High-resolution Ocean Modeling

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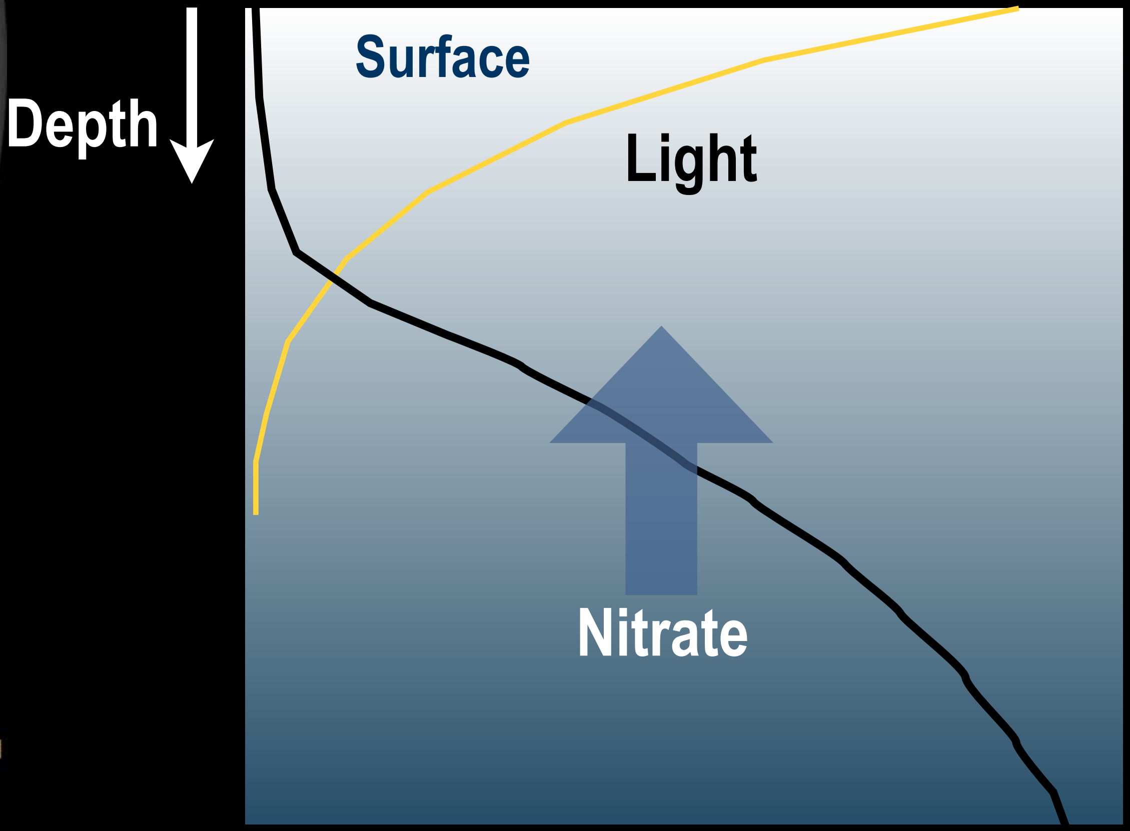
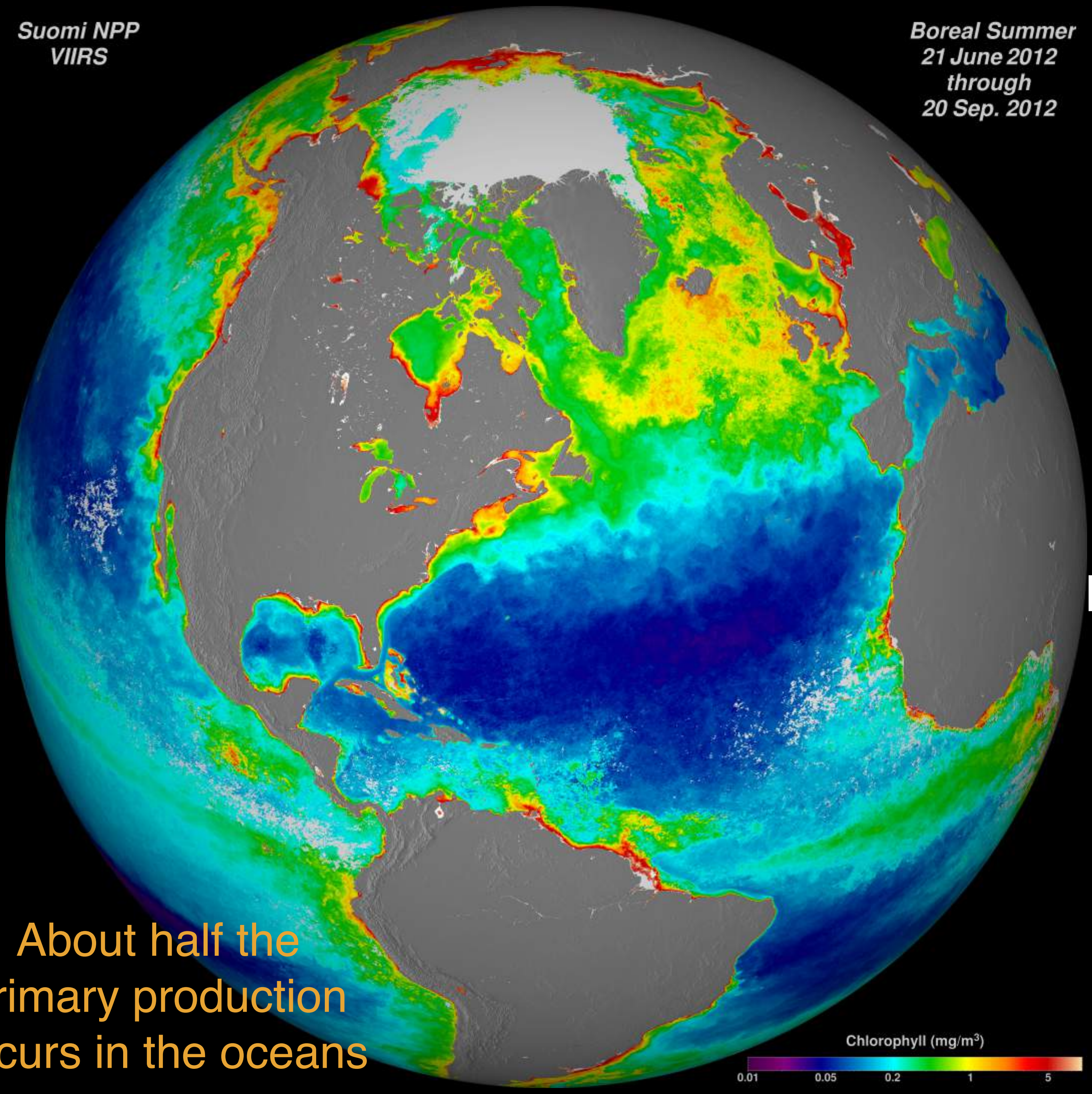
Vertical transport - how does it occur, where and when? What are the dynamics, space and time-scales? Implications: ecology, carbon cycle, oxygen, air-sea flux, SST, heat fluxes





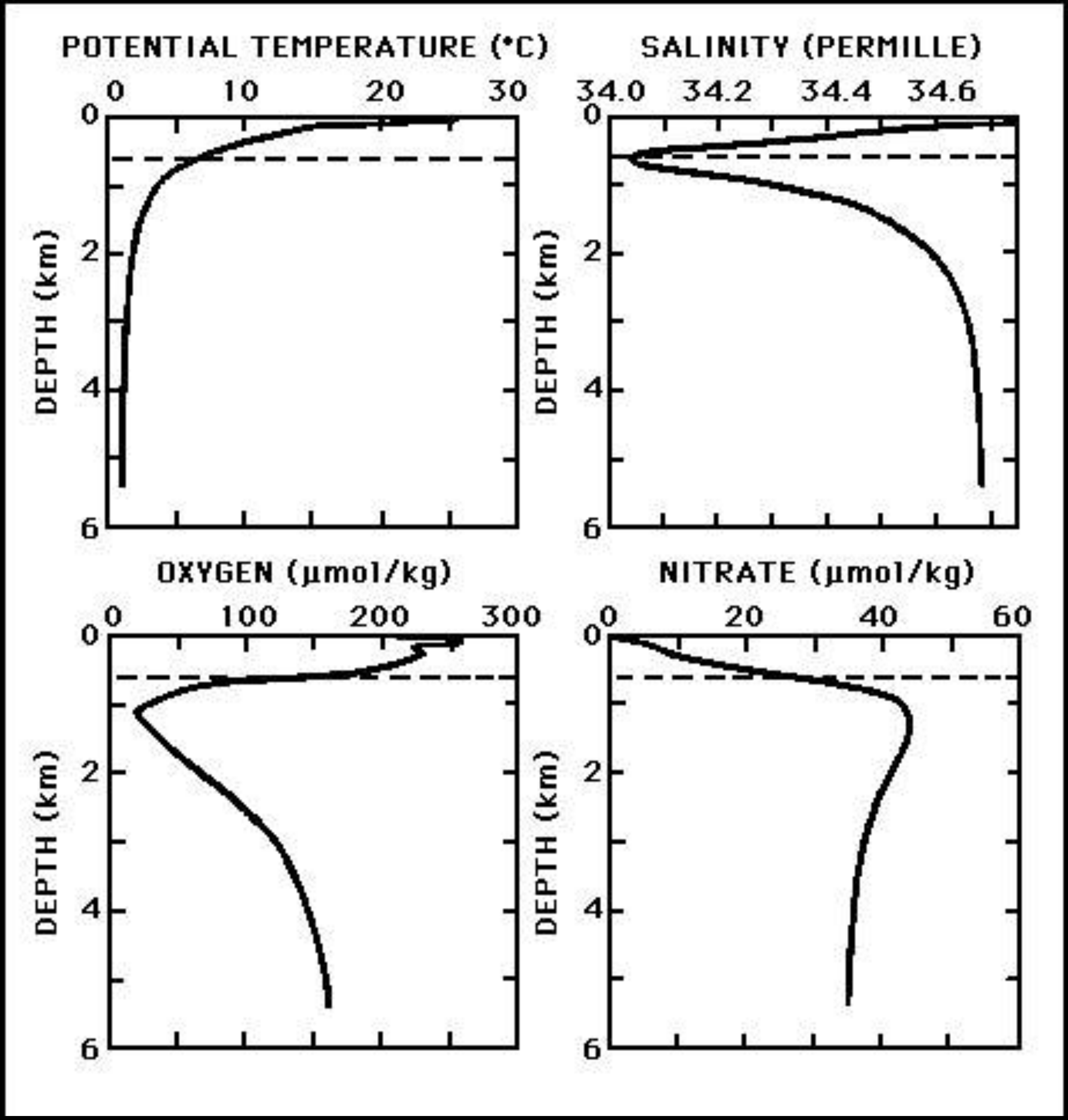
About half the primary production occurs in the oceans

Seasonal Composite of Ocean Chlorophyll

Credit: NASA SUOMI NPP VIIRS instrument, Norman Kuring

Vertical motion - occurs on multiple scales

Vertical profiles of T, S, O_2, NO_3



Basin scale	**Meridional overturning** form dense water, dense overflows
Meso-scale dynamics	**Wind stress curl, topography** **Ekman pumping, coastal upwelling** **Uplift of isopycnal surfaces** (eddies / fronts)
Submeso-scale dynamics	**Advective transport** (along isopycnal)
	Internal waves
Small scale mixing	**Mixing and mixed layer entrainment**

Vertical Transport?

High Resolution Modeling

~ O(1 km) horizontal, ~ O(1 m) vertical resolution

Why higher resolution? What are we missing in coarser resolution models?

Submesoscale dynamics

- **Vertical transport**
- **Restratification by eddies**
- **Topographic interaction**
- **Internal waves**

Biogeochemical implications - production and export of phytoplankton carbon/oxygen

In this talk:
Processes that we are understanding through high-resolution process studies

Fronts: Lateral density gradients

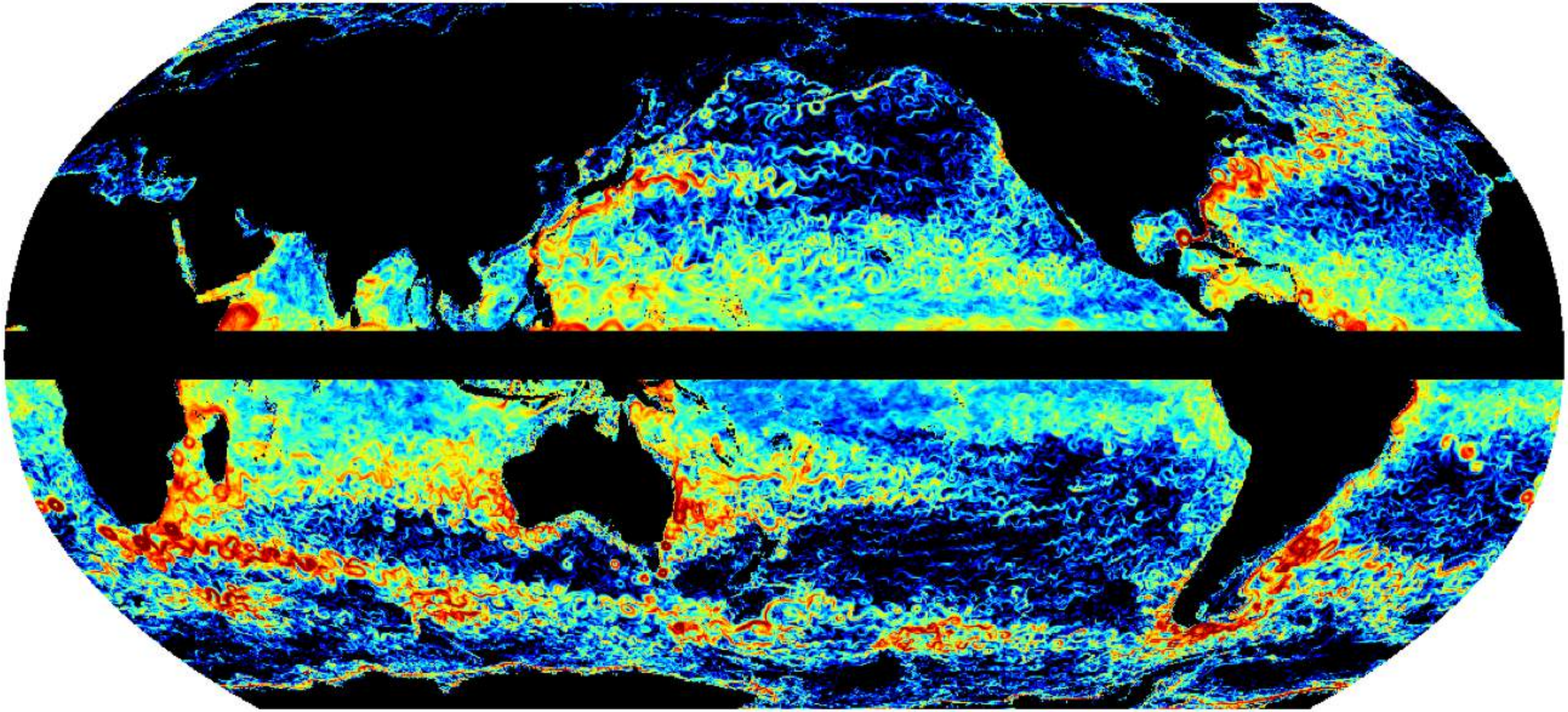
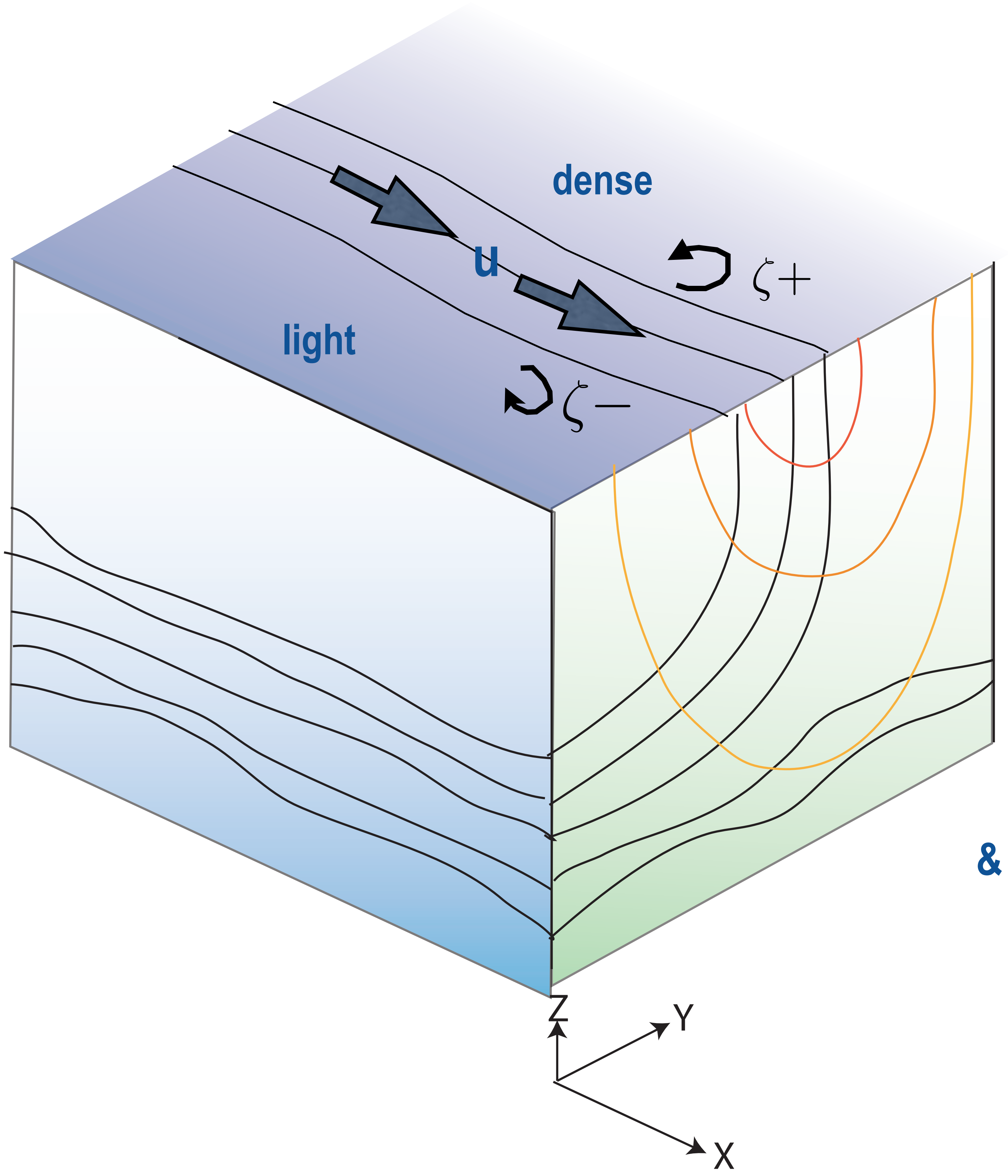


Fig: Takeyoshi Nagai (from OFES model output)

Fronts



Buoyancy

$$b = -\frac{g}{\rho_0}\rho'$$

Buoyancy conserved in the absence of forcing.

$$\frac{Db}{Dt} = 0$$

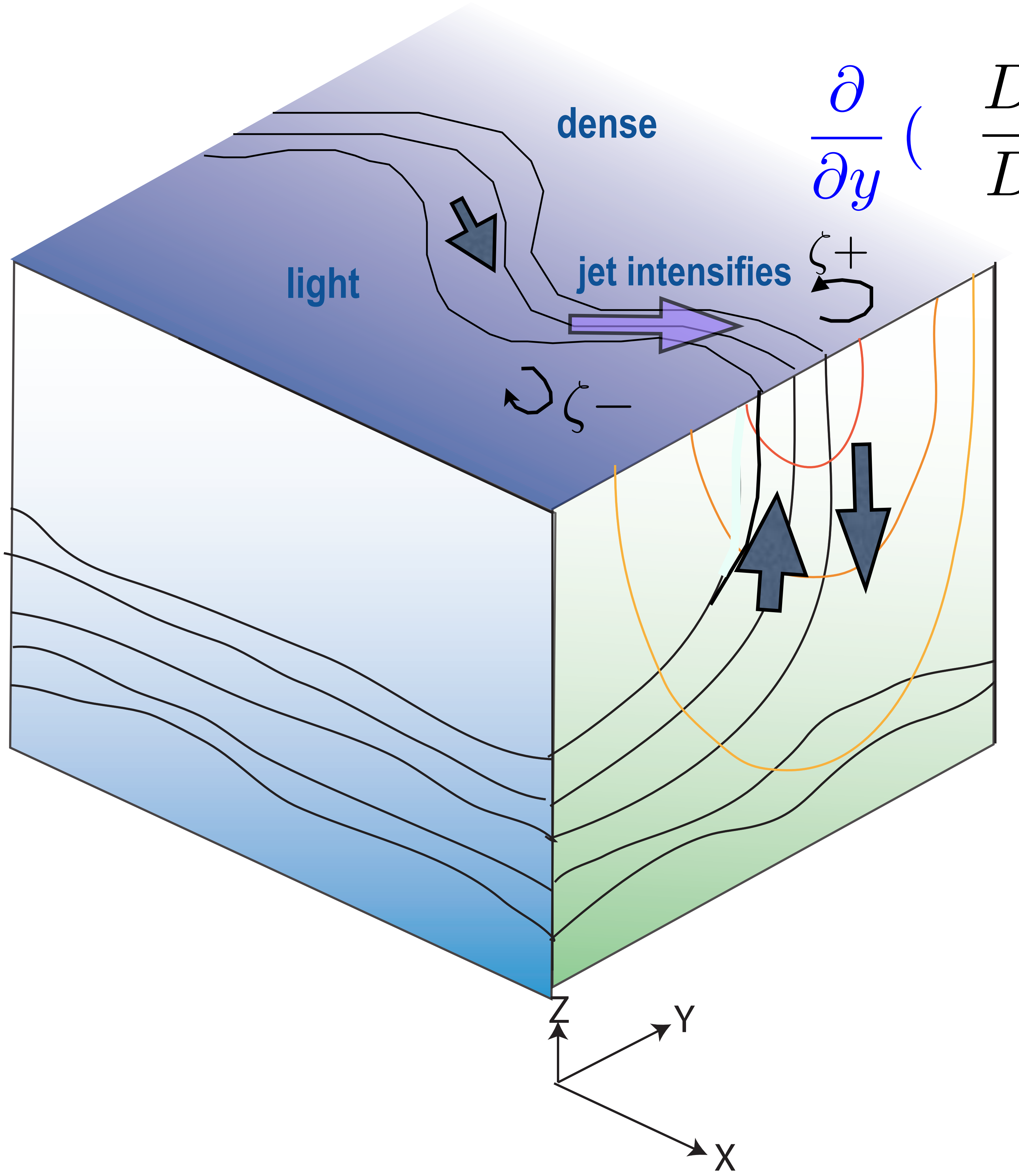
Geostrophic balance

$$fu = -p_y$$

& thermal wind balance, for small Ro

$$fu_z = b_y$$

Fronts spontaneously intensify



Frontogenesis

$$\frac{\partial}{\partial y}\left(\quad \frac{Db}{Dt} = \frac{\partial b}{\partial t} + ub_x + vb_y = 0\right)$$

