Role of Turbulent Mixing in Plankton Dynamics Simulated by Large Eddy Simulation (LES)

YIGN NOH

Yonsei University, S. Korea

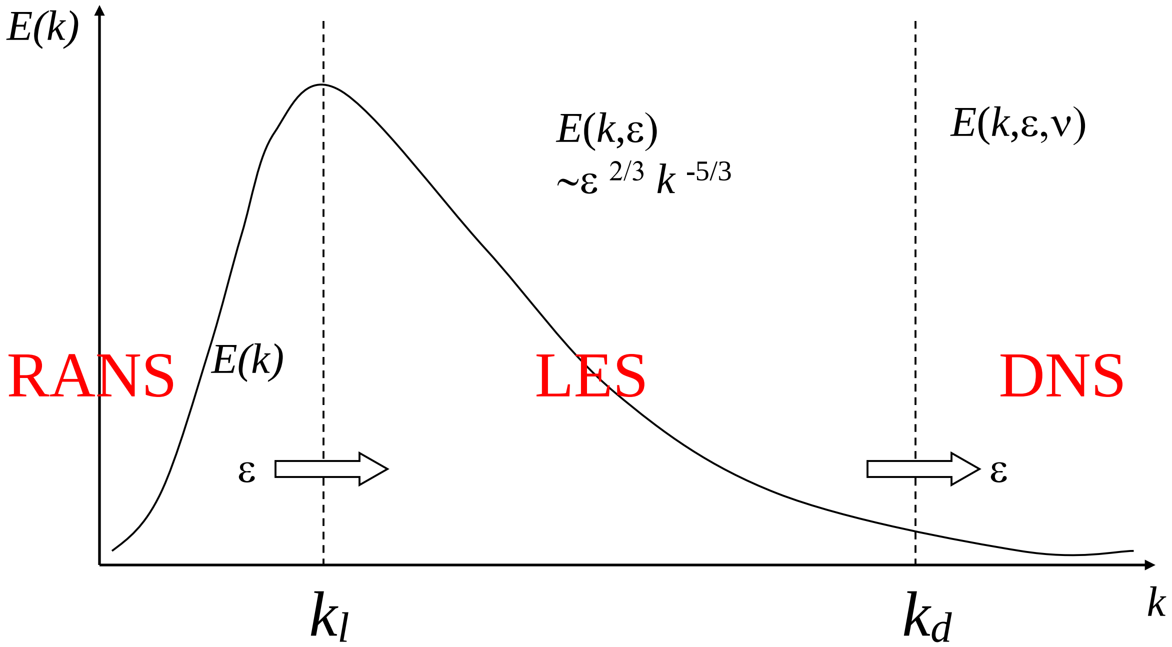
Application of LES of the ocean mixed layer to

1. *the parameterization of the ocean mixed layer*

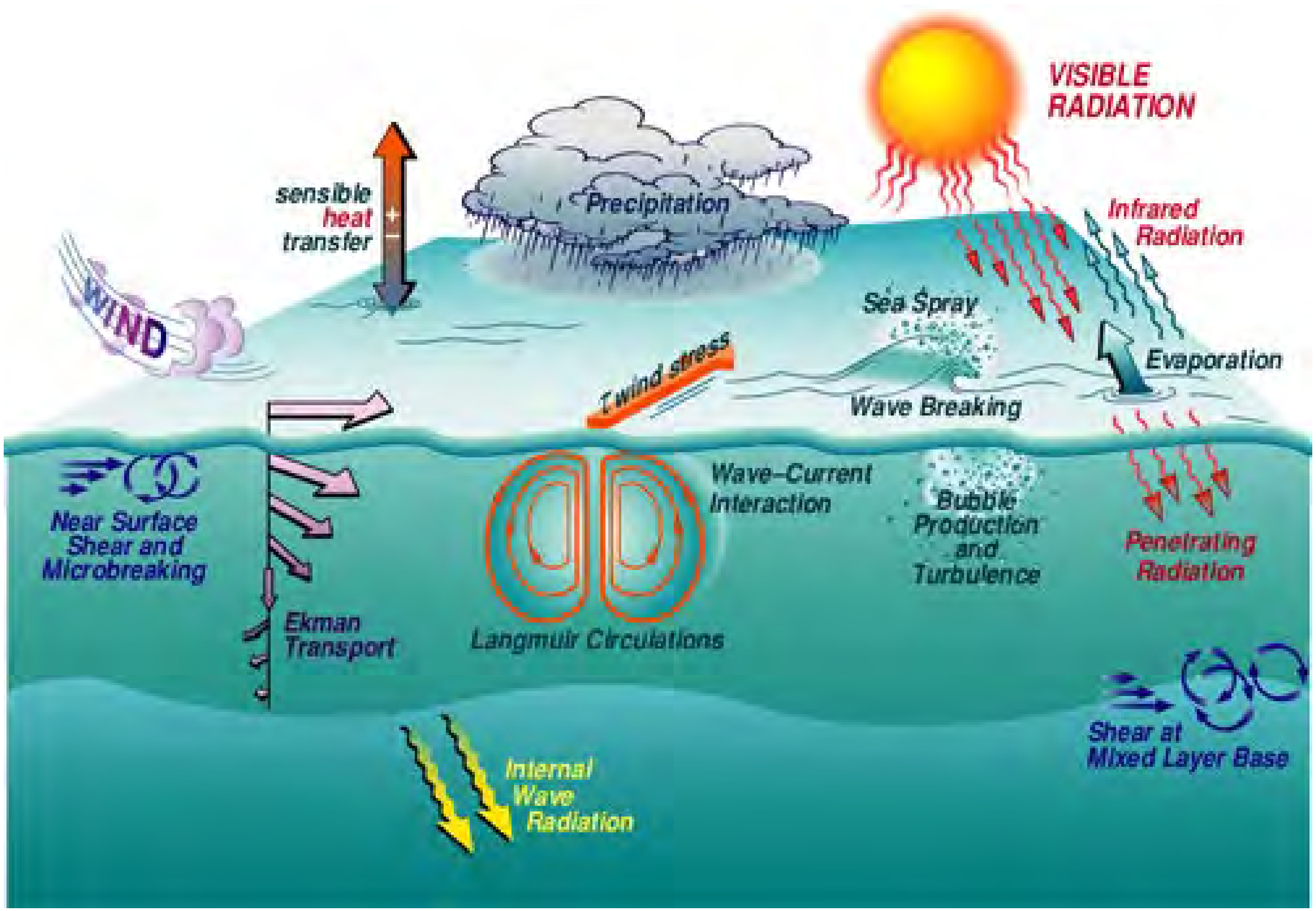
2. *the motion of suspended particles in the ocean mixed layer*

3. *Lagrangian plankton model*

What is LES?



LES is a new technique of turbulence simulation which reproduces the realistic 3-D structure of fluctuating turbulent flows, while parameterizing small-scale isotropic eddies in the inertial subrange.



The application of LES to the ocean mixed layer has been delayed because of the difficulty in handling the free surface (e.g., wave breaking, Langmuir circulation).

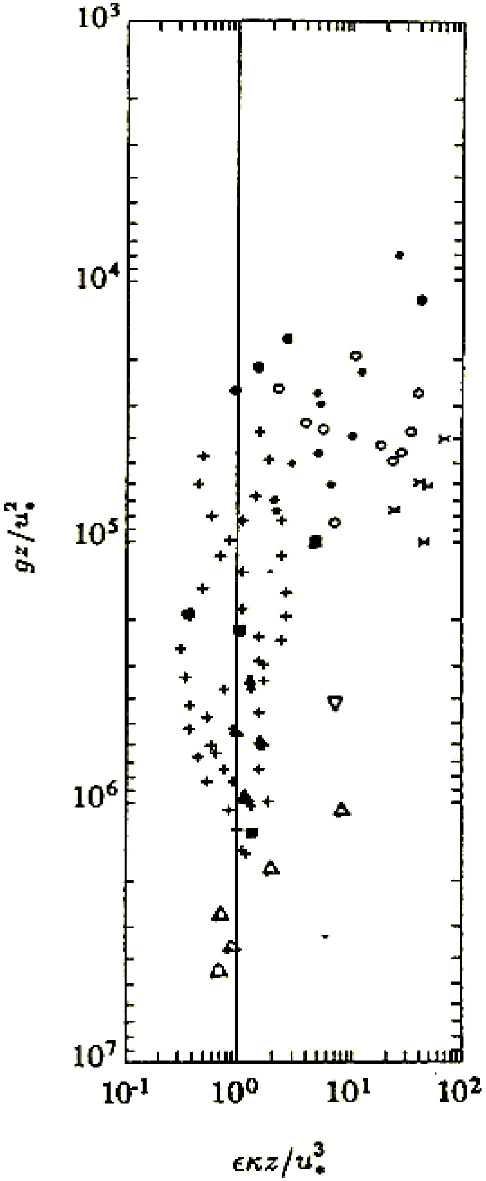
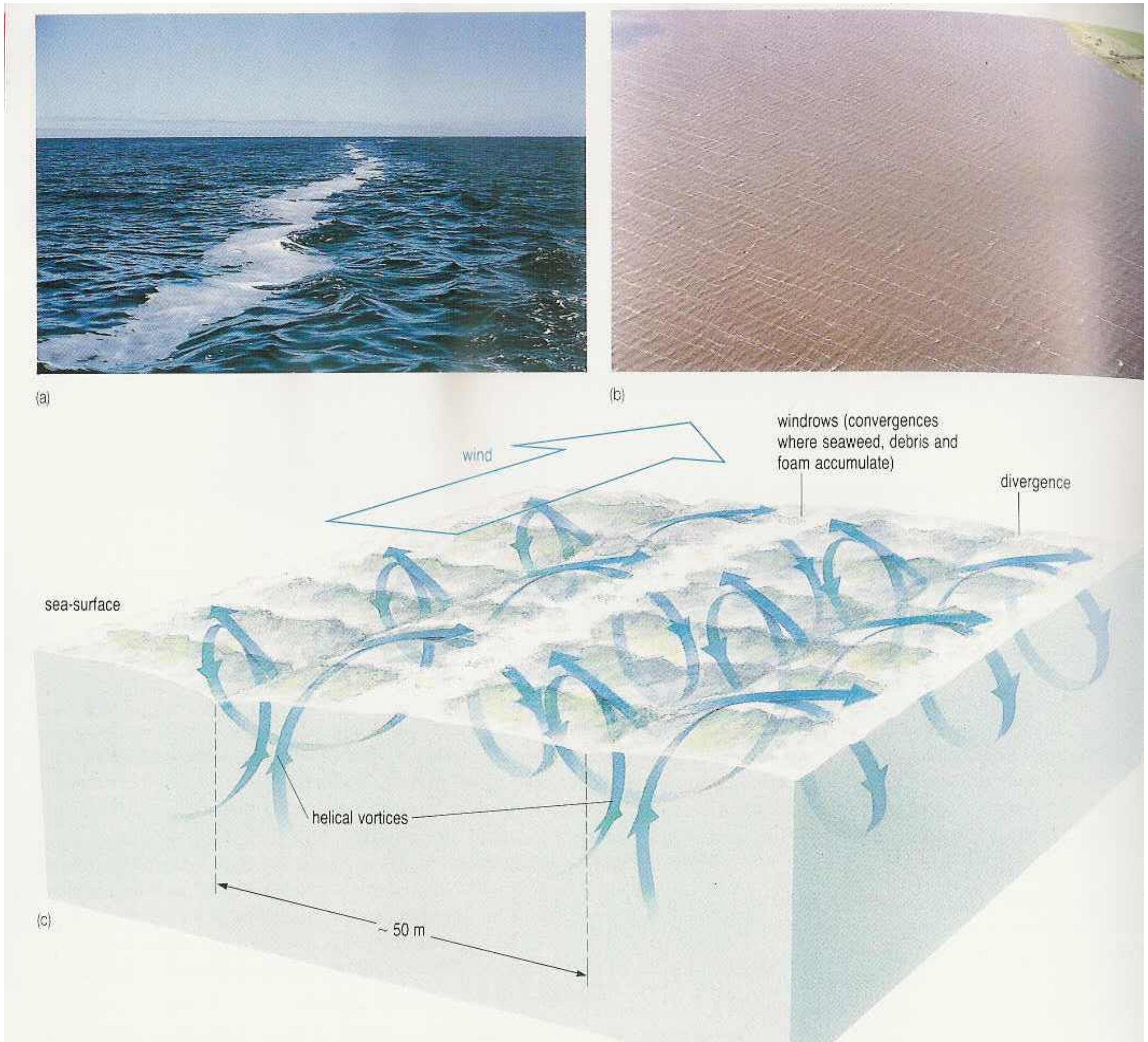


Figure 8 Dissipation in “wall-layer” coordinates $\epsilon\kappa z/u_{*w}^3$ vs zg/u_{*w}^2 measured and collated by Agrawal et al (1992). Included are both lake and ocean data; the vertical line represents the dissipation level in a conventional boundary layer over a rigid surface. [Reprinted with permission from *Nature*. Copyright (1992) Macmillan Magazines Limited.]

