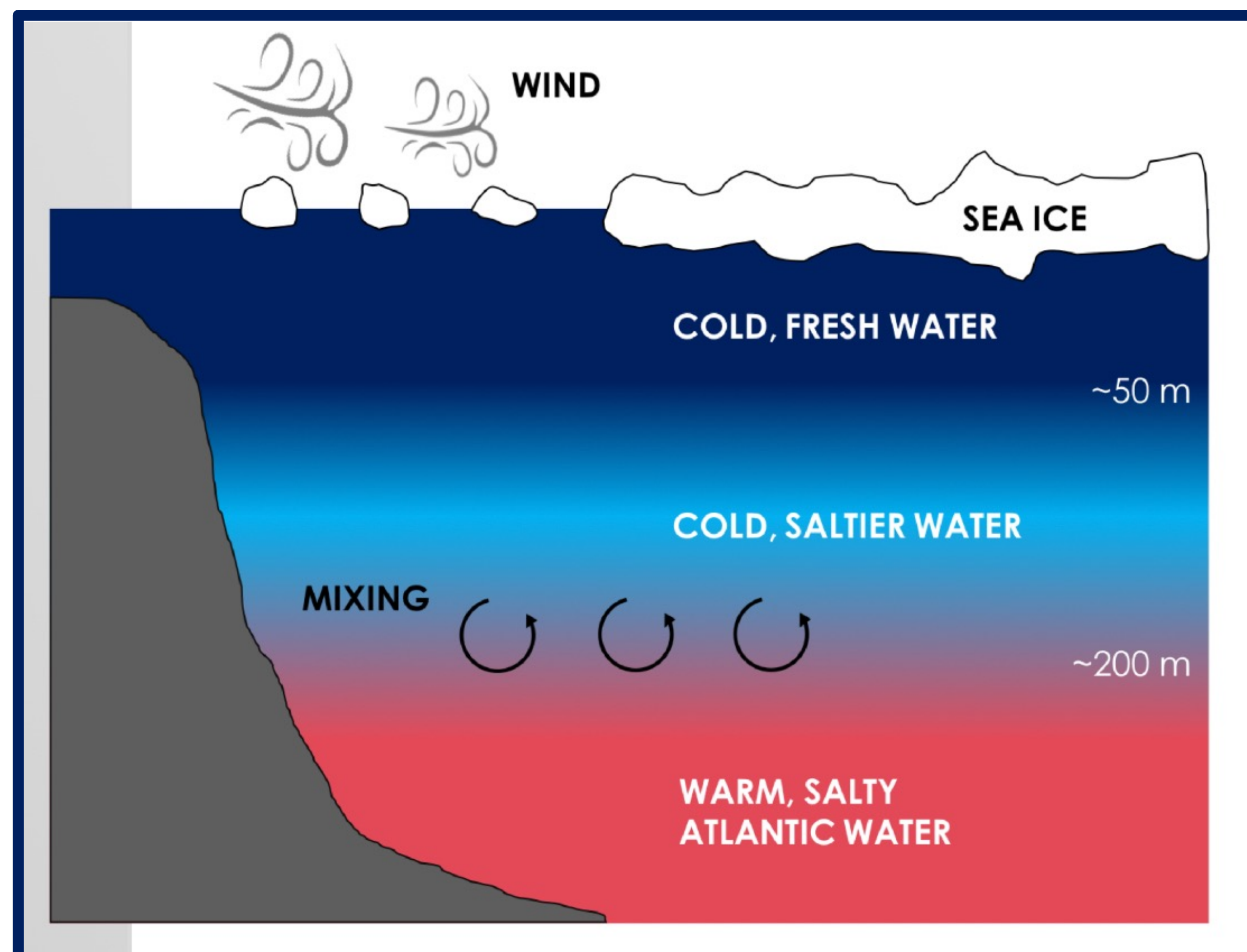


Arctic Climate
Change Update
2021: Key
Trends and
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- However, Arctic sea-ice is in decline and ice-free period are increasing

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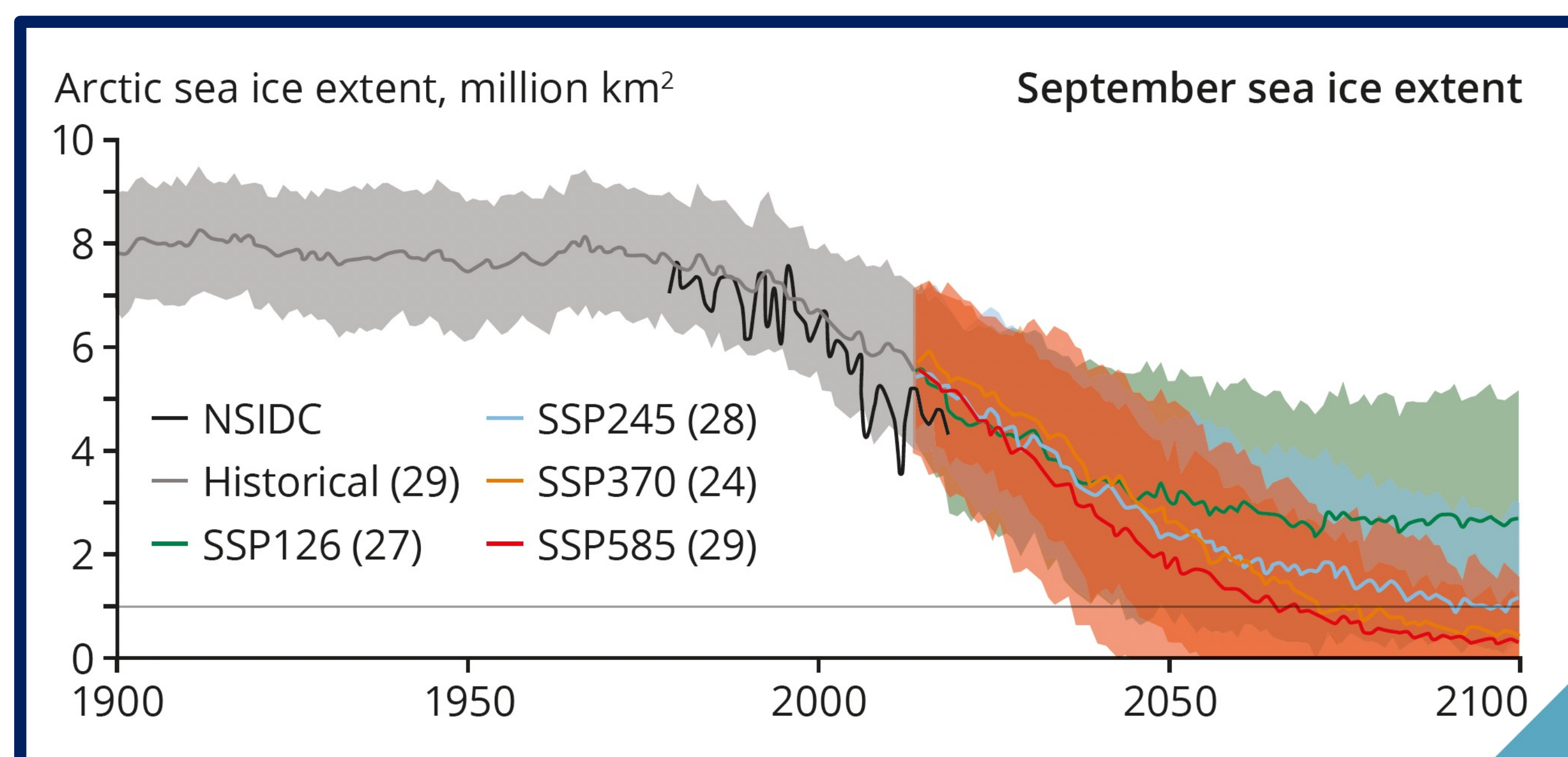
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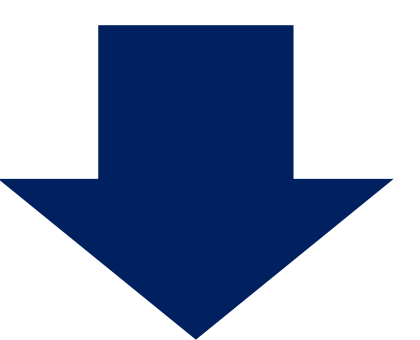
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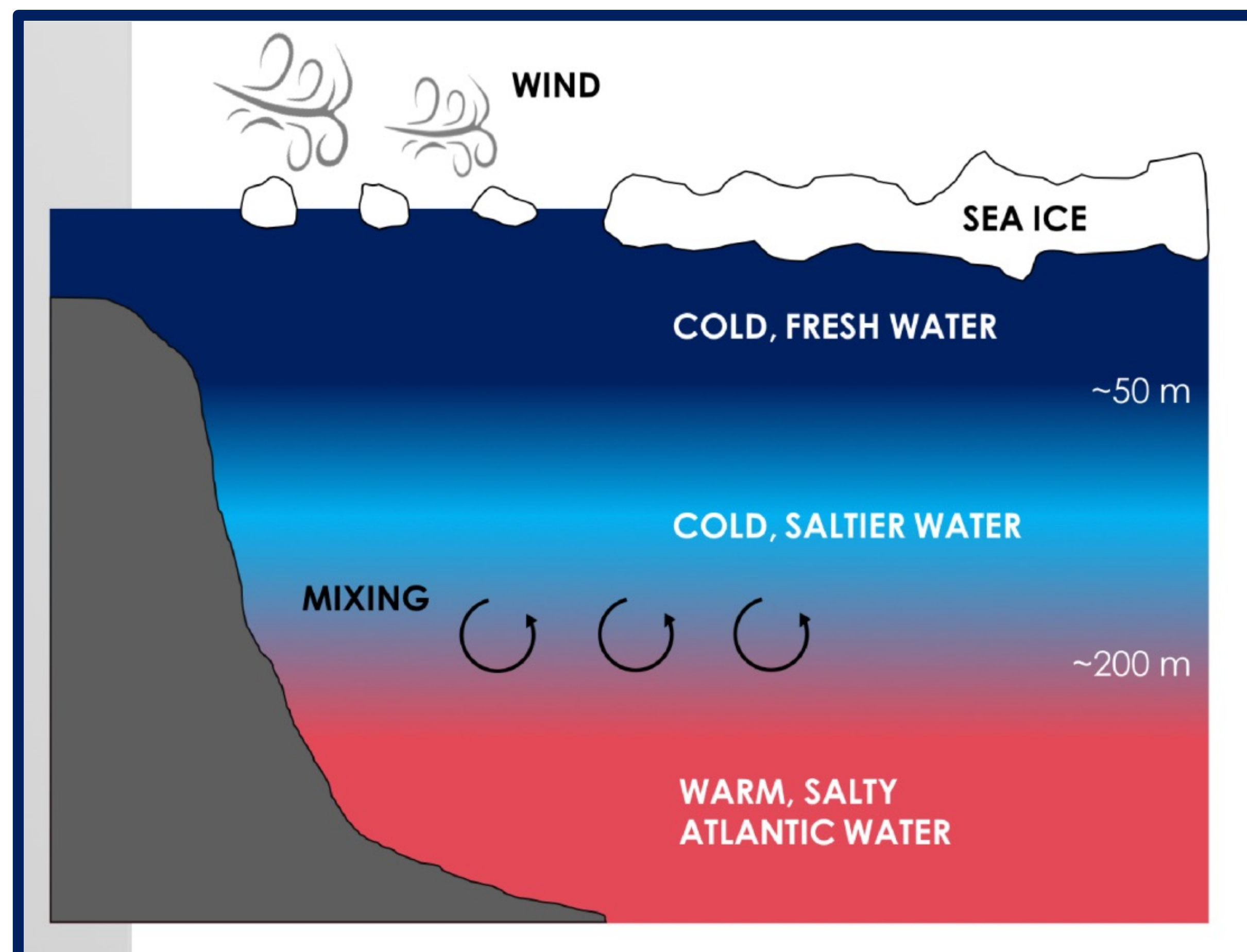
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Arctic sea-ice cover



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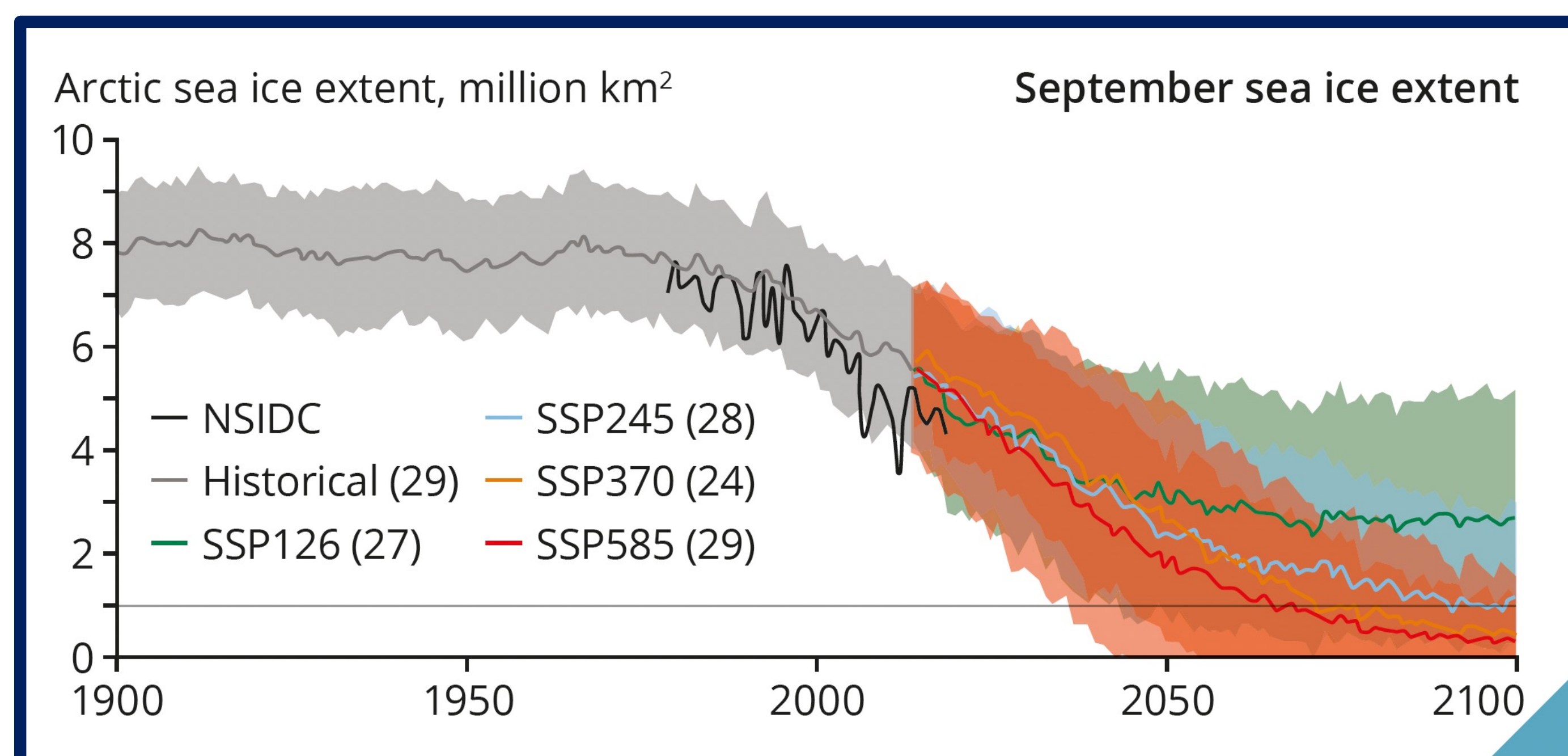
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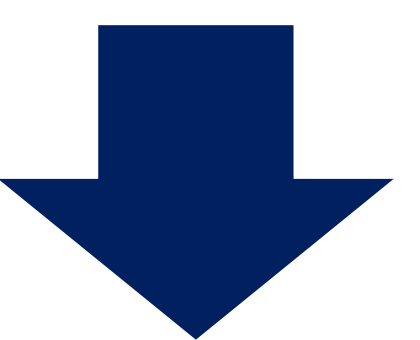
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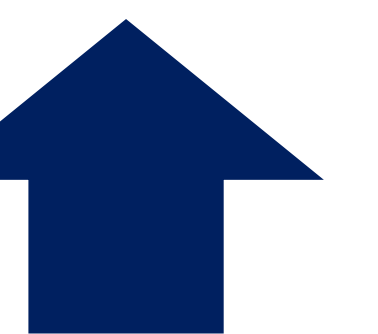
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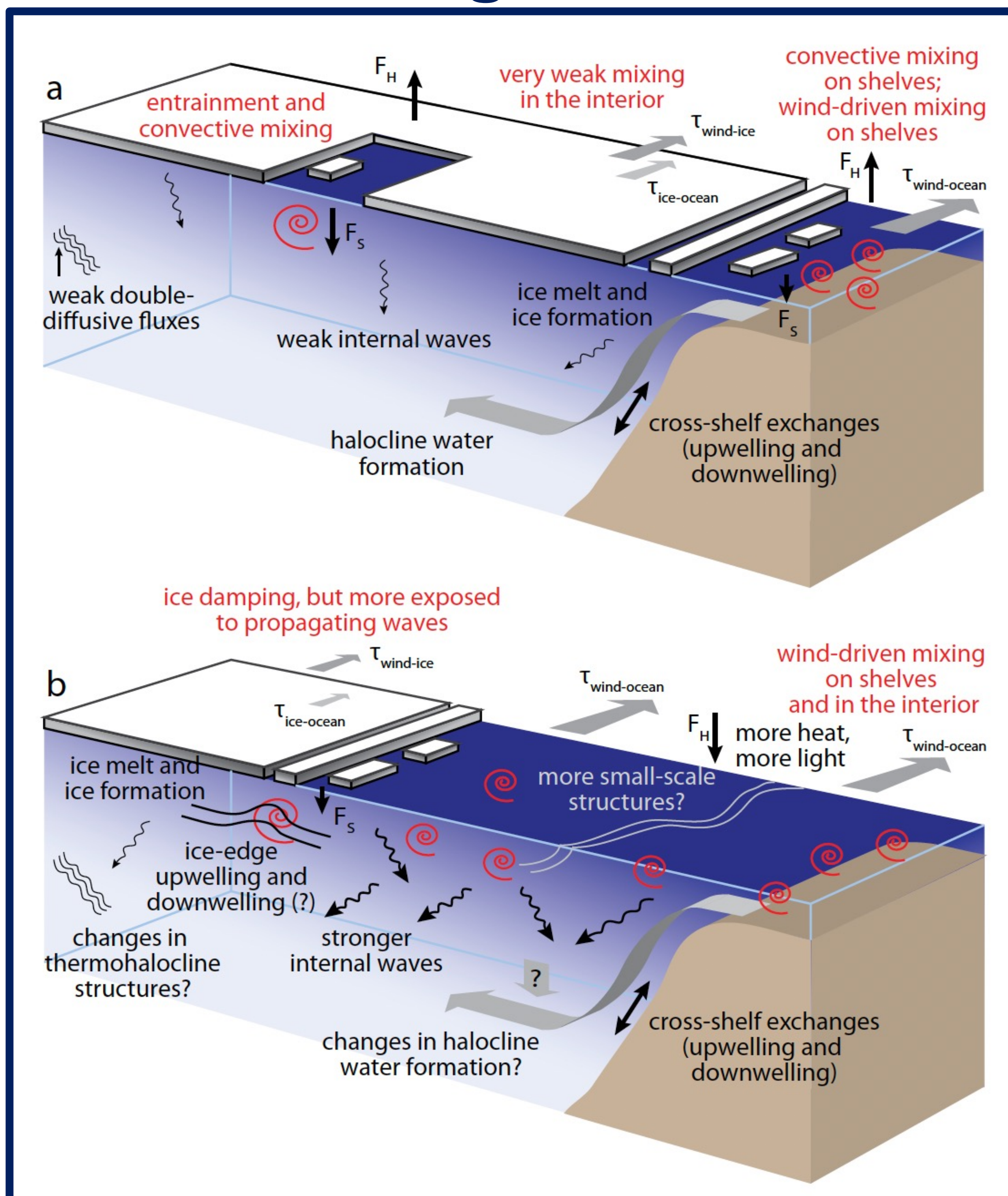
Exposure to atmos. forcing



Background/Motivation

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Arctic Mixing Mechanisms

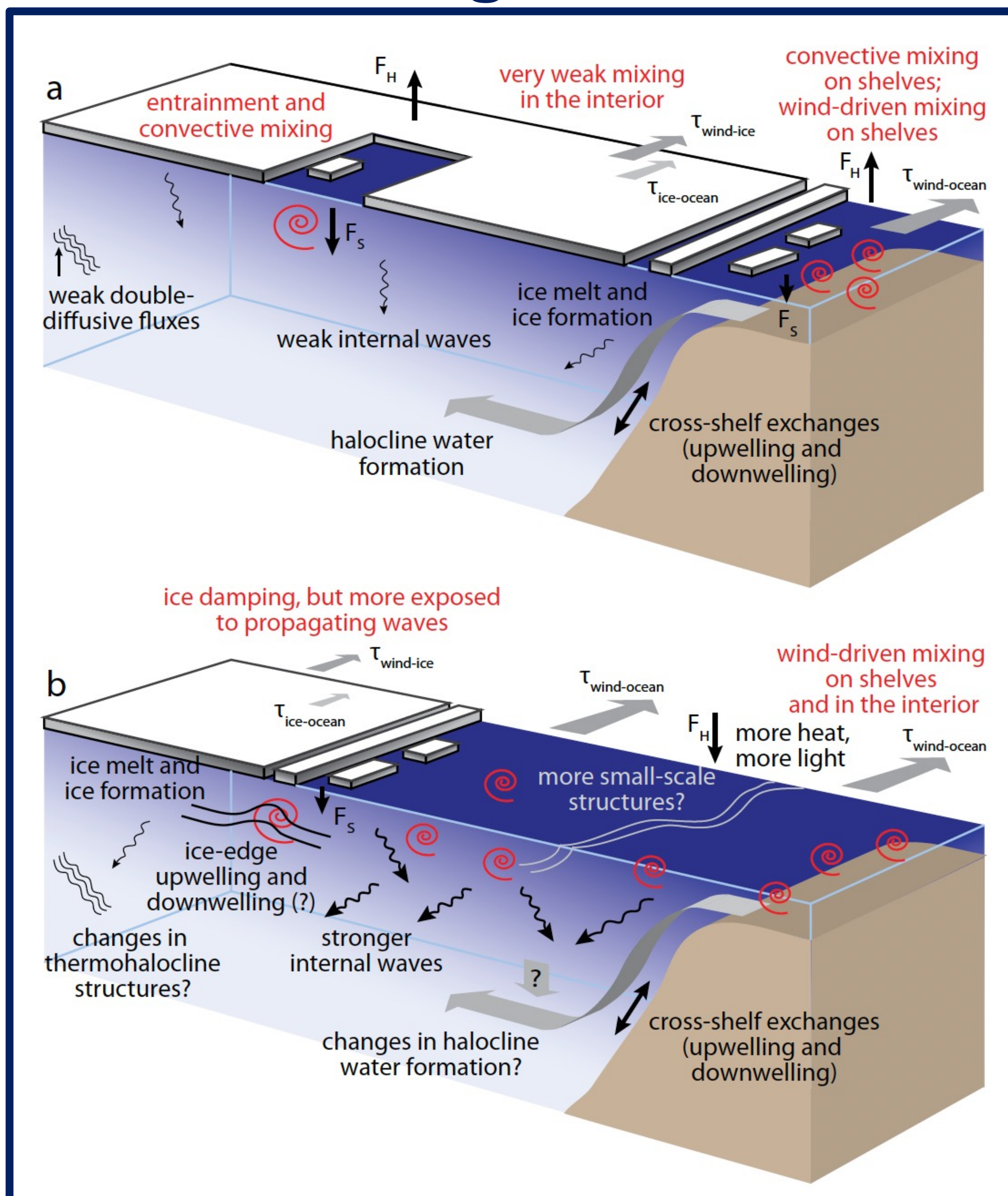


Rainville et al 2011

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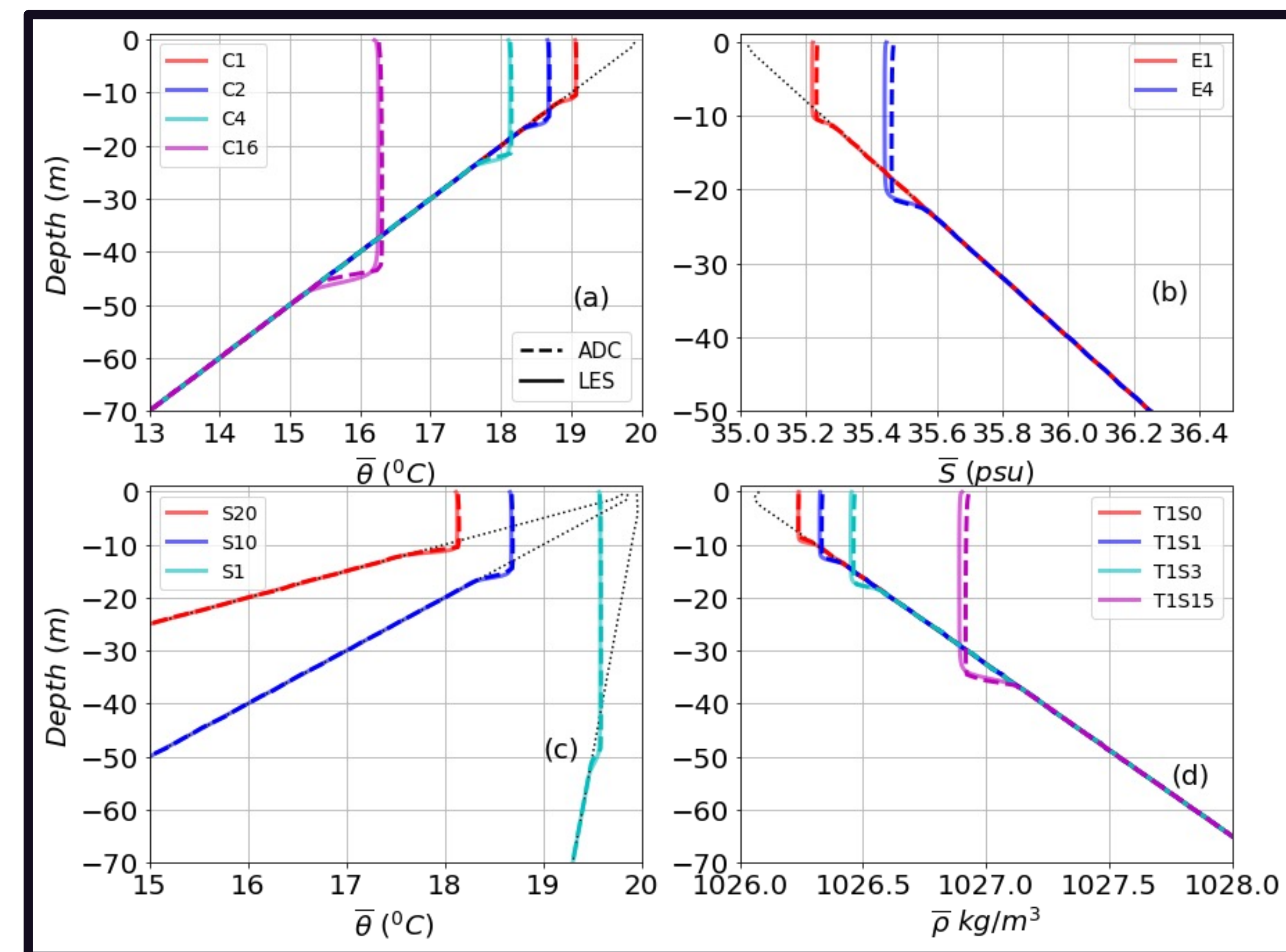
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Arctic Mixing Mechanisms



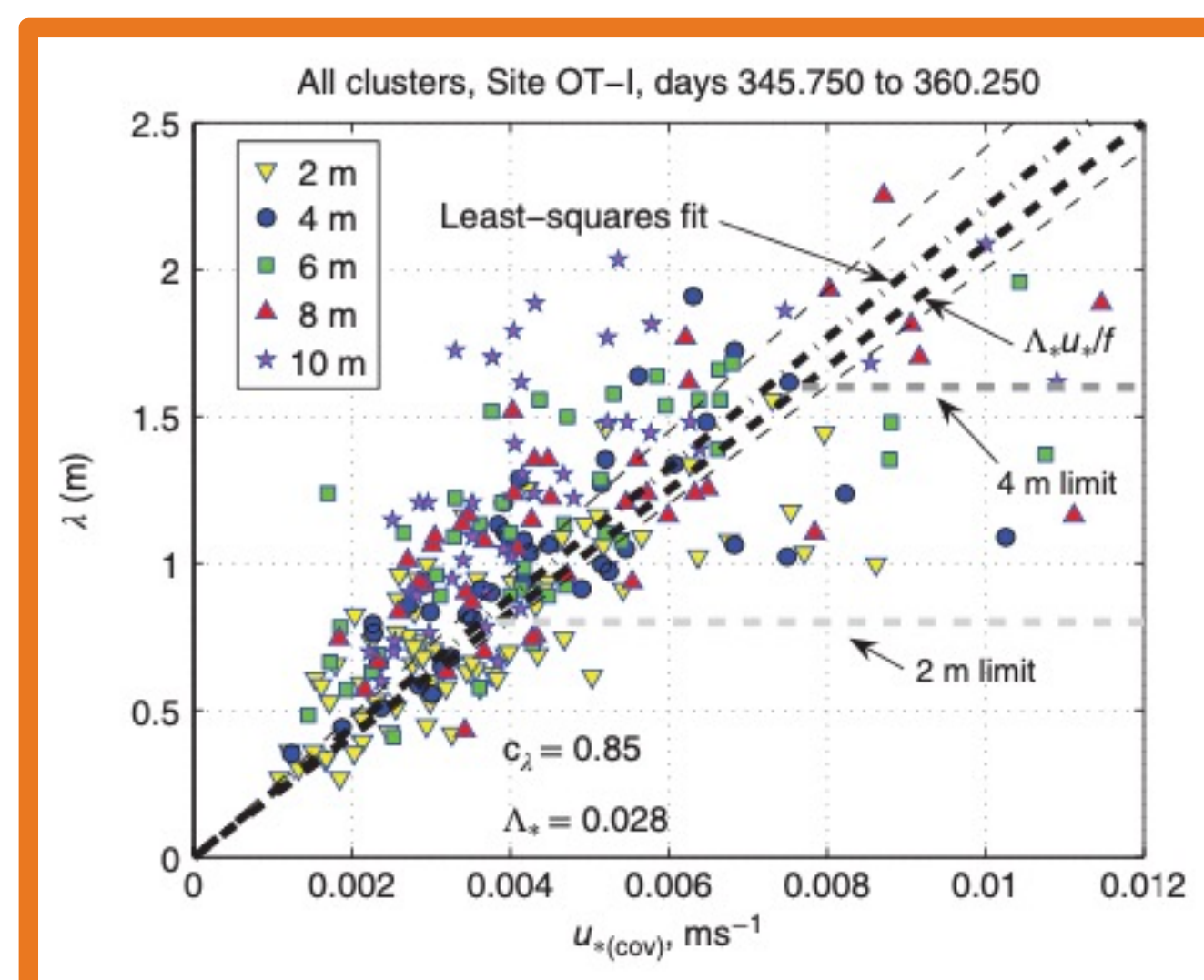
Rainville et al 2011

- What are the dominant mechanisms of vertical heat transport and mixing in the Arctic? How will these change?
- Are these mechanisms captured by parameterizations? (validation is primarily for mid-latitudes so far, i.e. alpha oceans)

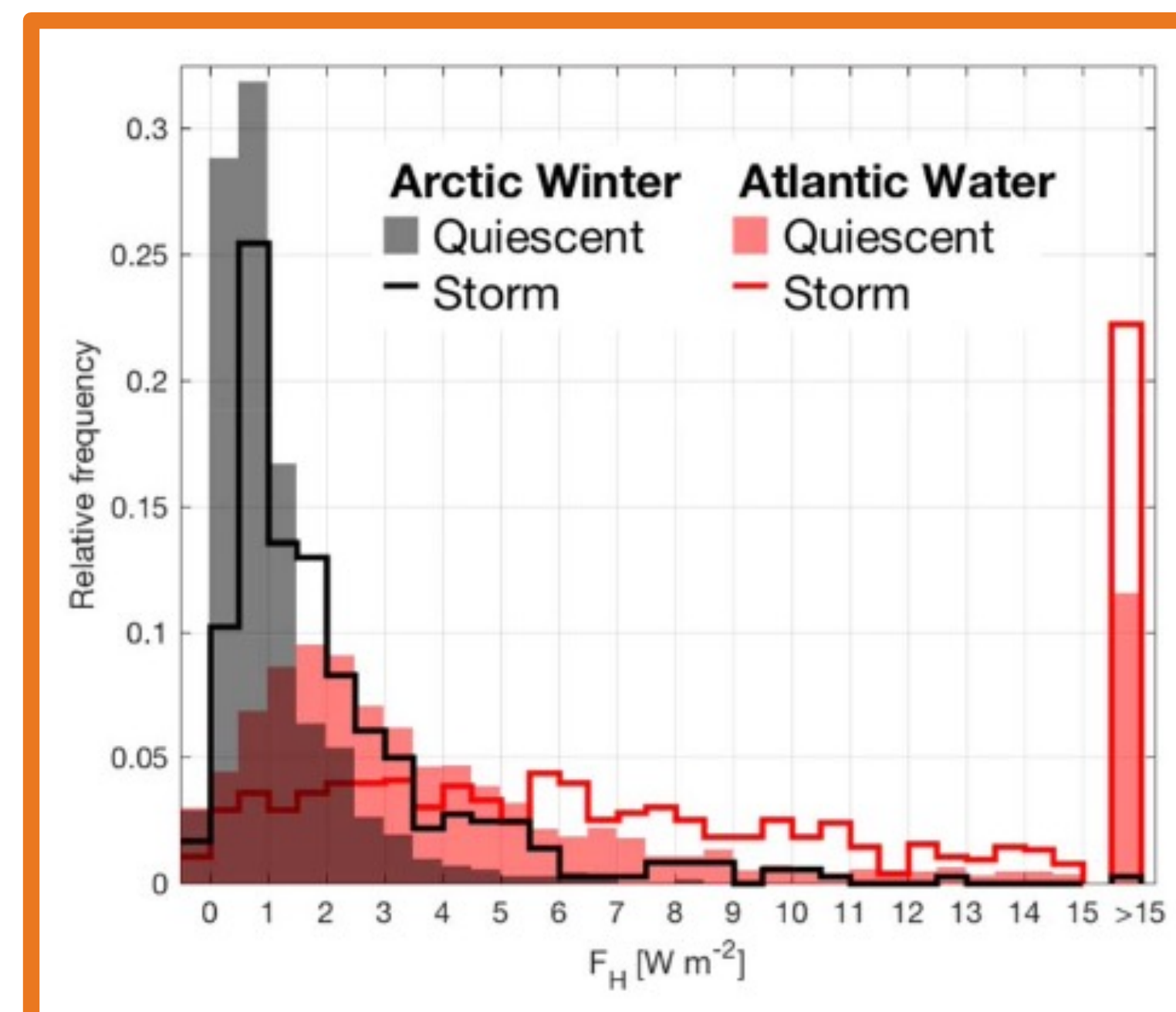


Garanaik et al
(submitted to JAMES)

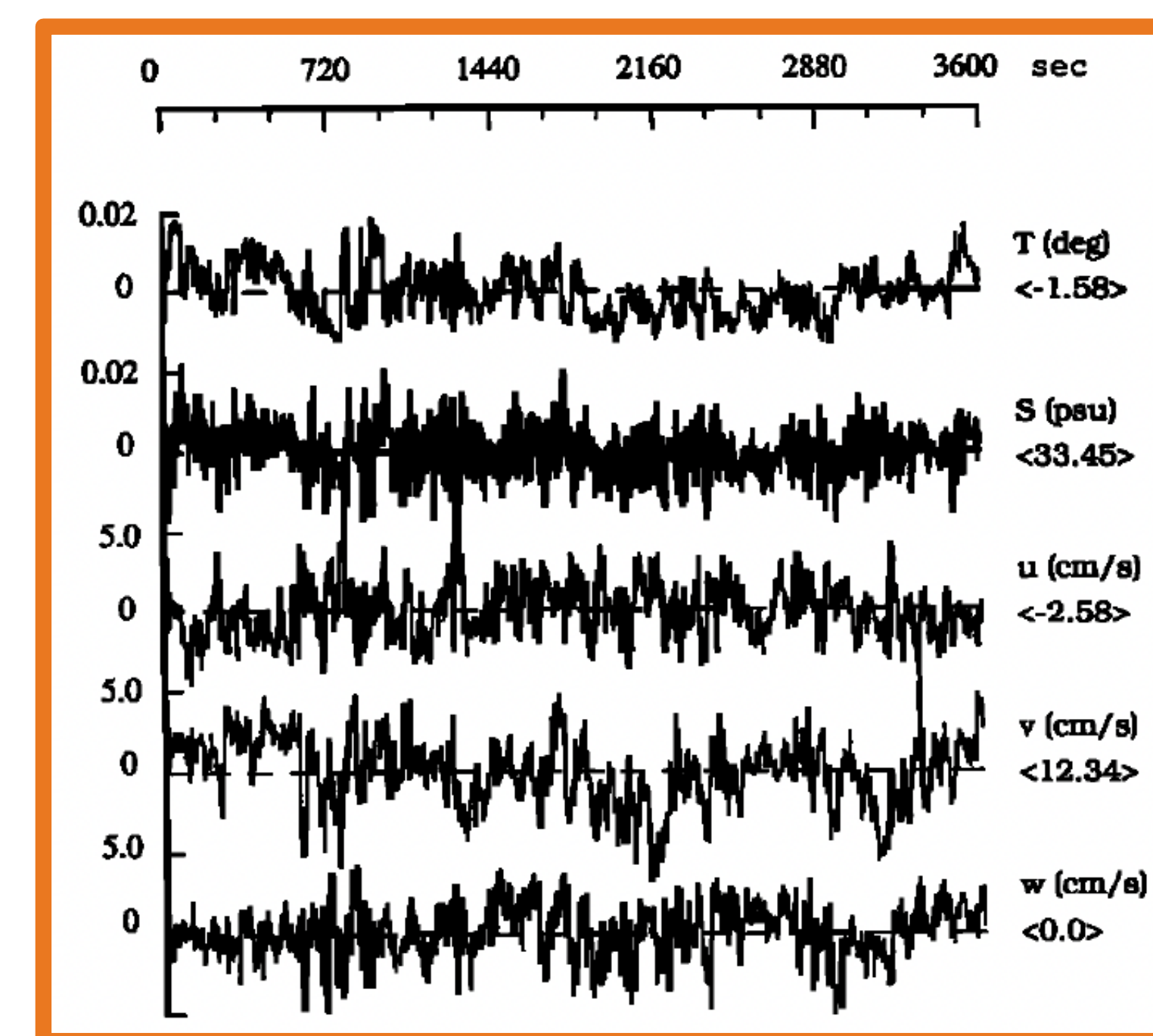
What Do We Know? - Observations



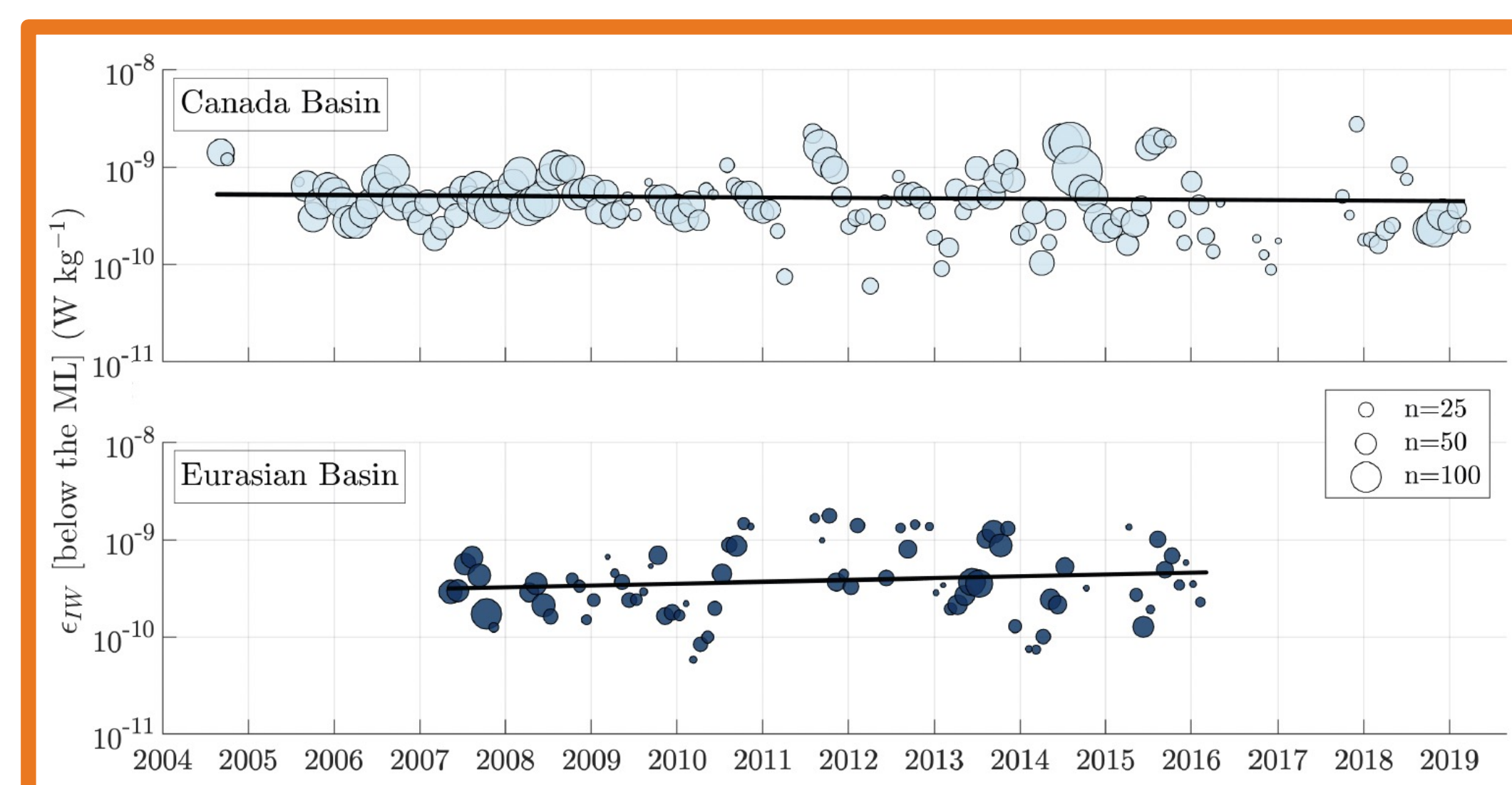
McPhee 2017: turbulence mixing length under sea-ice