$$\frac{\partial b_y}{\partial t} + u(b_y)_x + v(b_y)_y$$

$$= -u_y b_x - v_y b_y$$

$$b_y$$
$$fu_z \sim -b_y$$
$$\zeta = v_x - u_y$$

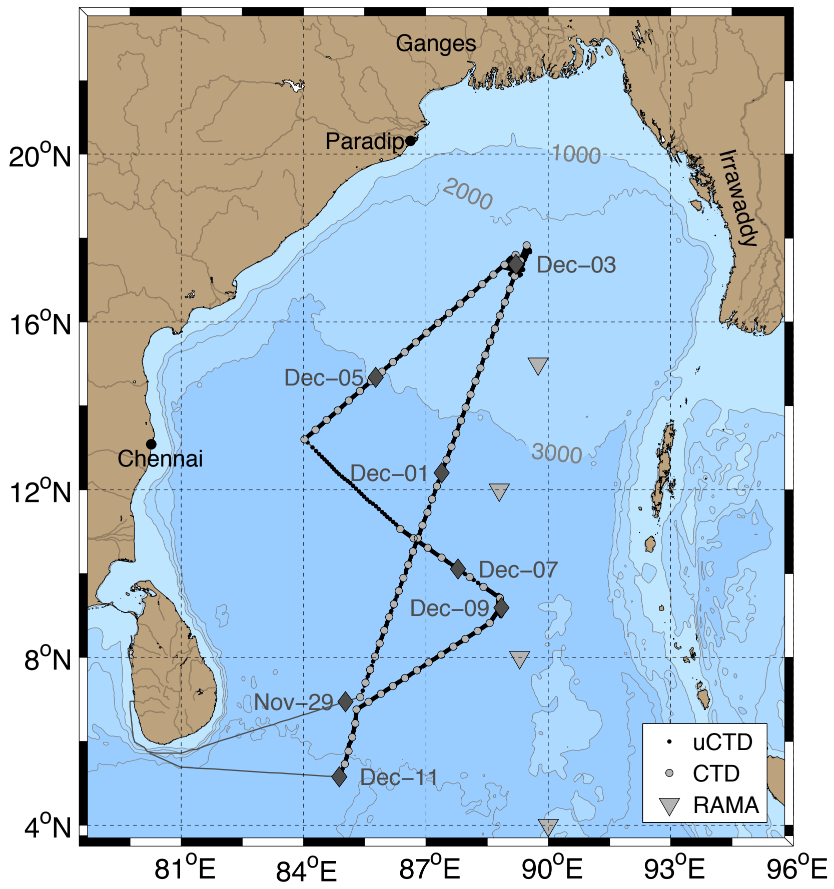
increase due to frontogenesis

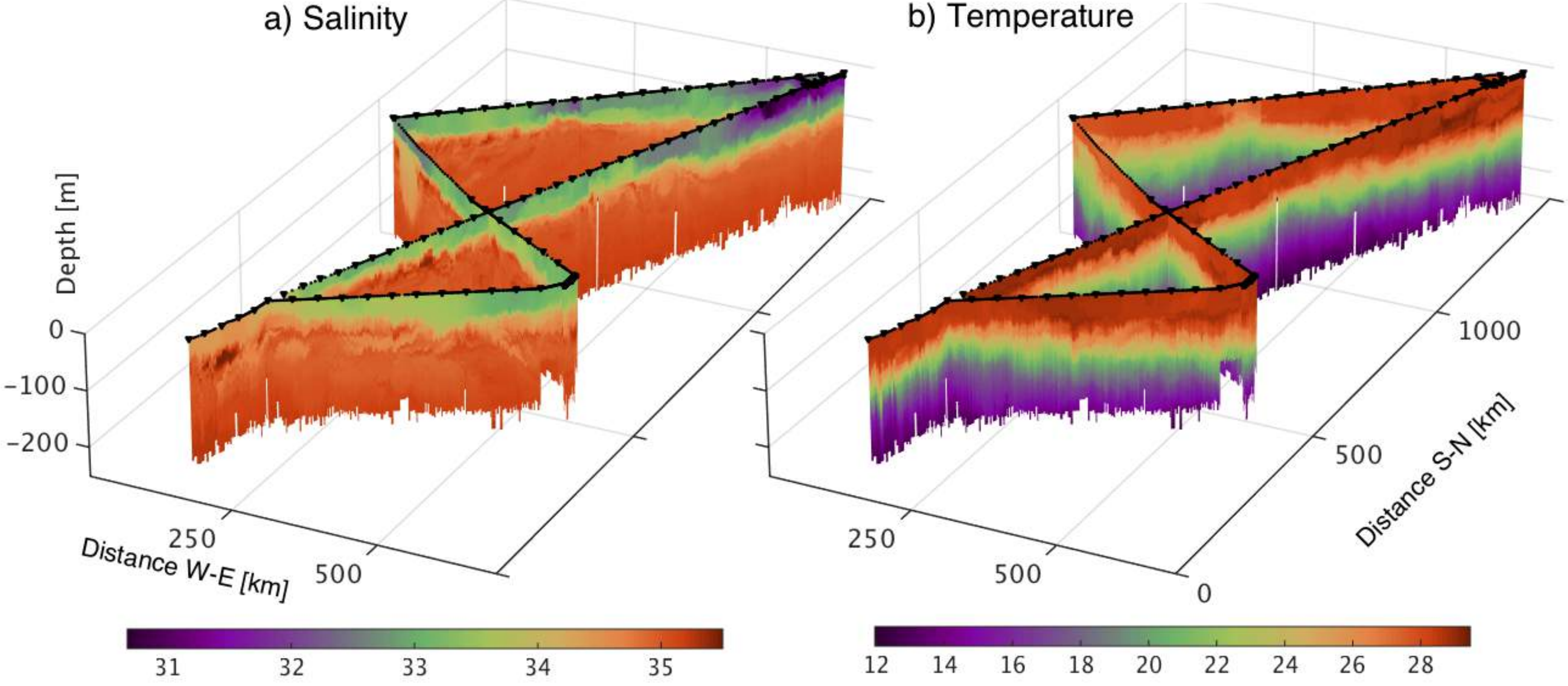
$$\zeta/f = Ro = O(1)$$

Submesoscale Dynamics

Ship-based observations in the Bay of Bengal

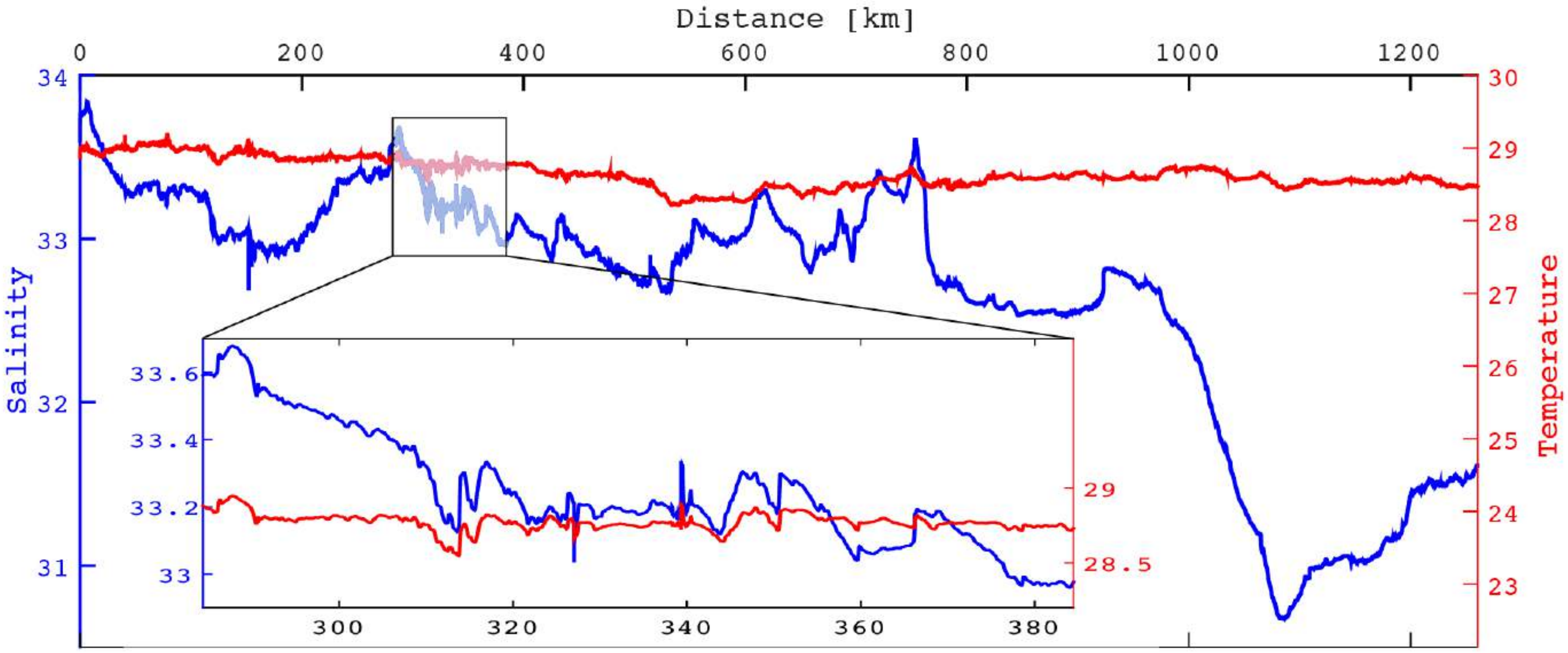
Observations: ASIRI cruise 2013
Shroyer et al. (in rev. DSR 2019)



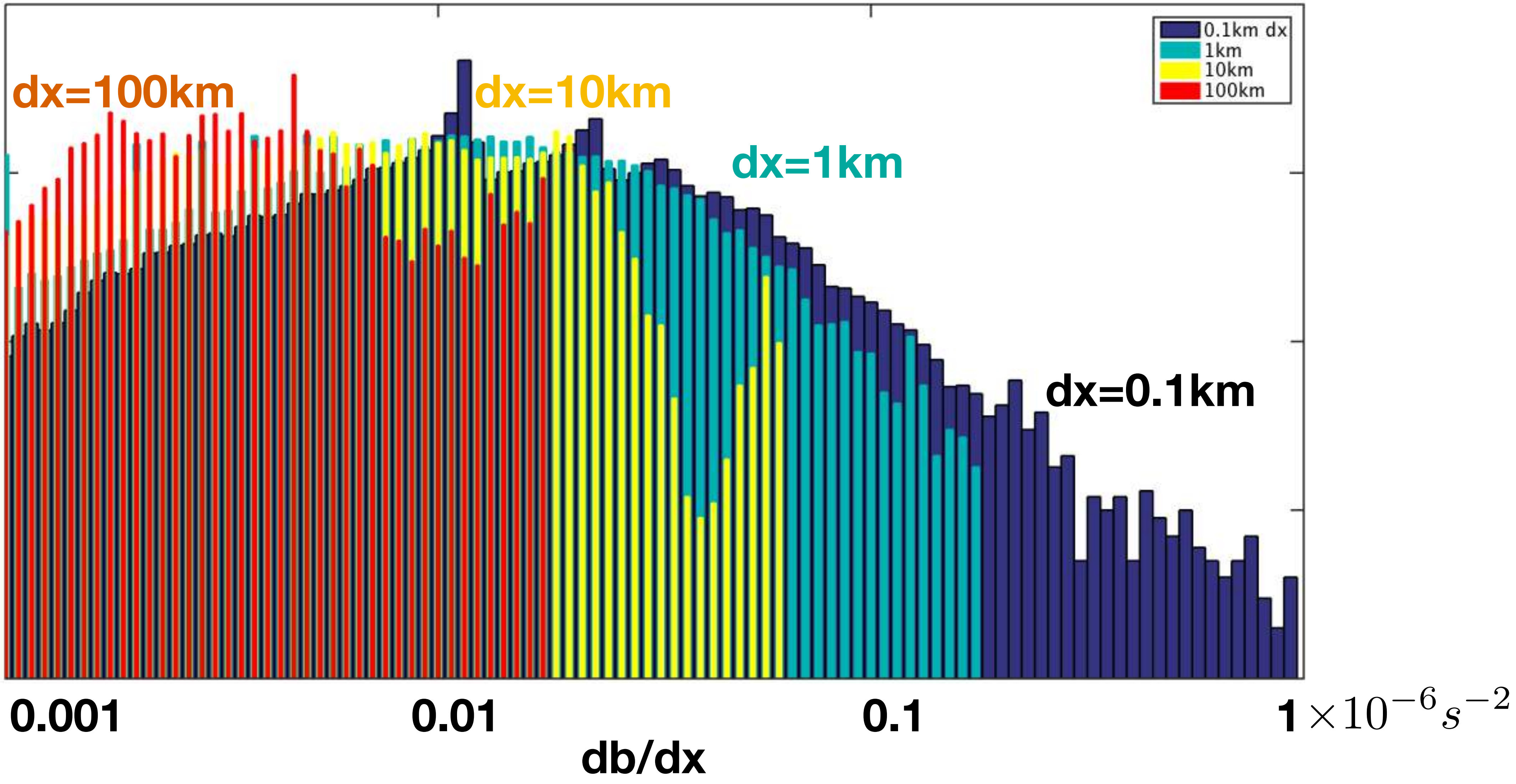

a) Salinity

b) Temperature

For a uniform density gradient db/dx would not be scale-dependent



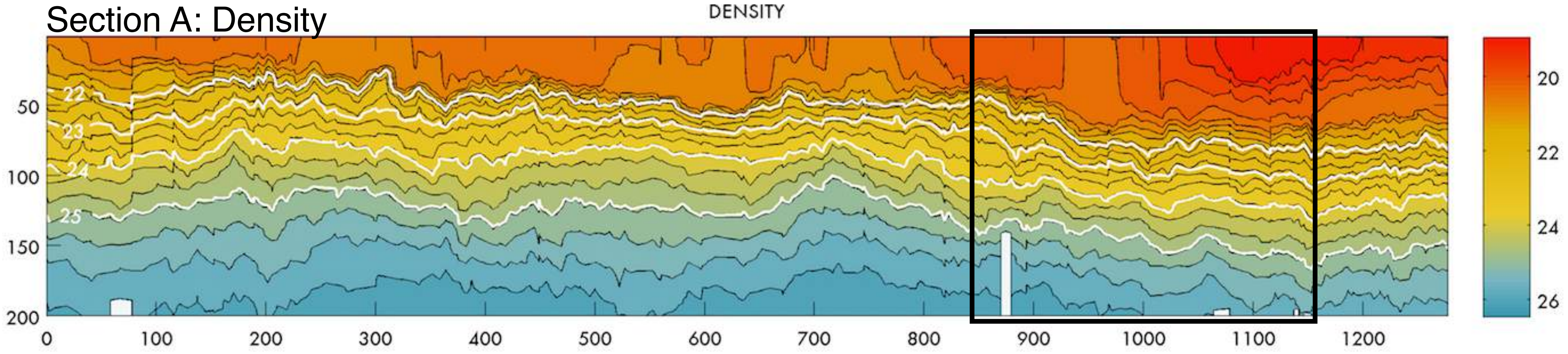
Histograms of lateral buoyancy gradient near surface from ship's TSG data in the Bay of Bengal



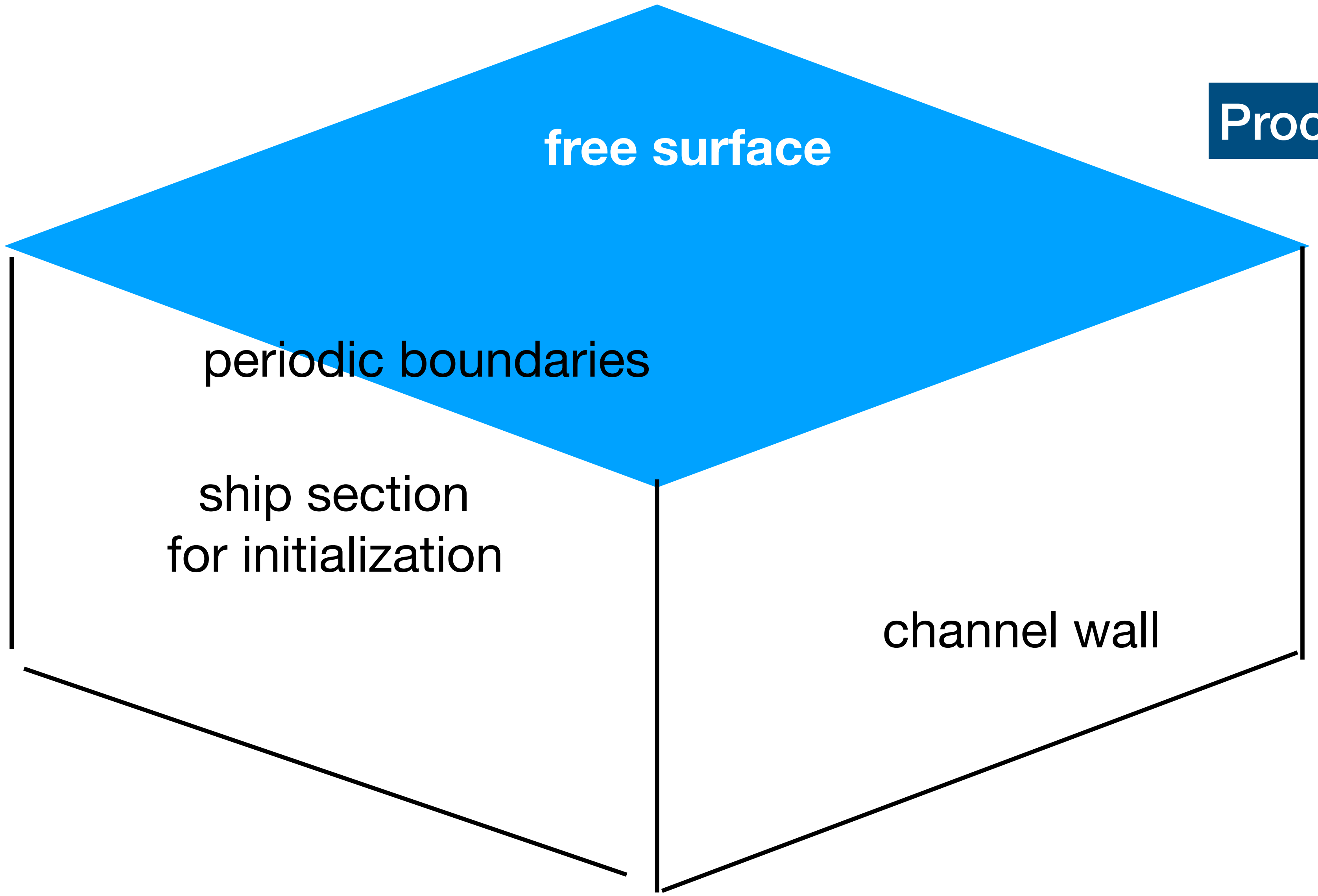
Sharpest fronts are at O(1 km) scale

Underway CTD : upper 200 m sampled every ~3km

Section A: Density



Process study ocean model



free surface

periodic boundaries

ship section
for initialization

channel wall

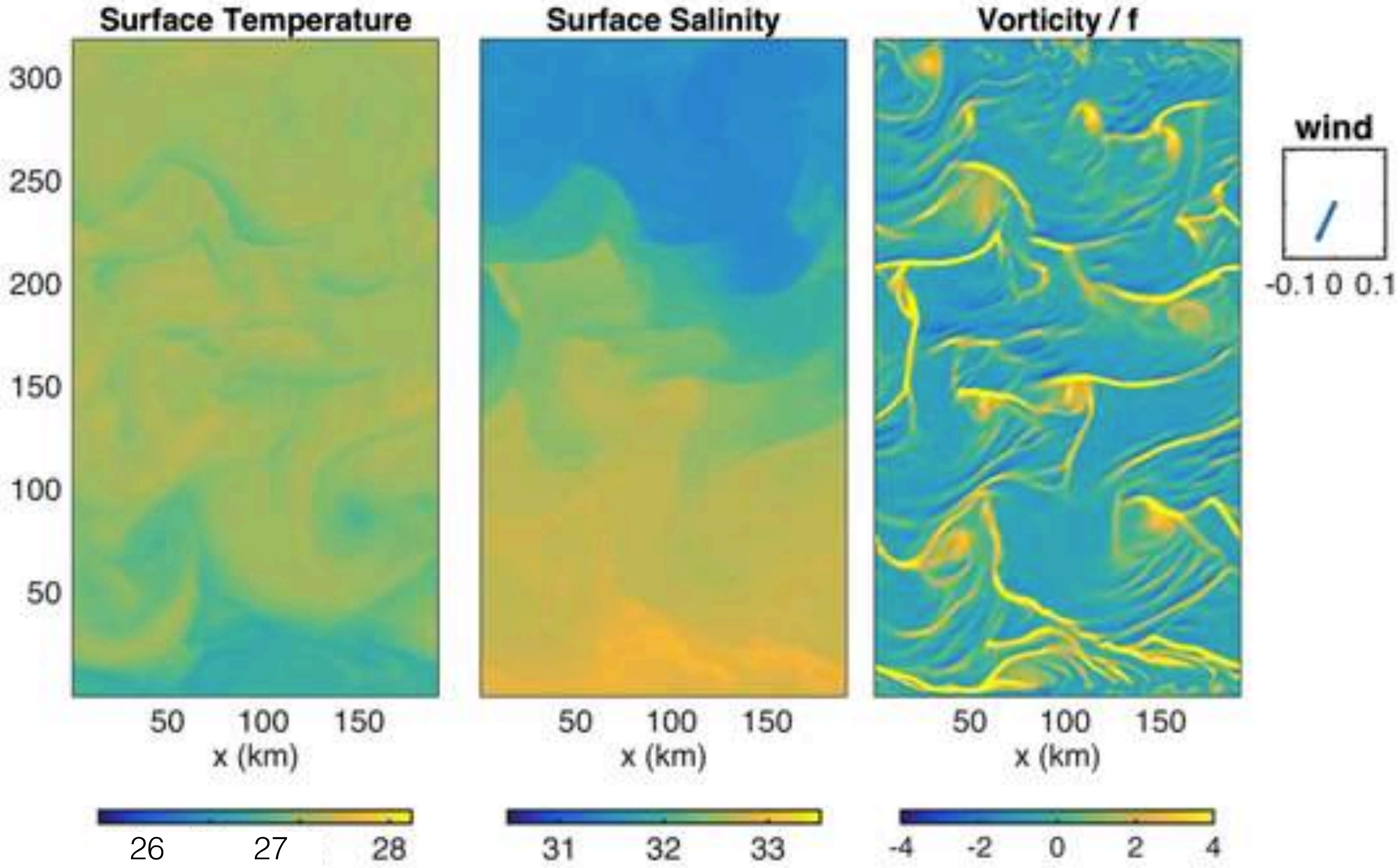
Non-hydrostatic
Stretched vertical grid
Hor res. 0.5 km
Vertical: 1m to 6 m

