Submesoscale processes, biophysical interactions, and the Arctic

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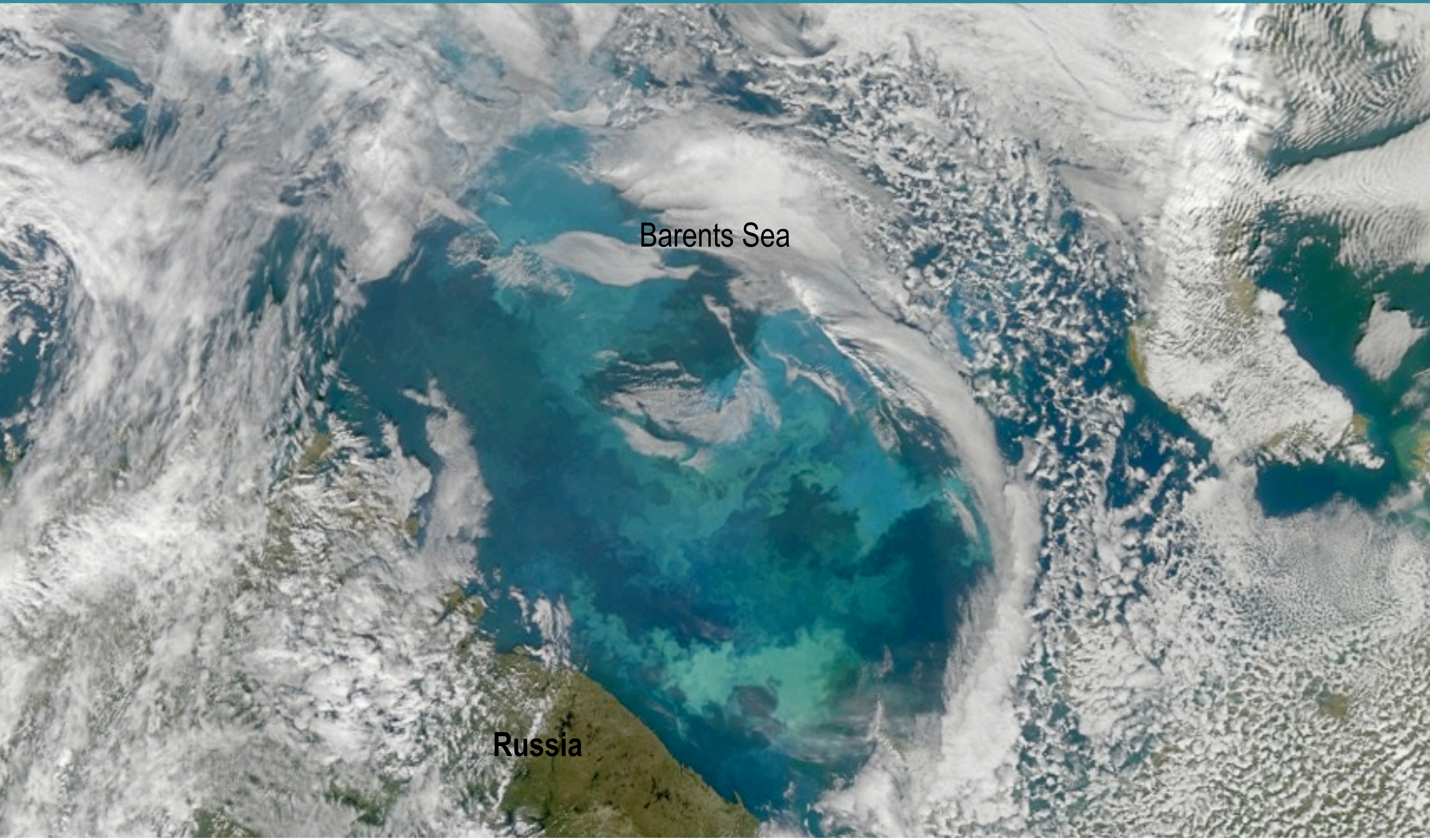
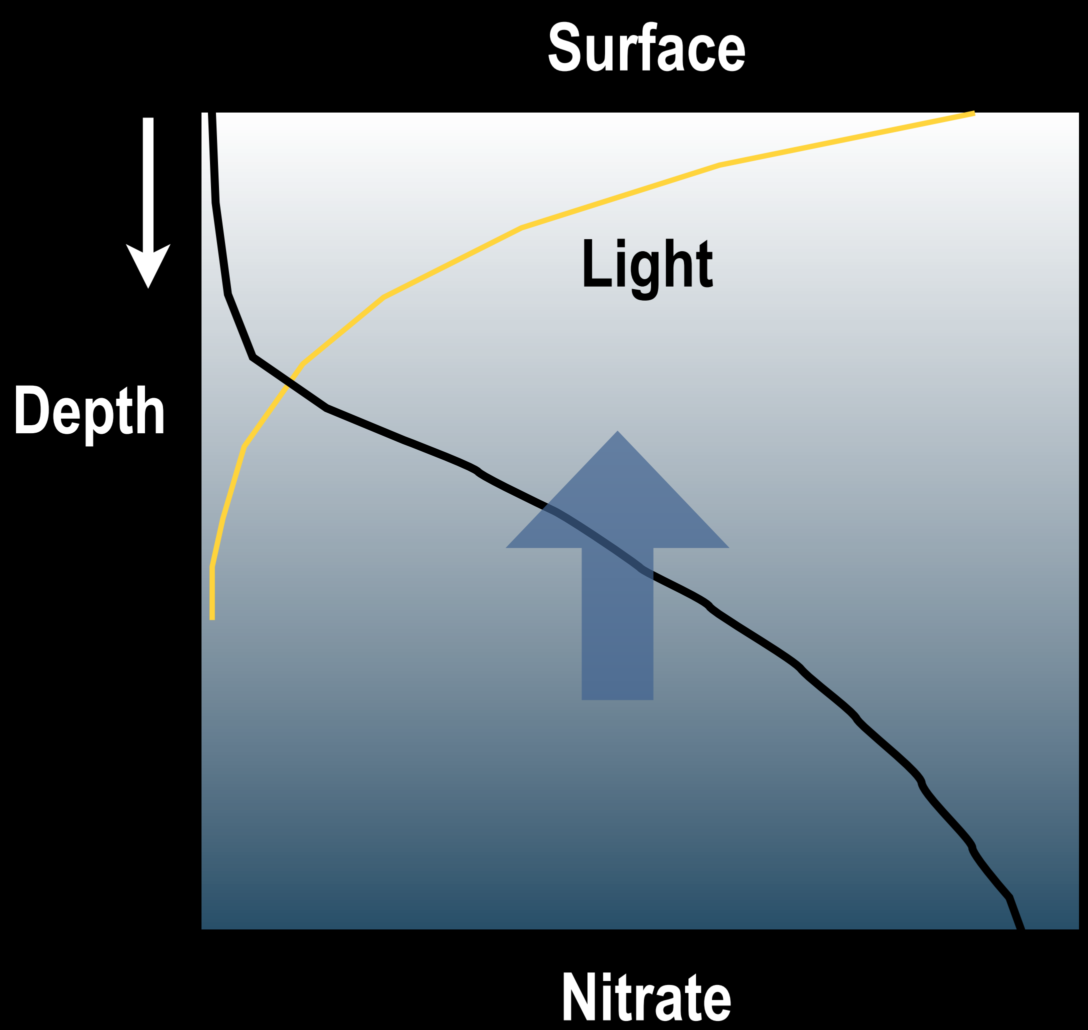


Oligotrophic regions



How are nutrients supplied to the euphotic zone?

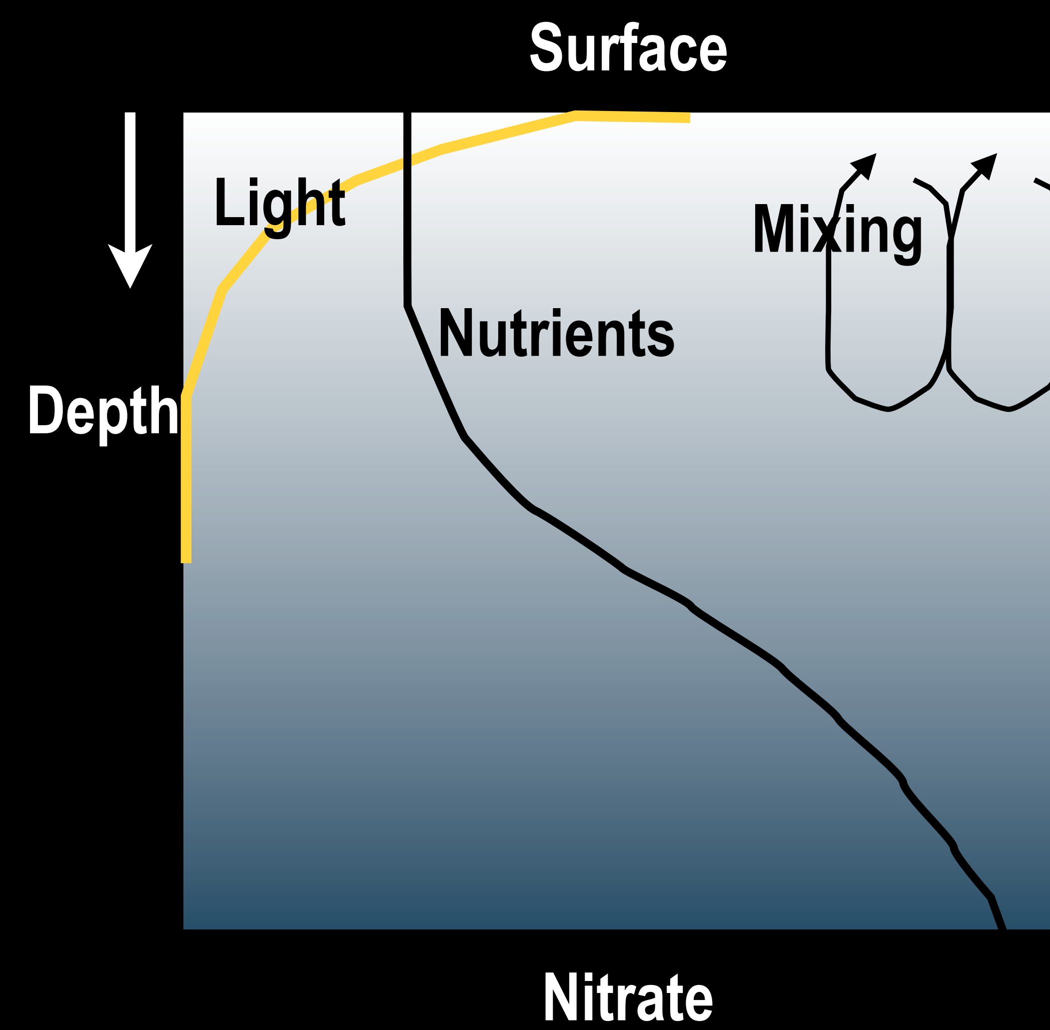
Basin scale

Meso-scale dynamics

Submeso-scale dynamics

Small scale mixing

Nutrient replete regions



How is phytoplankton sustained in the euphotic zone?

$\zeta = v_x - u_y$ Vorticity (vertical component)

Mesoscale Dynamics

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

Submesoscale Dynamics

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

Why?