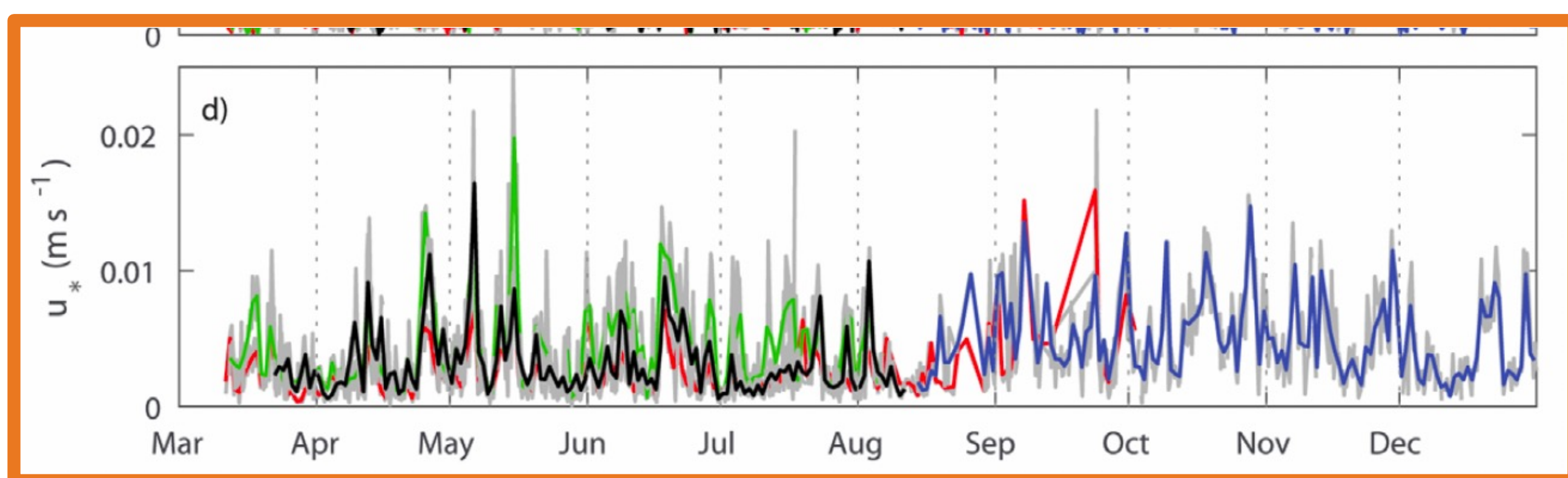
Peterson et al 2017: heat flux under sea-ice, wind doubles heat flux



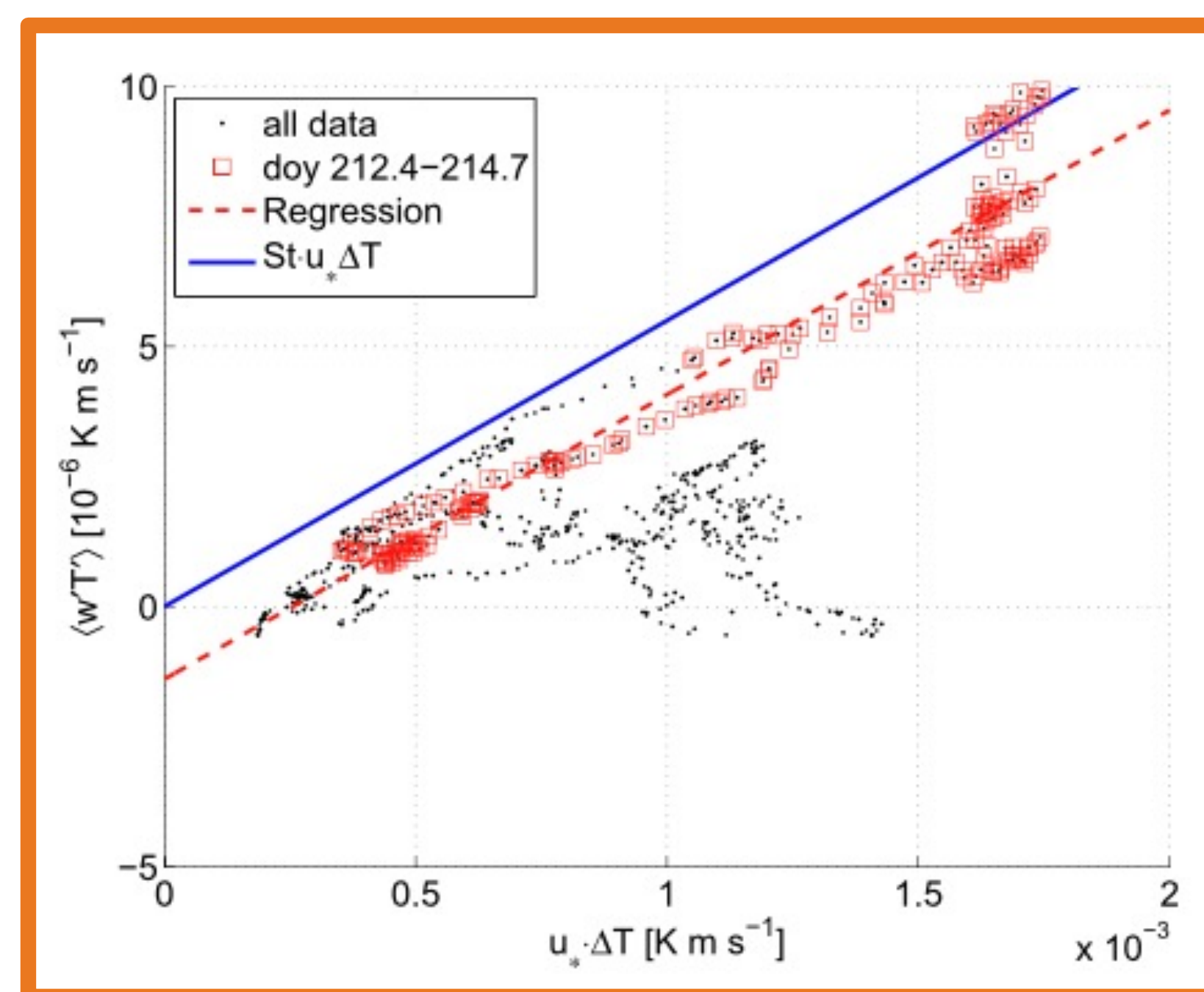
McPhee 1992: turbulent heat flux under sea-ice



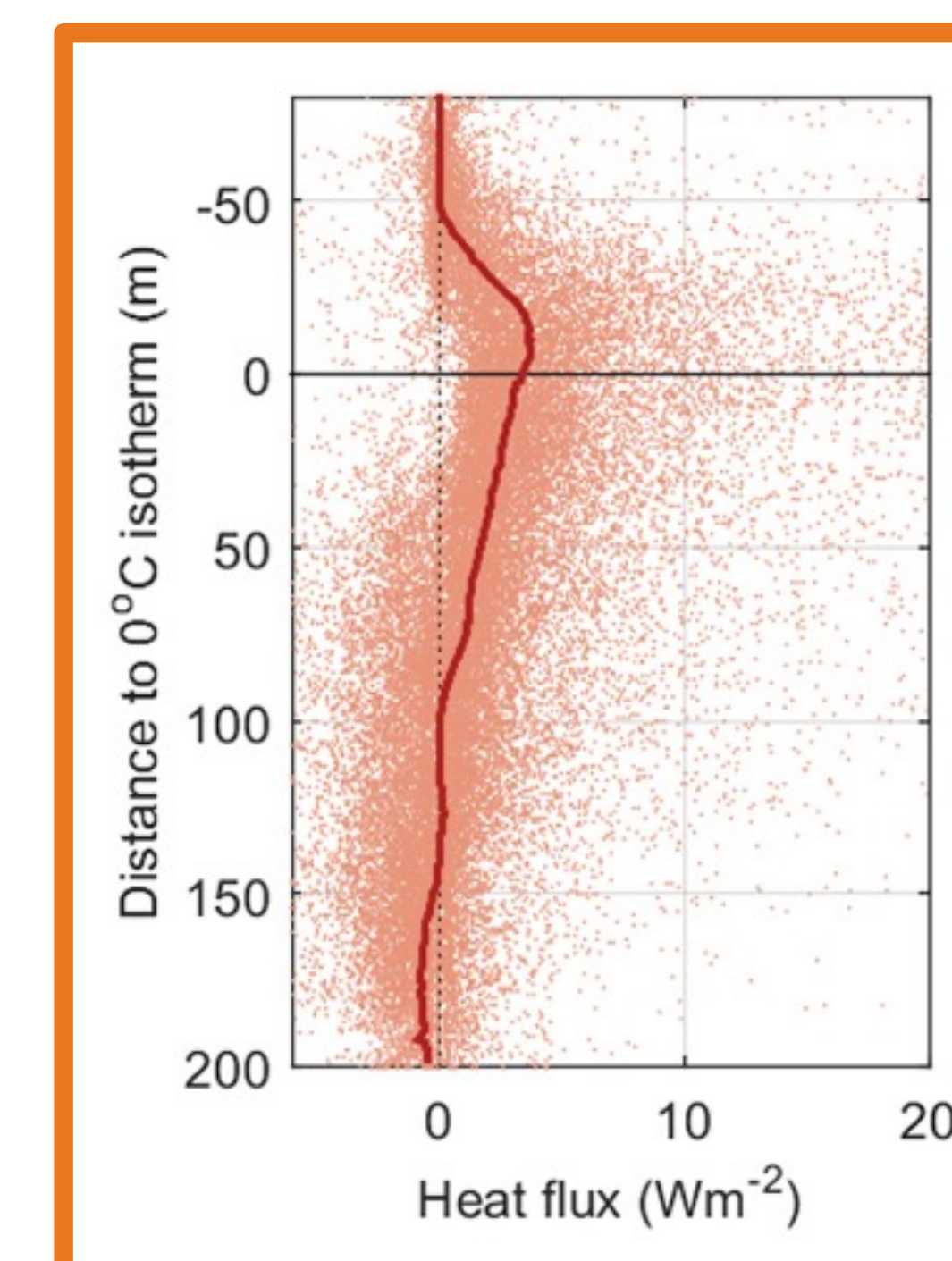
Chanona et al (poster): no significant change in wave dissipation



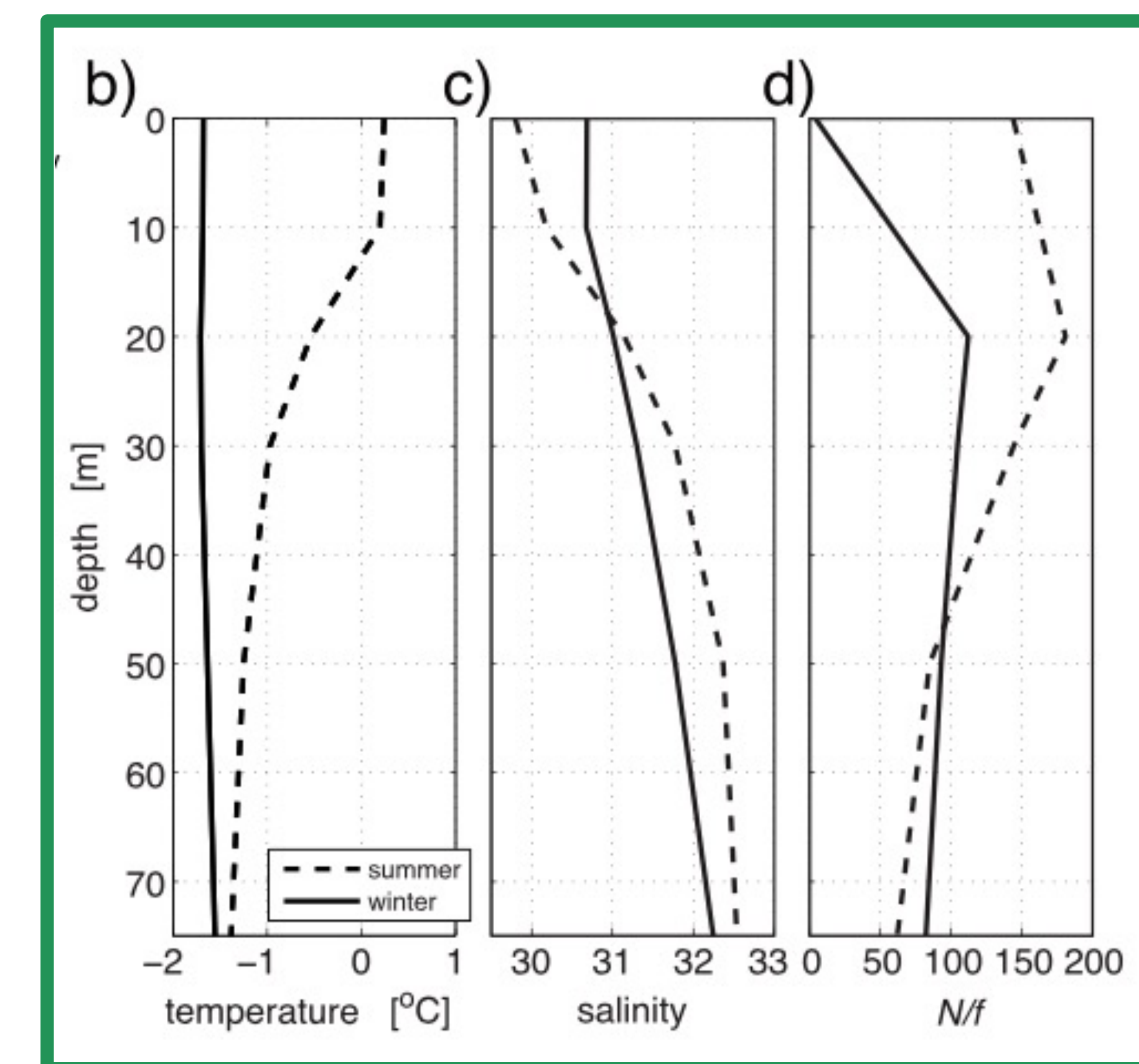
Cole et al 2017: less sea-ice = faster sea-ice/ocean surface velocities



Randelhoff et al 2014: simple down gradient parameterization does not estimate obs heat flux well



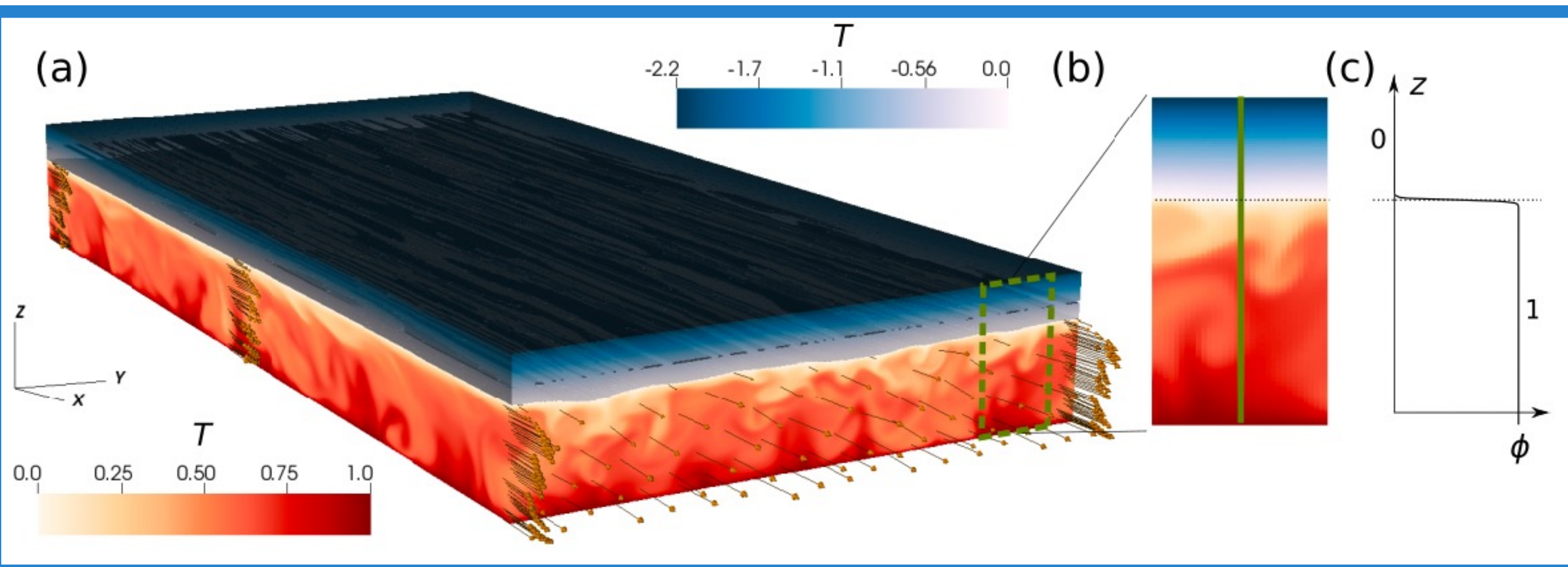
Meyer et al 2017: heat flux under sea-ice, wind doubles heat flux



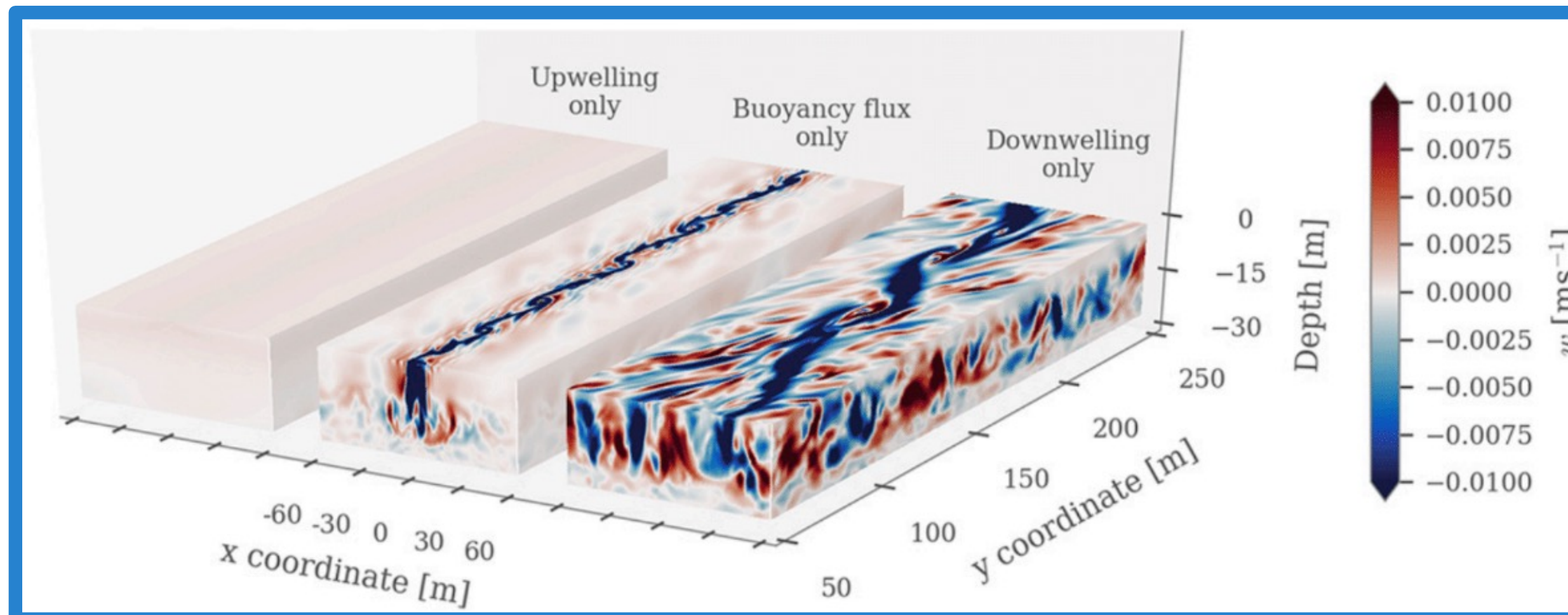
Rainville & Woodgate 2009: increasing ice-free periods allow for more internal wave driven mixing

Under Sea Ice
Ice Free

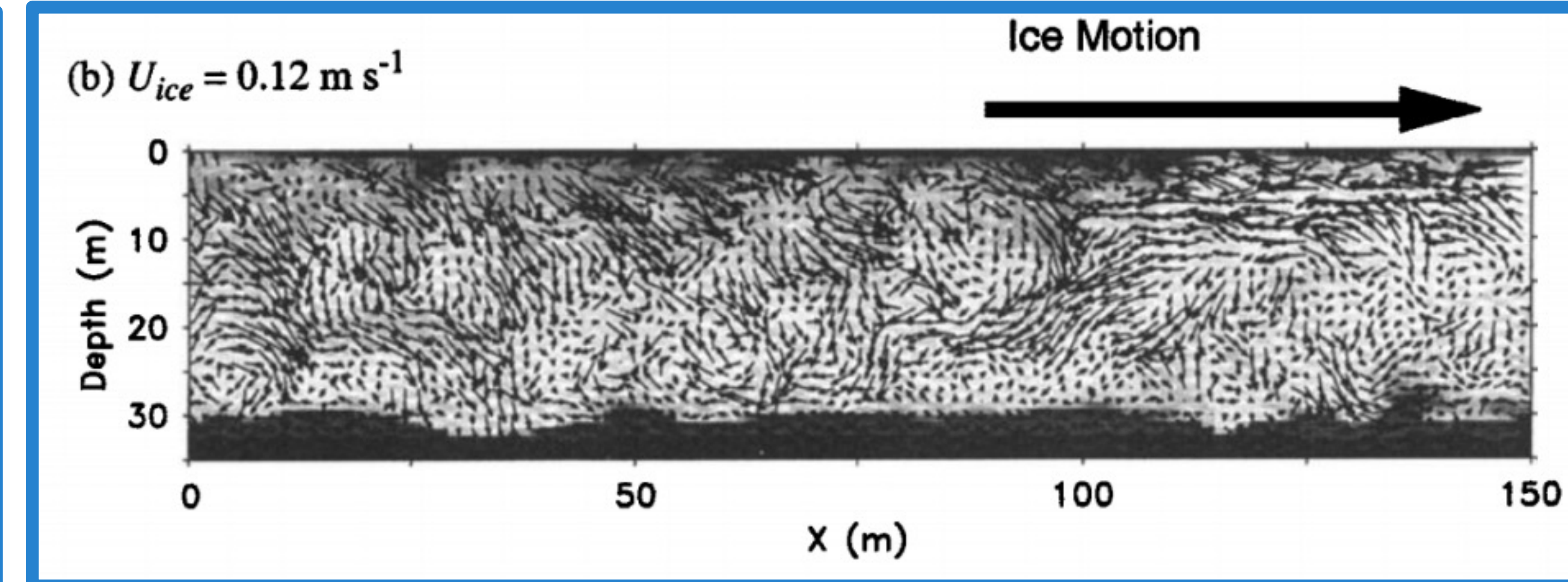
What Do We Know? - Models



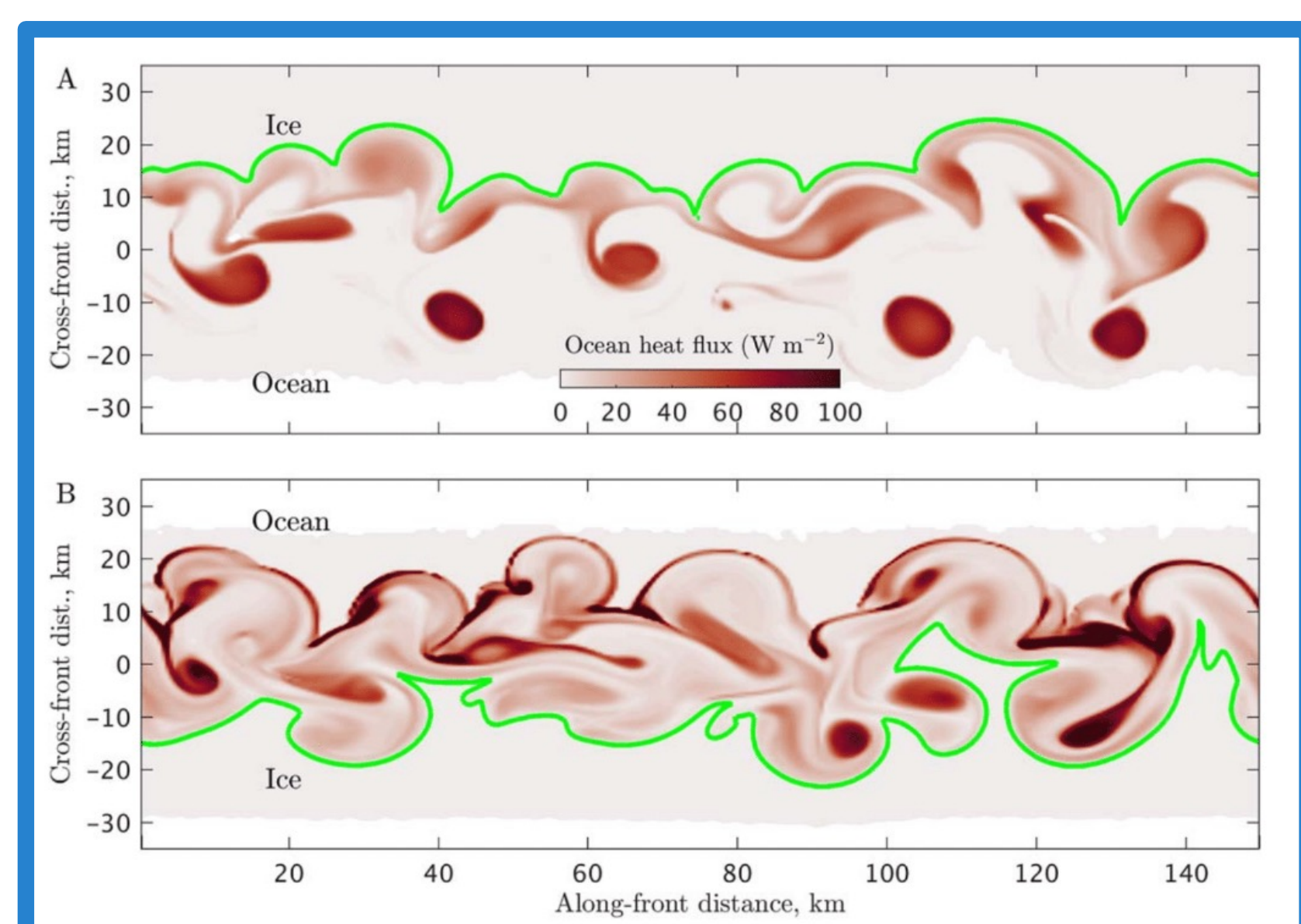
Couston et al 2020: ice-ocean interactions, ice-roughness



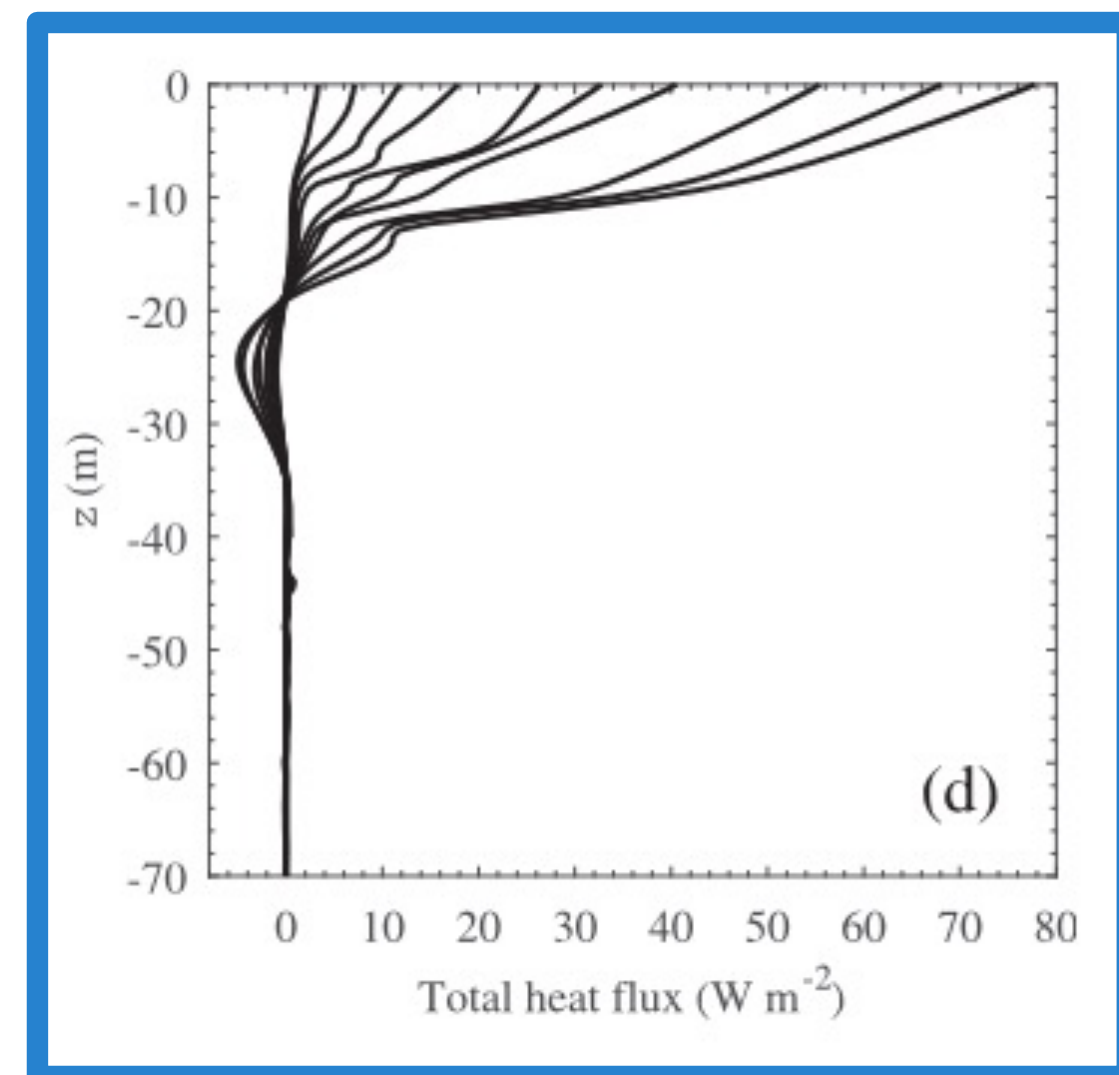
Bourgault et al 2020: LES of sea-ice leads (400 W/m²)



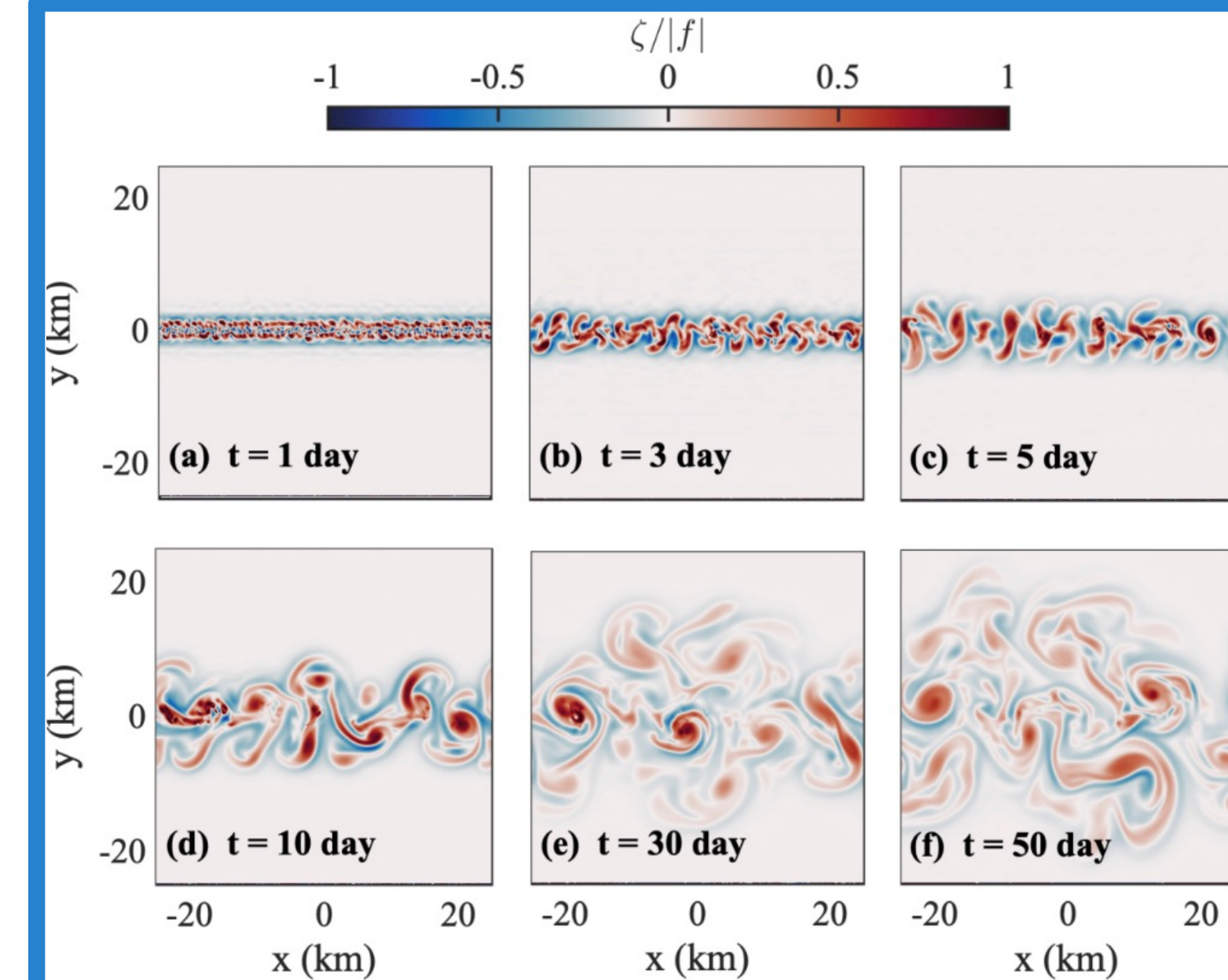
Skyllingstad & Denbo 2001: LES of sea-ice leads and drift



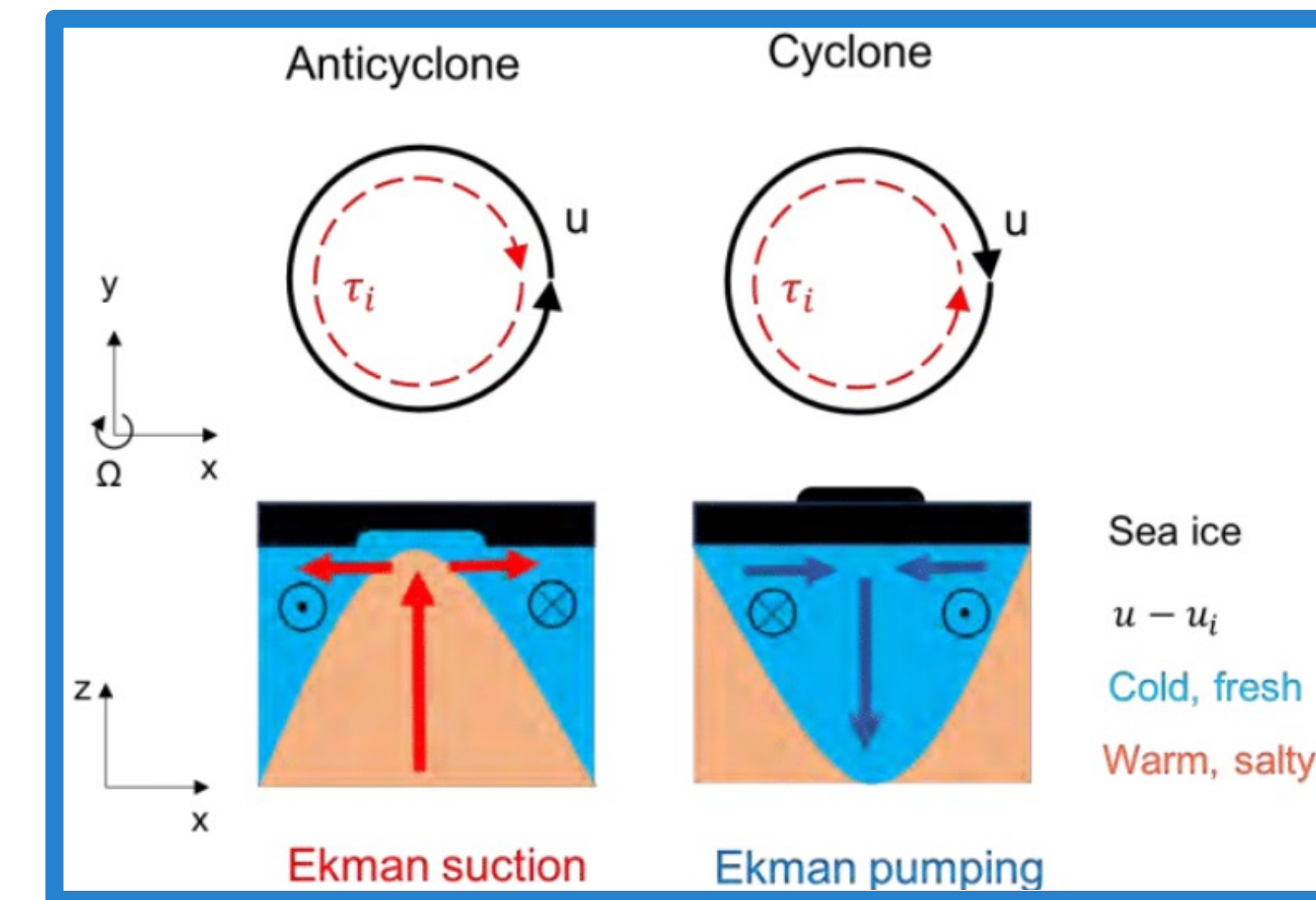
Manucharyan & Thompson 2017



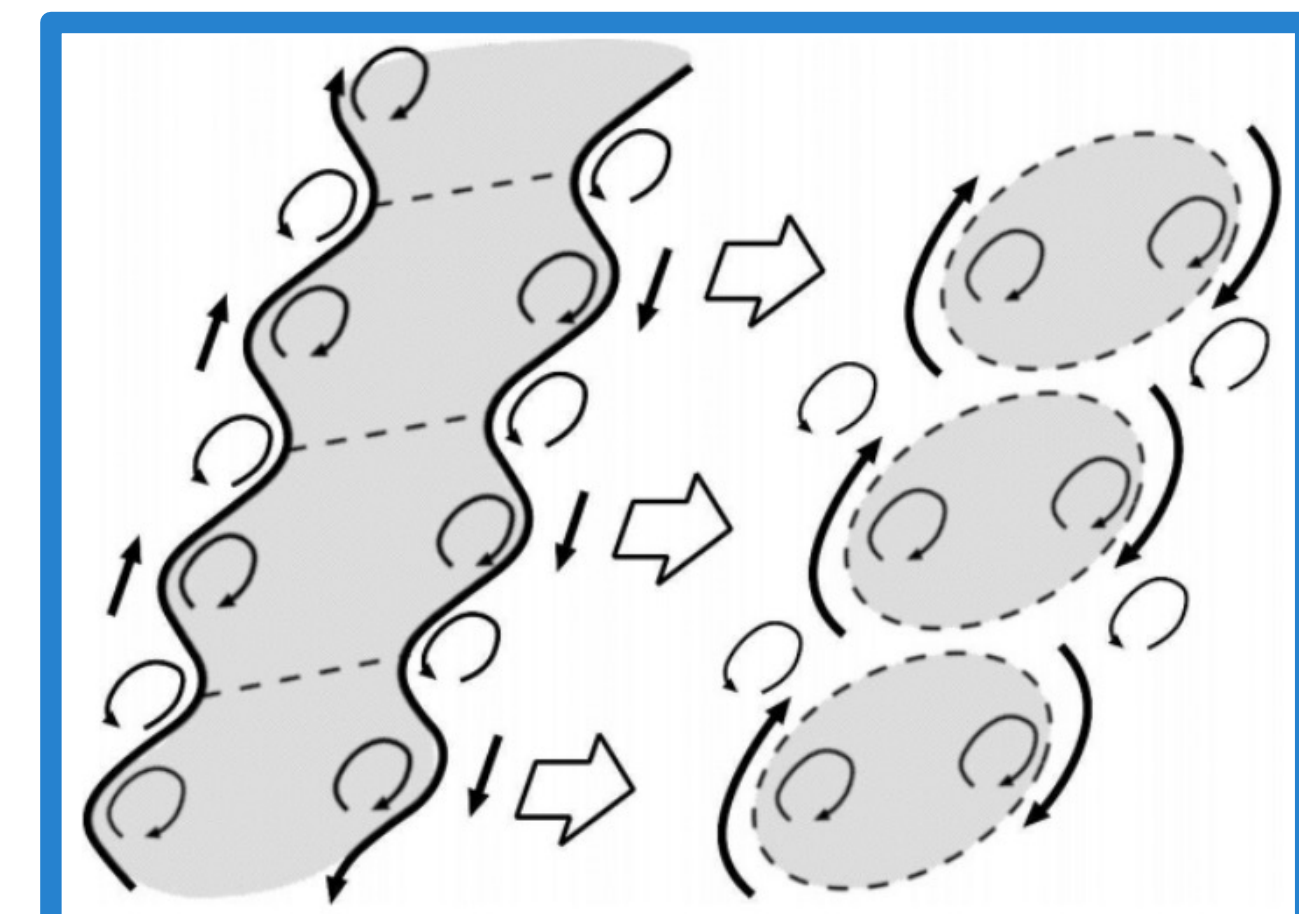
Ramudu et al 2017: LES of under sea-ice heat entrainment