Lx=192 km
Ly= 300 km
dx= 1 km
Kx= 0.3 m2/s
Kz= 1e-6 m2/s
below 30 m

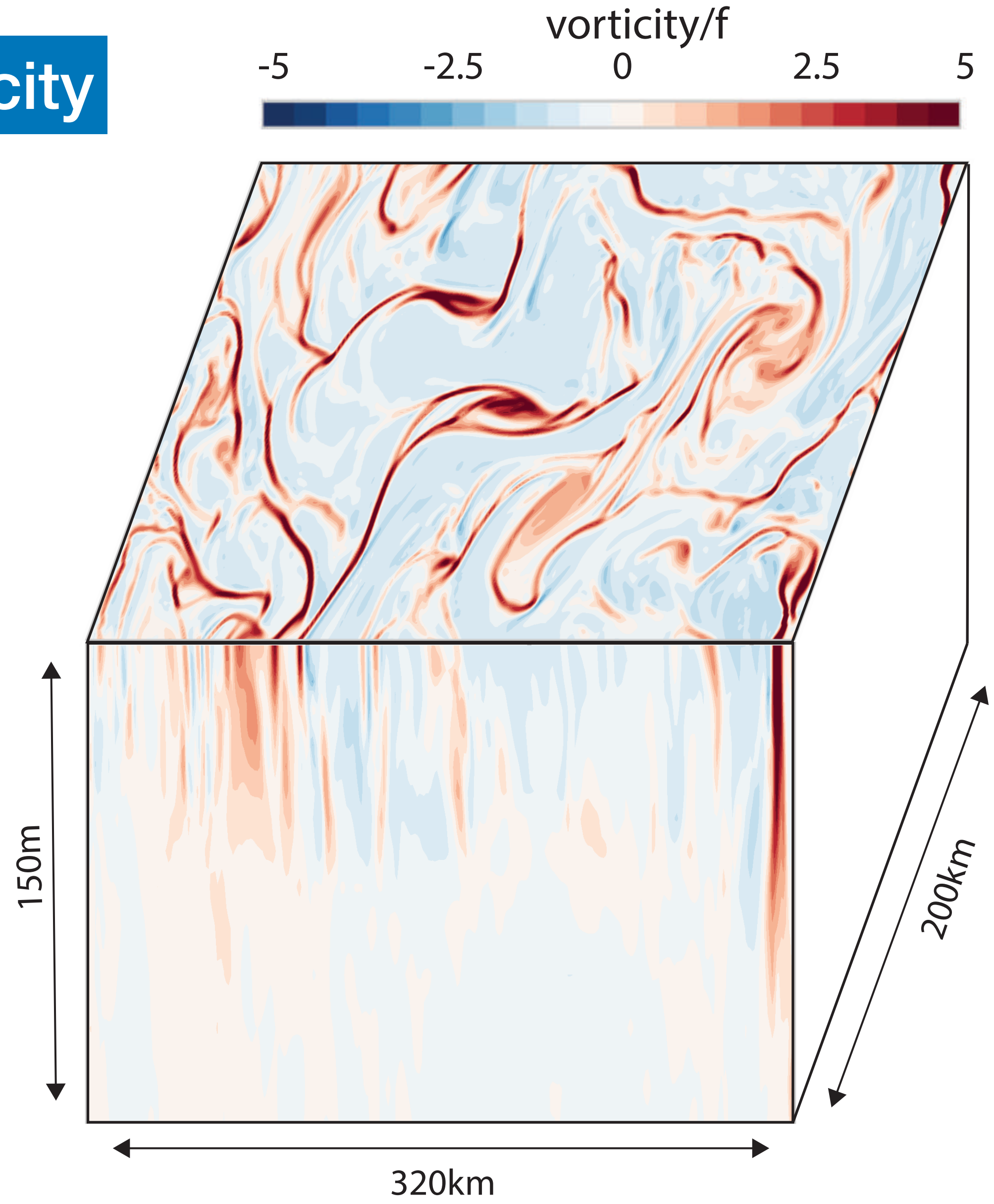
Submesoscale fronts

Initialize the model with a part of the ship section
Force with heat fluxes and winds from mooring (2014)

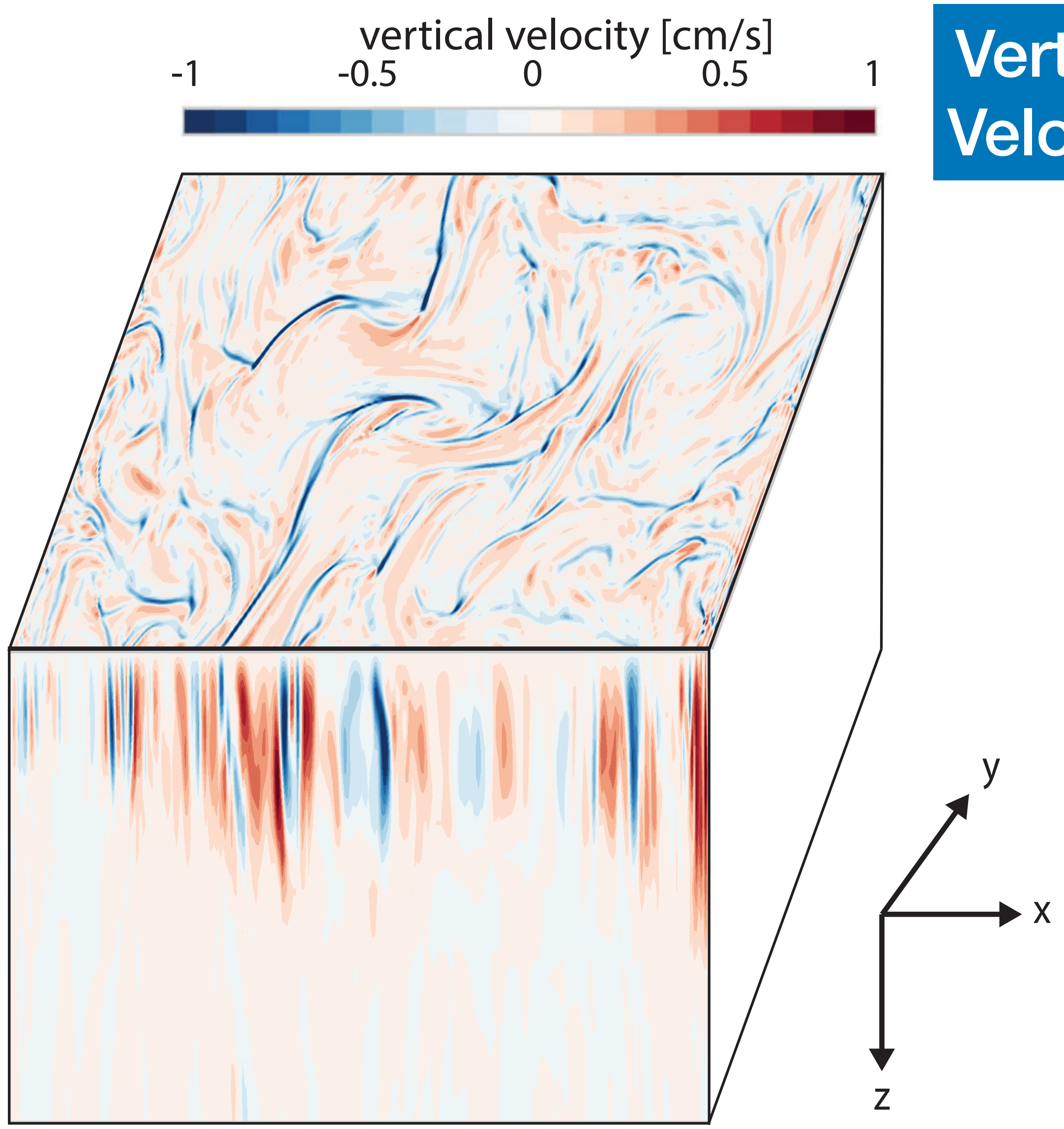
Mean eddy transport is westward



Vorticity

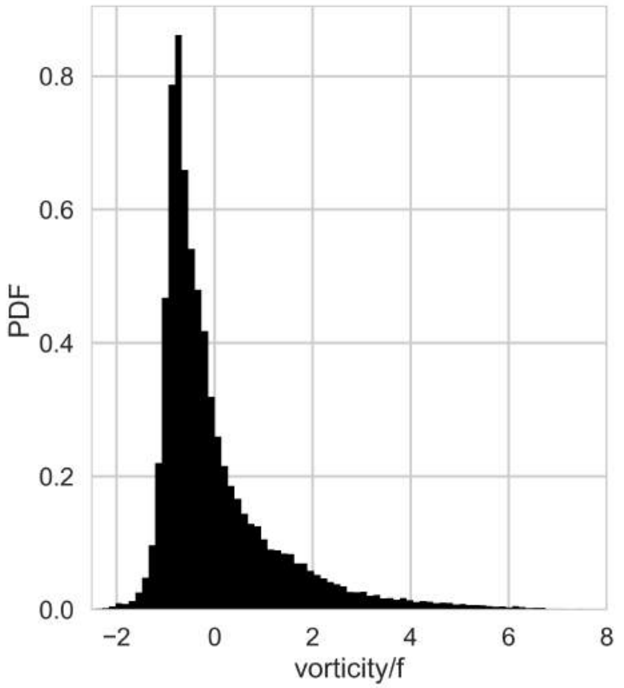


Vertical Velocity



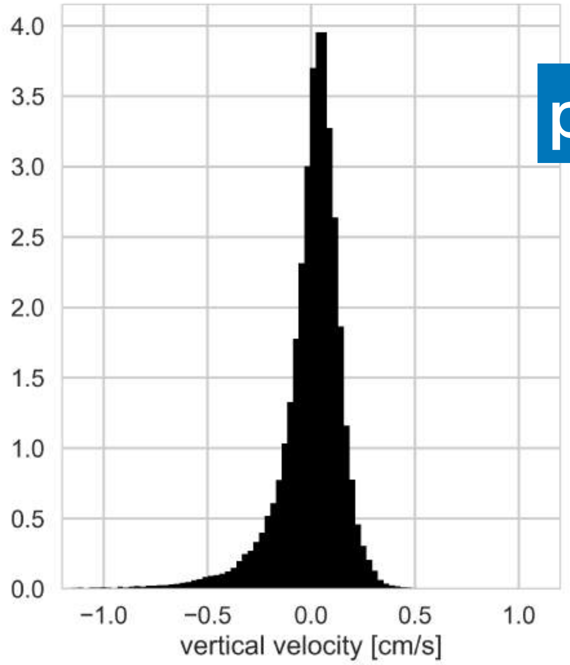
pdf vorticity

positively skewed



pdf vertical velocity

negatively skewed



Vertical Velocity
How large?

$$u_x + v_y = -w_z$$

$$\frac{U}{L} \qquad \frac{U}{L} \qquad \qquad \frac{W}{D}$$

$$\frac{W}{D} \leq \frac{U}{L}$$

$$\boxed{W = Ro\,\delta\,U}$$

$$\delta = \frac{D}{L} = \frac{f}{N}$$

$$= 0.01$$

Mesoscale Dynamics

$$Ro = \frac{U}{fL} = \frac{\zeta}{f} = O(0.1 - 0.01)$$

U=0.1m/s

W ~ $(10^{-3}$- 10^{-4}) U ~ 1-10 m/d

Submesoscale Dynamics

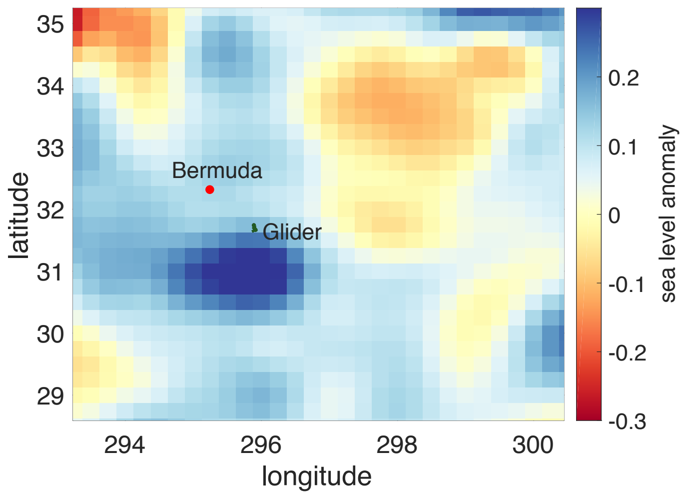
$$\text{Locally, } Ro = \frac{\zeta}{f} = O(1)$$

W ~ (10^{-2}) U ~ 100 m/d

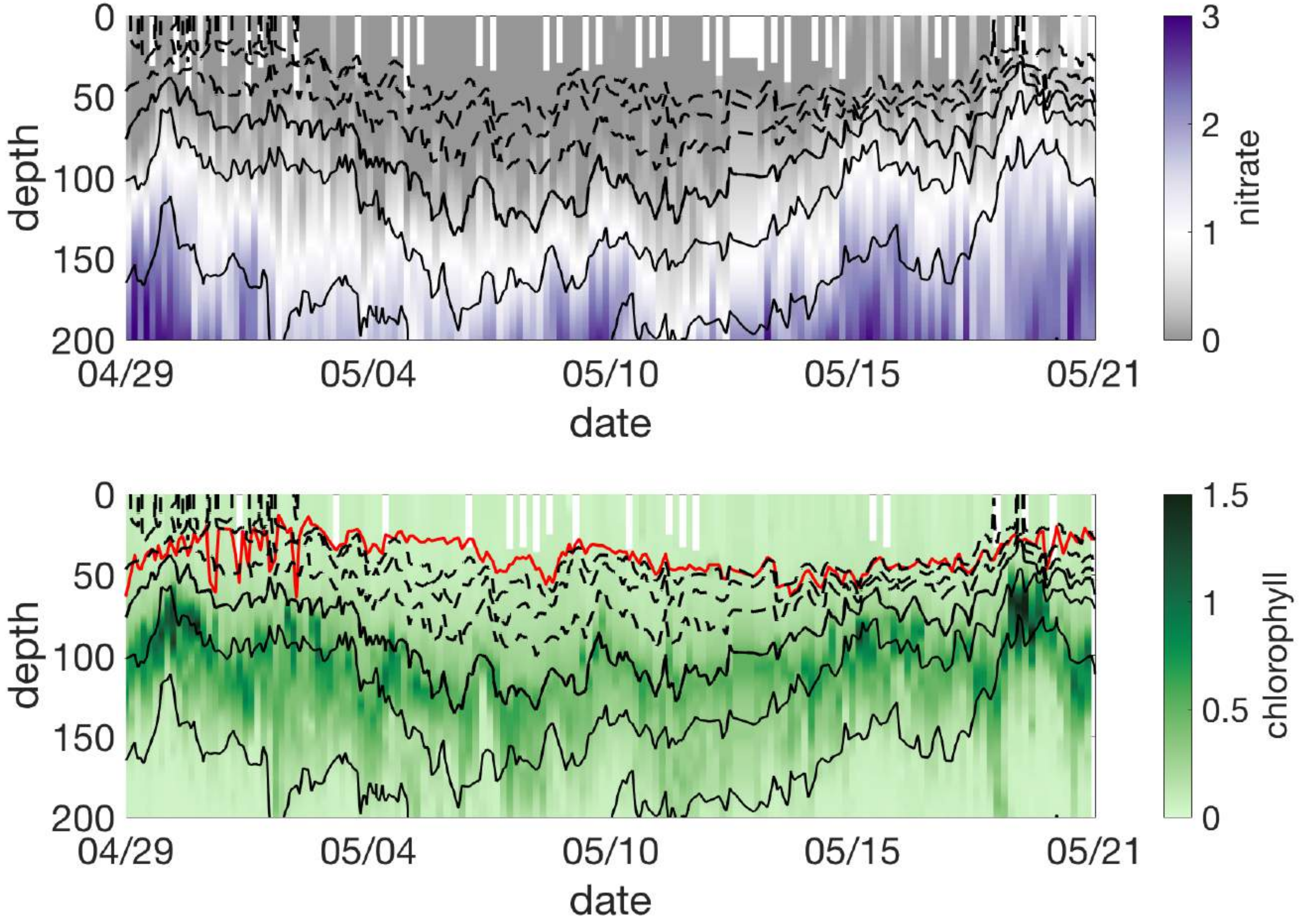
Submesoscale dynamics can sustain higher vertical velocities of O(100 m/day)

Glider Observations near Bermuda

from Ruth Curry



Nitrate and chlorophyll time series near Bermuda

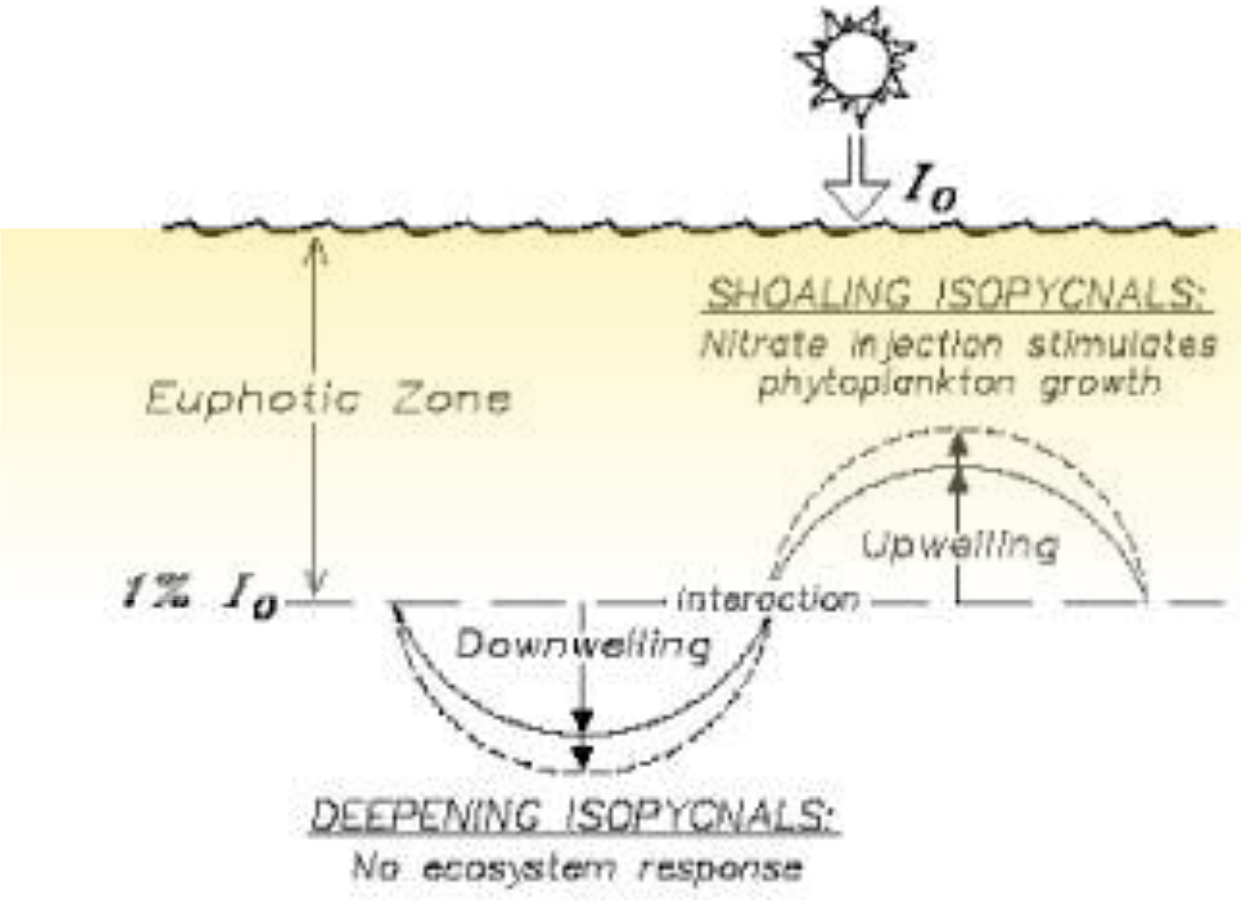


Growth rate of phytoplankton is depth-dependent (based on light).
Nutrients are transported across the euphotic depth

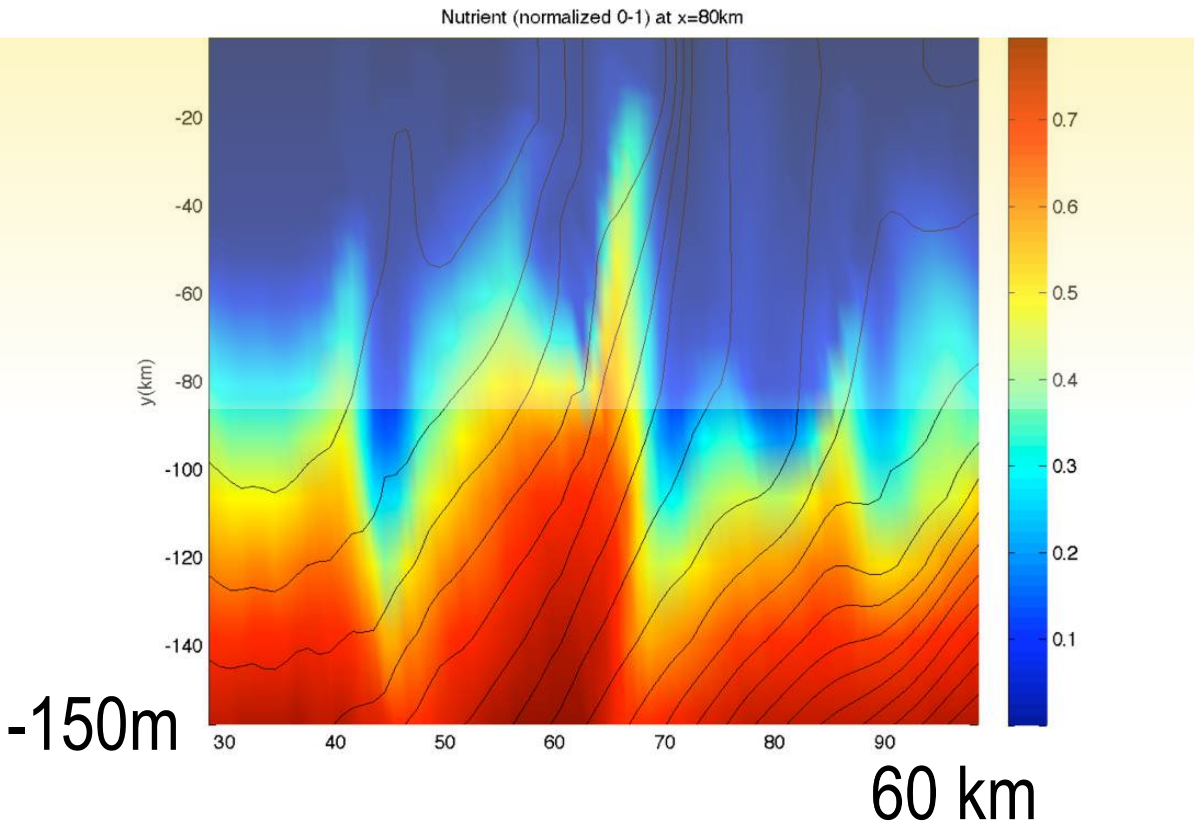
What is the mechanism for vertical nutrient transport?