Melville, ARFM (1996)

Enhancement of near-surface turbulence by wave breaking



Langmuir Circulation

LES Model of the Ocean Mixed Layer

(Noh et al., *JPO* 2004)

- The surface boundary of the oceanic boundary layer is the free surface → Langmuir circulation (LC), wave breaking (WB)

- The LES code for PBL is modified by including the effects of LC and WB.

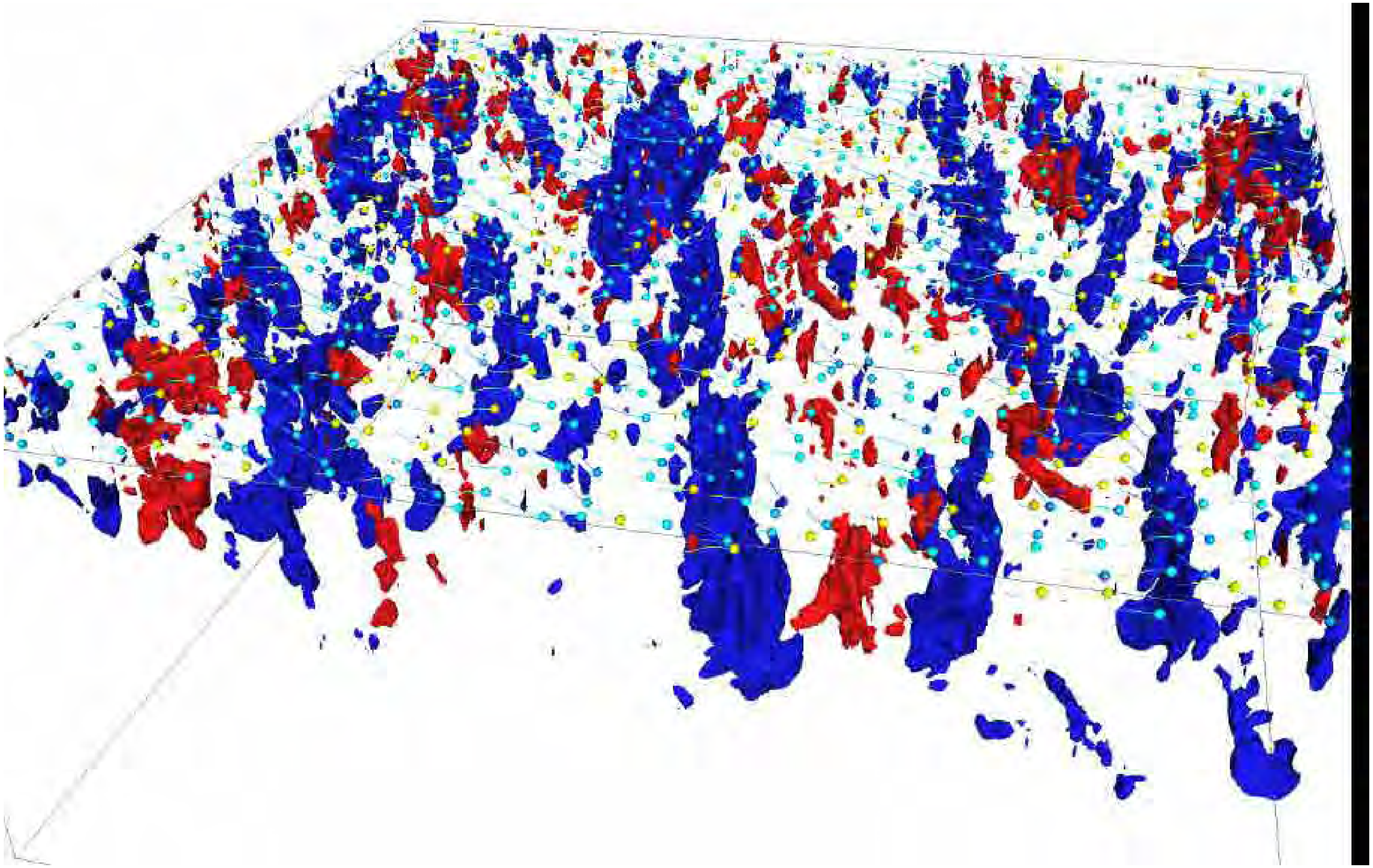
$$\frac{\partial u_i}{\partial t} + (u_j + u_{sj})\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial p}{\partial x_i} + \nu\frac{\partial^2 u_i}{\partial x_j \partial x_j} - \varepsilon_{ijk} f_j \left(u_k + u_{sk}\right)$$

$+\varepsilon_{ijk} u_{sj} \omega_k$ → *LC by vortex force,* (Craik & Liebovich 1967)

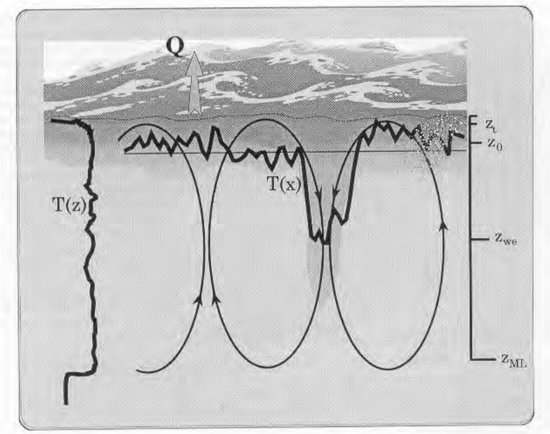
u_{sj} : Stokes drift velocity

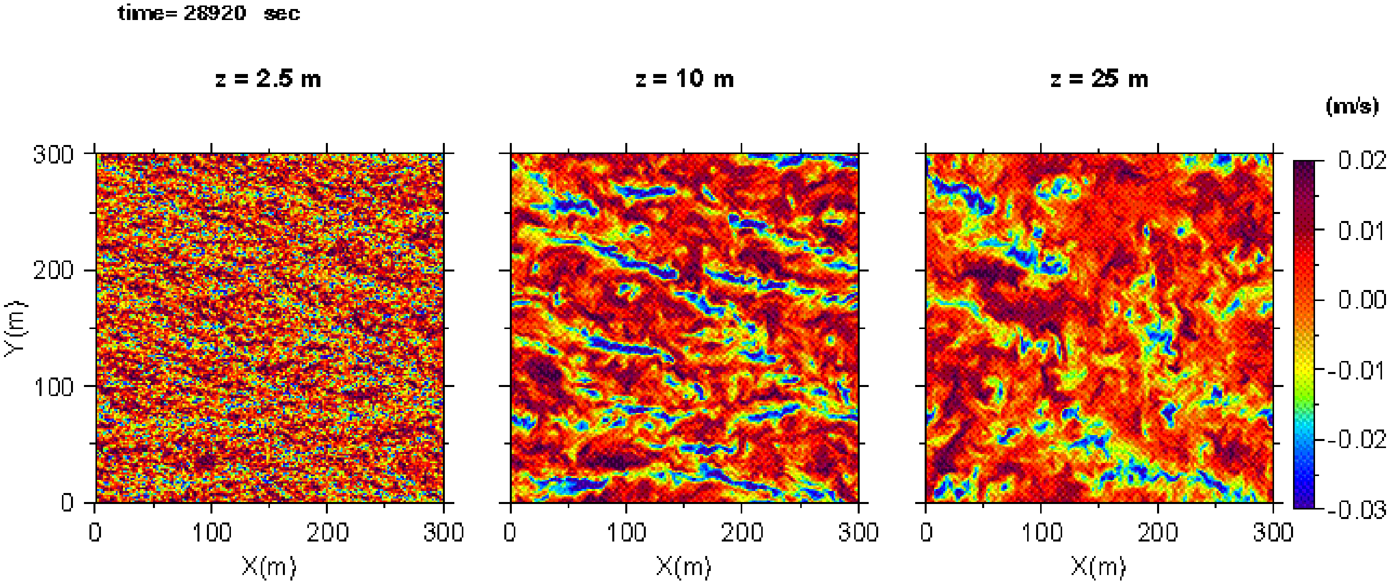
$+F_i(\mathbf{x}, t)$ → *WB by stochastic forcing,*

$$F_i = \frac{\alpha u_*}{\tau_0} G(x, y, t)\delta(z)\delta\left(1 - \delta_{i3}\right)$$



3D View of the Ocean Mixed Layer
with LC and Particle Settling





SBH_homo; w (H= 1.0, α = 0.8, u_* = 0.01, Q_0 =0)

Distribution of Vertical Velocity at Horizontal Crosssection

Application of LES to geophysical turbulence,

1. provide the 'pseudo' observational data,
- obtained under the ideal condition
- provide the whole spectrum of information

⇨ **examine the parameterization of mixing**

2. investigate the 3-D structure of turbulence

ex) Langmuir circulation, dust devils, convection

3. investigate the Lagrangian motion of suspended particles in turbulent flows

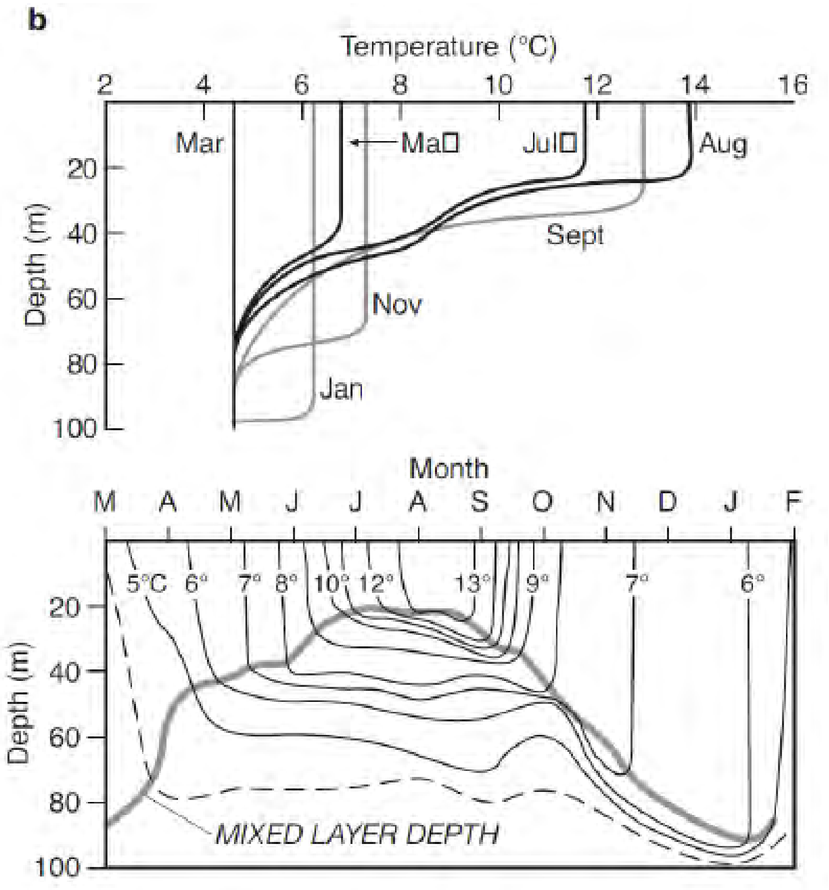
ex) cloud microphysics, aerosol, sediment transport, plankton dynamics,