Mahadevan & Tandon, 2006

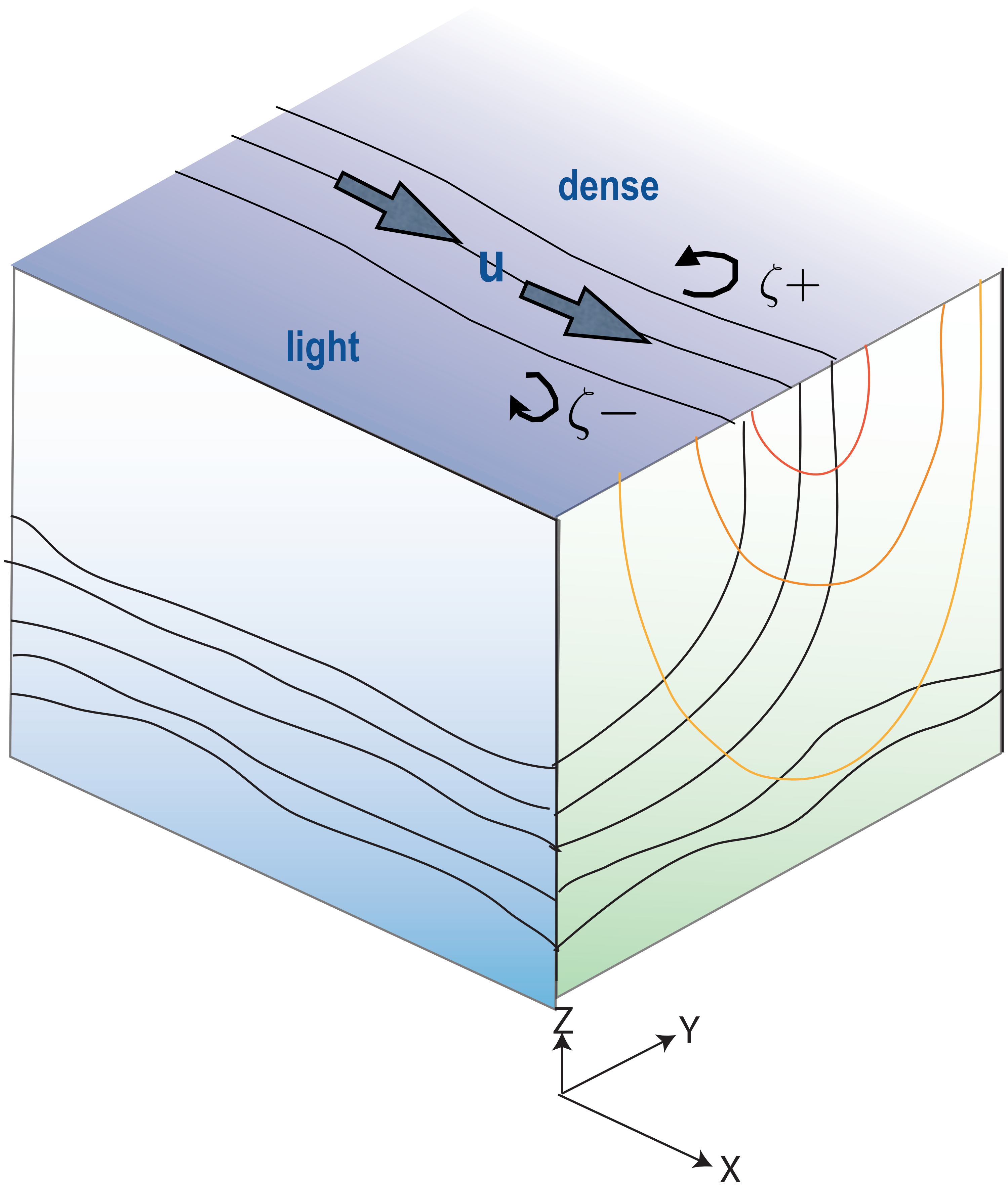
Mahadevan, 2006

Review on submesoscale process

Thomas, Tandon, Mahadevan, 2008

Capet et al, 2008

Fronts - Lateral gradients in density (buoyancy) -present everywhere



Buoyancy

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

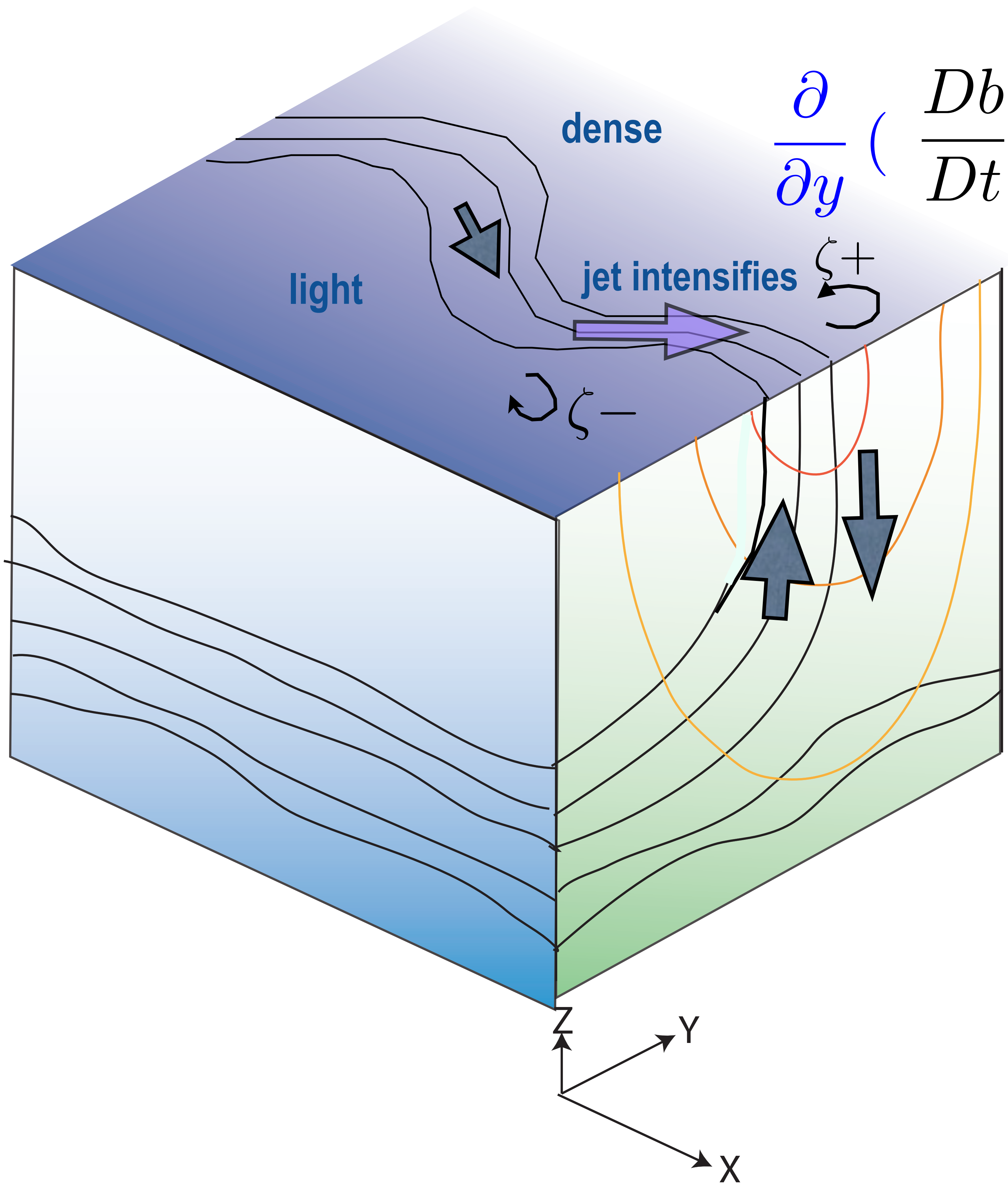
$$\frac{Db}{Dt} = 0$$

Conserved in the absence of forcing.

Geostrophic & thermal wind balance, for small Ro

$$fu = -p_y \qquad fu_z = b_y$$

Fronts spontaneously intensify



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

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

$$= -u_y b_x - v_y b_y$$

Frontogenesis

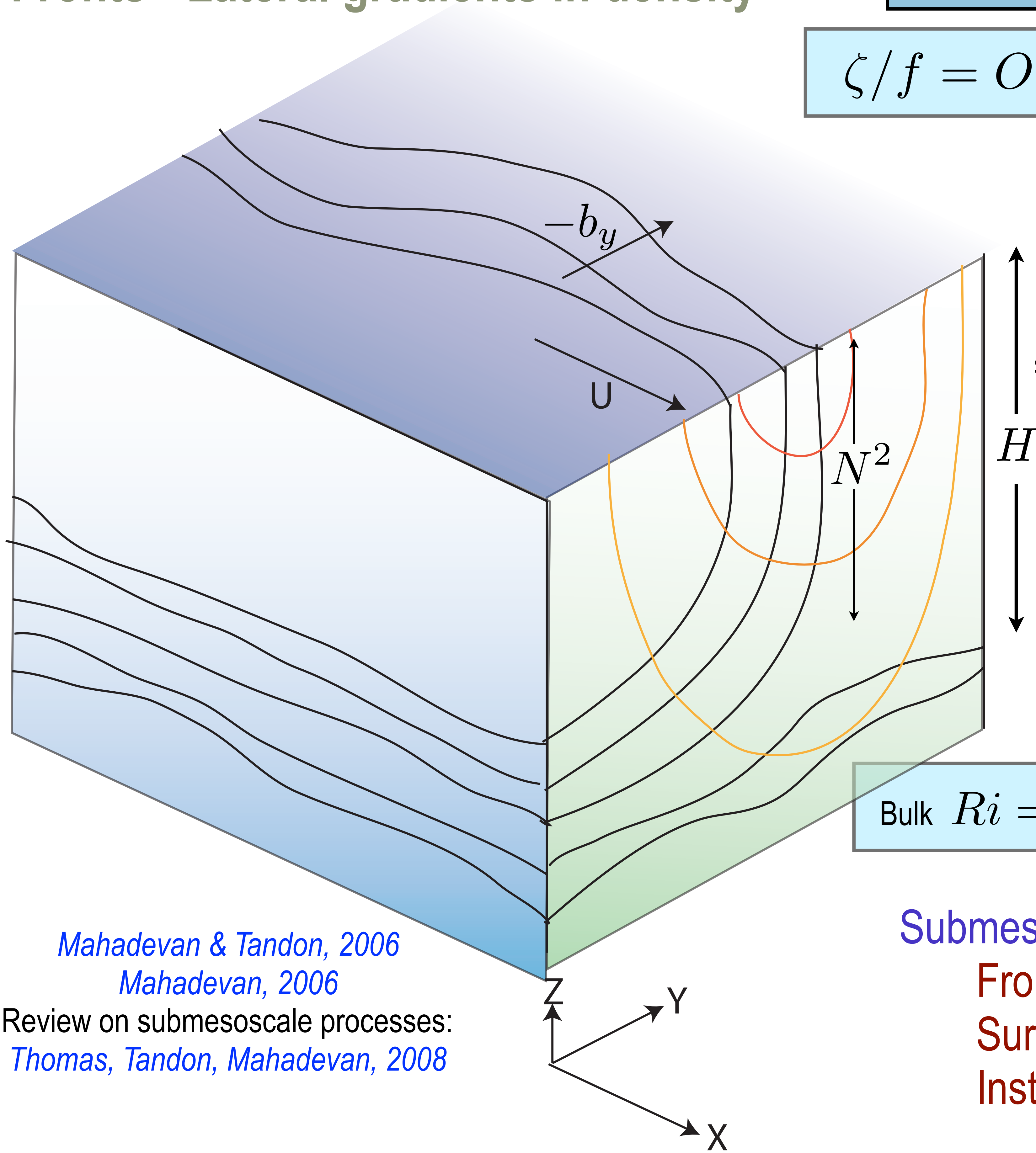
locally...

u increases

vorticity increases. $\frac{\zeta}{f} = O(1)$

vertical velocity

Fronts - Lateral gradients in density



Submesoscale Processes

$$\zeta/f = O(1), \quad Ro = U/fL = O(1)$$

$$L = b_y H/f^2 = NH/f$$

since (Tandon & Garrett, 1994) $b_y \sim Nf$

Vertical velocity $W \sim Ro\,\delta\,U = \delta\,U$

where $\delta = H/L = f/N$

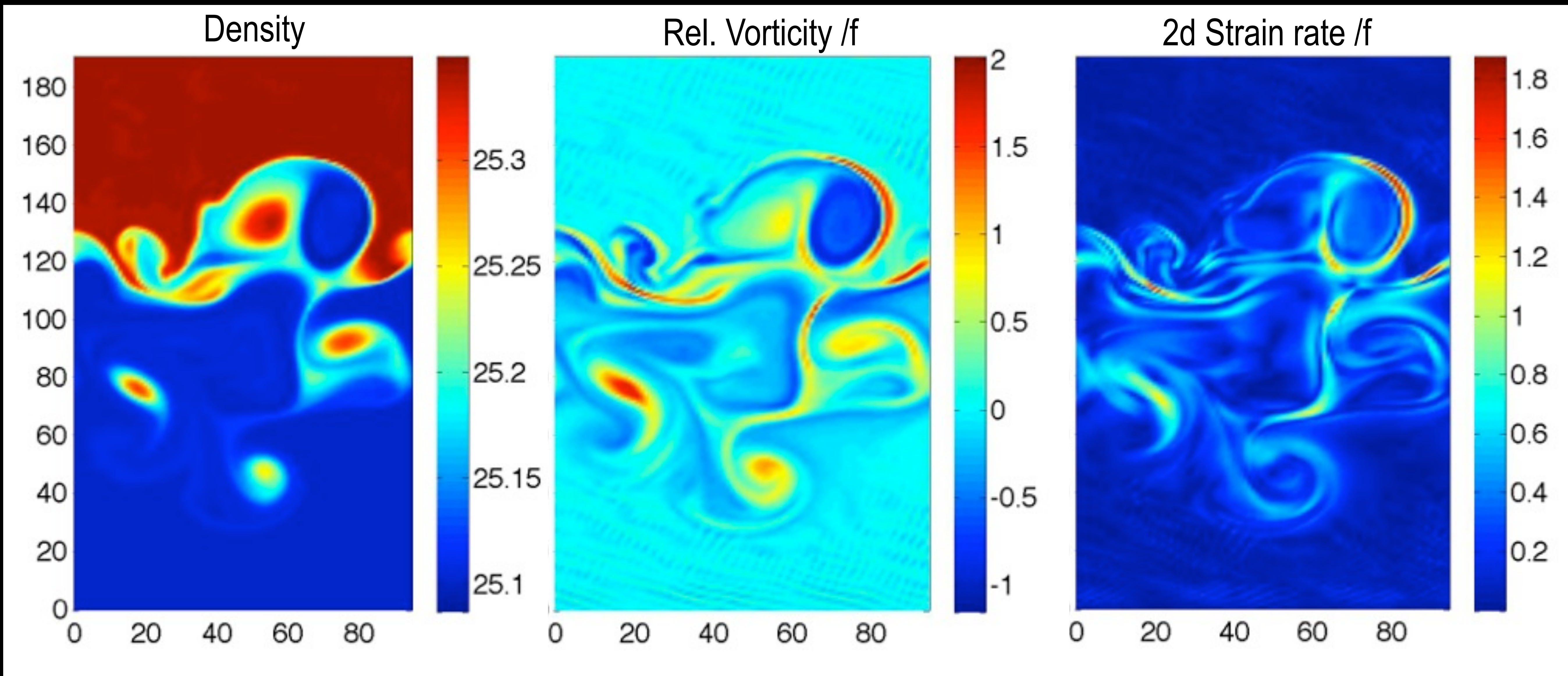
Bulk $Ri = N^2H^2/U^2 = Ro^{-1/2} = O(1)$

Submesoscale motion can arise from:

- Frontogenesis
- Surface forcing
- Instabilities, ...

Mahadevan & Tandon, 2006
Mahadevan, 2006
Review on submesoscale processes:
Thomas, Tandon, Mahadevan, 2008

Front - forms eddies and filaments



Vertical Velocity How large?

$$u_x + v_y = -w_z$$

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

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

$$W = Ro\,\delta\,U$$

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

$$= 0.01$$

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

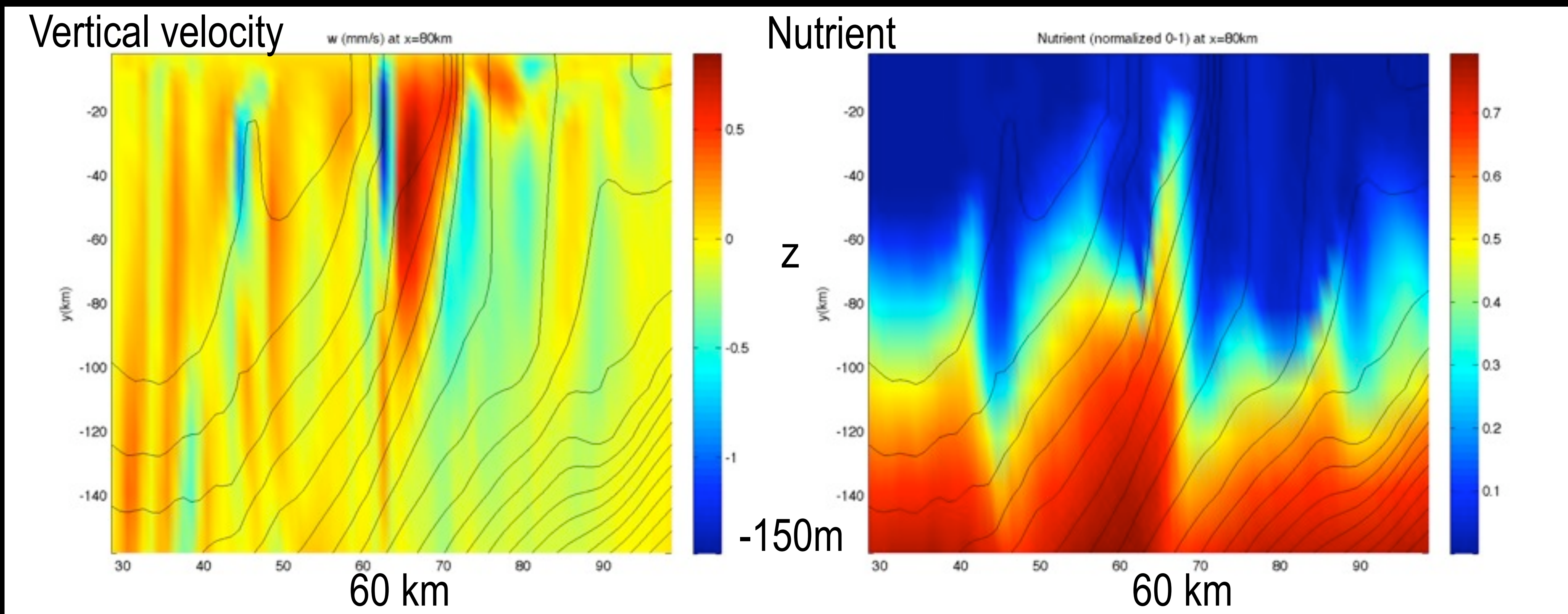
$$\frac{W}{D} \approx \frac{1}{\mu} \qquad t_{advec} \approx t_{bio}$$

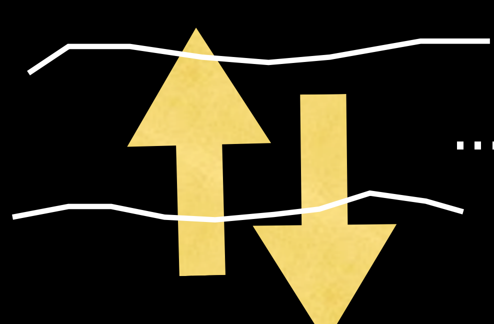
Submesoscale dynamics can sustain higher growth rates of O(1 day)

Vertical Transport is largely along-isopycnal

but, because of the vertical gradient in nutrients and consumption near-surface,

$$\langle wN' \rangle_{z_{prod}} \sim \langle \text{nitrate uptake} \rangle_{\text{prod zone}}$$





...and, nutrients (tracers) get transported across the mean isopycnal surfaces.