Uplift by eddies

Advection in model



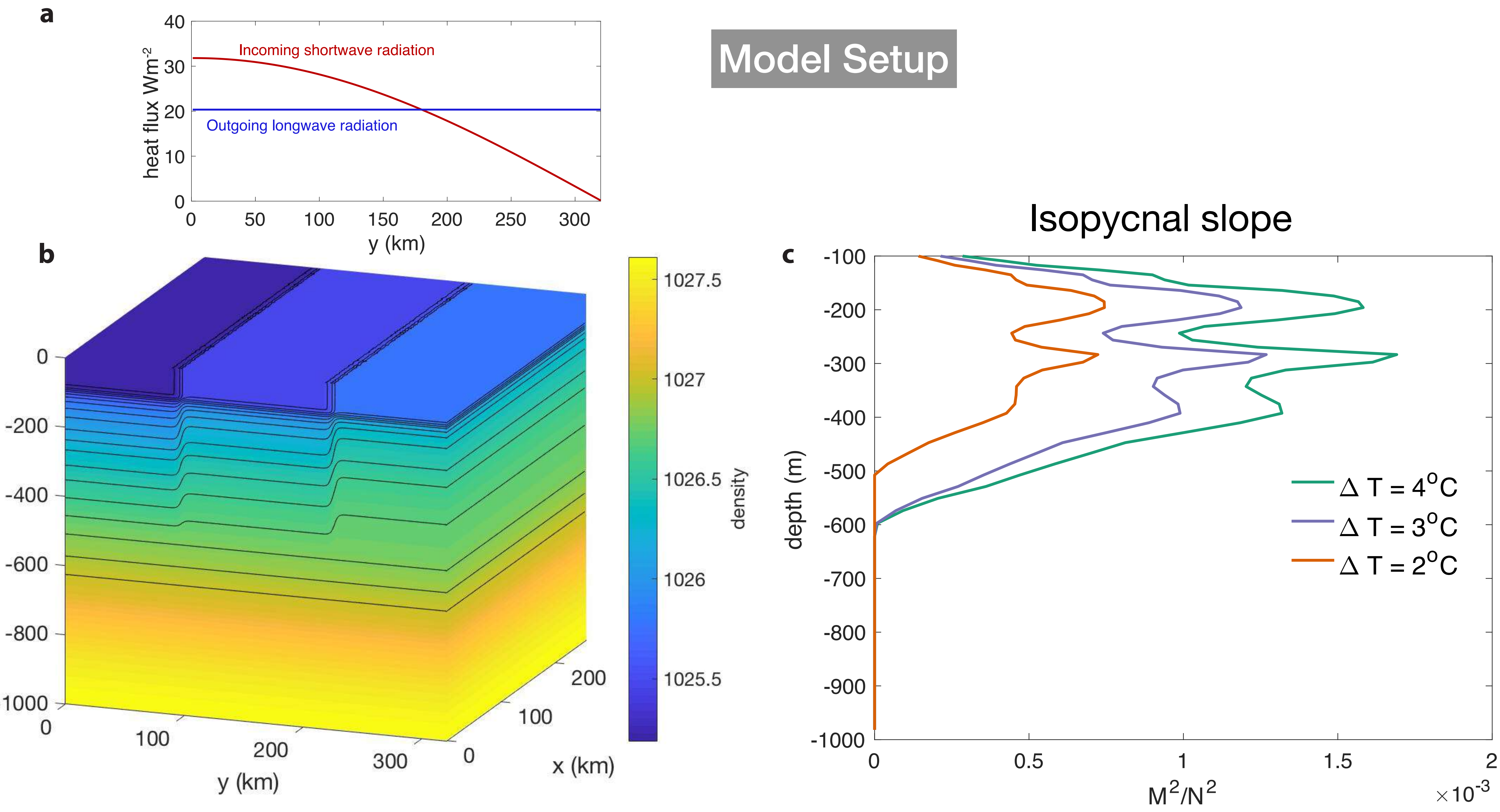
Nutrient in model



How does vertical velocity vary with frontal strength (isopycnal slope)?

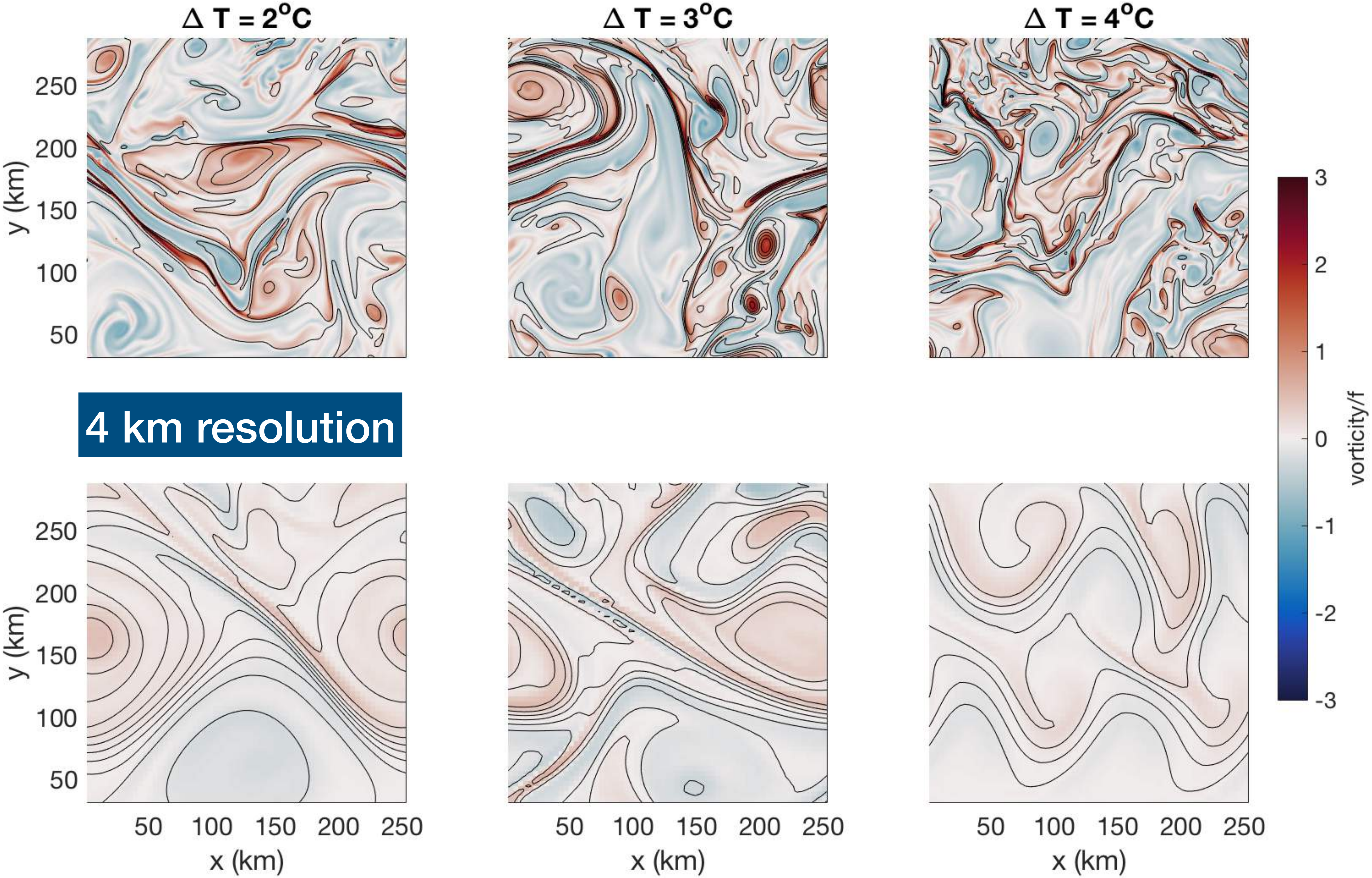
Freilich & Mahadevan, JPO (2019)

Model Setup



1 km resolution

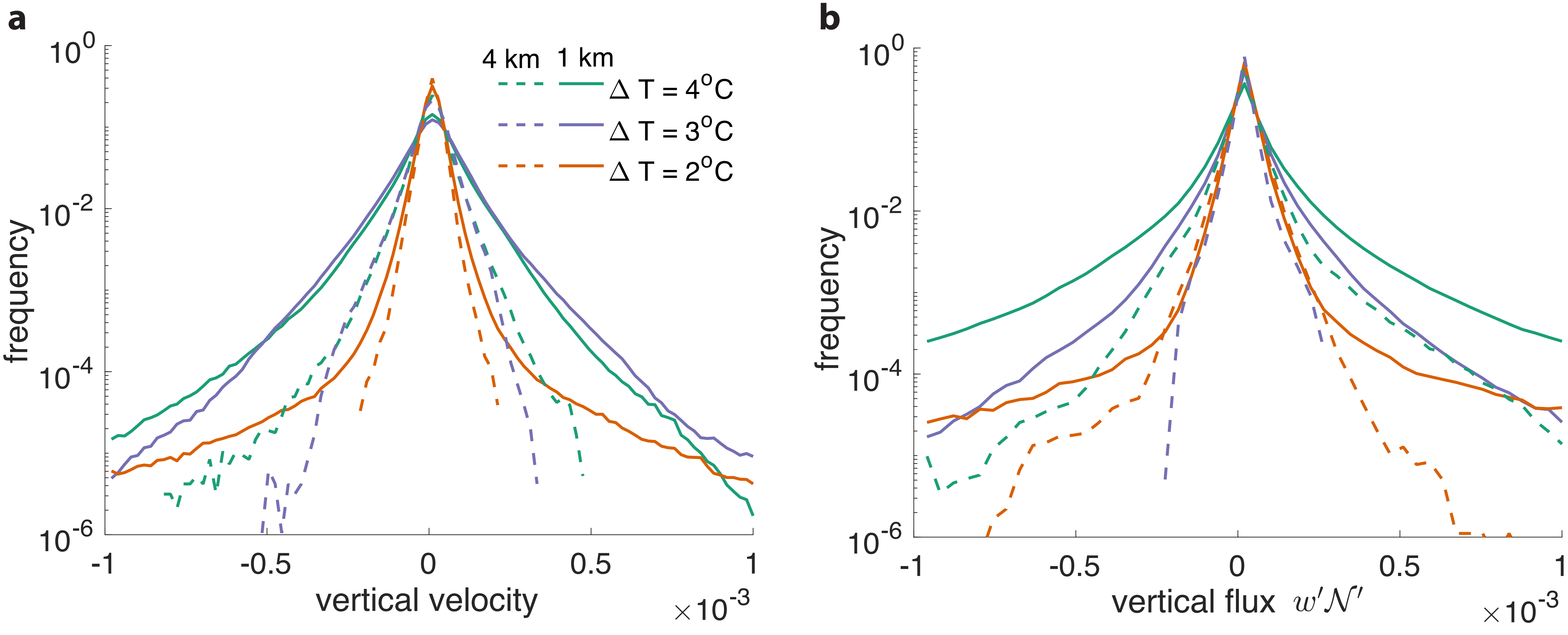
Vorticity/ f



4 km resolution

pdf of vertical velocity

pdf of vertical nutrient flux



Freilich & Mahadevan, 2019

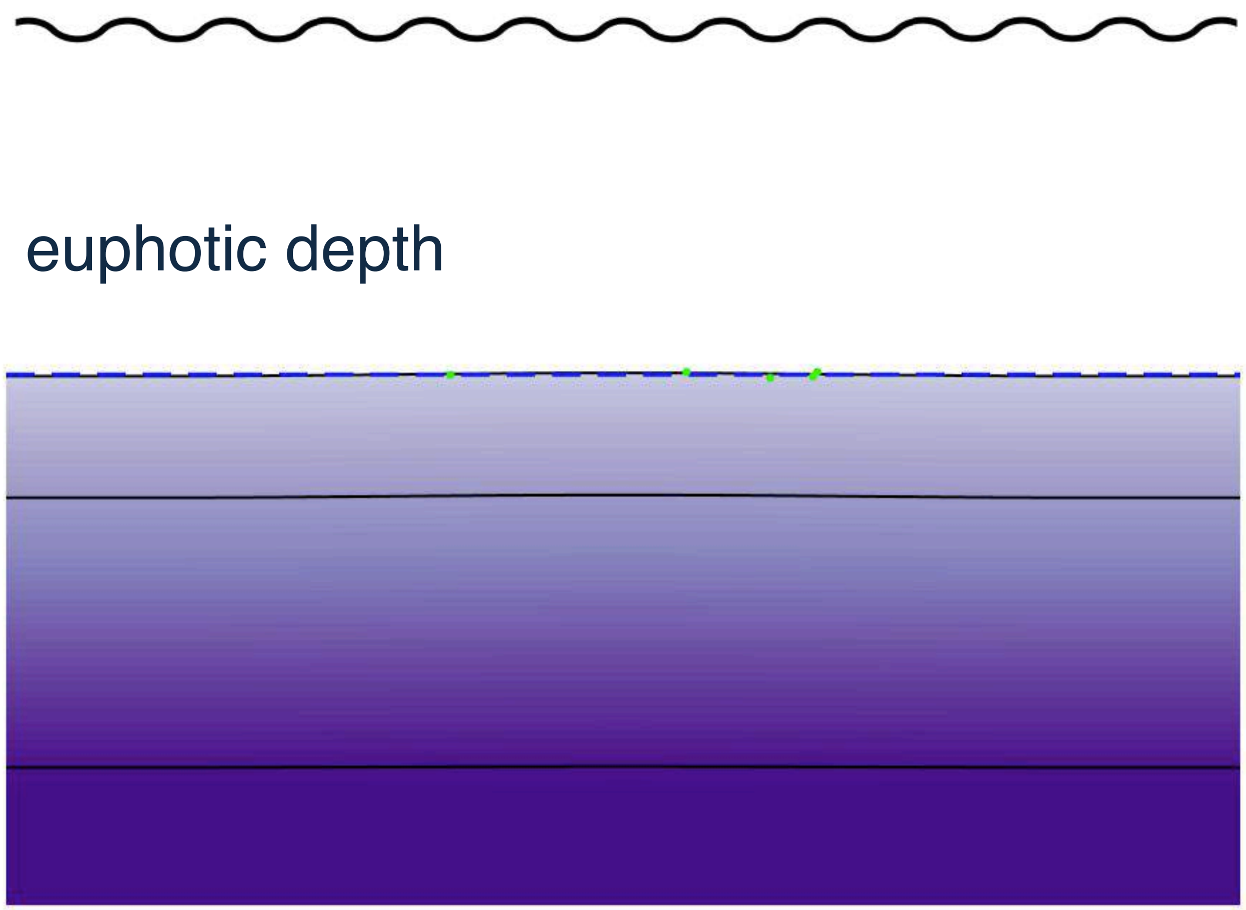
A closer look at the vertical velocity w

For details on how to do this, see
Freilich & Mahadevan, JPO (2019)

