Phytoplankton Thin Layers Simulated by Large-Eddy Simulation

Ashley Brereton and Yign Noh

연세대학교
YONSEI UNIVERSITY

Introduction

- Plankton live near the surface of the ocean.
- They are subjected to wind, wave and convection driven turbulence
- Despite turbulent mixing, spatial structures in the plankton are common in the surface waters
- One commonly observed structure is the phytoplankton ***thin layer***
- We use a Large-eddy simulation model coupled to a simple biological model to investigate this phenomenon

Thin layer observation, Mcmanus et. al (2003)

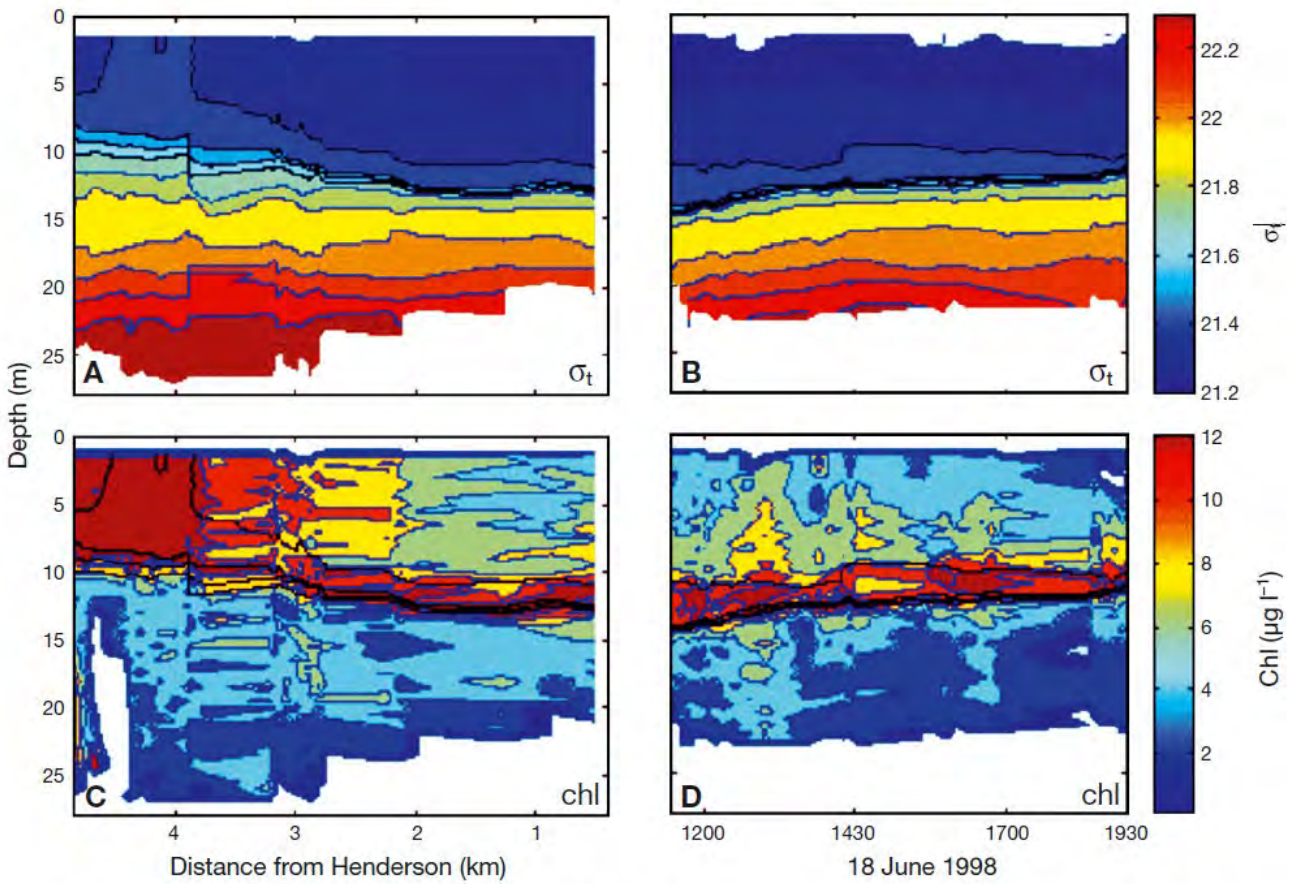
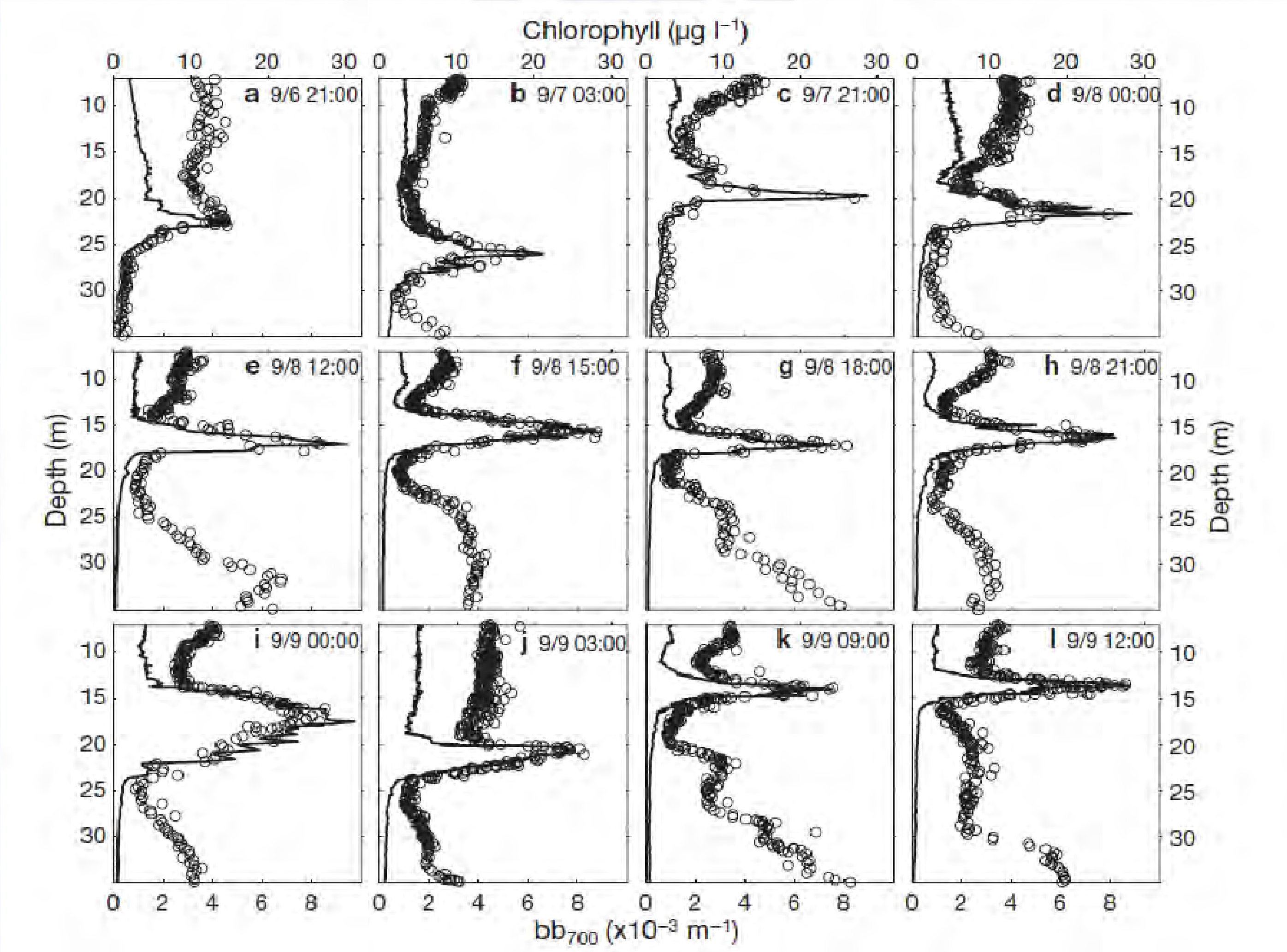


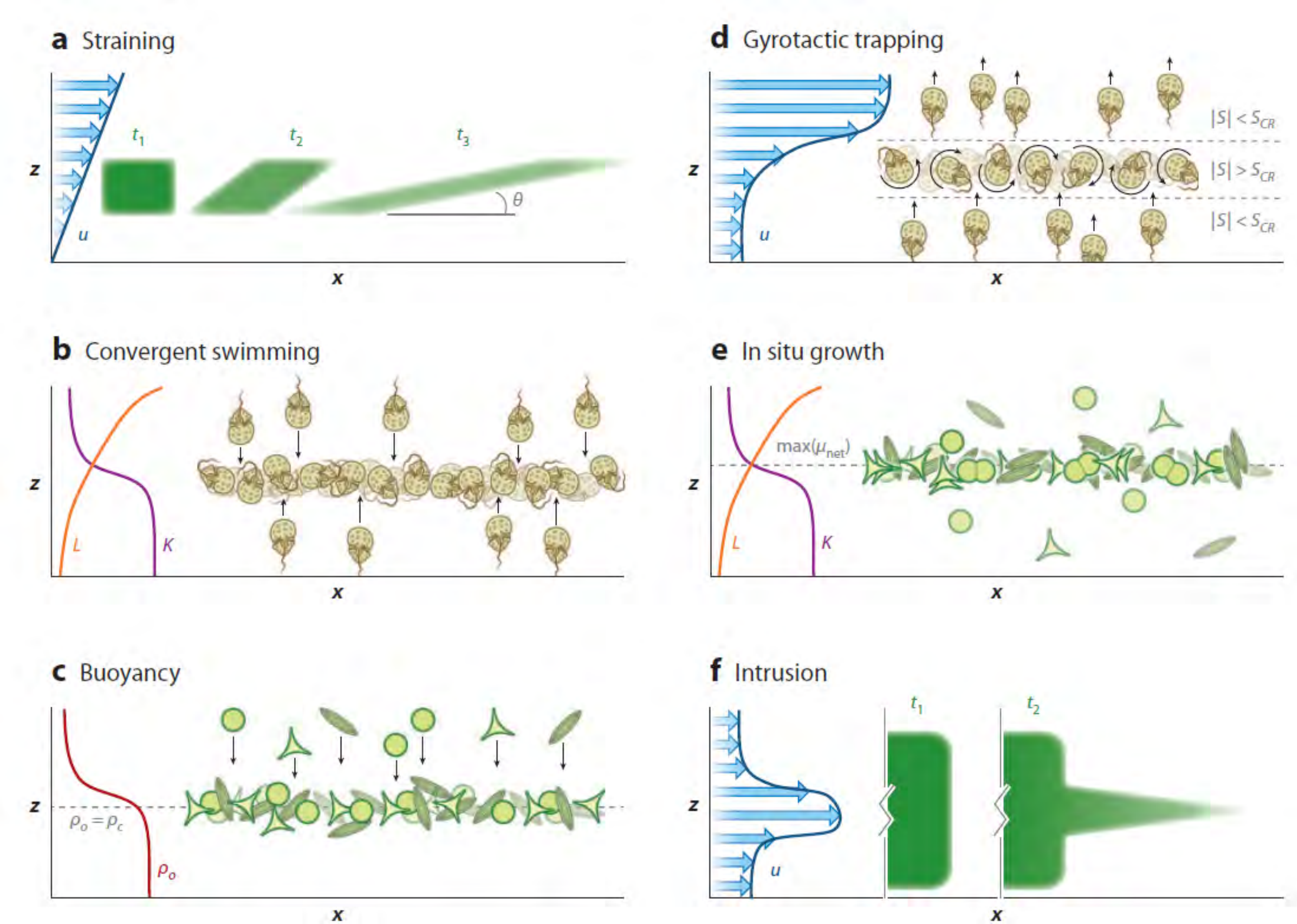
Fig. 3. (A) σ_t along transect from Rosario Point to RV 'Henderson'. (B) Time-series of σ_t measured from RV 'Henderson'. σ_t contours (21.4, 21.5, 21.6, 21.7) are drawn in black in (A) and (B). (C) Chlorophyll concentration ($\mu g\ l^{-1}$) along transect from Rosario to RV 'Henderson'. (D) Chlorophyll concentration ($\mu g\ l^{-1}$) at RV 'Henderson'. Chlorophyll concentration estimated from $(a_p676 - a_p650)/0.012$ (where a_p = phytoplankton absorption); red = chlorophyll concentrations >12 $\mu g\ l^{-1}$. 'Third Love' was next to RV 'Henderson' at approximately 14:30 h on June 18; non-plotted values at bottom of graphs are due to sediments for which $a_p676 - a_p650 < 0$