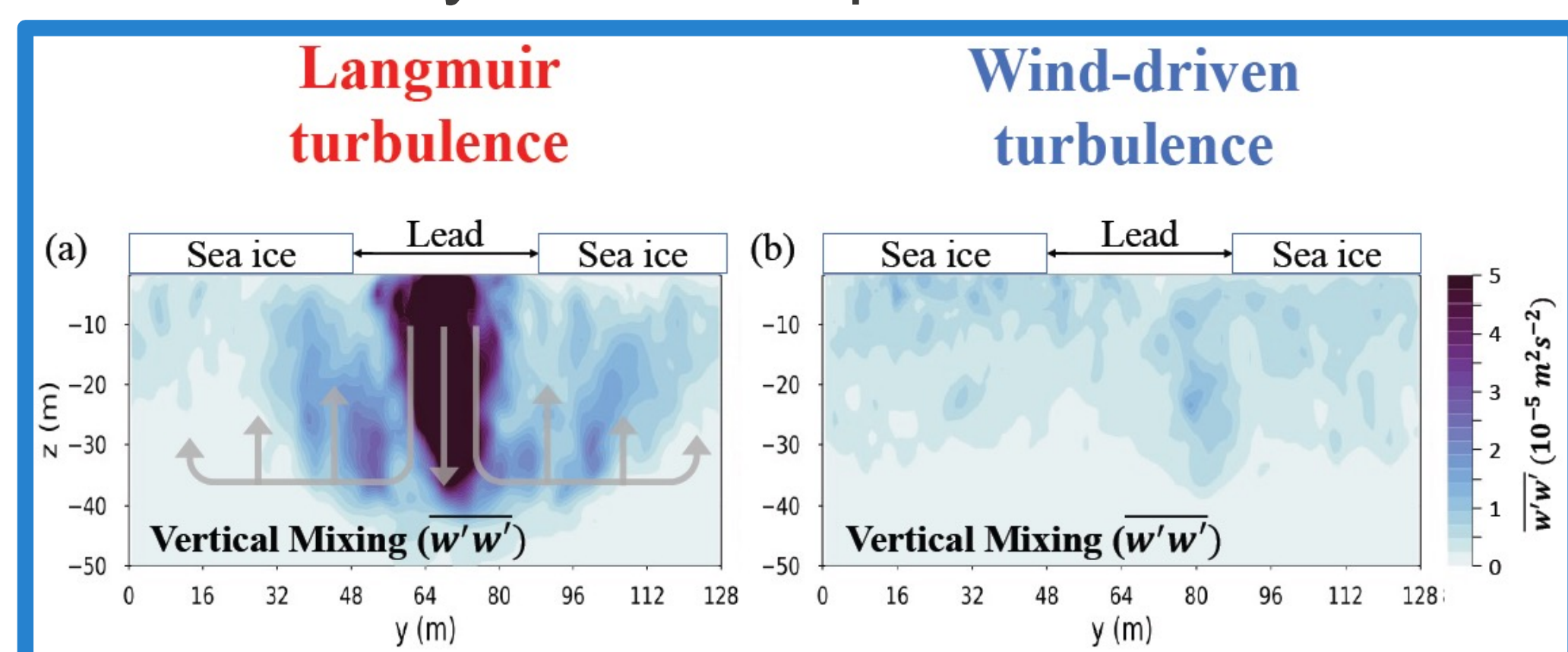
Cohan et al 2021: submesoscale spreading of salt anomalies



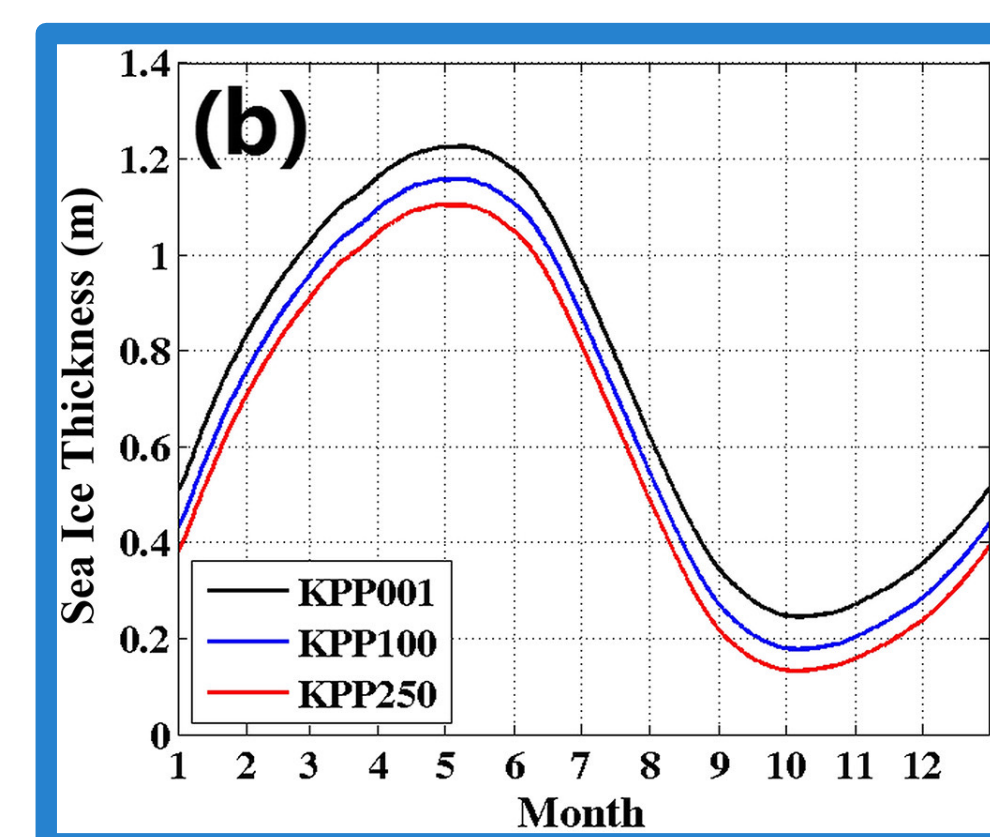
Gupta et al 2020: Mesoscale eddy-ice pumping



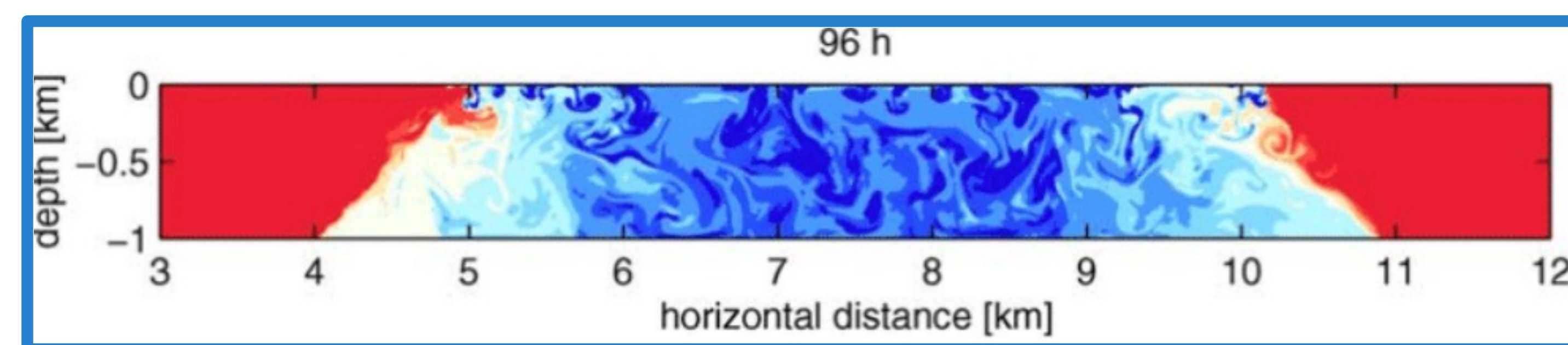
Matsumura & Hasumi 2006



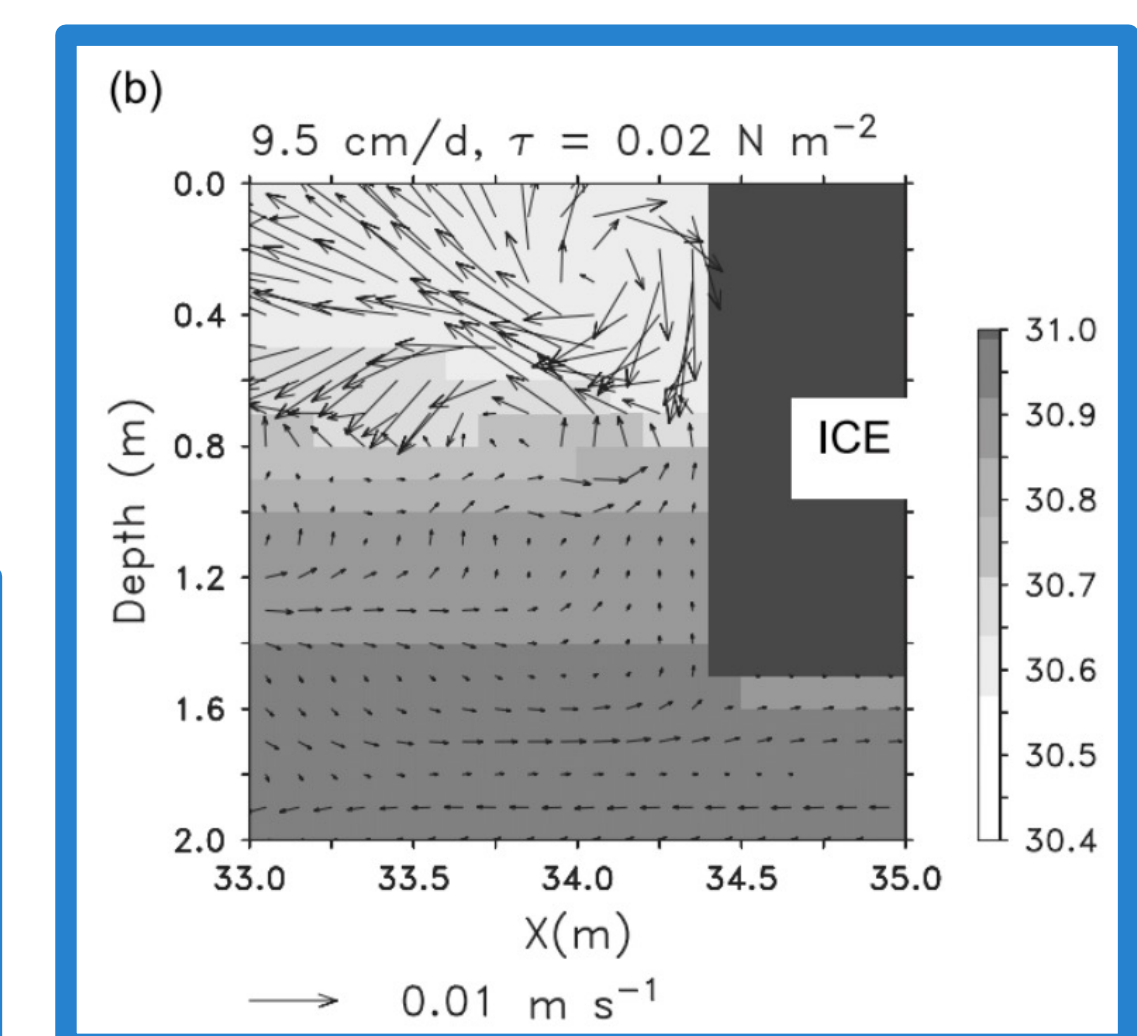
Lee & Pearson OSM 2022: surface waves increase vert. mixing



Liang & Losch 2018: increasing vert. mixing



Losch et al 2006: biases due to heterogeneous surface fluxes



Skyllingstad et al 2005: winds with sea ice leads

Methods – Large Eddy Simulations

Set-up

Constant surface forcing applied for 5 days to Arctic-like initial conditions (MLD[t=0] ~ 25 m), periodic in horizontal

Domain

- Physical: 128m x 128m x -150m
- Grid: 256^3
- Resolution: 0.5m x 0.5m x (0.5-0.7m)

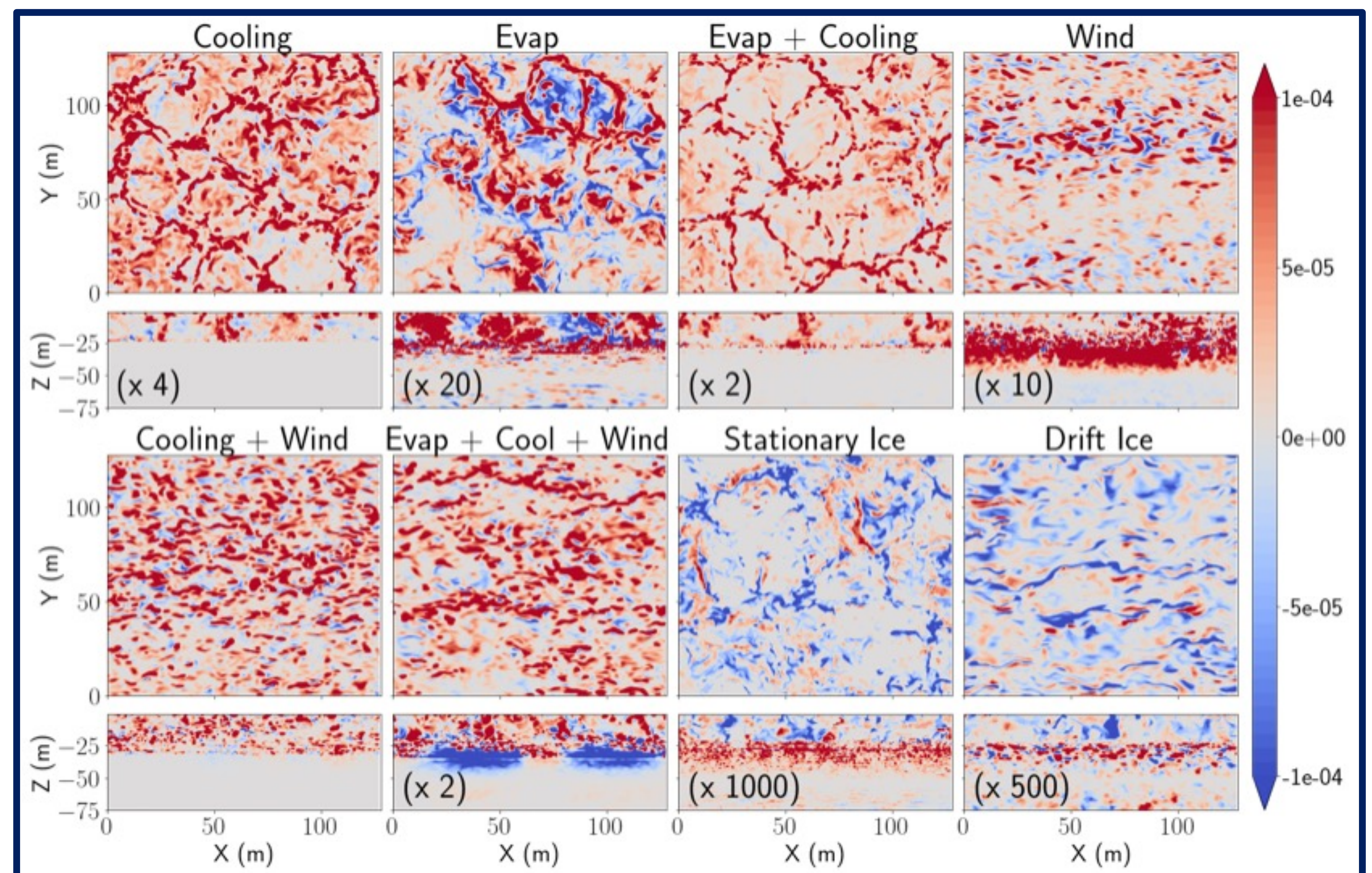
Density

- Non-linear EOF, $f(T,S)$

LES Model

- Finite Difference (Horiz and Vert)
- Third-order RK Time Stepping
- 1.5 Order Closure (Deardorff 1980)

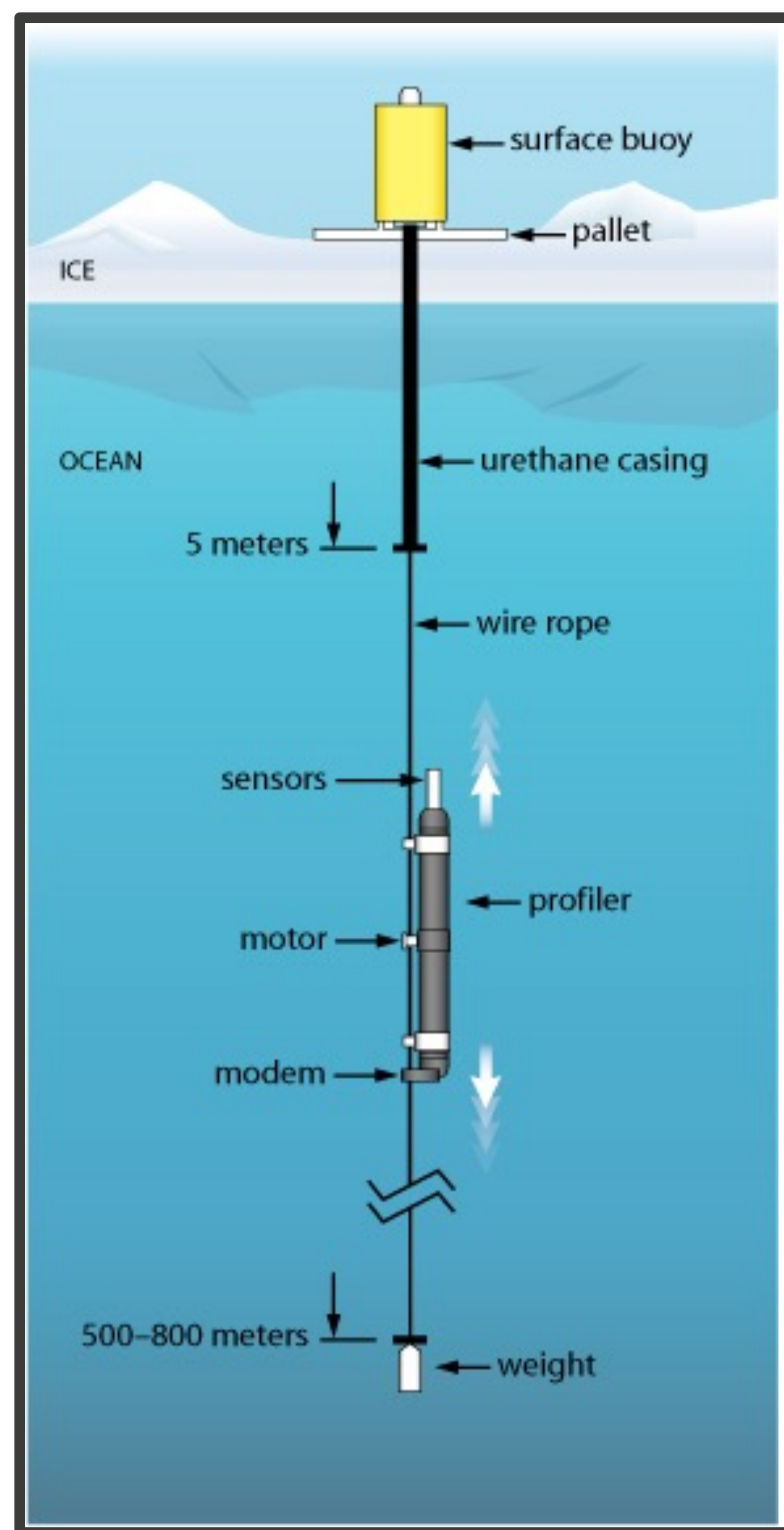
Parallelized Large-Eddy Simulation Model (PALM)



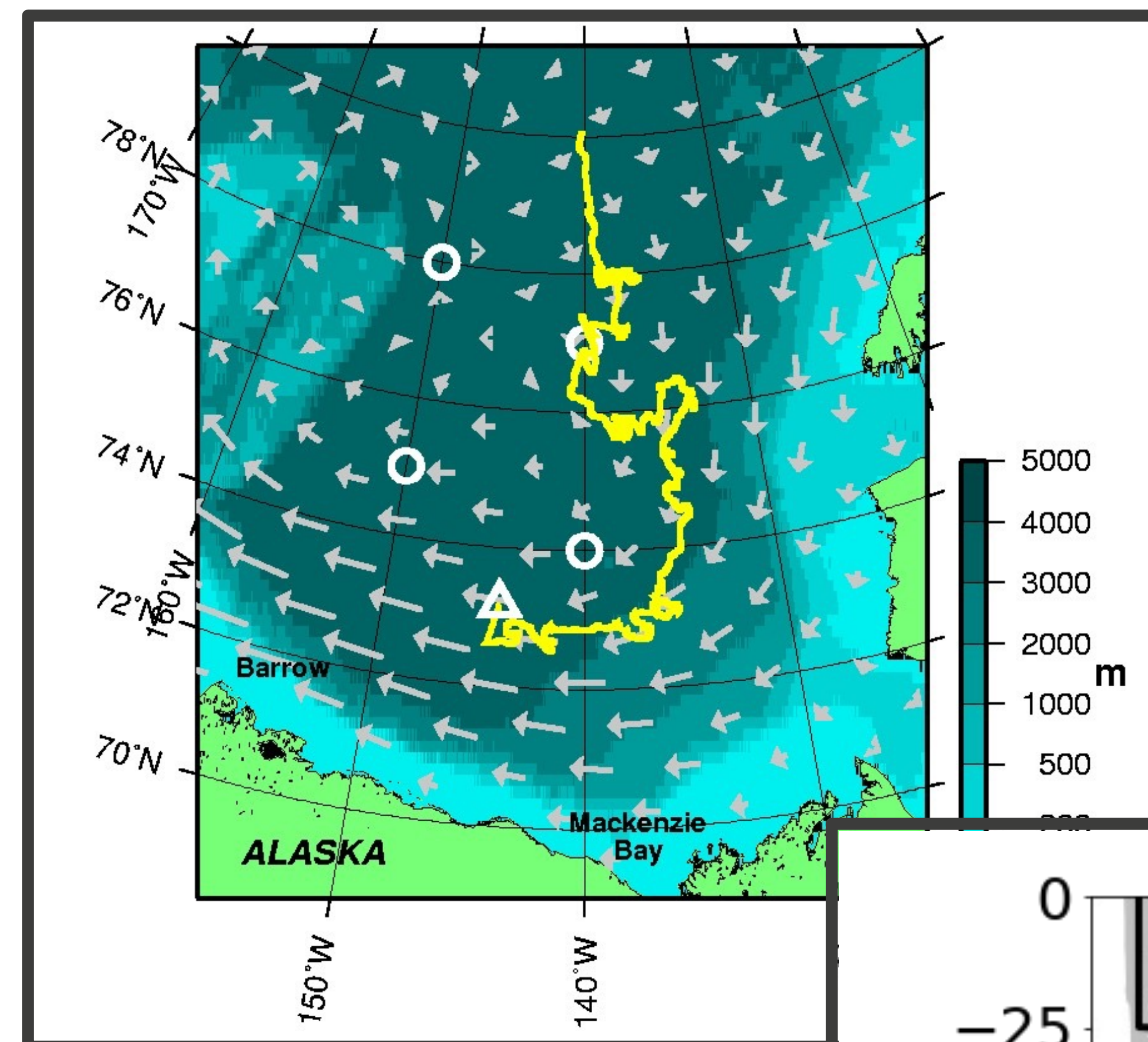
Horiz. And Vert. Slices of Heat Flux

Initial Conditions - Beaufort Sea/Alaskan North Slope

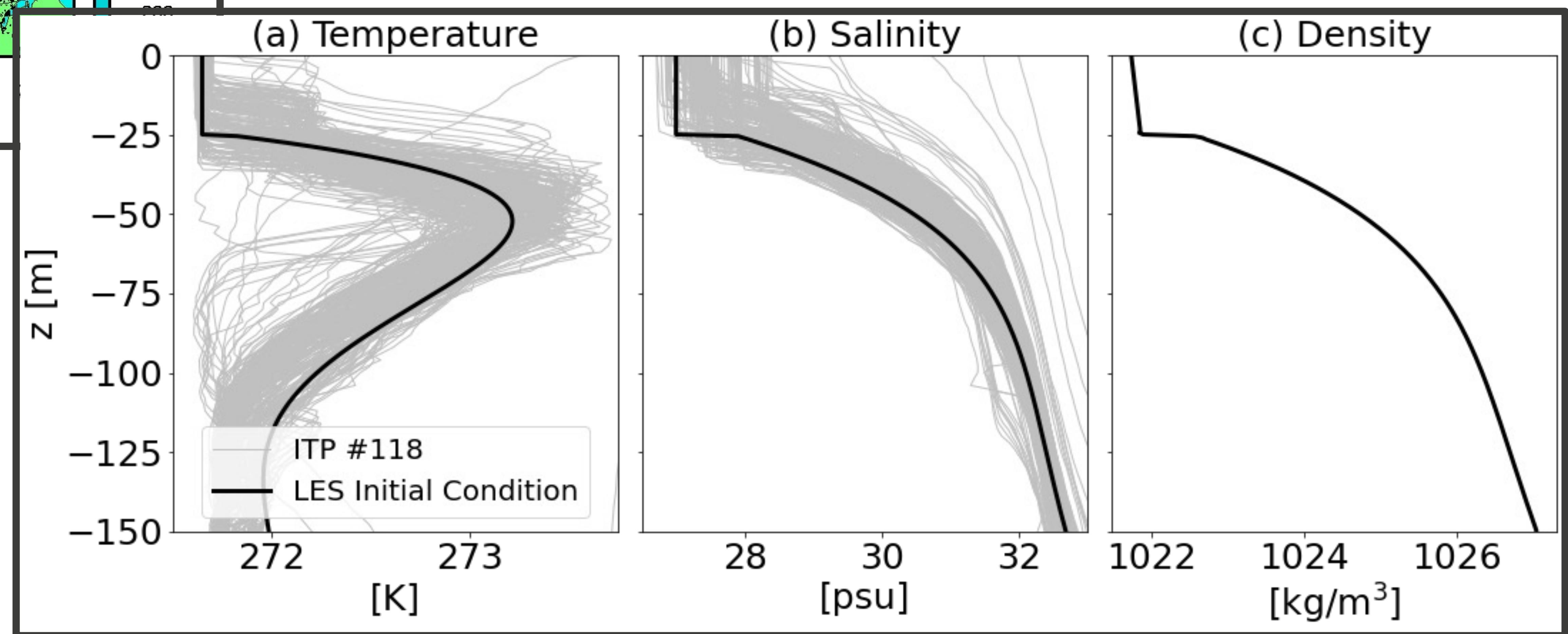
Ice-Tethered Profiler (ITP) Schematic



ITP #118 Drift Track

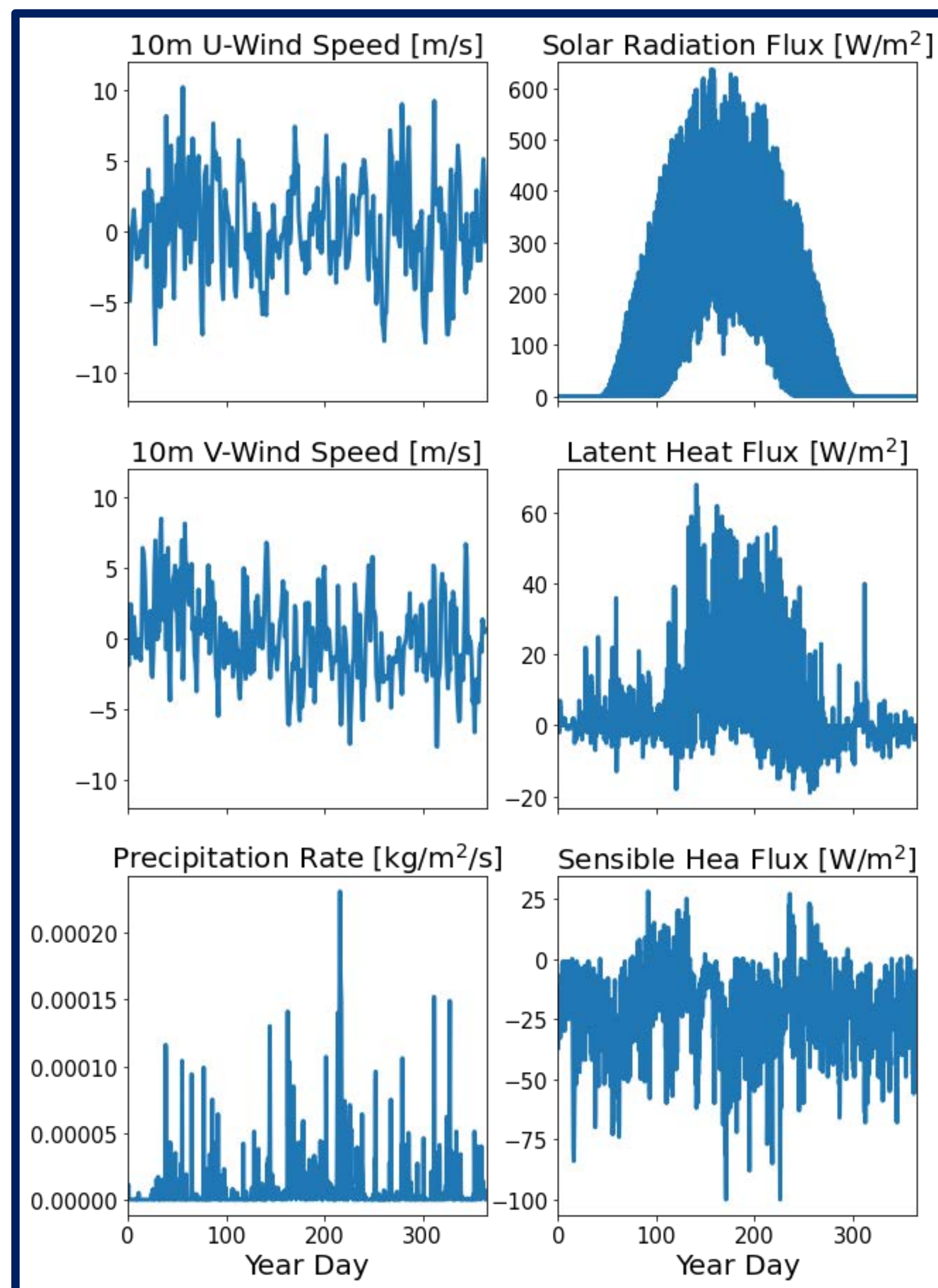


LES Initial Conditions From Ice-Tethered Profilers

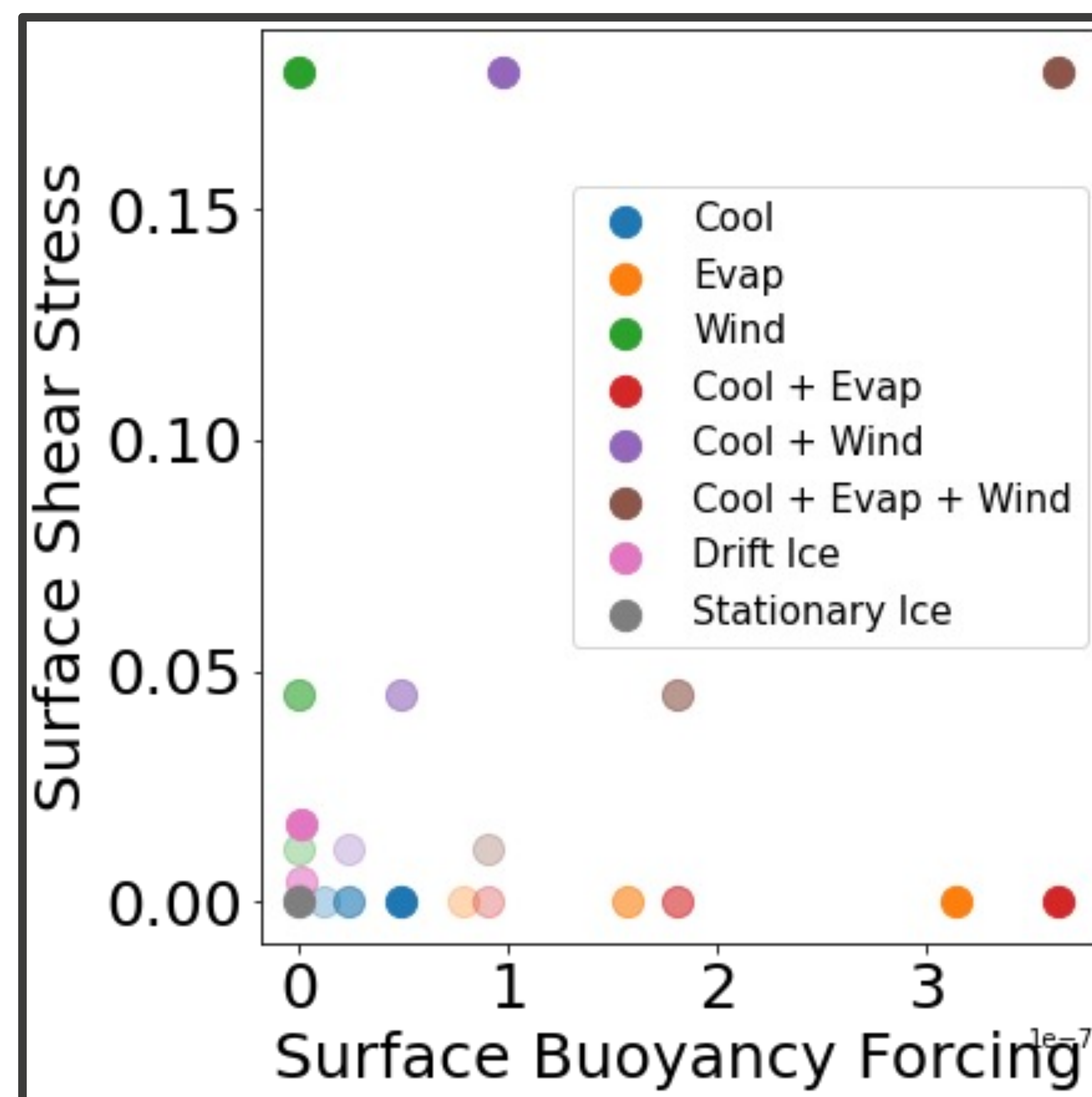


Forcing Conditions – Beaufort Sea/Alaskan North Slope

NCEP Reanalysis



Simulation Phase Space



LES Forcing From NCEP Reanalysis

- Surface Cooling
- Wind
- Surface Evaporation
- Land-Fast Ice[†]
- Drifting Sea-Ice^{†‡}

[†]Melt parameterized according to McPhee et al 1987

[‡]Drift speed determined from ITP #118

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Cool3	100	0.0	0.0
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Evap2	0.0	-2×10^{-5}	0.0
Evap3	0.0	-4×10^{-5}	0.0
Wind1	0.0	0.0	3
Wind2	0.0	0.0	6
Wind3	0.0	0.0	12

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LA-UR-20-21004

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SID3	McPhee	McPhee	0.30

Name	Heat Flux Q_H [W m ⁻²]	Salinity Flux Q_S [kg m ⁻² s ⁻¹]	Wind Vel., Ice Vel. U_{10}, U_{ice} [m s ⁻¹]
Cool1	25	0.0	0.0
Cool2	50	0.0	0.0
Cool3	100	0.0	0.0
Evap1	0.0	-1×10^{-5}	0.0
Evap2	0.0	-2×10^{-5}	0.0
Evap3	0.0	-4×10^{-5}	0.0
Wind1	0.0	0.0	3
Wind2	0.0	0.0	6
Wind3	0.0	0.0	12

Single-Forcing (SF) Cases

EC1	25	-1×10^{-5}	0.0
EC2	50	-2×10^{-5}	0.0
EC3	100	-4×10^{-5}	0.0
CW1	50	0.0	3
CW2	100	0.0	6
CW3	200	0.0	12
ECW1	25	-1×10^{-5}	3
ECW2	50	-2×10^{-5}	6
ECW3	100	-4×10^{-5}	12
LFI	McPhee	McPhee	0.0
SID1	McPhee	McPhee	0.05
SID2	McPhee	McPhee	0.15
SID3	McPhee	McPhee	0.30

Name	Heat Flux Q_H [W m ⁻²]	Salinity Flux Q_S [kg m ⁻² s ⁻¹]	Wind Vel., Ice Vel. U_{10}, U_{ice} [m s ⁻¹]
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Evap3	0.0	-4×10^{-5}	0.0
Wind1	0.0	0.0	3
Wind2	0.0	0.0	6
Wind3	0.0	0.0	12

Single-Forcing (SF) Cases

Multi-Forcing (MF) Cases

EC1	25	-1×10^{-5}	0.0
EC2	50	-2×10^{-5}	0.0
EC3	100	-4×10^{-5}	0.0
CW1	50	0.0	3
CW2	100	0.0	6
CW3	200	0.0	12
ECW1	25	-1×10^{-5}	3
ECW2	50	-2×10^{-5}	6
ECW3	100	-4×10^{-5}	12
LFI	McPhee	McPhee	0.0
SID1	McPhee	McPhee	0.05
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Evap1	0.0	-1×10^{-5}	0.0
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SID1	McPhee	McPhee	0.05
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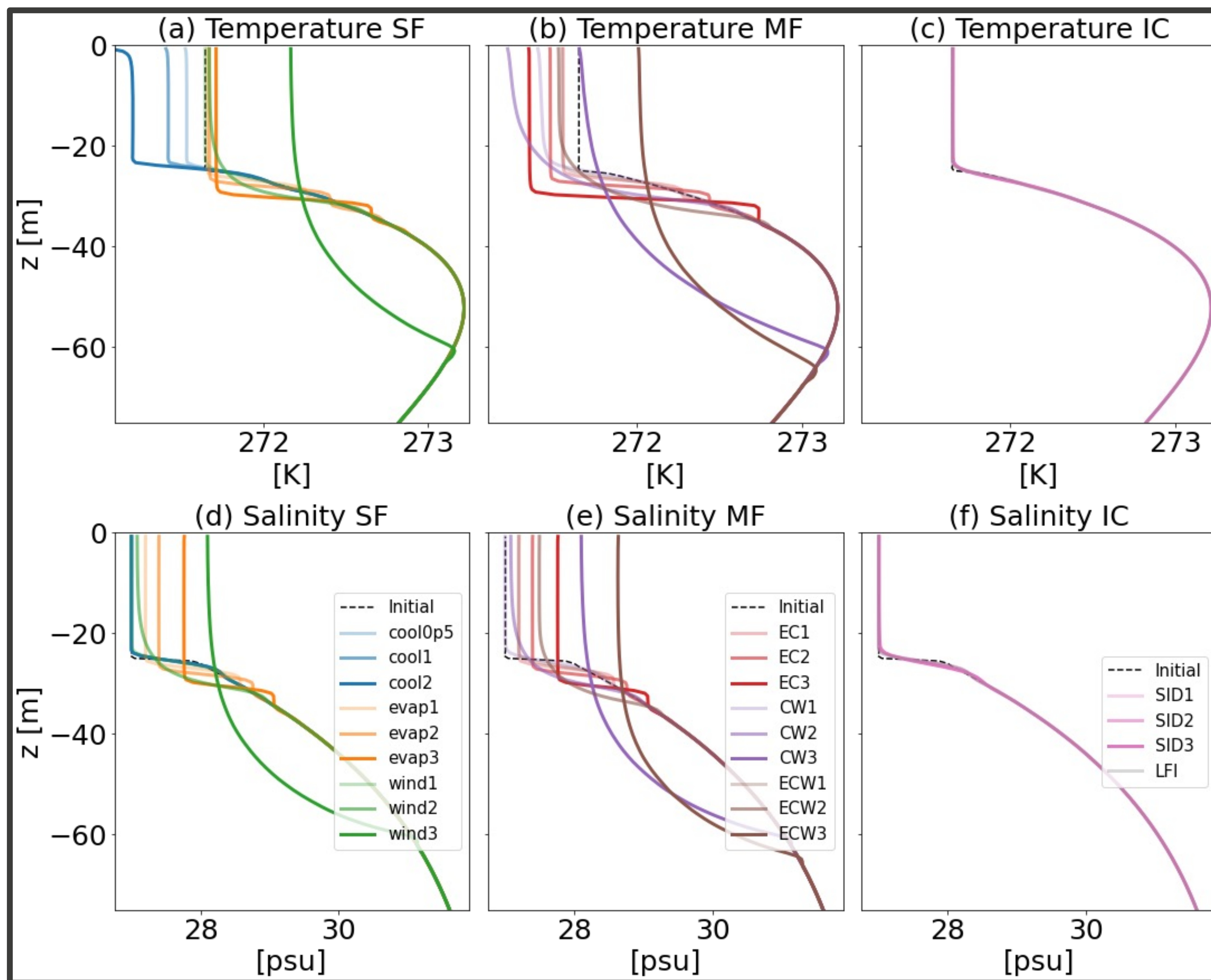
Single-Forcing (SF) Cases

Multi-Forcing (MF) Cases

EC1	25	-1×10^{-5}	0.0
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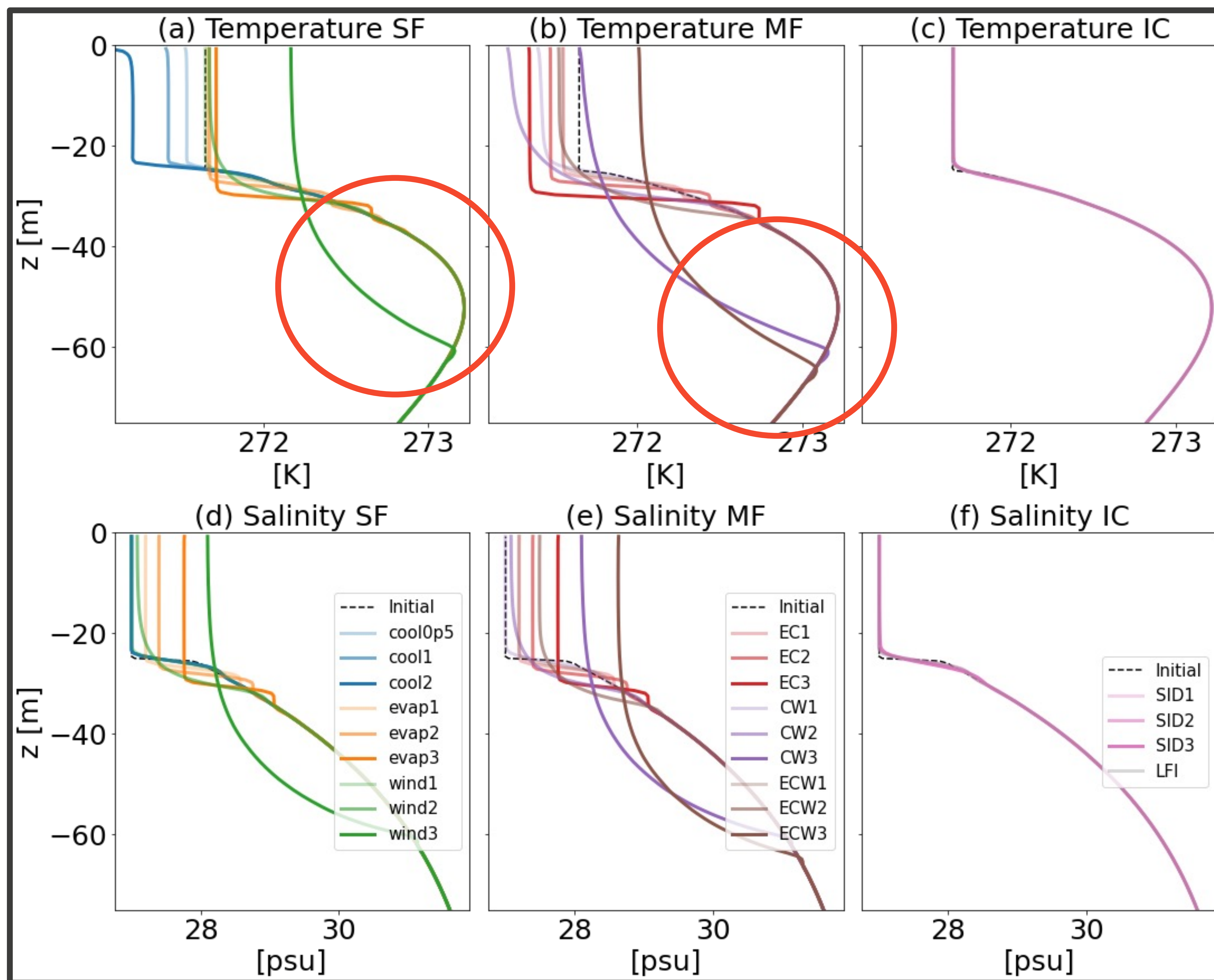
Ice-Covered (IC) Cases