Vertical supply of nutrients

Large-scale wind stress curl

Ekman Pumping

Coastal upwelling

Uplift of isopycnal surfaces (eddies/ internal waves)

Variability of wind-stress due to ocean velocity

Nonlinear Ekman dynamics

Advective transport at fronts

Mixing and mixed layer entrainment

Basin scale

Meso-scale dynamics

Submeso-scale dynamics

Small scale mixing

Limiting depth of mixing

Increasing light (length of day)

- Thinning ice / melt ponds)

Reduce depth of mixing

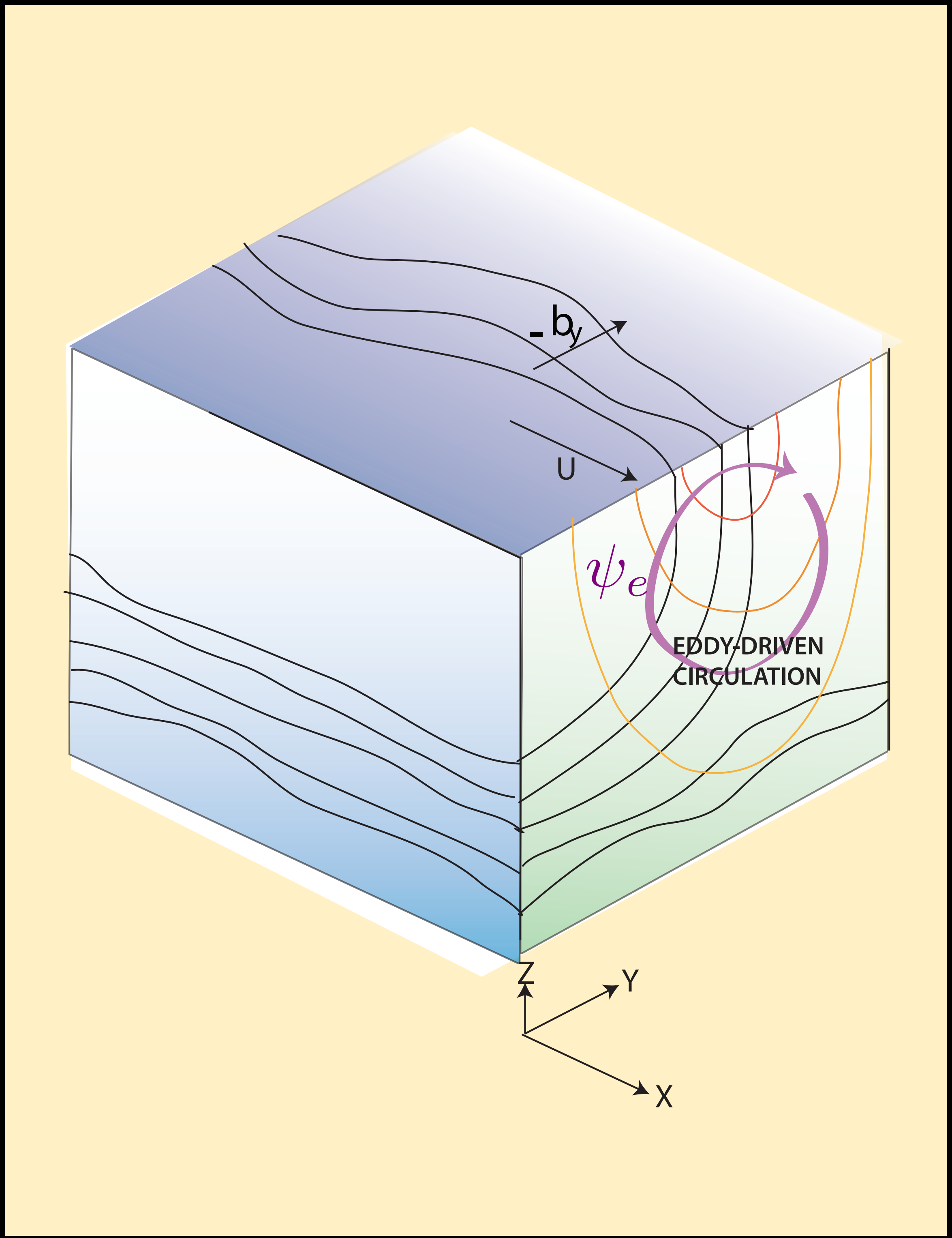
- Reduced buoyancy loss

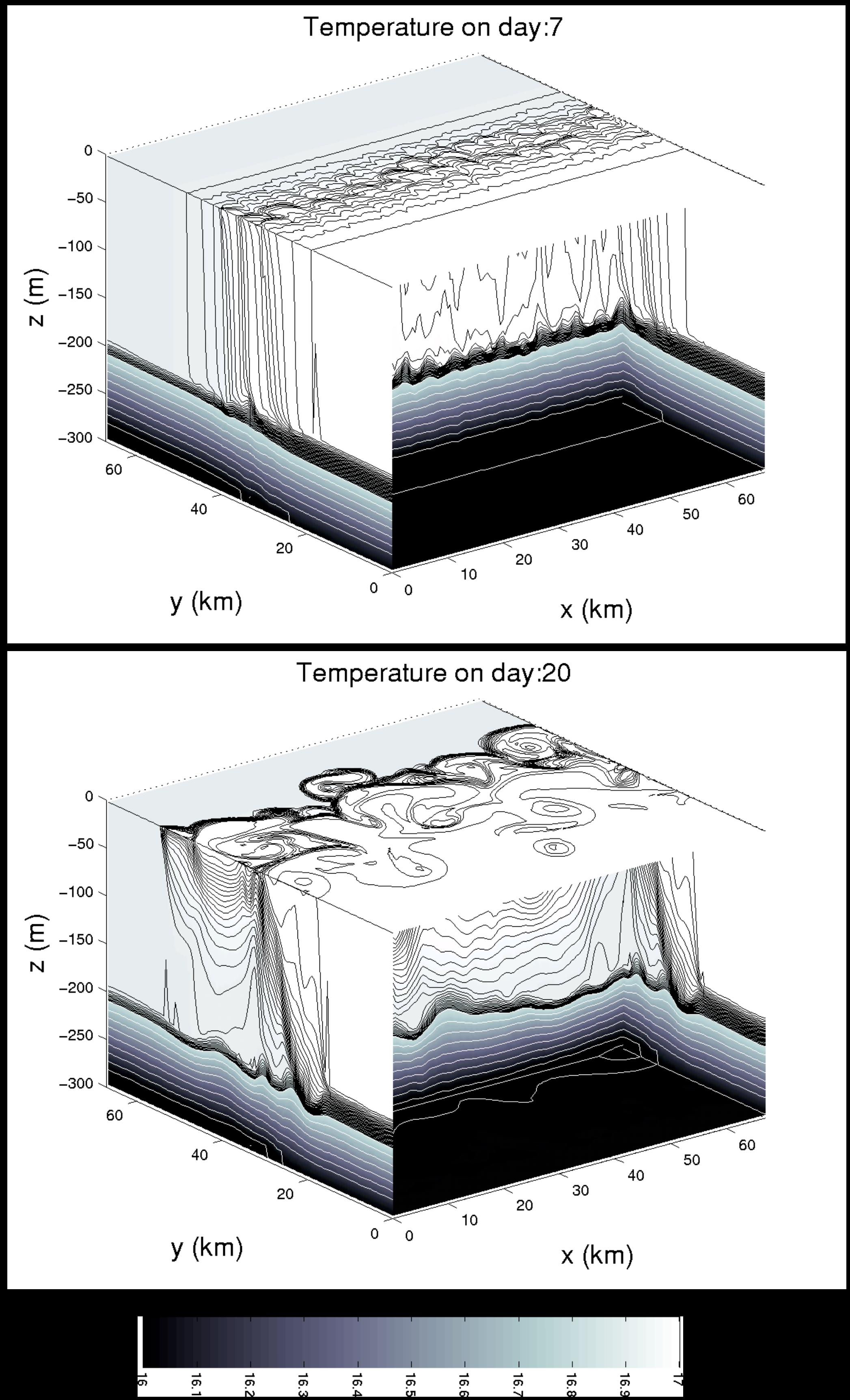
Enhance stratification

- Surface buoyancy
- Mixed layer eddies

Restratification of the mixed layer by eddies

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





Eddy-driven stream function

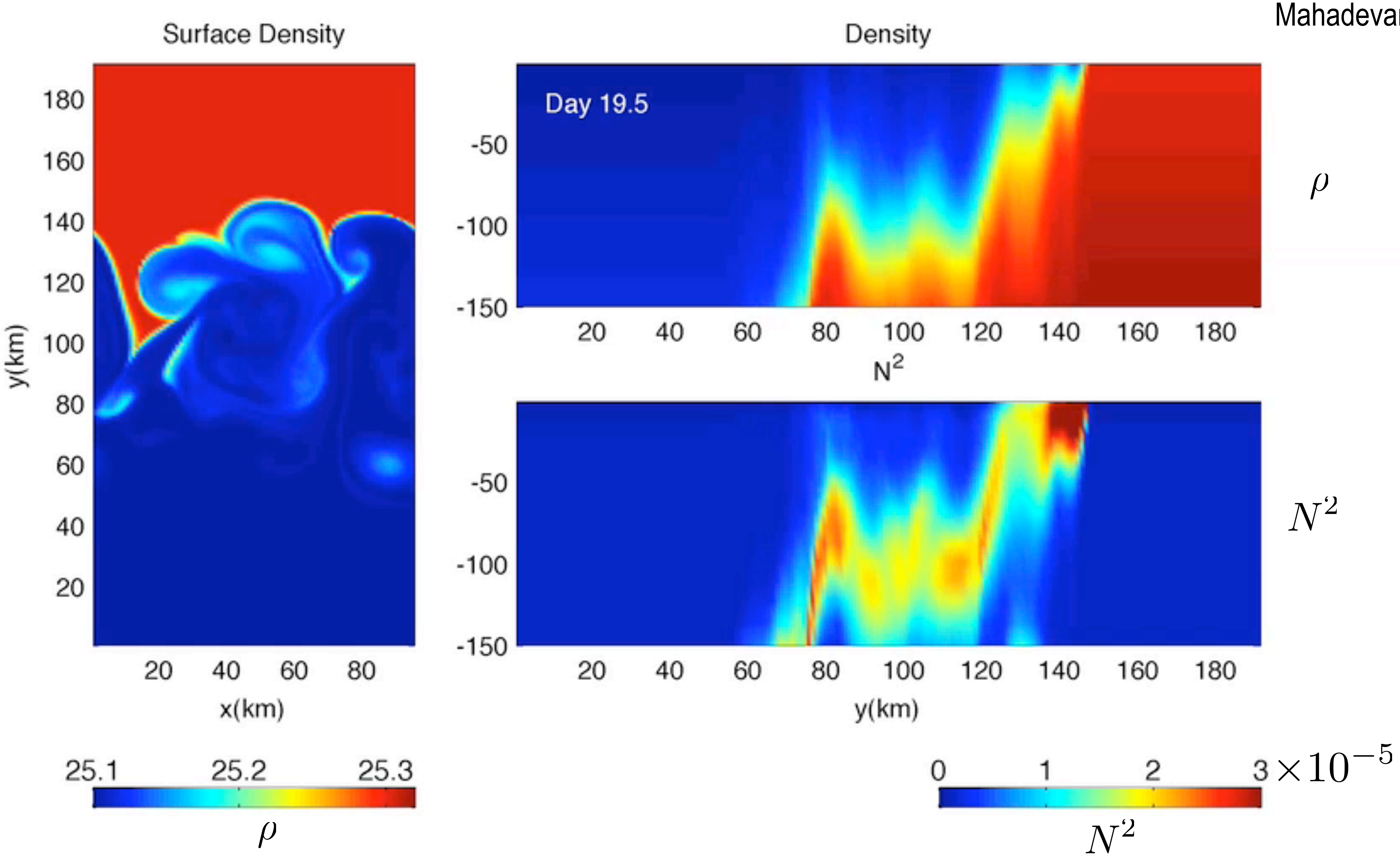
$$\psi_e = 0.06\, b_y H^2 / f$$

Mixed Layer Instability

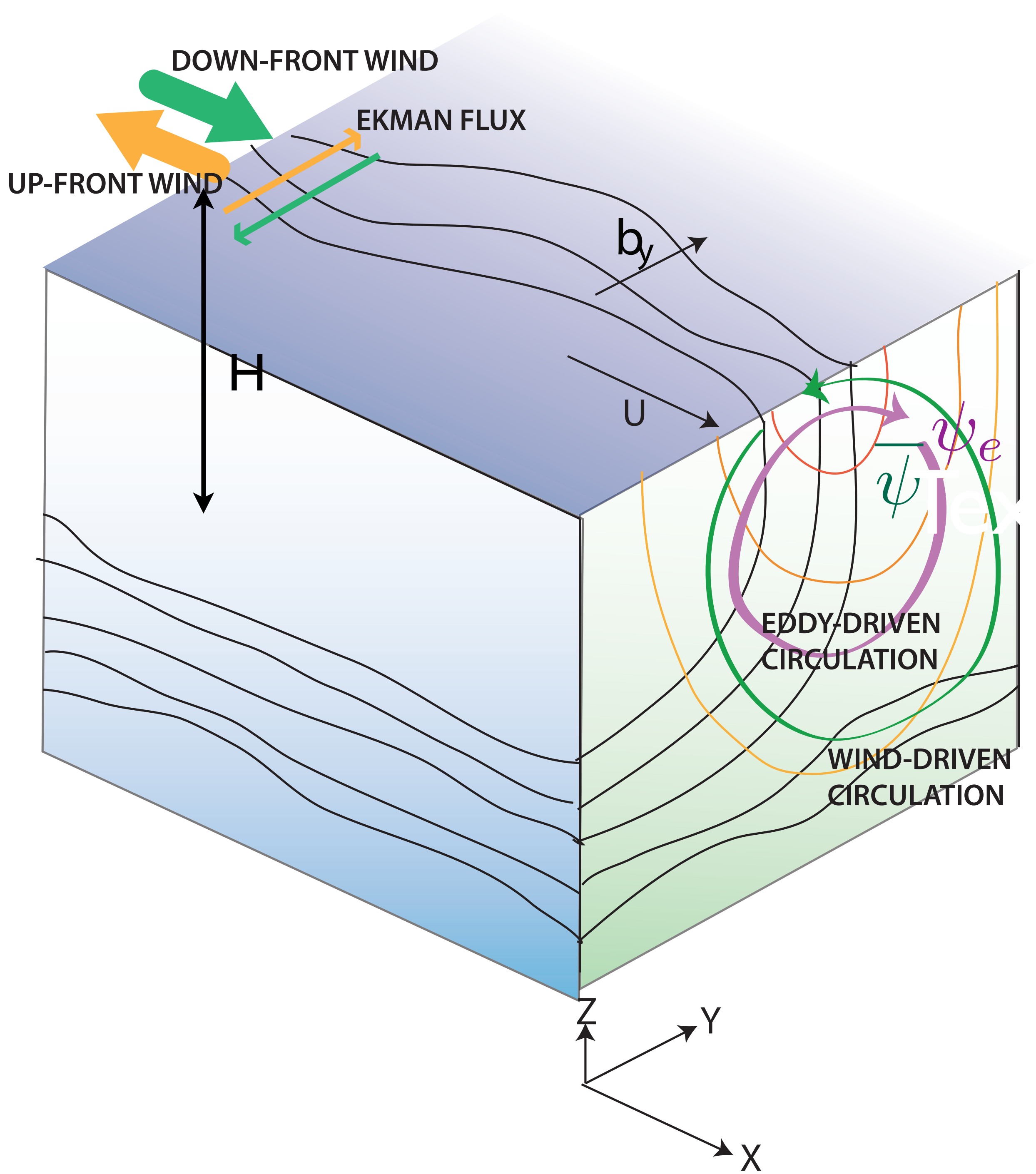
Rapid adjustment of the mixed layer by submesoscale eddies