Decompose w into uplift and along-isopycnal components

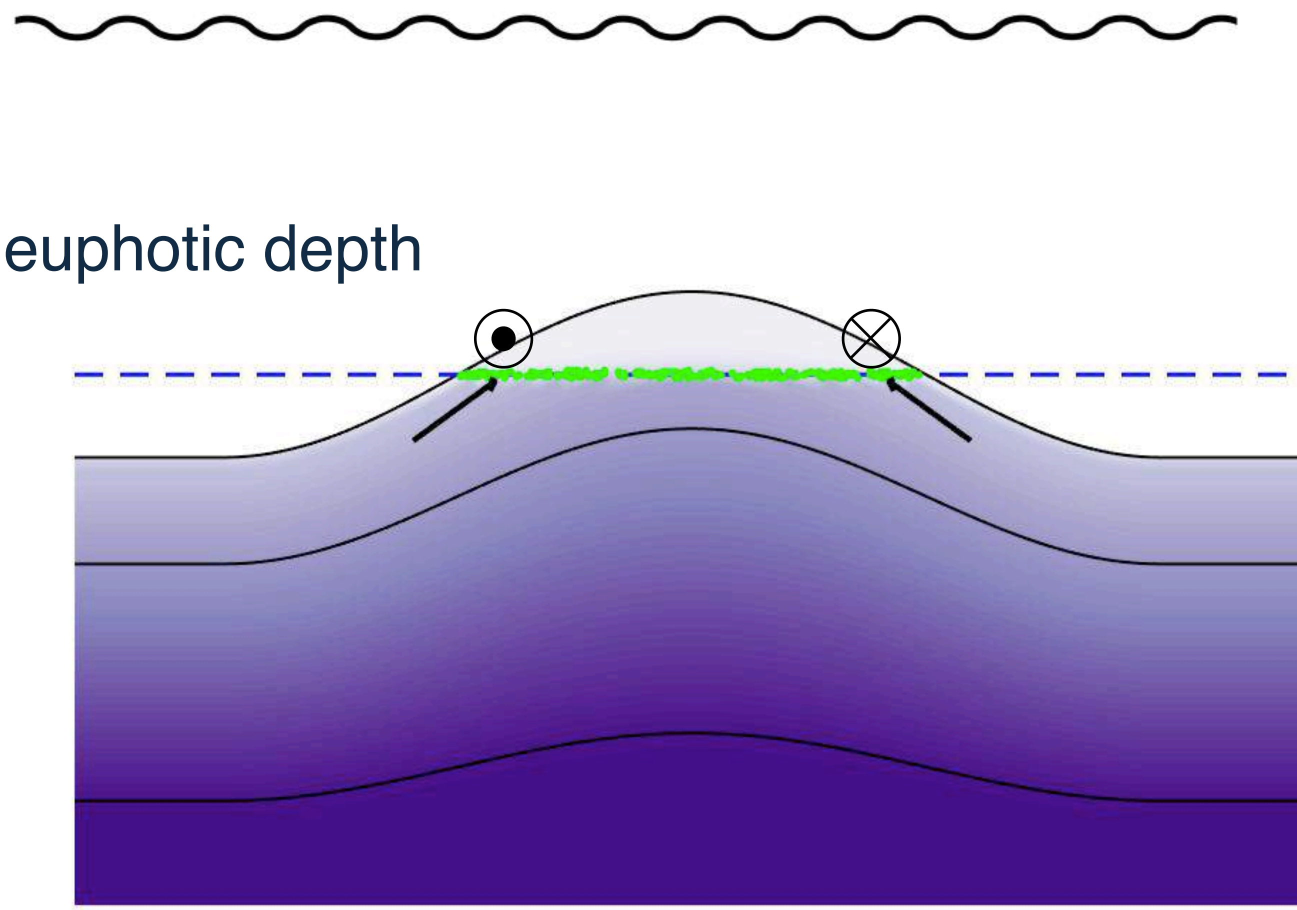
$$w = w_{uplift} + w_{iso}$$

w_{uplift} supplies nutrient



euphotic depth

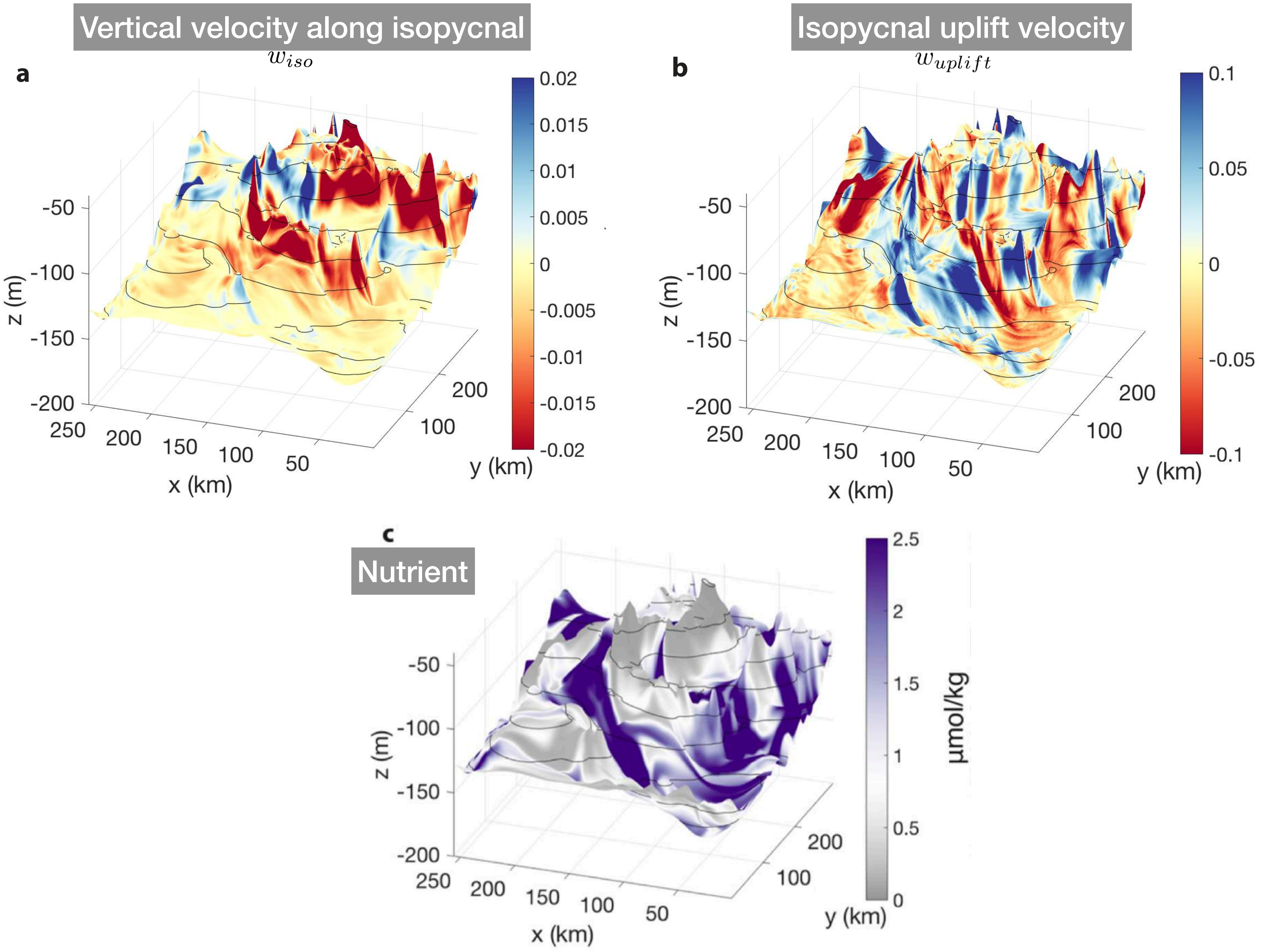
w_{iso} supplies nutrient



euphotic depth

● phytoplankton

On an isopycnal surface



Vertical velocity along isopycnal

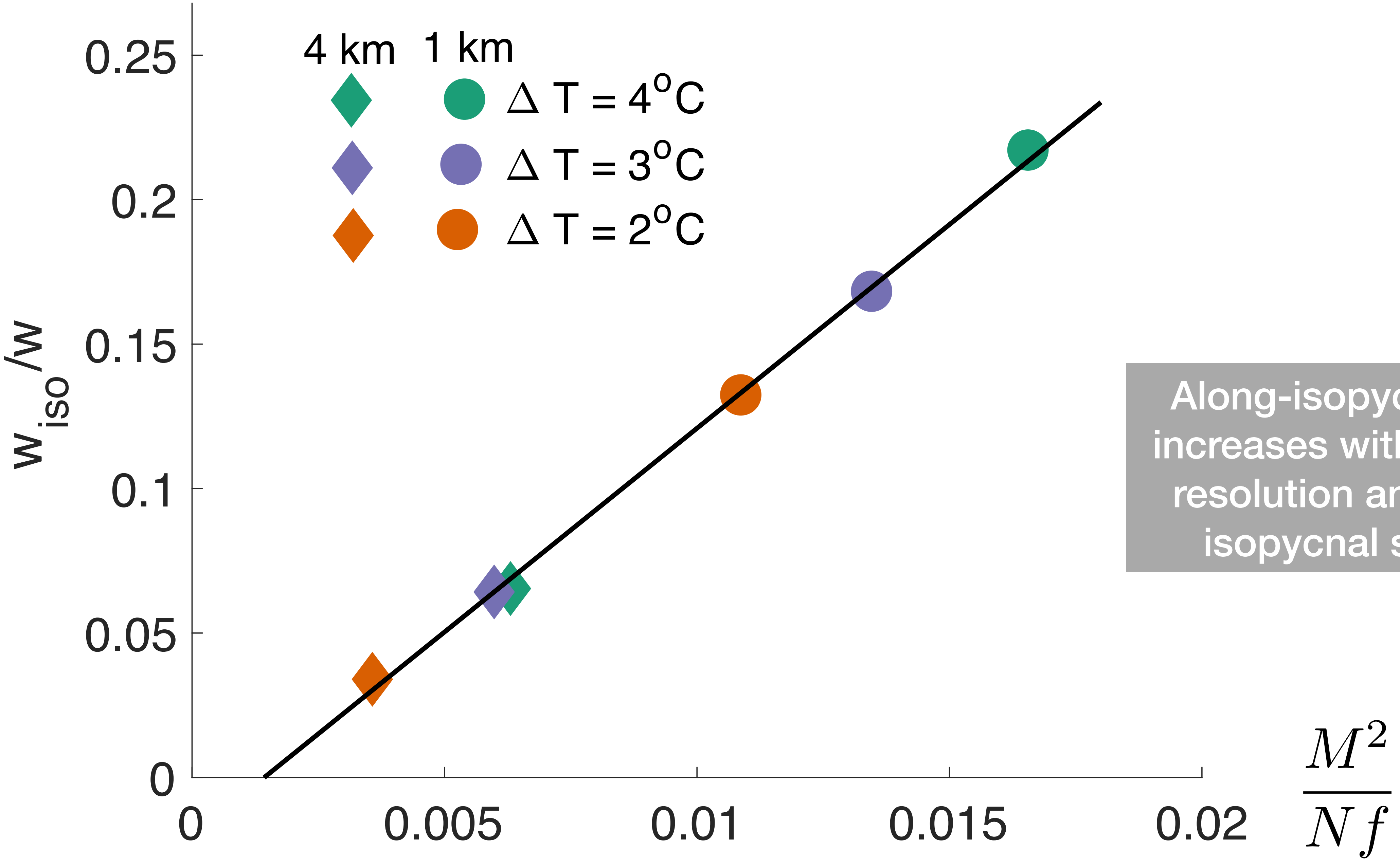
Isopycnal uplift velocity

Nutrient

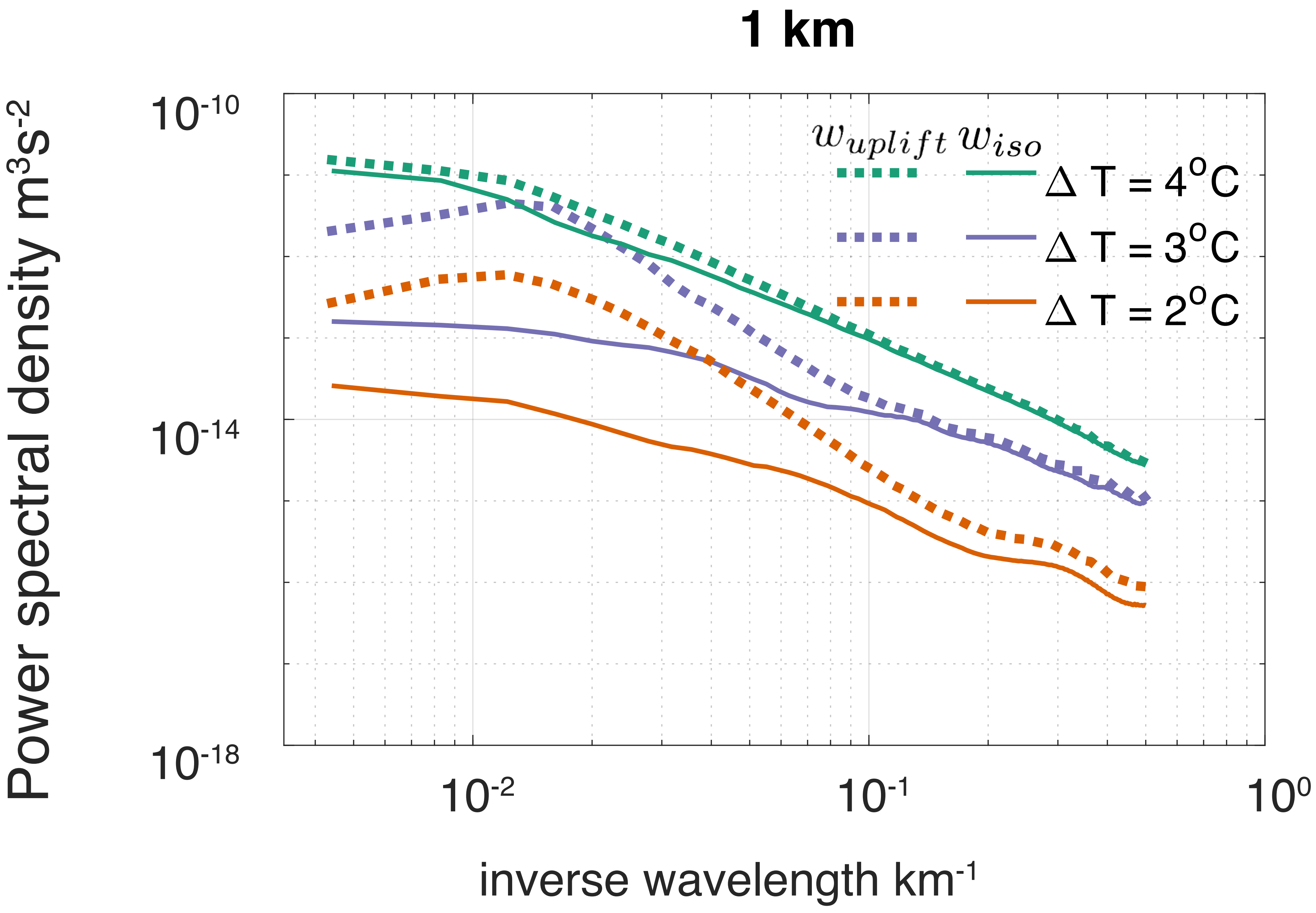
How does along-isopycnal vertical velocity vary with frontal strength (isopycnal slope)?

$$\frac{w_{iso}}{w} = \frac{M^2}{N^2}\frac{L}{H}$$

$$\frac{L}{H} = \frac{N}{f}$$

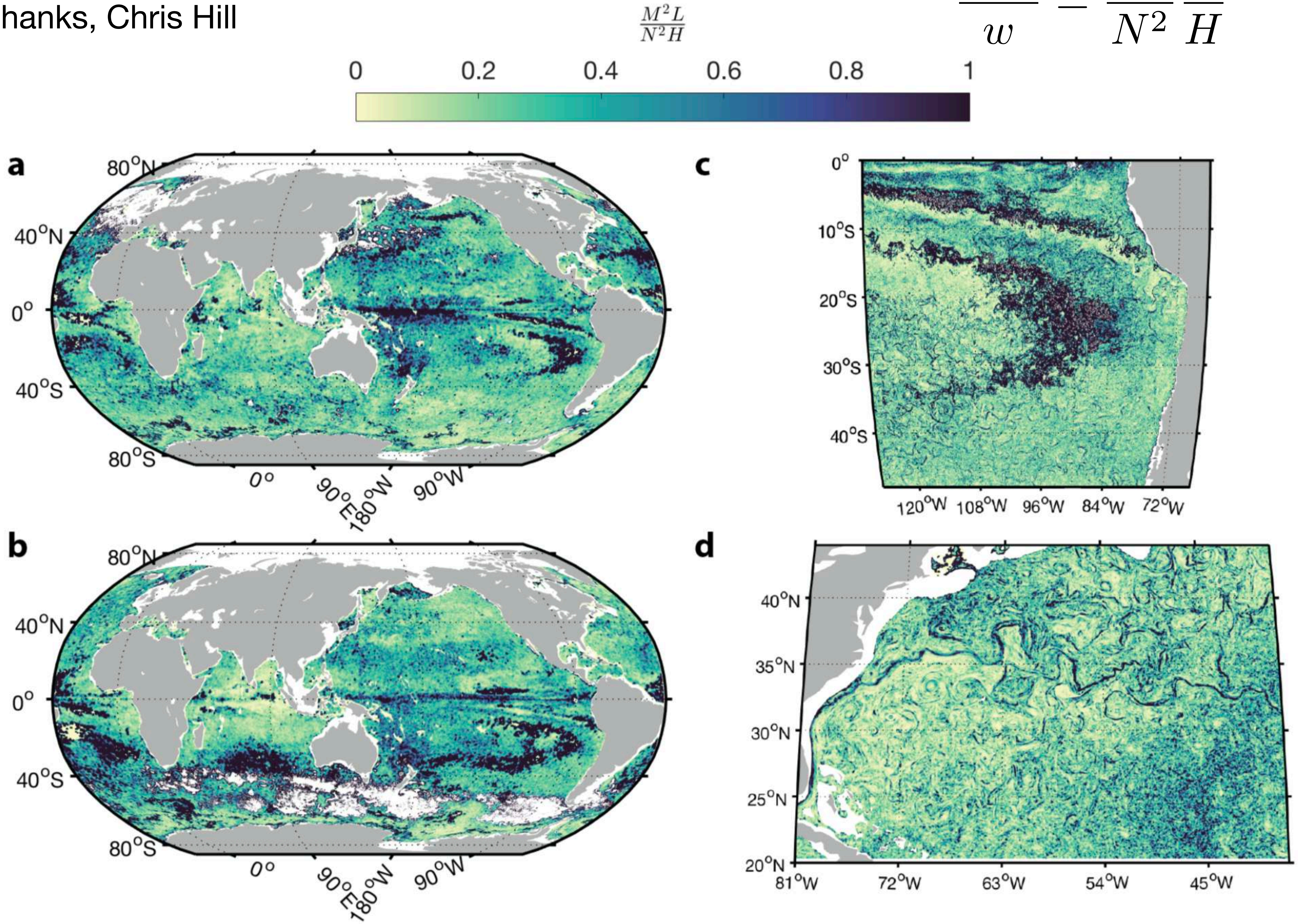


Along-isopycnal w increases with model resolution and with isopycnal slope


1 km
Power spectral density m^{3}s^{-2}
10^{-10}
10^{-14}
10^{-18}
10^{-2}
10^{-1}
10^{0}
inverse wavelength km^{-1}
w_{uplift} w_{iso}
Δ T = 4^{o}C
Δ T = 3^{o}C
Δ T = 2^{o}C

Ecco fields
thanks, Chris Hill

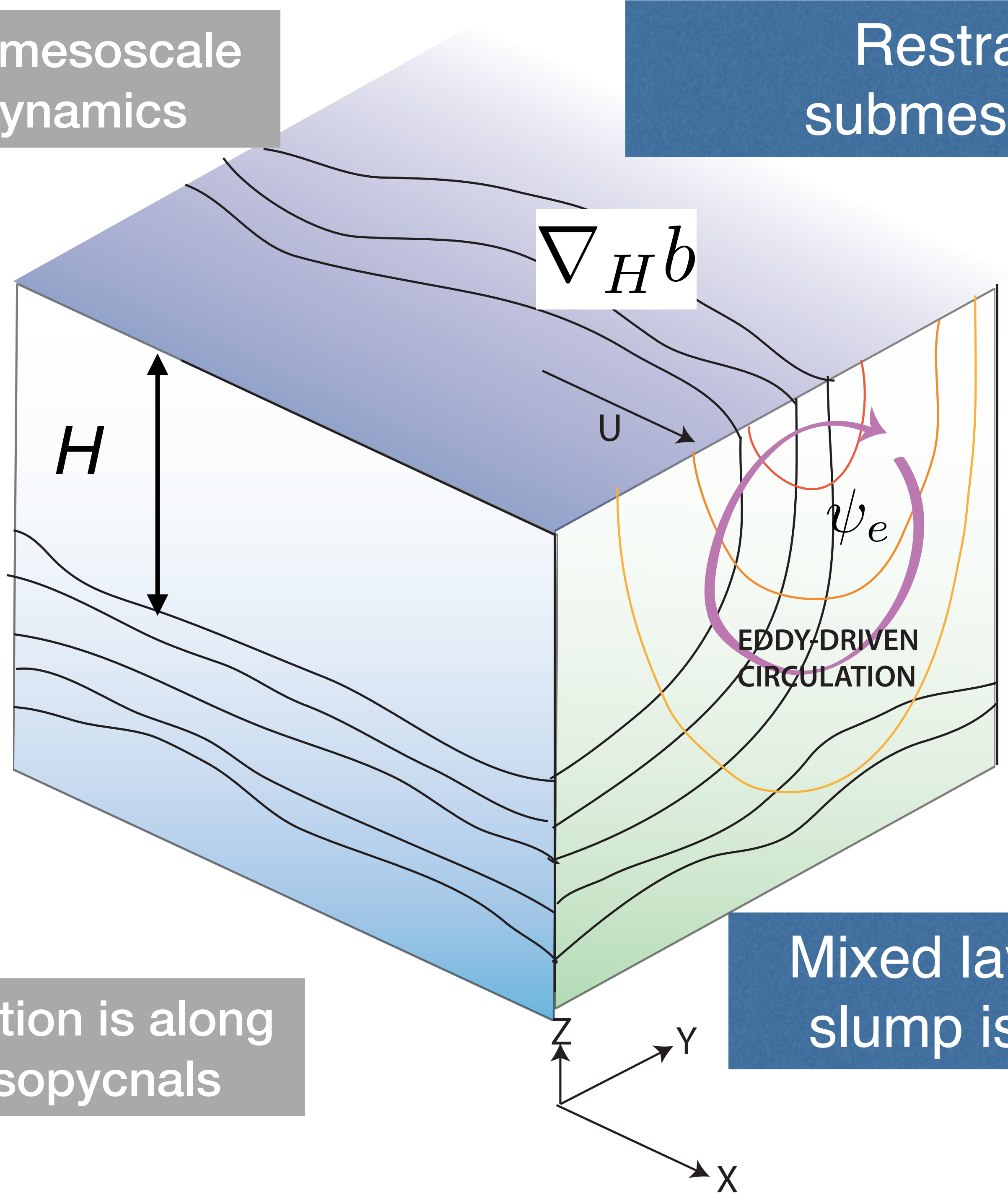
$$\frac{w_{iso}}{w} = \frac{M^2}{N^2}\frac{L}{H}$$