4. investigate the mixing process
- predict realistic fluctuating concentration field

ex) oil spill, air pollution

The Parameterization of the Ocean Mixed Layer

Examination of Parameterization for Convective Deepening Using LES (Noh et al., *JPO* 2010)



Seasonal Variation of the Ocean Mixed Layer

- NK model [Niiler and Kraus, 1977]

$$-\overline{bw}_h = -nQ_0 + 2m_0 u_*^3/h + m_s w_e (\Delta U)^2/h \qquad (\, n = 0.21,\ m_0 = 0.39,\ m_s = 0.48 \,)$$

$$* \qquad -\overline{bw}_h = w_e \Delta B, \qquad w_e = \partial h/\partial t$$

- PWP model [Price et al., 1986]

$$\mathrm{Ri}_b = \frac{[B_0 - B(h)]h}{|\mathbf{U}_0 - \mathbf{U}(h)|^2}, \quad \mathrm{Ri}_g = \frac{\partial B/\partial z}{(\partial \mathbf{U}/\partial z)^2} = \text{const. at the MLD}$$

- KPP model [Large et al., 1994]

$$\mathrm{Ri}_b^* = \frac{[B_0 - B(h)]h}{|\mathbf{U}_0 - \mathbf{U}(h)|^2 + V_t^2} = \text{const. at the MLD}$$

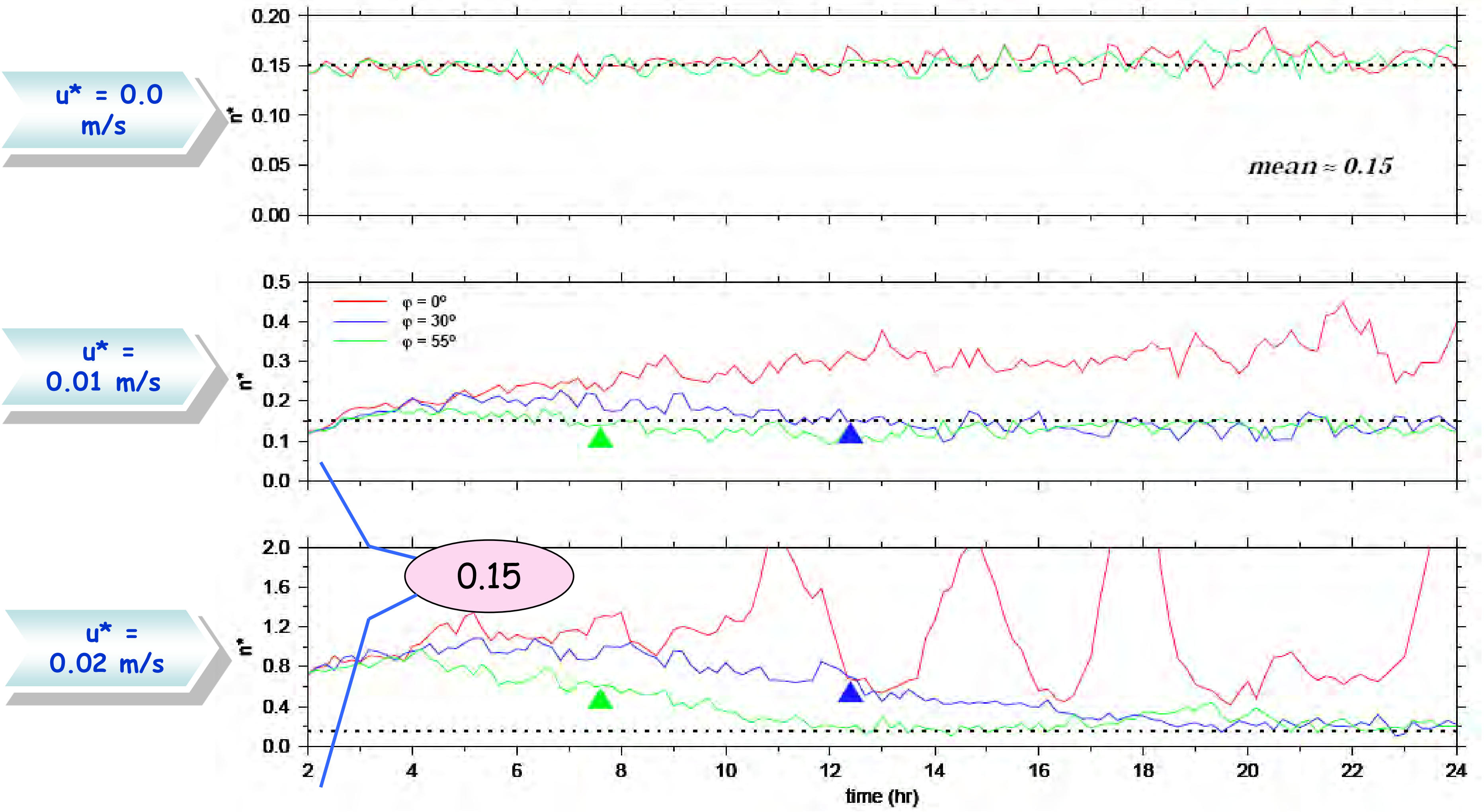
* Q_0 = surface buoyancy flux, ρu_*^2 = wind stress, V_t = convective velocity scale

$$-\overline{bw_h} = -nQ_0 + 2m_0u_*^3/h + m_s w_e(\Delta U)^2/h$$

(NK model)

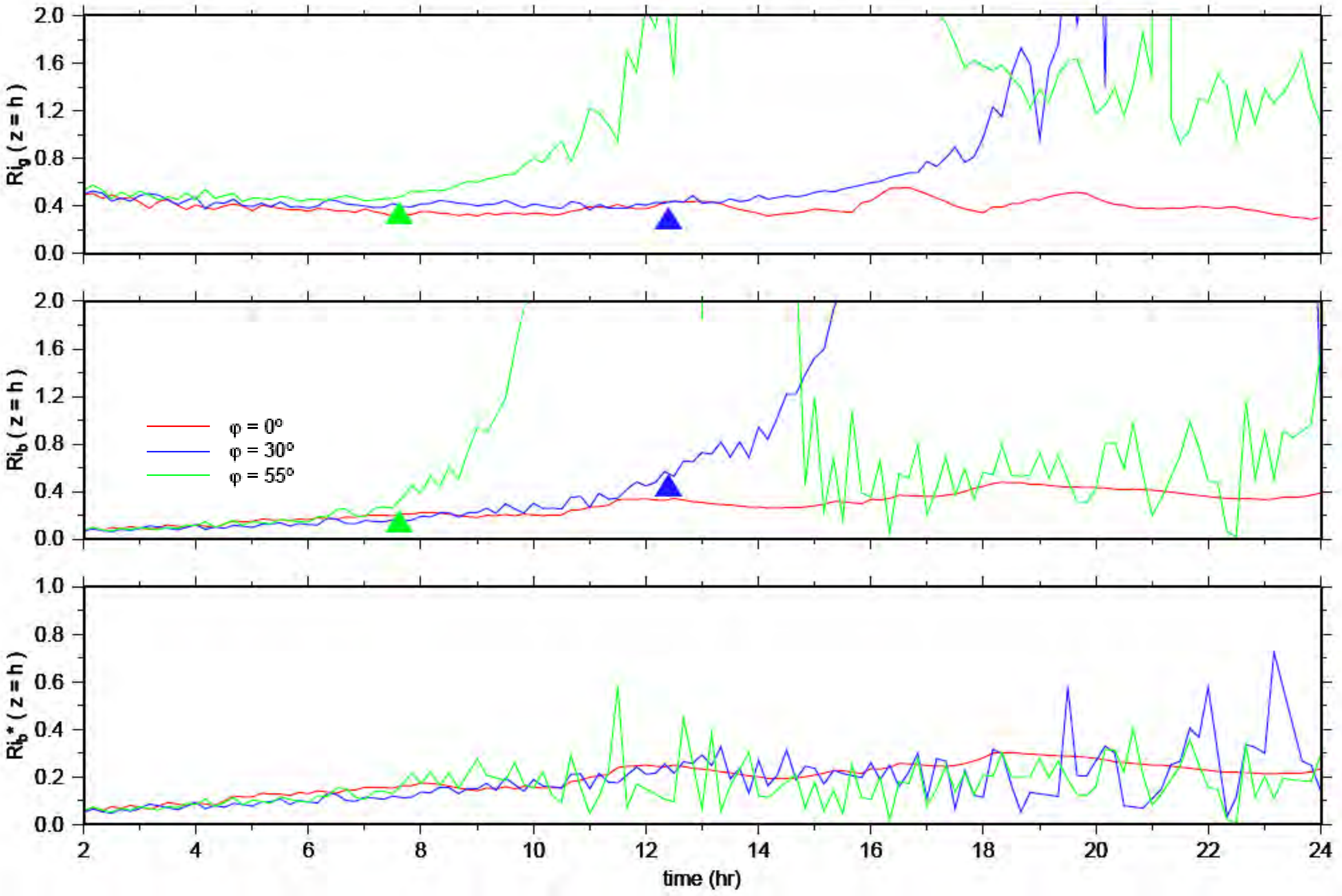
$$-\overline{bw_h} = -n^* w_*^3/h, \quad w_*^3 = Q_0 h$$

▲ : $t \sim \pi/f$



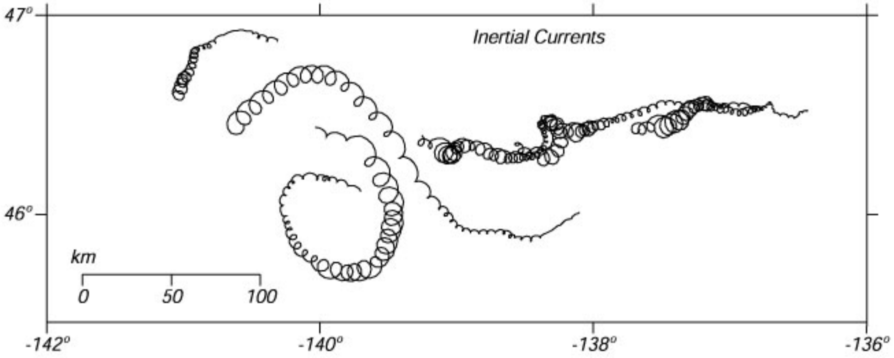
The contribution from wind forcing disappears after the inertial time scale.