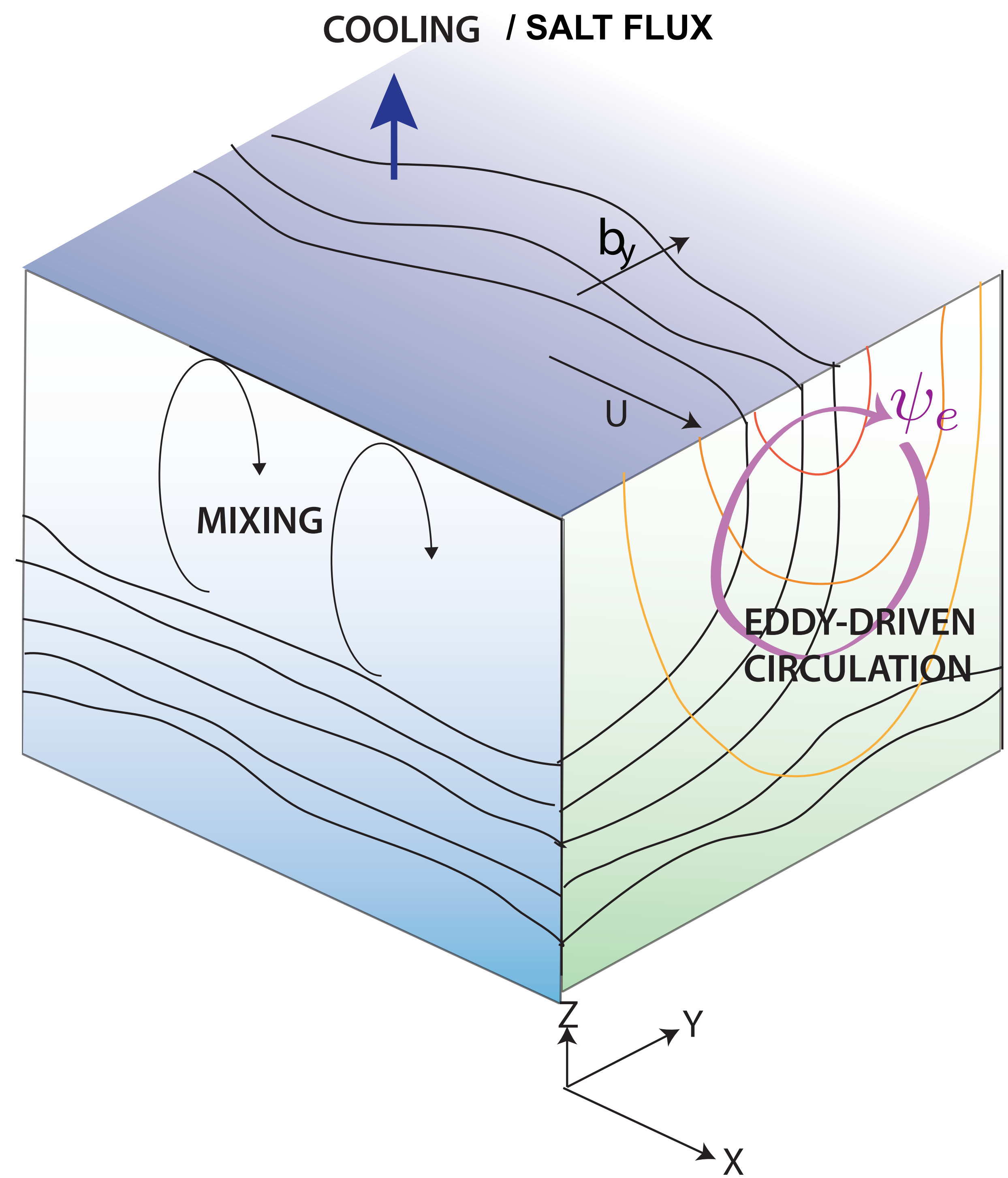
Effect on phytoplankton spring blooms, see Mahadevan et al., 2012

Vertical Section at x=48 km



In the presence of wind forcing? ...and buoyancy loss?



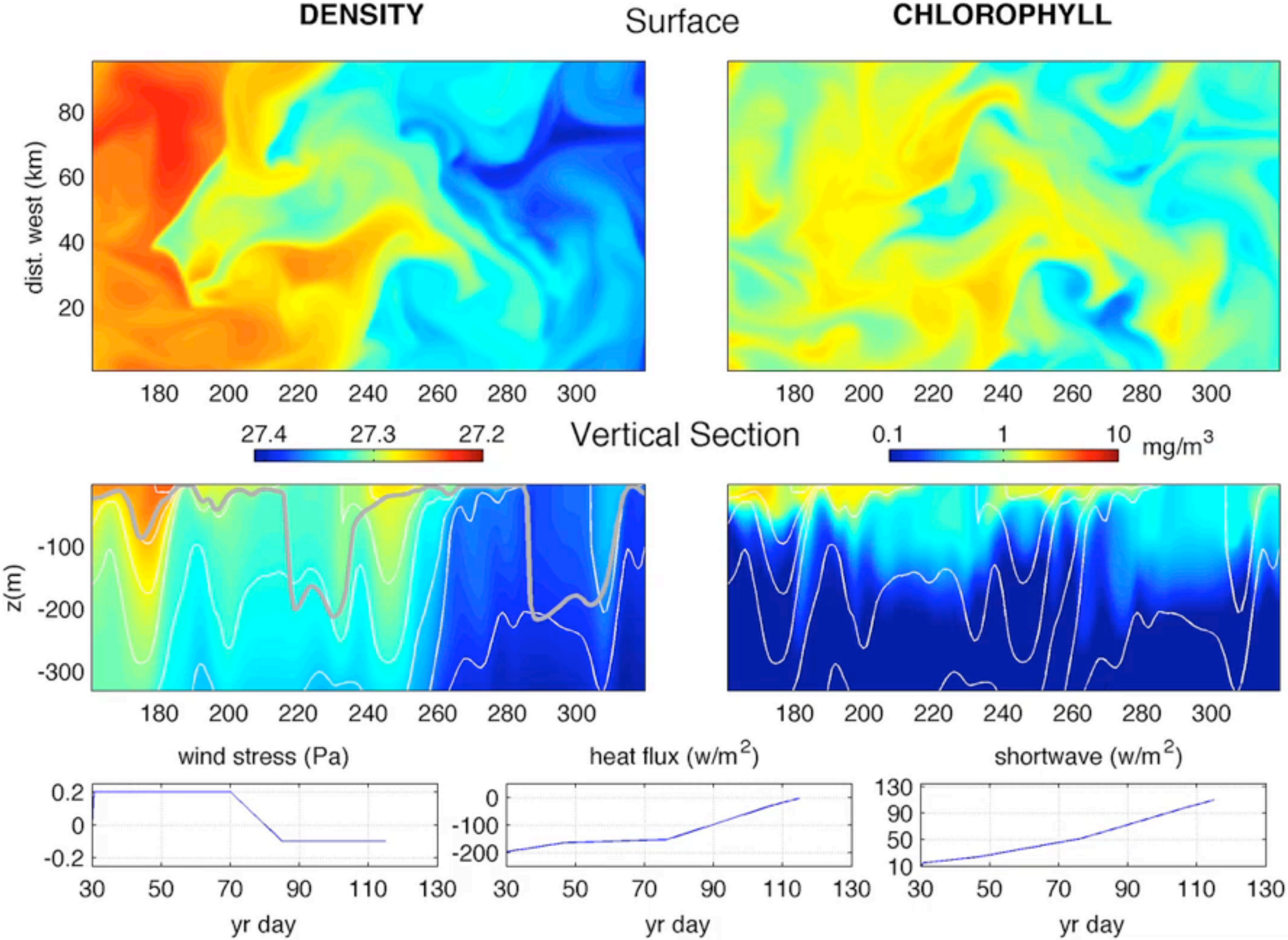


Mahadevan, Tandon, Ferrari (2010)

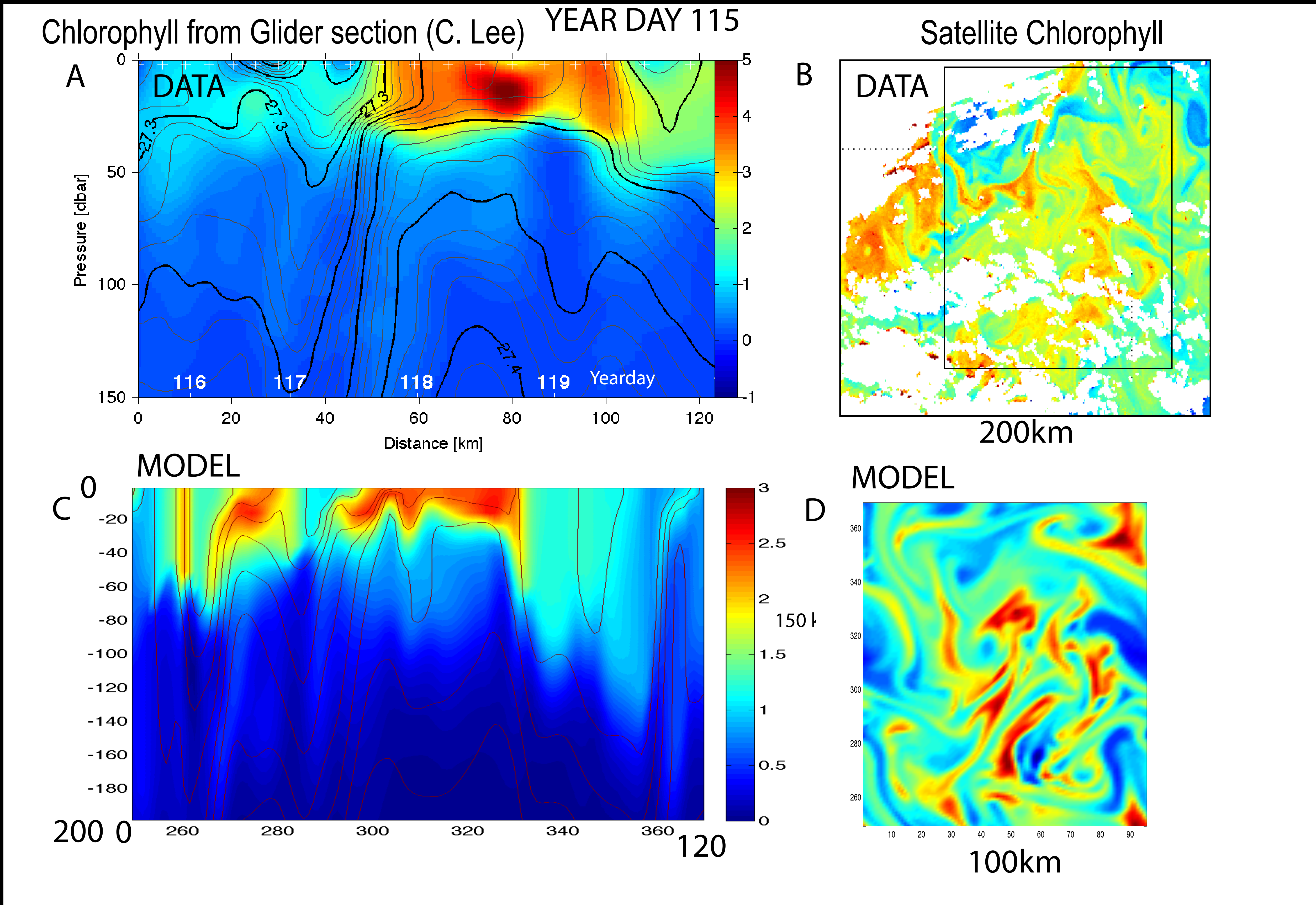
North Atlantic Bloom study

Yr Day 115

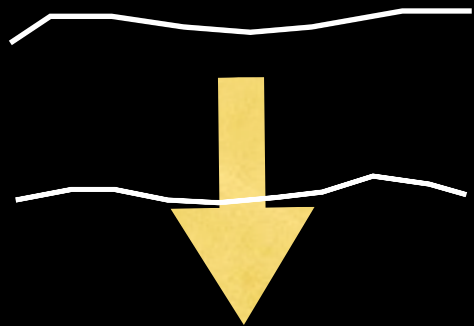
Mahadevan, D'Asaro, Lee, Perry (2012)



North Atlantic Bloom study

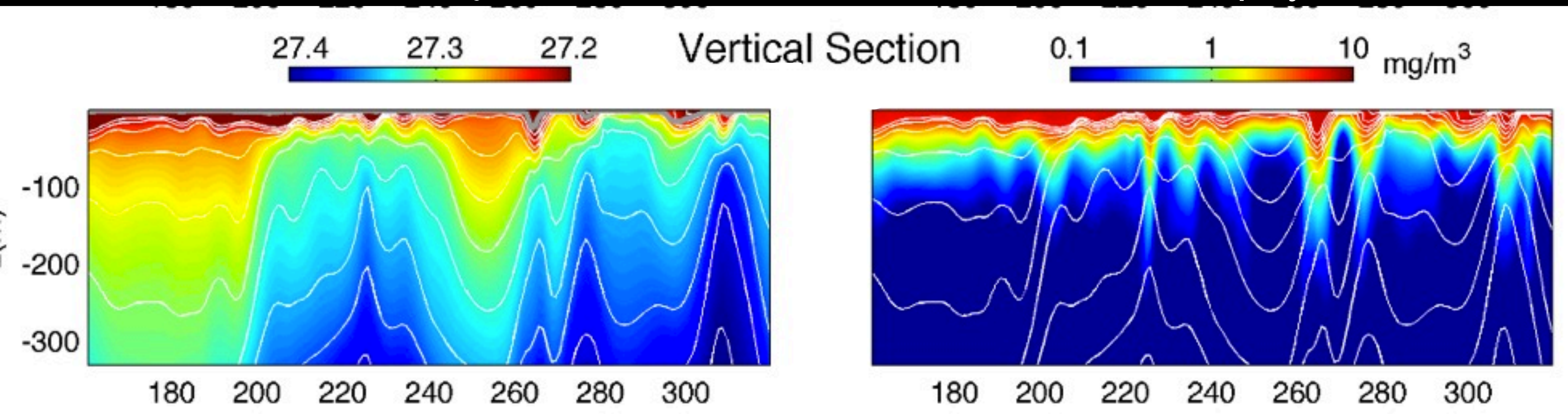


In the Arctic, eddy-driven restratification is likely below ice cover in late winter