Results - Mean Profiles



Temperature and Salinity on Day 5

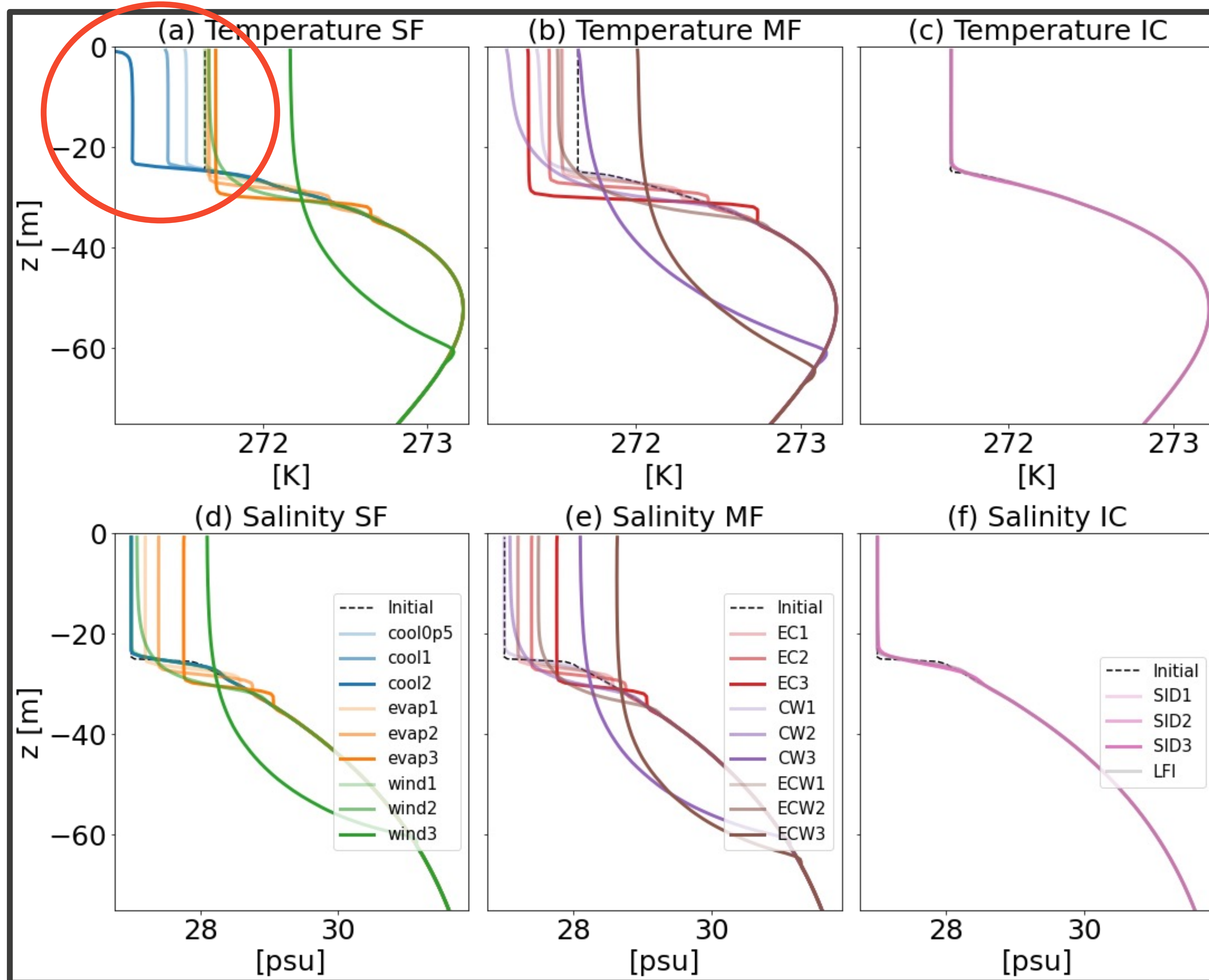
Results - Mean Profiles



Temperature and Salinity on Day 5

Without ice to act as a buffer, wind forcing erodes stratification profile quickly (evaporation plays a roll too)

Results - Mean Profiles

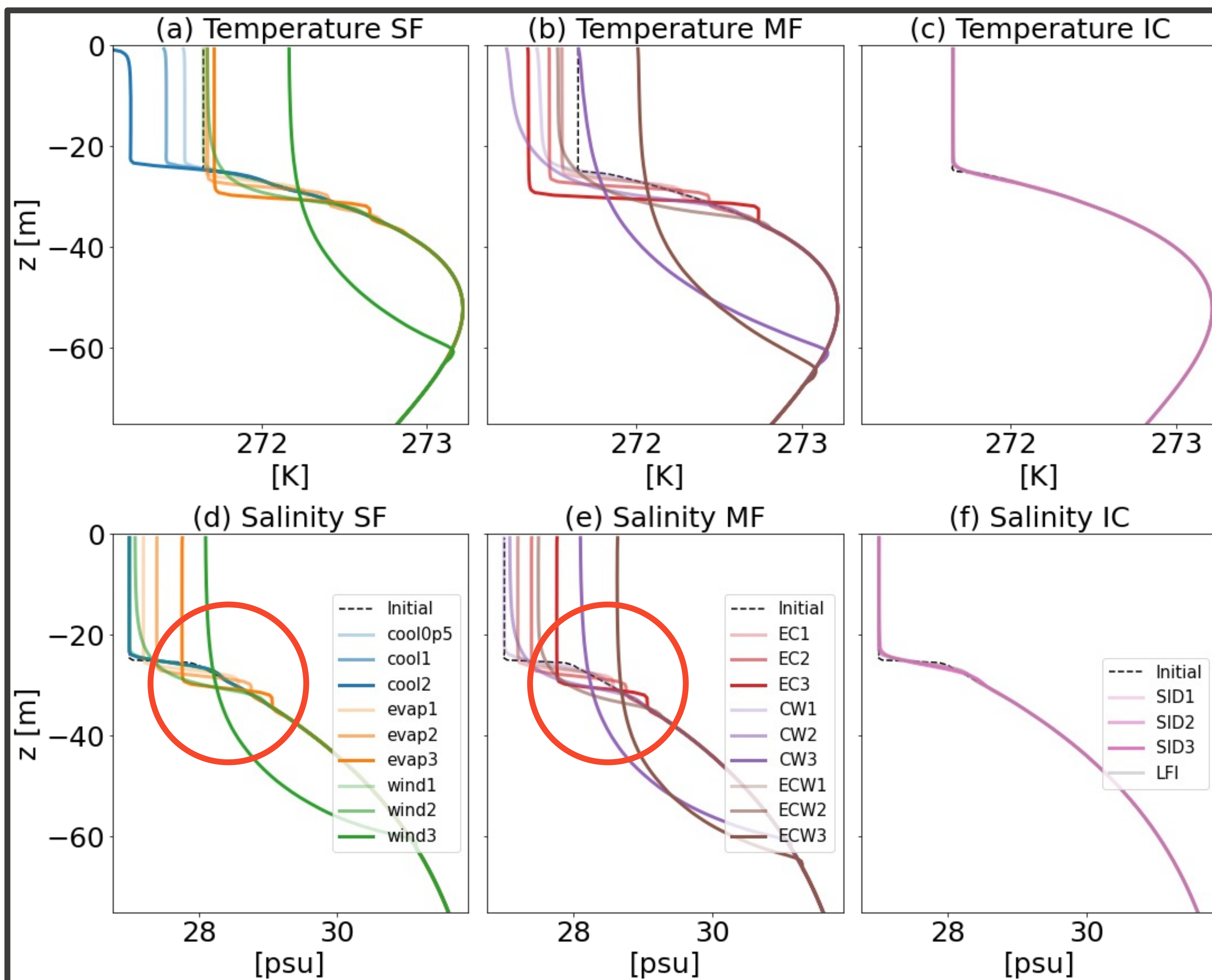


Temperature and Salinity on Day 5

Without ice to act as a buffer, wind forcing erodes stratification profile quickly (evaporation plays a roll too)

Salinity, not temperature, dictates maintenance or erosion of stratification profile
(ie. heat driven convection is not a dominant form of mixing)

Results - Mean Profiles



Temperature and Salinity on Day 5

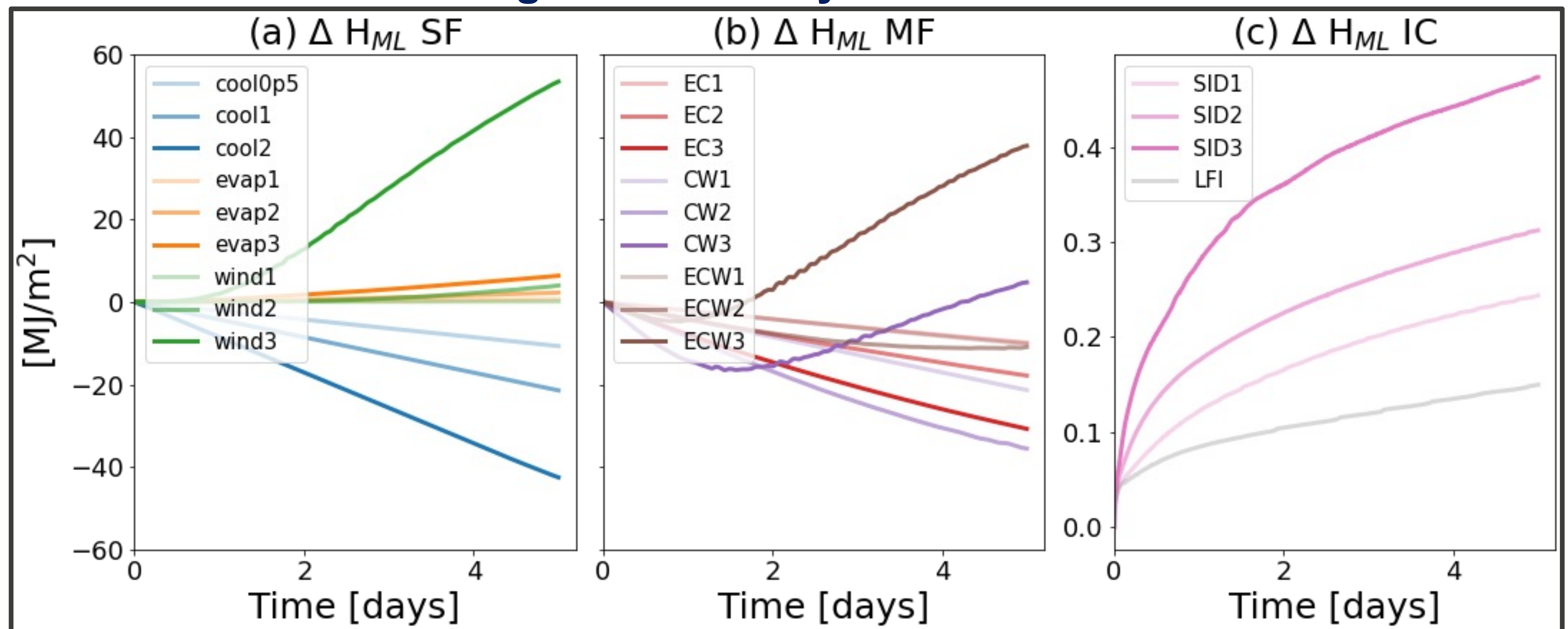
Without ice to act as a buffer, wind forcing erodes stratification profile quickly (evaporation plays a roll too)

Salinity, not temperature, dictates maintenance or erosion of stratification profile
(ie. heat driven convection is not a dominant form of mixing)

A build up of salt occurs in evaporative/salinity forced cases

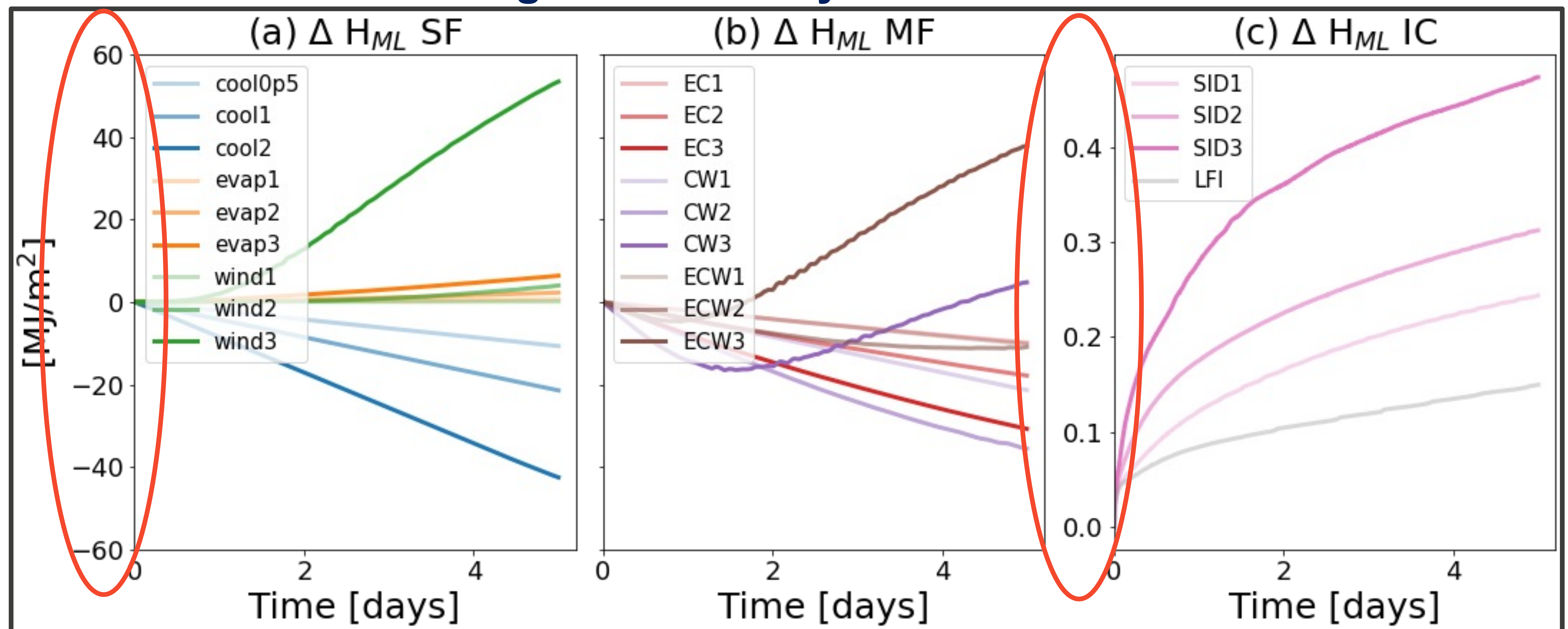
Results - Mixed Layer Depth/Heat Entrainment

Change in Mixed Layer Heat Content



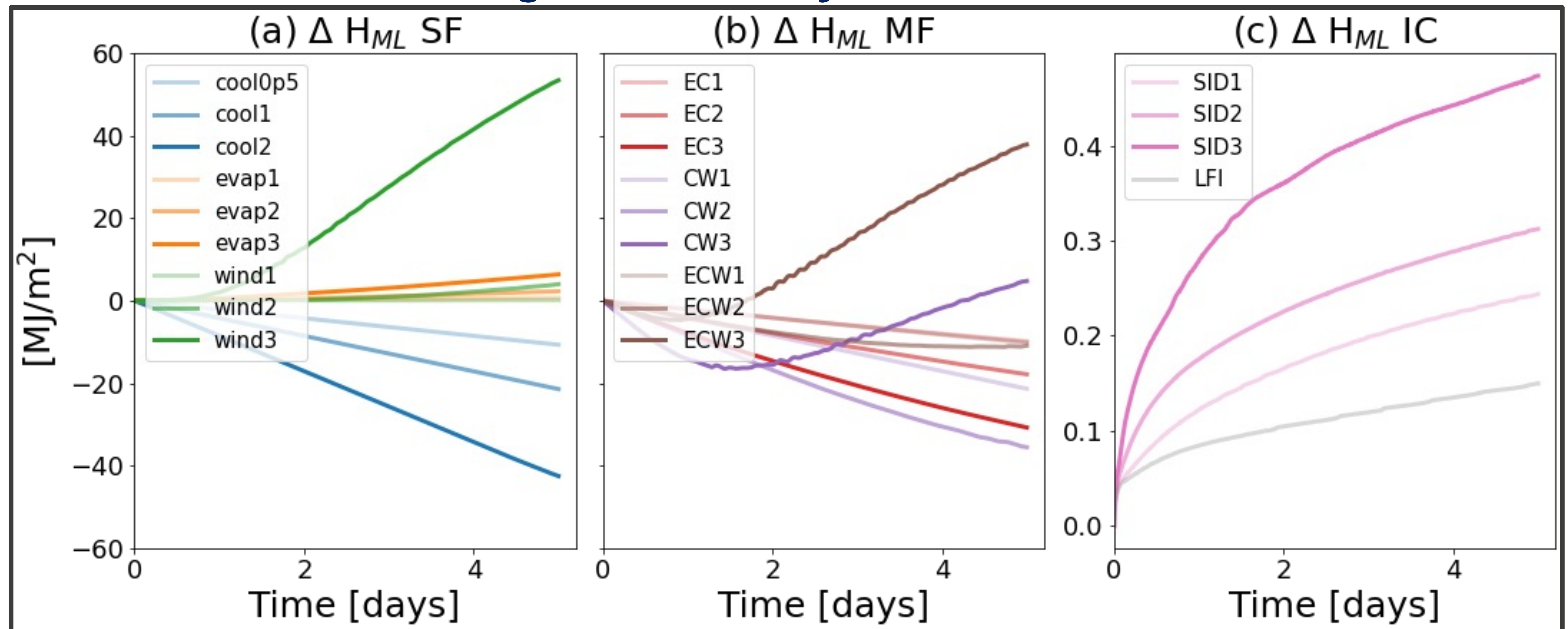
Results - Mixed Layer Depth/Heat Entrainment

Change in Mixed Layer Heat Content



Results - Mixed Layer Depth/Heat Entrainment

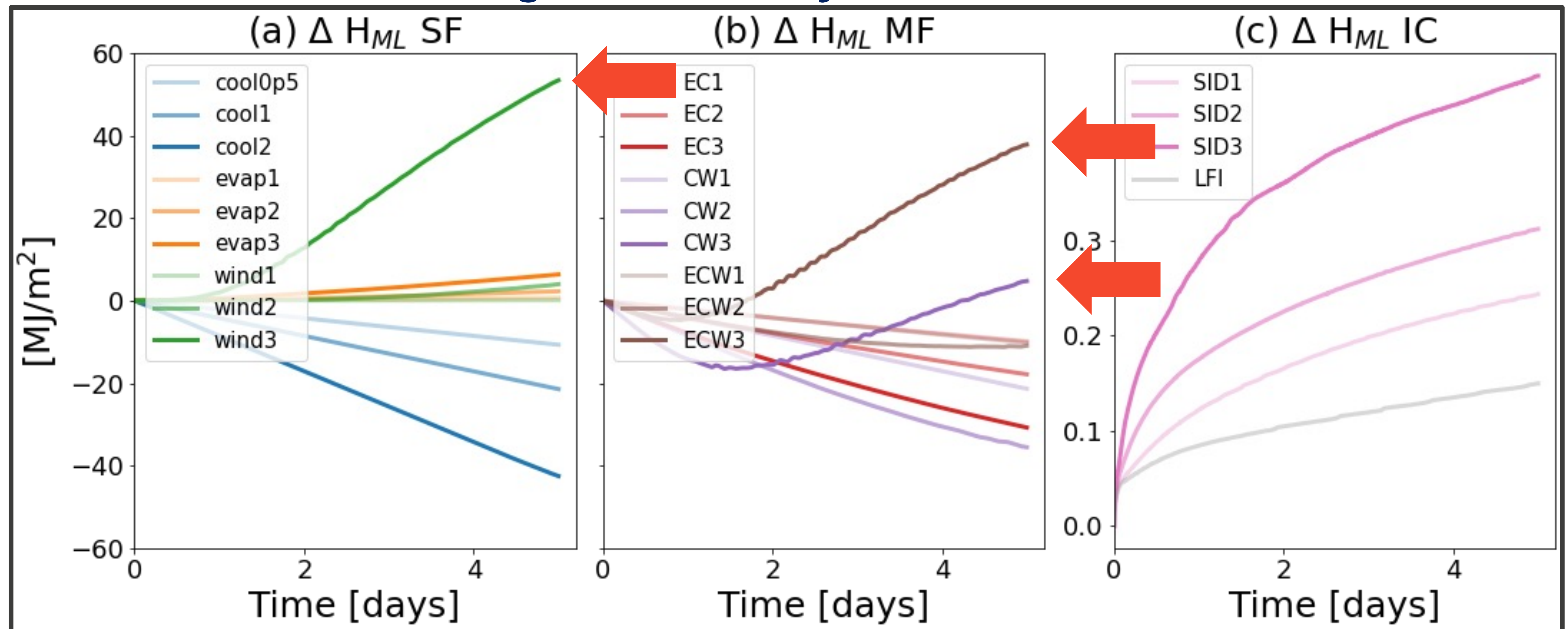
Change in Mixed Layer Heat Content



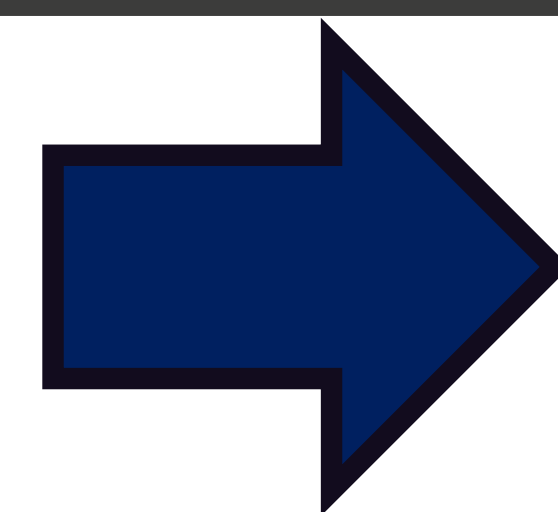
Wind erodes salinity
stratification buffer

Results - Mixed Layer Depth/Heat Entrainment

Change in Mixed Layer Heat Content



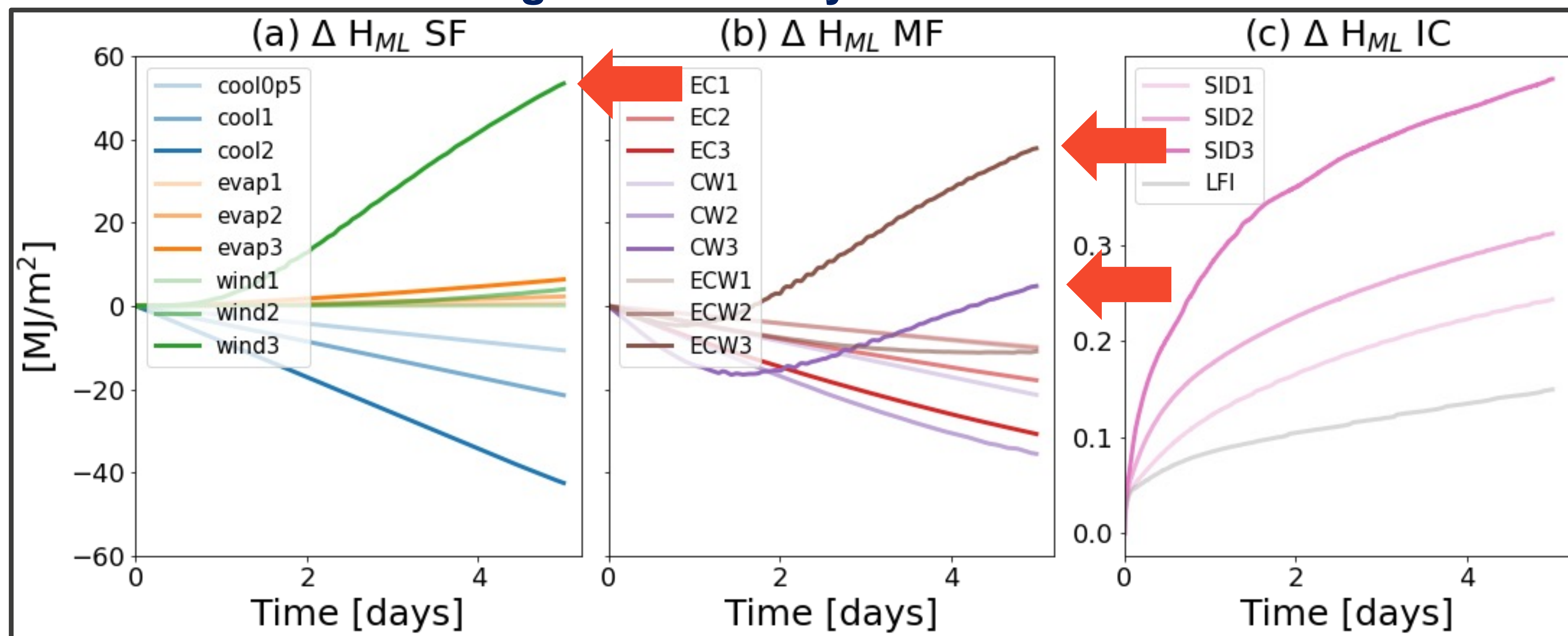
Wind erodes salinity stratification buffer



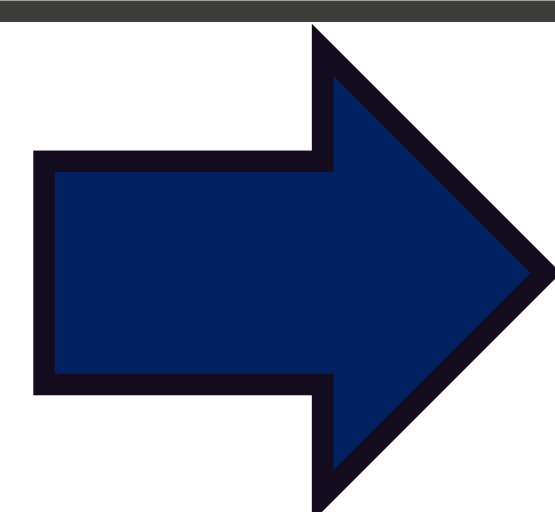
Drives heat into the mixed layer

Results - Mixed Layer Depth/Heat Entrainment

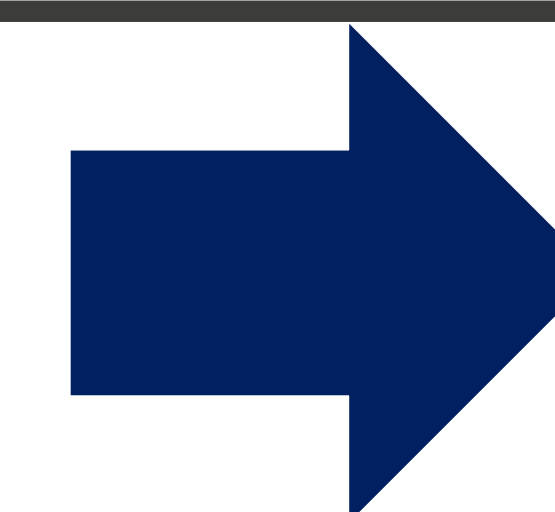
Change in Mixed Layer Heat Content



Wind erodes salinity stratification buffer



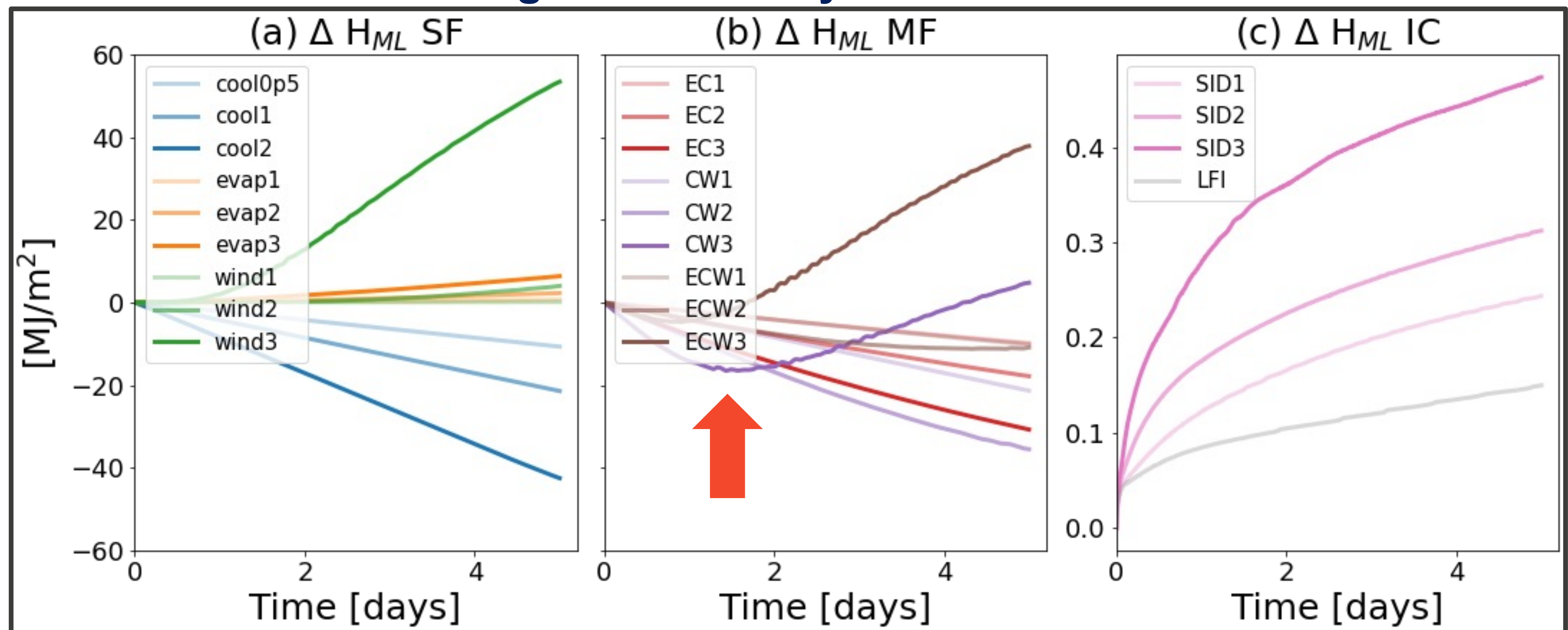
Drives heat into the mixed layer



More sea-ice loss/less sea-ice regrowth

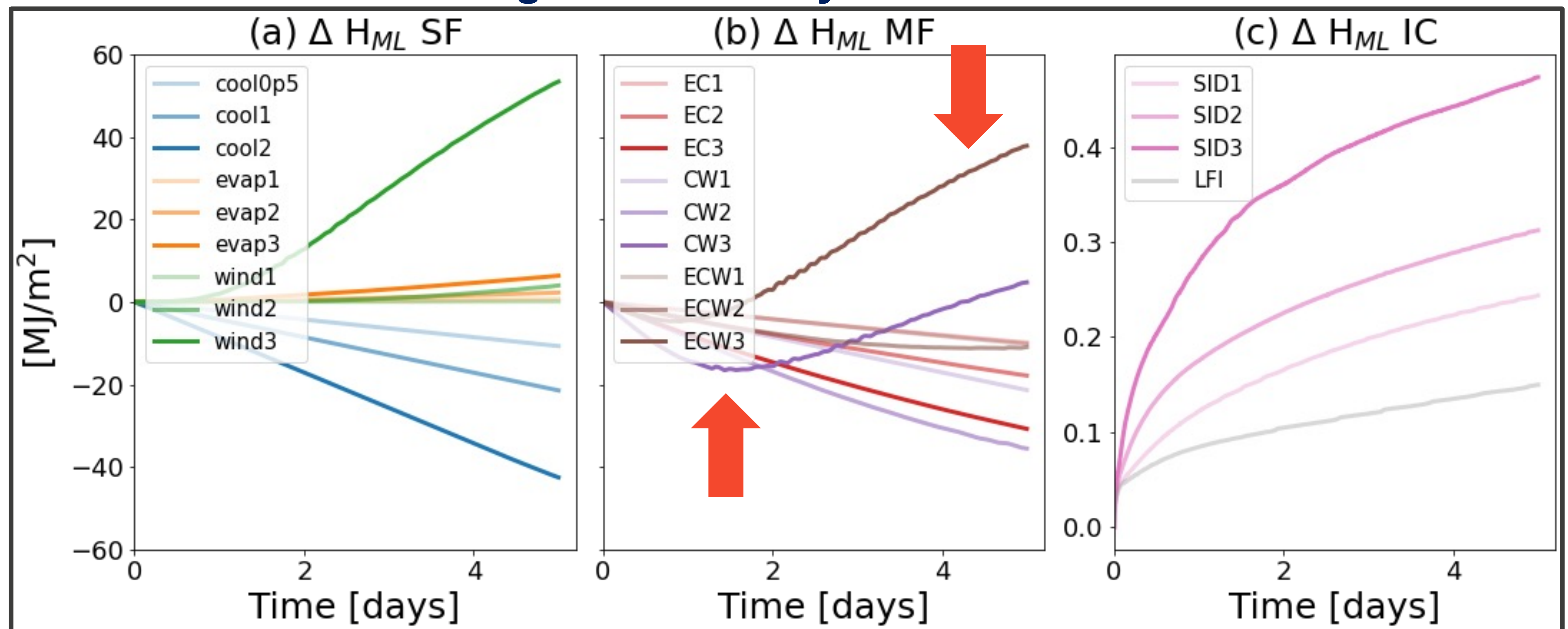
Results - Mixed Layer Depth/Heat Entrainment

Change in Mixed Layer Heat Content

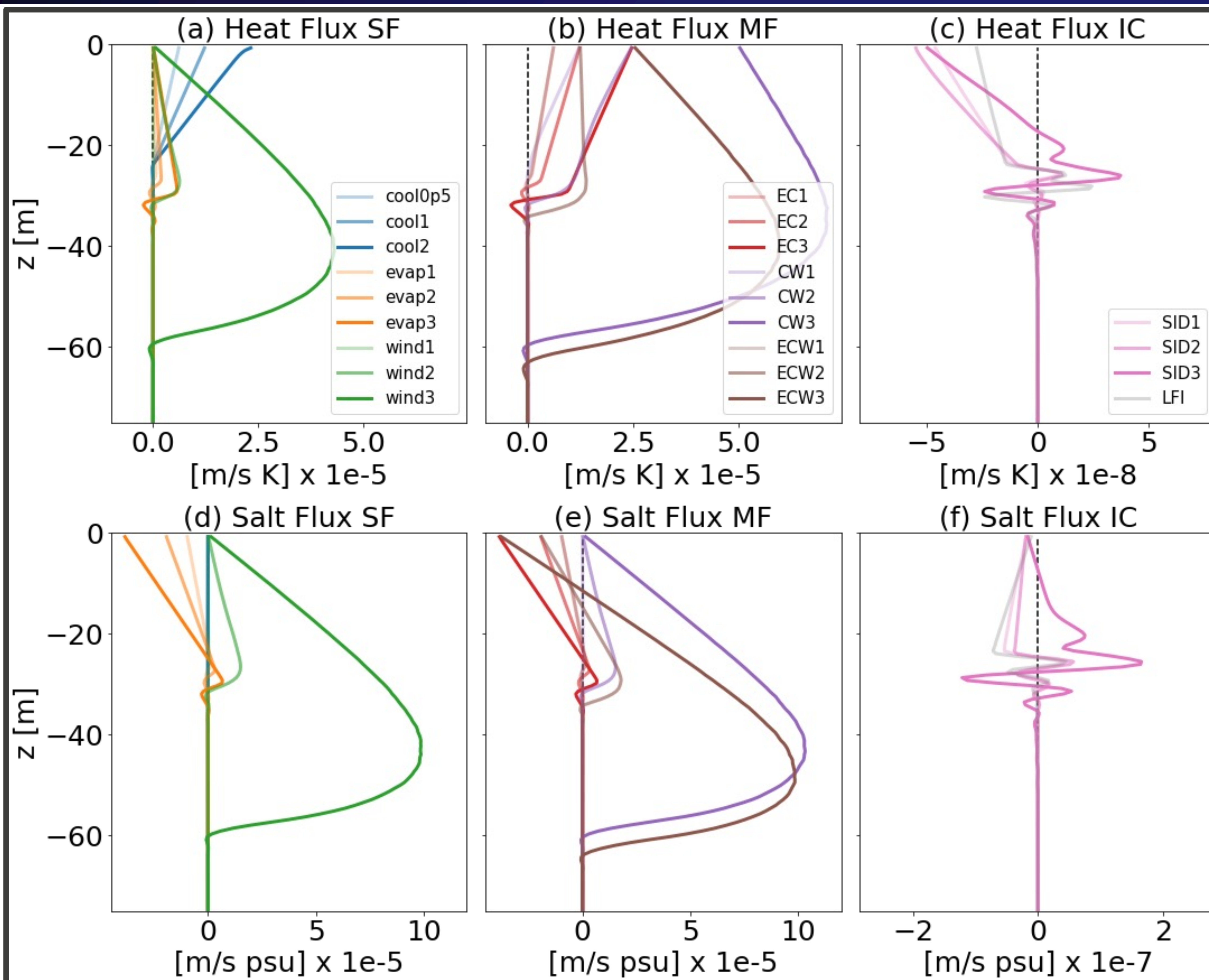


Results - Mixed Layer Depth/Heat Entrainment

Change in Mixed Layer Heat Content

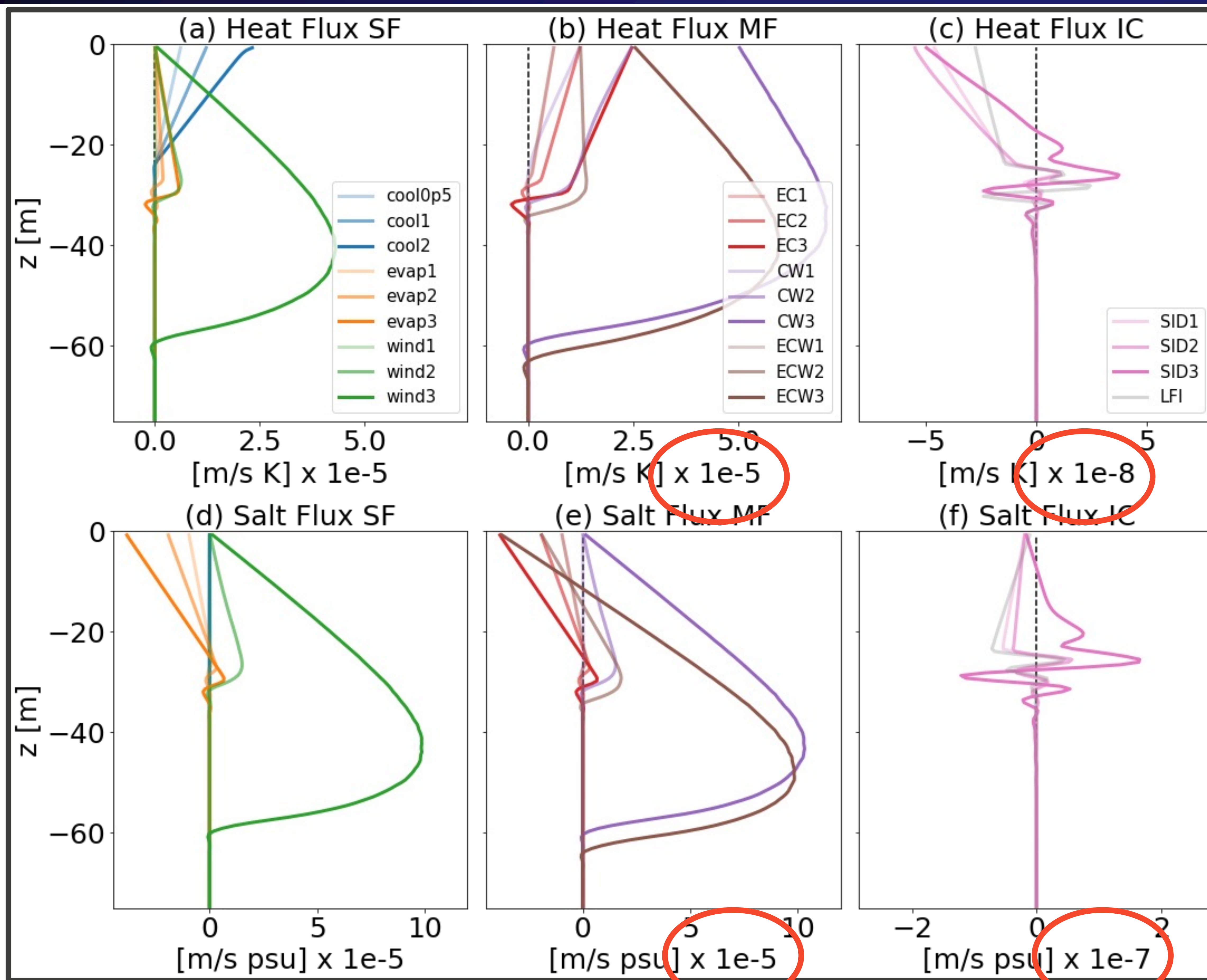


Vertical Heat and Salt Fluxes



**Heat and Salt Fluxes
(Last 12 Hours)**

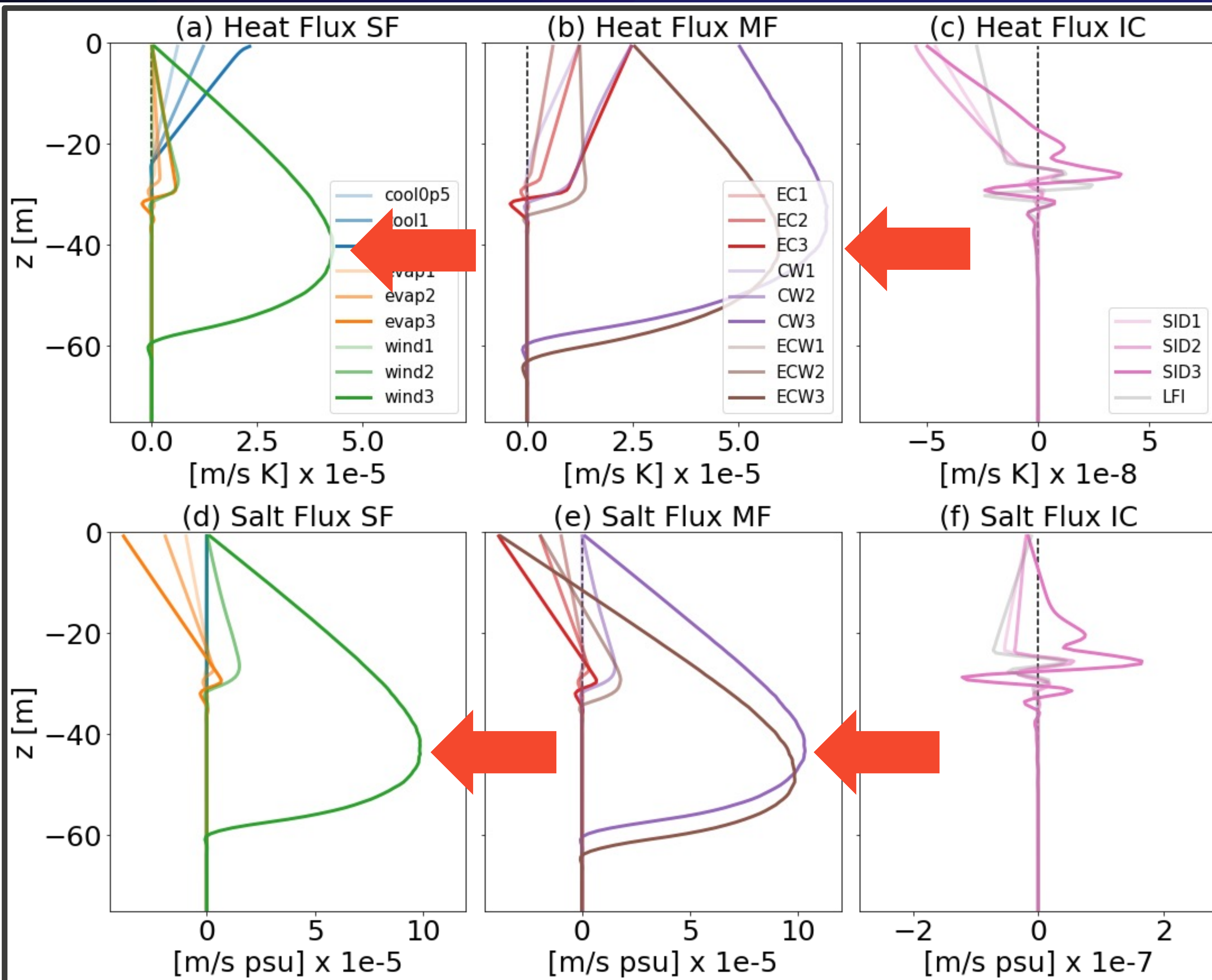
Vertical Heat and Salt Fluxes



Heat and Salt Fluxes (Last 12 Hours)