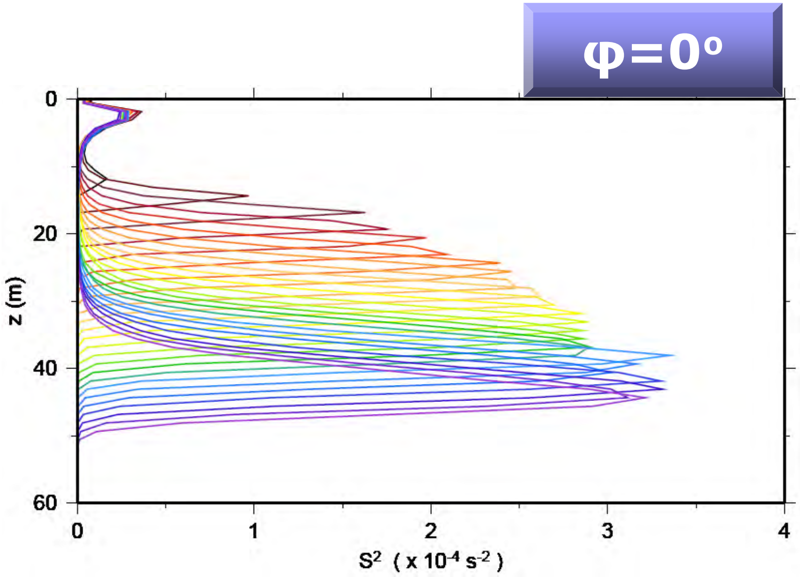
- Ri_g, Ri_b, and Ri_b* (z = h) for **u* = 0.02 m/s**

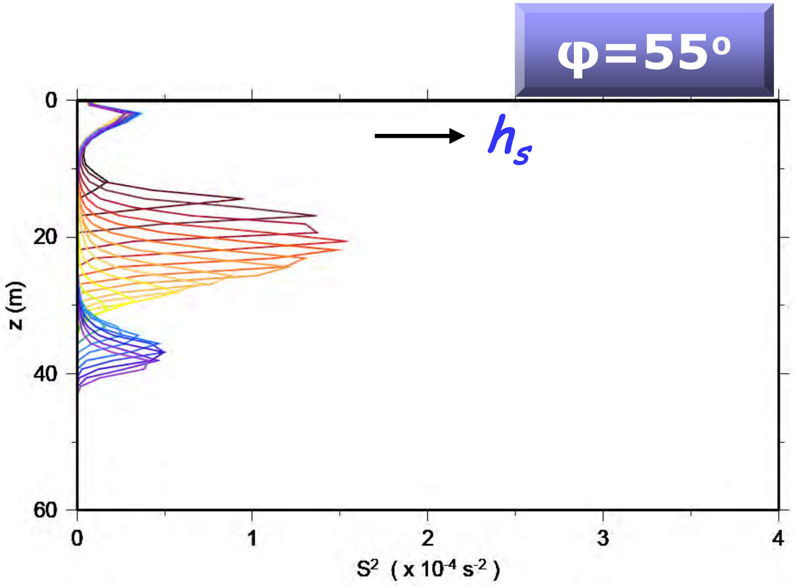


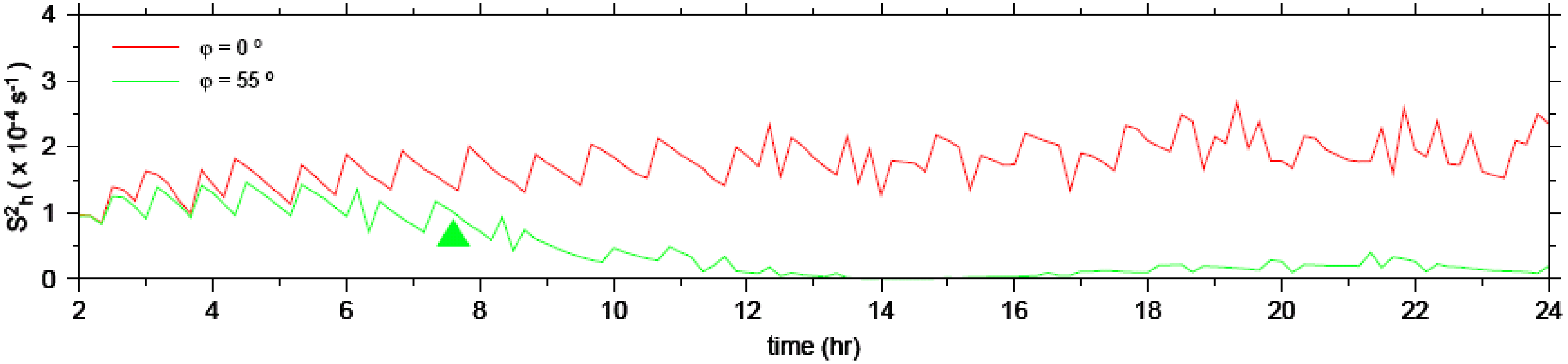
Ri_g and Ri_b do not remain constant at MLD.

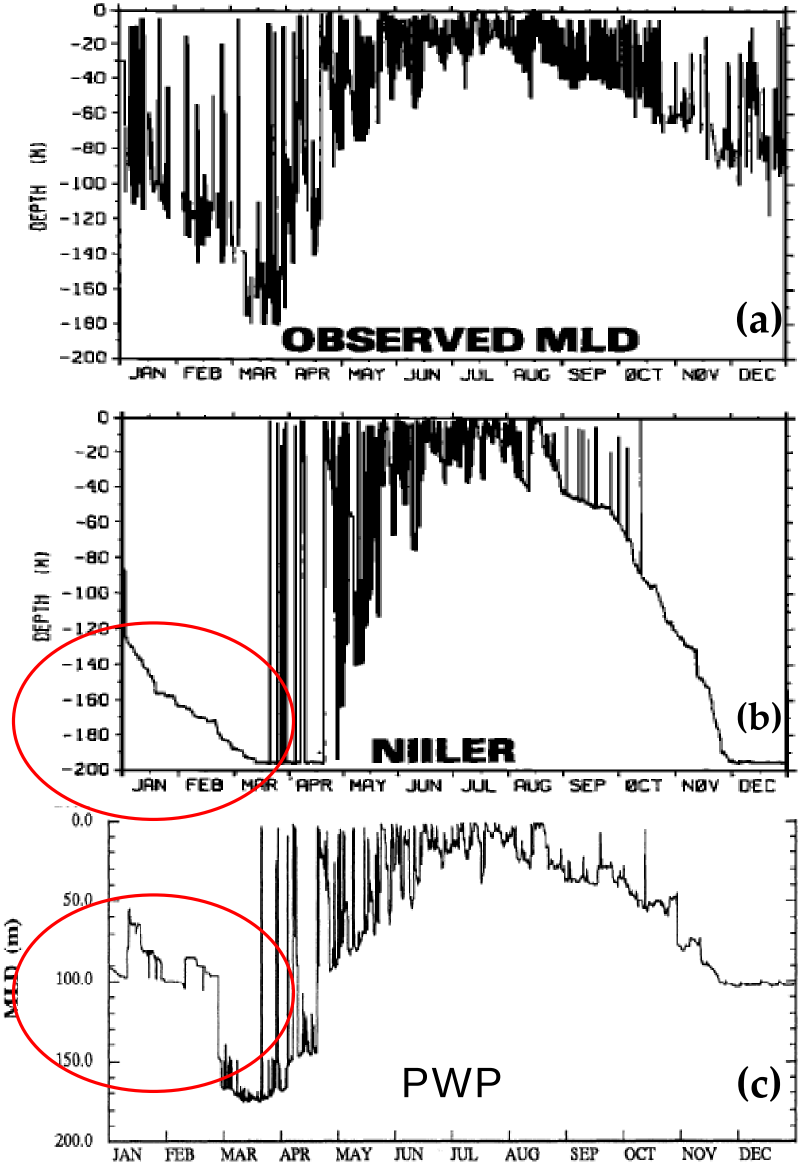
- $$S^2 = \left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2 ,$$
- h_s = the depth of maximum shear









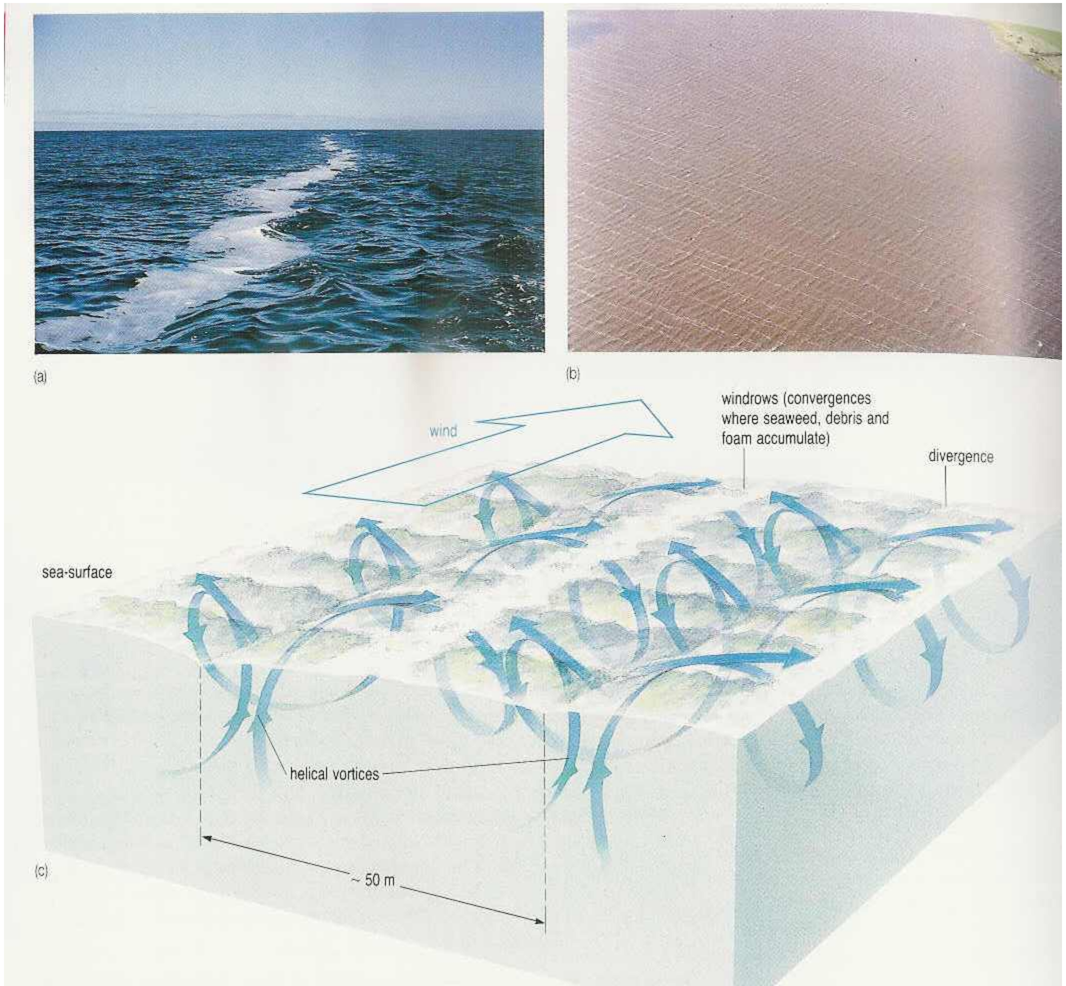


overestimation

underestimation

Seasonal variation of MLD simulated by NK and PWP model
(Station PAPA 1961; 50 N)

Role of Langmuir Circulation in the Vertical Mixing of the Upper Ocean (Noh et al, *JPO* 2011, 2016)



- It has been well known now that LC enhances vertical mixing greatly within the mixed layer