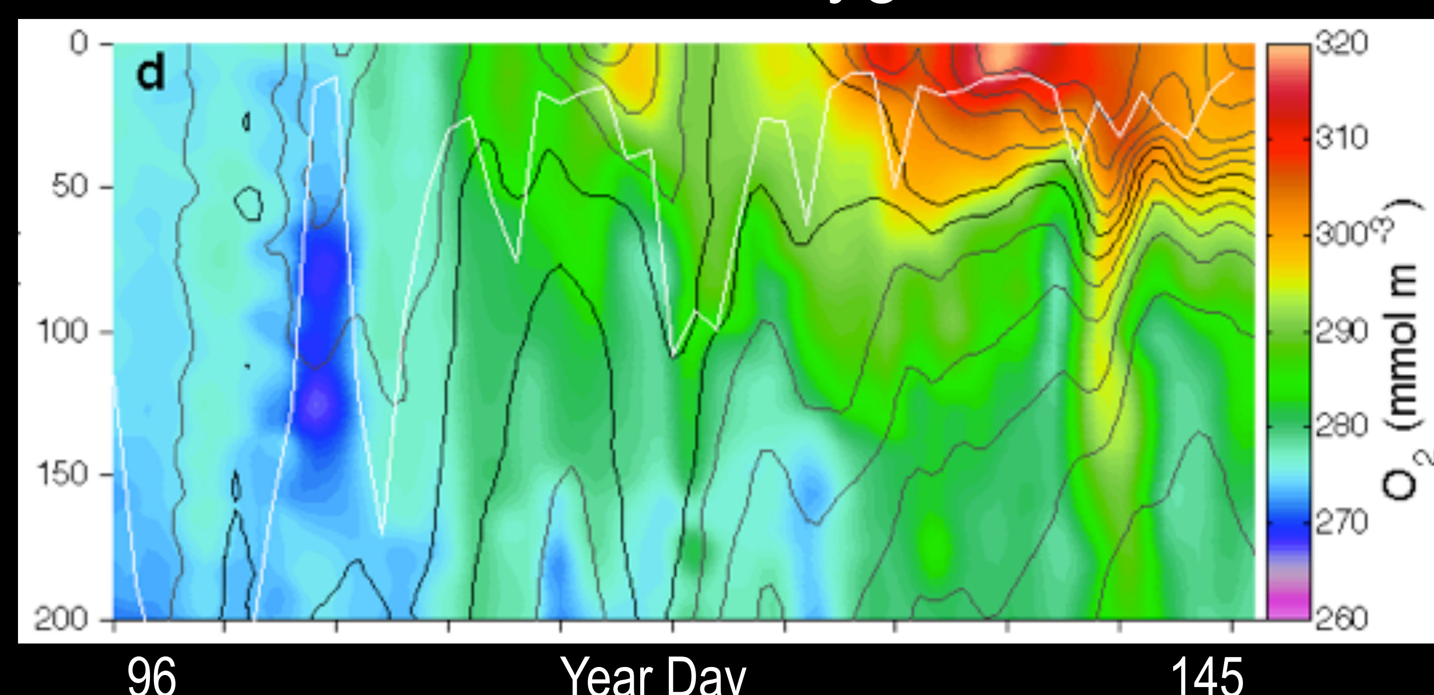
Eddy-driven subduction

Density **Model section** Chlorophyll

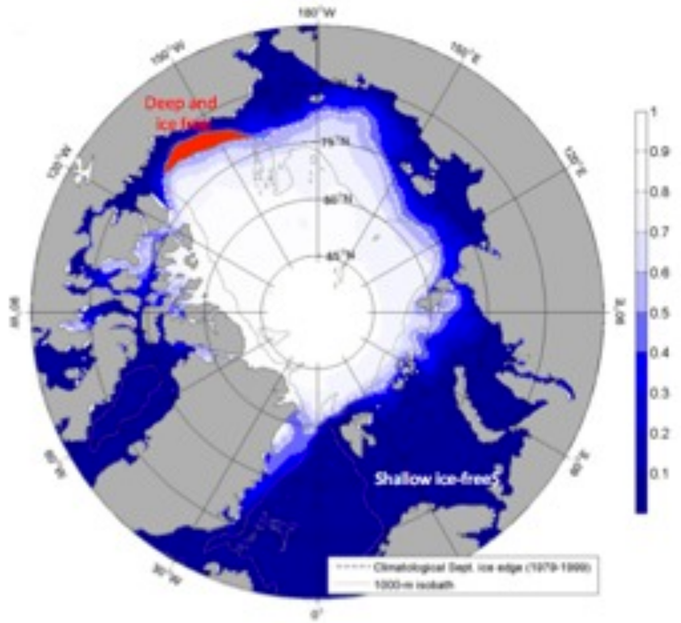


Omand et al., (in prep)

Float data Alkire et al., 2011 Oxygen

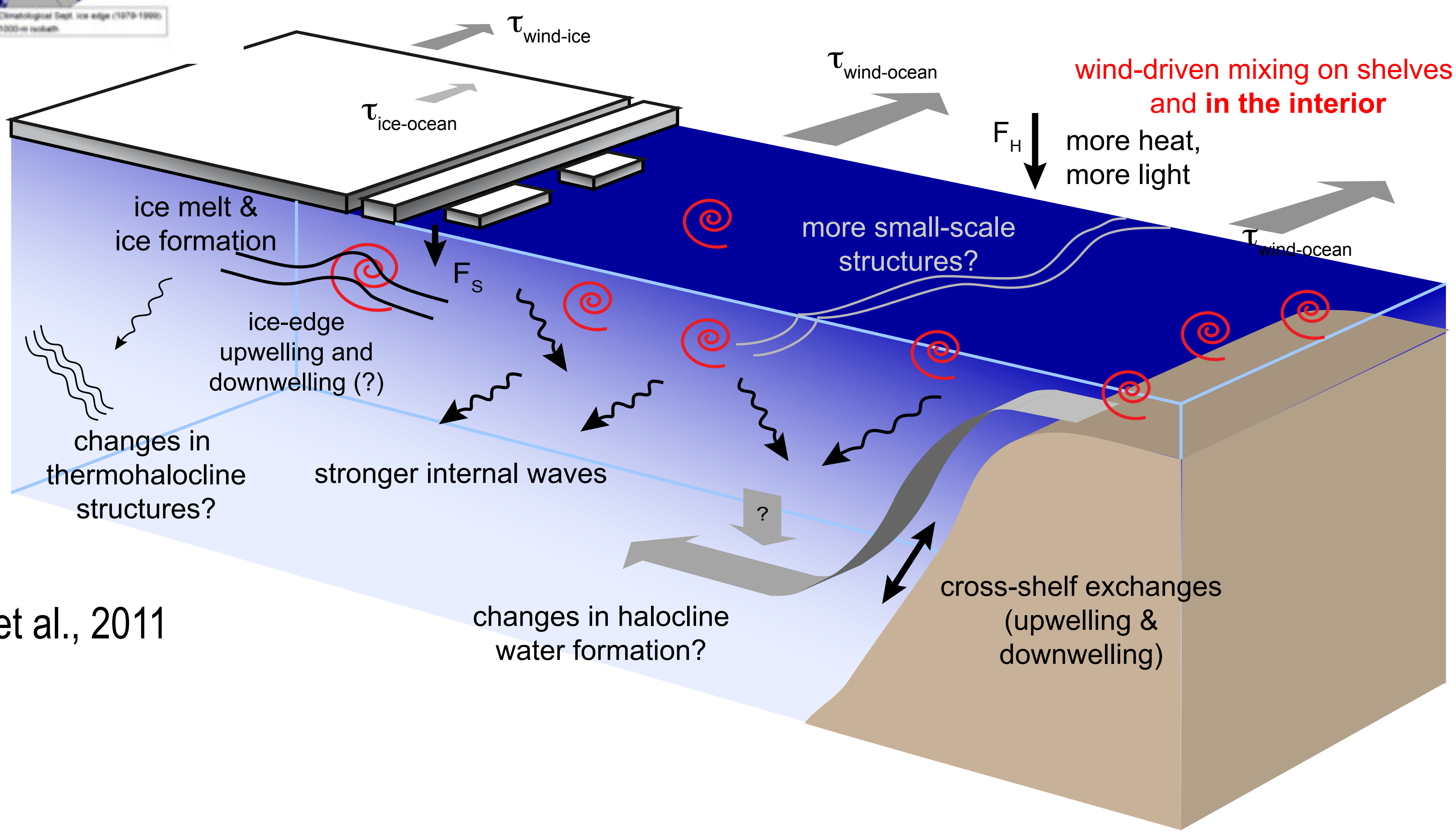


Arctic sea-ice cover
September climatology



Submesoscale Processes at the Ice Edge

Mahadevan, Rainville, Woodgate, Matrai, Wang



Rainville et al., 2011

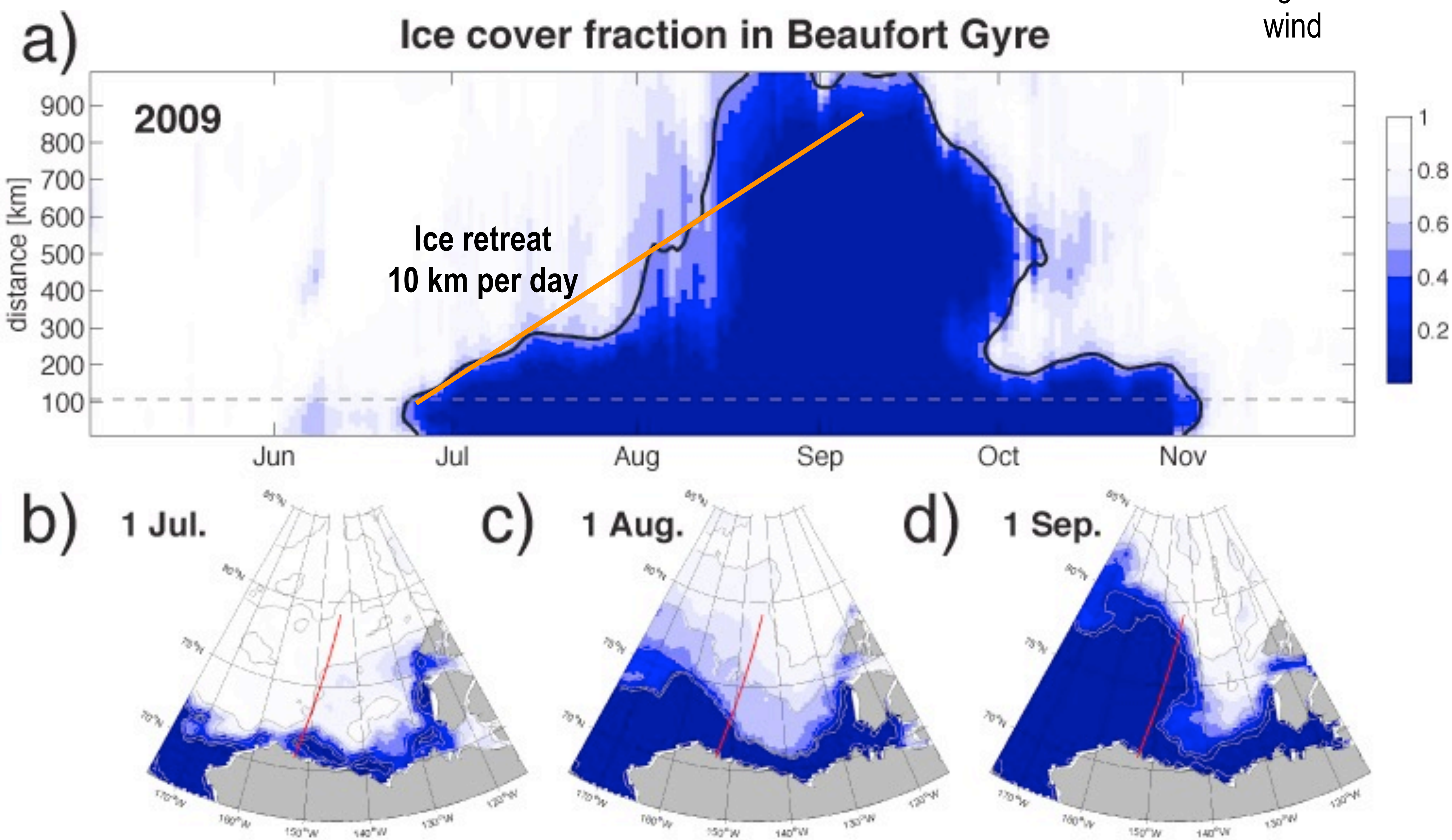
Effects of enhanced seasonal ice retreat on phytoplankton productivity?