연세대학교
YONSEI UNIVERSITY

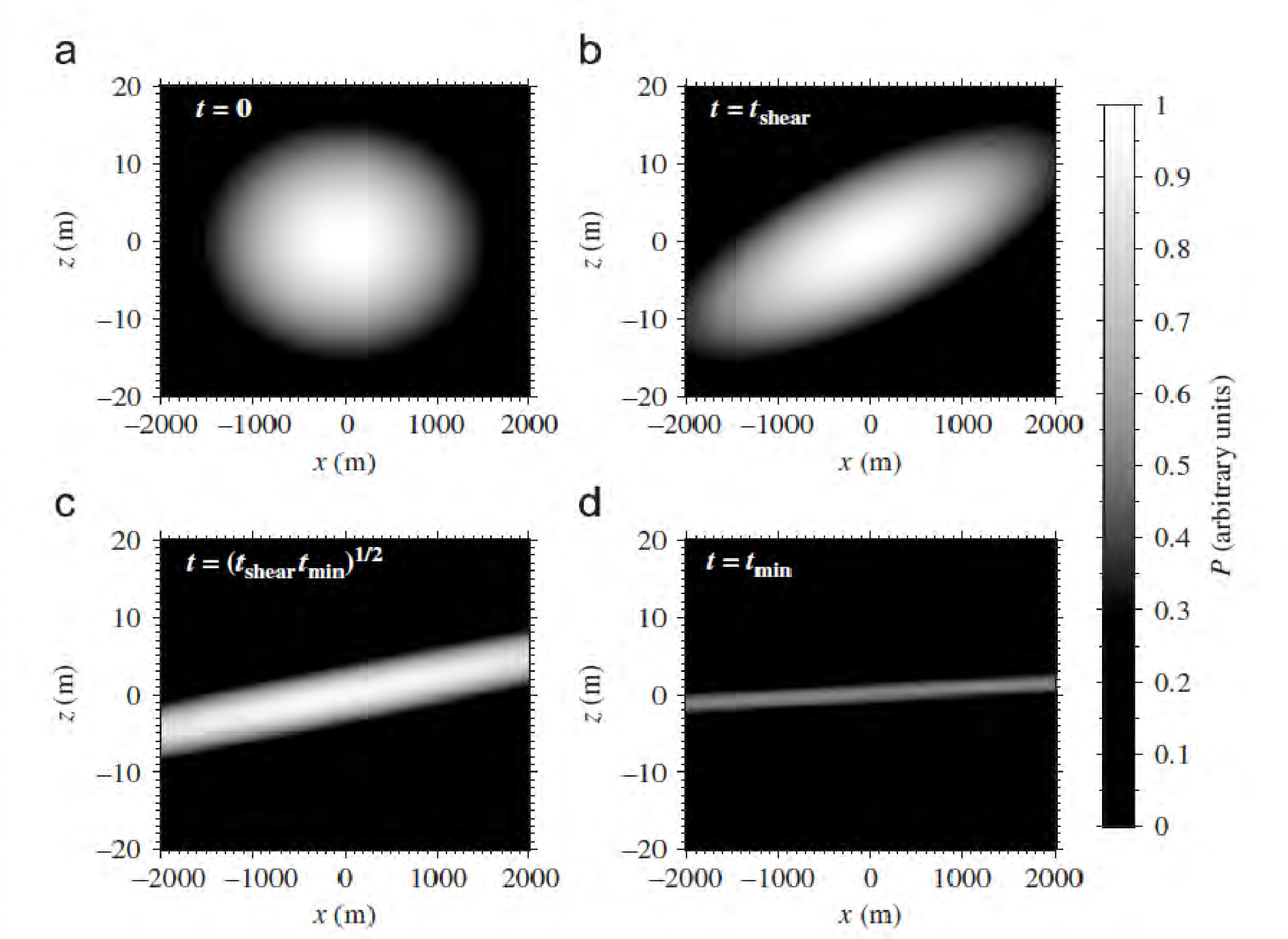
Thin layer observations, Ryan et. al (2008)



Proposed Mechanisms, Durham and Stocker (2012)



Thin layer models, Birch et al. (2007)



연세대학교
YONSEI UNIVERSITY

Dekshenieks et. al (2001)

ness from 0.12 m to 3.61 m (mean 1.20 m). Roughly 44 % of layers were <1 m in thickness, and 80 % of

to 6.45 m^{-1} (mean 1.33 m^{-1}) (Table 1, Fig. 4c). About 72 % of the thin layers had absorption intensities that ranged from 0.25 to 1.5 m^{-1} (Fig. 4c).

There is a second class of thin optical layer adjacent to the bottom. These bottom layers were found in 31 (26 %) of the profiles. They ranged from 0.23 to 3.11 m in thickness (mean 1.30 m). Bottom layer intensities ranged from 0.26 to 2.24 m^{-1} (mean 0.80 m^{-1}). Thus, bottom layers had similar thickness to and slightly lower intensities than water column thin layers. We do not include bottom layers in these

(>2.3 m^{-1}) occurred at lower wind speeds (<4 m s^{-1}). In East Sound, surface waters from 2 to 10 m are strongly

tain higher layer intensities.

Thin phytoplankton layers and the pycnocline

Thin layer depth was closely associated with depth and strength of the pycnocline. Roughly 62 % of all thin layers were at the base of the pycnocline (Fig. 6a). This pattern was observed on all cruises, but was strongest in May. Approximately 9 % of thin layers were distributed

and strength of the pycnocline. Roughly 62 % of all thin layers were at the base of the pycnocline (Fig. 6a). This

연세대학교
YONSEI UNIVERSITY

Model description

- Physical model: Large-Eddy Simulation (LES)

- PALM 5.0

$$\frac{\partial u}{\partial t} + u \cdot \nabla u + f \times u = -\frac{\nabla p}{\rho_0} + \nabla \cdot \nu_t \nabla u - \frac{\rho g}{\rho_0}$$

$$\nabla \cdot u = 0$$

- Filtered Navier-Stokes equations
- Fully 3-dimensional
- Turbulence resolving

연세대학교
YONSEI UNIVERSITY

Model description

- Biological model: Nutrient-Phytoplankton model (NP)
- Phytoplankton are treated as Lagrangian particles
- Each particle is representative of a number of phytoplankton cells, denoted by a weighting factor W.
- This weighting factor varies with the net growth rate of the phytoplankton i.e.

$$W_{t+\delta t} = W_t \times (1 + \delta t \times \text{Net growth rate})$$

$$\text{Net growth rate} = \overbrace{Ge^{Kz}\frac{N}{N_0}}^{growth} - \overbrace{D}^{death}$$

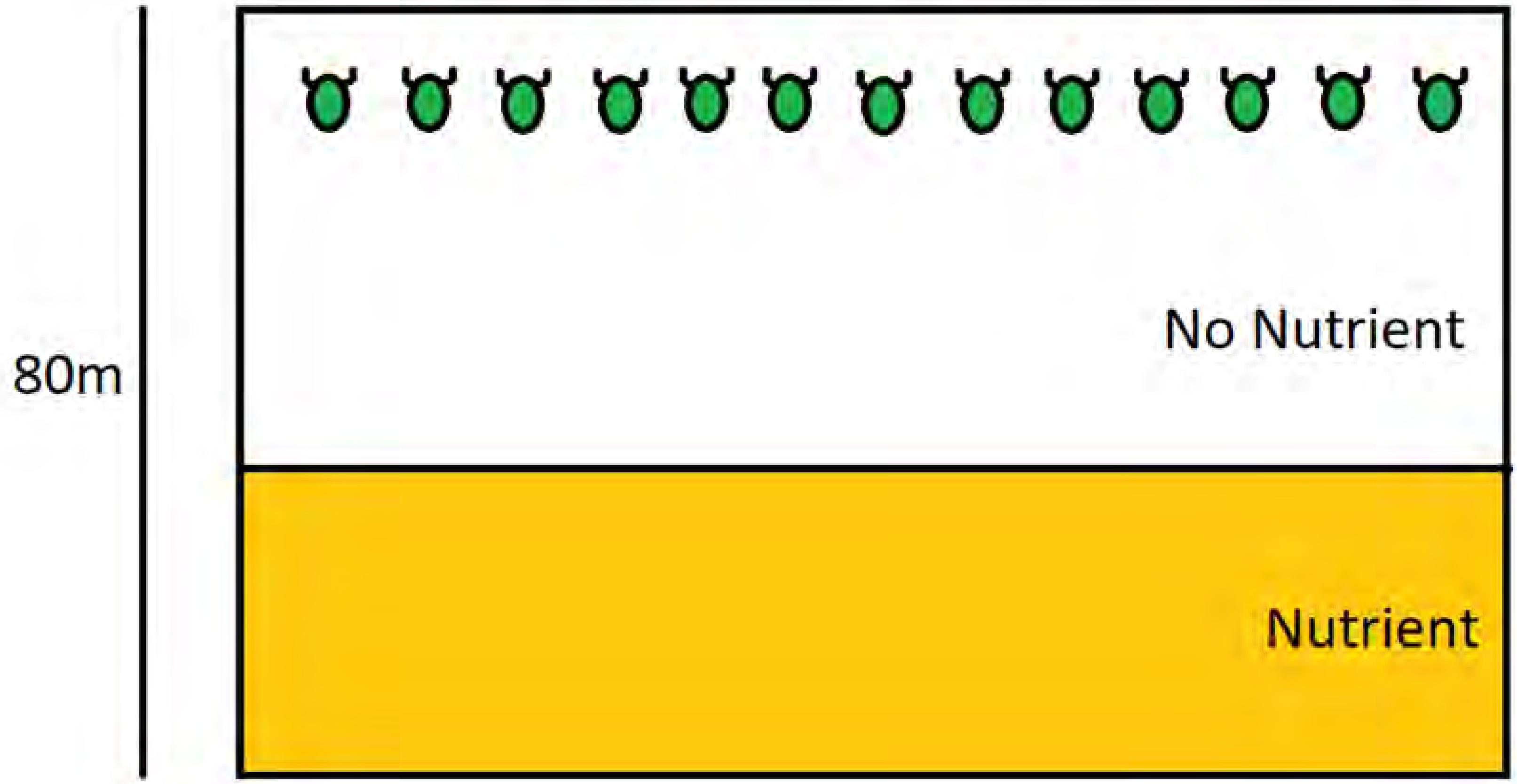
Model description

❖ Biological model: Nutrient-Phytoplankton model (NP)

❖ Nutrient is treated as an Eularian scalar

$$\frac{\partial N}{\partial t} + \boldsymbol{u} \cdot \nabla N = \nabla \cdot D_t \nabla N - P \times \text{Net growth rate}$$