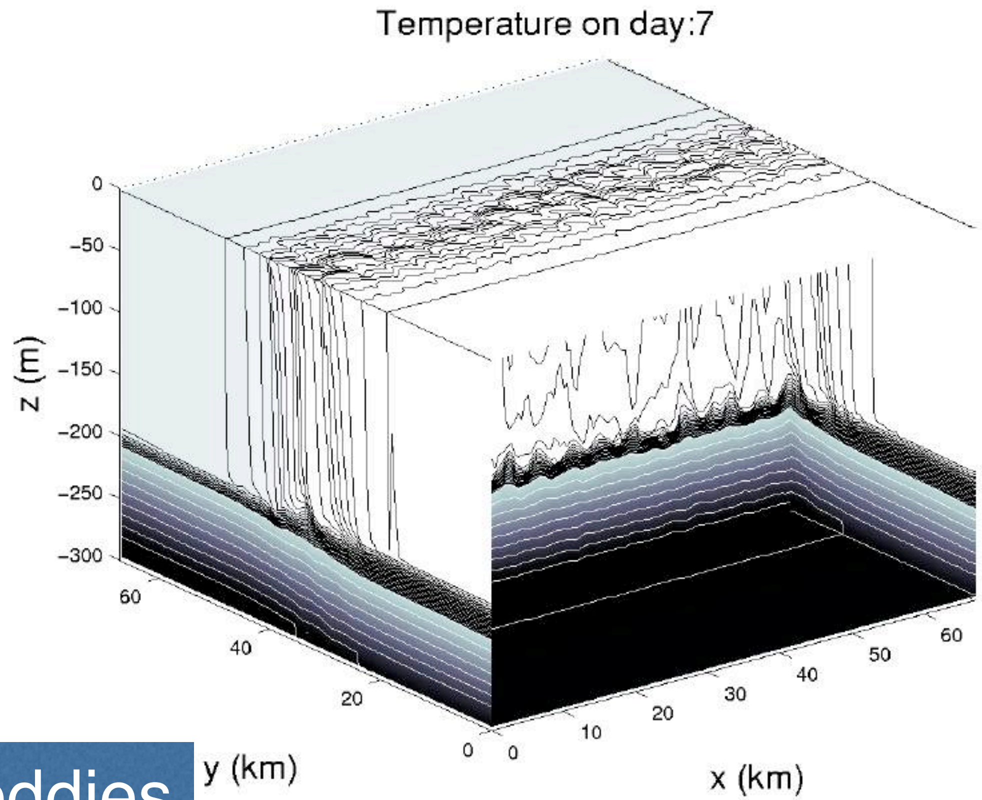


Submesoscale Dynamics

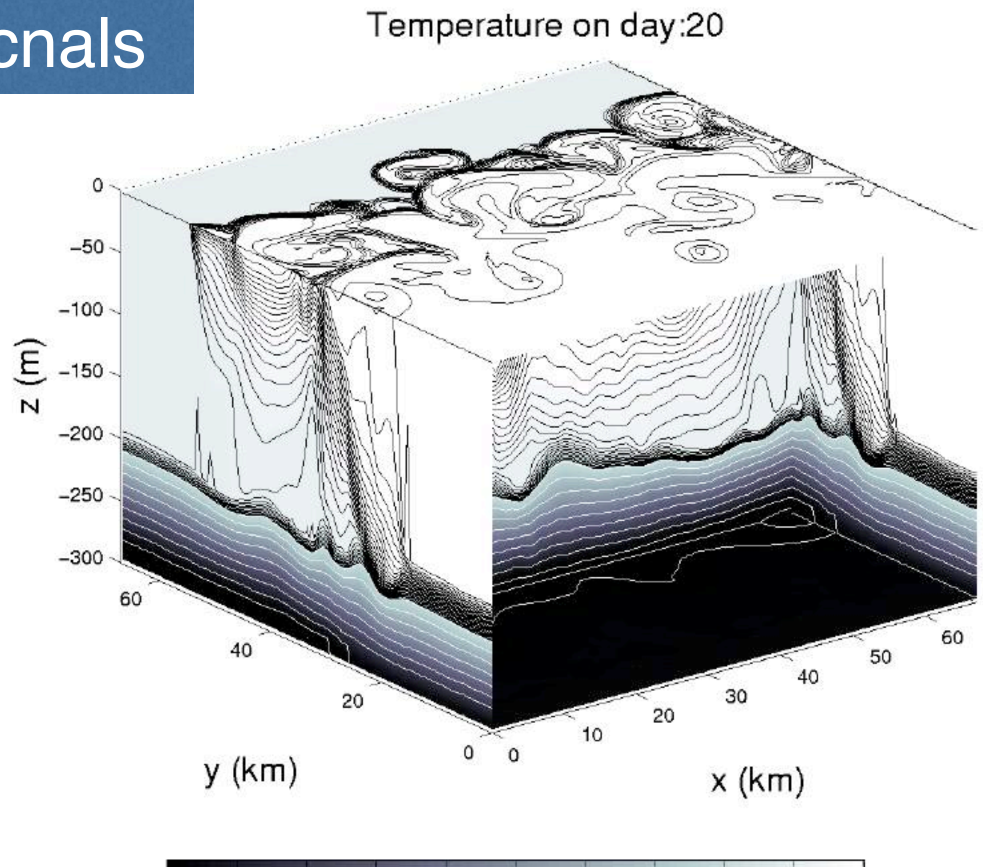
Restratification by submesoscale eddies

Boccaletti et al., 2006
Fox-Kemper et al., 2008





Mixed layer eddies slump isopycnals



Motion is along isopycnals

$$\langle w'b' \rangle = \psi_e |\nabla_H b|$$

Held and Schneider, 1998

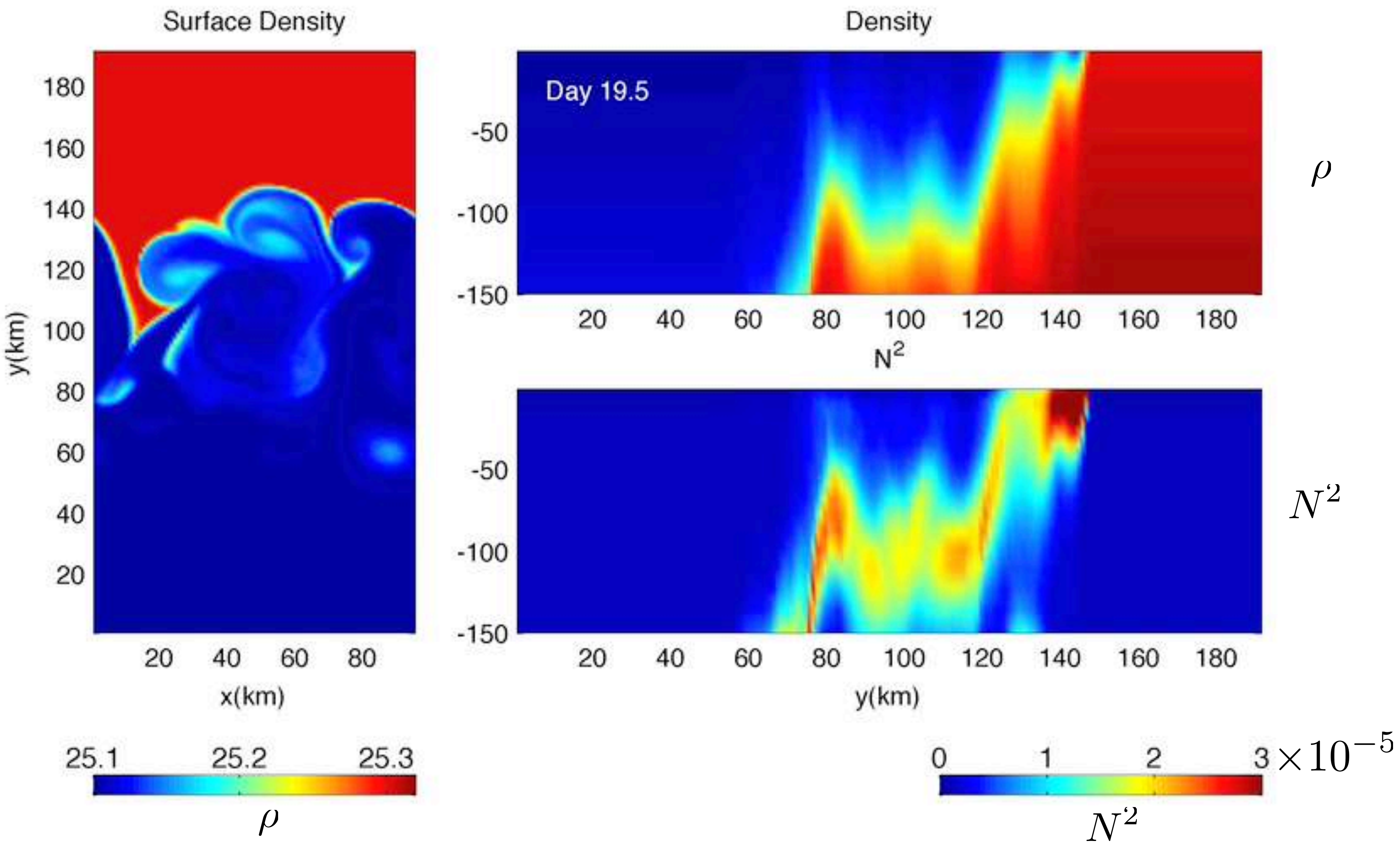
$$\psi_e = C_e |\nabla_H b| H^2 / f$$

Fox-Kemper et al., 2008

Mixed Layer Instability

Rapid adjustment of the mixed layer by submesoscale eddies

Vertical Section at x=48 km



Winds

$$\psi \approx -\tau^x/\rho f$$

Ekman buoyancy flux

$$\langle w'b'\rangle_{wind} = -\tau^x b_y/\rho f$$

Eddies

$$\langle w'b'\rangle_e = \langle \psi_e\, b_y\rangle$$

$$= 0.06\, b_y^2\, H^2/f$$

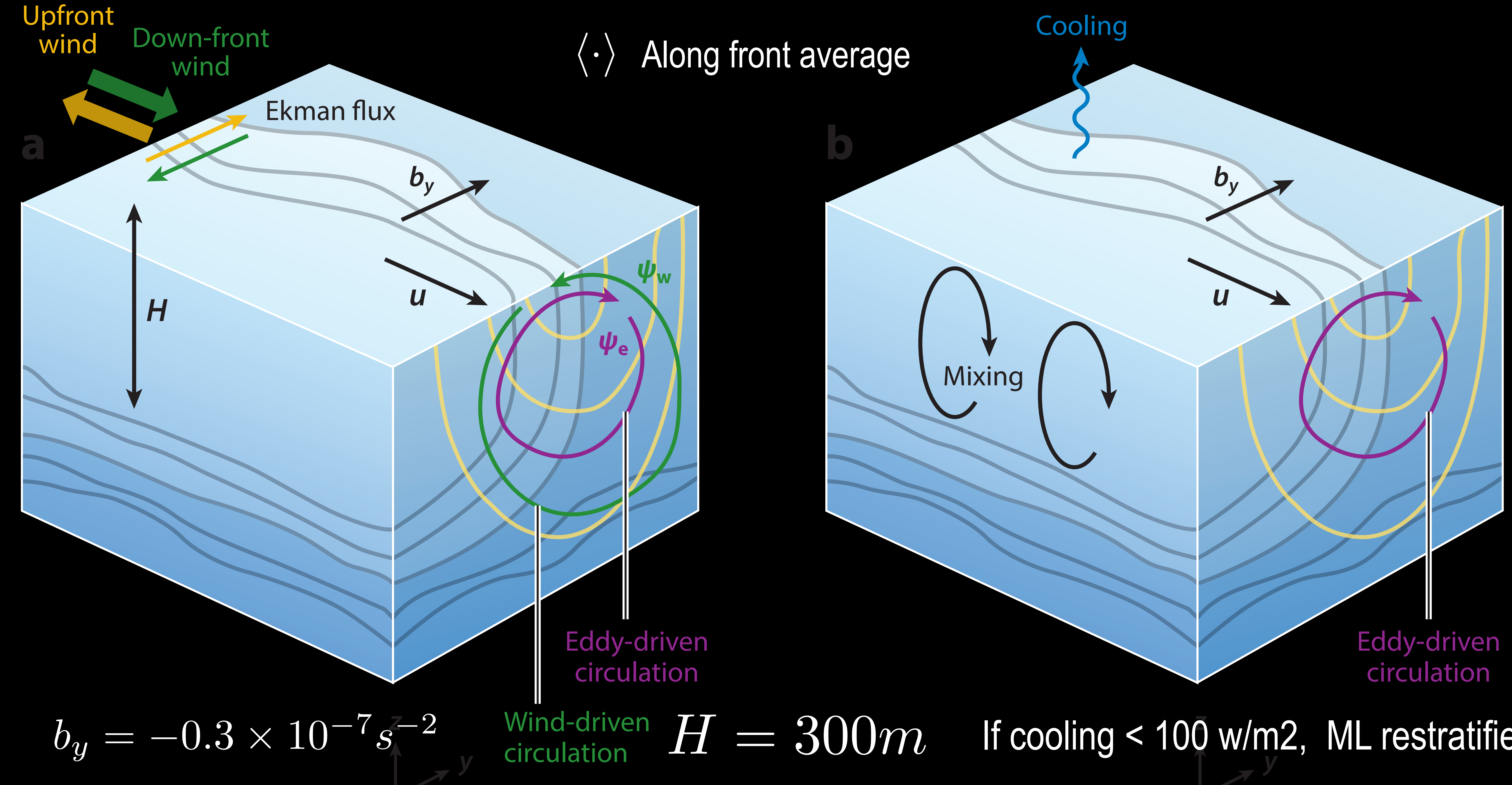
Cooling

$$\langle w'b'\rangle_{cool} = -\frac{\alpha Q g}{\rho C_p}$$

α Thermal expansion coefficient

Q Heat Flux

$\langle\cdot\rangle$ Along front average



$b_y = -0.3\times10^{-7}s^{-2}$

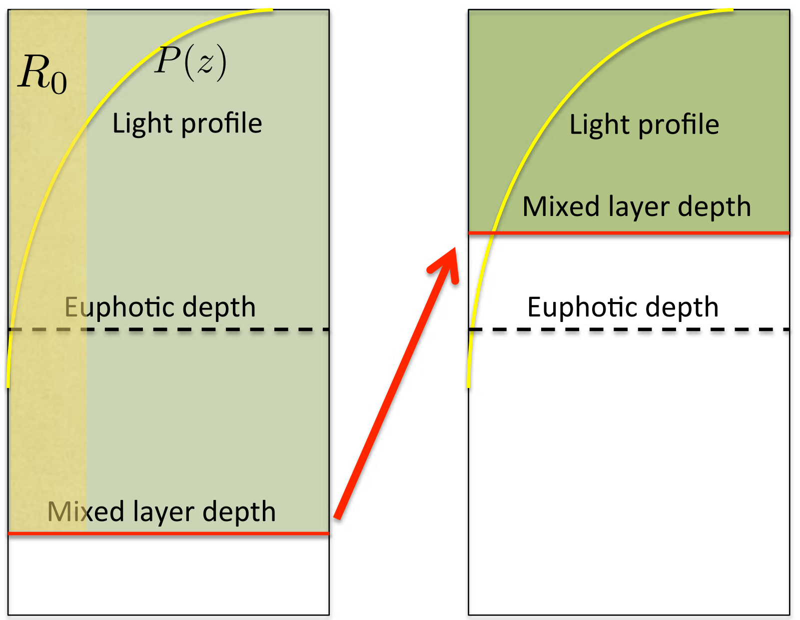
$H = 300m$

If cooling < 100 w/m2, ML restratifies.

Spring bloom: Plenty of nutrients post-winter, but light-limited

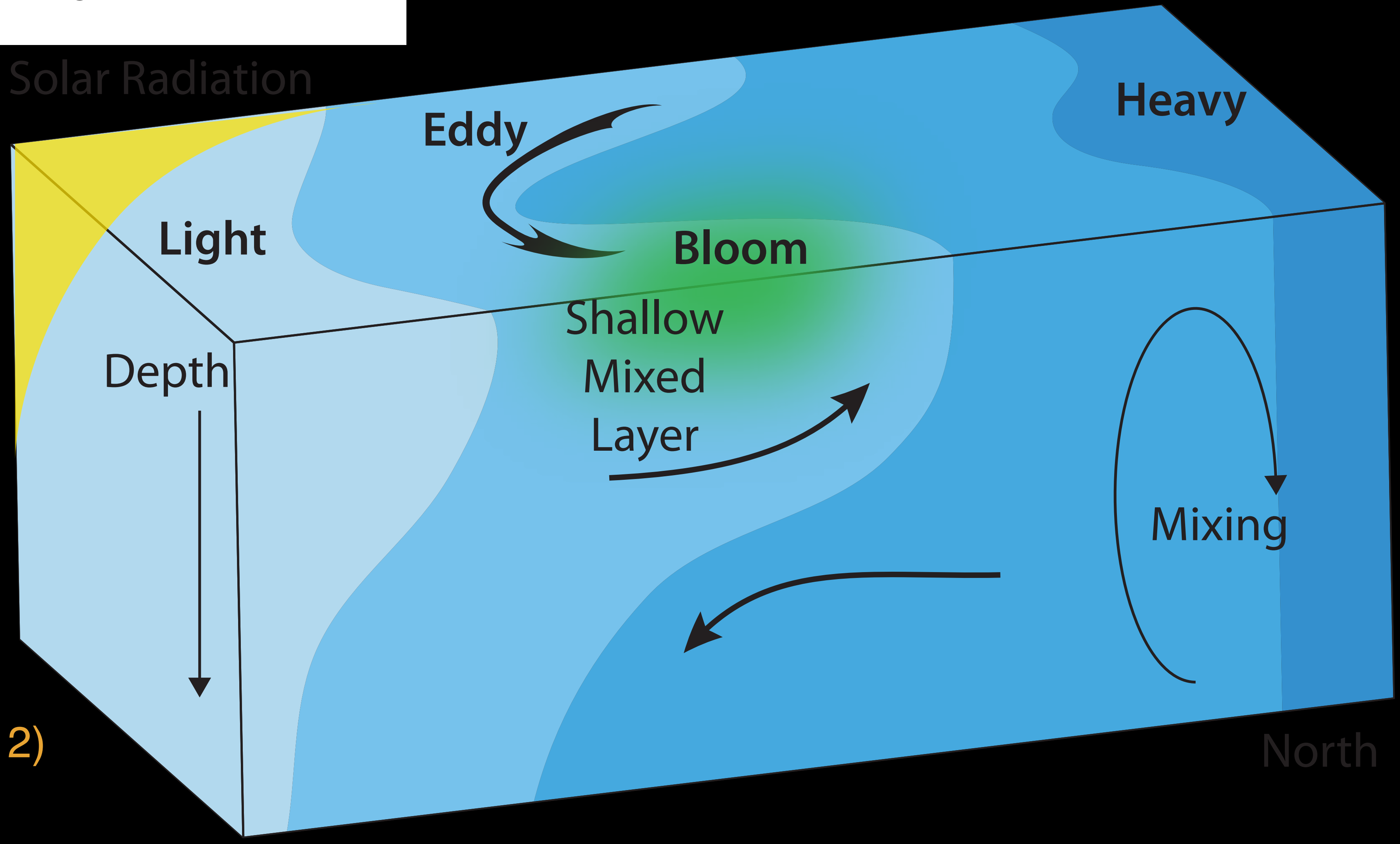
Light limitation is overcome when

- Incoming solar radiation increases
- Mixed layer (ML) depth decreases



Winter: Mixed layer is deep and the average light in the mixed layer is low

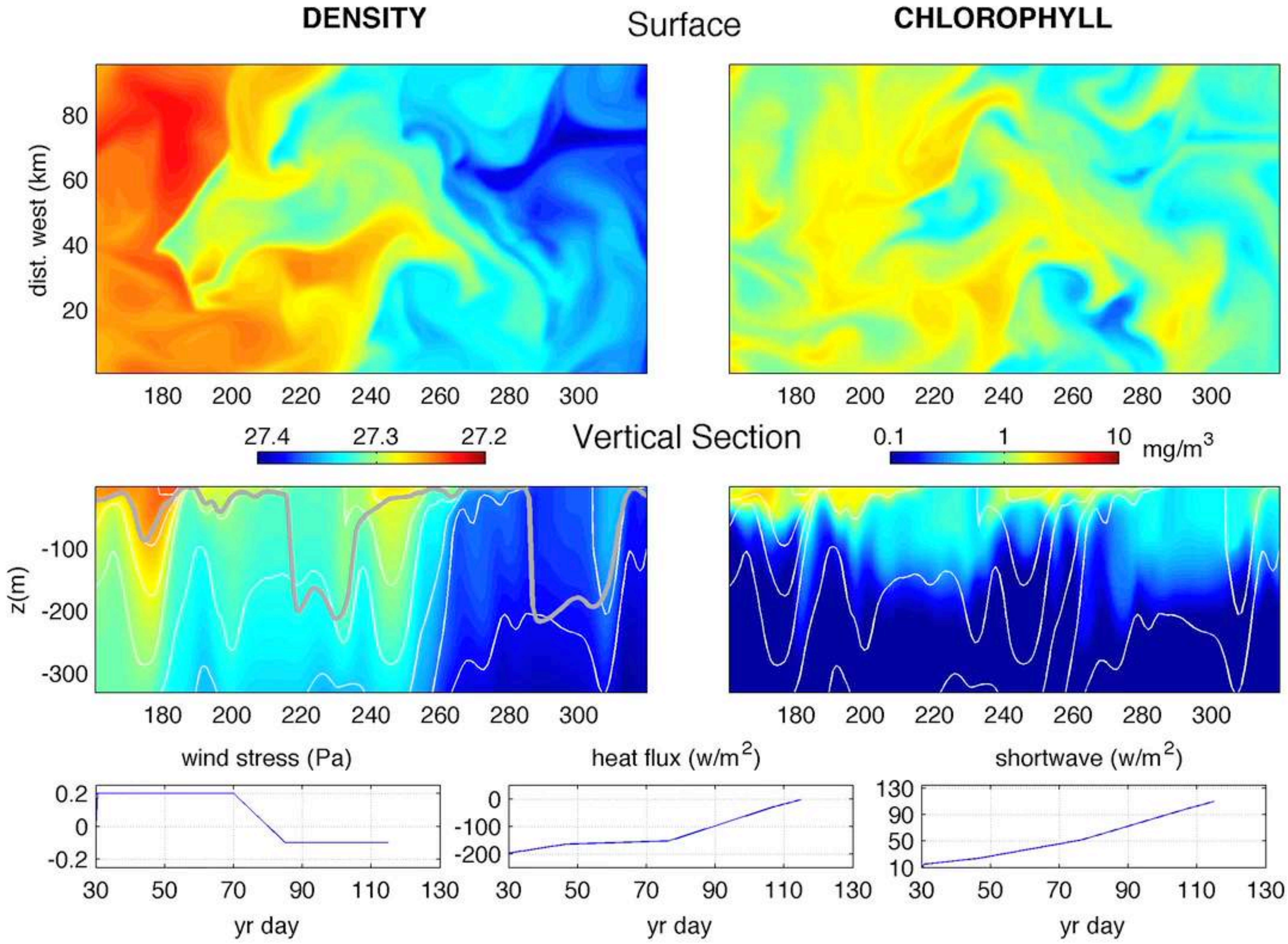
Spring: Mixed Layer Shallows and the average light is higher



Eddy-driven stratification: initiates & prolongs the bloom

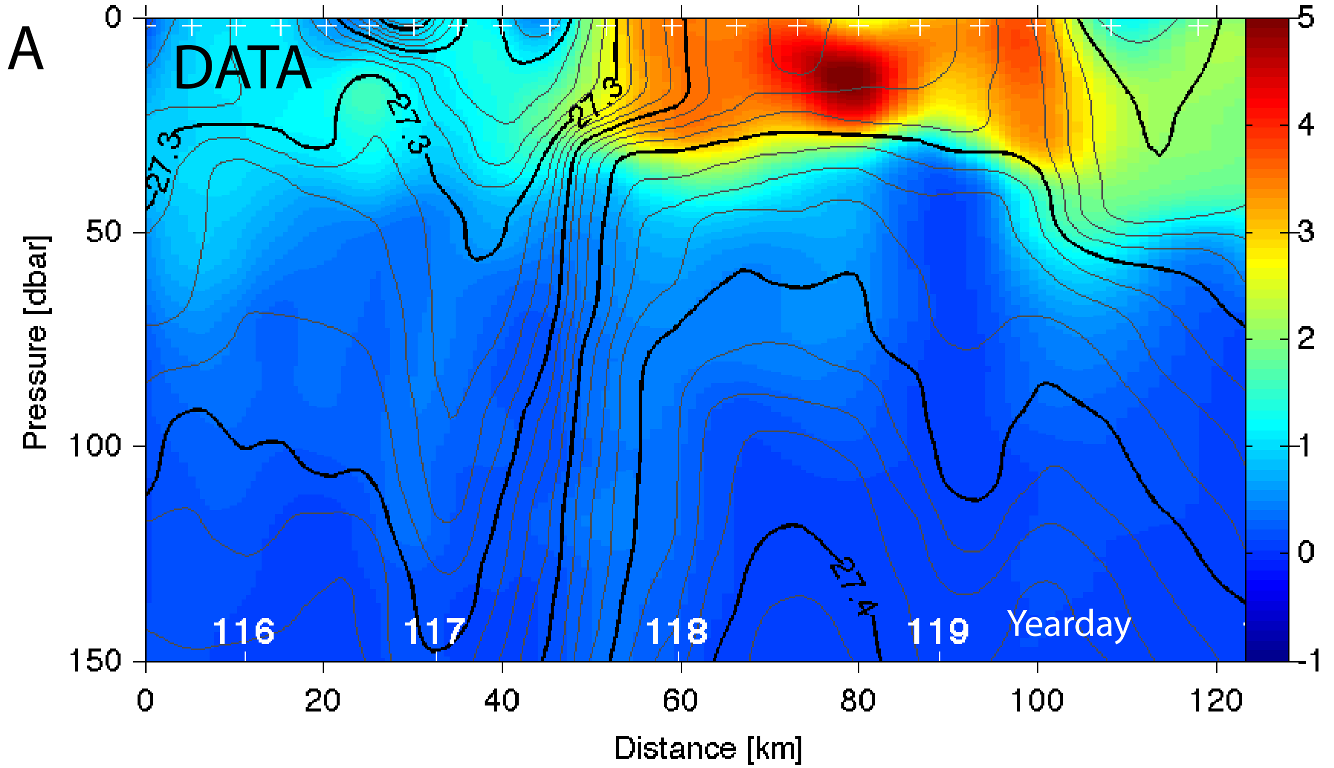
Mahadevan et al. (Science 2012)

Yr Day 115

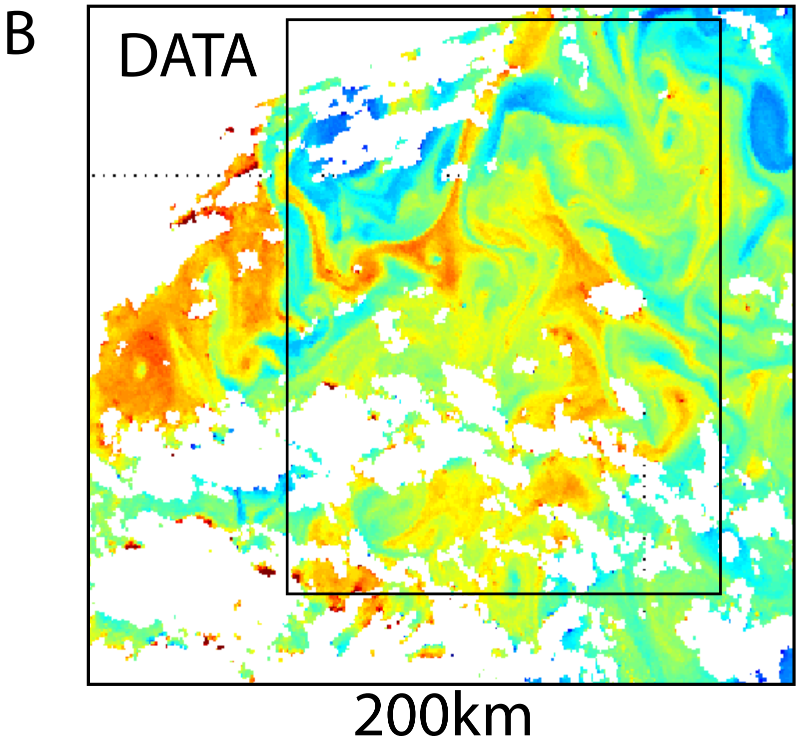

DENSITY
Surface
CHLOROPHYLL
dist. west (km)
80
60
40
20
180
200
220
240
260
280
300
27.4
27.3
27.2
Vertical Section
0.1
1
10
mg/m^3
z(m)
-100
-200
-300
wind stress (Pa)
0.2
0
-0.2
heat flux (w/m^2)
0
-100
-200
shortwave (w/m^2)
130
90
50
10
30
50
70
90
110
130
yr day

YEAR DAY 115

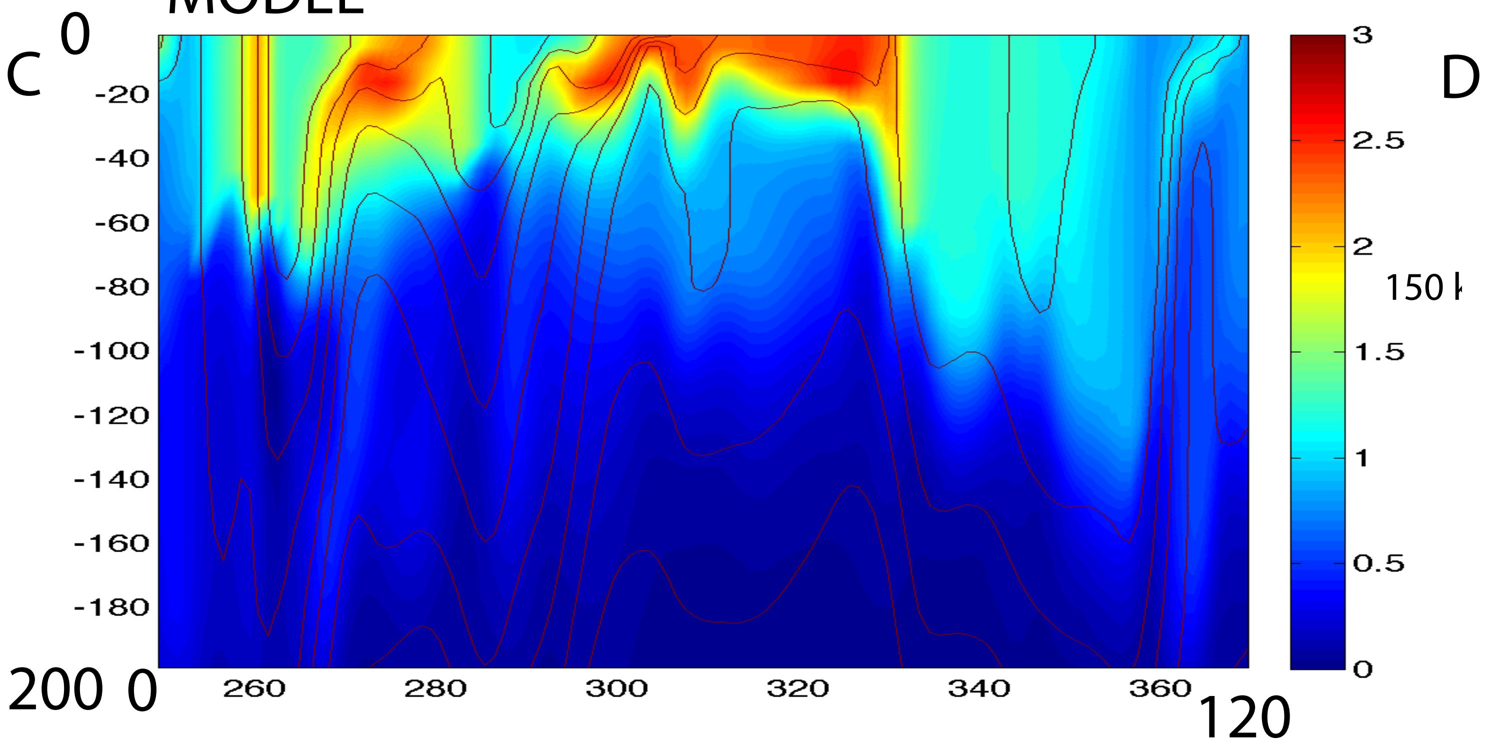
Chlorophyll from Glider section (C. Lee)