2009 Ice Extent

Luc Rainville

Effect on productivity

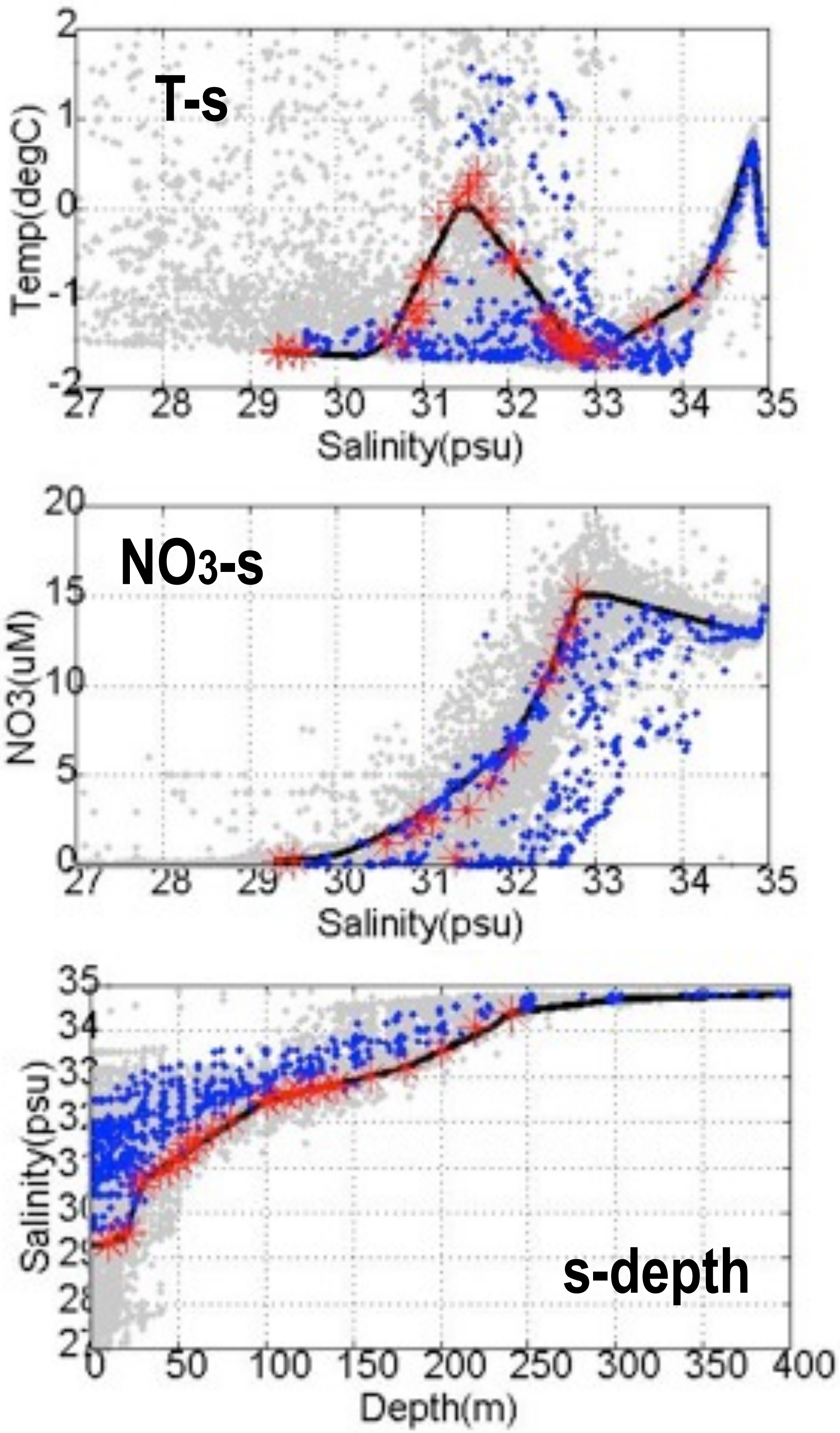
Enhanced
stratification
light
lateral gradients
wind

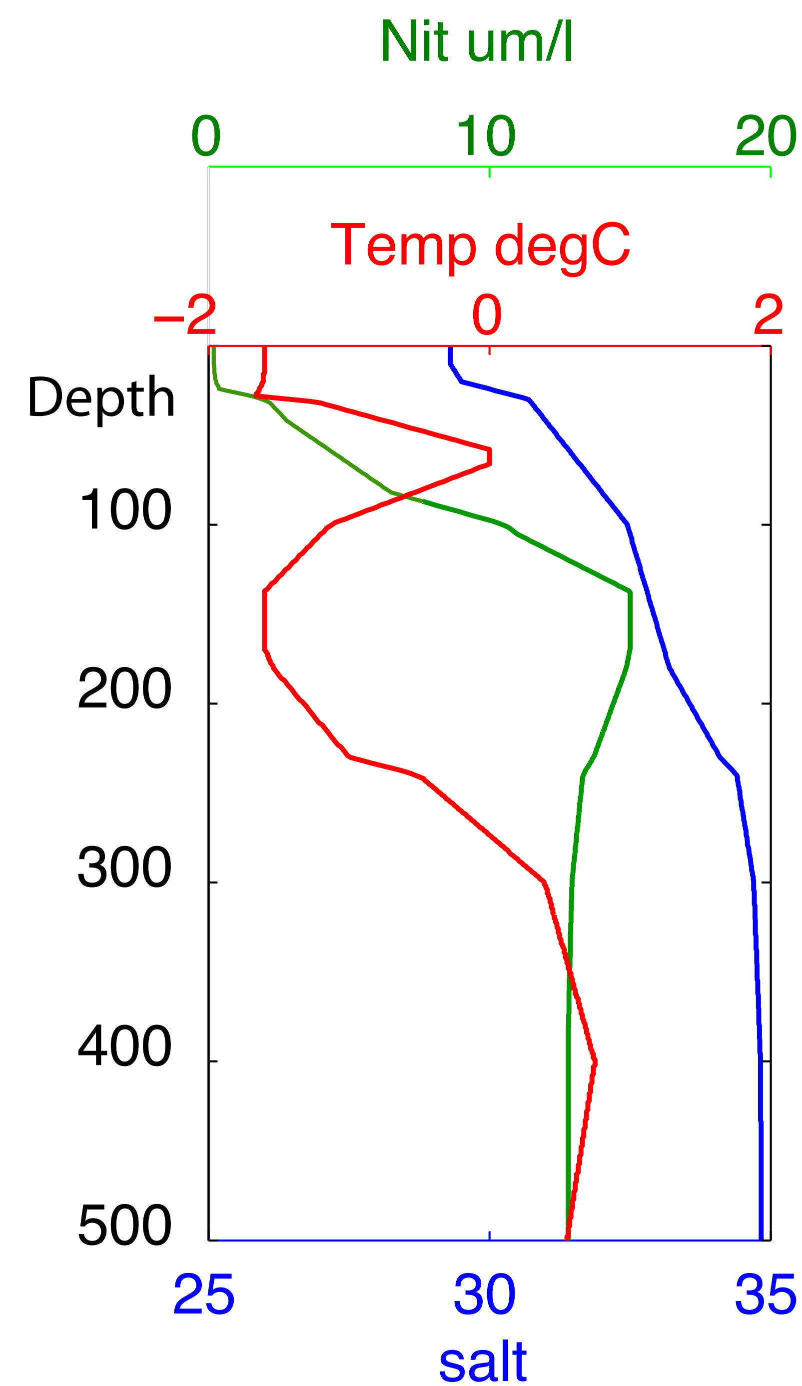


Compilation of Nitrate, salinity, temperature profiles from 155-165W Early Spring