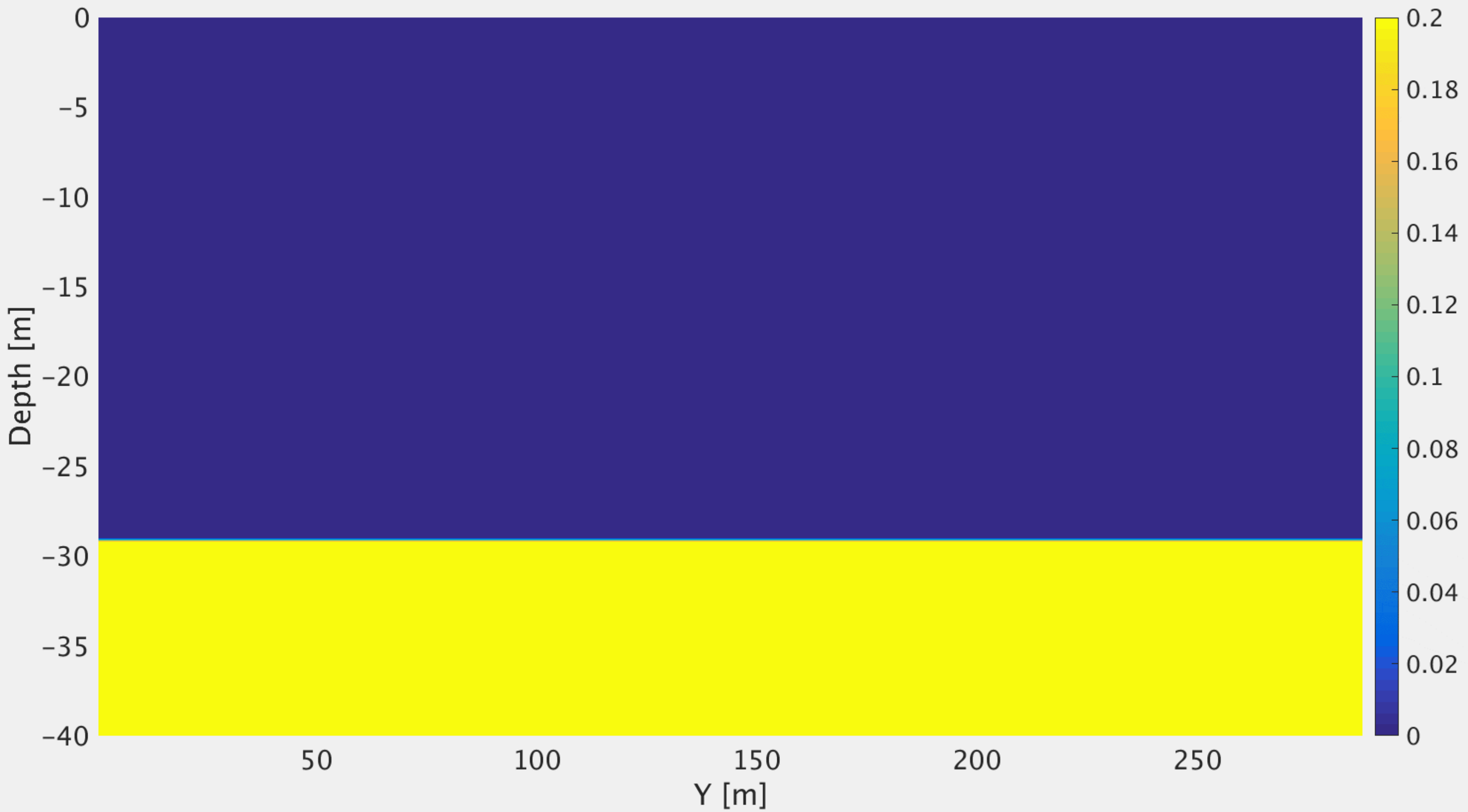
Model setup



Model setup

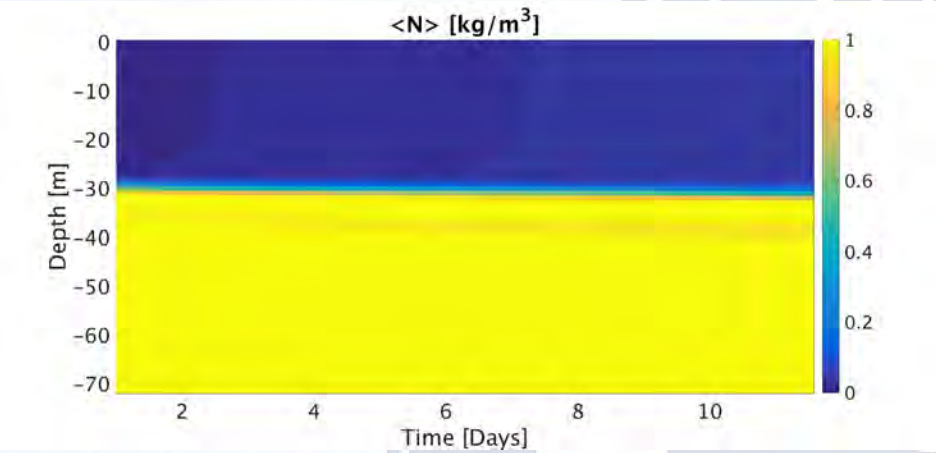
- Domain size: $L_x = L_y = 300\text{m} \quad L_z = 80\text{m}$
- Domain resolution: $\delta x = \delta y = \delta z = 1\text{m}$
- Period horizontal boundary conditions
- Wind forcing: $4\text{ms}^{-1} - 12\text{ms}^{-1}$
- Initial surface mixed layer: 30m
- Initial stratification: 0.1 Kelvin/m
- Initial Nutrient: $10\mu\text{mol l}^{-1}$
- Amount of particles: 9,000,000
- Phytoplankton size: 50µm

Simulation design

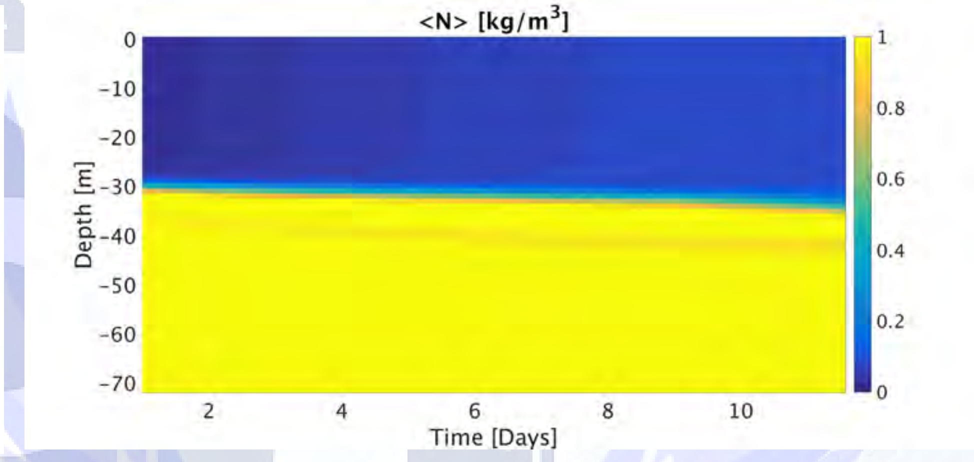


Nutrient response to wind

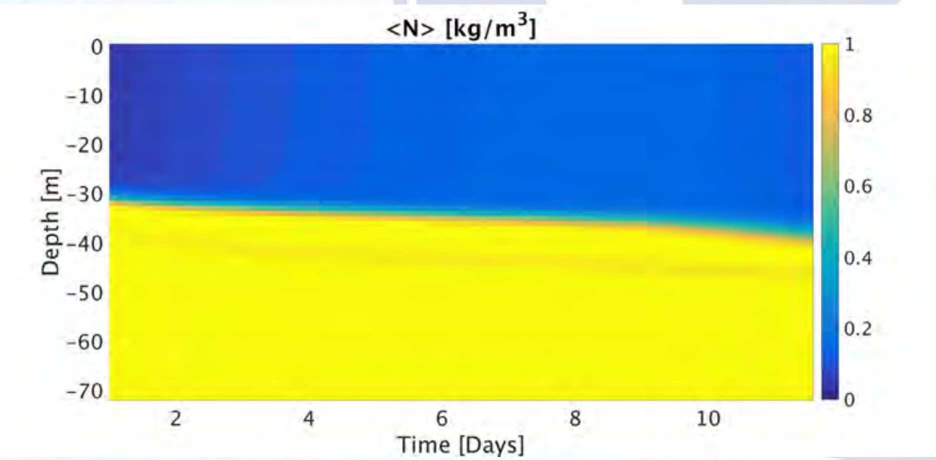
Low wind $(4ms^{-1})$



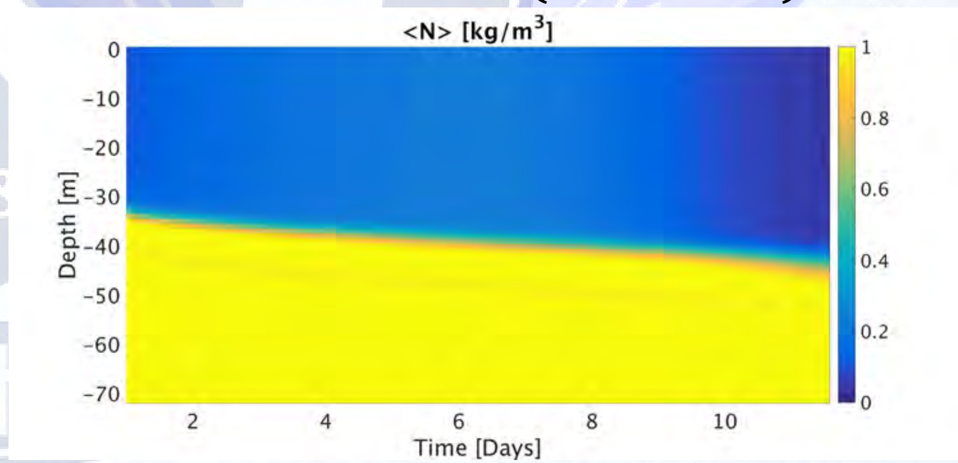
$(6ms^{-1})$



$(8ms^{-1})$



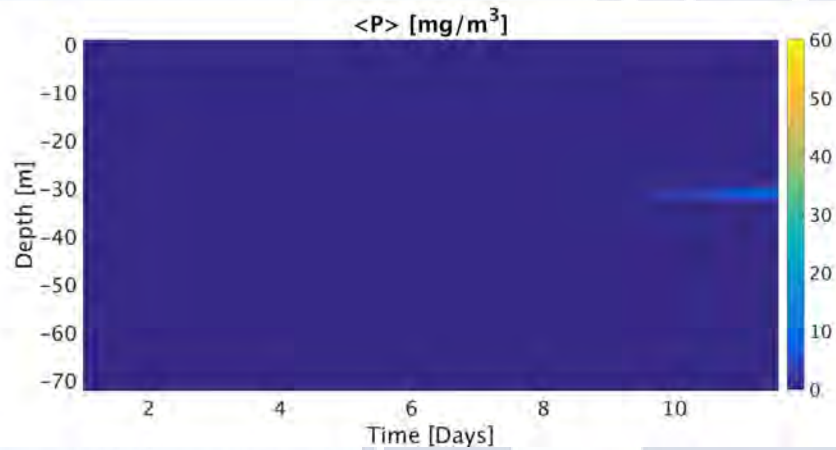
High wind $(10ms^{-1})$



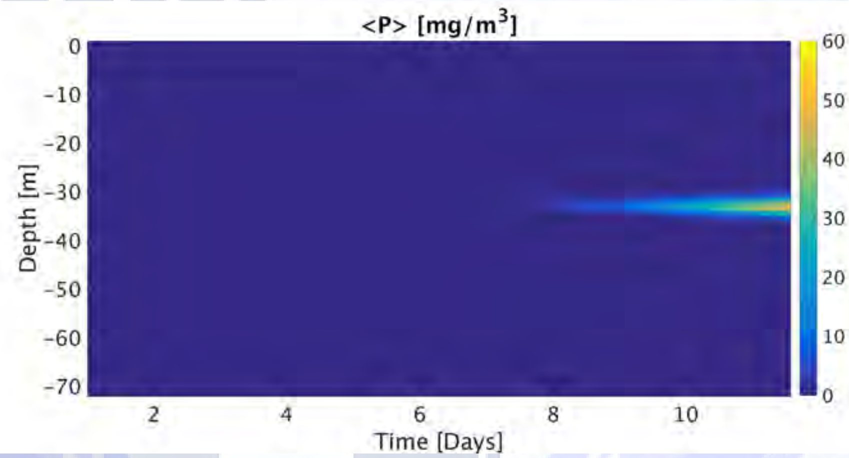
연세대학교
YONSEI UNIVERSITY

Plankton response to wind

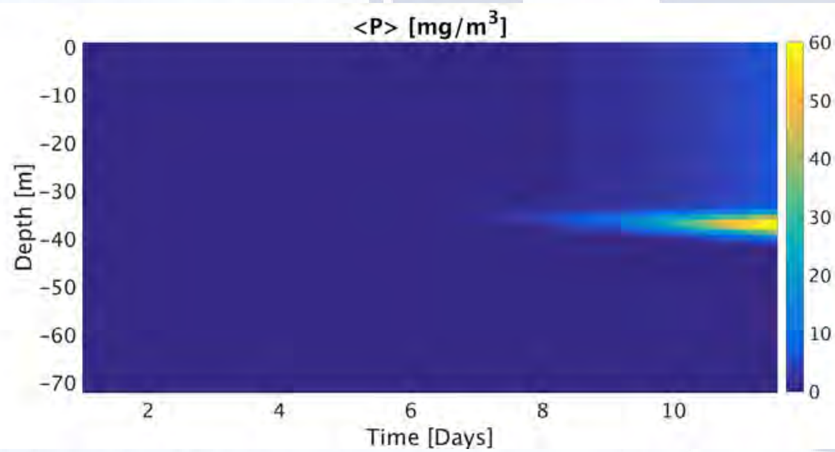
Low wind ($4ms^{-1}$)