Satellite Chlorophyll

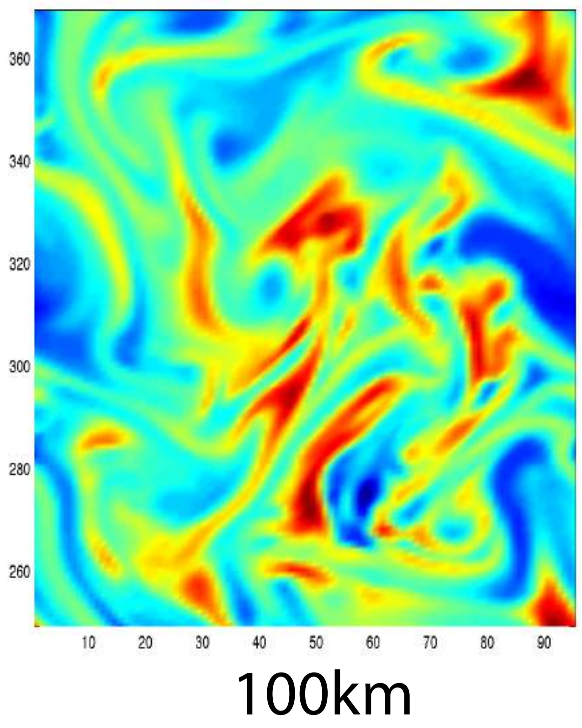


MODEL

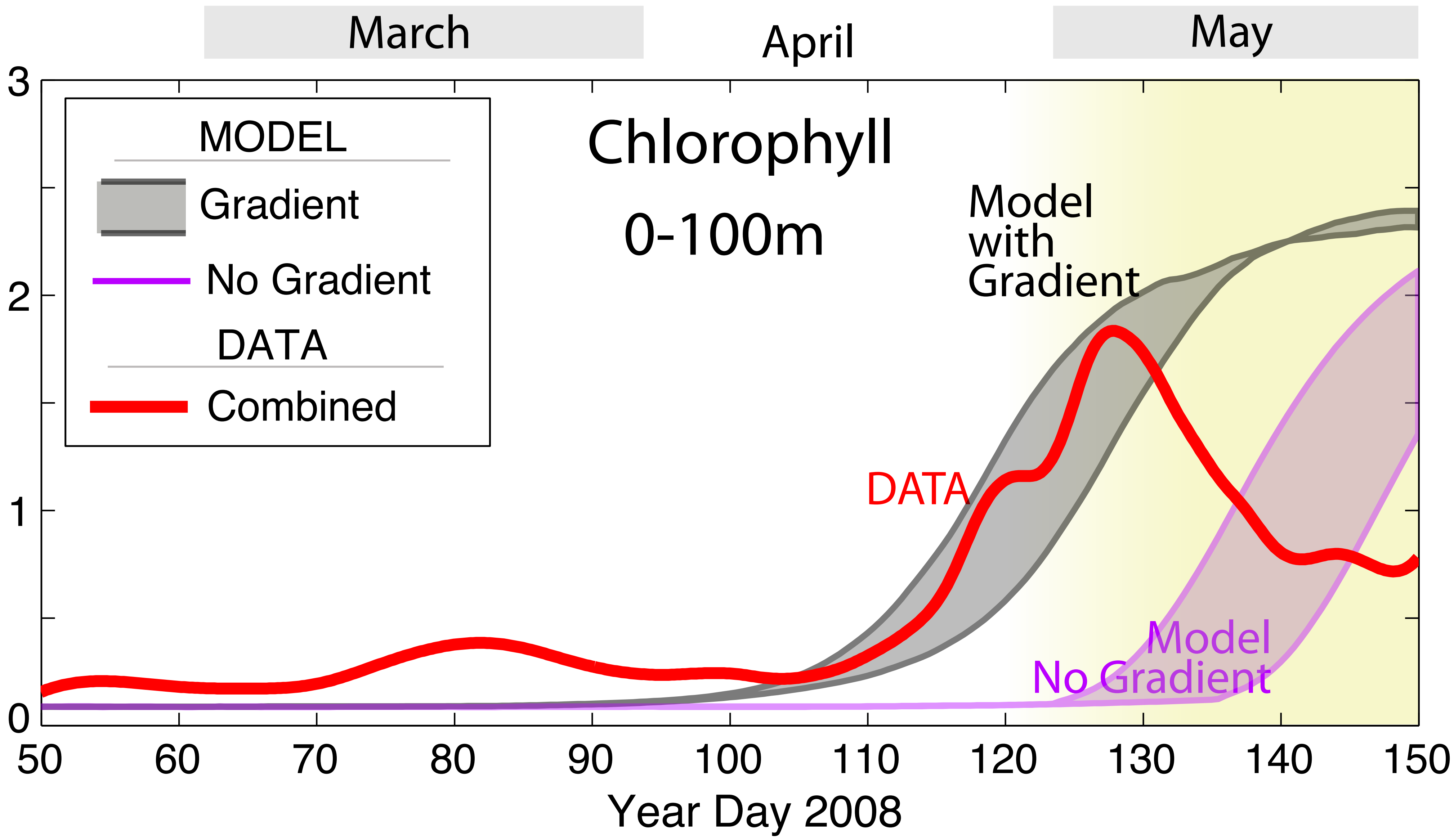


MODEL

D

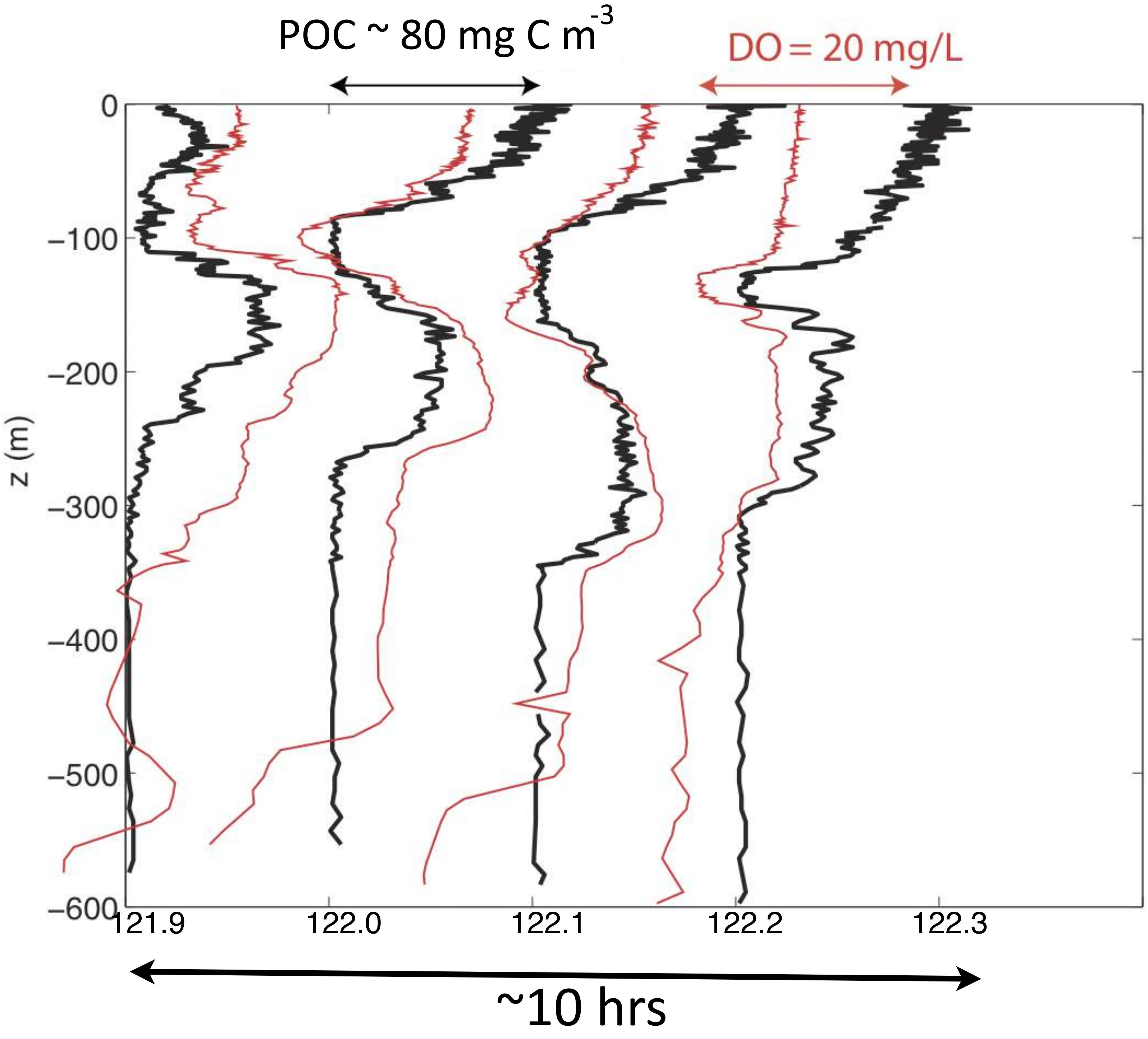


Model


March
April
May
Chlorophyll
0-100m
MODEL
Gradient
No Gradient
DATA
Combined
Model
with
Gradient
DATA
Model
No Gradient
3
2
1
0
50
60
70
80
90
100
110
120
130
140
150
Year Day 2008

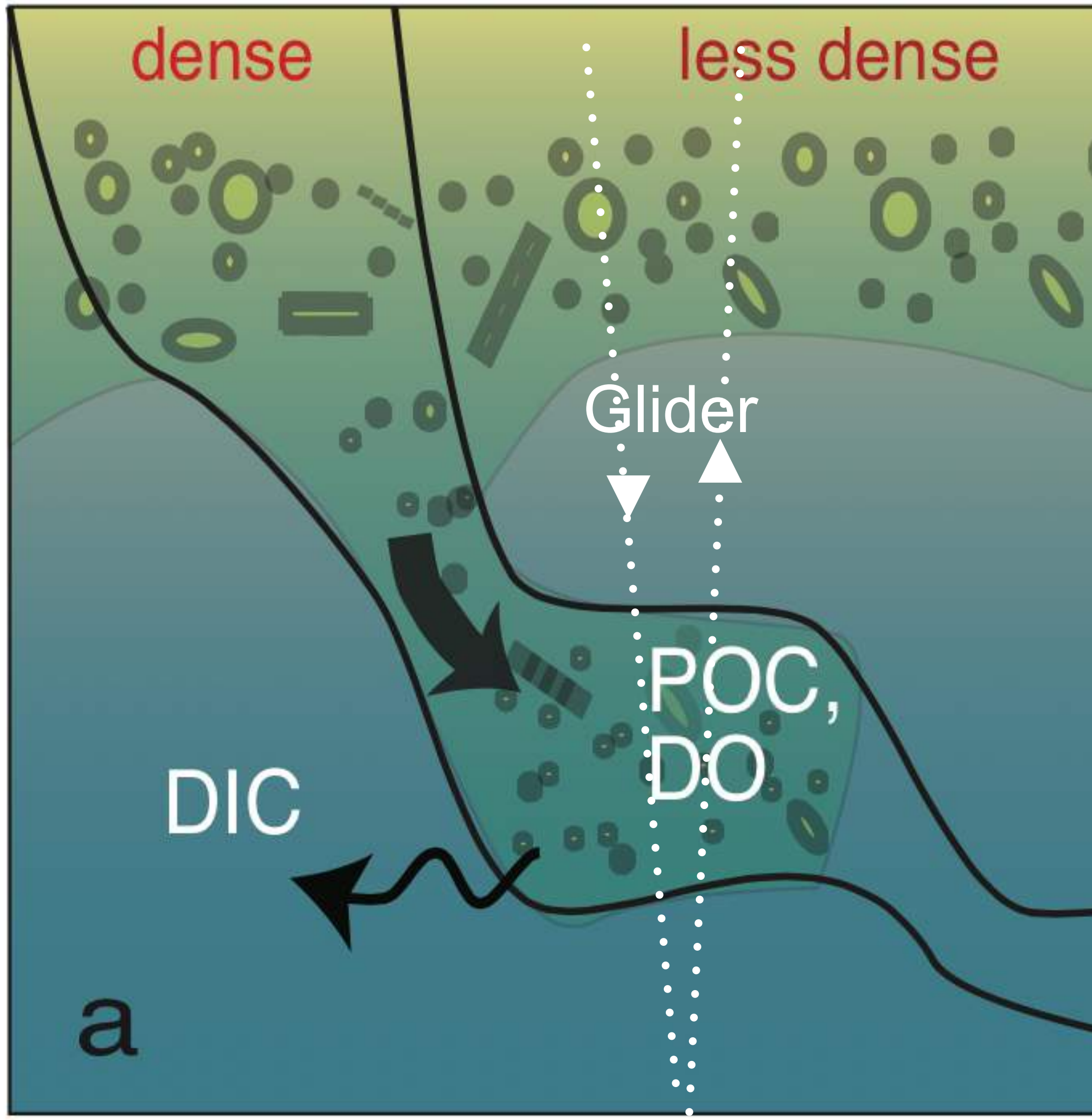
Glider profiles show elevated POC and oxygen subsurface

Features below ML & euphotic dep. Elevated POC, Chl, oxygen, unique T-s charac.


POC ~ 80 mg C m^{-3}

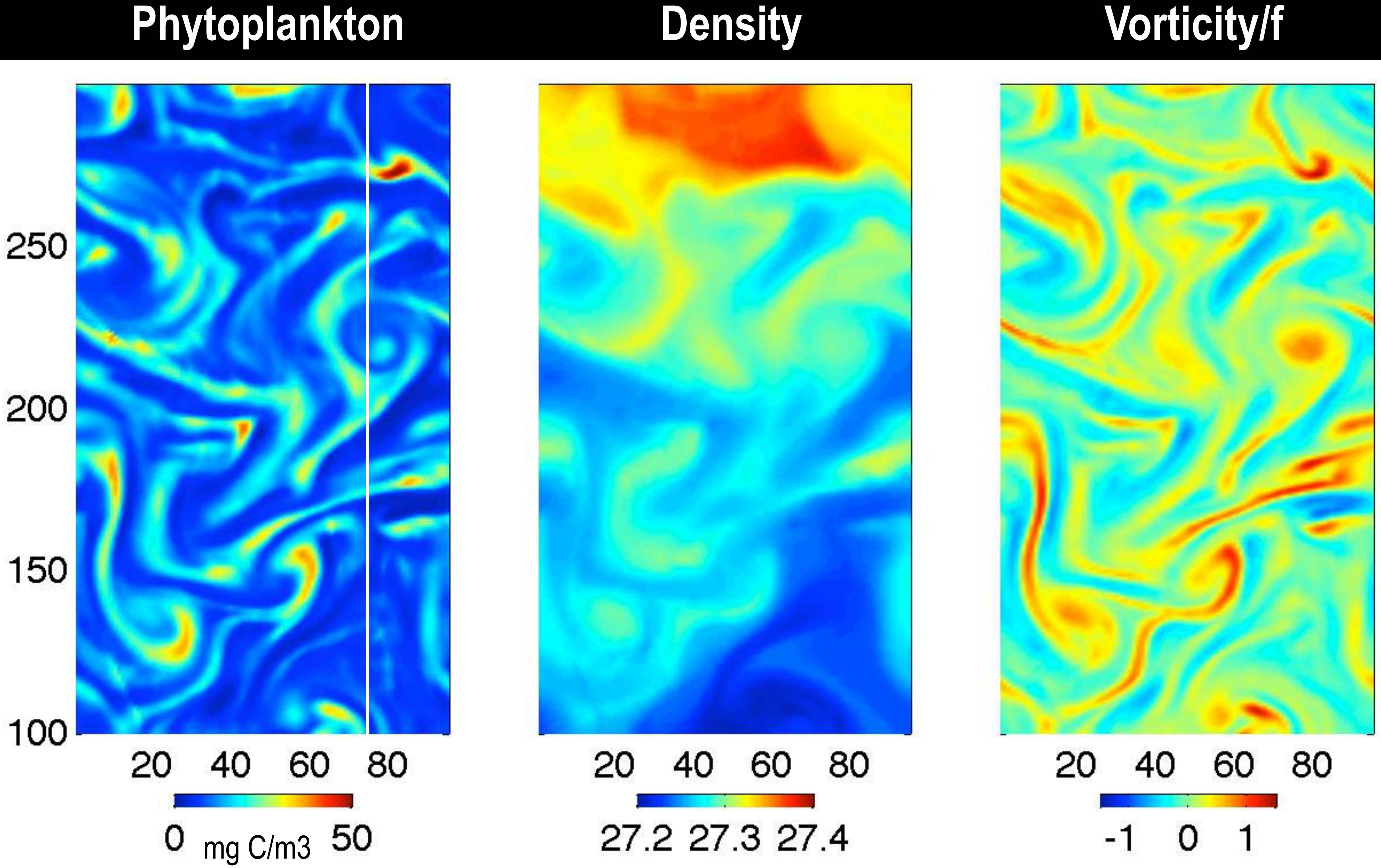
DO = 20 mg/L

~10 hrs



Omand et al. *Science* (2015)

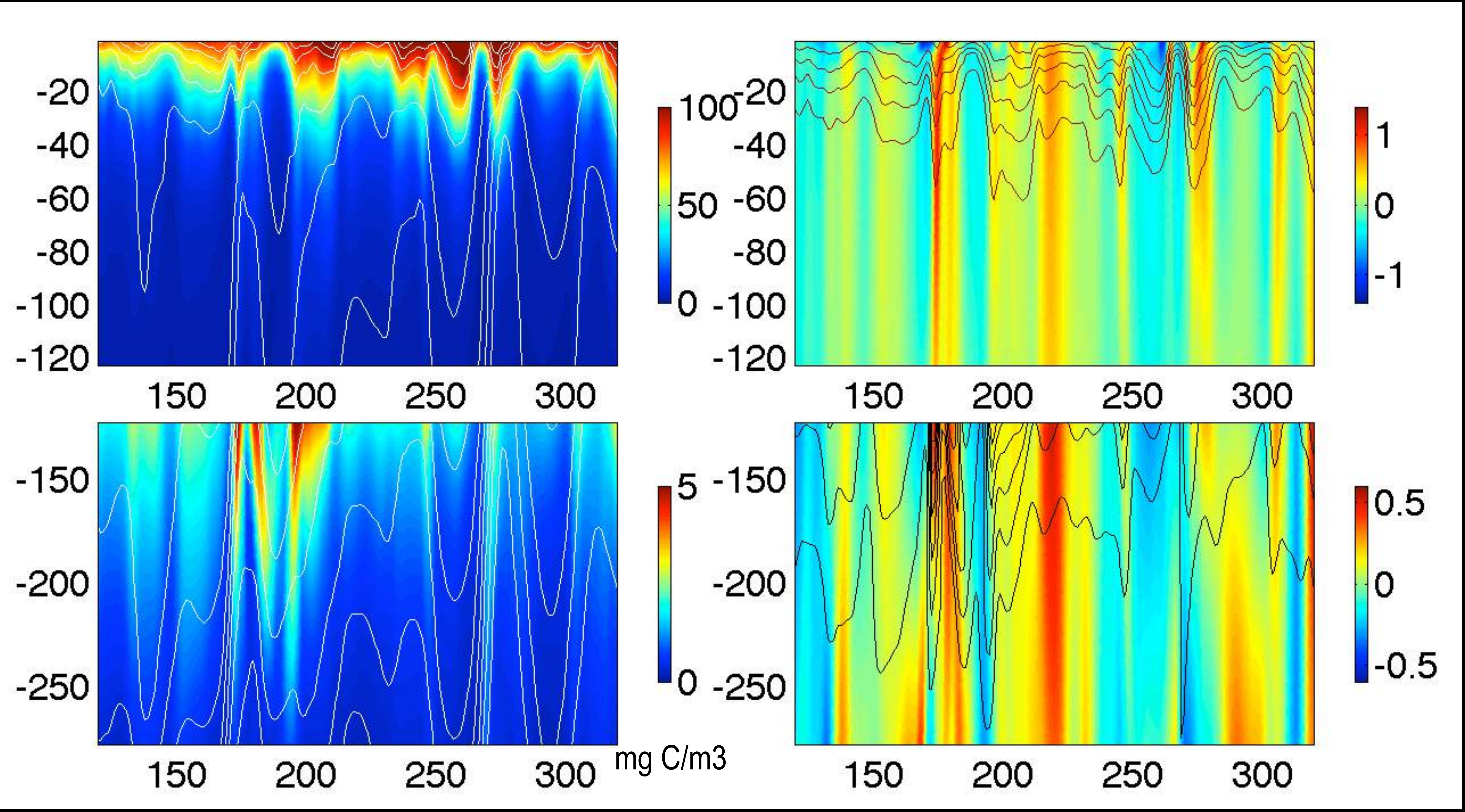
At 50 m depth


Phytoplankton
Density
Vorticity/f
250
200
150
100
20
40
60
80
0
mg C/m3
50
27.2
27.3
27.4
-1
0
1