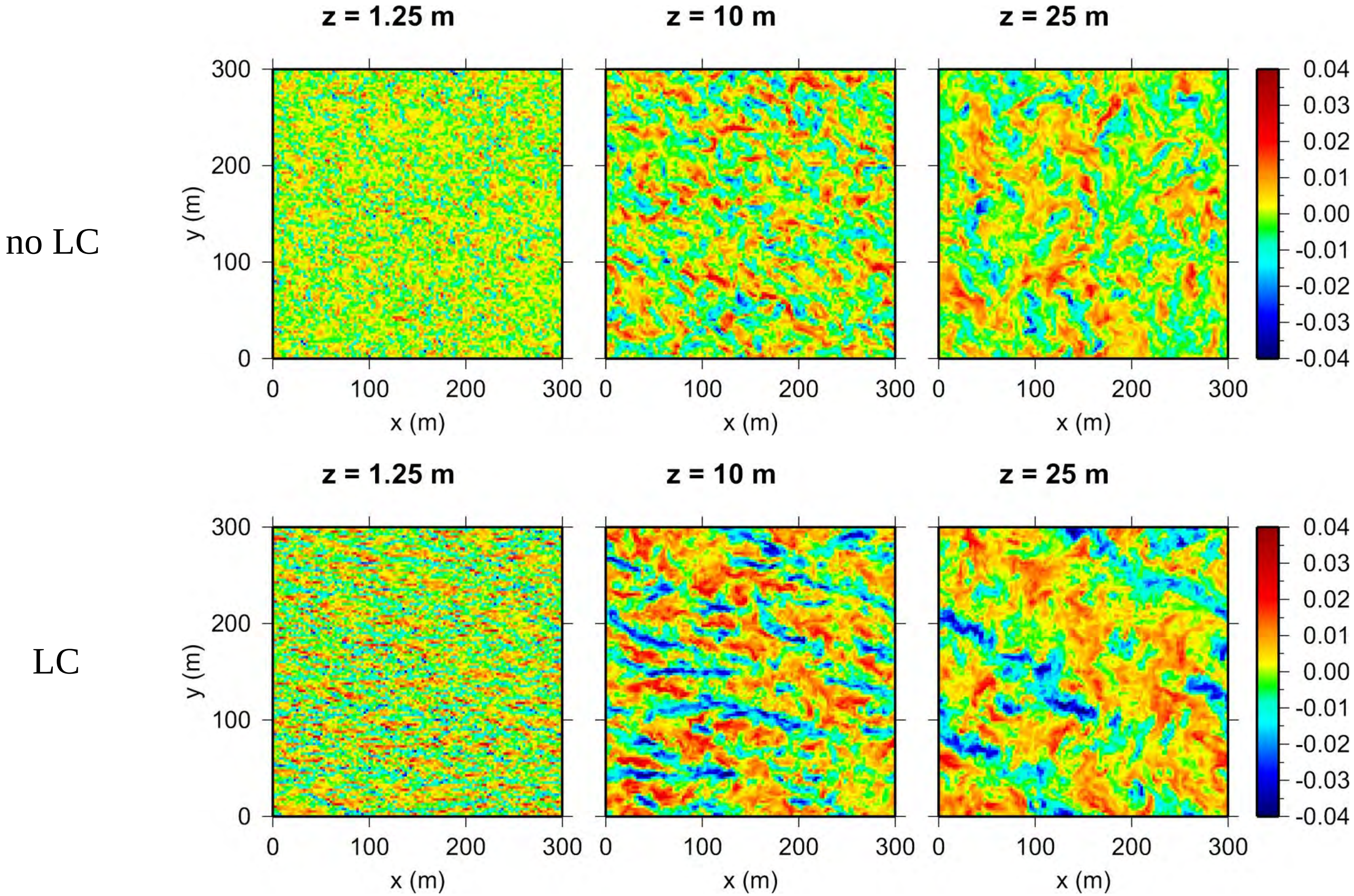
→ uniform temperature profiles within the mixed layer

- **The role of LC in the mixed layer deepening is still under debate.**

* Li et al. (1995), Sullivan et al. (2007), Grant and Belcher (2009), Kukulka et al. (2009)
 - enhanced mixed layer deepening

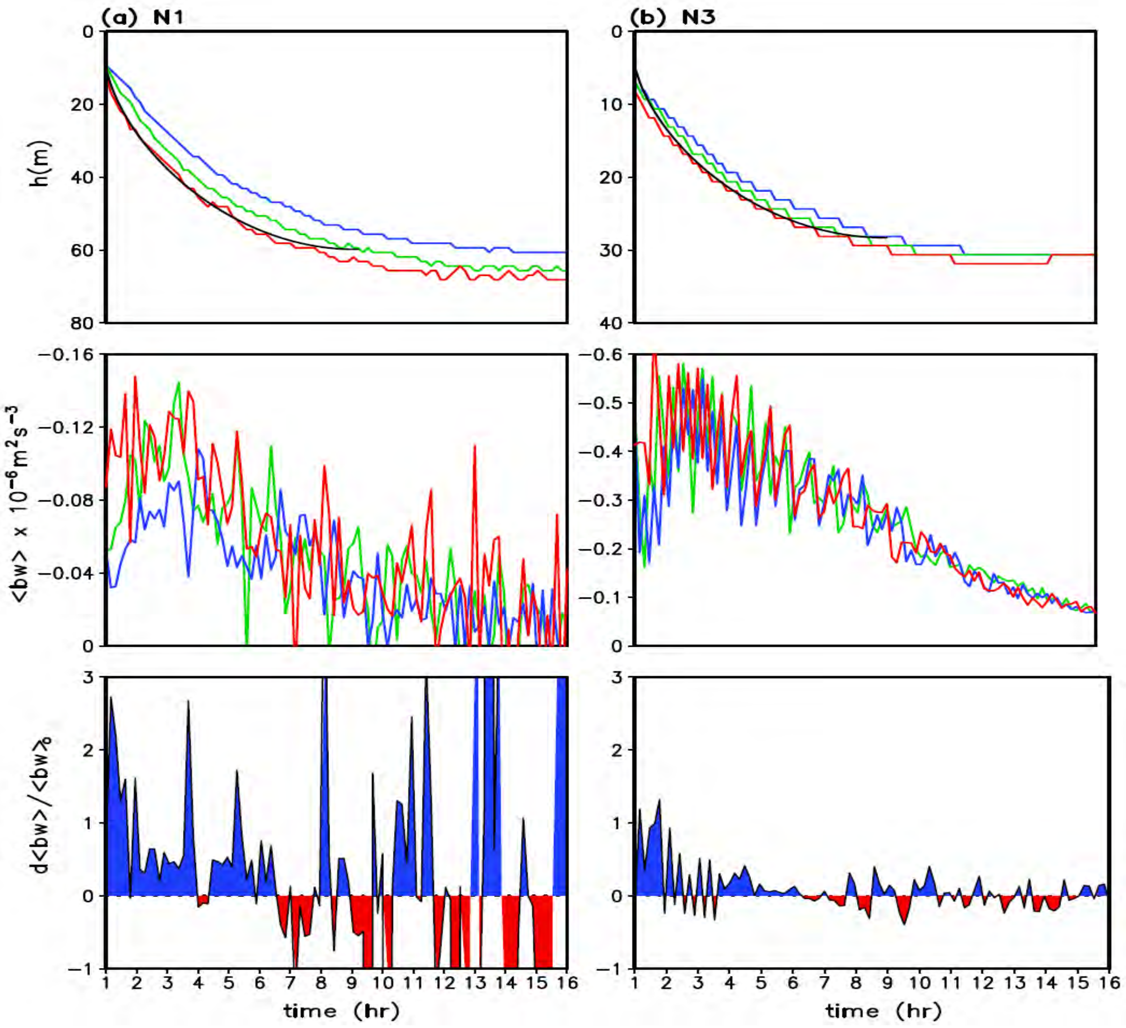
* Weller & Price (1988), Thorpe et al. (2003)
 - no evidence of the contribution by LC

* Skyllingstad et al. (2000)
 - The effects of LC are mostly confined to the initial stage of mixed layer growth.



Horizontal cross-section of vertical velocity(w)

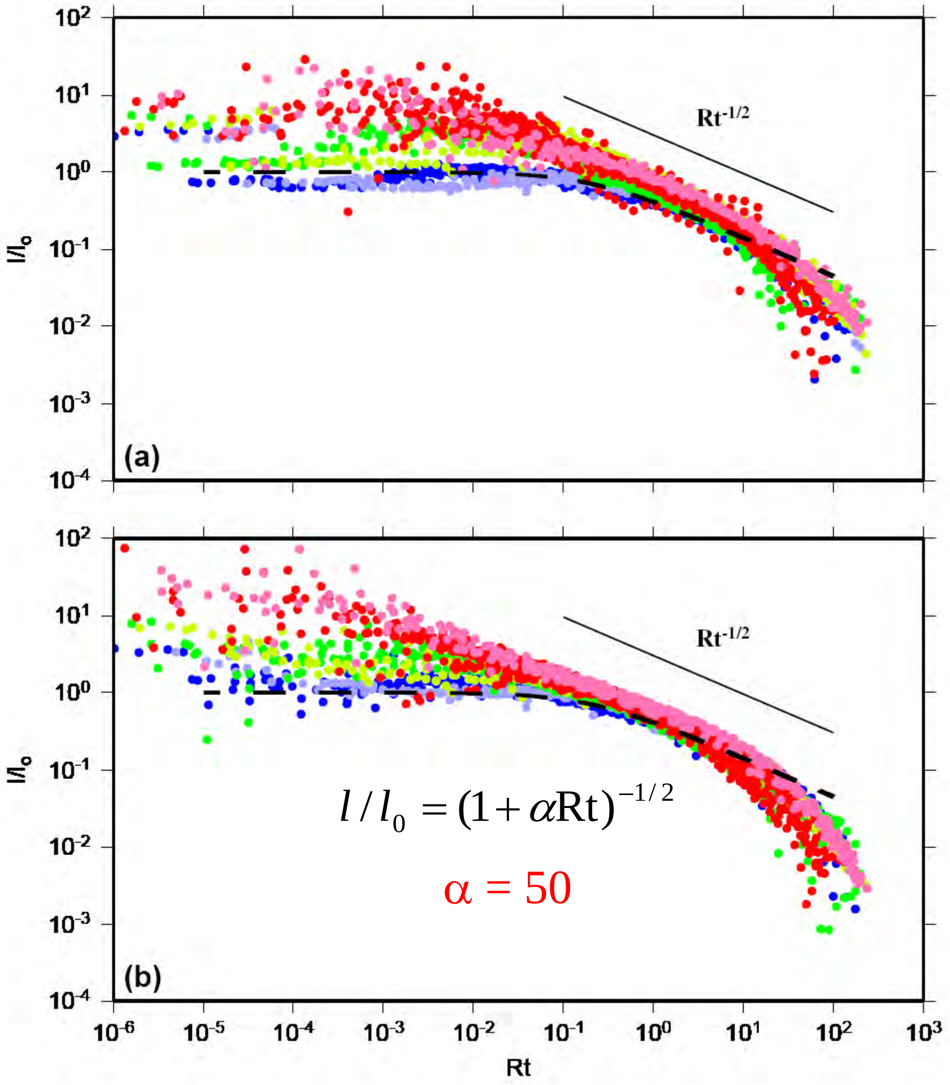
Mixed Layer Deepening by Wind Mixing



— strong LC
— no LC

The contribution of LC to the mixed layer deepening is important, only if stratification is weak and MLD is shallow!