Red: February -- Blue: June

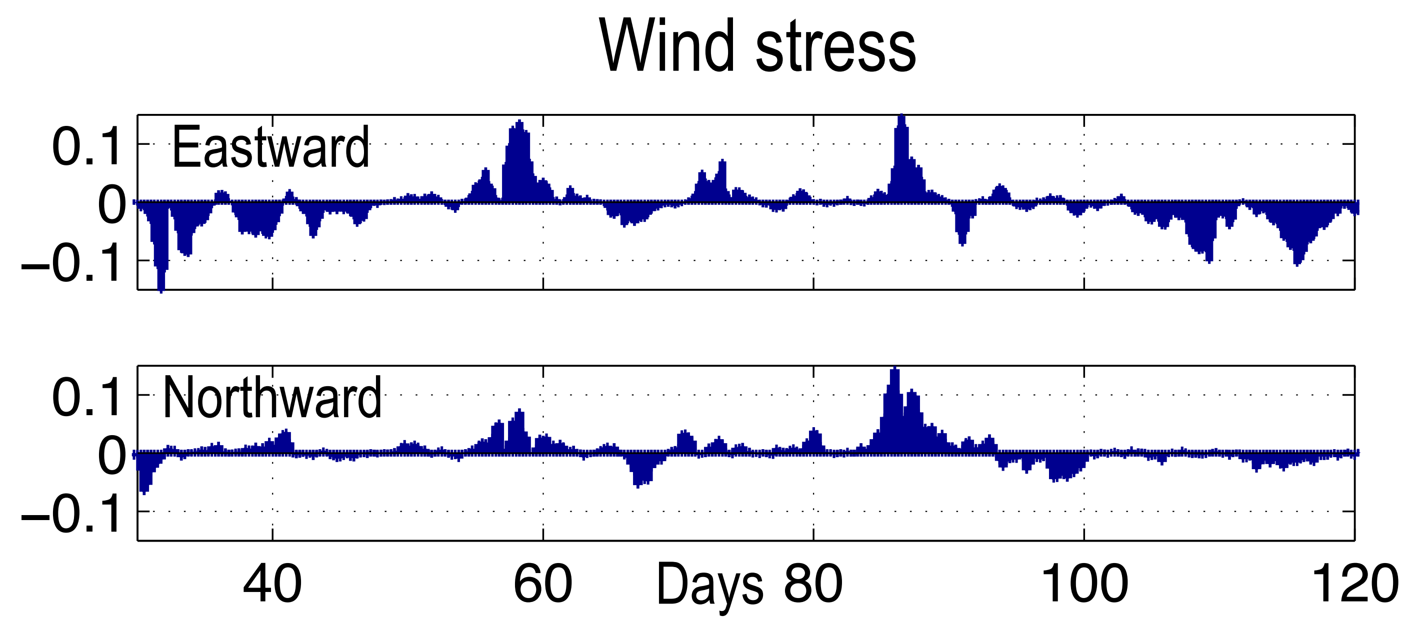
Rebecca Woodgate

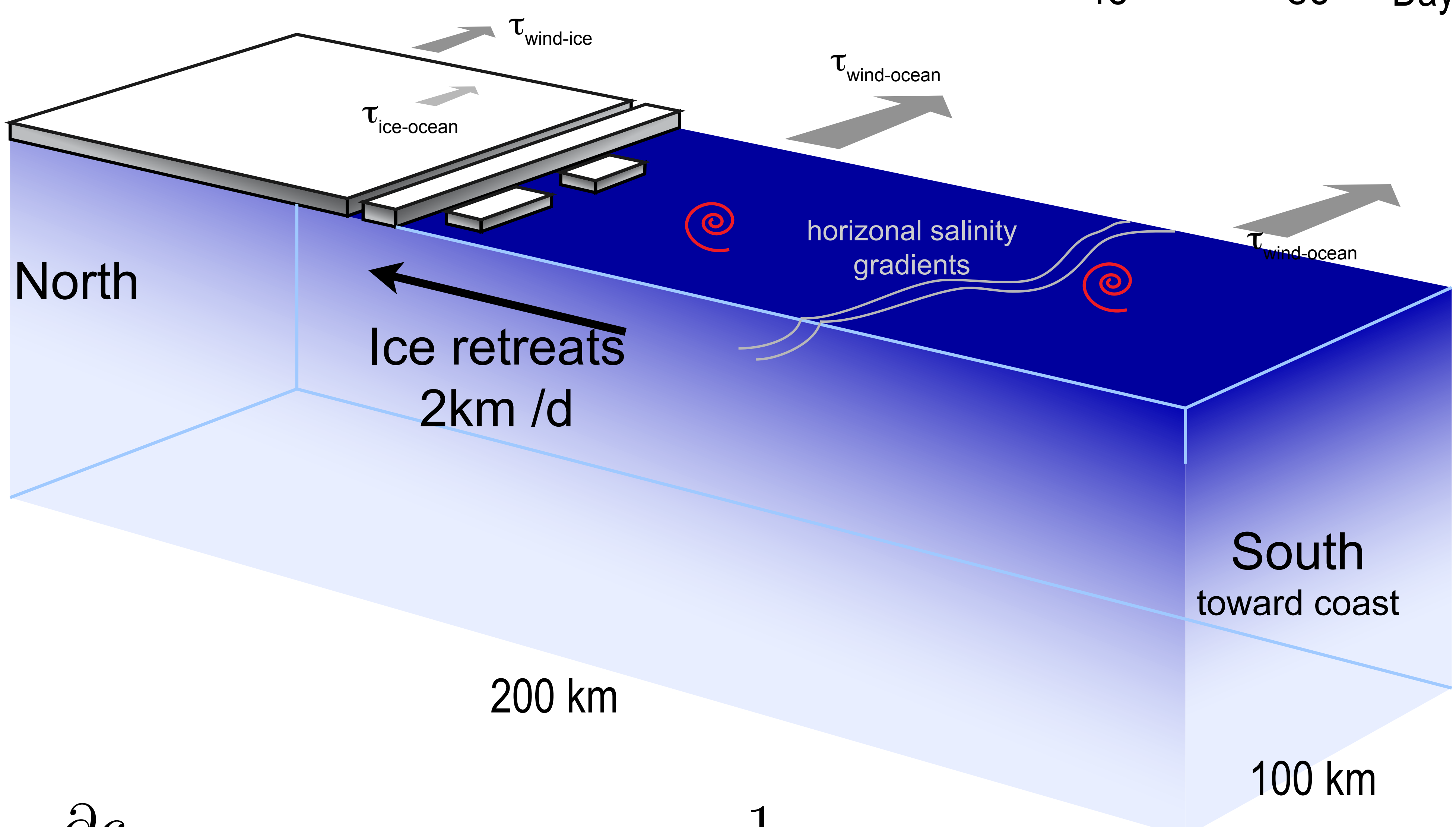


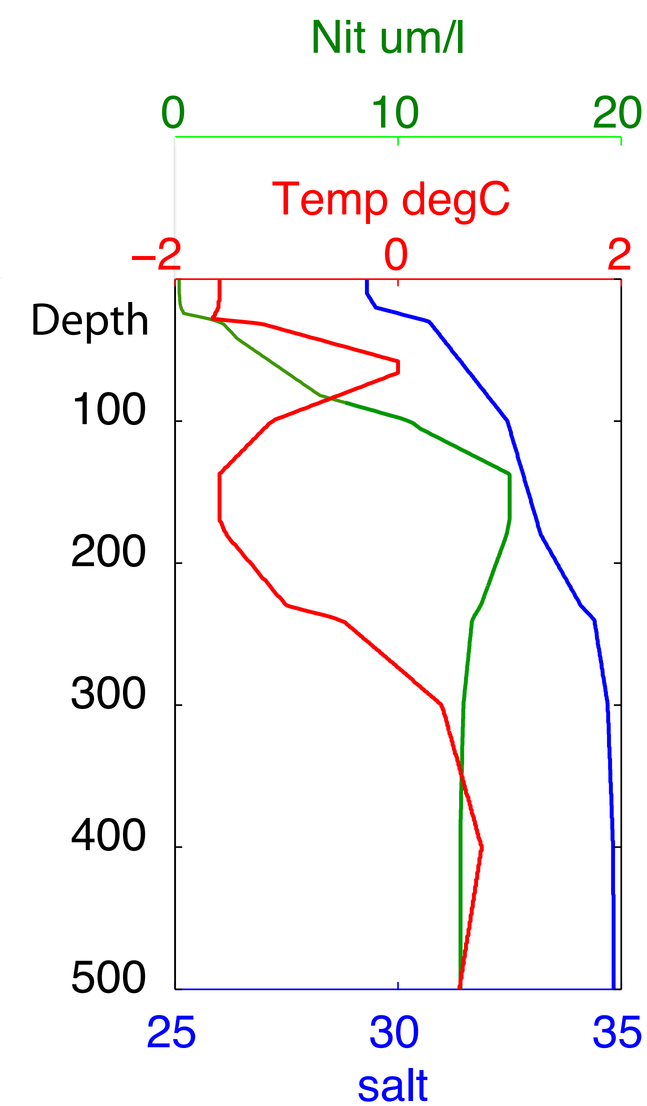


Nutrient profiles from Lou Codispoti

Process Study - Model Domain
Beaufort Sea

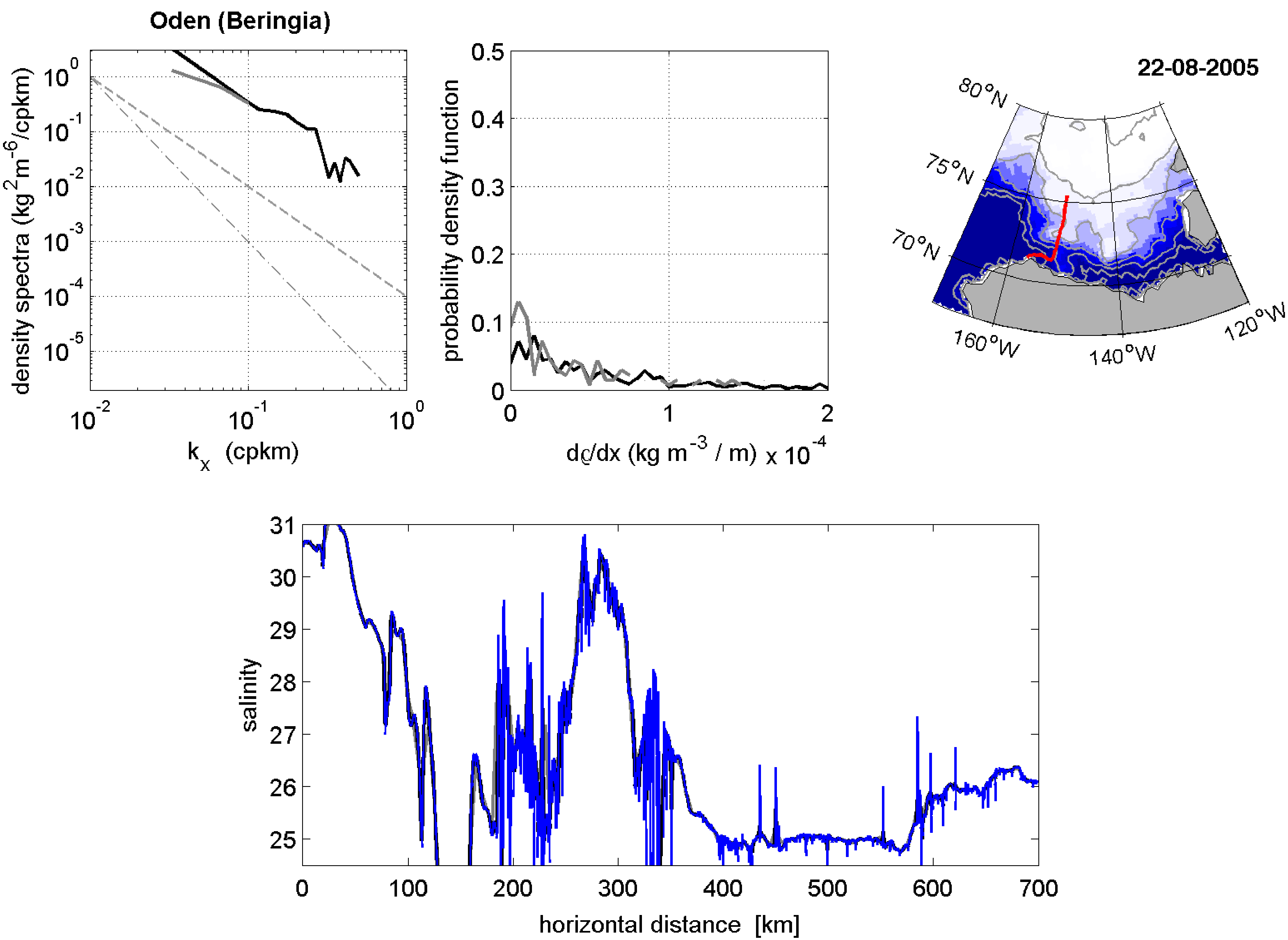






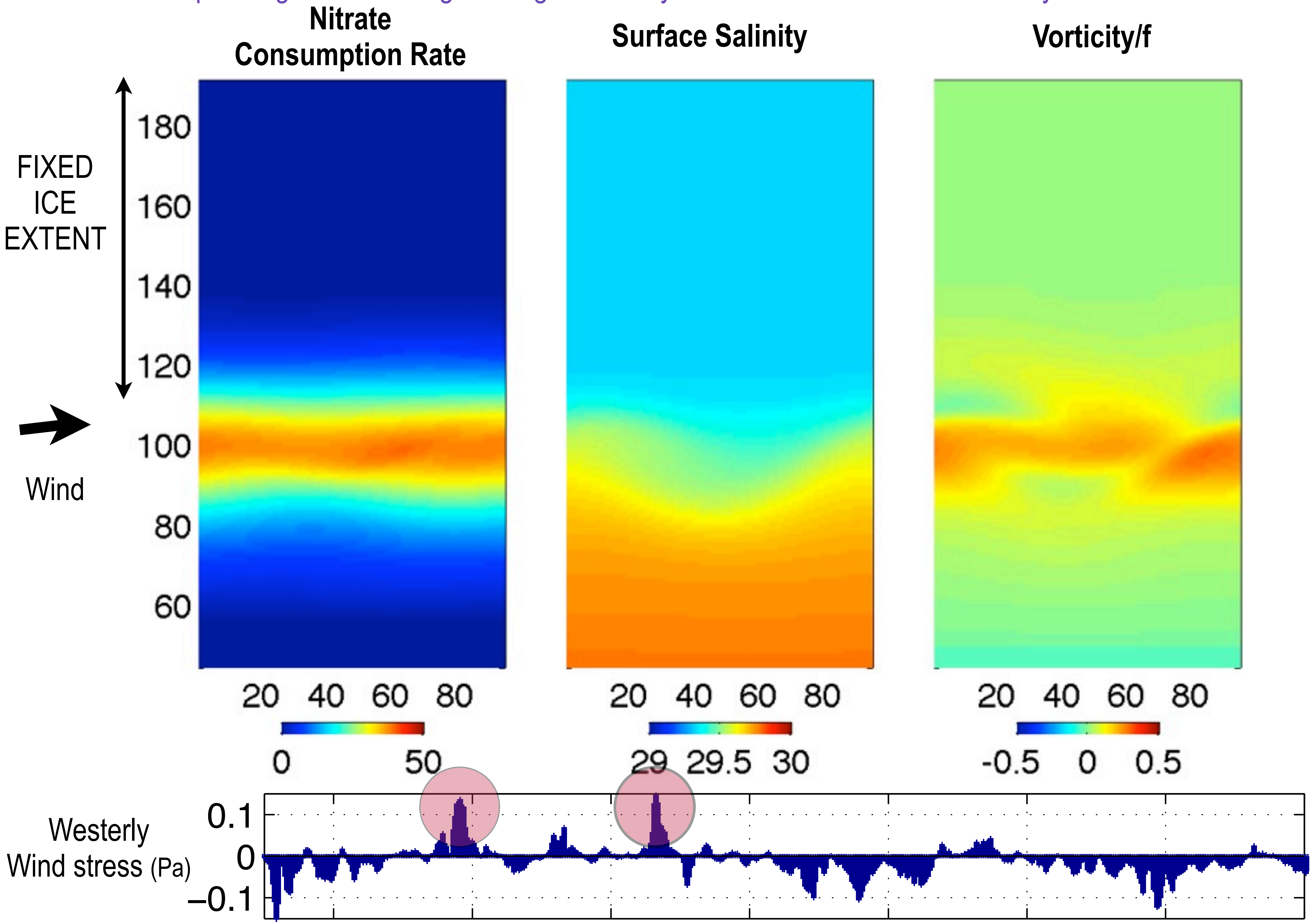
$$\frac{\partial c}{\partial t} + \mathbf{u}_H \cdot \nabla c + w c_z = -\frac{1}{\tau}\left(c - c_0(z)\right)$$

= Consumption of nutrient (production of phytoplankton)

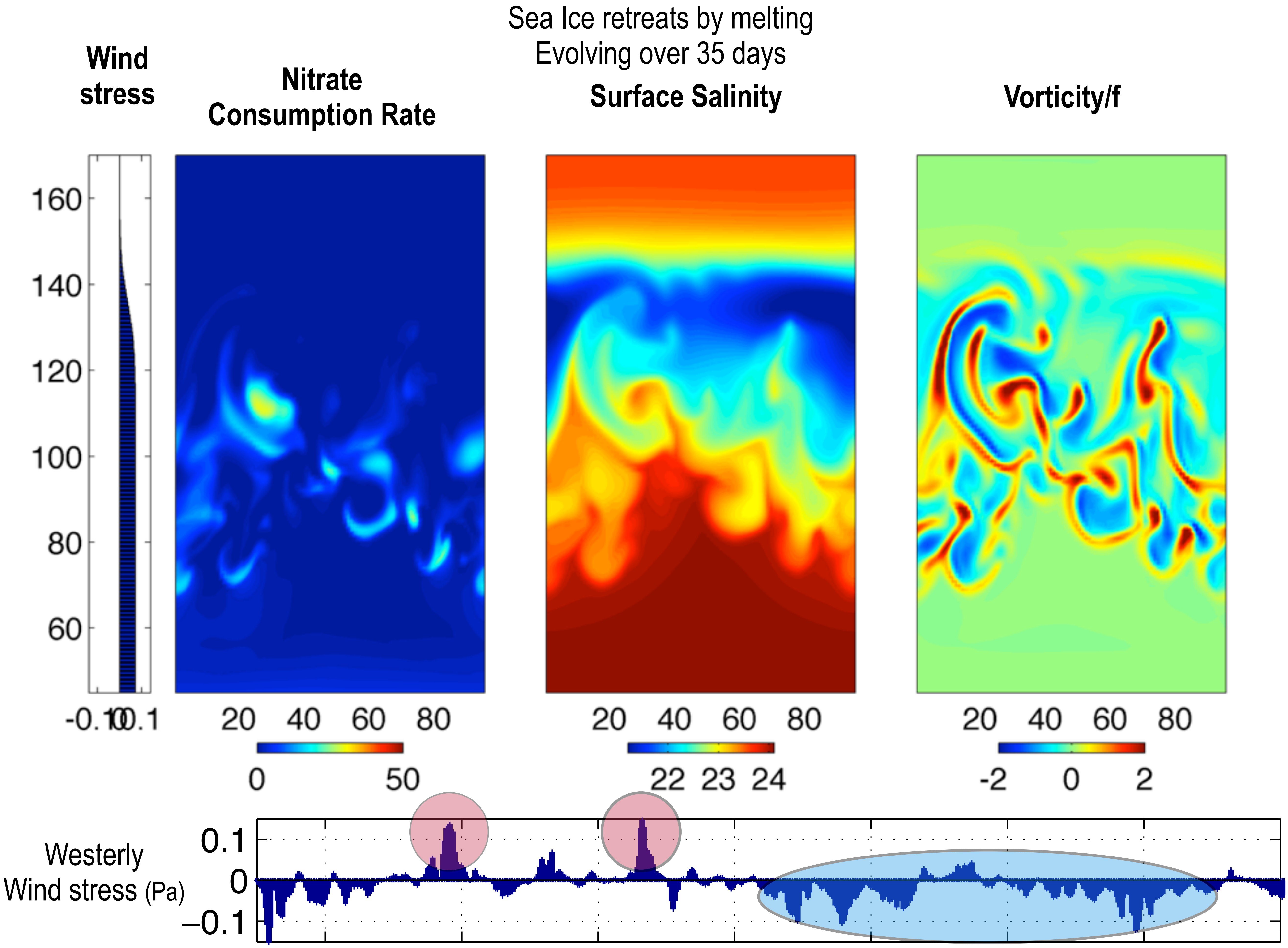

Oden (Beringia)
density spectra (kg^2 m^-6/cpkm)
k_x (cpkm)
probability density function
dϱ/dx (kg m^-3 / m) x 10^-4
22-08-2005
80°N
75°N
70°N
160°W
140°W
120°W
salinity
horizontal distance [km]

Model Results

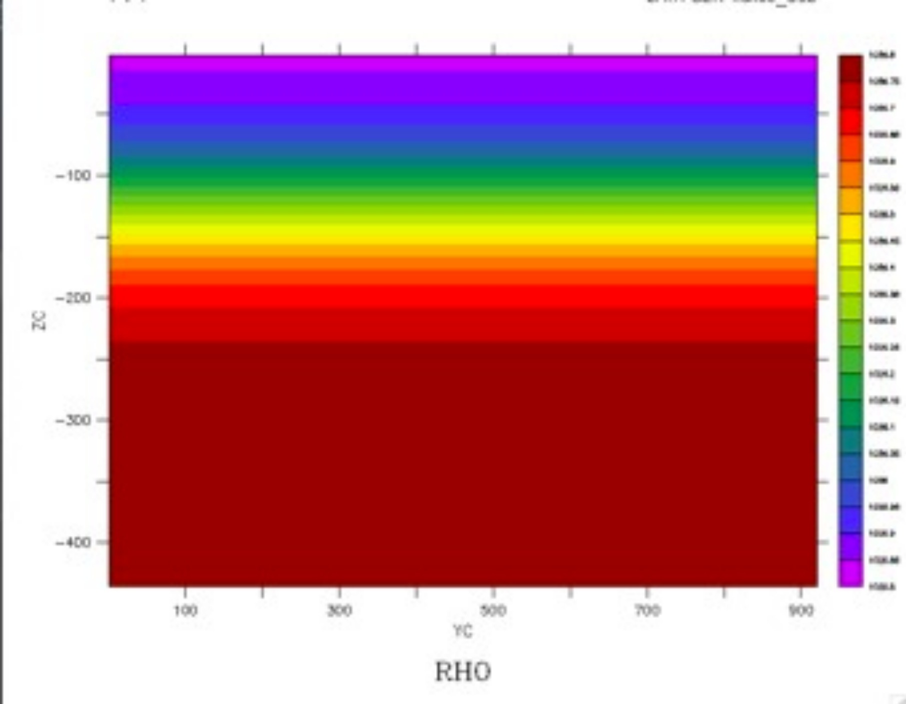
Upwelling at the ice edge during a westerly wind burst. But winds are mostly from the east.



Large lateral density gradients are generated and lead to instability and eddies that draw nutrients up.



Tuesday, October 29, 13



Mixing - Will it be enhanced in an ice-free Arctic?