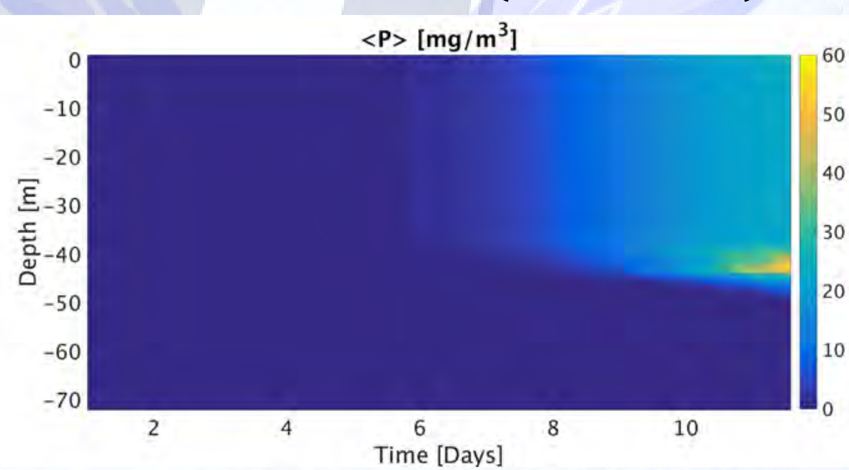
($6ms^{-1}$)



($8ms^{-1}$)

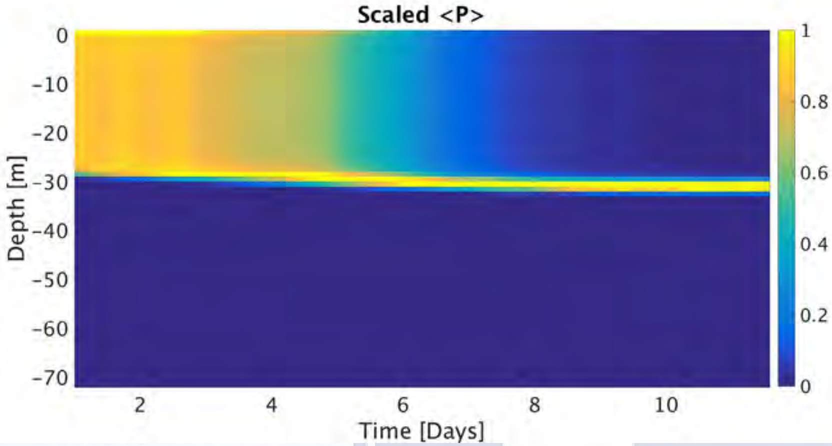


High wind ($10ms^{-1}$)

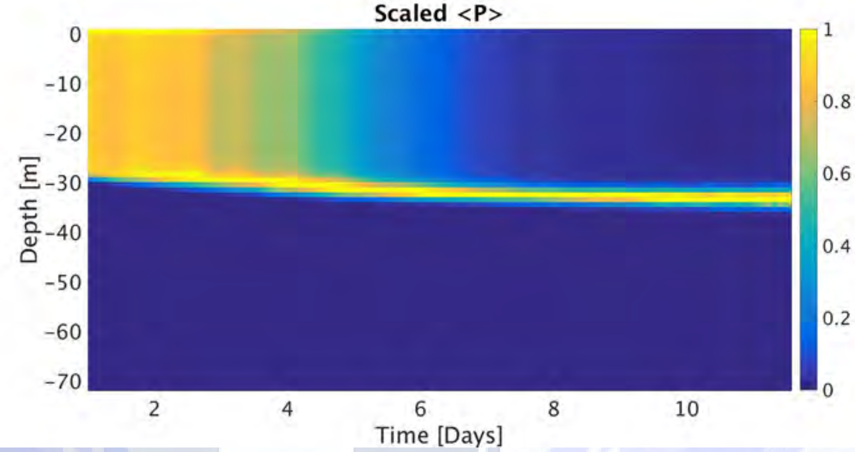


Plankton (Scaled by max) response to wind

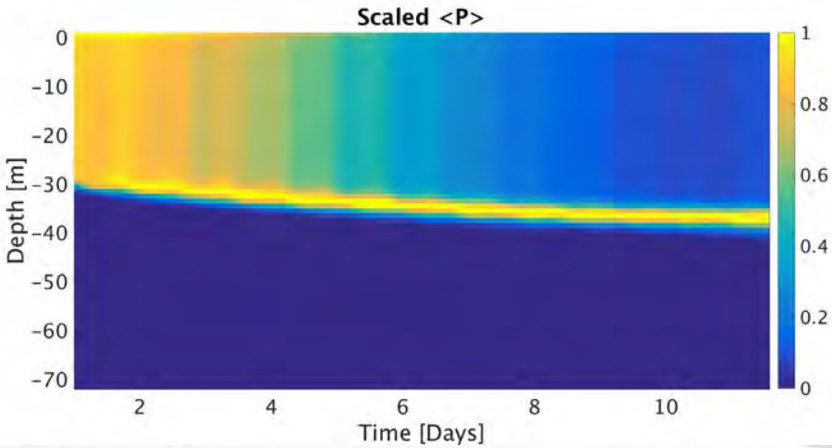
Low wind ($4ms^{-1}$)



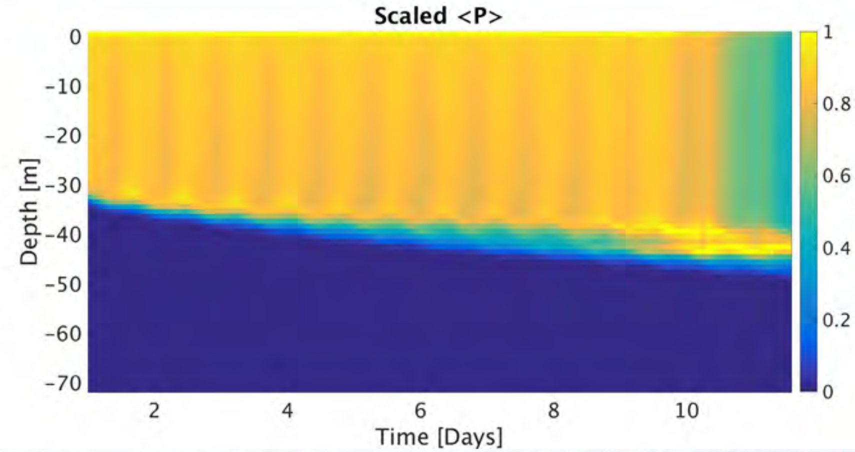
($6ms^{-1}$)



($8ms^{-1}$)

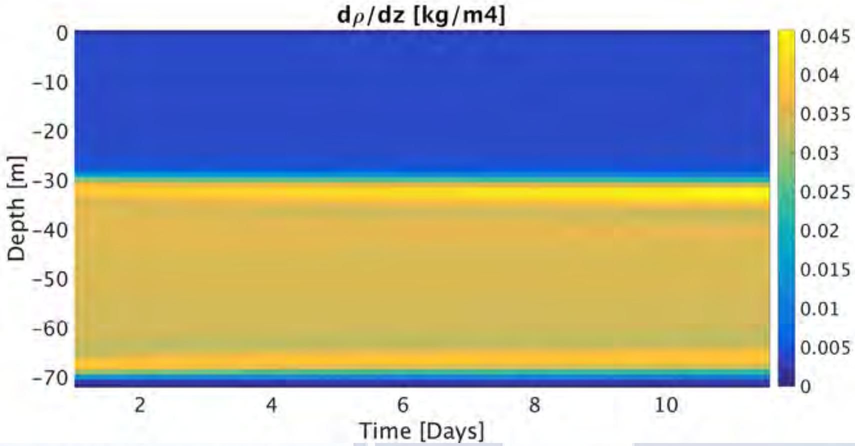


High wind ($10ms^{-1}$)