Heat fluxes are negligible with ice cover

Vertical Heat and Salt Fluxes



Heat and Salt Fluxes (Last 12 Hours)

Heat fluxes are negligible with ice cover

Fluxes are largest with wind (and evaporative) forcing

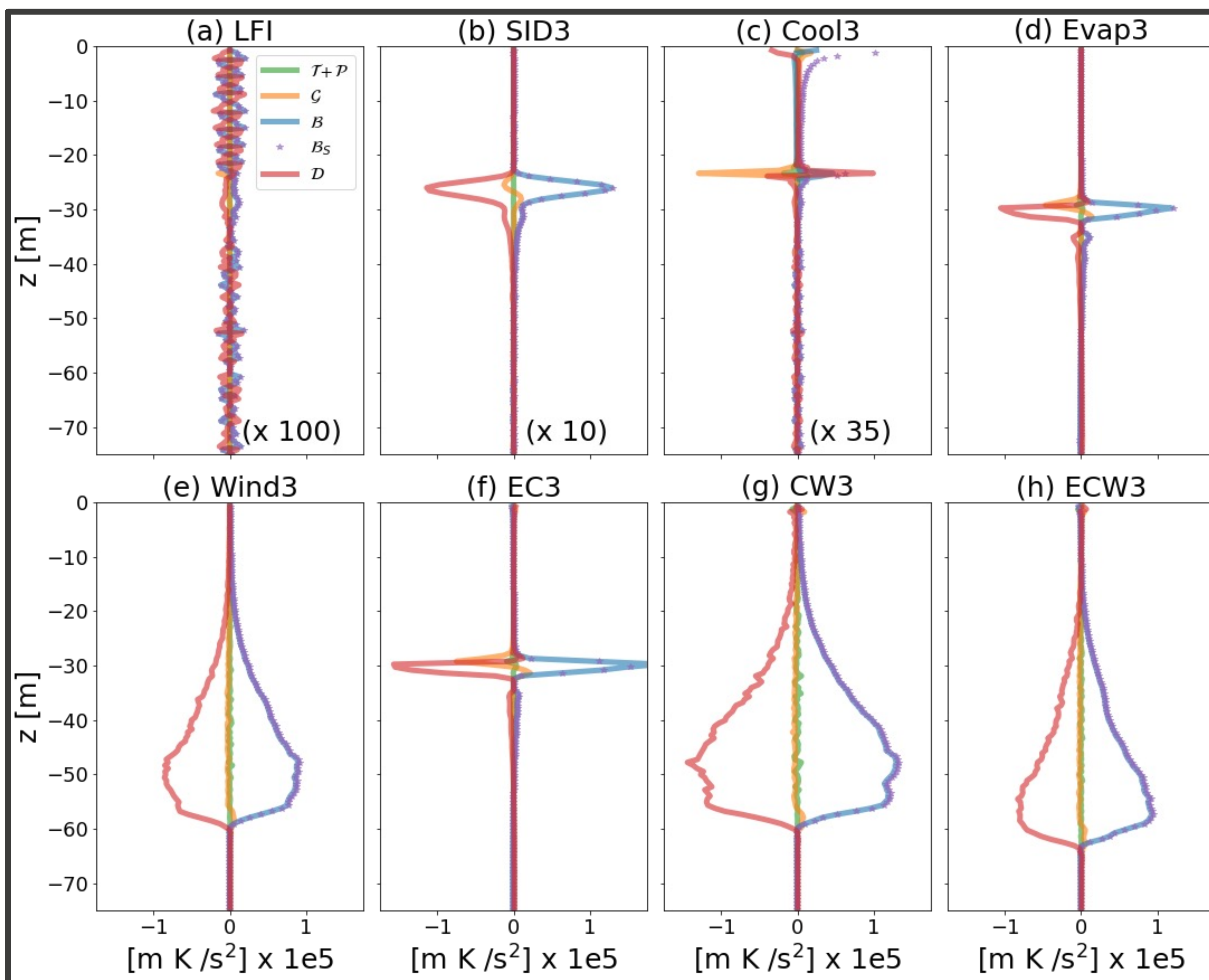
Questions

- What are the dominant mechanisms of vertical heat transport and mixing in the Arctic? How will these change?
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Questions

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Results - Mechanisms: Heat Flux

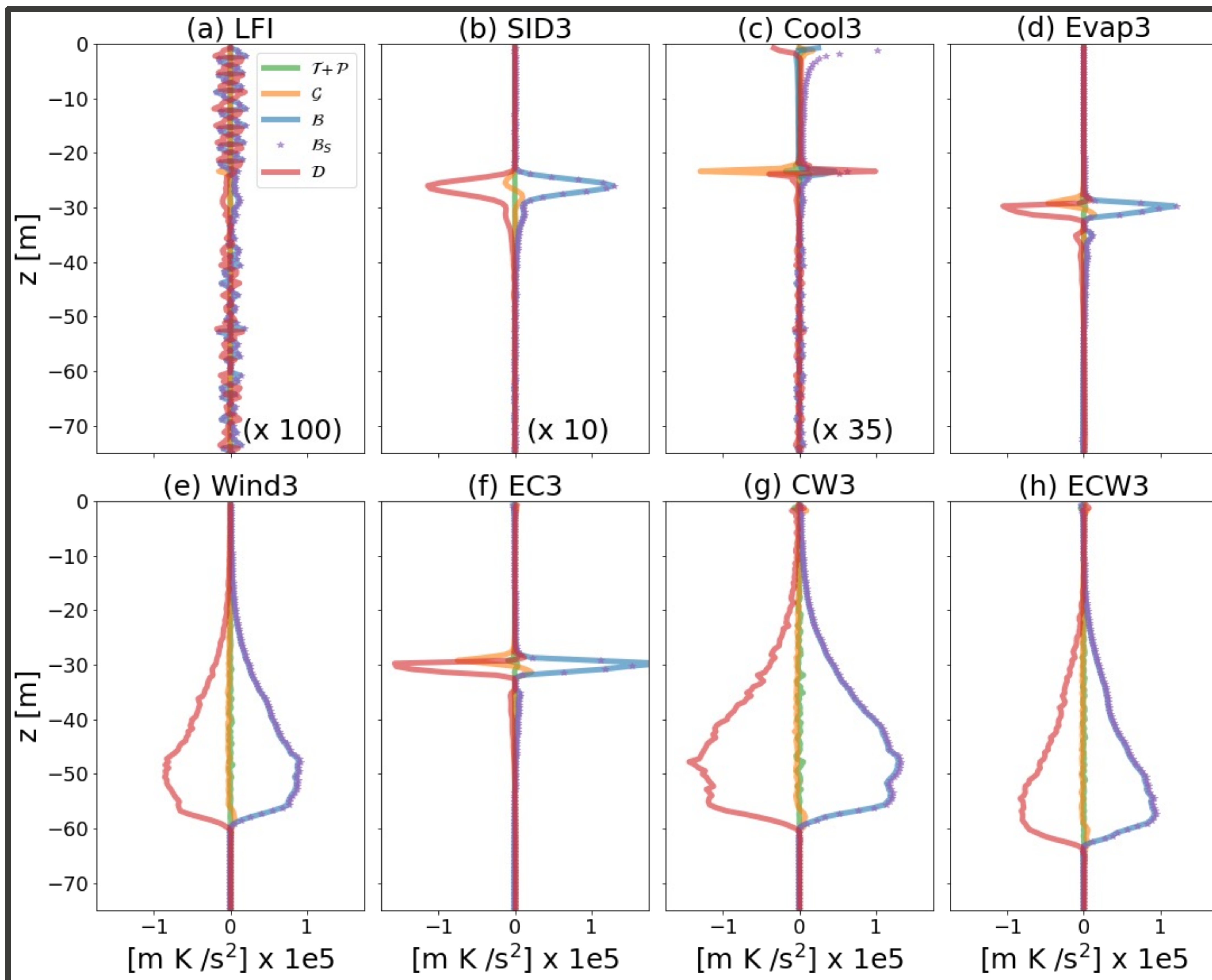


Vertical Heat Flux Budget (Last 12 hours)

$$\frac{\partial \overline{w'\theta'}}{\partial t} = - \underbrace{\overline{w'^2} \frac{\partial \bar{\theta}}{\partial z}}_{\text{Gradient Prod, } \mathcal{G}} + g \left(\underbrace{\alpha_{\theta} \overline{\theta'^2}}_{\mathcal{B}_{\tau}} - \underbrace{\beta_S \overline{\theta' S'}}_{\mathcal{B}_S} \right) \underbrace{\hspace{10em}}_{\text{Buoyancy Prod, } \mathcal{B}}$$

$$- \underbrace{\frac{\partial \overline{w'w'\theta'}}{\partial z} - \frac{\overline{\theta'} \partial p'}{\rho_0 \partial z}}_{\text{Trans/Press Work, } \mathcal{T}+\mathcal{P}} - \underbrace{\varepsilon_{w'\theta'}}_{\text{Dissipation, } \mathcal{D}}$$

Results - Mechanisms: Heat Flux

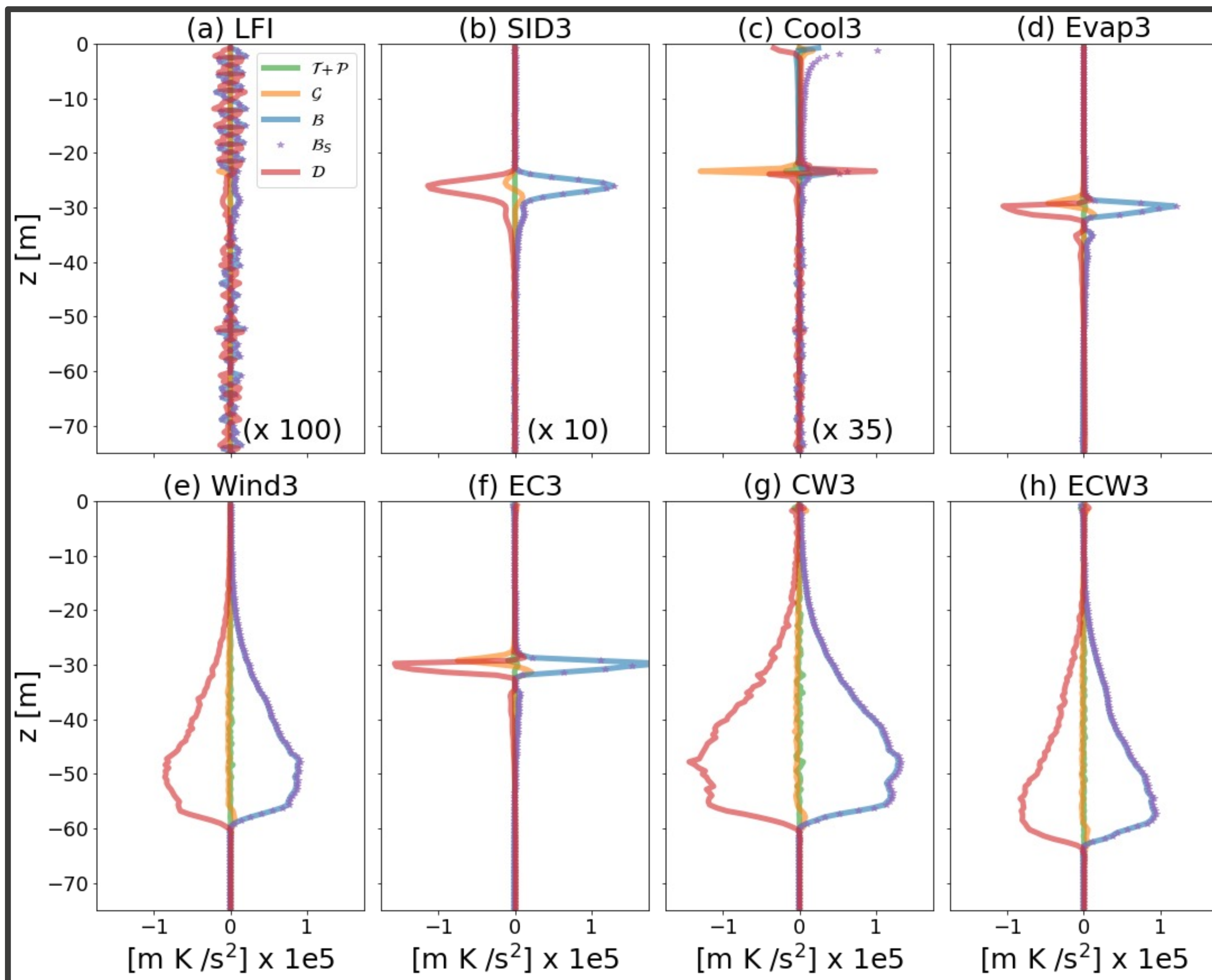


Vertical Heat Flux Budget (Last 12 hours)

$$\frac{\partial \overline{w'\theta'}}{\partial t} = - \underbrace{\overline{w'^2} \frac{\partial \bar{\theta}}{\partial z}}_{\text{Gradient Prod, } \mathcal{G}} + g \left(\underbrace{\alpha_{\theta} \overline{\theta'^2}}_{\mathcal{B}_{\tau}} - \underbrace{\beta_S \overline{\theta' S'}}_{\mathcal{B}_S} \right) + \underbrace{- \left(\frac{\partial \overline{w'w'\theta'}}{\partial z} - \frac{\overline{\theta'} \partial p'}{\rho_0 \partial z} \right)}_{\text{Trans/Press Work, } \mathcal{T}+\mathcal{P}} - \underbrace{\mathcal{E}_{w'\theta'}}_{\text{Dissipation, } \mathcal{D}}$$

Buoyancy Prod, $\mathcal{B}$

Results - Mechanisms: Heat Flux

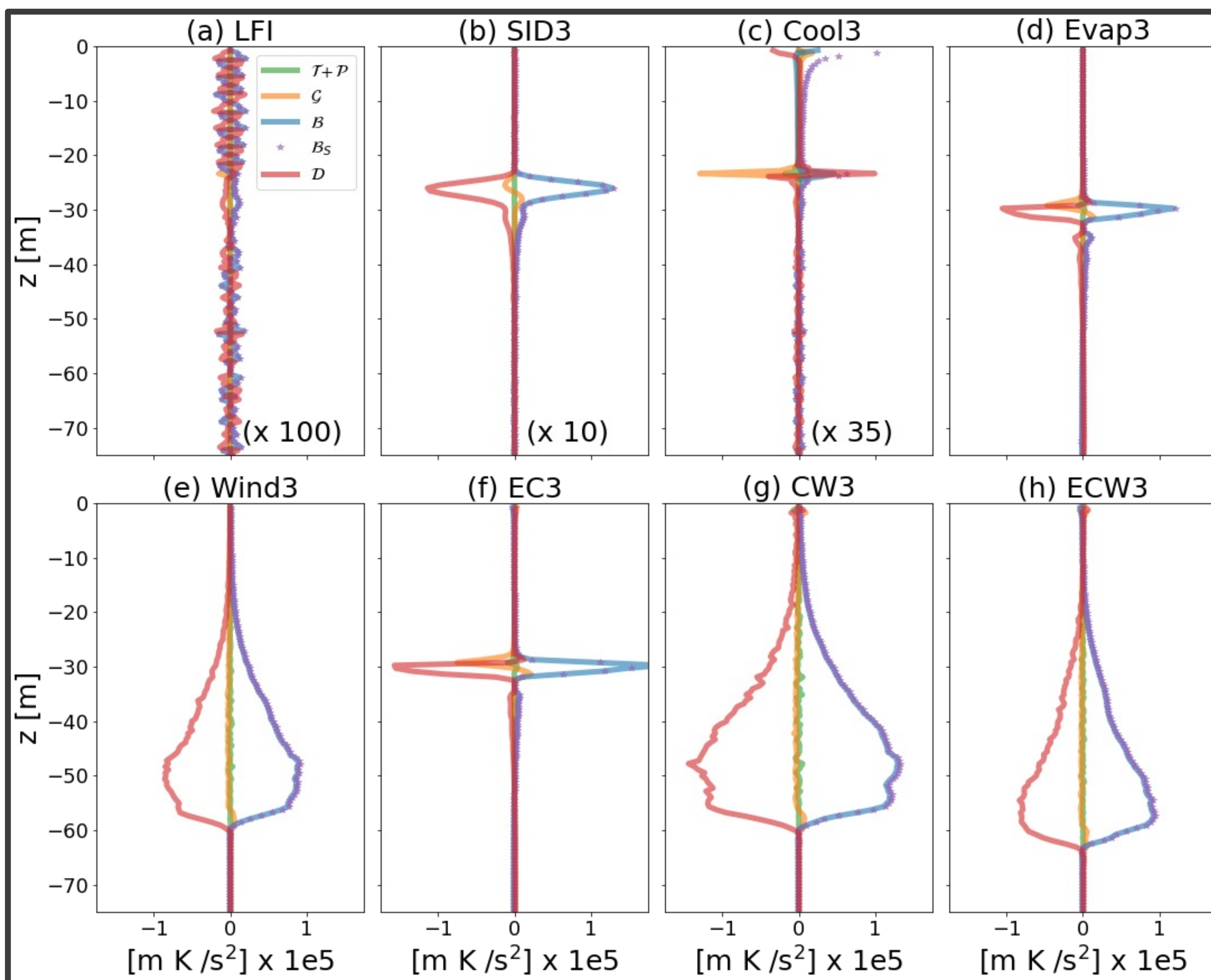


Vertical Heat Flux Budget (Last 12 hours)

$$\frac{\partial \overline{w'\theta'}}{\partial t} = - \underbrace{\overline{w'^2} \frac{\partial \bar{\theta}}{\partial z}}_{\text{Gradient Prod, } \mathcal{G}} + g \left(\underbrace{\alpha_{\theta} \overline{\theta'^2}}_{\mathcal{B}_{\tau}} - \underbrace{\beta_S \overline{\theta' S'}}_{\mathcal{B}_S} \right) - \underbrace{\left(- \frac{\partial \overline{w'w'\theta'}}{\partial z} - \frac{\overline{\theta'} \partial p'}{\rho_0 \partial z} \right)}_{\text{Trans/Press Work, } \mathcal{T}+\mathcal{P}} - \underbrace{\mathcal{E}_{w'\theta'}}_{\text{Dissipation, } \mathcal{D}}$$

Buoyancy Prod, $\mathcal{B}$

Results - Mechanisms: Heat Flux



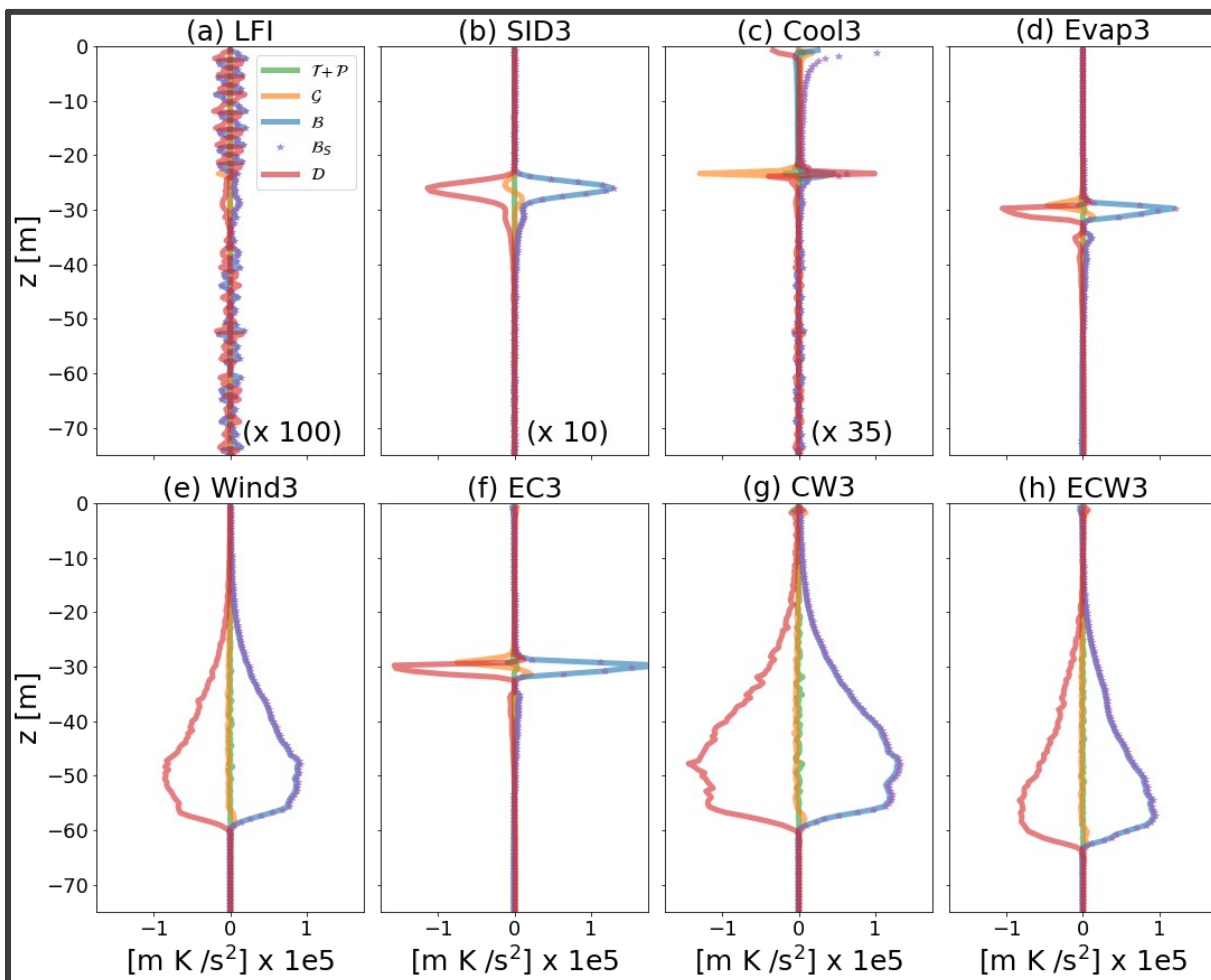
Vertical Heat Flux Budget (Last 12 hours)

$$\frac{\partial \overline{w'\theta'}}{\partial t} = - \underbrace{\overline{w'^2} \frac{\partial \bar{\theta}}{\partial z}}_{\text{Gradient Prod, } \mathcal{G}} + g \left(\underbrace{\alpha_{\theta} \overline{\theta'^2}}_{\mathcal{B}_{\tau}} - \underbrace{\beta_S \overline{\theta' S'}}_{\mathcal{B}_S} \right) - \underbrace{\left(\frac{\partial \overline{w'w'\theta'}}{\partial z} - \frac{\overline{\theta'} \partial p'}{\rho_0 \partial z} \right)}_{\text{Trans/Press Work, } \mathcal{T}+\mathcal{P}} - \underbrace{\mathcal{E}_{w'\theta'}}_{\text{Dissipation, } \mathcal{D}}$$

Buoyancy Prod, $\mathcal{B}$

Buoyancy drives most of the vertical heat flux

Results - Mechanisms: Heat Flux



Vertical Heat Flux Budget (Last 12 hours)

$$\frac{\partial \overline{w'\theta'}}{\partial t} = \underbrace{-\overline{w'^2} \frac{\partial \bar{\theta}}{\partial z}}_{\text{Gradient Prod, } \mathcal{G}} + g \left(\underbrace{\alpha_{\theta} \overline{\theta'^2}}_{\mathcal{B}_{\tau}} - \underbrace{\beta_S \overline{\theta' S'}}_{\mathcal{B}_S} \right) - \underbrace{\left(\frac{\partial \overline{w'w'\theta'}}{\partial z} - \frac{\overline{\theta'} \partial p'}{\rho_0 \partial z} \right)}_{\text{Trans/Press Work, } \mathcal{T}+\mathcal{P}} - \underbrace{\mathcal{E}_{w'\theta'}}_{\text{Dissipation, } \mathcal{D}}$$

Buoyancy Prod, $\mathcal{B}$

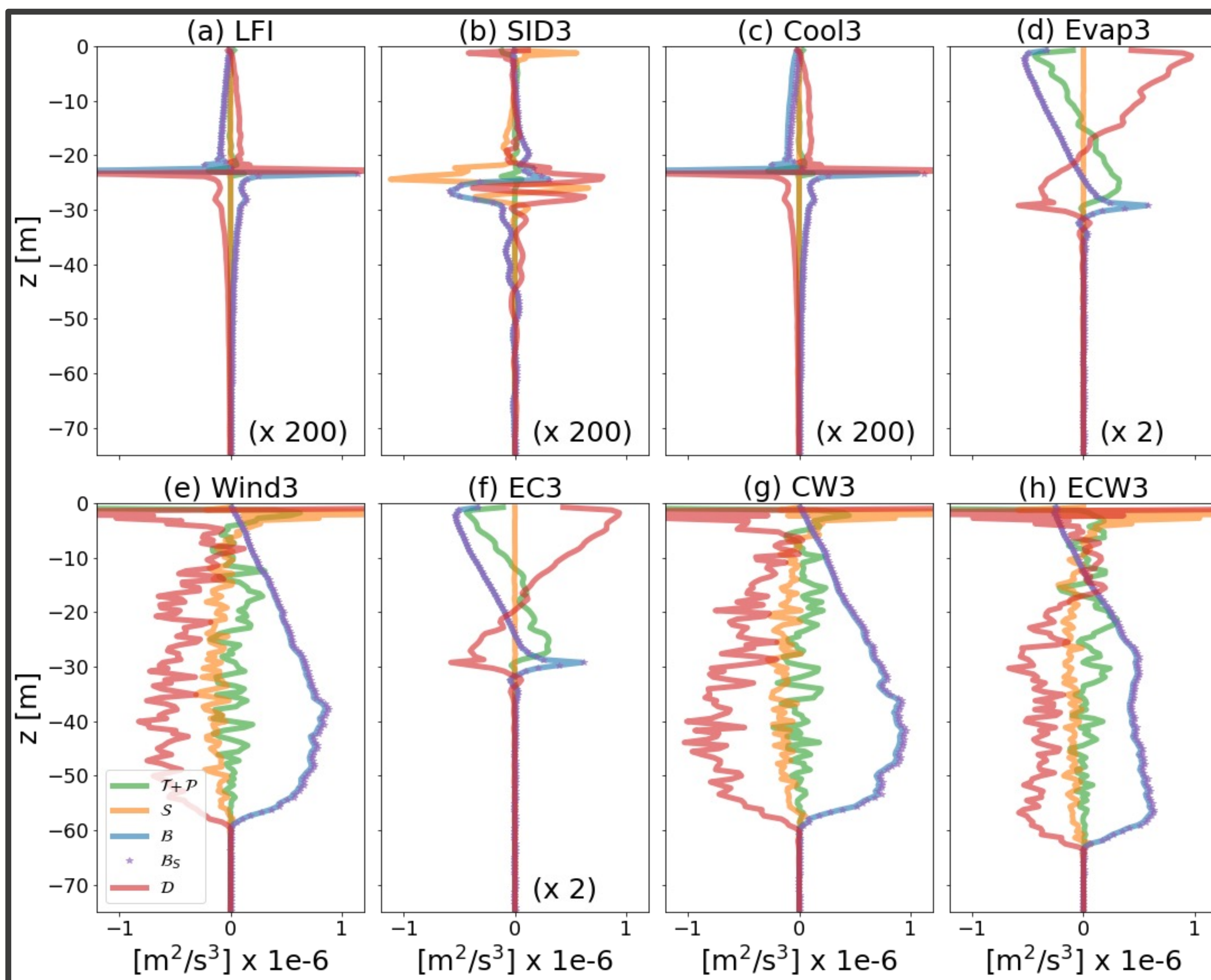
Buoyancy drives most of the vertical heat flux

Specifically, the salt contribution to buoyancy

Questions

- What are the dominant mechanisms of vertical heat transport and mixing in the Arctic? How will these change?
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Results - Mechanisms: Mixing/Turbulent Kinetic Energy

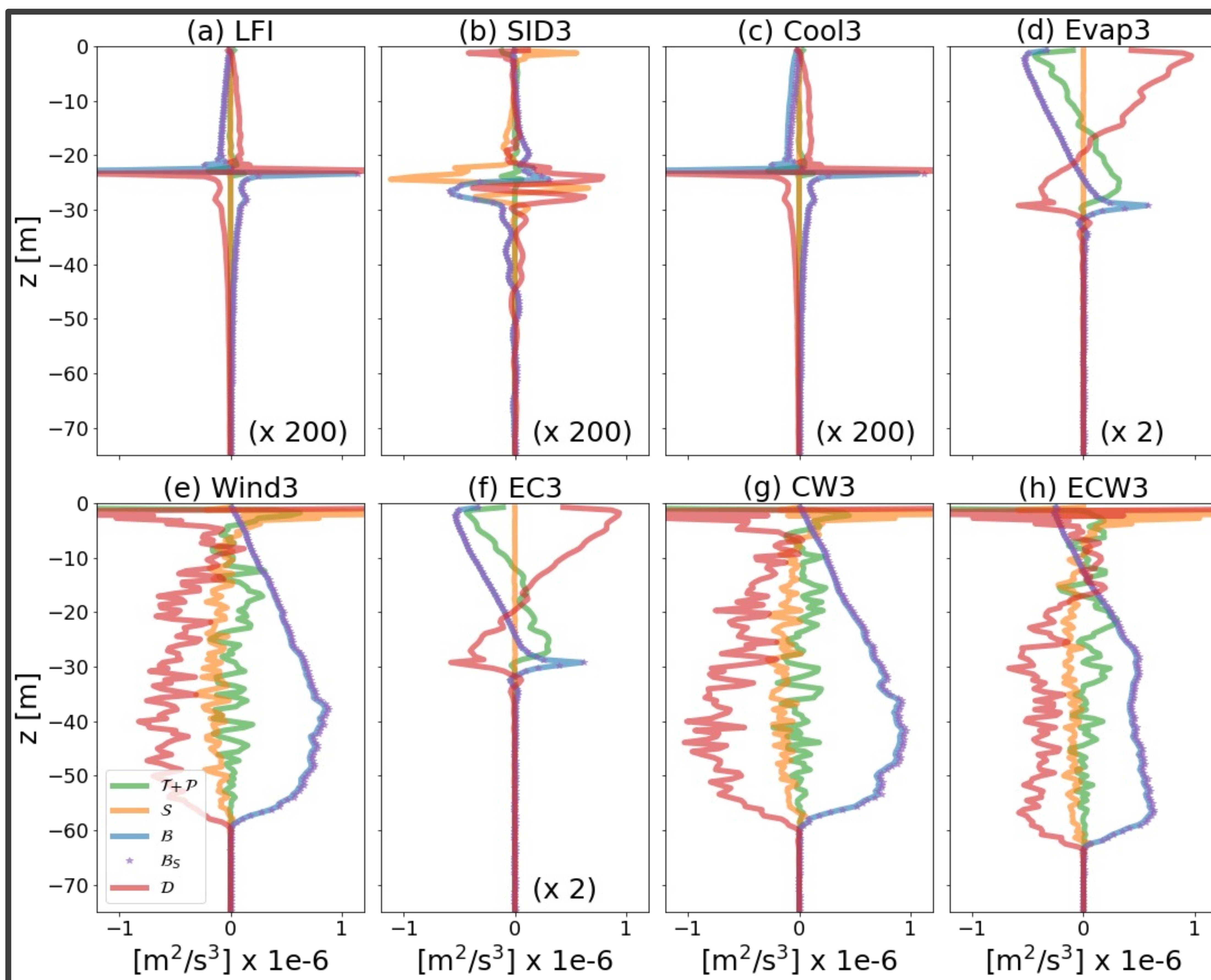


TKE Budget (Last 12 hours)

$$\frac{D\bar{e}}{Dt} = \underbrace{-\overline{u'w'}\frac{d\bar{u}}{dz} - \overline{v'w'}\frac{d\bar{v}}{dz}}_{\text{Shear Prod, } S} + g \left(\underbrace{\alpha_\theta \overline{w'\theta'}}_{\mathcal{B}_T} - \underbrace{\beta_S \overline{w'S'}}_{\mathcal{B}_S} \right) - \underbrace{\frac{\partial}{\partial z} \left(\overline{w'e'} + \frac{1}{\rho_0} \overline{w'p'} \right)}_{\text{Trans/Press Work, } \mathcal{T}+\mathcal{P}} - \underbrace{\varepsilon_e}_{\text{Dissipation, } \mathcal{D}}$$

Buoyancy Prod, $\mathcal{B}$

Results - Mechanisms: Mixing/Turbulent Kinetic Energy

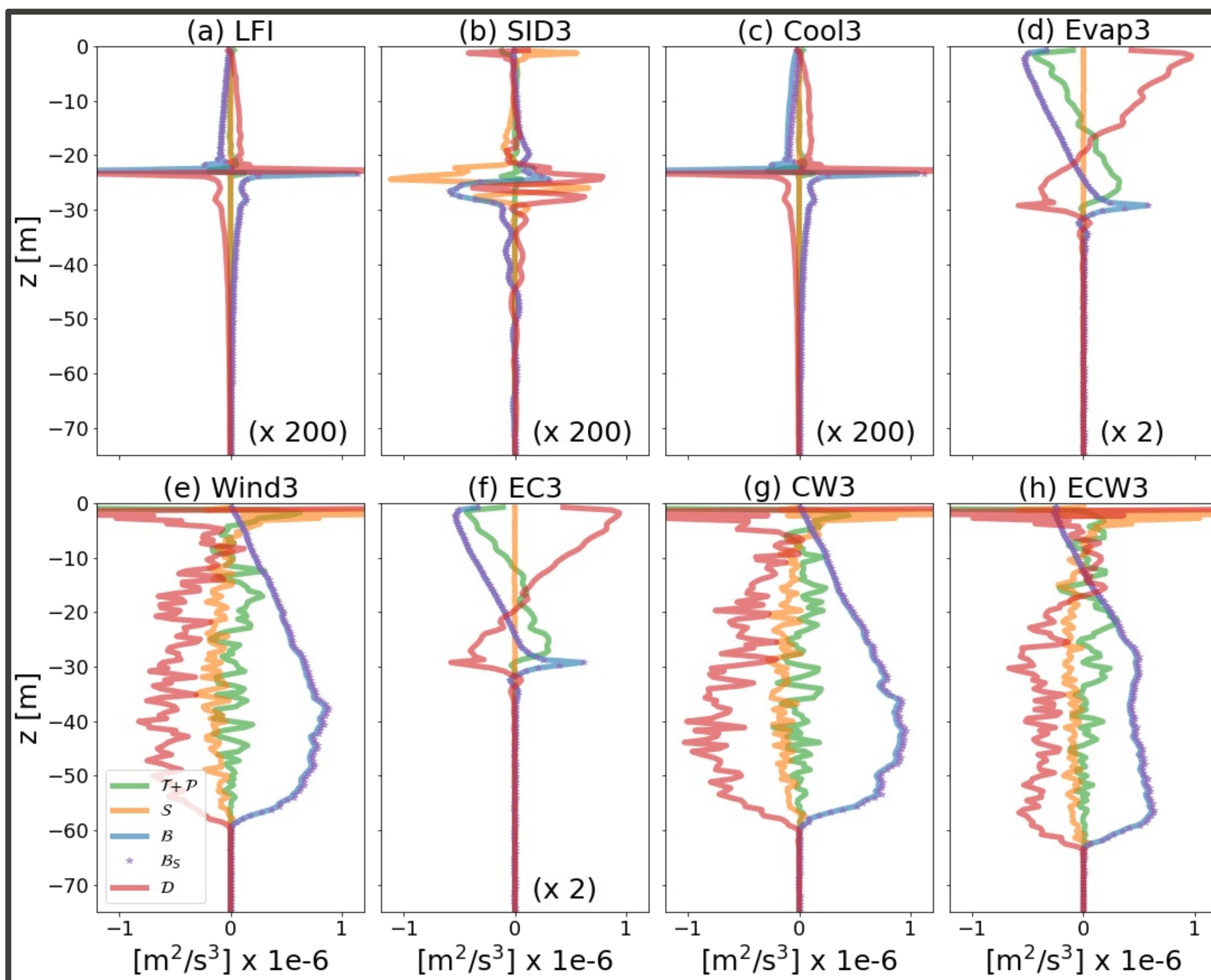


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Buoyancy Prod, $\mathcal{B}$

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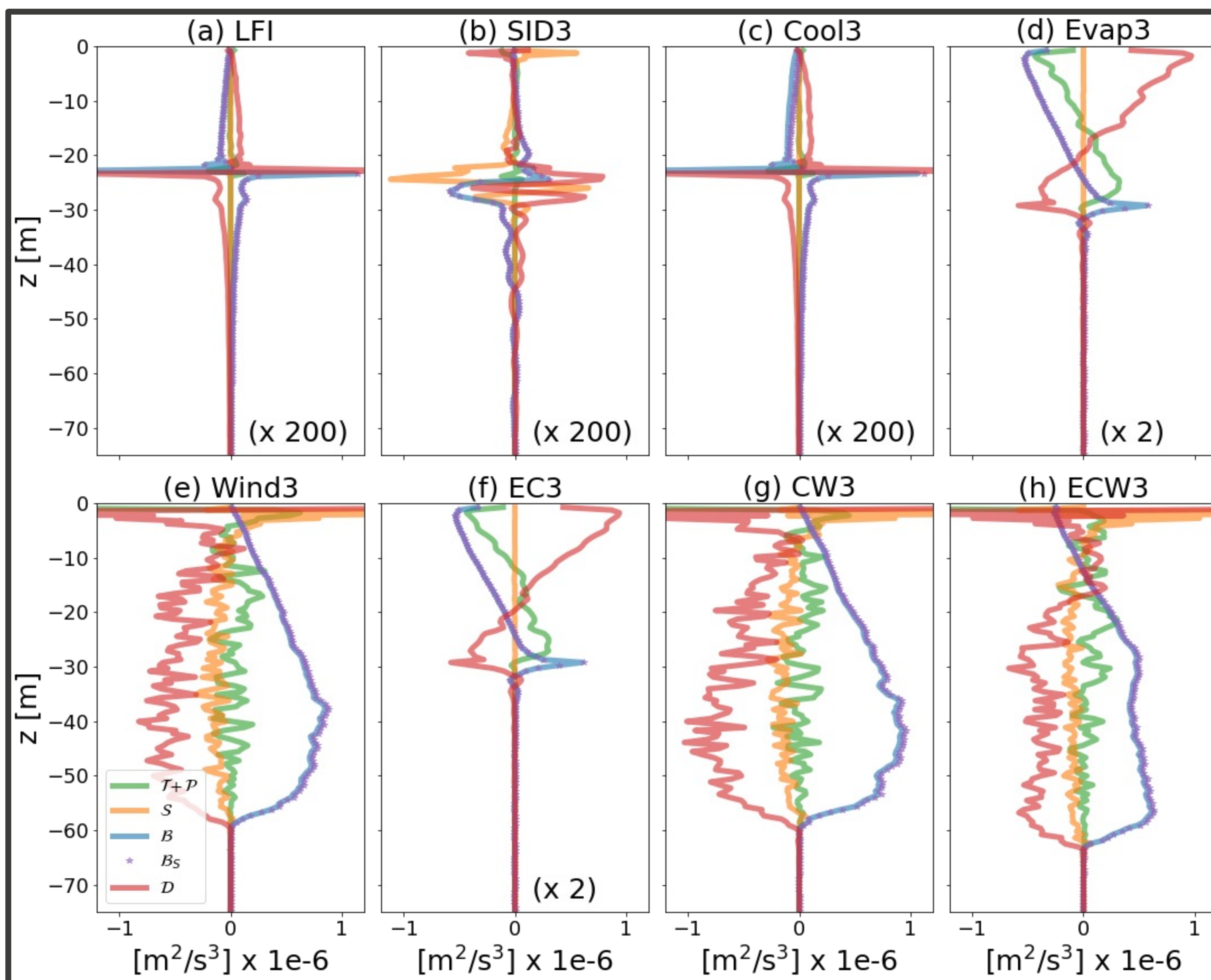