Fig. 1 Time series of MLD (*h*) (upper), the buoyancy flux at the MLD (middle), and the difference of buoyancy flux at MLD between the cases with and without LC (lower). (blue: L0 (La = ∞), green: L1 (La = 0.64), red: L2 (La = 0.32), black: theoretical prediction by Pollard et al. (1973)): (a) N1 (= 10-5 s-2), (b) N3 (= 2 × 10-4 s-2).



$$l/l_0 = (1+\alpha \mathrm{Rt})^{-1/2}$$

$\alpha = 50$

Variation of length scale with stratification
(L0: blue, L1: green, L2: red)

- old model

$$l_0 = \frac{\kappa(z+z_0)}{1+\kappa(z+z_0)/h}$$

- new model with LC effects

$$l_0 = \frac{\kappa\Gamma(z+z_0)}{1+\kappa\Gamma(z+z_0)/h}$$

with $\Gamma = 1 + ALa^{-2}$

$$l/l_0 = (1+\alpha\,\mathrm{Rt})^{-1/2}$$
$$\mathrm{Rt} = (Nl_0/q)^2$$

i) $\mathrm{Rt} \to 0$

$\Rightarrow l \sim l_0 \;\Rightarrow l_{\mathrm{new}} = \Gamma l_{\mathrm{old}}$

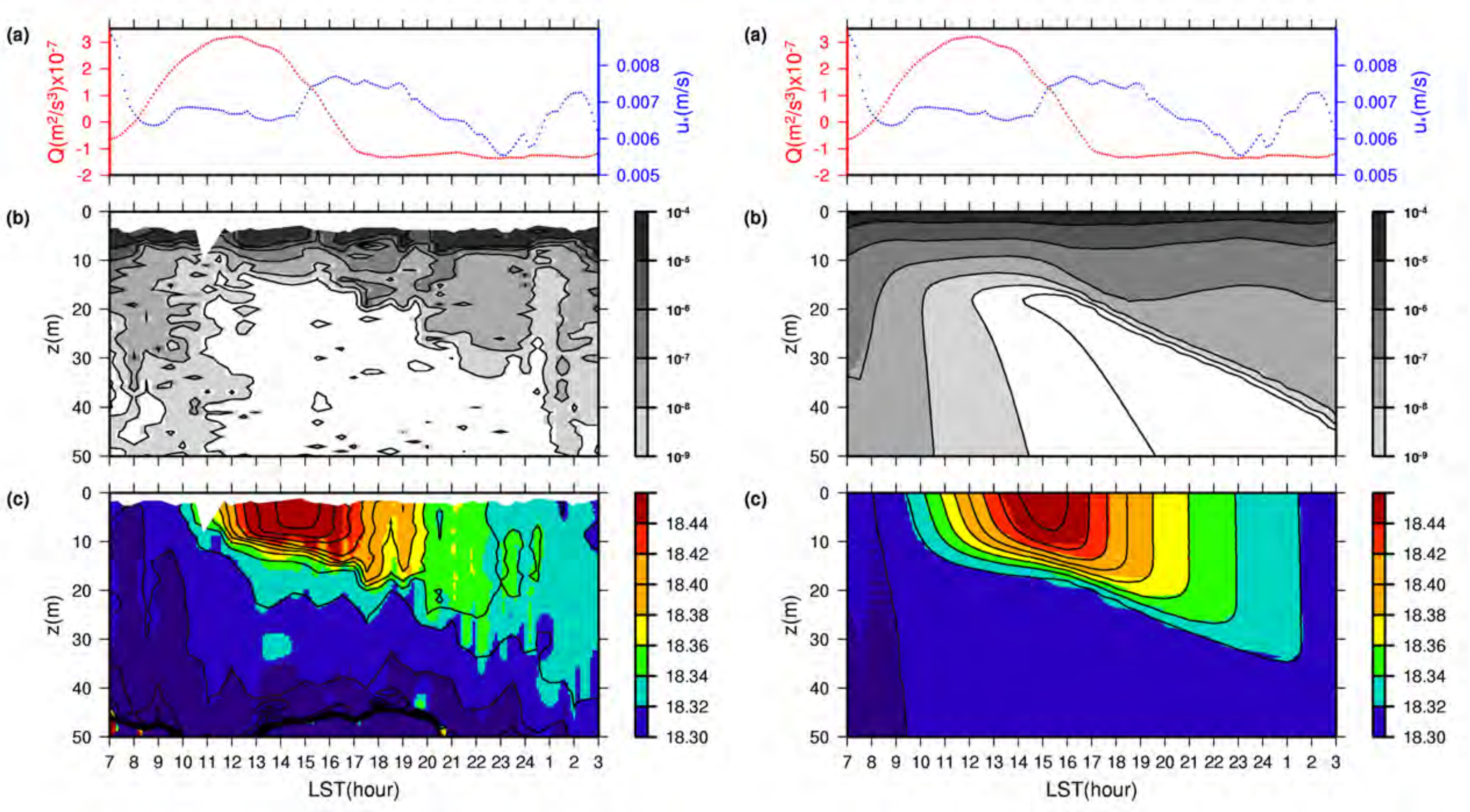
ii) $\mathrm{Rt} >> 1$

$\Rightarrow l \sim q/N \Rightarrow l_{\mathrm{new}} = l_{\mathrm{old}}$

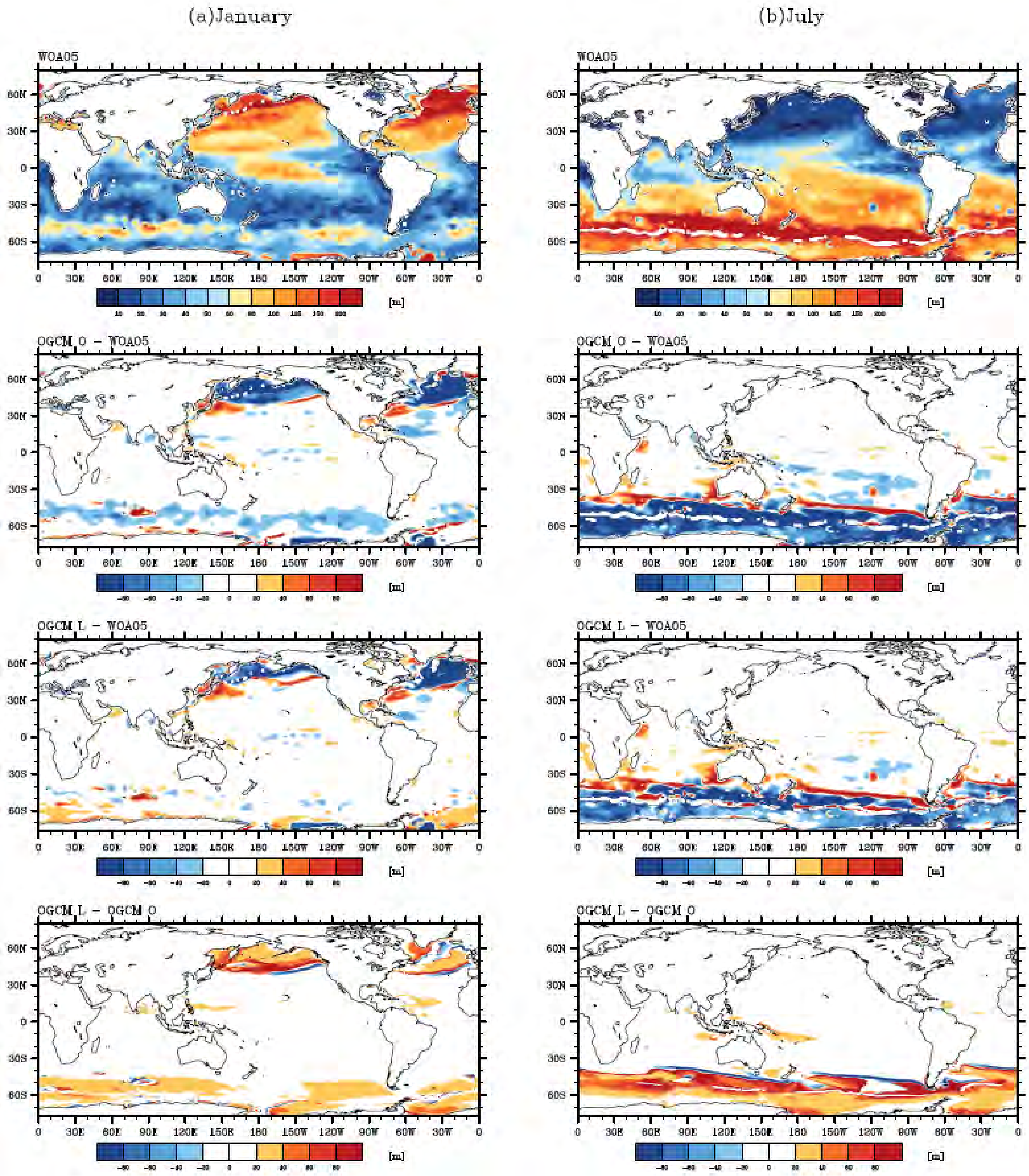
Noh Mixed Layer Model

(*JGR* 1999, *JPO* 2002, *GRL* 2004, *JGR* 2011)

- Based on the analysis of the upper ocean turbulence structure with wave breaking
- Turbulence closure model, but reproduces a well-mixed layer consistent with the bulk model



Evolution of the OML from the observation (PATCHEX) (left) and simulation (right): (a) surface forcing, (b) dissipation rate ($m^2\ s^{-3}$) and (c) temperature (^{0}C)



Distribution of MLD

*OGCM-O ← OMLM-O
OGCM-L ← OMLM-L

OGCM-L

- *In the high-latitude*
  → Deeper MLD
  → More realistic

- *In the low-latitude*
  → no change

Formation of a Diurnal Thermocline

(Noh et al. *JPO* 2009)