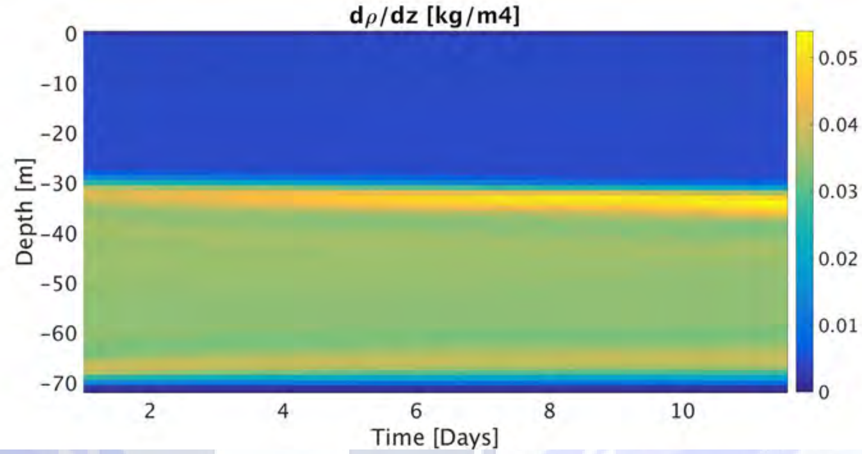


Stratification

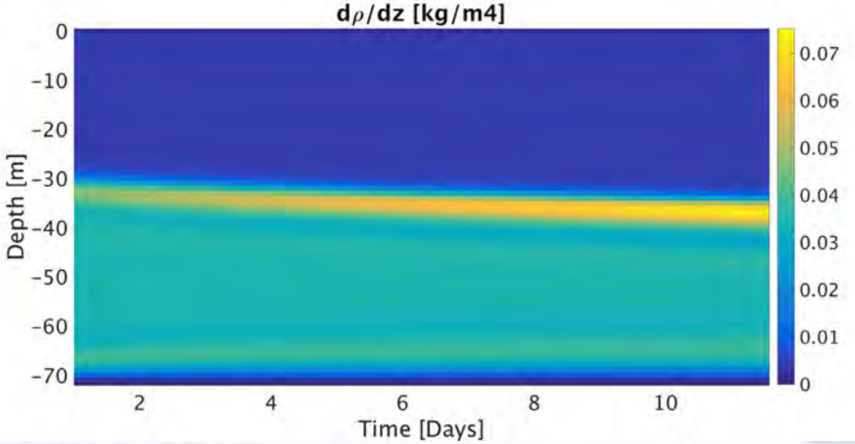
Low wind $(4ms^{-1})$



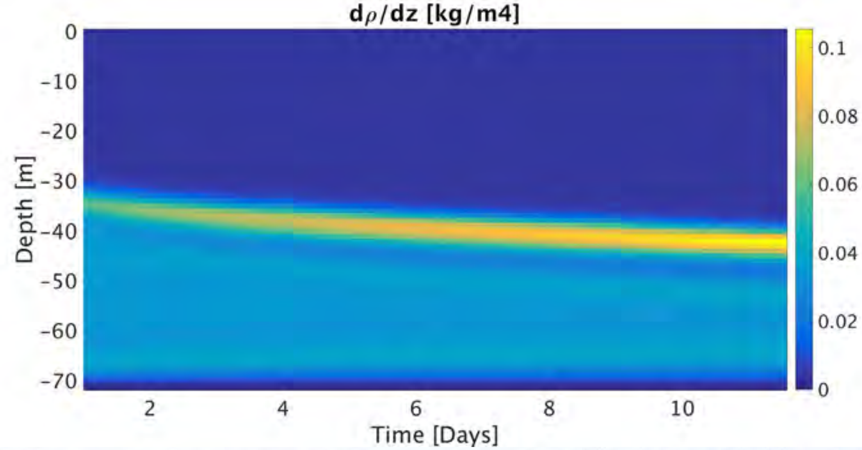
$(6ms^{-1})$



$(8ms^{-1})$

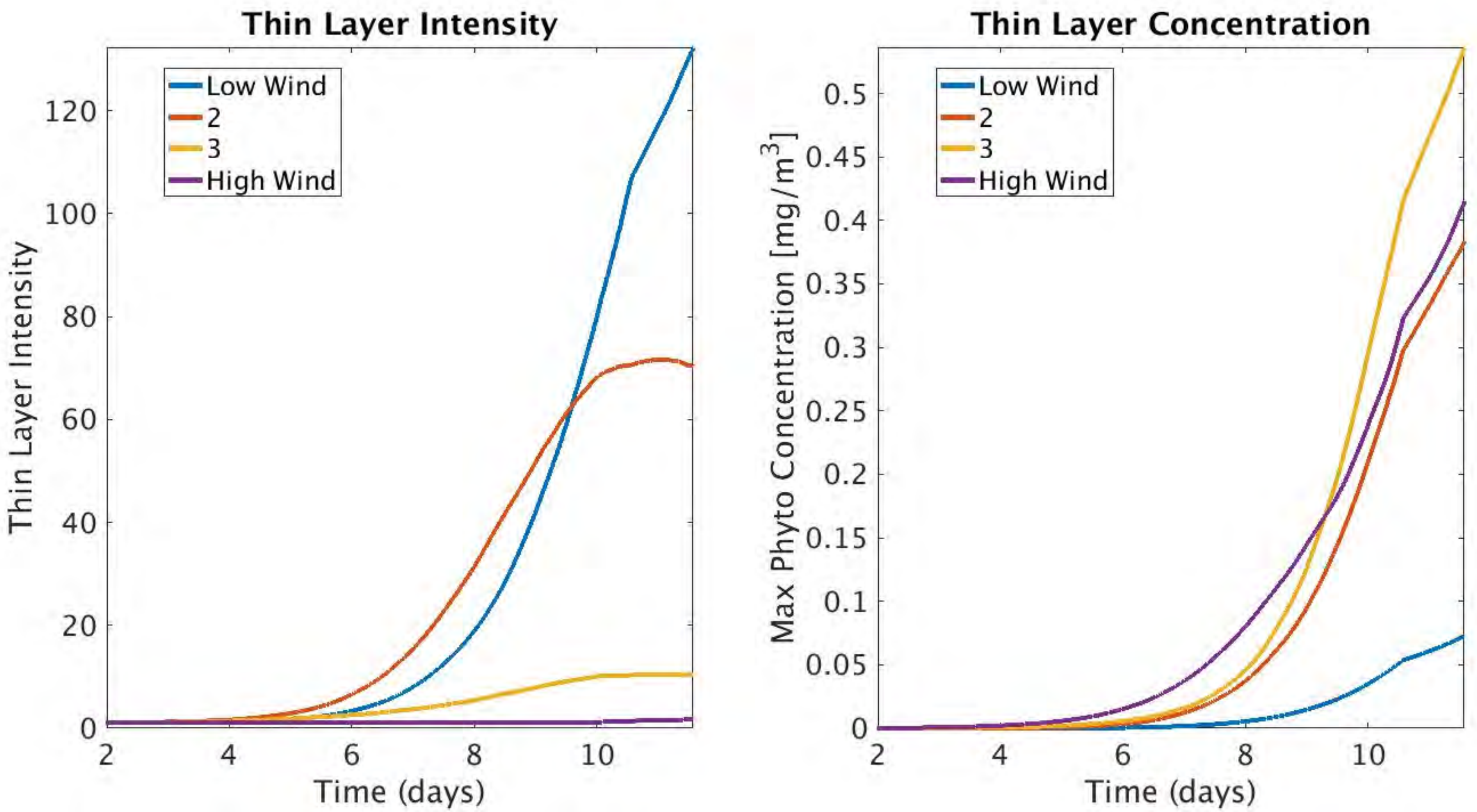


High wind $(10ms^{-1})$



연세대학교
YONSEI UNIVERSITY

DCM Intensity



$$\text{Thin Layer Intensity} = \frac{\text{Maximum Phytoplankton concentration}}{\text{Surface Phytoplankton concentration}}$$

연세대학교
YONSEI UNIVERSITY

Quick Summary I

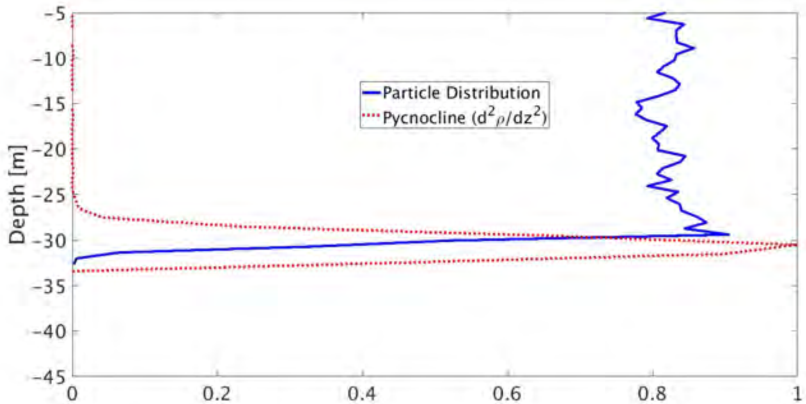
❖Thin layers form at the pycnocline

❖Low wind = Low concentration in thin layer

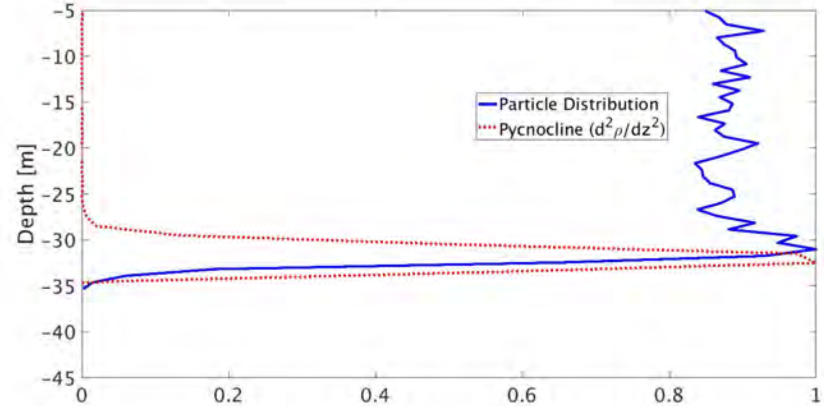
❖High wind = Low thin layer intensity

Phytoplankton (particle) injection

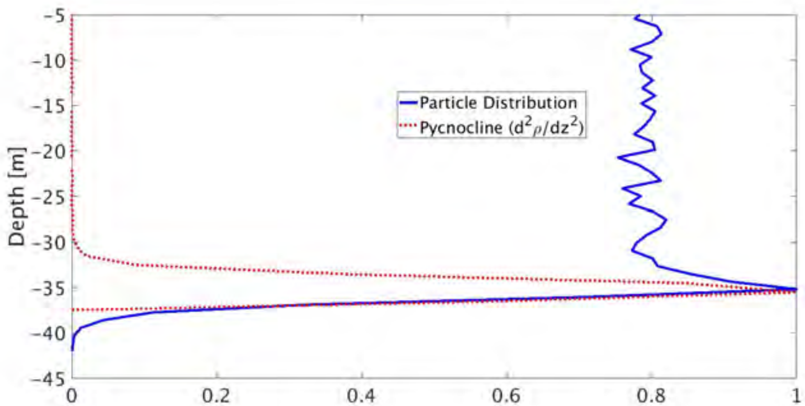
Low wind ($4ms^{-1}$)



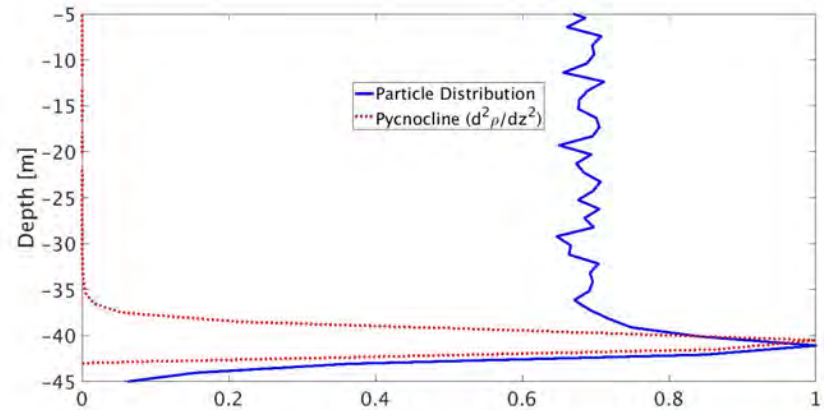
($6ms^{-1}$)



($8ms^{-1}$)



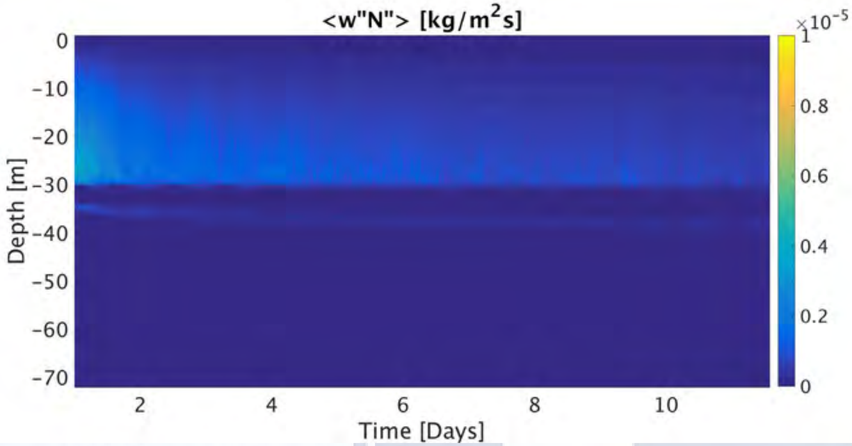
High wind ($10ms^{-1}$)