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Buoyancy Prod, $\mathcal{B}$

Results - Mechanisms: Mixing/Turbulent Kinetic Energy



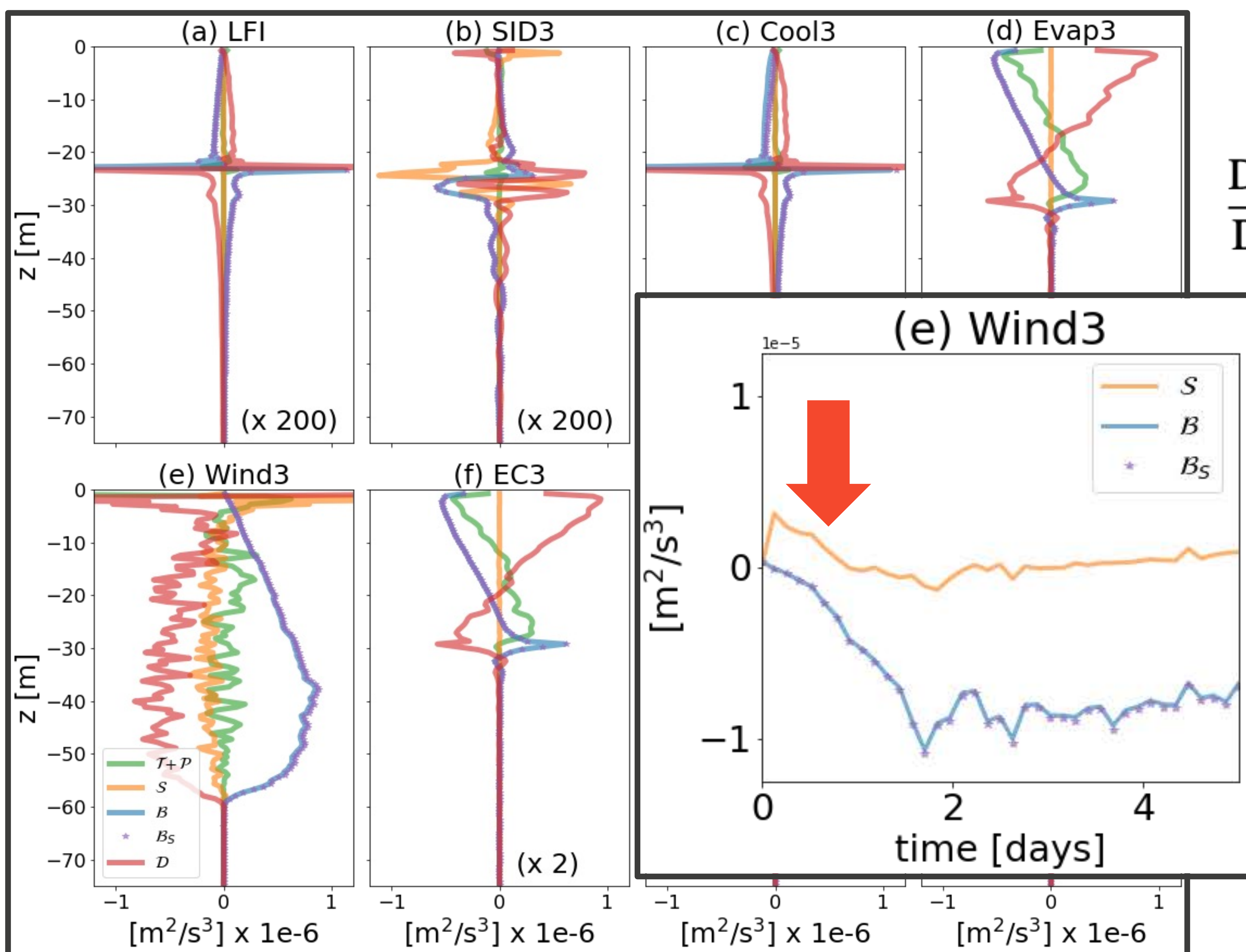
TKE Budget (Last 12 hours)

$$\frac{D\bar{e}}{Dt} = \underbrace{-\overline{u'w'}\frac{d\bar{u}}{dz} - \overline{v'w'}\frac{d\bar{v}}{dz}}_{\text{Shear Prod, } S} + g \left(\underbrace{\alpha_\theta \overline{w'\theta'}}_{\mathcal{B}_T} - \underbrace{\beta_S \overline{w'S'}}_{\mathcal{B}_S} \right) - \underbrace{\frac{\partial}{\partial z} \left(\overline{w'e'} + \frac{1}{\rho_0} \overline{w'p'} \right)}_{\text{Trans/Press Work, } \mathcal{T}+\mathcal{P}} - \underbrace{\varepsilon_e}_{\text{Dissipation, } \mathcal{D}}$$

Buoyancy Prod, $\mathcal{B}$

Mixing is driven by a combo of shear and buoyancy (shear sets off buoyancy)

Results - Mechanisms: Mixing/Turbulent Kinetic Energy



TKE Budget (Last 12 hours)

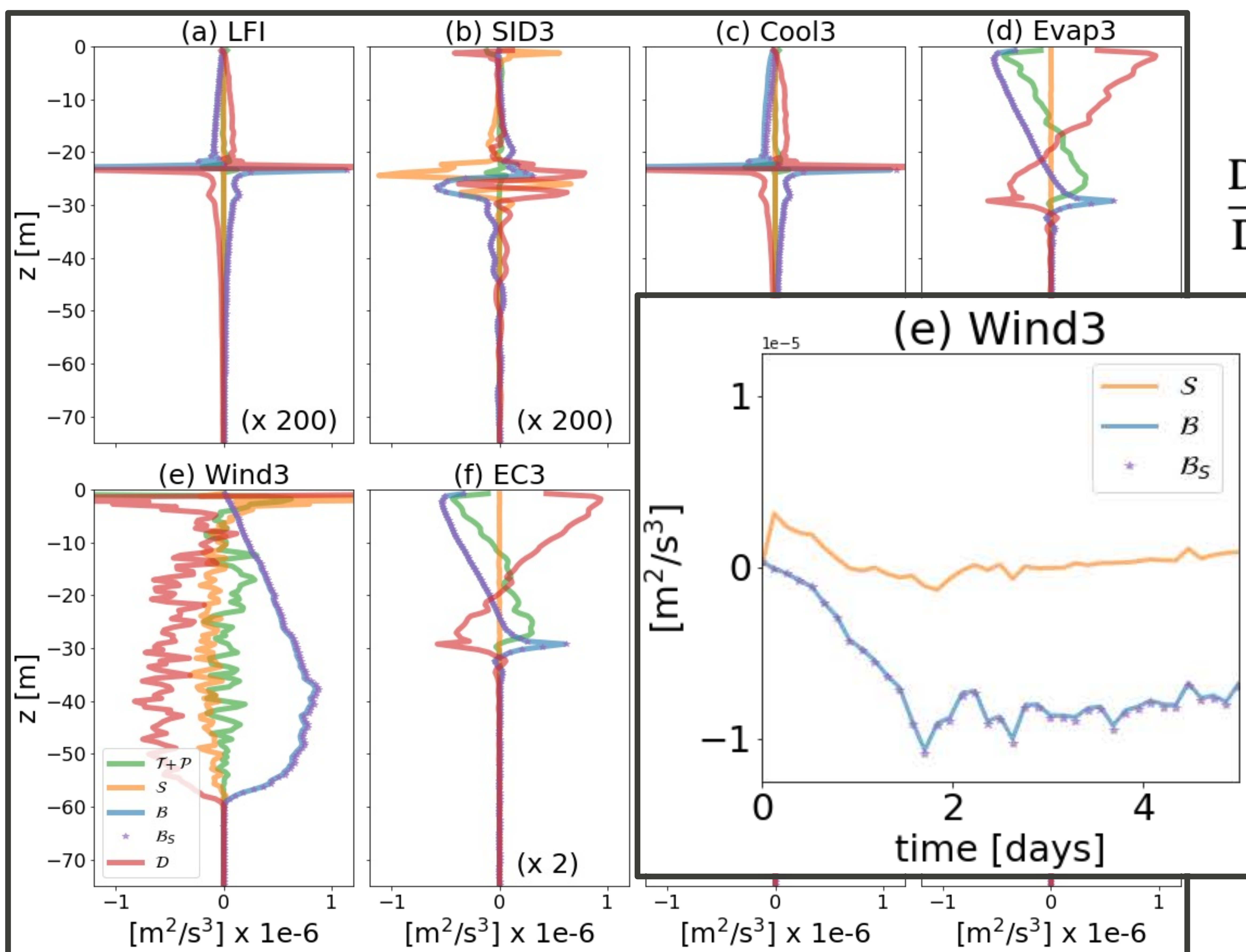
$$\frac{D\bar{e}}{Dt} = \underbrace{-\overline{u'w'}\frac{d\bar{u}}{dz} - \overline{v'w'}\frac{d\bar{v}}{dz}}_{\text{Shear Prod, } \mathcal{S}} + g \left(\underbrace{\alpha_\theta \overline{w'\theta'}}_{\mathcal{B}_\tau} - \underbrace{\beta_S \overline{w'S'}}_{\mathcal{B}_S} \right)$$

Buoyancy Prod, $\mathcal{B}$

$$\underbrace{-\frac{\partial}{\partial z} \left(\overline{w'e'} + \frac{1}{\rho_0} \overline{w'p'} \right)}_{\text{Trans/Press Work, } \mathcal{T} + \mathcal{P}} - \underbrace{\varepsilon_e}_{\text{Dissipation, } \mathcal{D}}$$

Mixing is driven by a combo of shear and buoyancy (shear sets off buoyancy)

Results - Mechanisms: Mixing/Turbulent Kinetic Energy



TKE Budget (Last 12 hours)

$$\frac{D\bar{e}}{Dt} = \underbrace{-\overline{u'w'}\frac{d\bar{u}}{dz} - \overline{v'w'}\frac{d\bar{v}}{dz}}_{\text{Shear Prod, } S} + g \left(\underbrace{\alpha_\theta \overline{w'\theta'}}_{\mathcal{B}_T} - \underbrace{\beta_S \overline{w'S'}}_{\mathcal{B}_S} \right)$$

Buoyancy Prod, $\mathcal{B}$

$$\underbrace{-\frac{\partial}{\partial z} \left(\overline{w'e'} + \frac{1}{\rho_0} \overline{w'p'} \right)}_{\text{Trans/Press Work, } \mathcal{T}+\mathcal{P}} - \underbrace{\varepsilon_e}_{\text{Dissipation, } \mathcal{D}}$$

Mixing is driven by a combo of shear and buoyancy (shear sets off buoyancy)

Salt contribution to buoyancy dominates

Questions

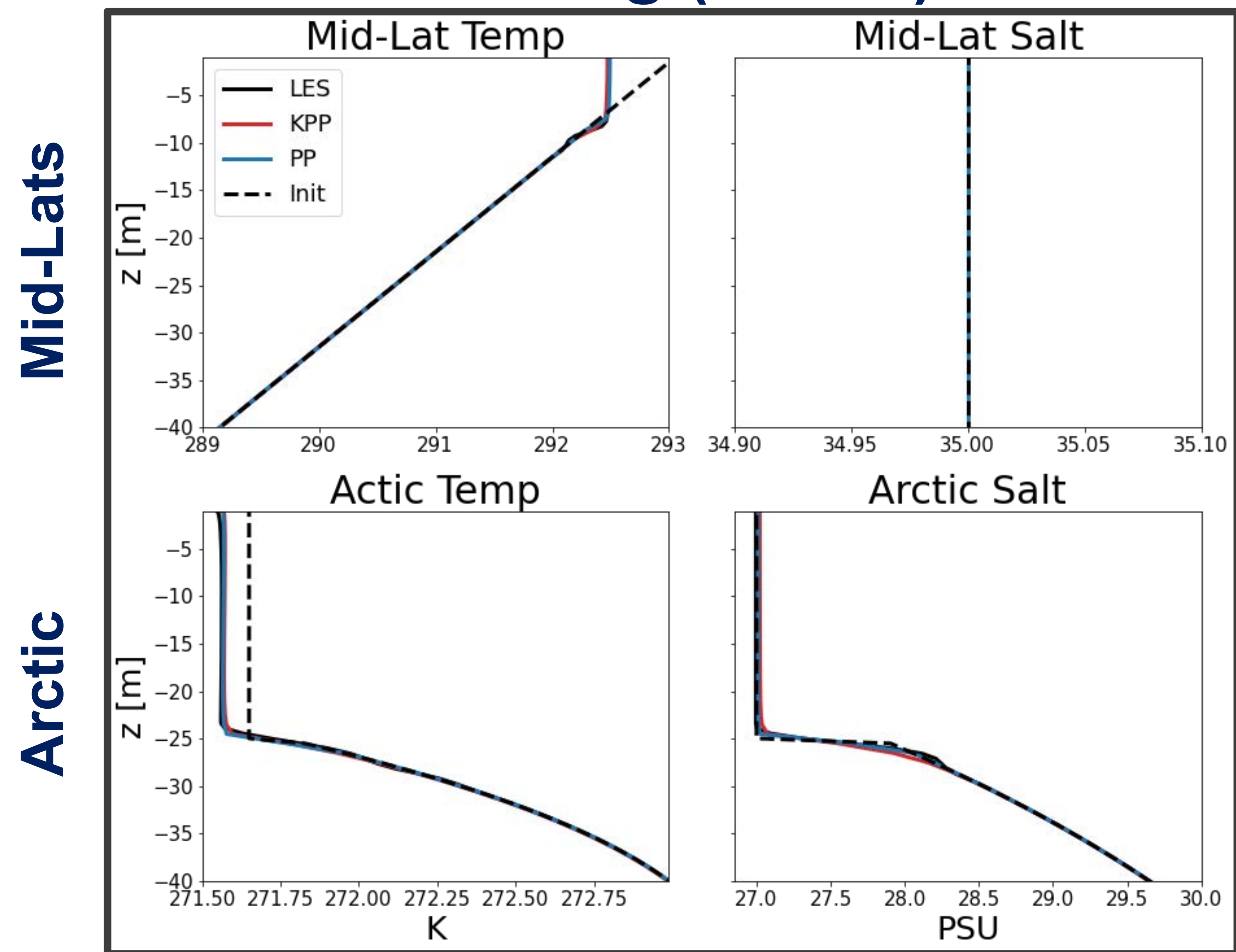
- What are the dominant mechanisms of vertical heat transport and mixing in the Arctic? How will these change?
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Results - Parameterizations

MPAS-O with CVMIX Package: Quick comparison, default values in MPAS-O, no-ice

Results - Parameterizations

MPAS-O with CVMIX Package: Quick comparison, default values in MPAS-O, no-ice
Cooling (100 W)

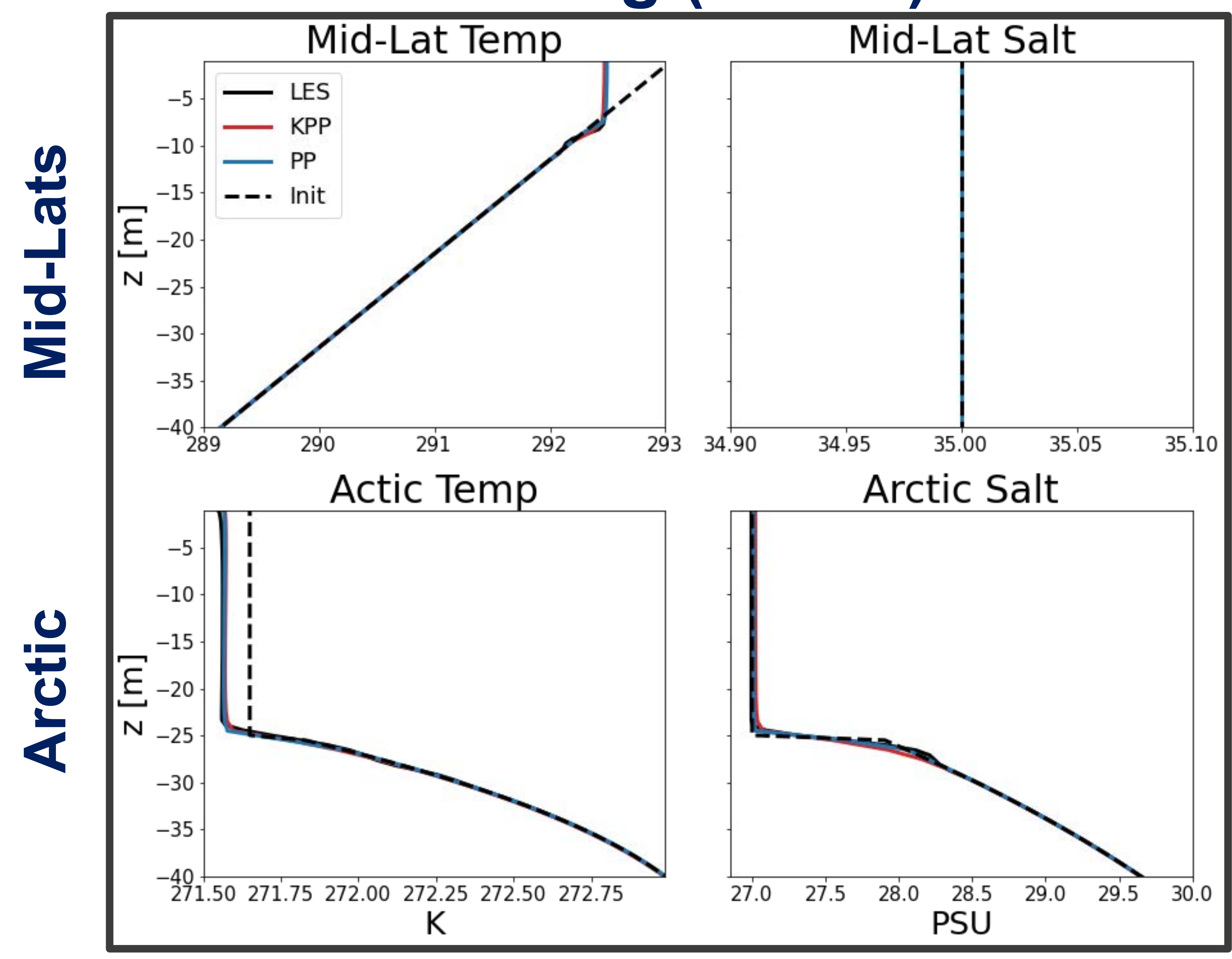


LA-UR-20-21004

Results - Parameterizations

MPAS-O with CVMIX Package: Quick comparison, default values in MPAS-O, no-ice

Cooling (100 W)

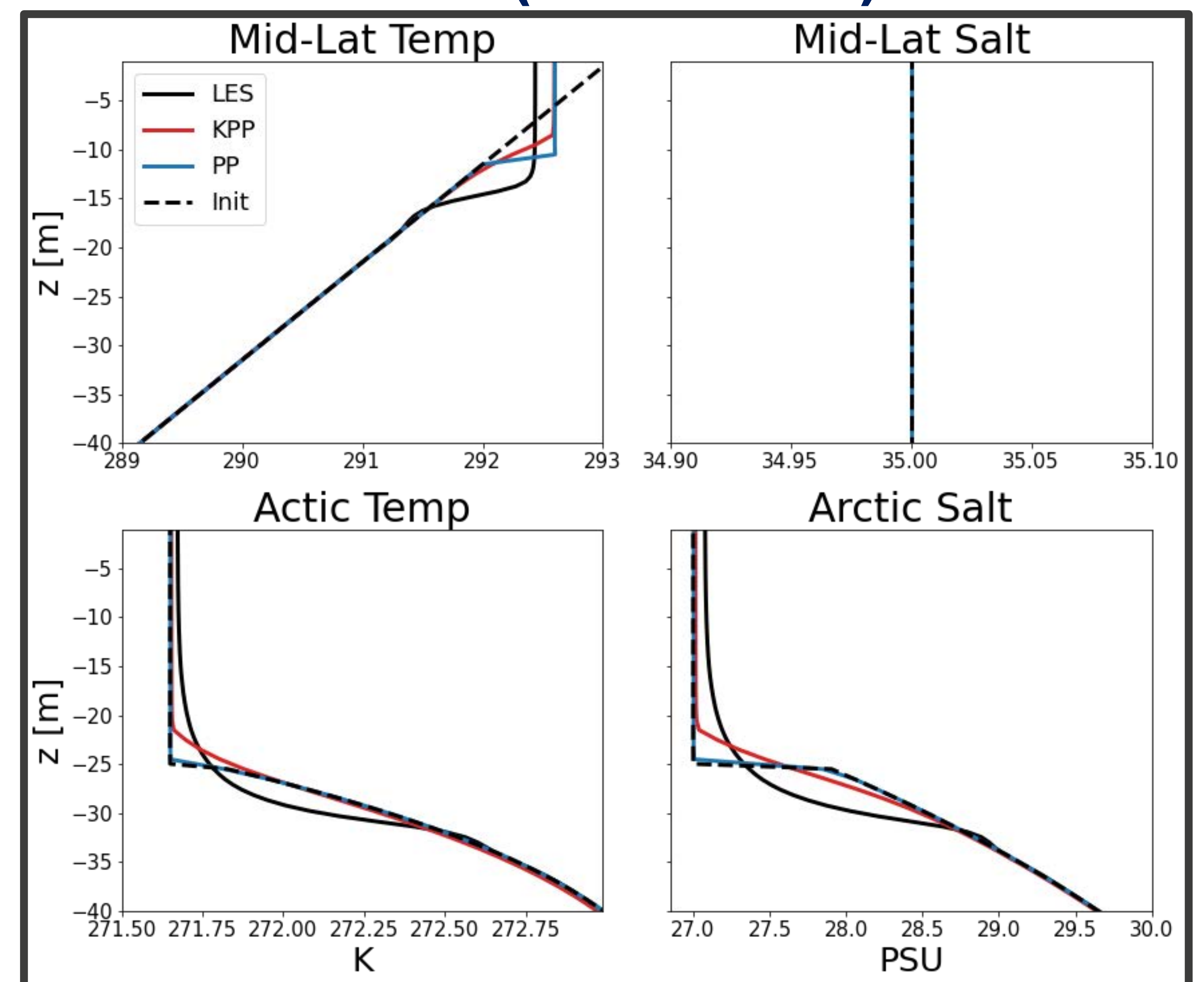
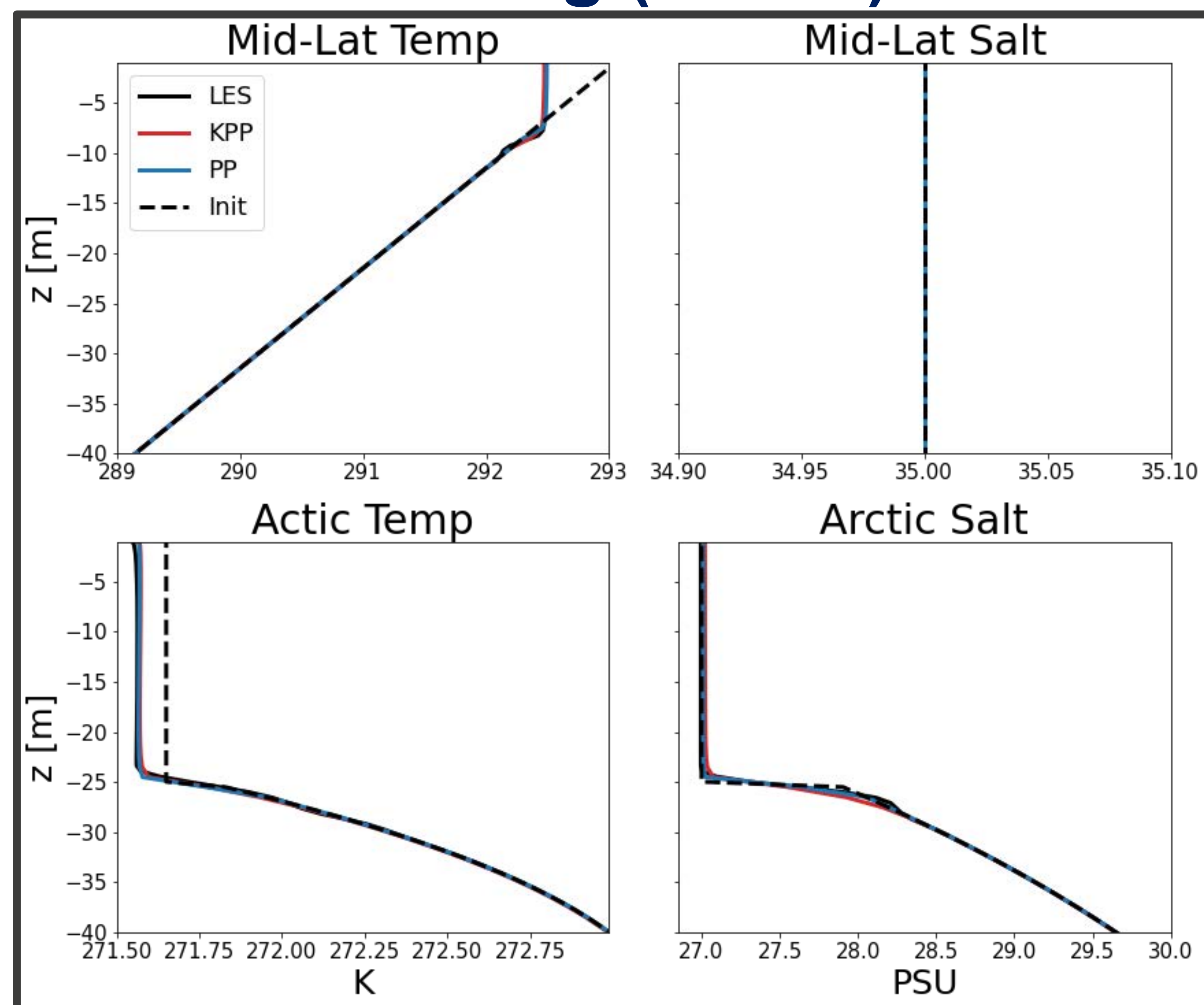


Results - Parameterizations

MPAS-O with CVMIX Package: Quick comparison, default values in MPAS-O, no-ice
Cooling (100 W)
Wind (0.02 N/m²)

Mid-Lats

Arctic



Results - Parameterizations

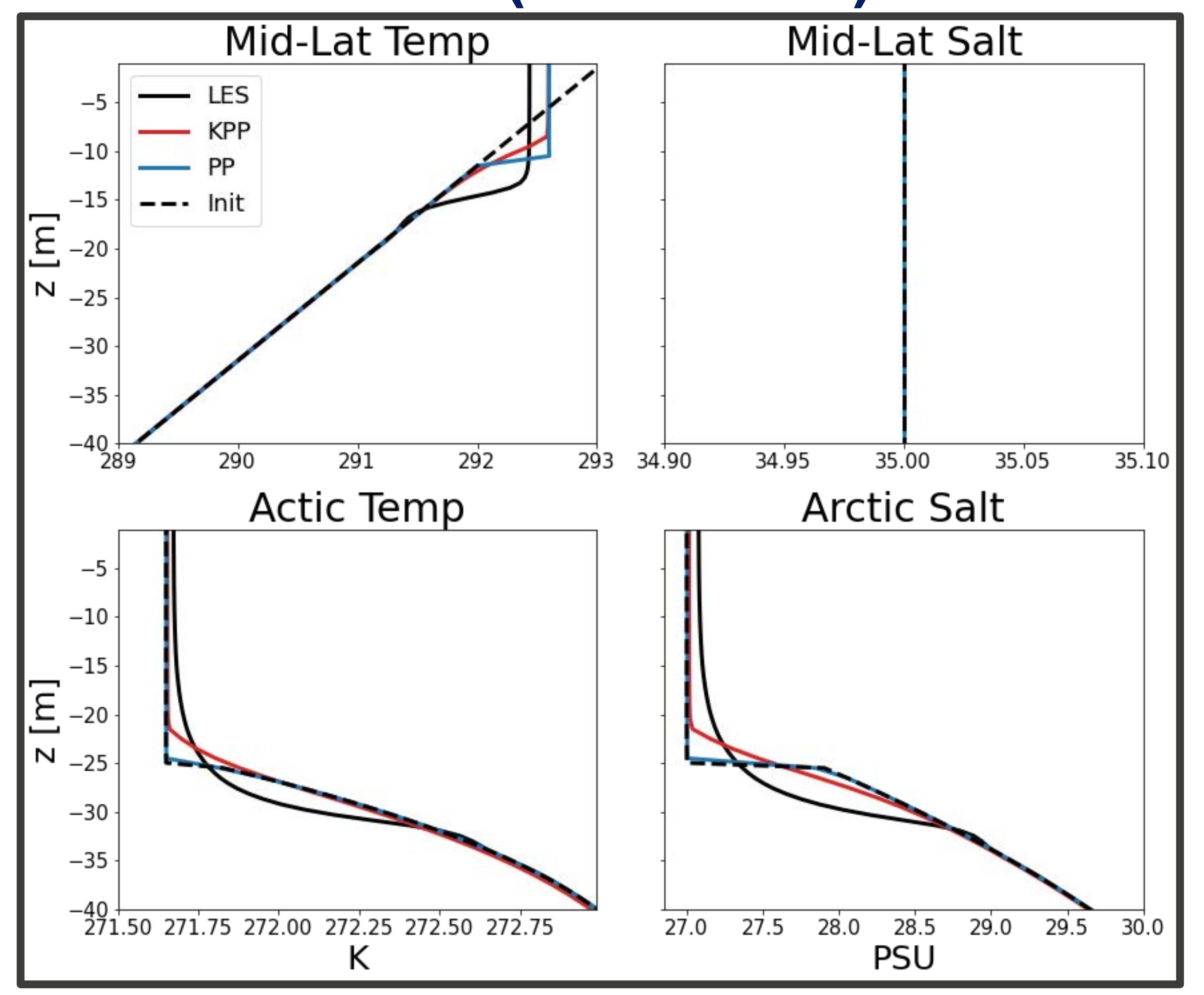
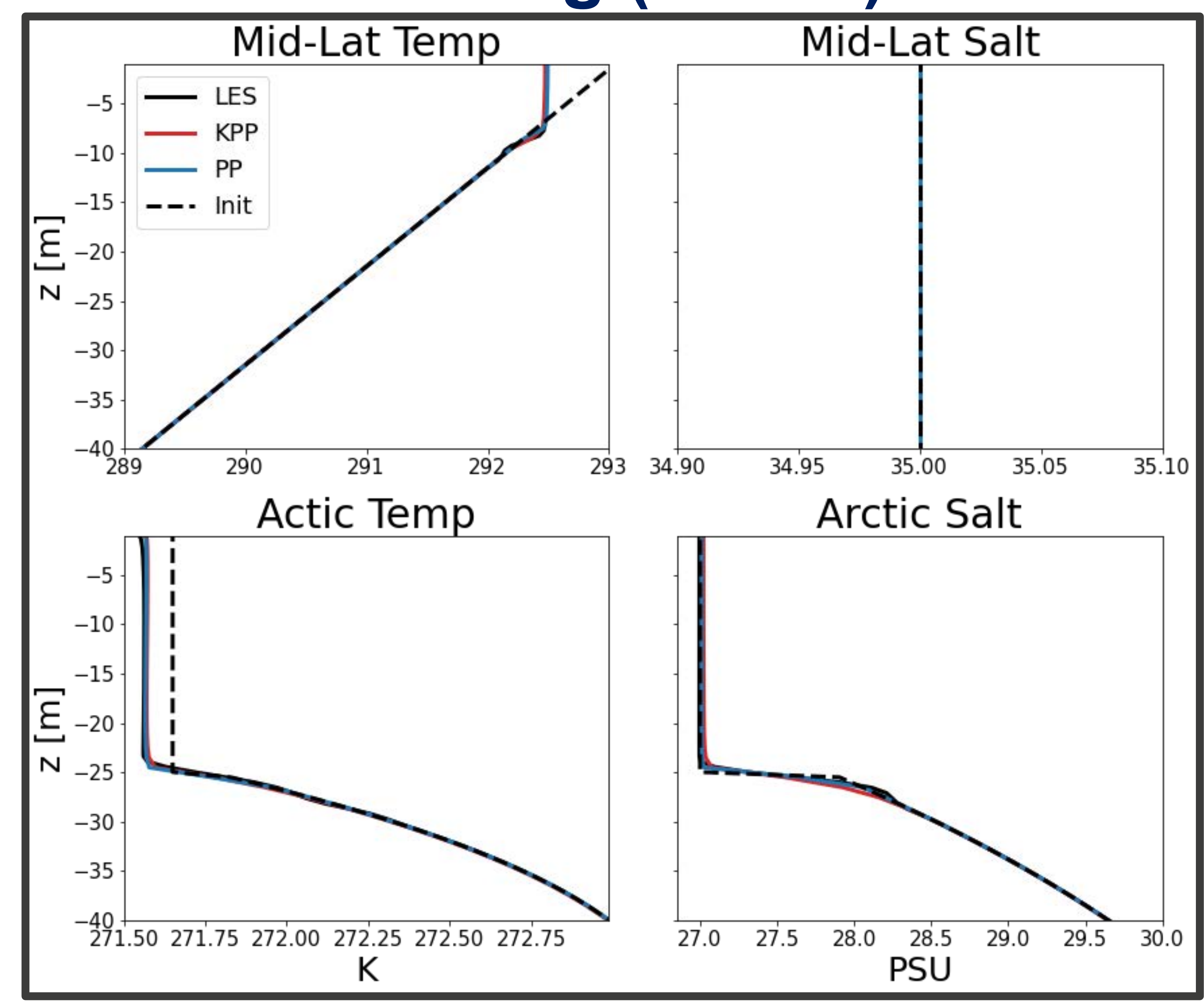
MPAS-O with CVMIX Package: Quick comparison, default values in MPAS-O, no-ice

Cooling (100 W)

Wind (0.02 N/m²)

Mid-Lats

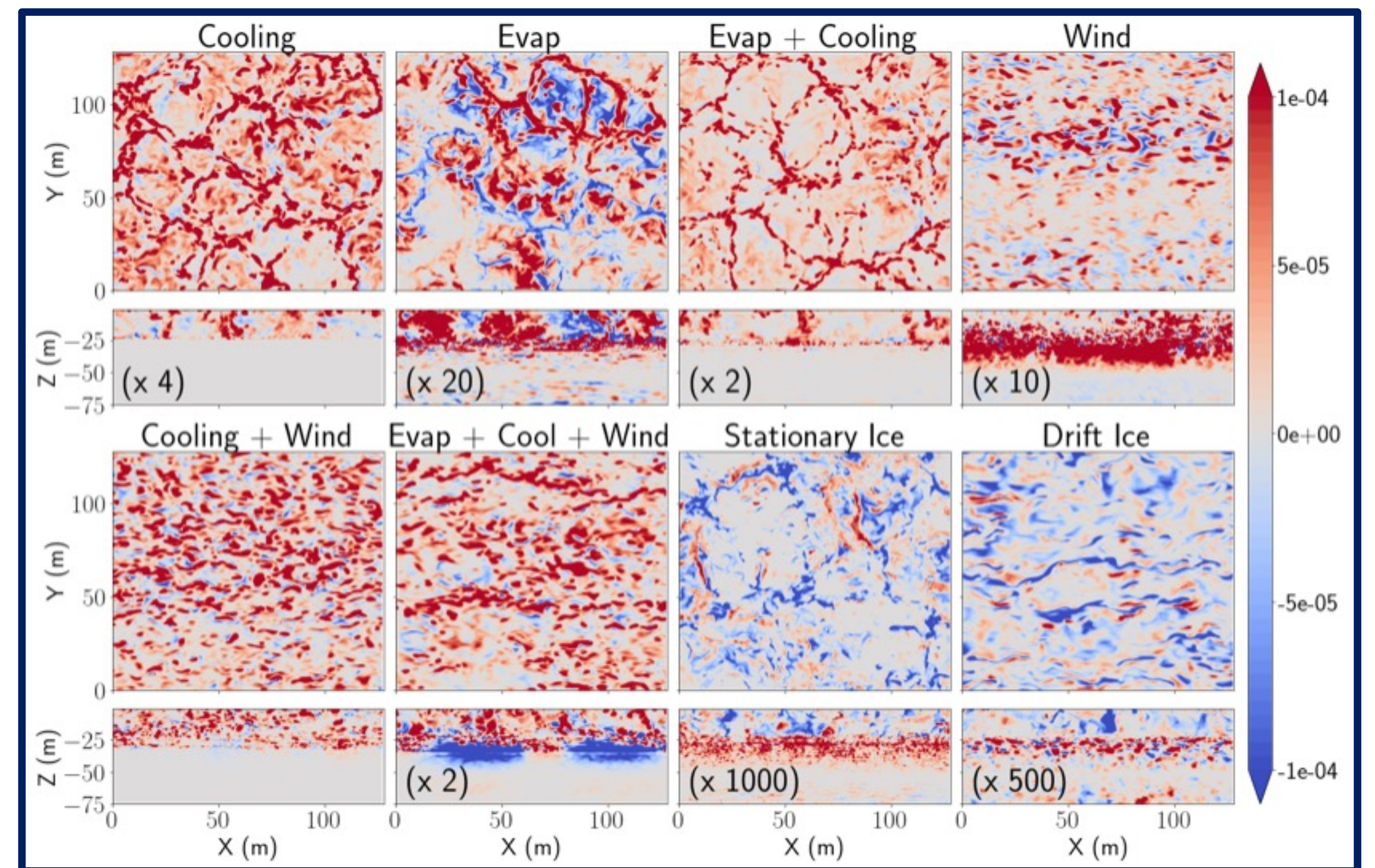
Arctic



Conclusions

What are the dominant mechanisms of vertical heat transport and mixing in the Arctic?

Are these mechanisms captured by parameterizations?



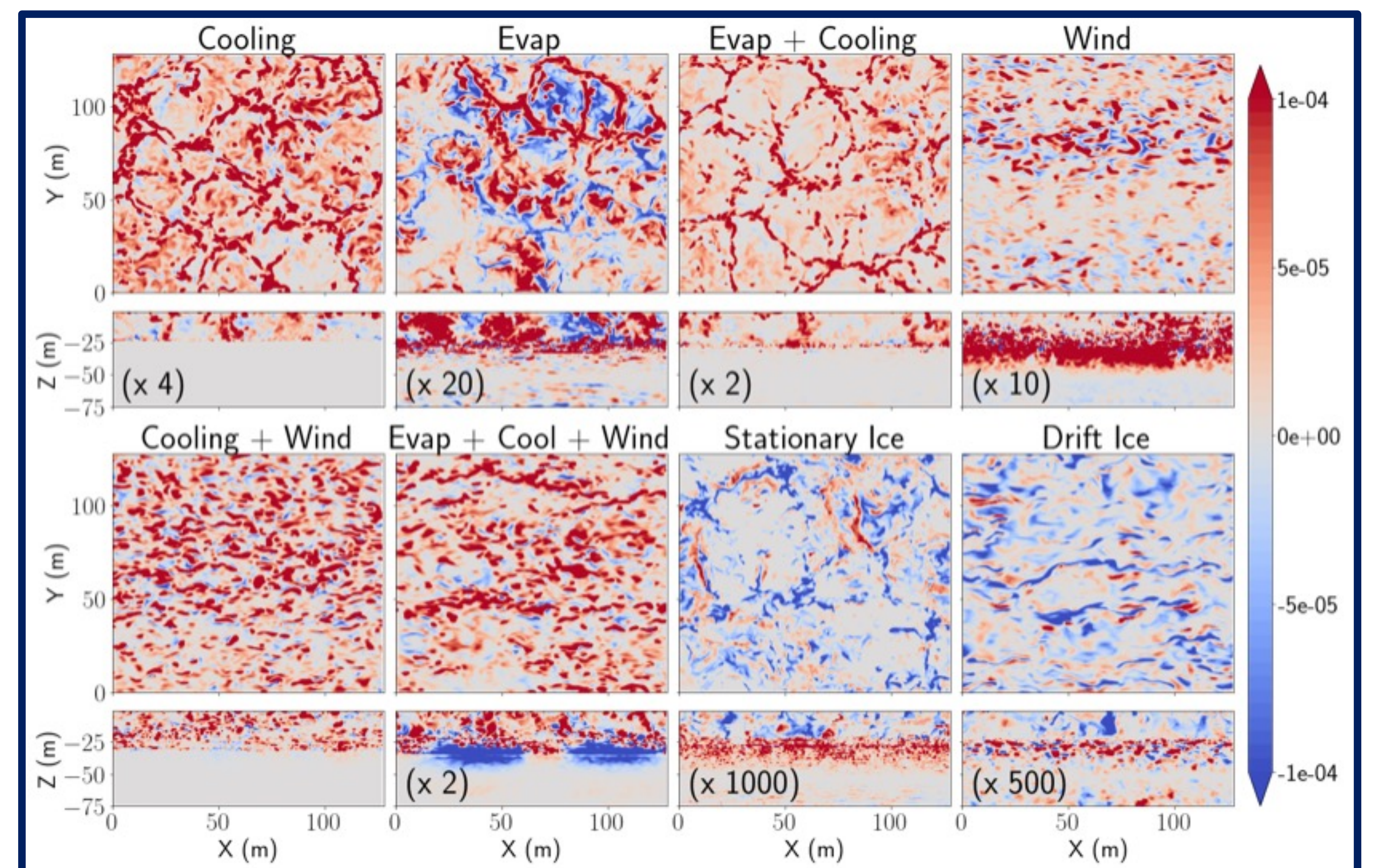
Horiz. And Vert. Slices of Heat Flux

Conclusions

What are the dominant mechanisms of vertical heat transport and mixing in the Arctic?