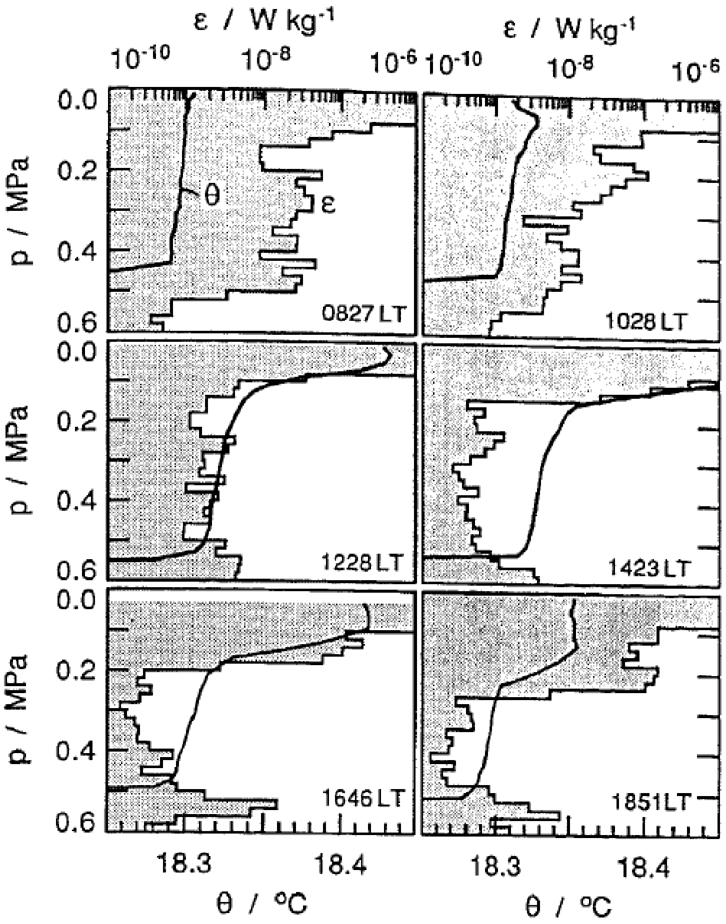
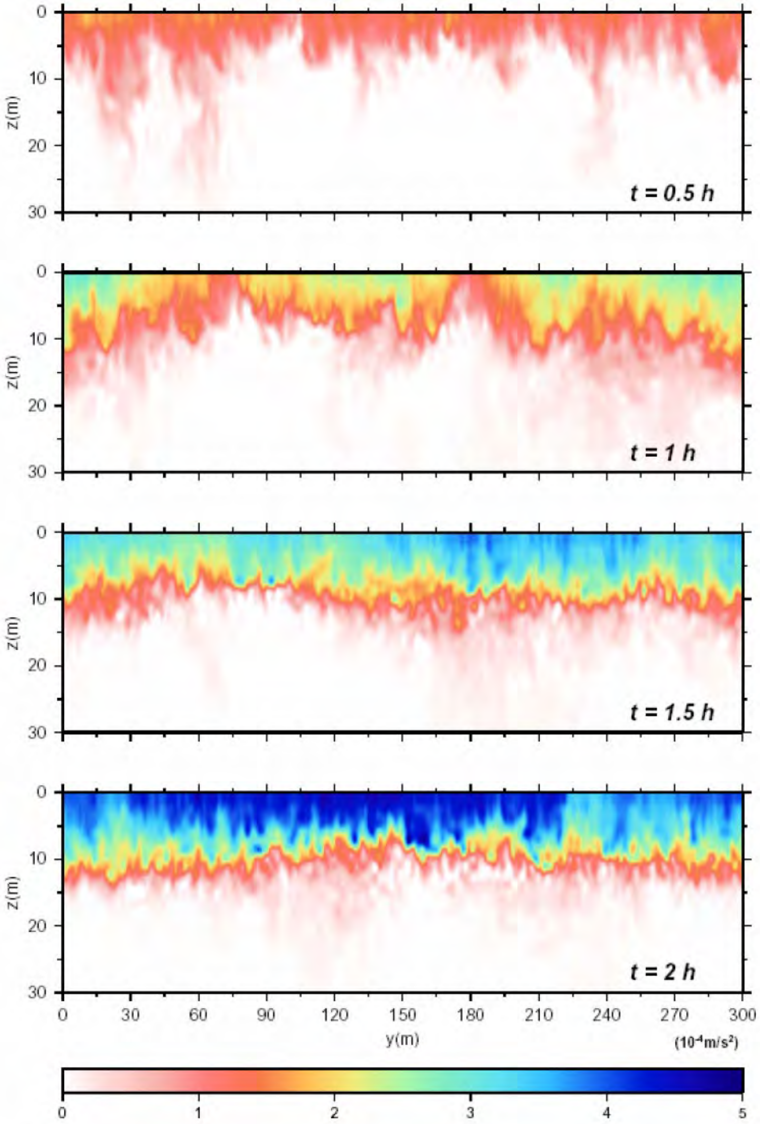
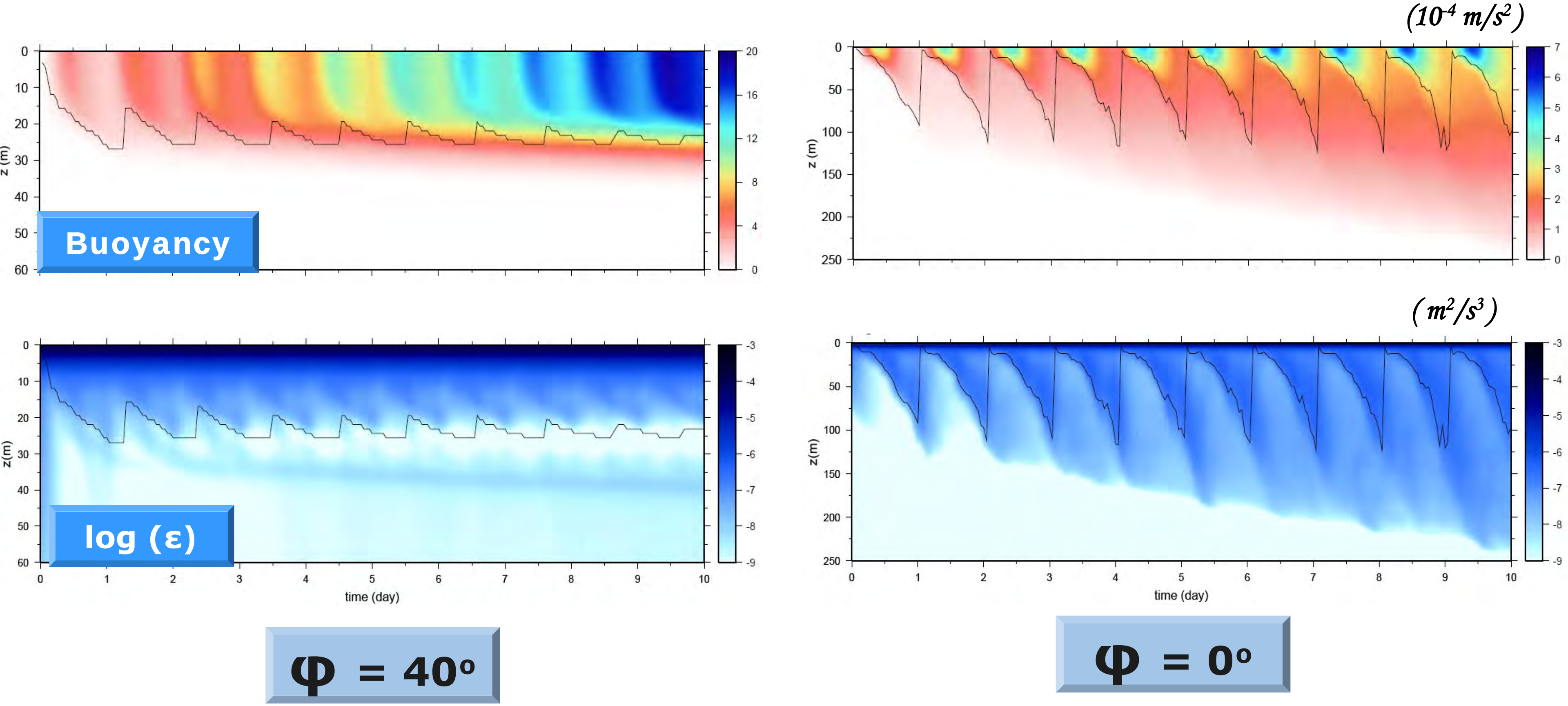


Fig. 12. Profiles of hour-averages of ε (shaded) and θ for October 17. The surface buoyancy flux J_b^0 was negative from 0900 LT until 1623 LT. Warming is mostly trapped in near-surface high-dissipation region, but also note growth of stratification deeper than 0.2 MPa.



Influence of the Coriolis Force in the Formation of a Seasonal And Diurnal Thermocline (Goh & Noh, *OD* 2013, Noh & Choi 2013)

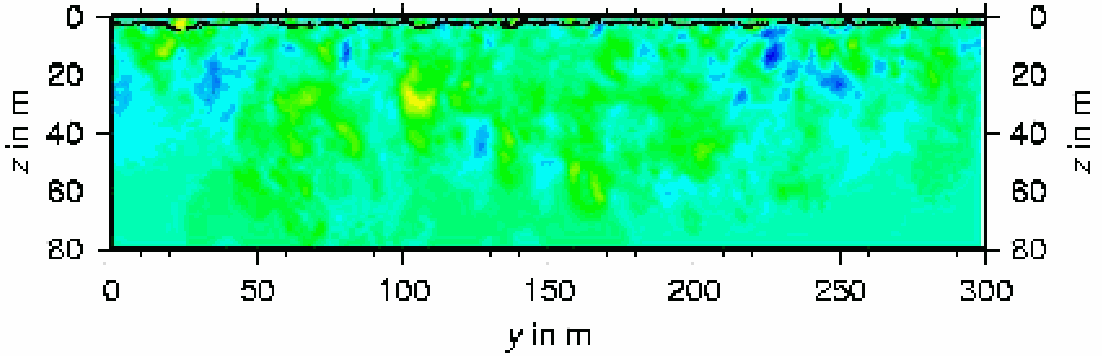


- *40 N - A thermocline is formed at a certain depth.*
  No downward heat transport across the thermocline.
- *Eq. - Heat continues to propagate downward to the deeper ocean.*
  A well-defined thermocline is not formed.

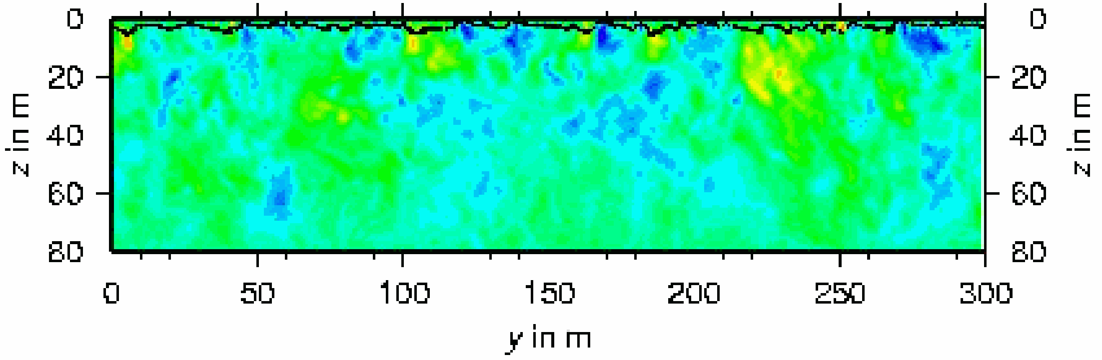
The Motion of Suspended Particles in the Ocean Mixed Layer

Particle Settling in the Ocean Mixed Layer

(Noh et al., *Phys. Fluids*, 2006)