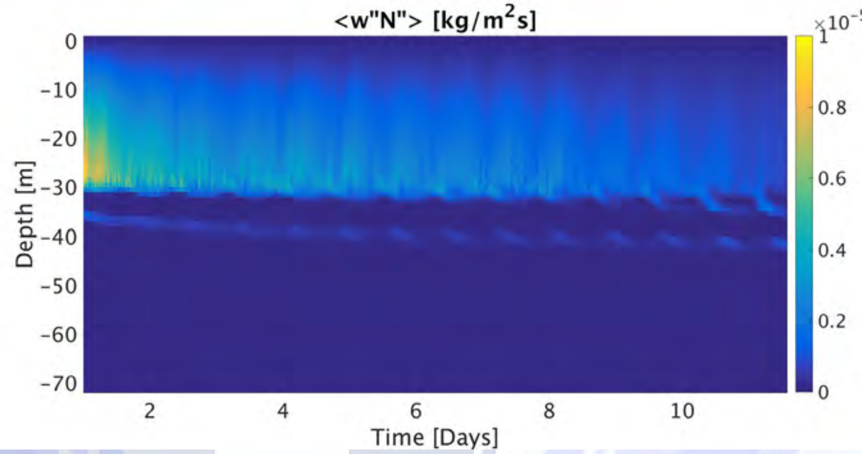
연세대학교
YONSEI UNIVERSITY

Nutrient Entrainment <N'w'>

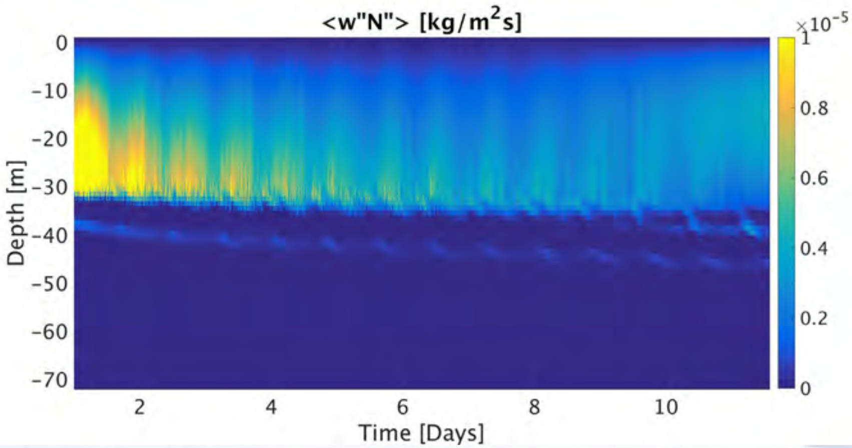
Low wind ($4ms^{-1}$)



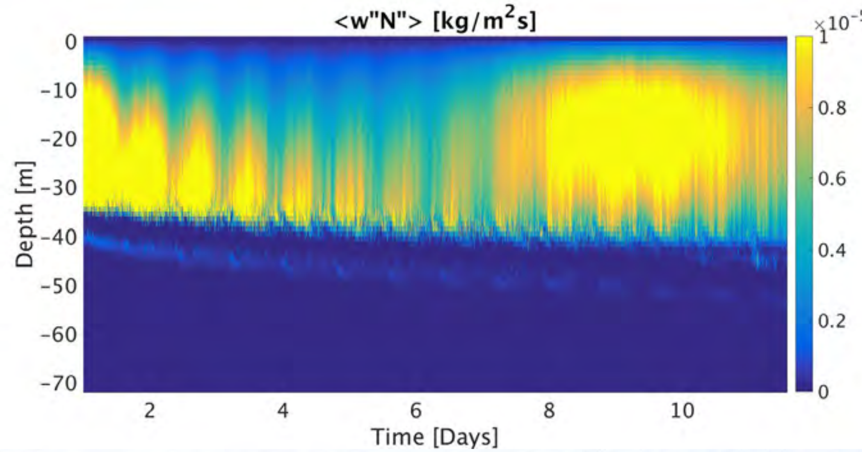
($6ms^{-1}$)



($8ms^{-1}$)



High wind ($10ms^{-1}$)

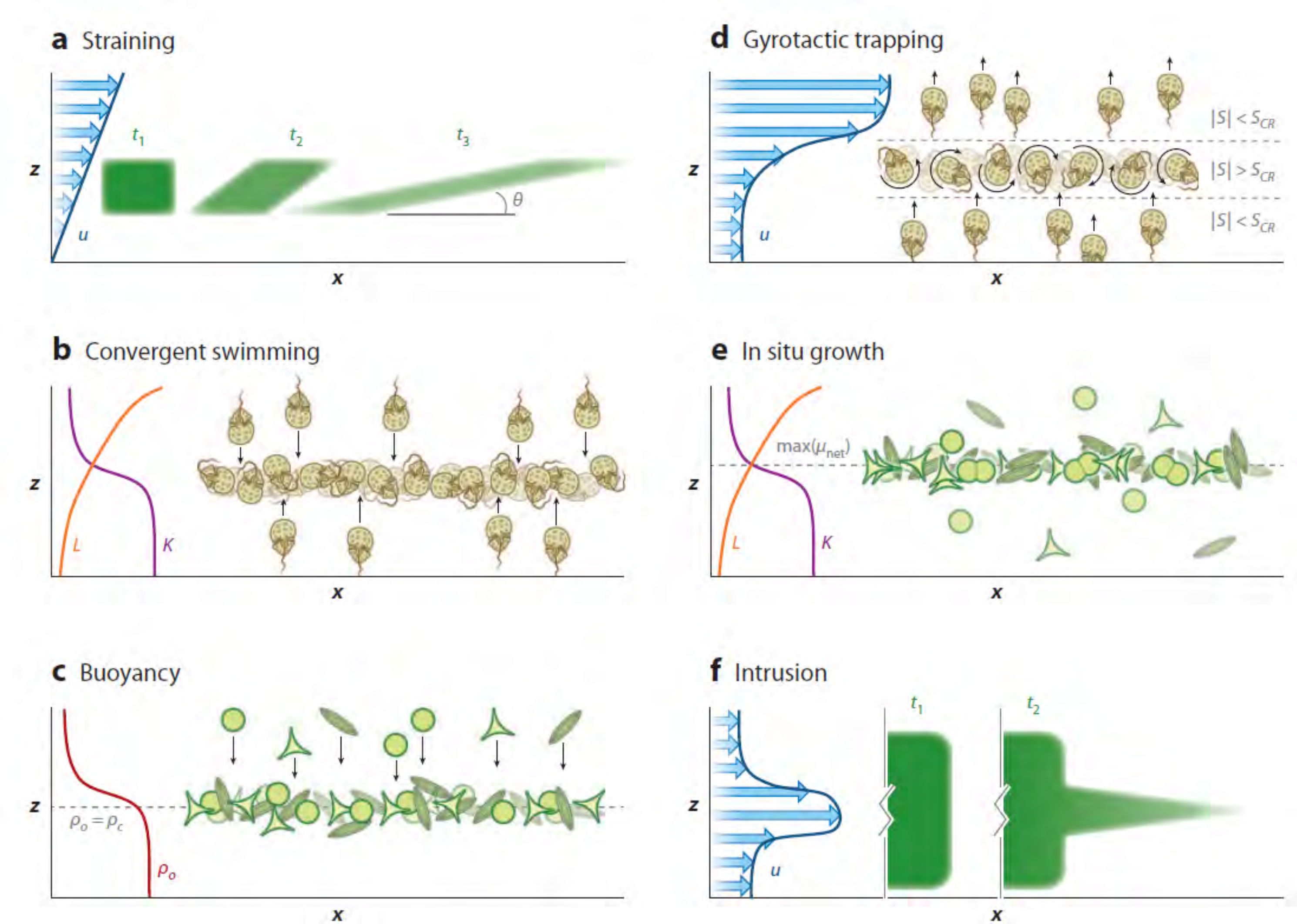


연세대학교
YONSEI UNIVERSITY

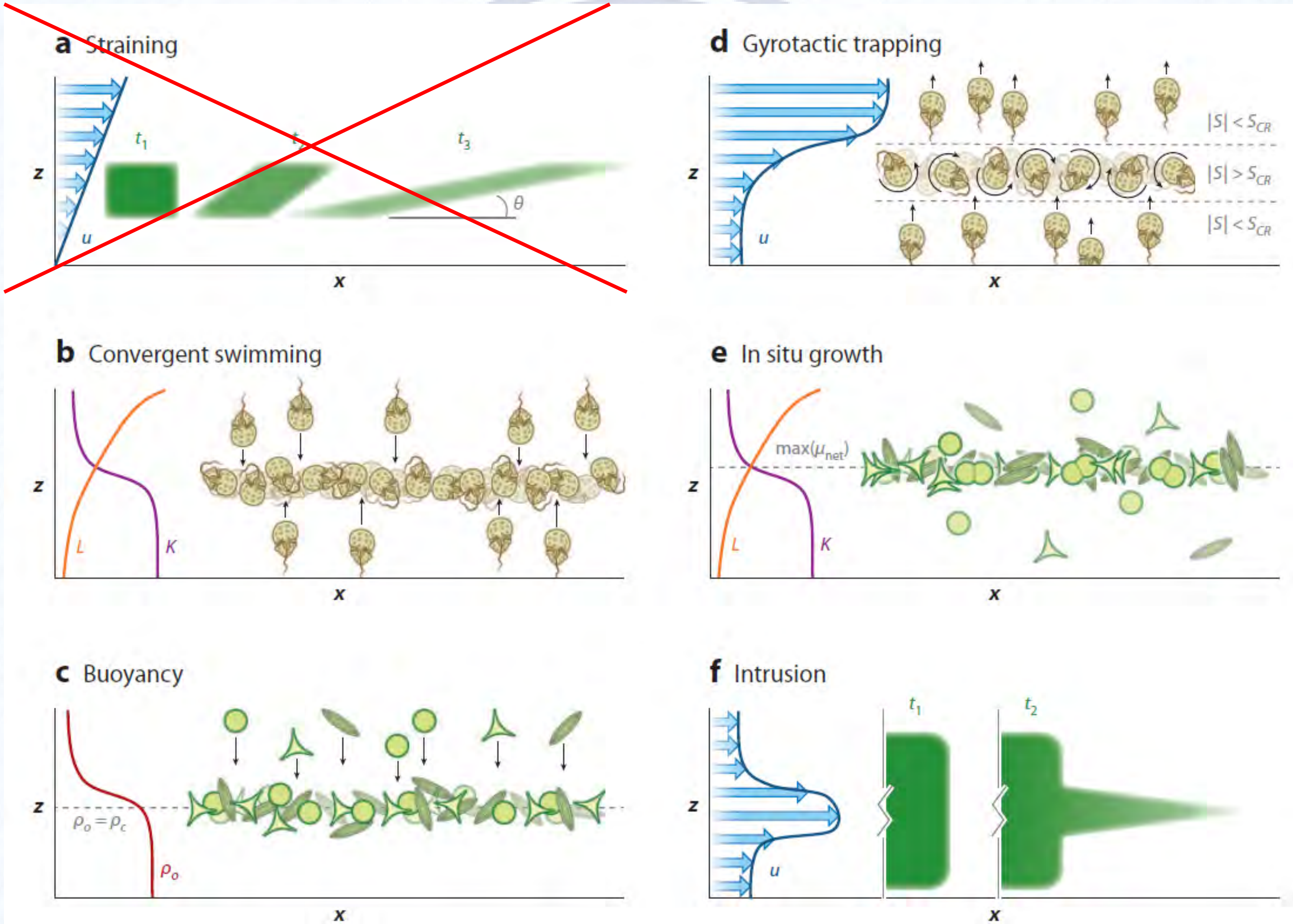
Quick Summary II

- ❖Low wind = Small amount of particles injected into pycnocline
- ❖High wind = Lots of nutrient entrainment into surface water

Proposed Mechanisms, Durham and Stocker (2012)