- Wind (and evaporation) has the largest effect on the mixed layer depth, TKE, heat entrainment, and heat flux

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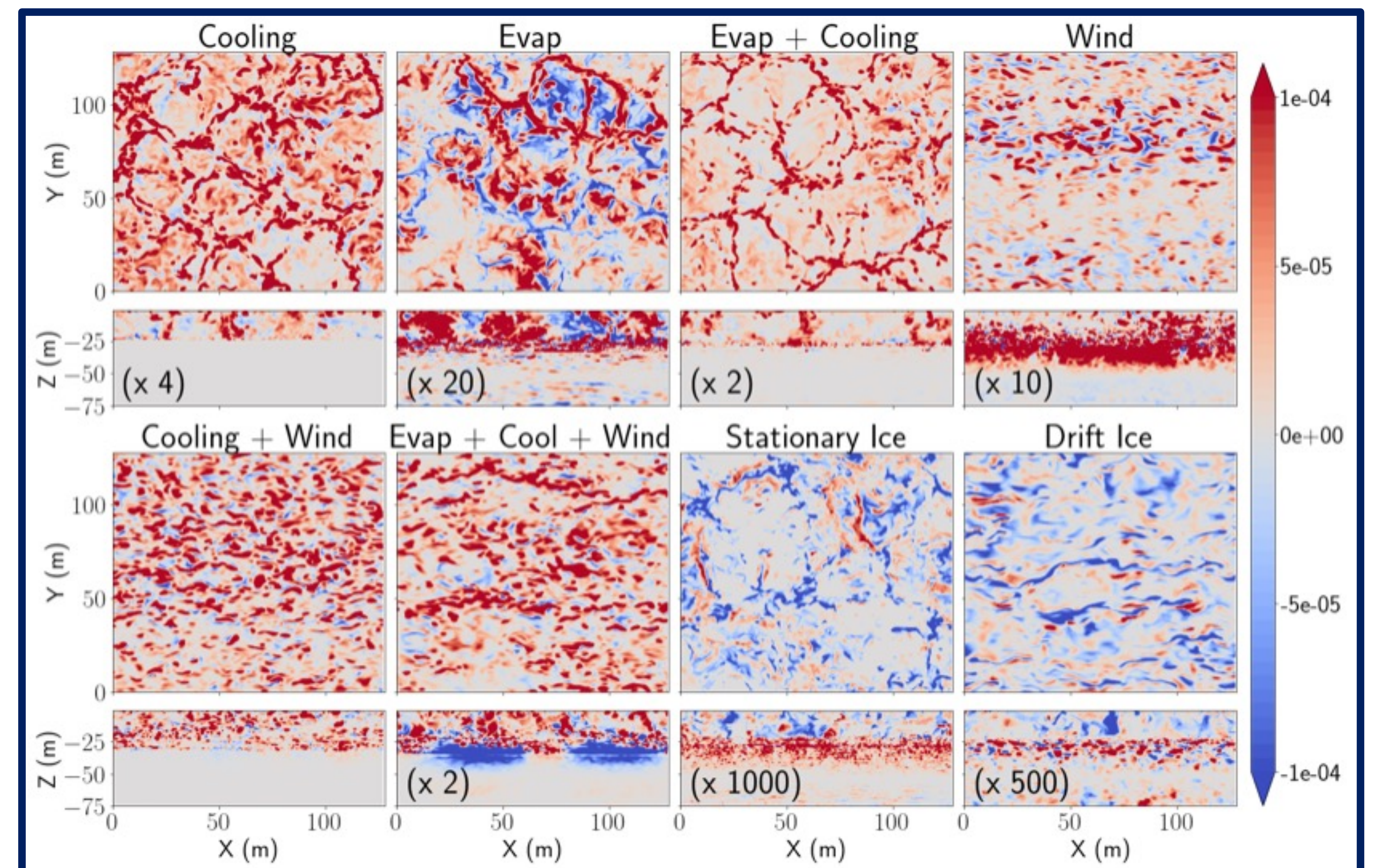
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Conclusions

What are the dominant mechanisms of vertical heat transport and mixing in the Arctic?

- Wind (and evaporation) has the largest effect on the mixed layer depth, TKE, heat entrainment, and heat flux
- Salinity dictates buoyancy flux and stability of pycnocline, not temperature

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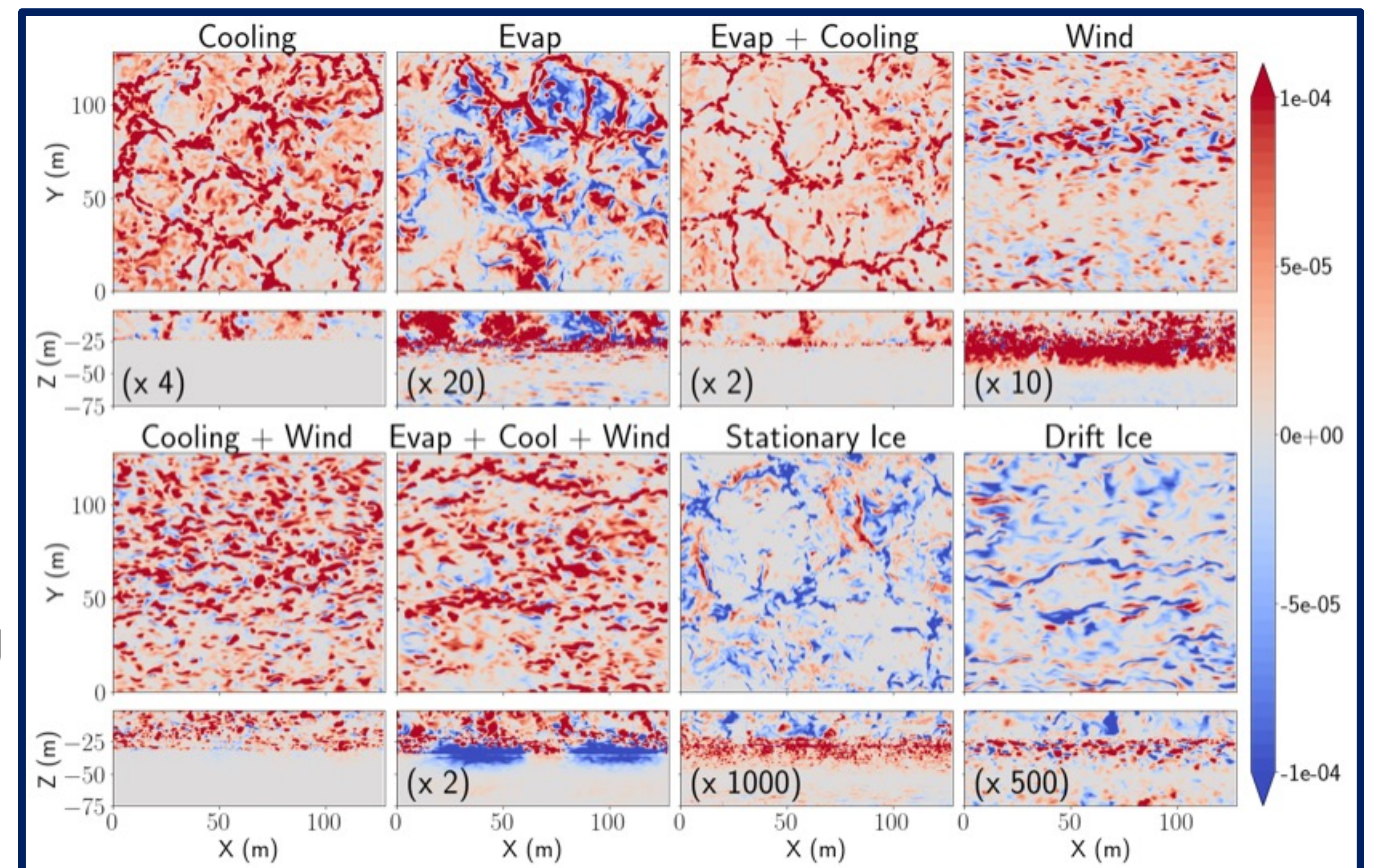
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- As the Arctic warms, its possible winter cooling will not be enough to overcome mixing effects of wind

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Horiz. And Vert. Slices of Heat Flux

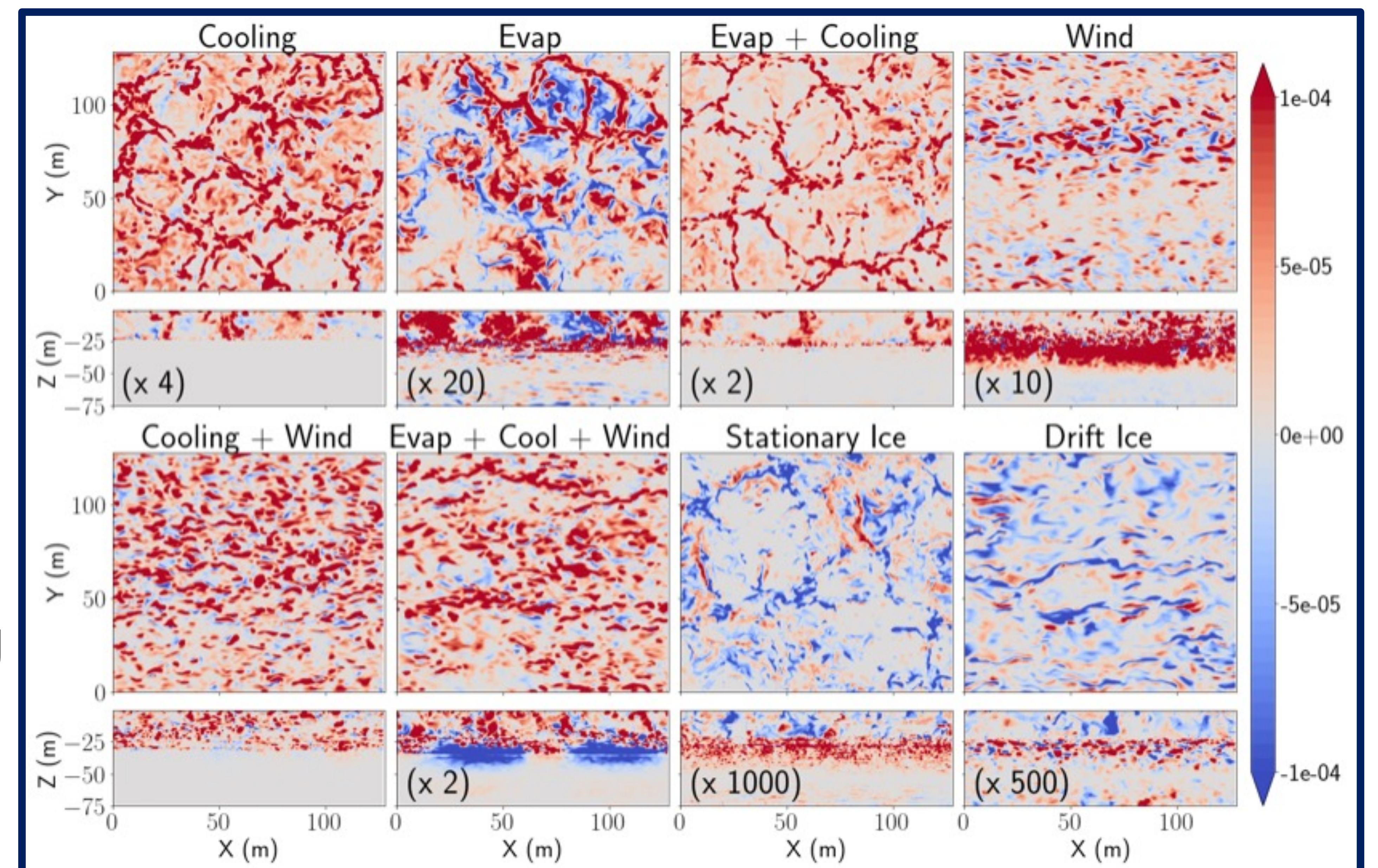
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Are these mechanisms captured by parameterizations?

- Convective forcing looks good, shear not so much

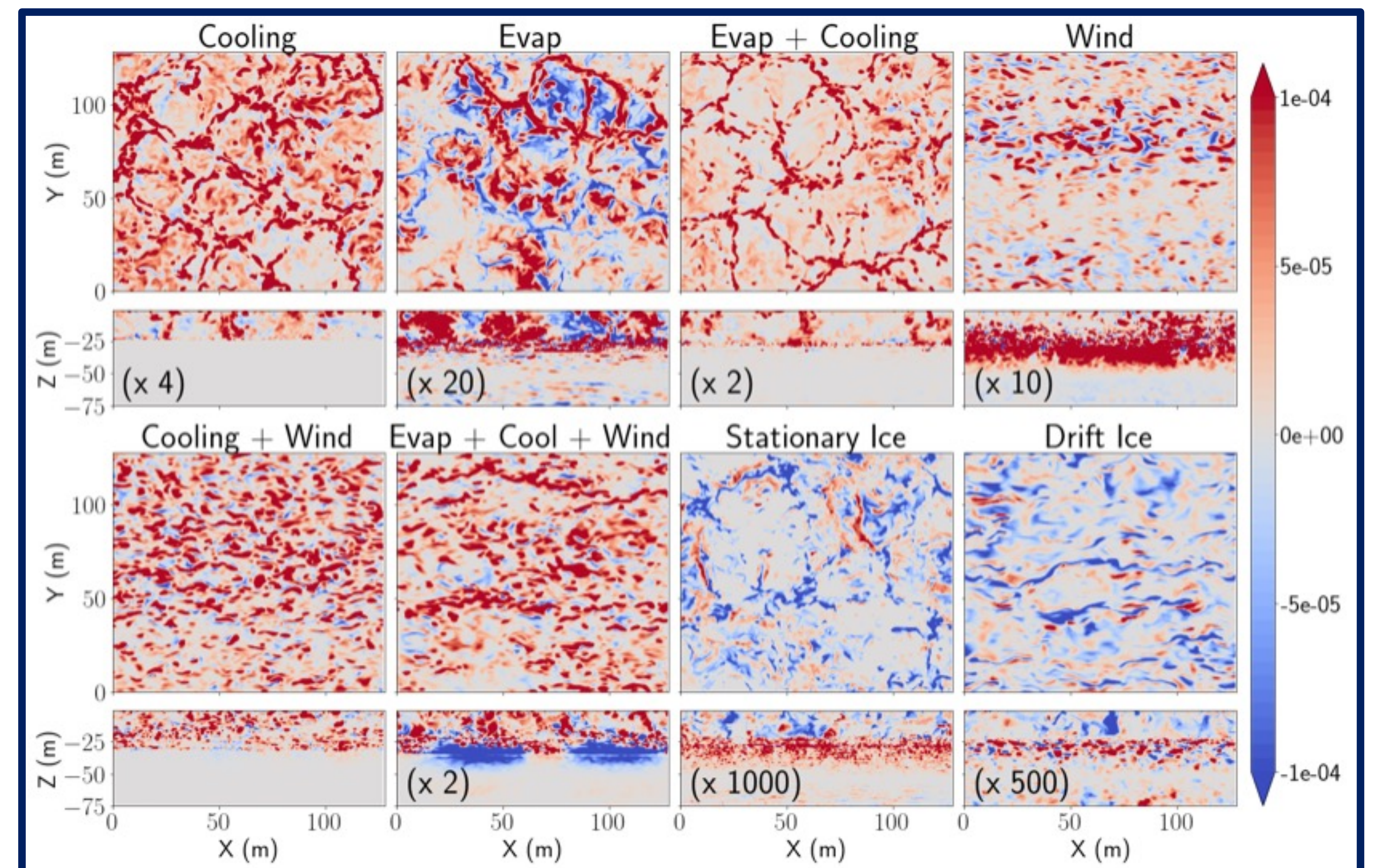


Horiz. And Vert. Slices of Heat Flux

Some Next Steps

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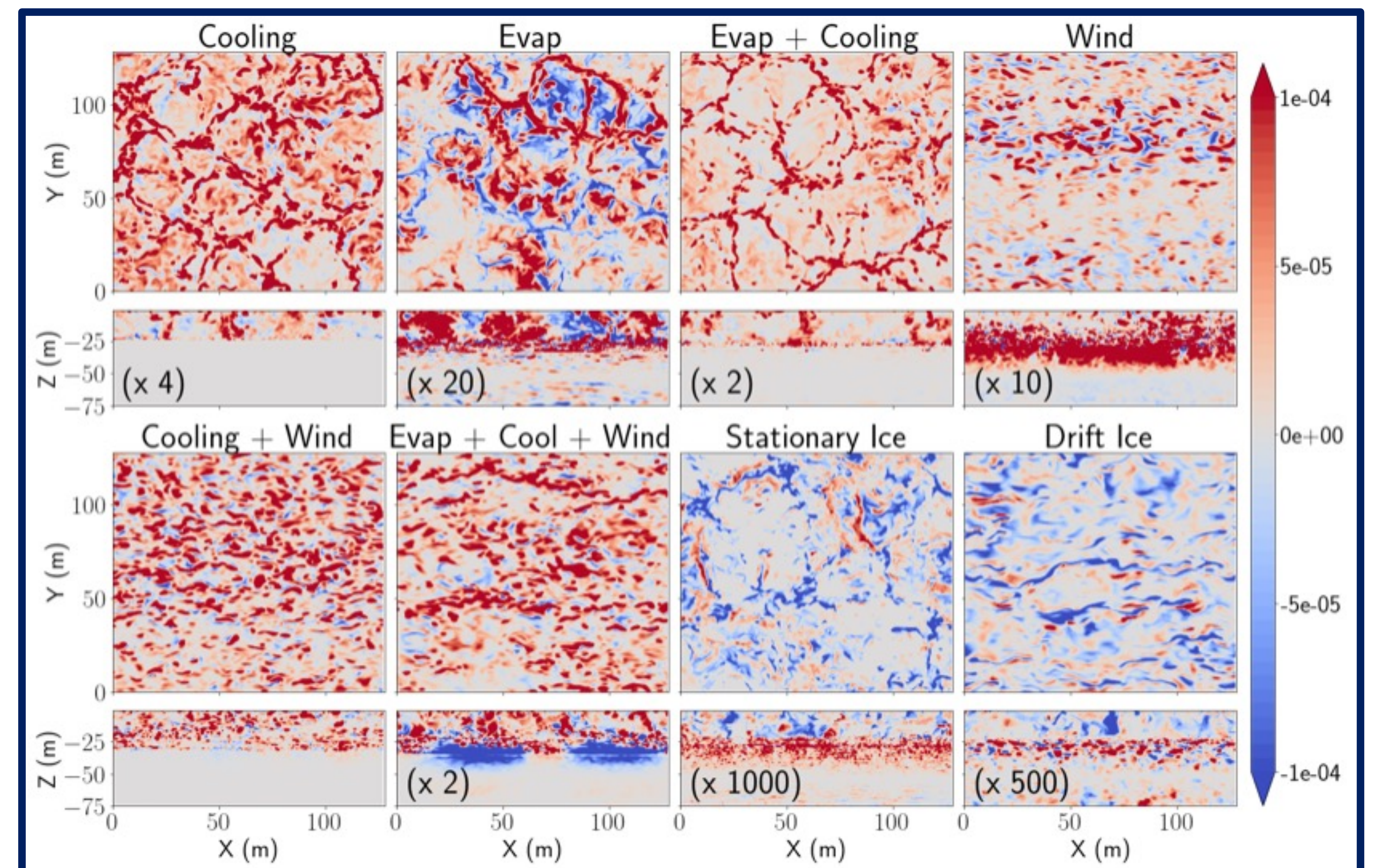
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- Adding more forcing scenarios/boundary conditions (river, coastal, etc)

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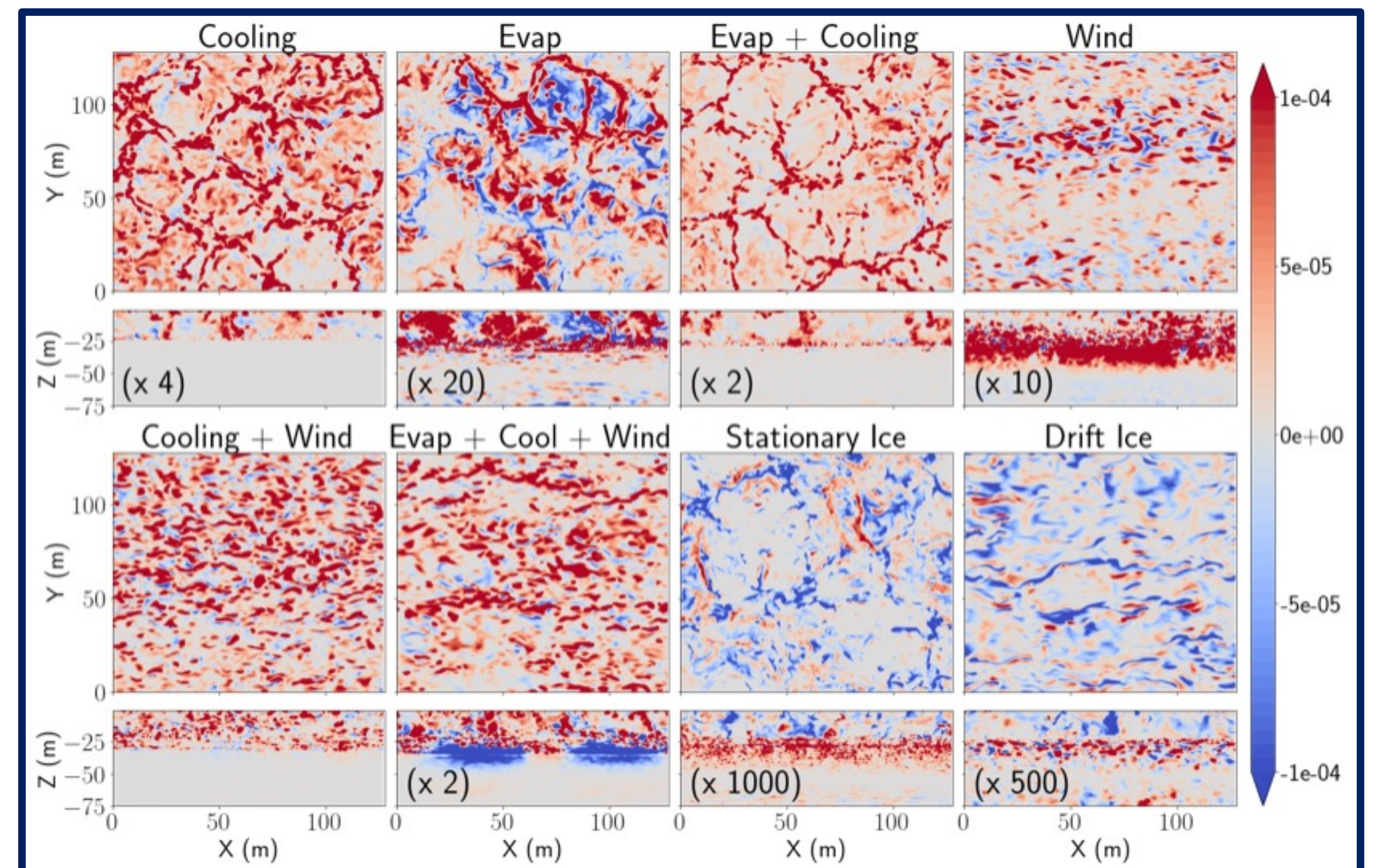
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Some Next Steps

What are the dominant mechanisms of vertical heat transport and mixing in the Arctic?

- Adding more forcing scenarios/boundary conditions (river, coastal, etc)
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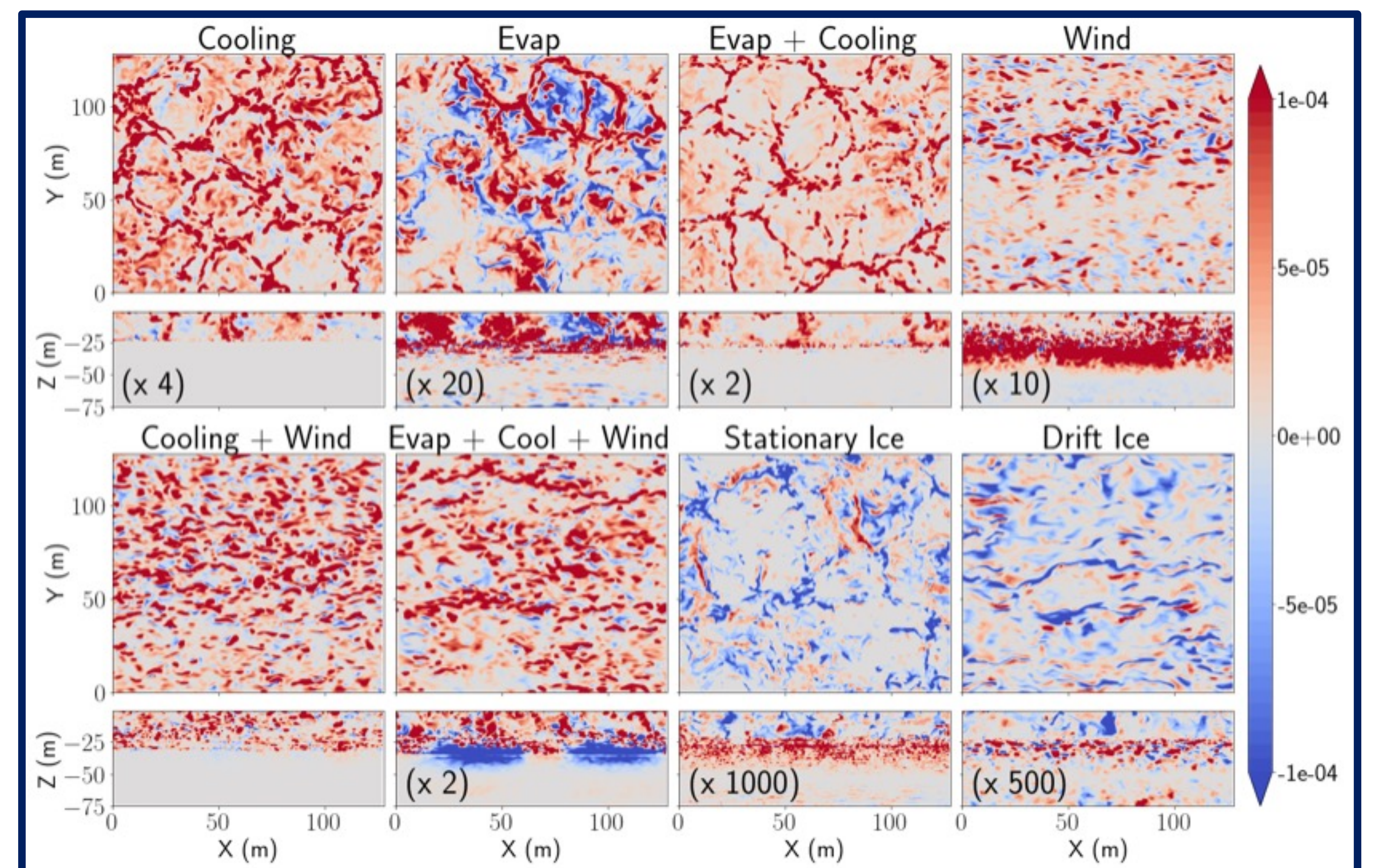
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Some Next Steps

What are the dominant mechanisms of vertical heat transport and mixing in the Arctic?

- Adding more forcing scenarios/boundary conditions (river, coastal, etc)
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- Include passive tracers injected along with surface heat and salt forcing

Are these mechanisms captured by parameterizations?



Horiz. And Vert. Slices of Heat Flux

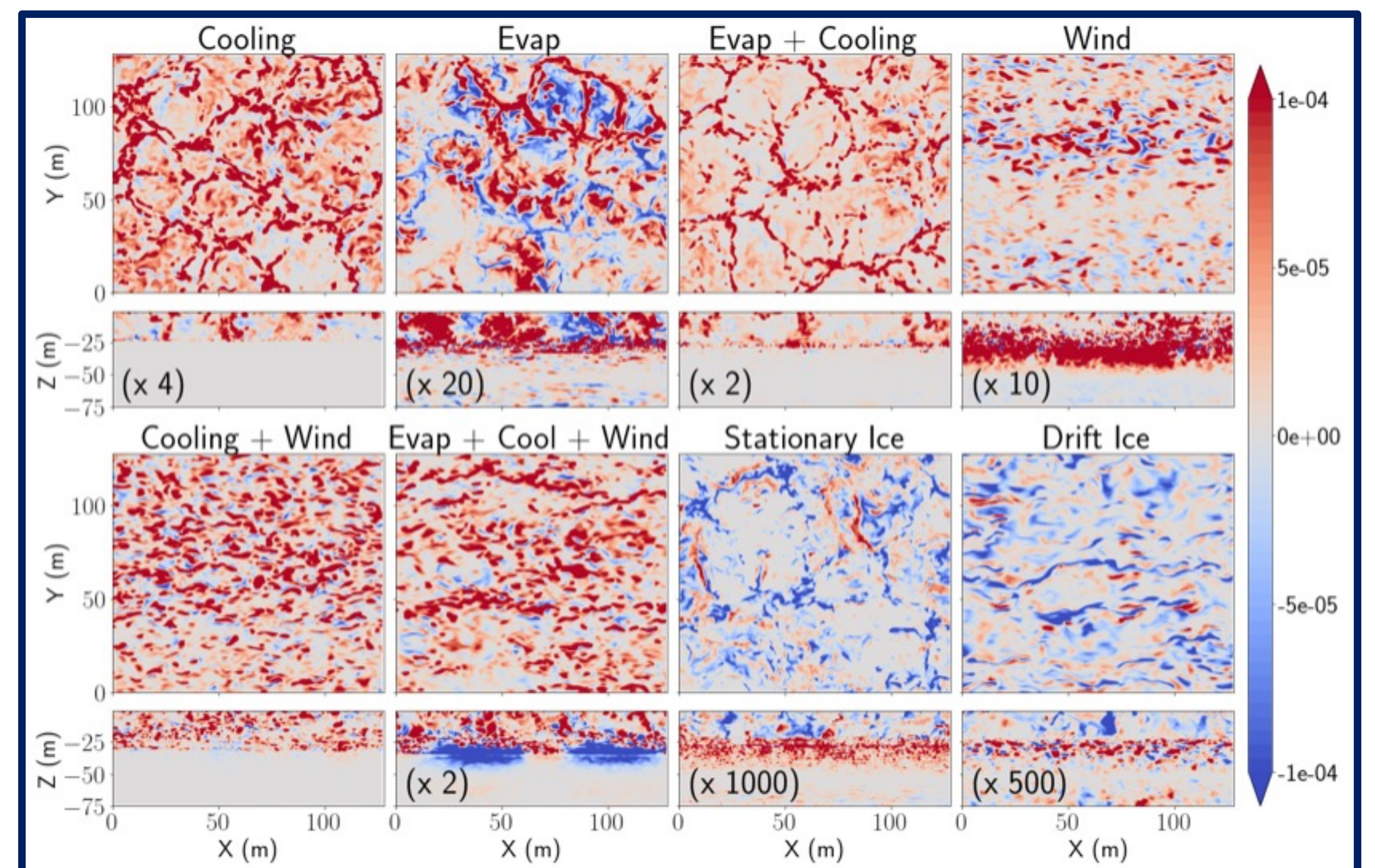
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- Does tuning remedy this? What mechanisms are missing?



Horiz. And Vert. Slices of Heat Flux

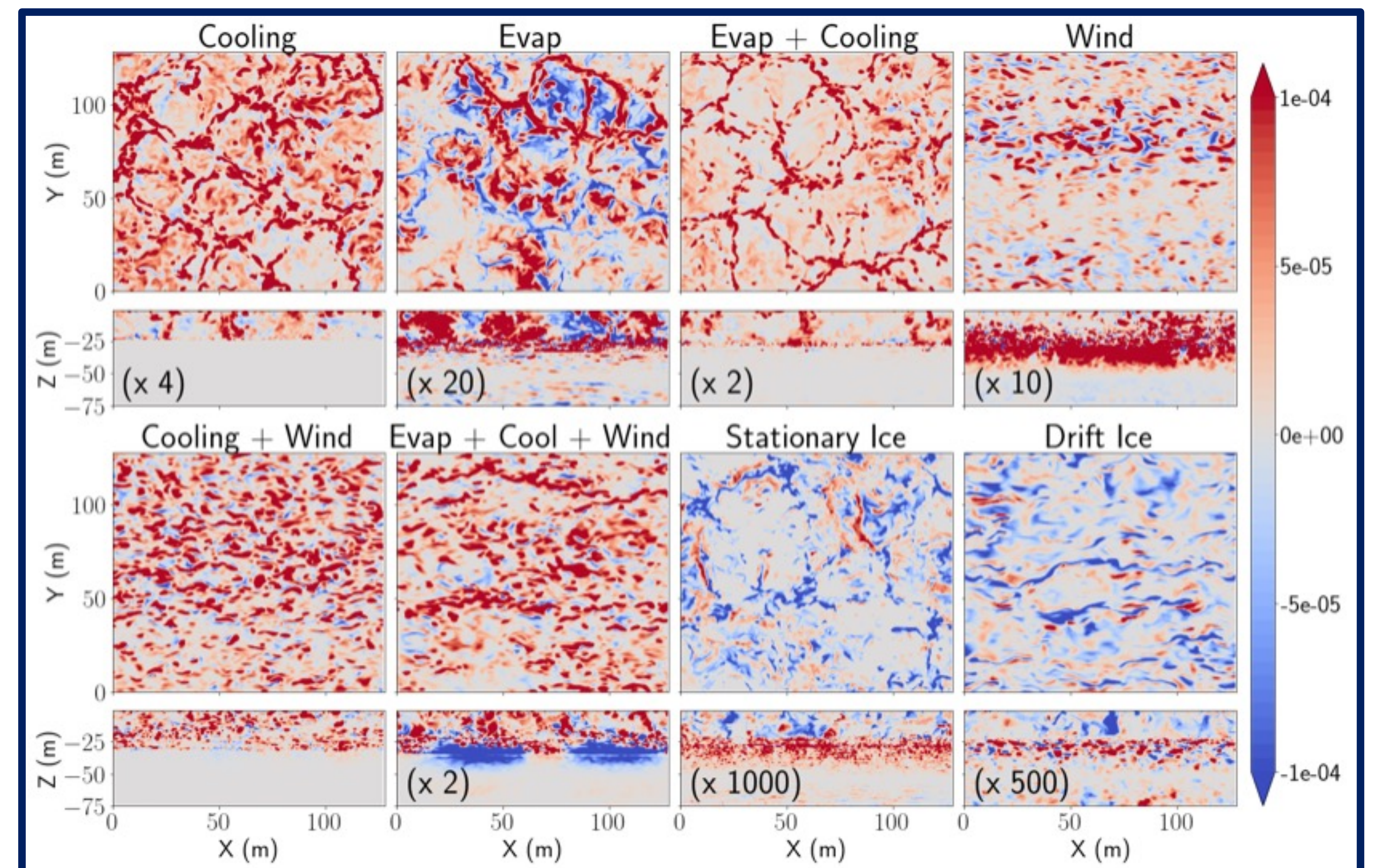
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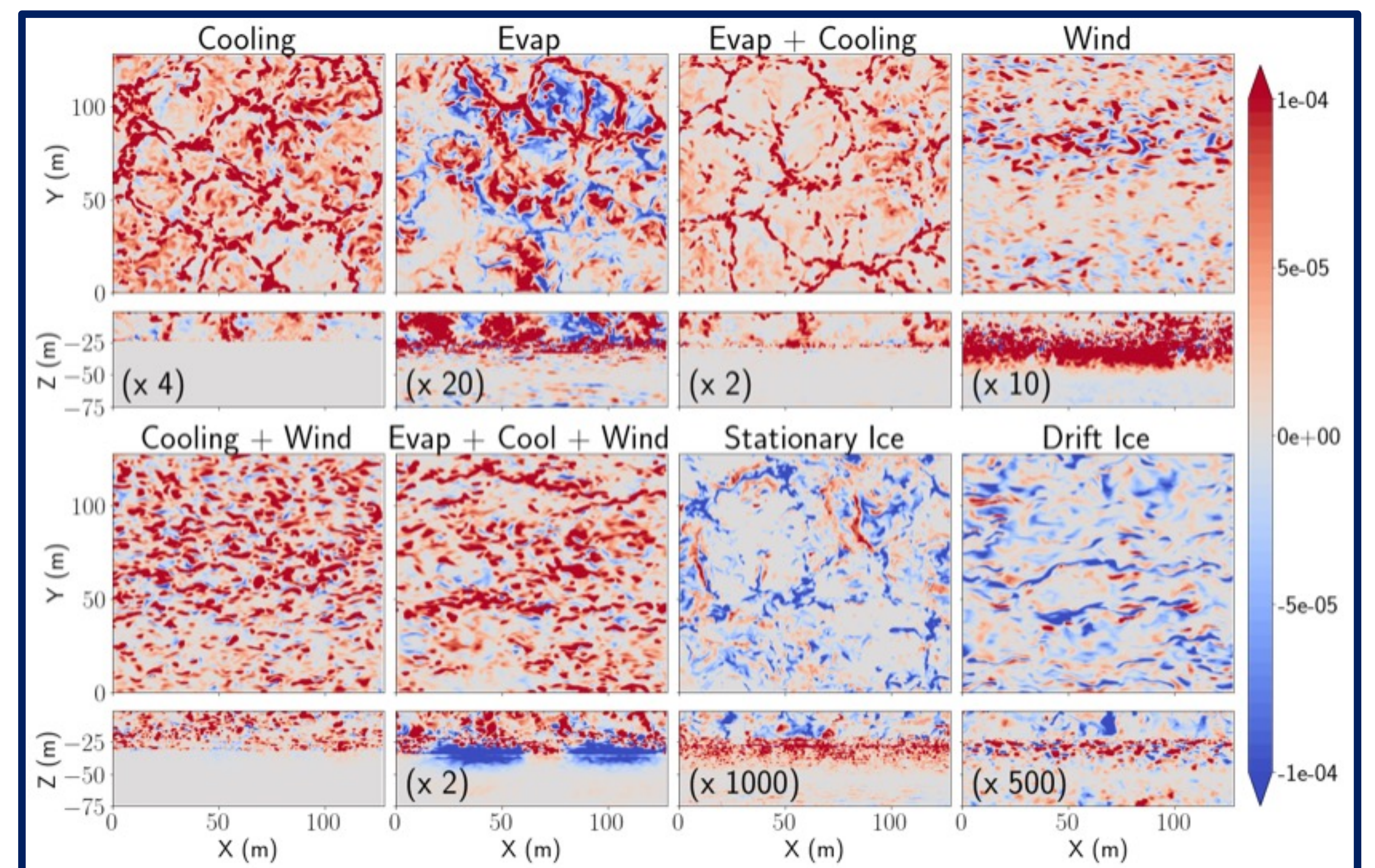
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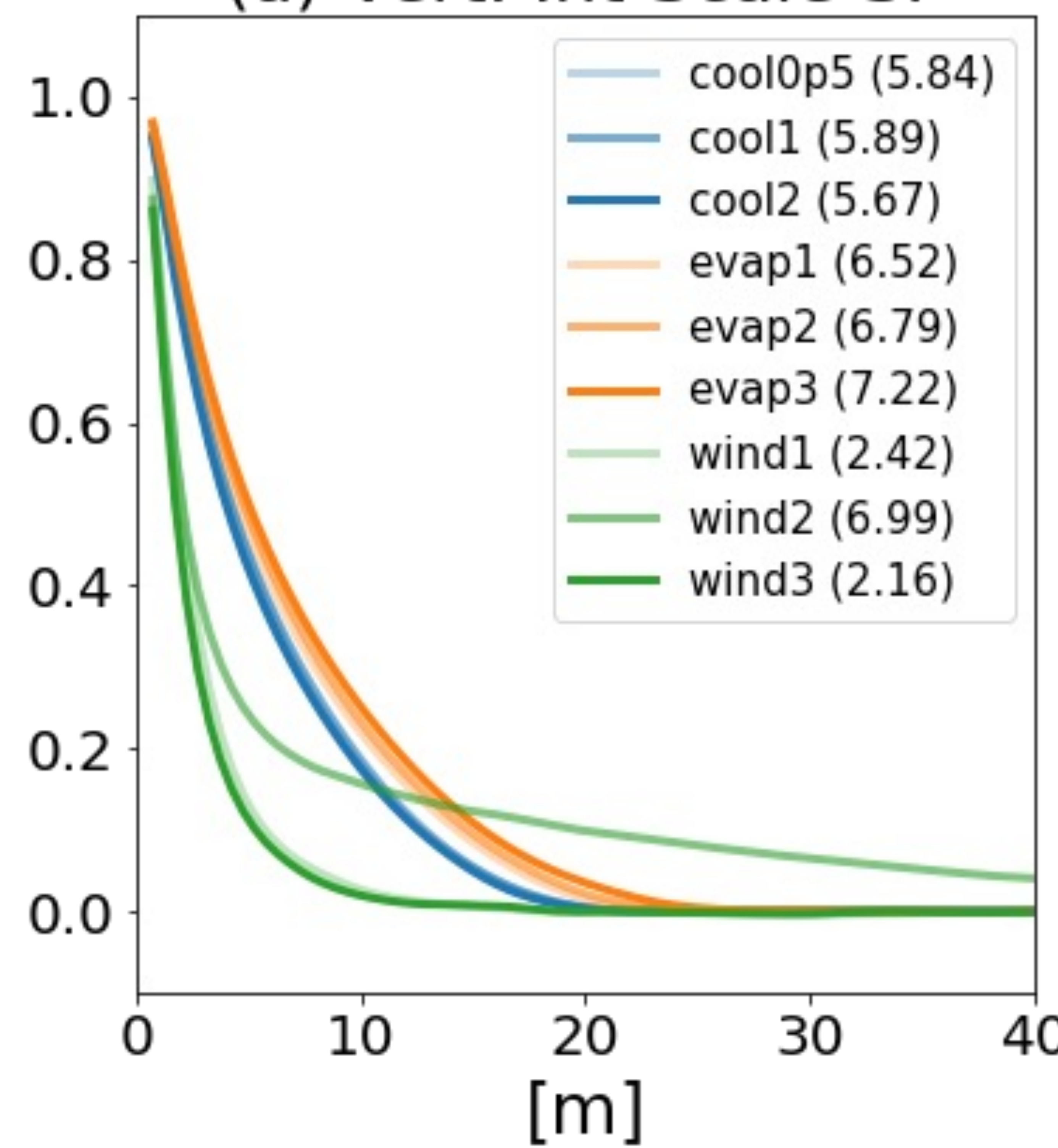
- Does tuning remedy this? What mechanisms are missing?
- Test more parameterizations (including new ADC model)
- Compare fluxes and higher order statistics