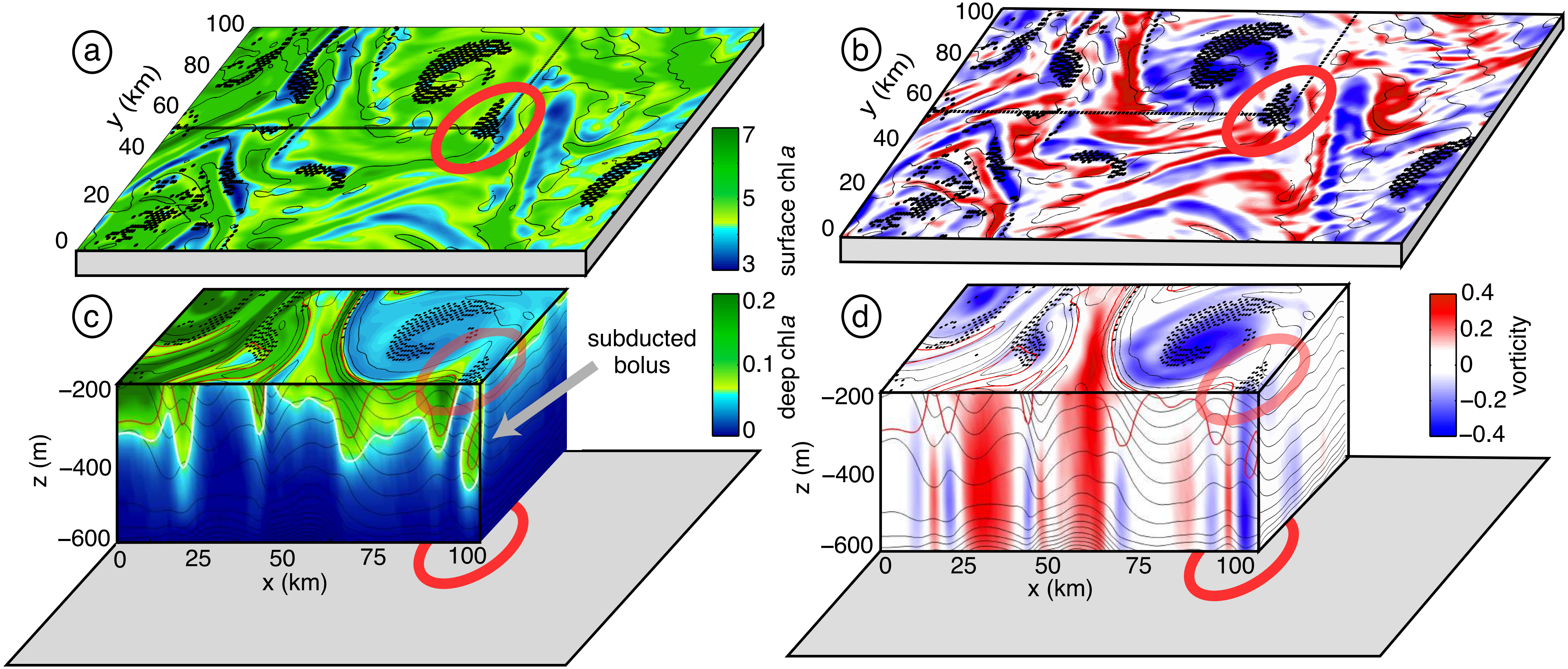
Vertical Section

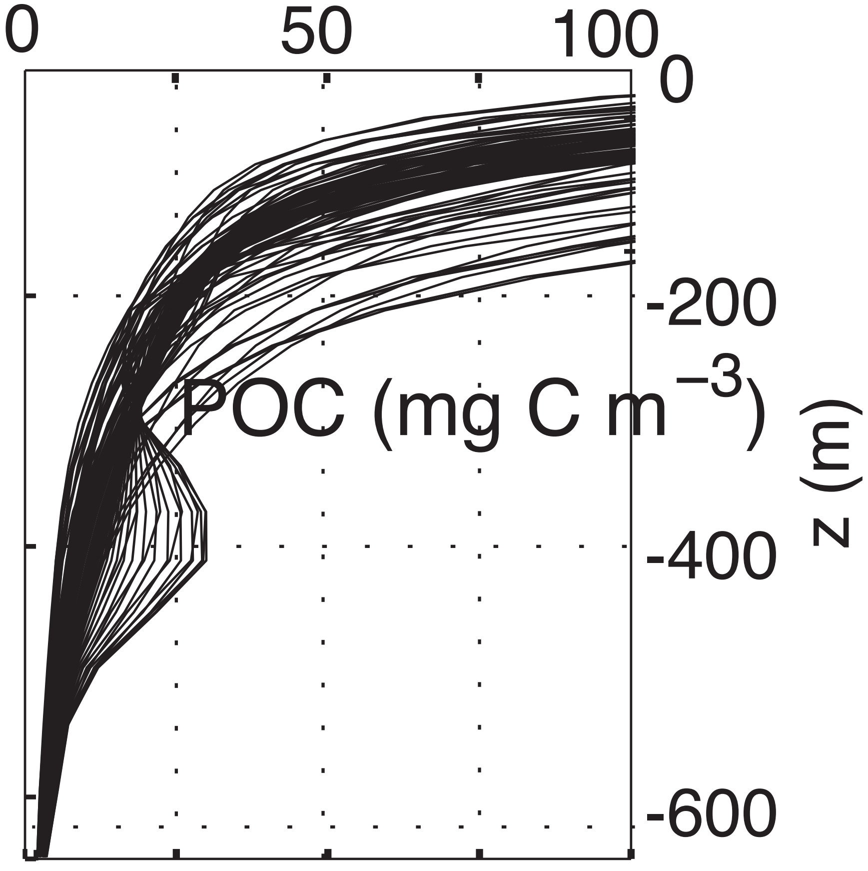
Phytoplankton

Vorticity /f



Omand et al. (2015)





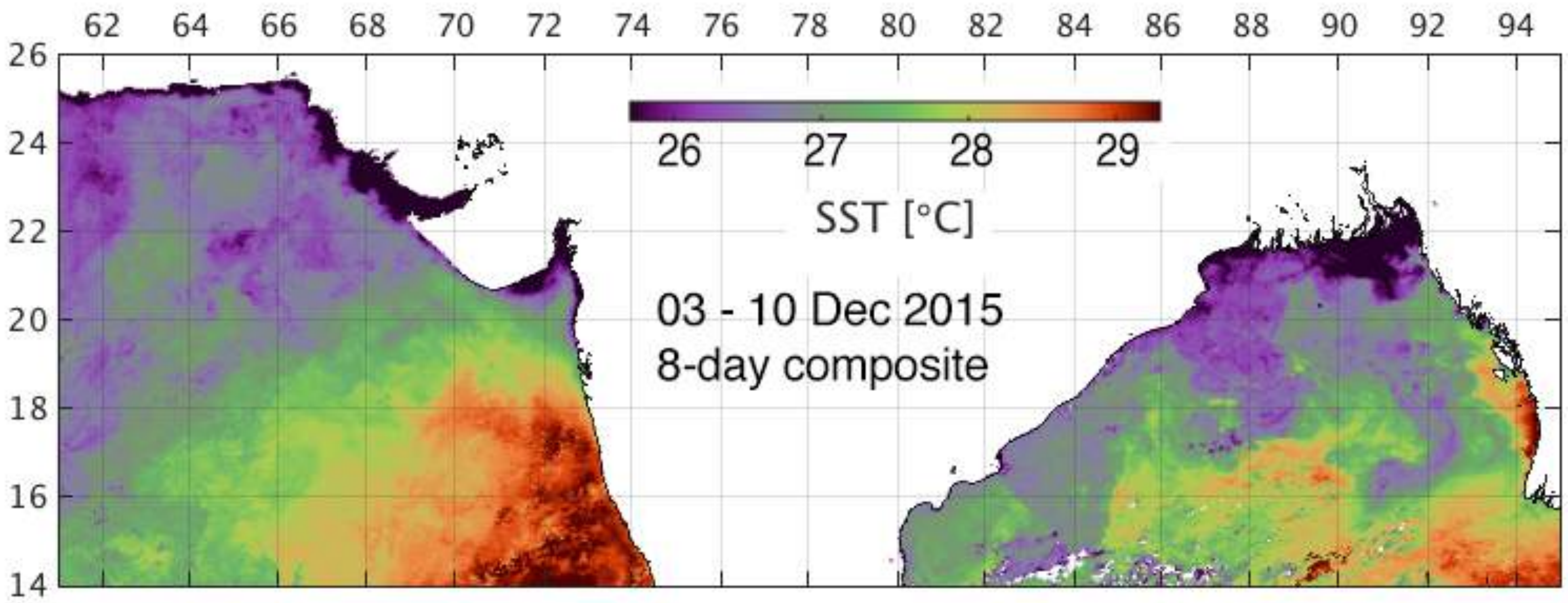
Vertical profiles from Model

~10% of domain has subsurface features in POC

Omand et al. (2015)

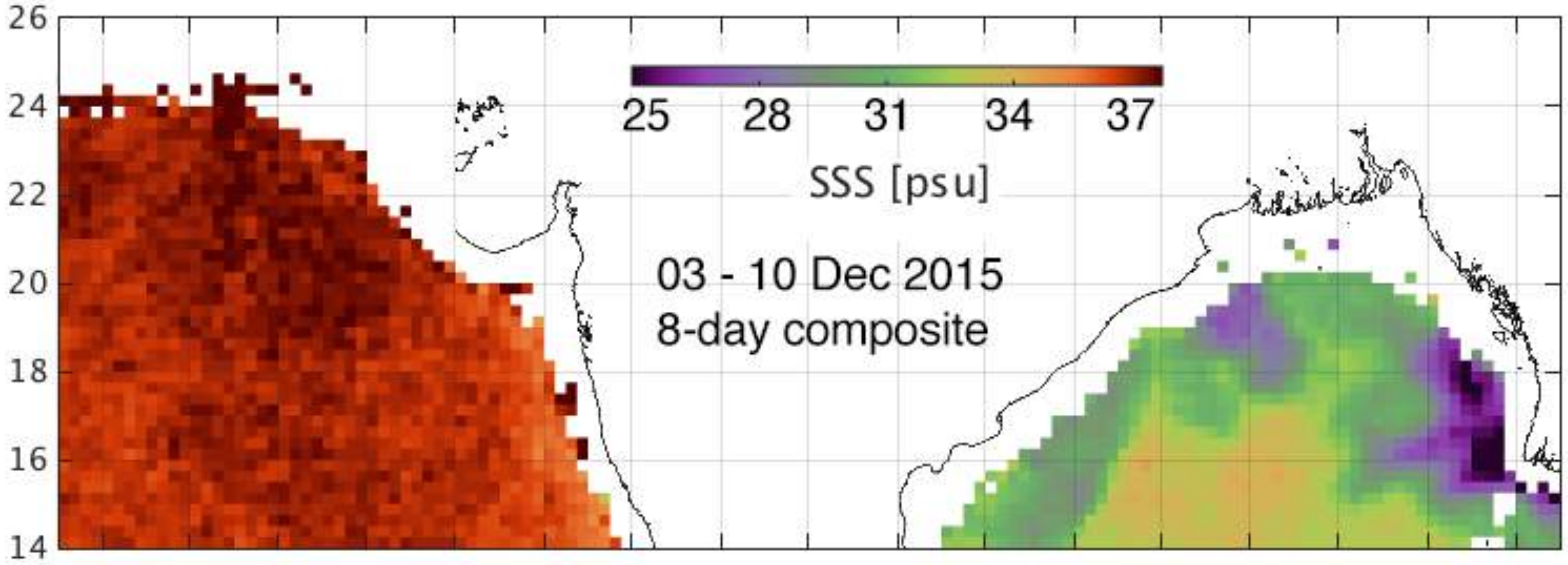
WINTER

SST



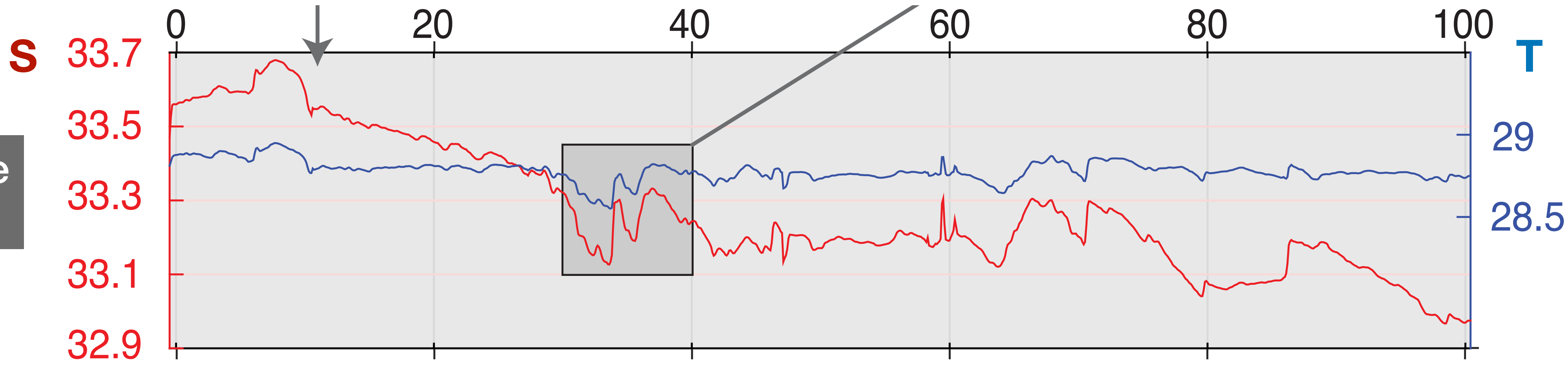
What controls the SST?

SSS



Salinity controls the near-surface density

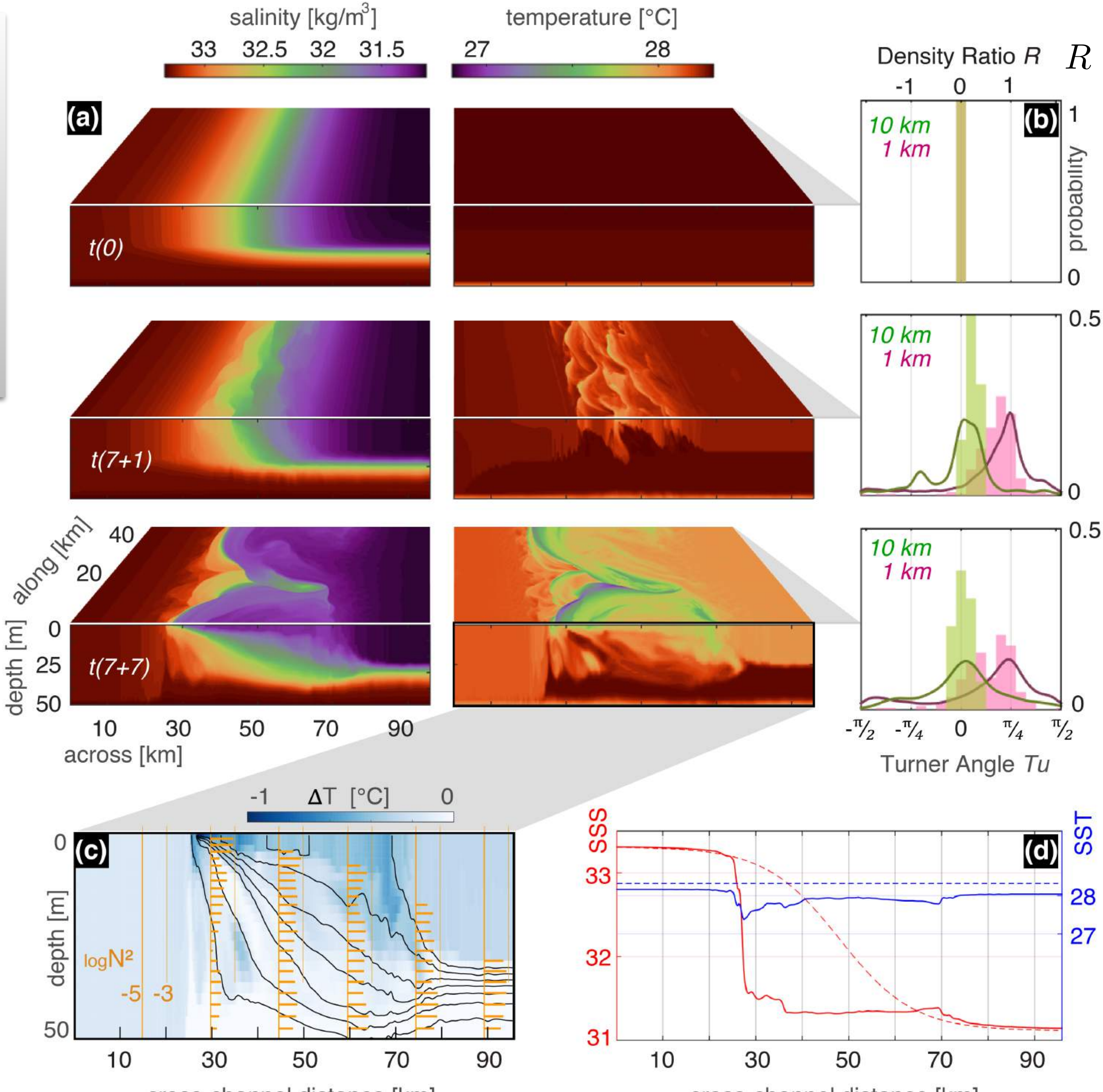
surface SSS



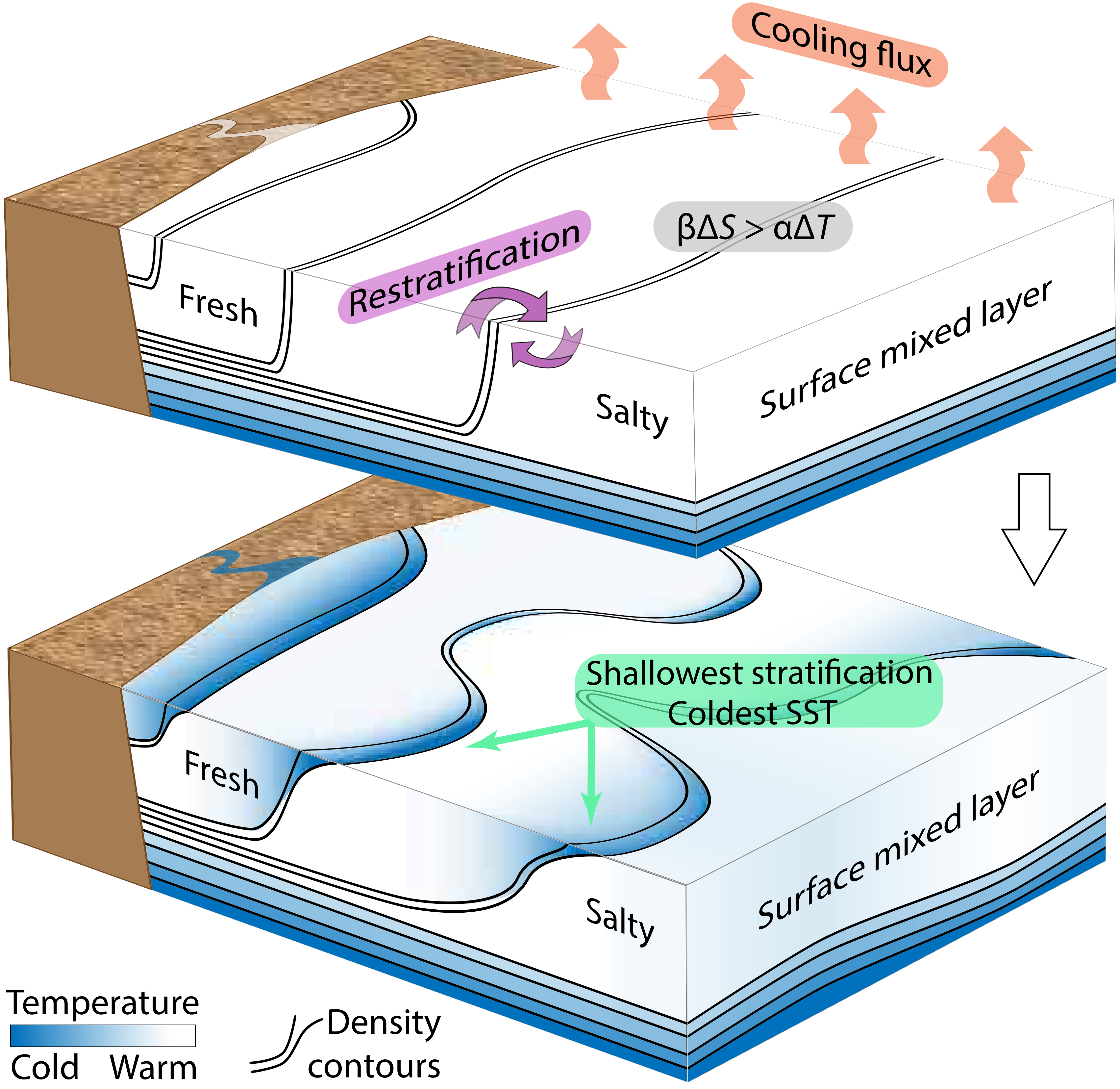
Jaeger and Mahadevan, Sci Adv. (2018)

Uniform cooling of a shallow salinity front

$$R = \frac{\alpha \Delta T}{\beta \Delta S}$$



Jaeger and Mahadevan, Sci Adv. (2018)

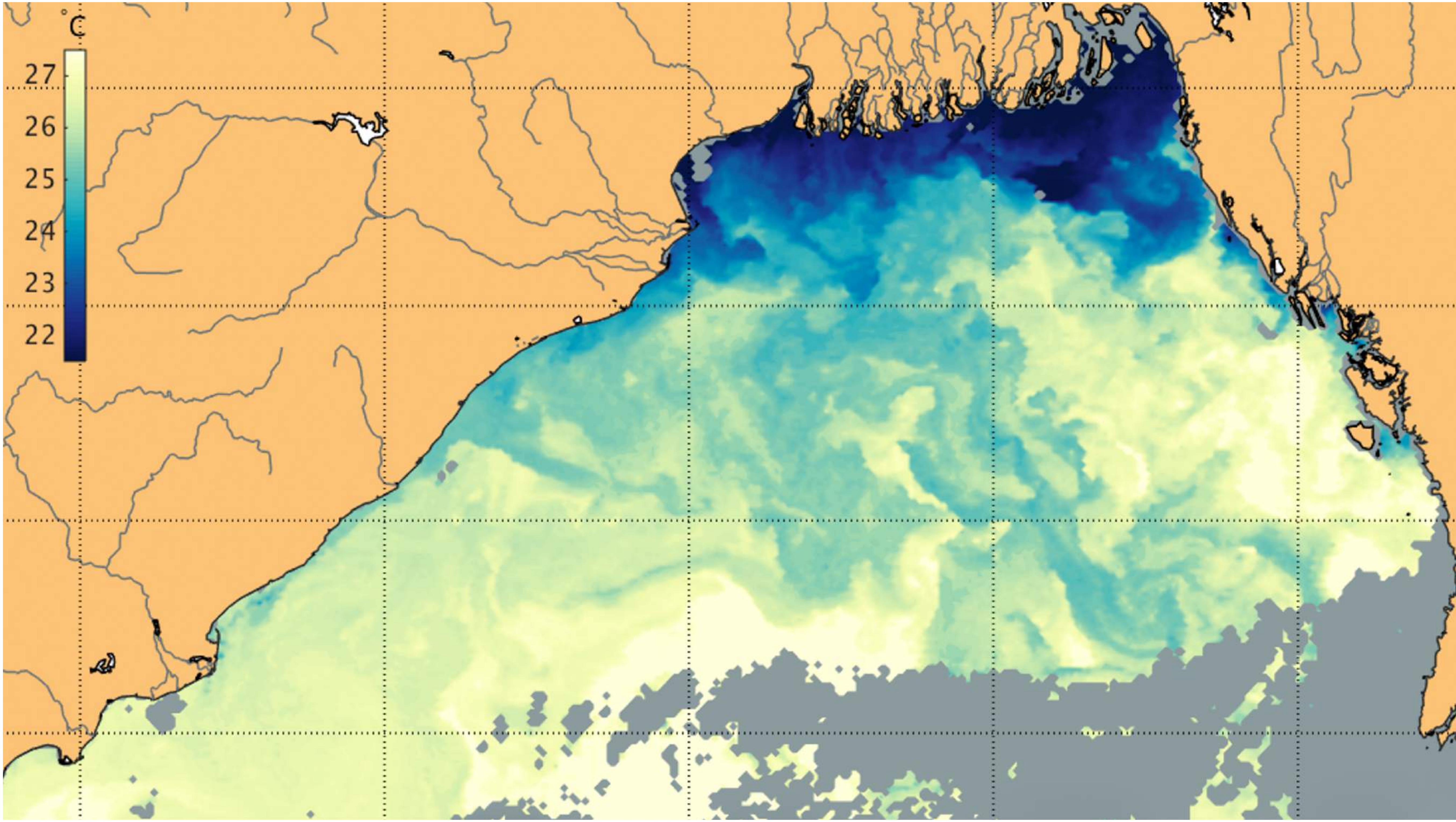


Density fronts
controlled by
salinity gradients:

Submesoscale
circulation
↓
Shallow vertical
re-stratification
(along front)
+
Atmosphere
cools ocean
↓
Largest SST drop
along front
⇓
Partial *T-S*
compensation at
frontal scale:

Salty (deep) warm
Fresh (shallow) cold

Winter SST in the Bay of Bengal
a salinity-stratified ocean



Summary

Why higher resolution?   What are we missing in coarser resolution models?

- Vertical transport -
  - Vertical fluxes - are concentrated in small regions

- Restratification by advection - fluxes buoyancy upward
  - Lateral buoyancy gradients are converted to vertical density gradients
  - Potential energy - > kinetic energy (more quickly than by mesoscale)

- Biological production and export influenced by:
  - enhanced nutrient supply by along-isopycnal advection
  - enhanced re-stratification
  - intensified downwelling