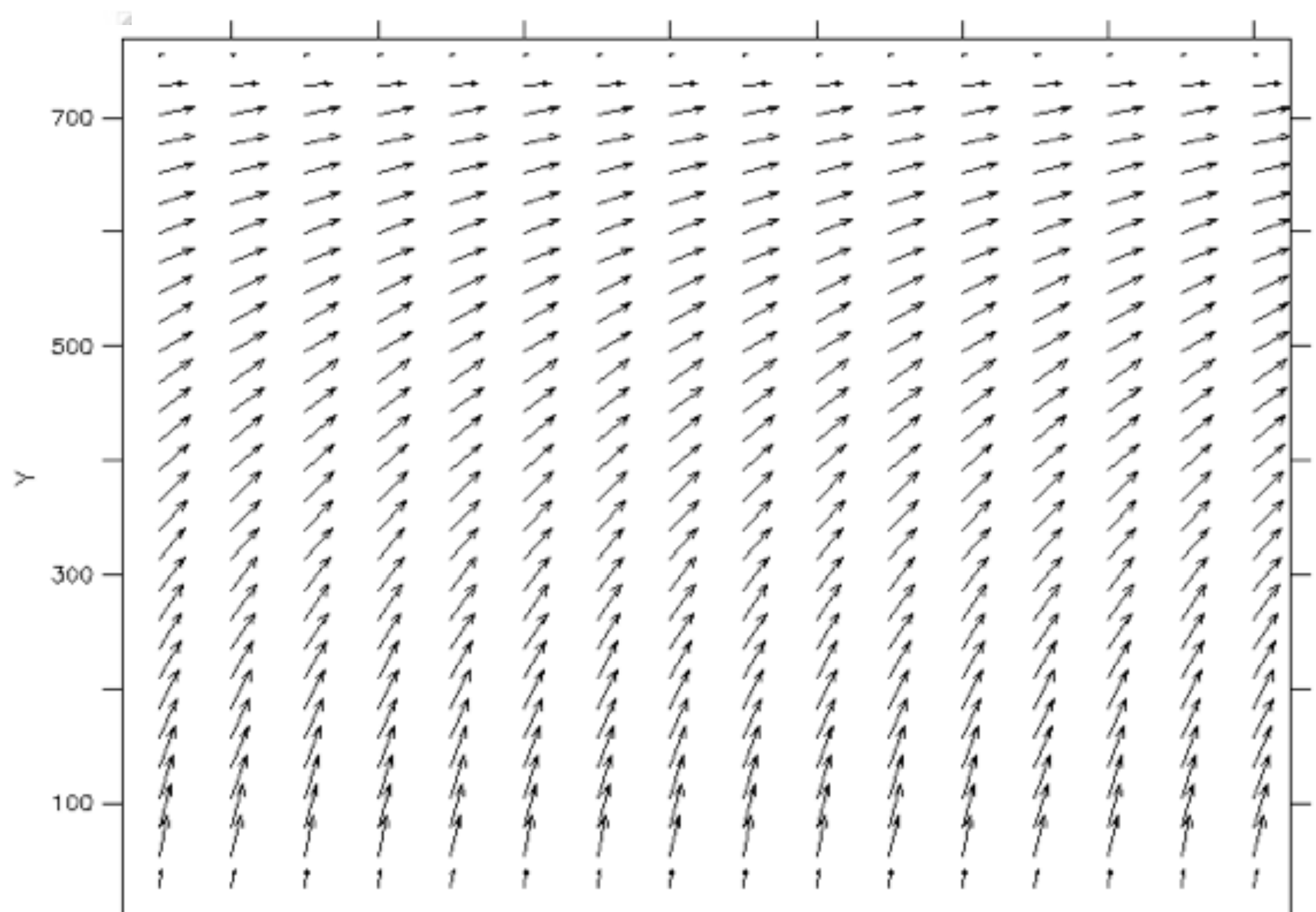
Wind-generated inertia gravity waves

Inertial motion is generated by a northward wind stress of 0.26 Pa applied for 12 hours and stopped

Stratified ocean

Inertial period ~ 12 hrs

M. Claret & Mahadevan (in prep)

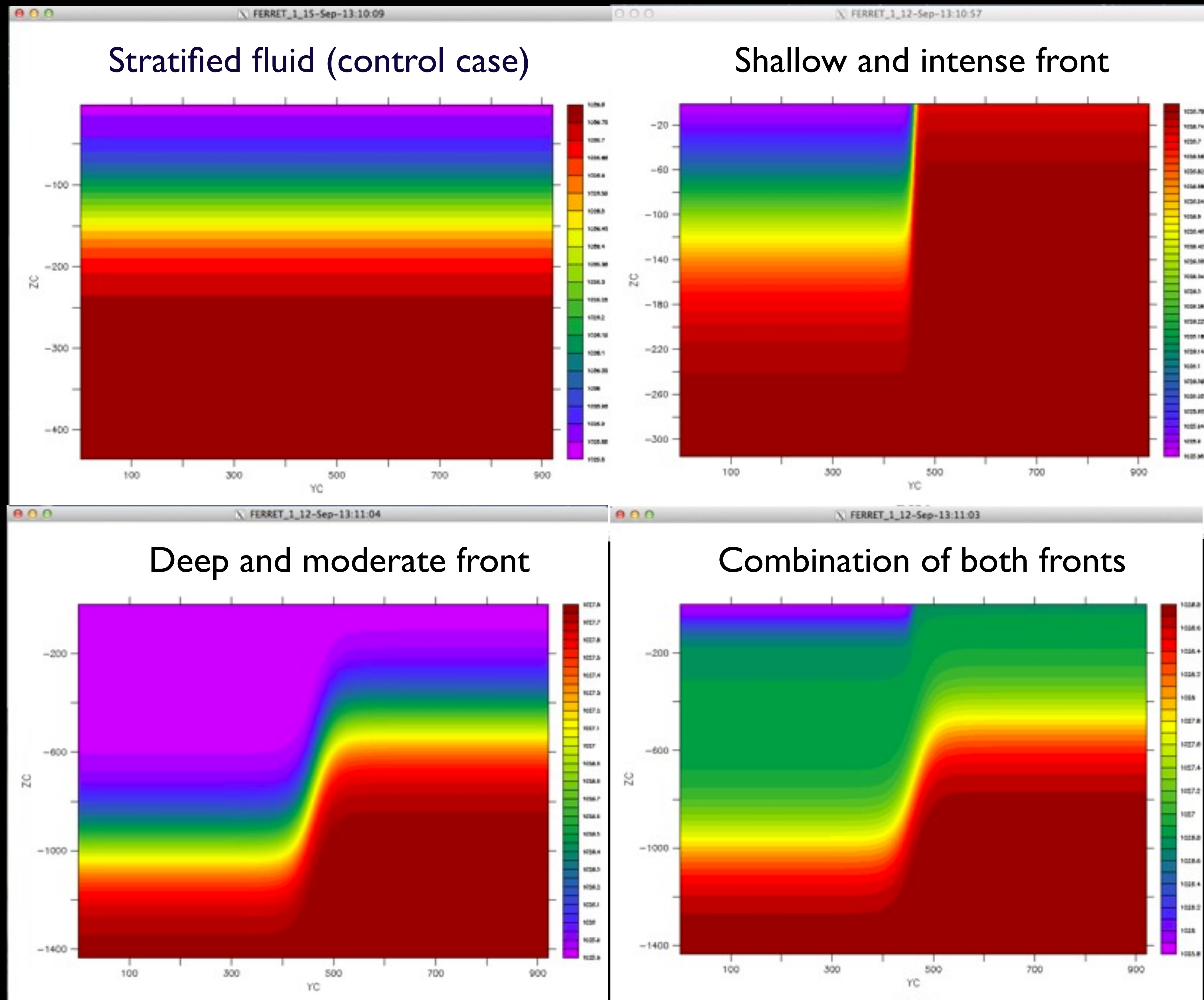


5 days time evolution of surface $\vec{u}$

What is the effect of a front on wind-forced IGWs?

$$\rho(y, z)$$

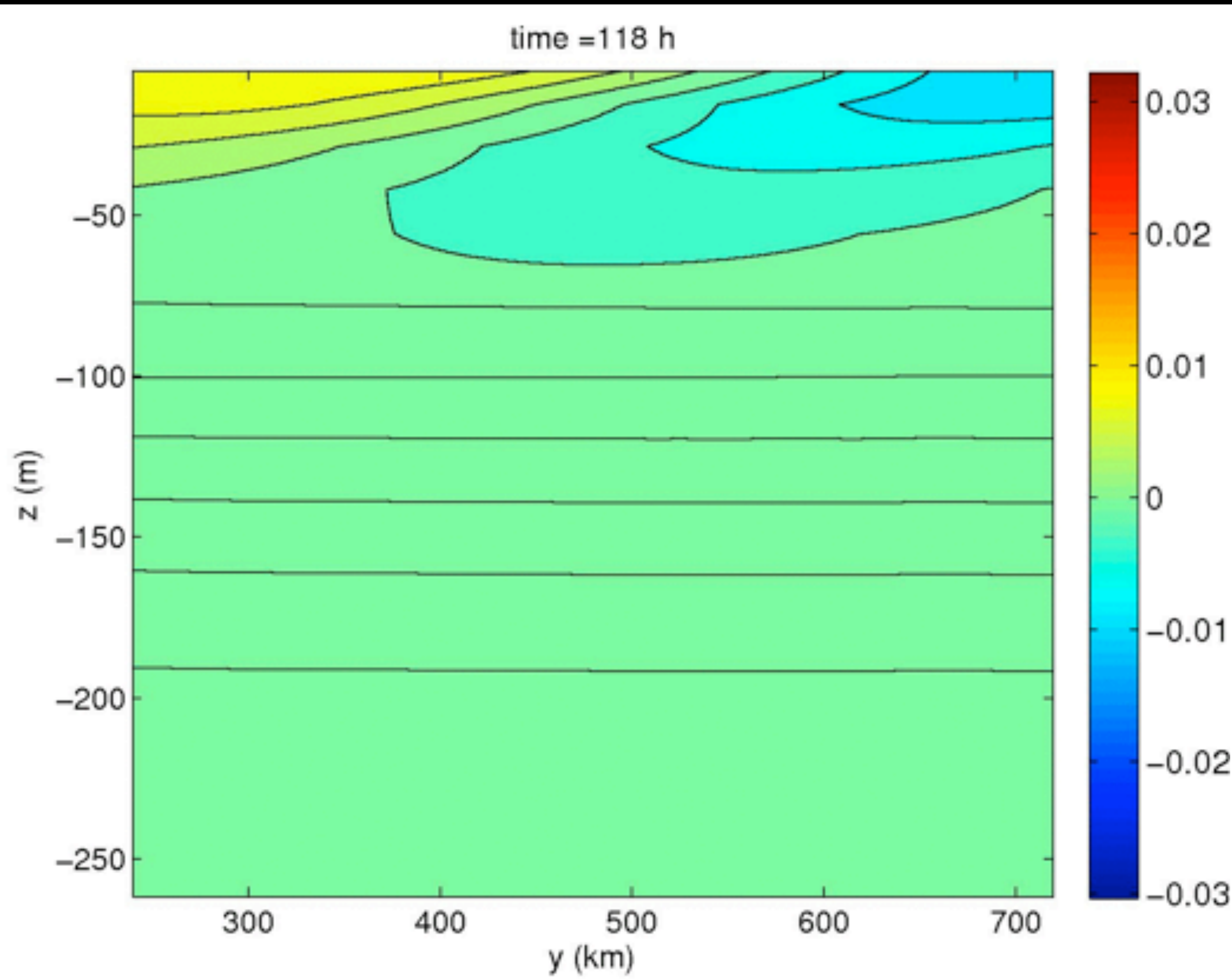
dy=1.2km
dt=180s
Ly=700km
Lz=2500m



Wind blows perpendicular to fronts

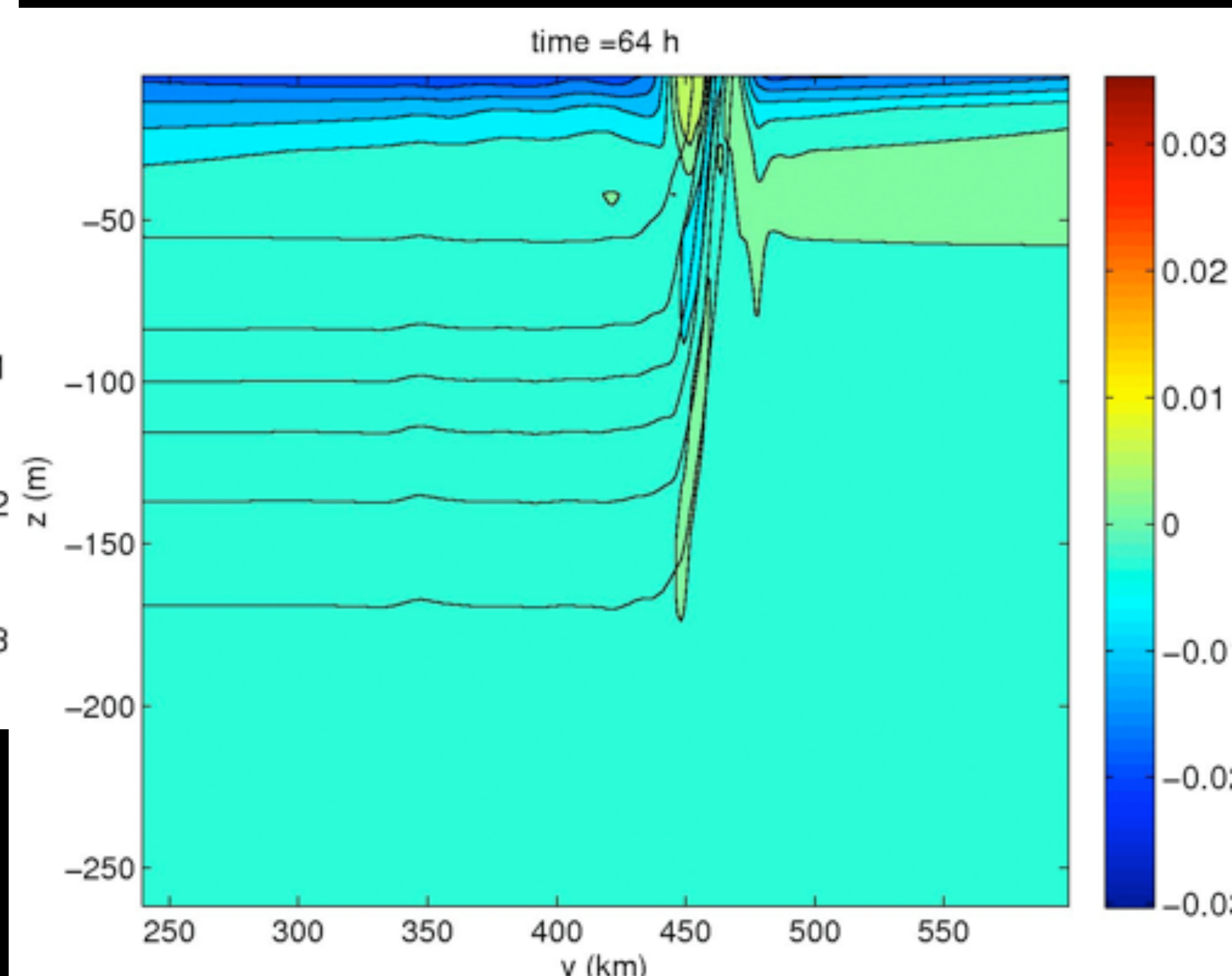
Inertia gravity waves propagate to depth along fronts.

Time-evolution of $\partial v/\partial z$



No front

Shallow front



Energy transfer depends on frontal intensity and depth.

Some effects of submesoscale dynamics

Submesoscale Dynamics

Intensification of vorticity, strain, vertical velocity associated with submesoscale dynamics

Mahadevan 2006
Mahadevan & Tandon 2006
Thomas, Tandon, Mahadevan 2008

Eddy-driven subduction

Surface freshwater and tracers can be dispersed by along-isopycnal filaments.

Badin, Tandon, Mahadevan, 2011

ML-Eddy-driven stratification

Countered by surface buoyancy loss and downfront winds

Mahadevan, Tandon, Ferrari, 2010

Mahadevan, D'Asaro, Lee, Perry, 2012

Ice edge phytoplankton blooms

Horizontal salinity gradients enhance vertical exchange in regions of meltwater

Mahadevan, Woodgate, Rainville, Matrai, Wang (in prep)

Near-inertial waves at a front

Wind-generated near-inertial waves propagate to depth at fronts

Claret, Tandon and Mahadevan (in prep)