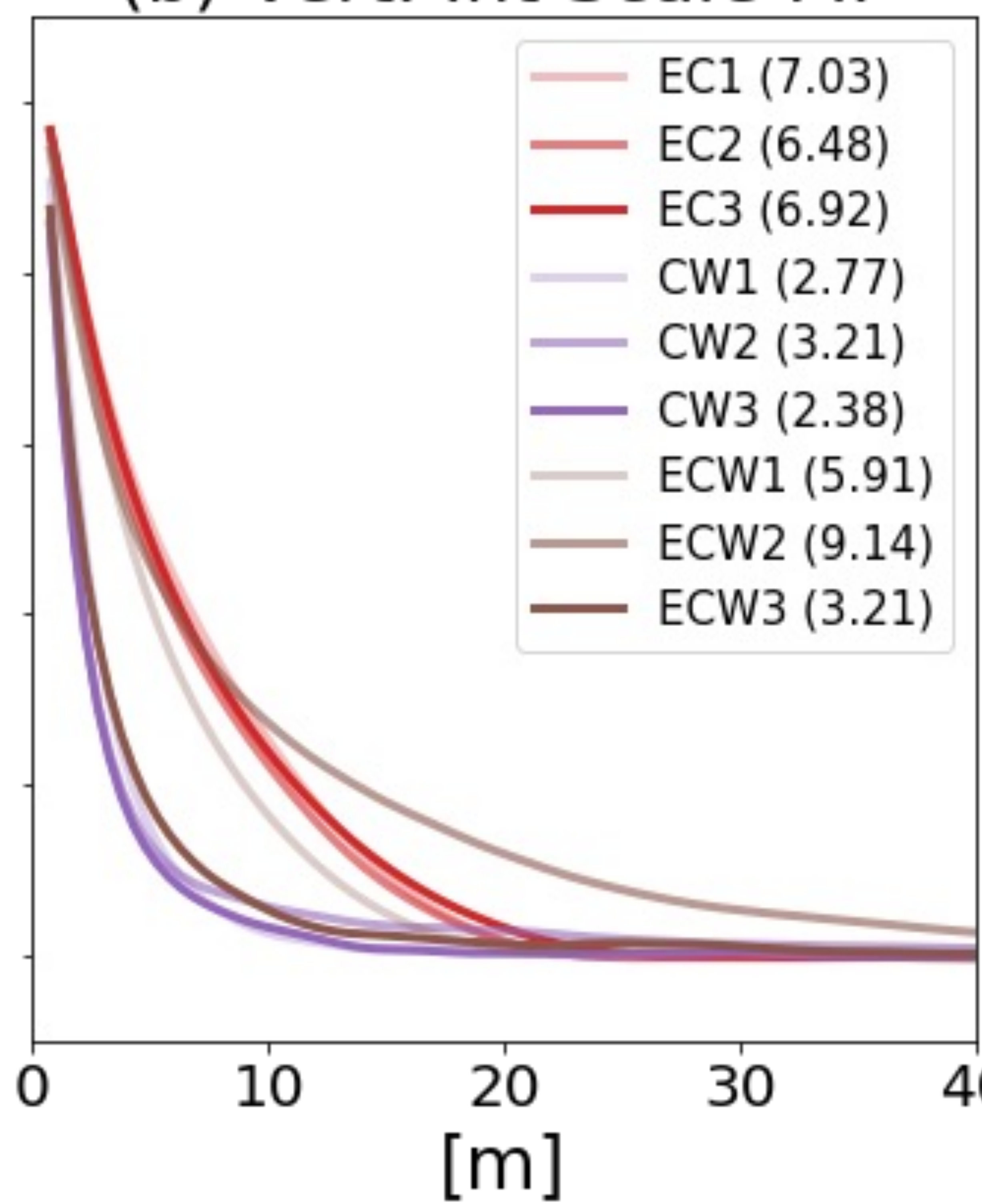
Horiz. And Vert. Slices of Heat Flux

Vertical Correlation Scale (Integral Scale)

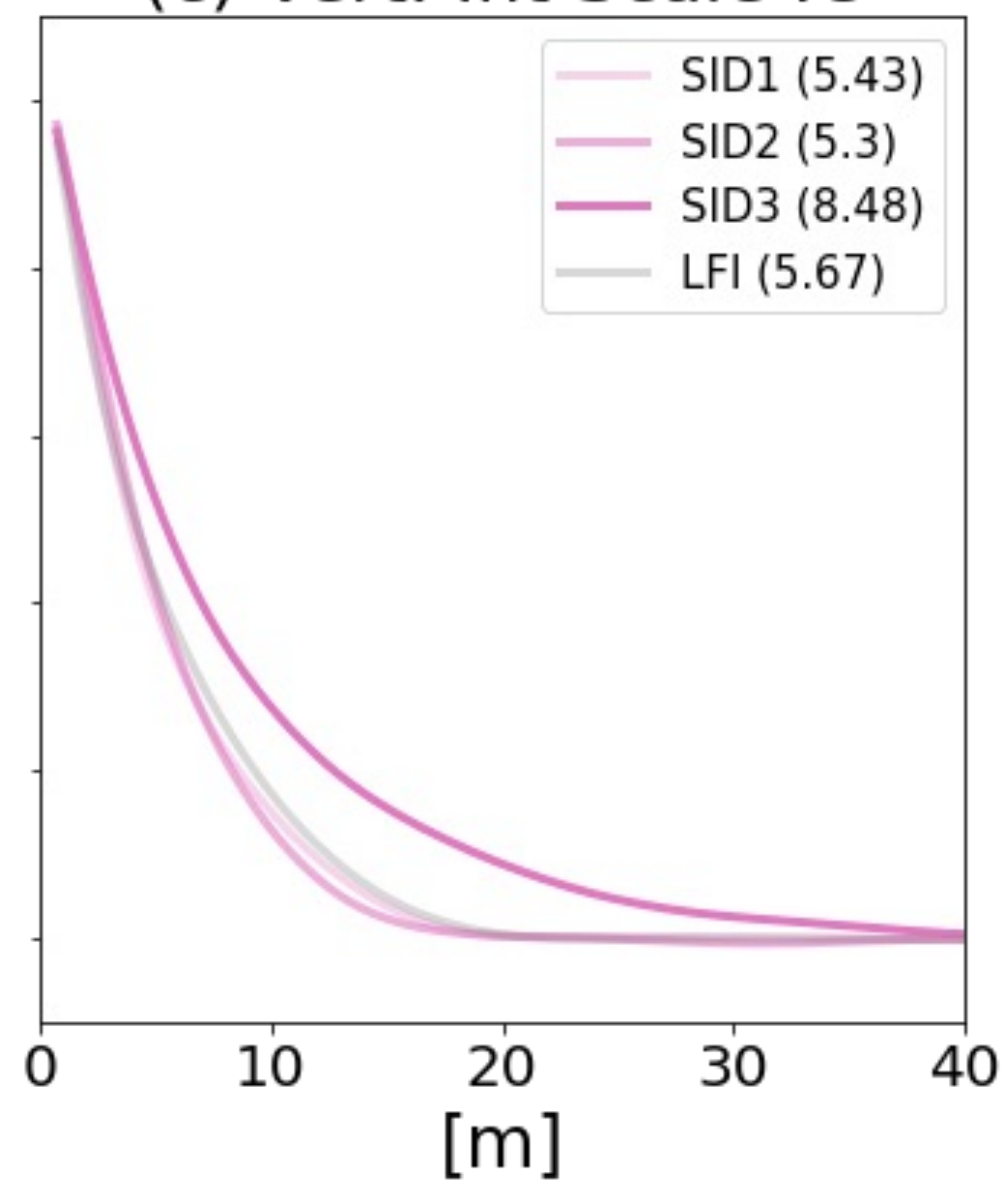
(a) Vert. Int Scale SF



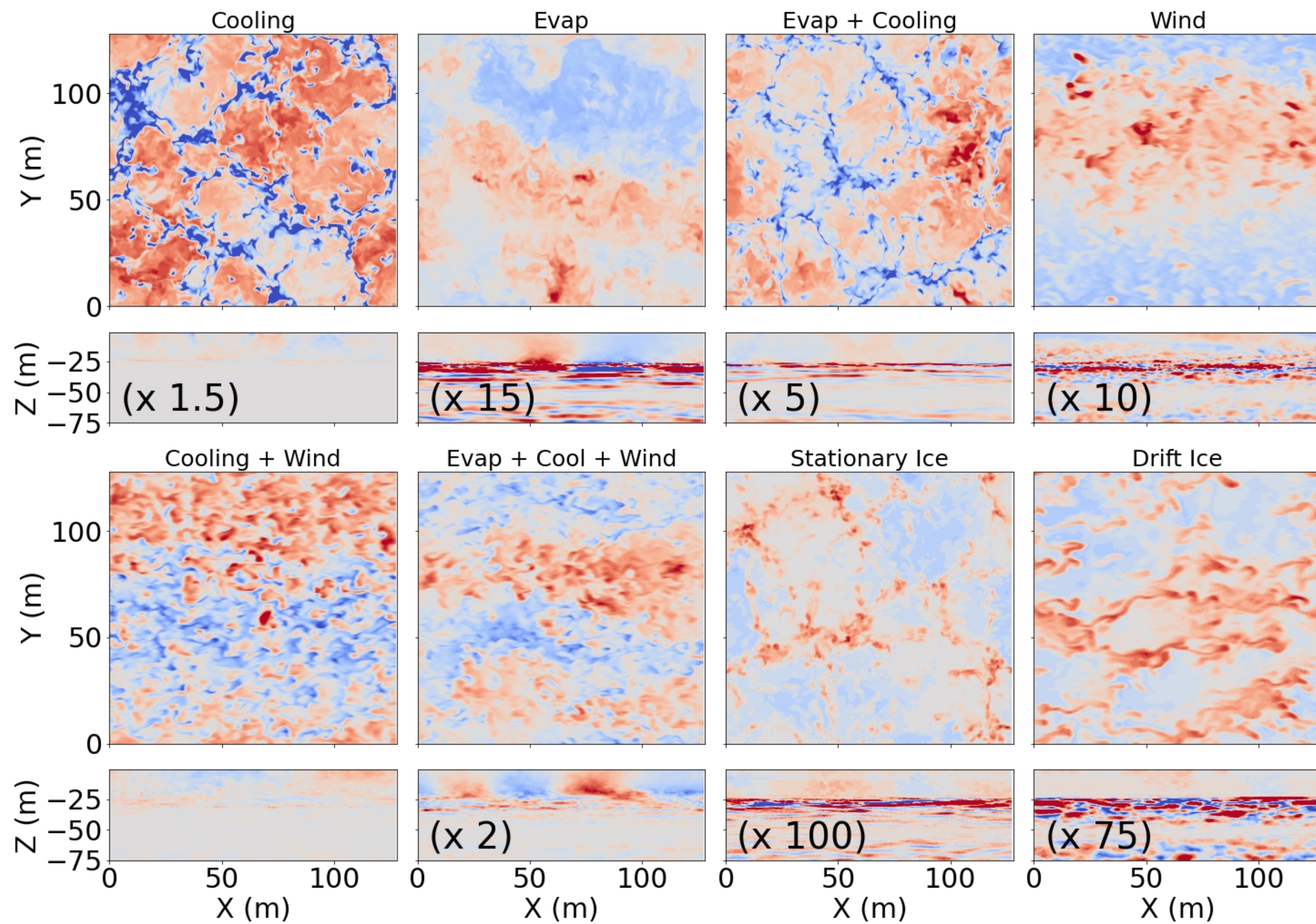
(b) Vert. Int Scale MF



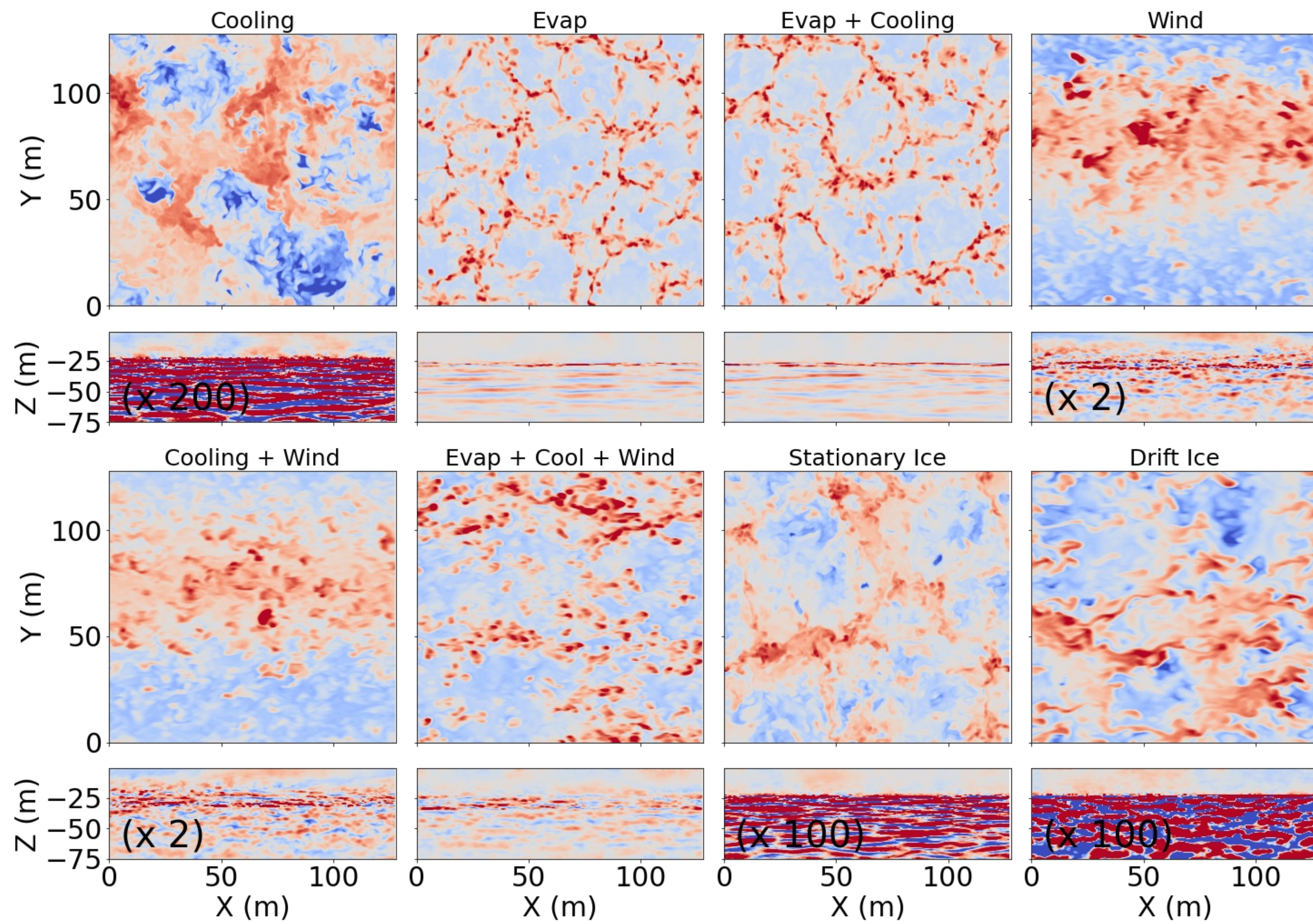
(c) Vert. Int Scale IC



Temp Slices

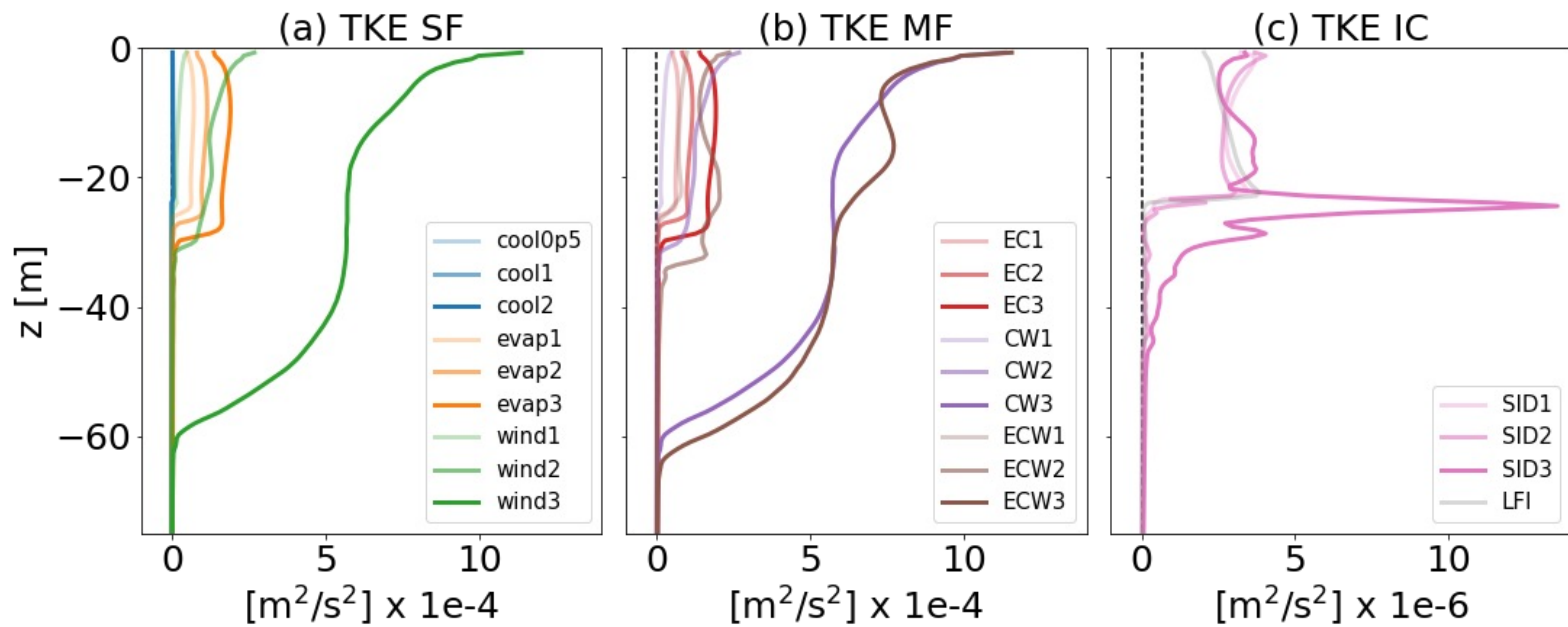


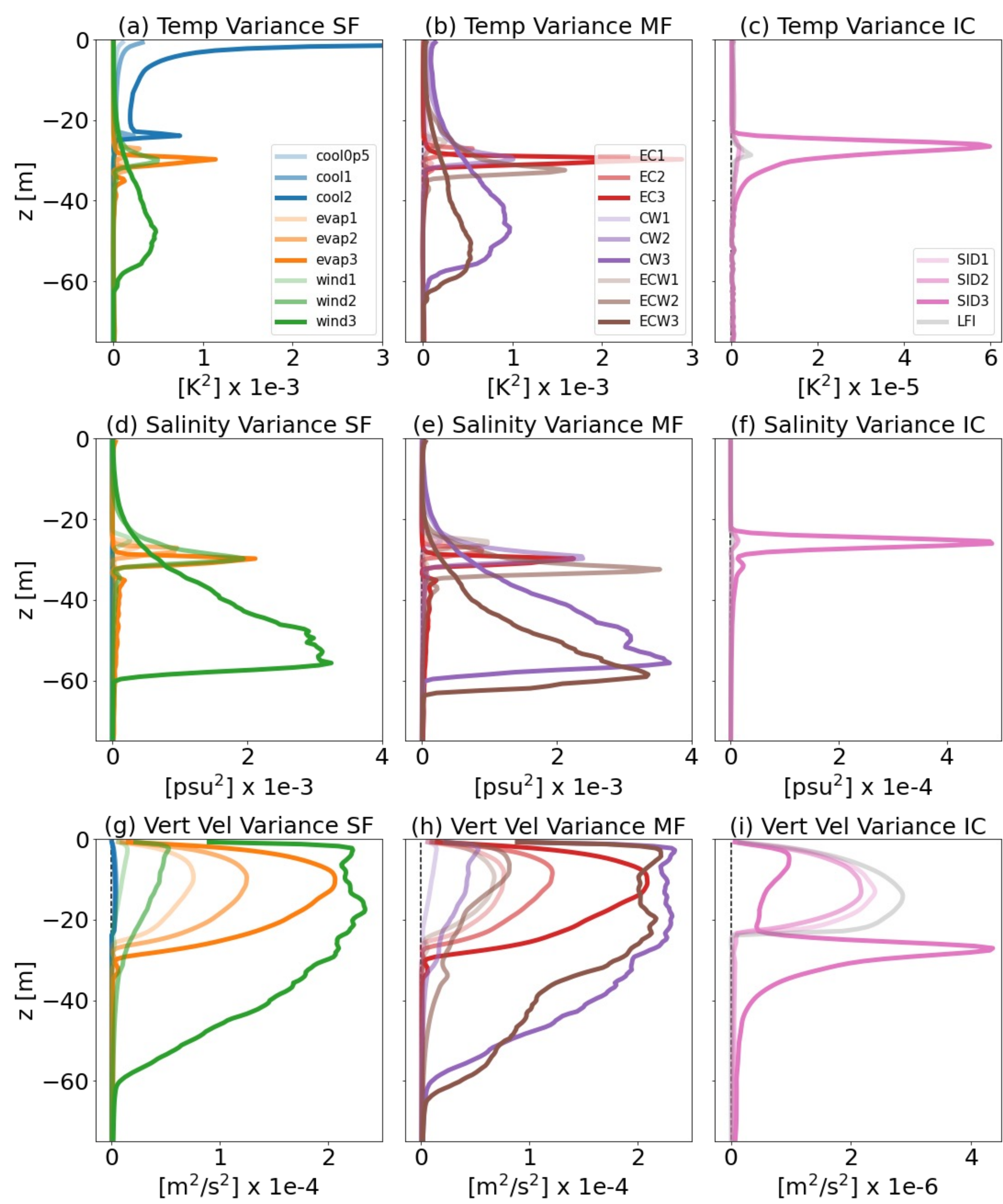
Salt Slices

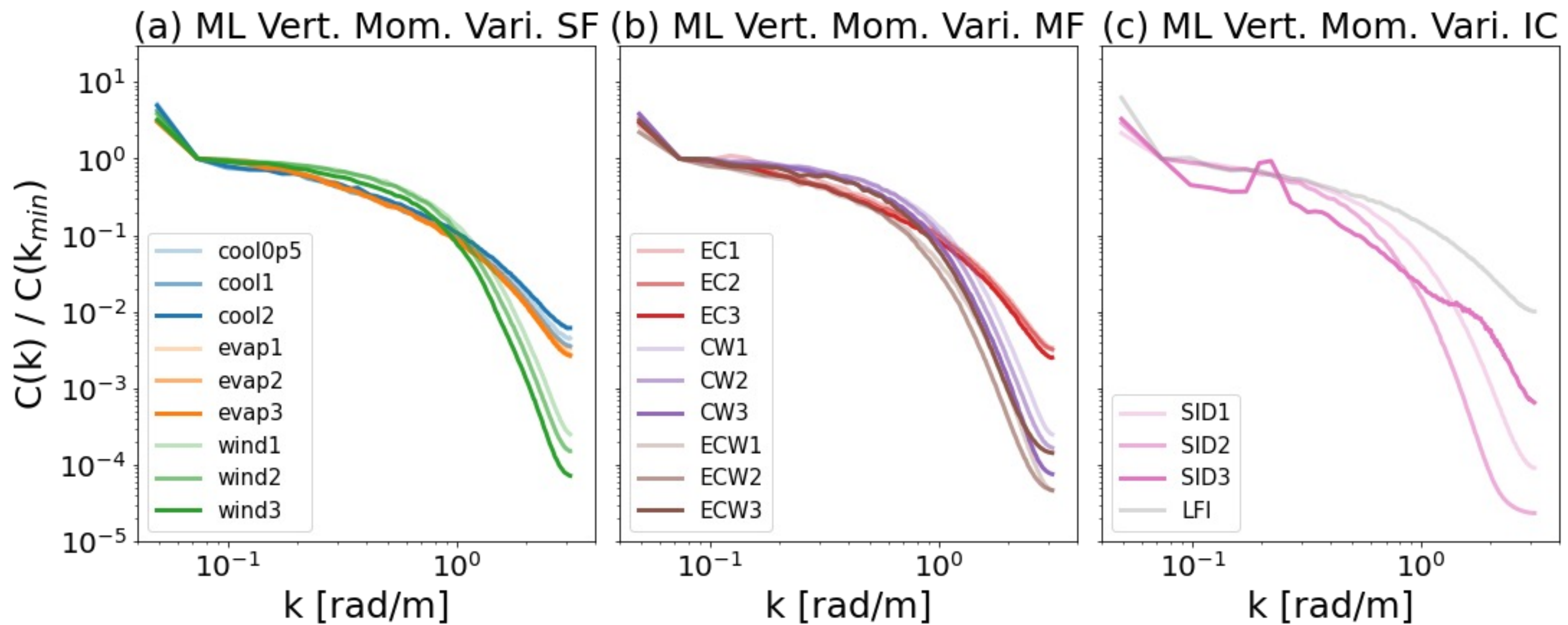


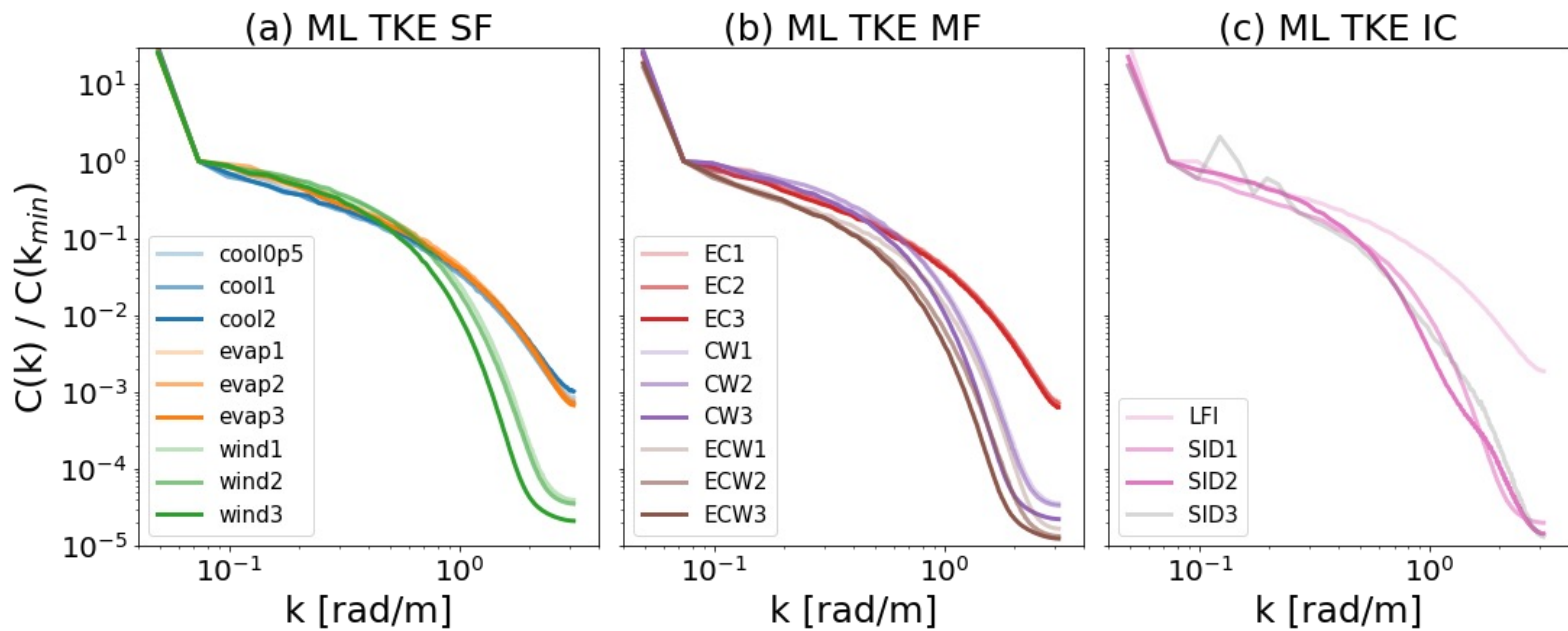
Mean TKE

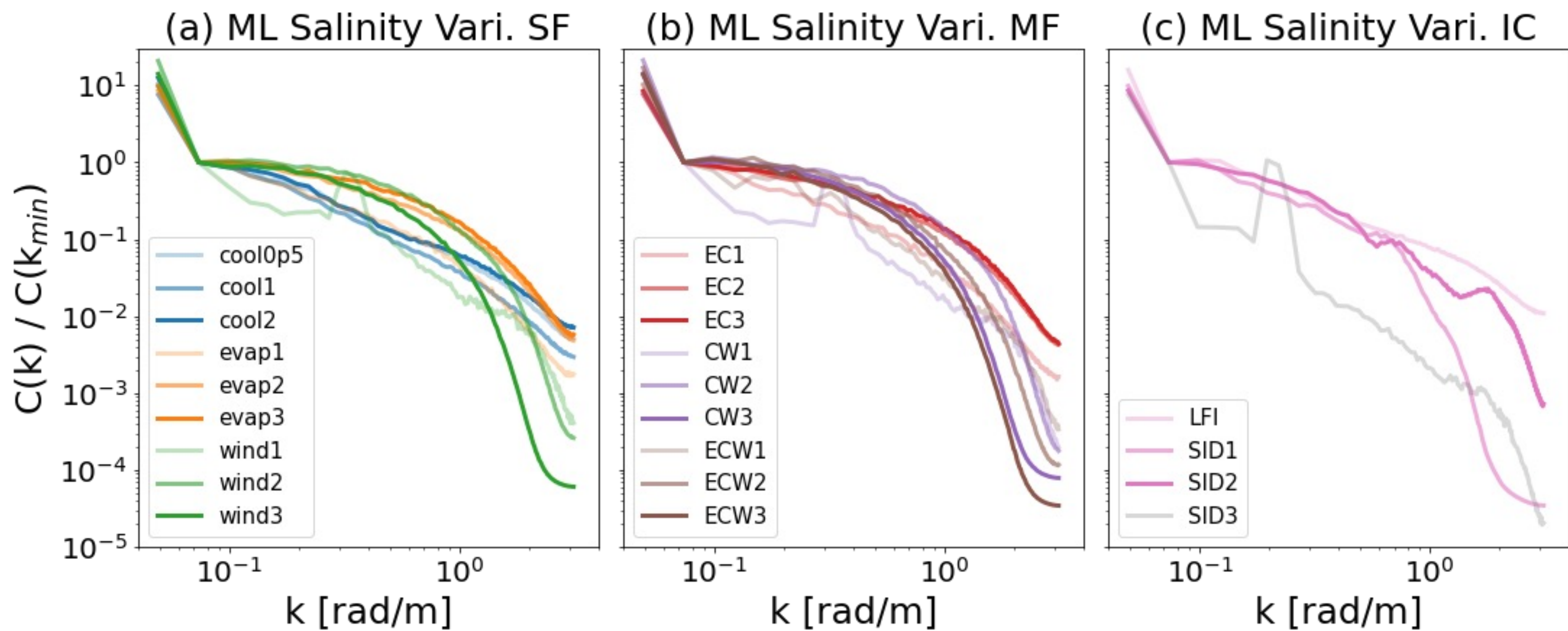
LA-UR-20-21004

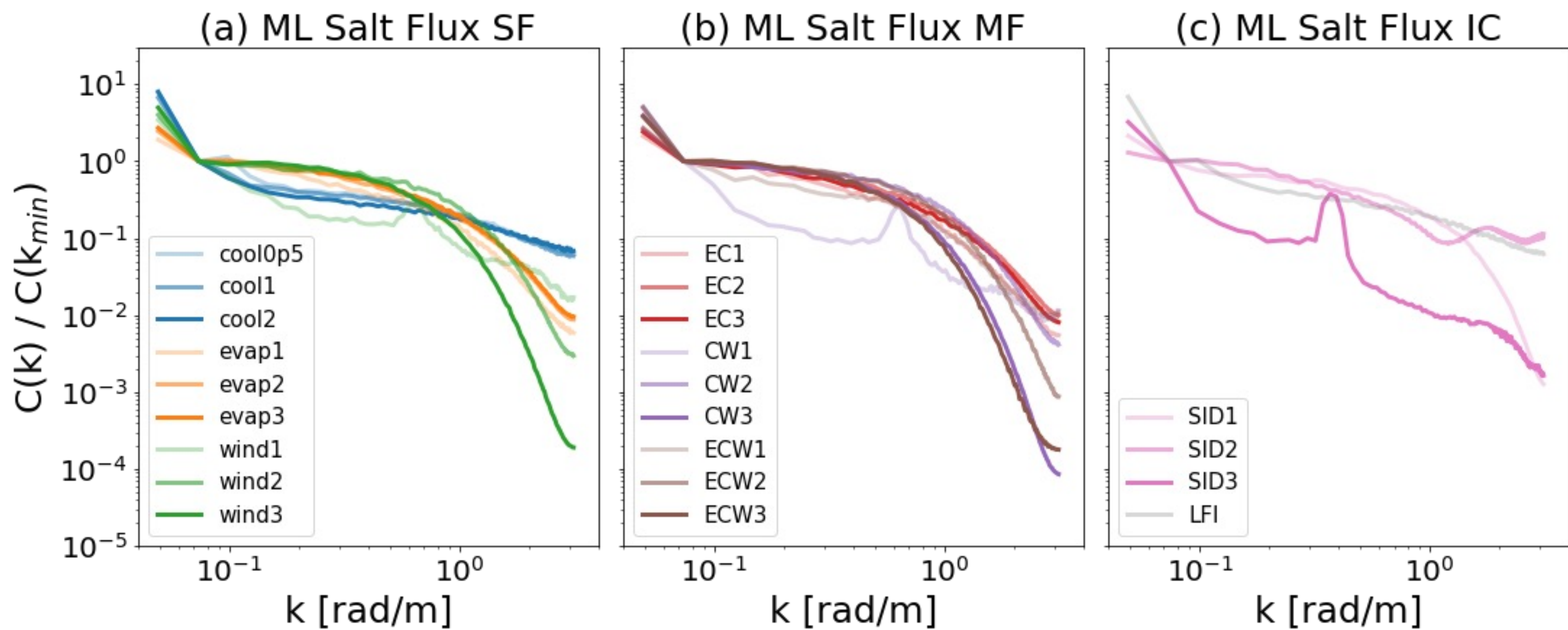




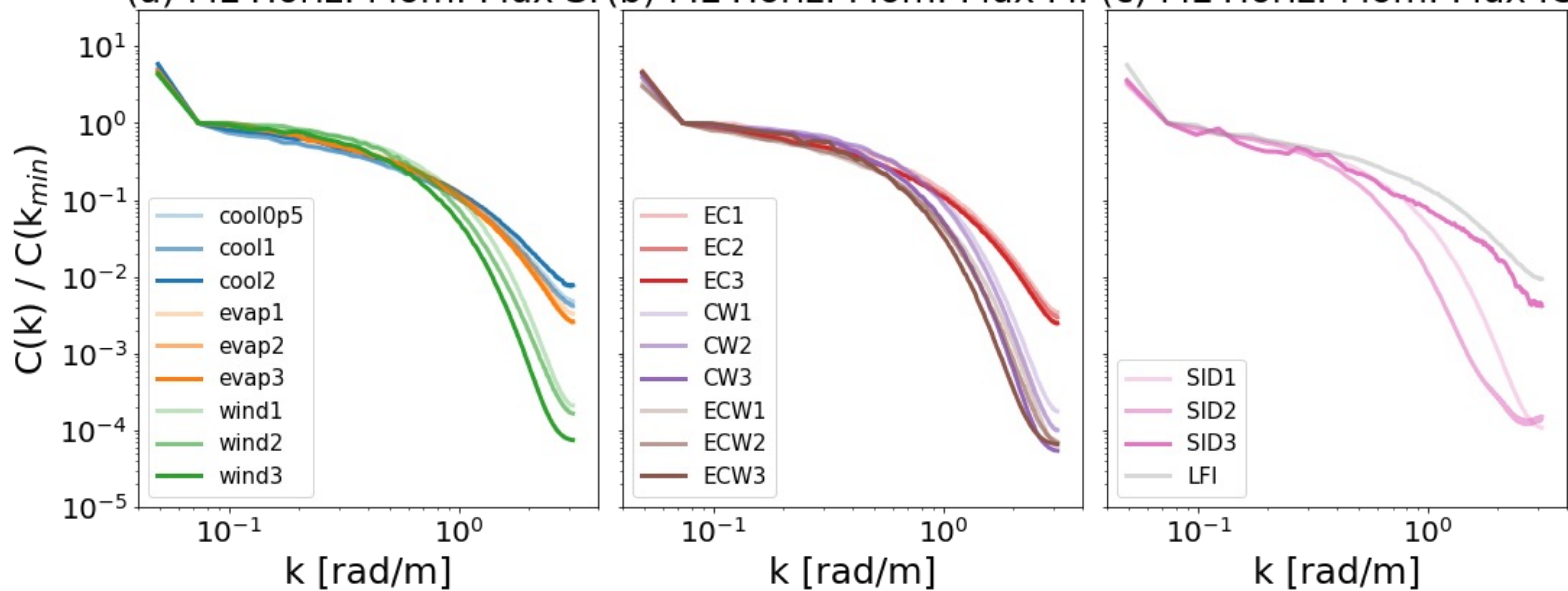




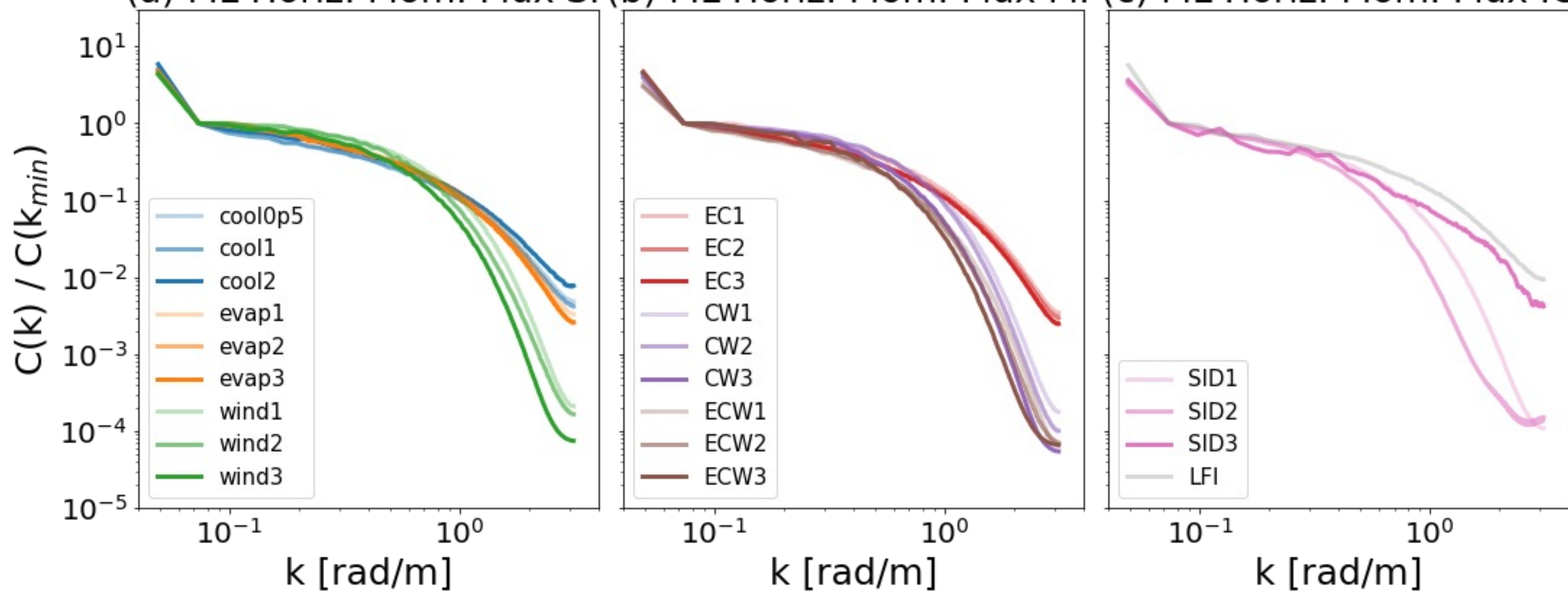




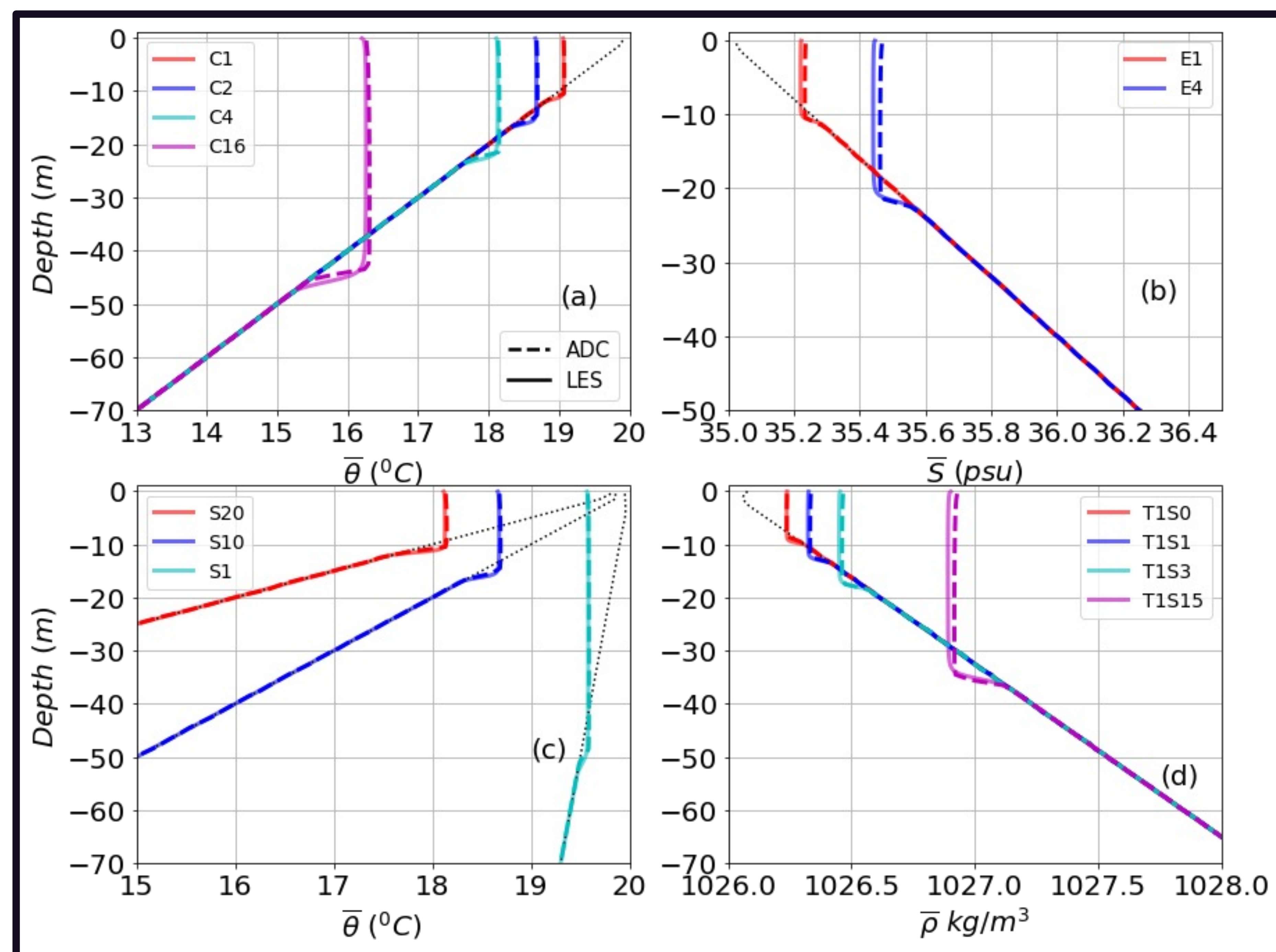
(a) ML Horiz. Mom. Flux SF (b) ML Horiz. Mom. Flux MF (c) ML Horiz. Mom. Flux IC



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Results - Parameterizations



New Assumed Distribution Closure (ADC) parameterization shows promise

Has not been tested for Arctic like conditions

Garanaik et al, *A new hybrid mass-flux/high-order turbulence closure for ocean vertical mixing*. JAMES, under review.