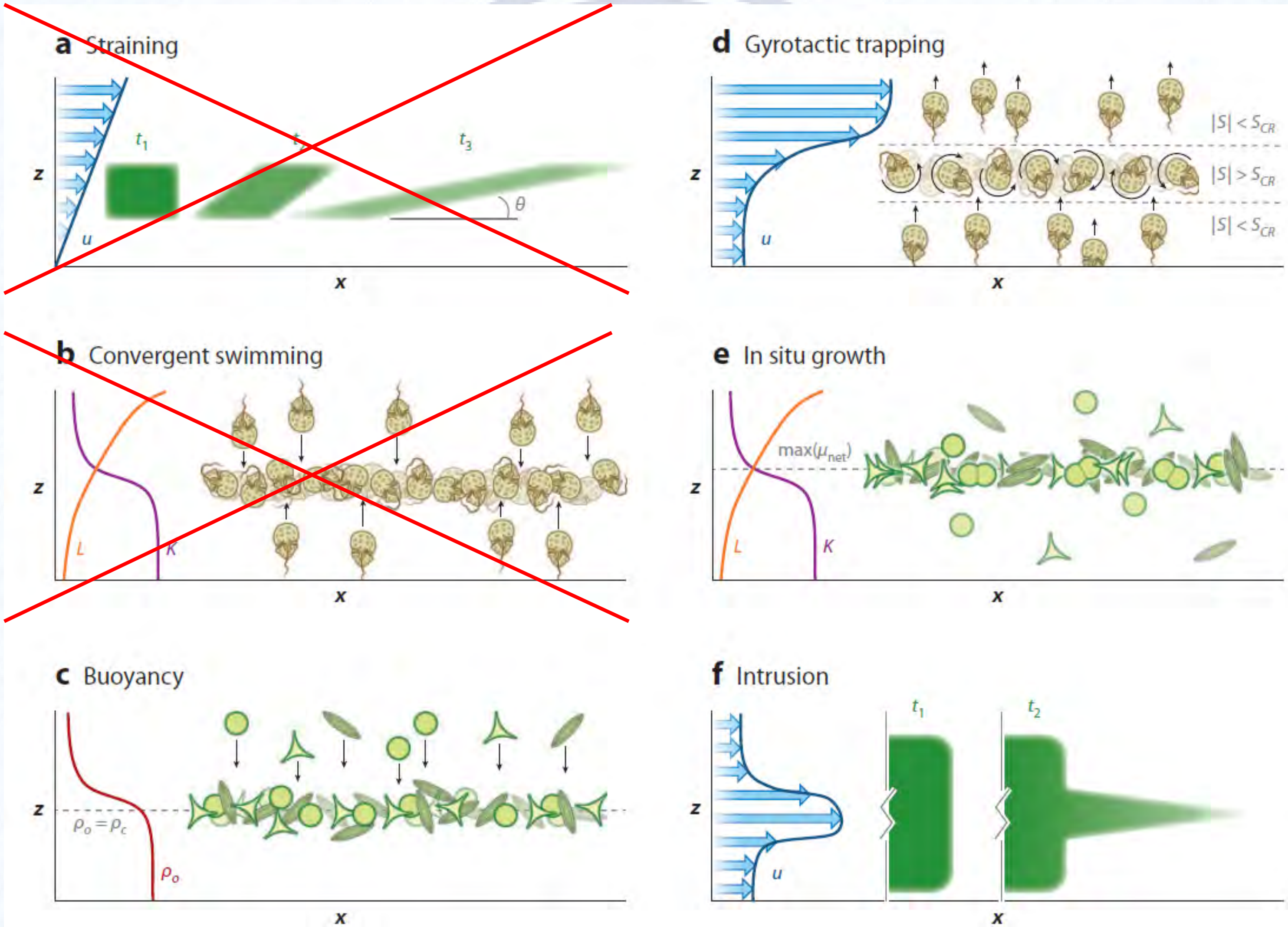


Proposed Mechanisms, Durham and Stocker (2012)

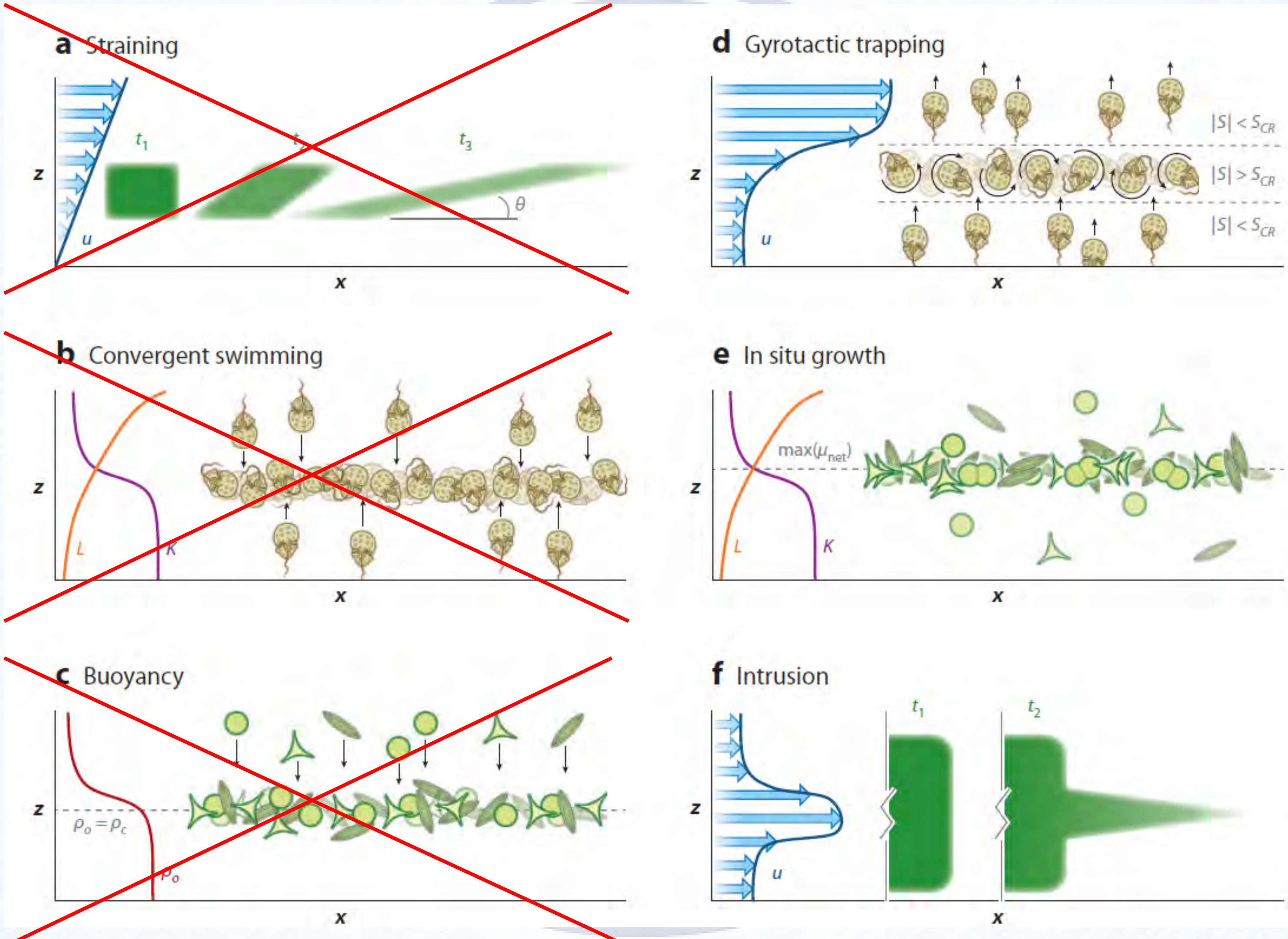


연세대학교
YONSEI UNIVERSITY

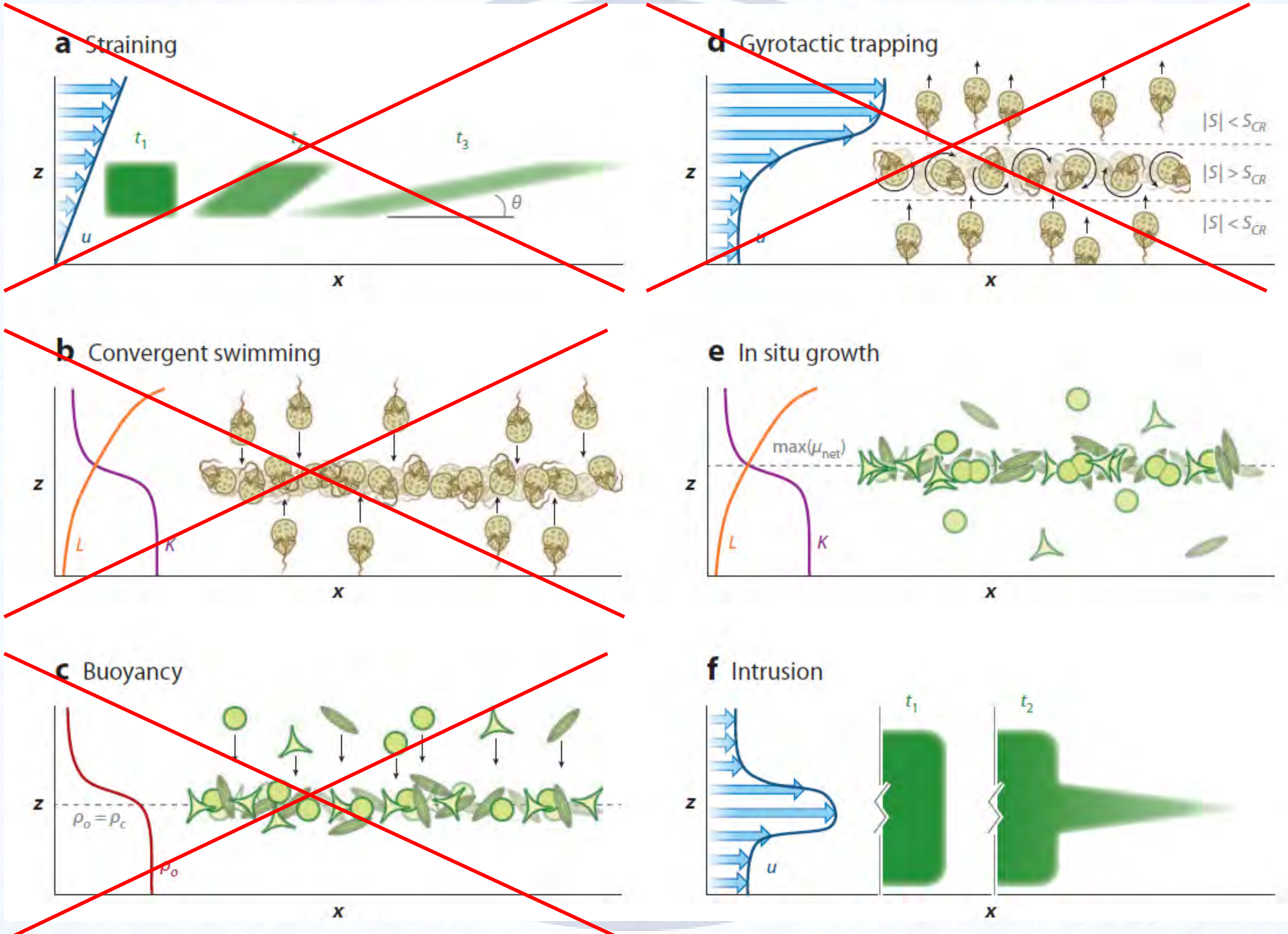
Proposed Mechanisms, Durham and Stocker (2012)



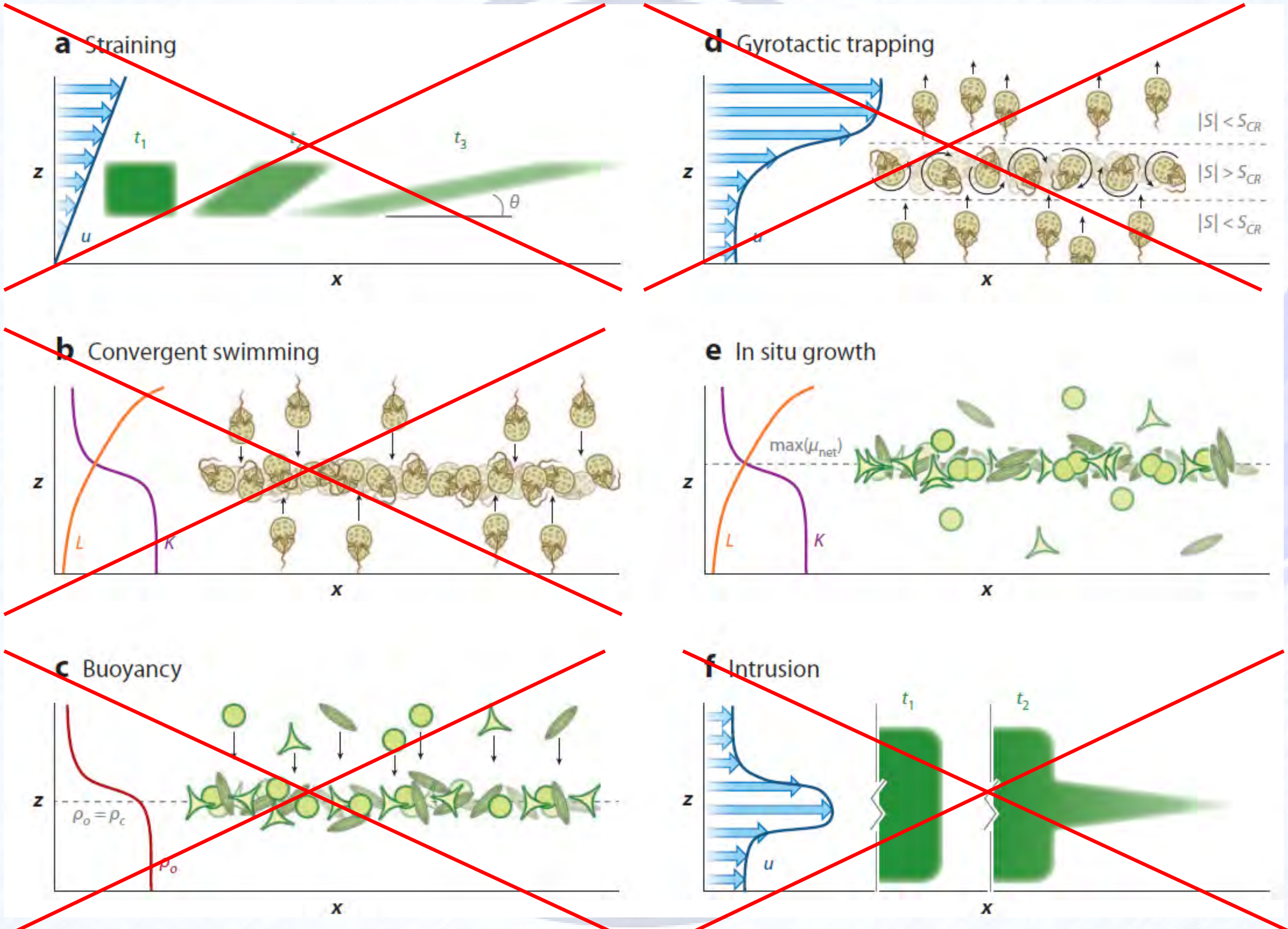
Proposed Mechanisms, Durham and Stocker (2012)



Proposed Mechanisms, Durham and Stocker (2012)



Proposed Mechanisms, Durham and Stocker (2012)



연세대학교
YONSEI UNIVERSITY

Dynamical consideration

❖ A thin layer should form if the timescale of growth is much larger than the timescale of vertical mixing.

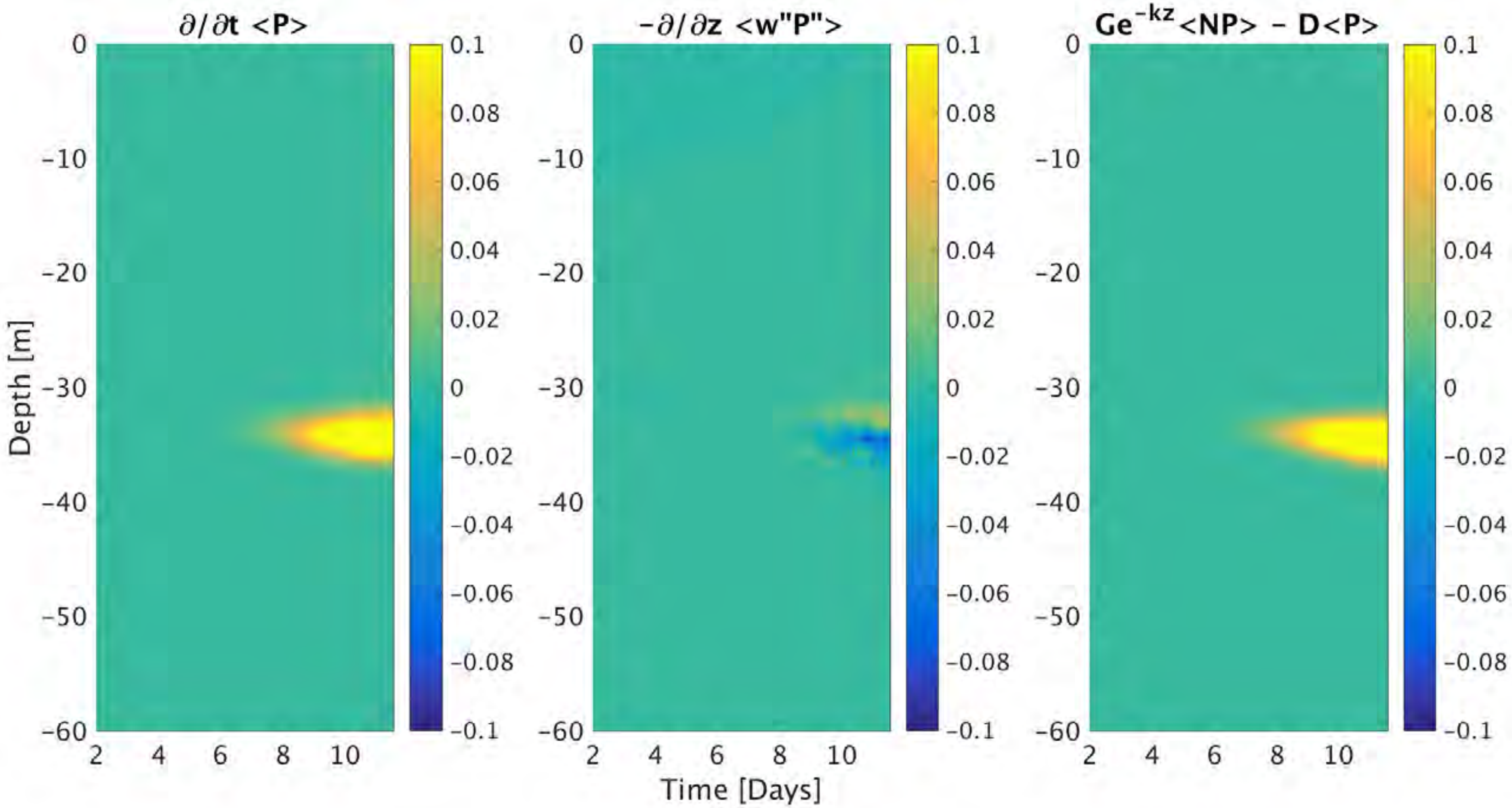
$$\frac{\partial < P >}{\partial t} = \overbrace{-\frac{\partial}{\partial z} < wP >}^{Mixing} + \overbrace{Ge^{-Kz} < PN > -D < P >}^{Growth}$$

$$< F > = \frac{1}{XY}\int_0^y \int_0^x F\, dxdy$$

❖ Which term is dominant?

Dynamics breakdown – Plankton

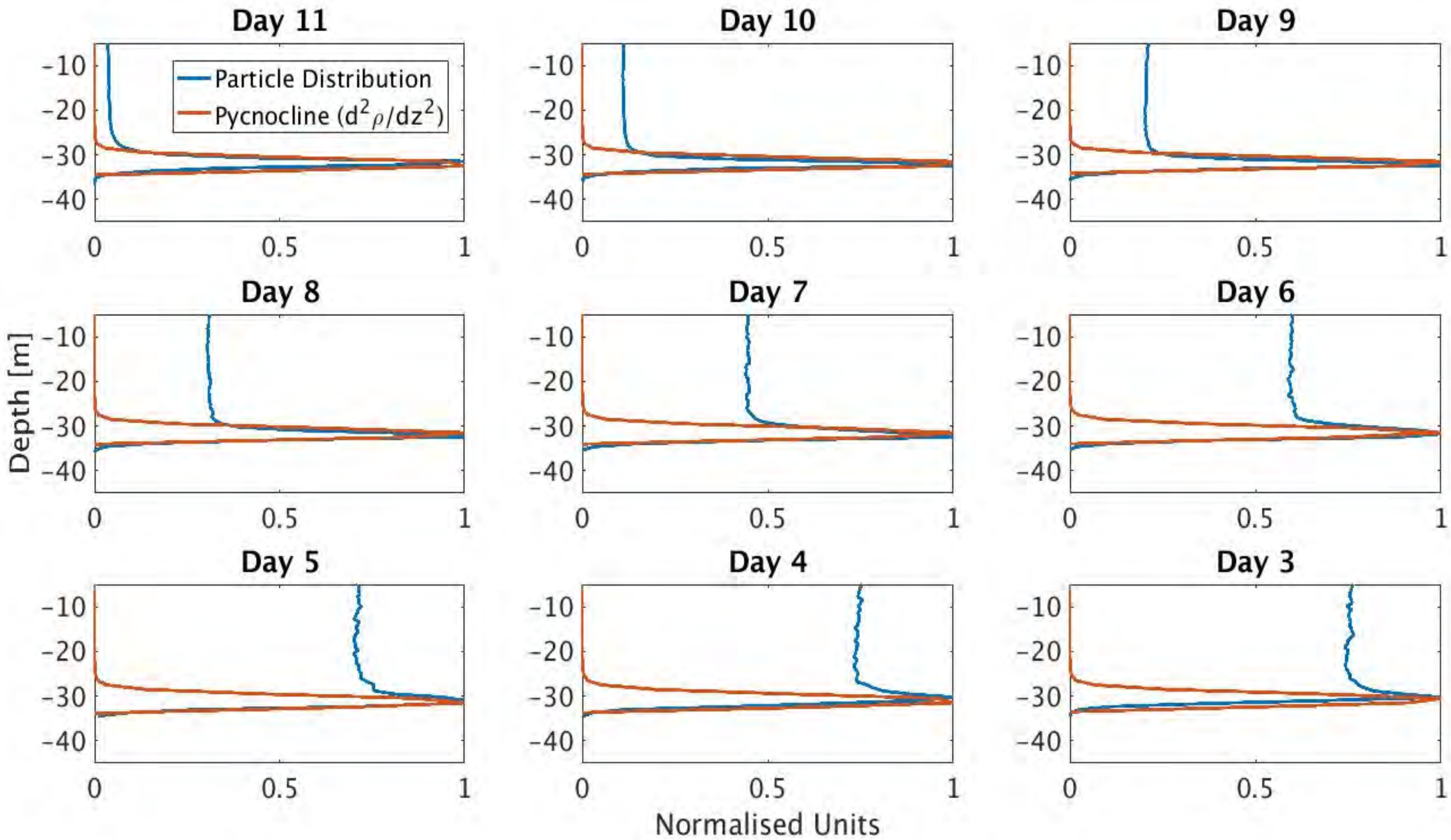
$$\frac{\partial <P>}{\partial t} = \overbrace{-\frac{\partial}{\partial z} <wP>}^{Mixing} + \overbrace{Ge^{-Kz} <PN> - D<P>}^{Phytoplankton\ Growth\ rate}$$



Quick Summary III

- Results show that in-situ growth is taking place
- Timescale of biological growth outweighs timescale of vertical mixing
- **Why do they grow here?**
- As we are using particles, we can trace the journey of the thin layer plankton back through time.

Thin layer particles at the pycnocline



Conclusions

- We demonstrated thin layer formation with simple passive particles.

- Thin layers always occur in the pycnocline

- Model results reveal patterns observed in the field

- Once particles reach the pycnocline, they are trapped for a sustained period, giving them time to feed in the nutrient rich water.

- The thin layer is strongest when a compromising level of wind is realised.

  - If wind is too weak, less particles are injected into the pycnocline
  - If wind is too strong, too many nutrients are brought to the surface to feed the competing surf ace plankton