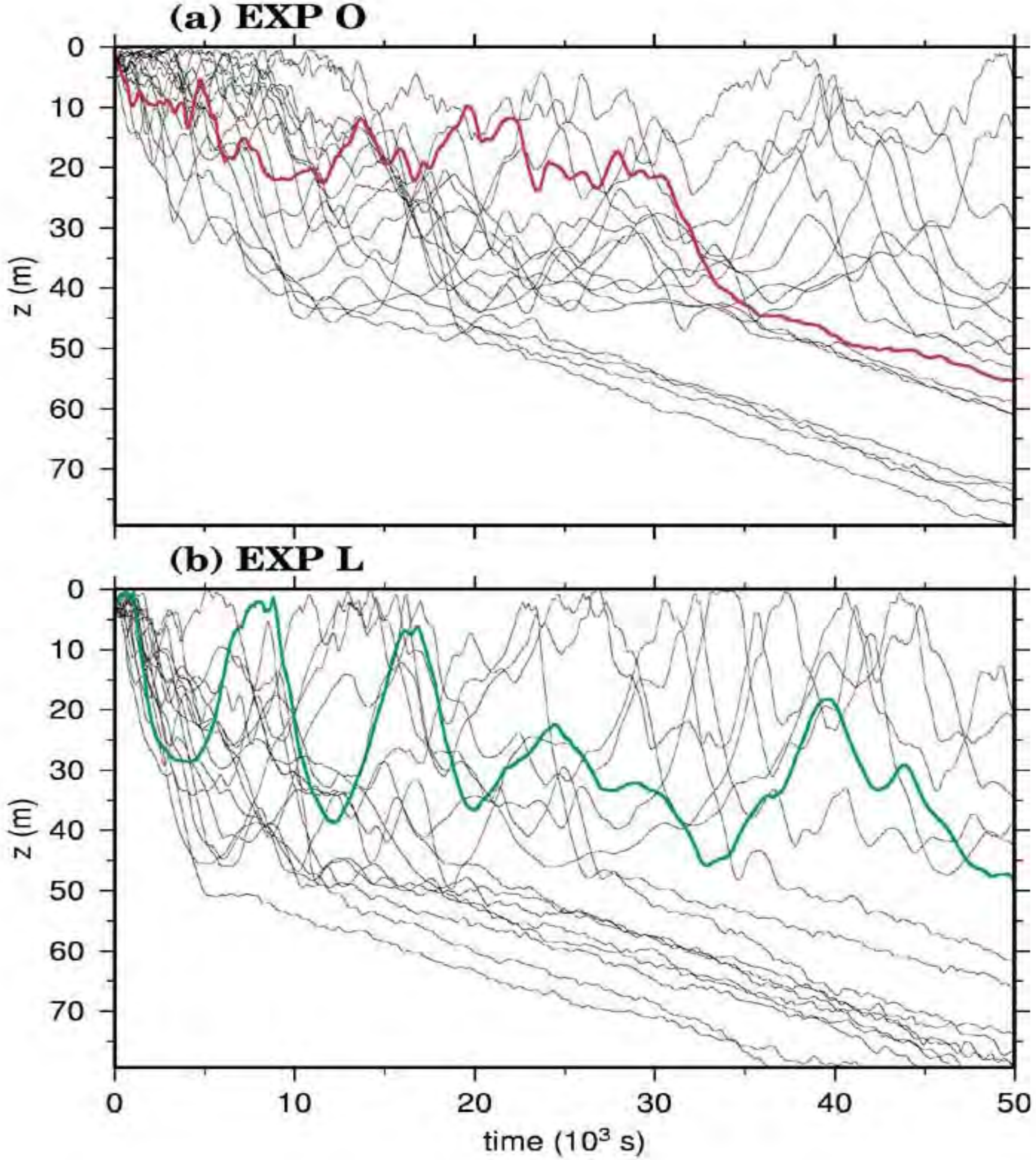
without LC

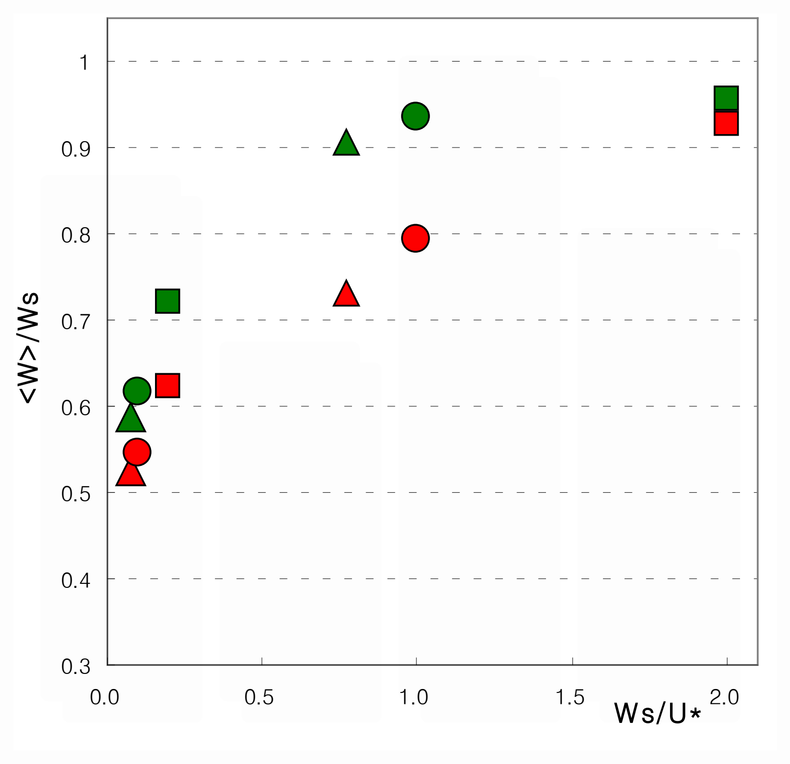


with LC

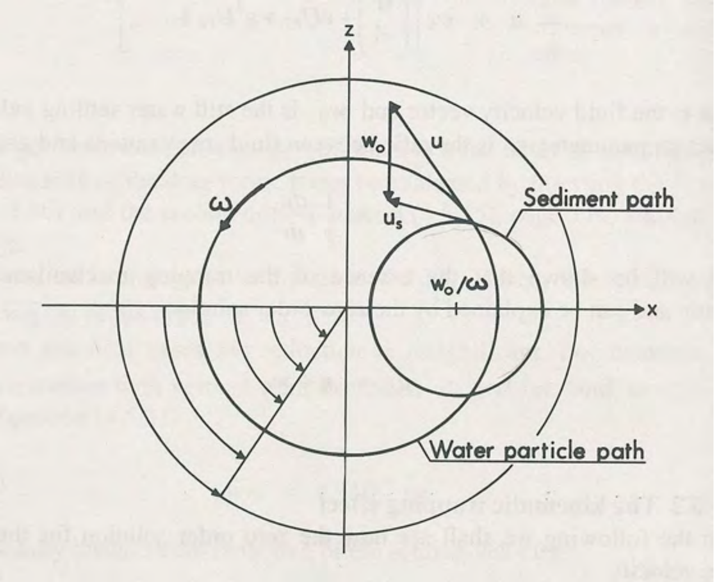
Sedimentation of suspended particle in the ocean mixed layer determines biological pump.

Tracks of the vertical positions of particles





Variation of settling velocity
(green: no LC, red: LC)



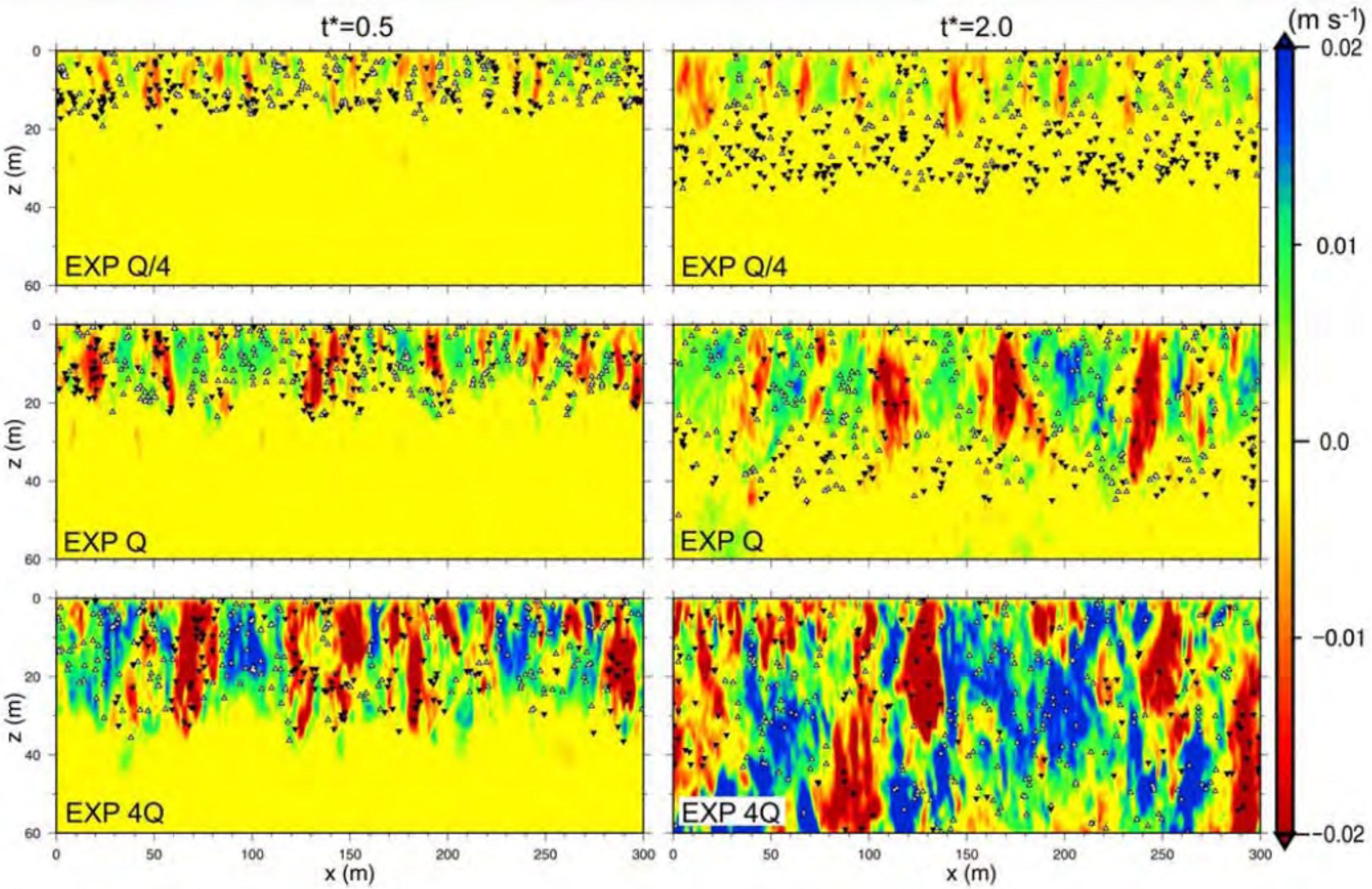
- Stommel (1949) - Particles can be suspended permanently within a vortex, even if ρ > 1.

Particles are trapped within vortices in the presence of LC

→ The settling velocity decreases.

Particle Flux across the MLD during Winter

(Noh & Nakada, *JGR*, 2010)



$w_s > dh/dt$

$w_s < dh/dt$

Figure 2. Distributions of instantaneous vertical velocity (color) and particles (triangles) at the vertical cross section ($y = 150$ m) at (left) $t^* = 0.5$ and (right) $t^* = 2$ in each experiment: (top) EXP Q/4, (middle) EXP Q, and (bottom) EXP 4Q. The white and black triangles represent the particles with upward and downward vertical motions, respectively. Here particles within the horizontal band of 2.5 m width for a given vertical section are drawn.

Fraction of phytoplankton that remains within the mixed layer during winter provides a seed for the bloom next spring.

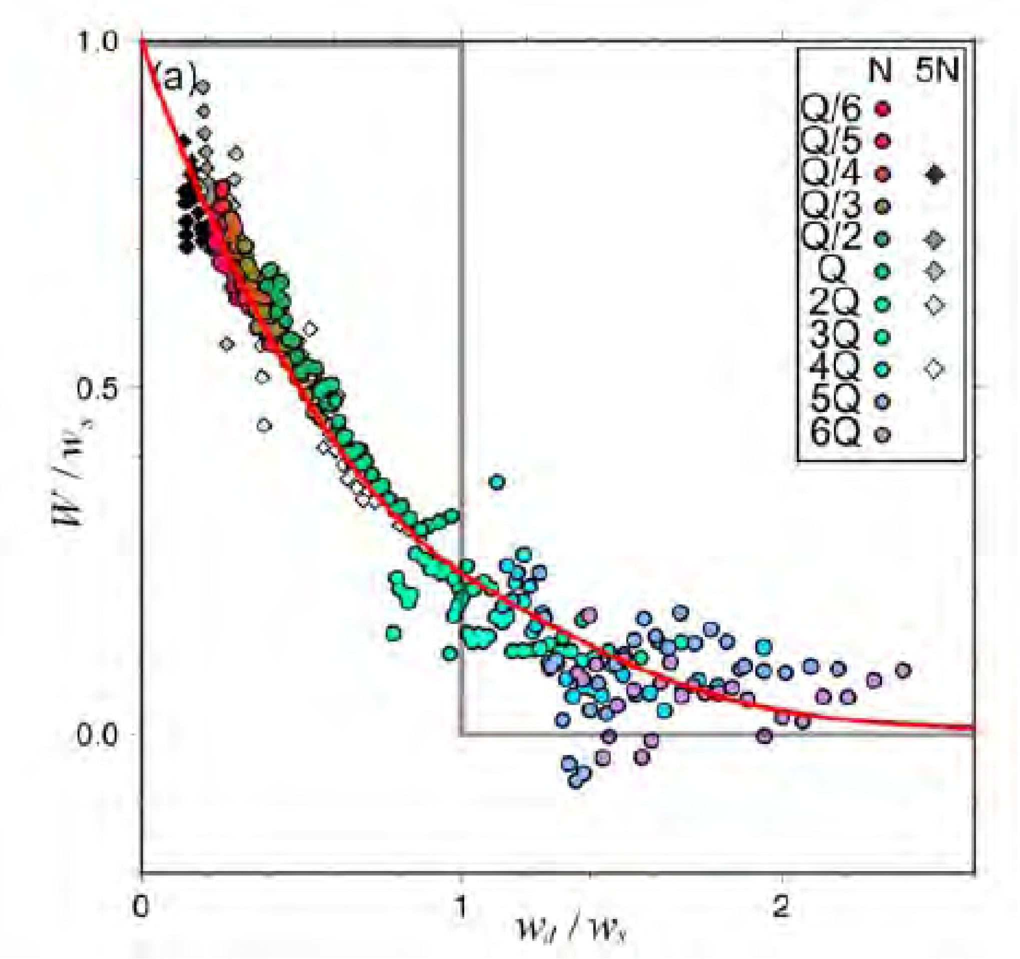
Previous hypothesis

(Lande and Wood 1987,
Ruiz et al. 1996, D'Asaro 2008)

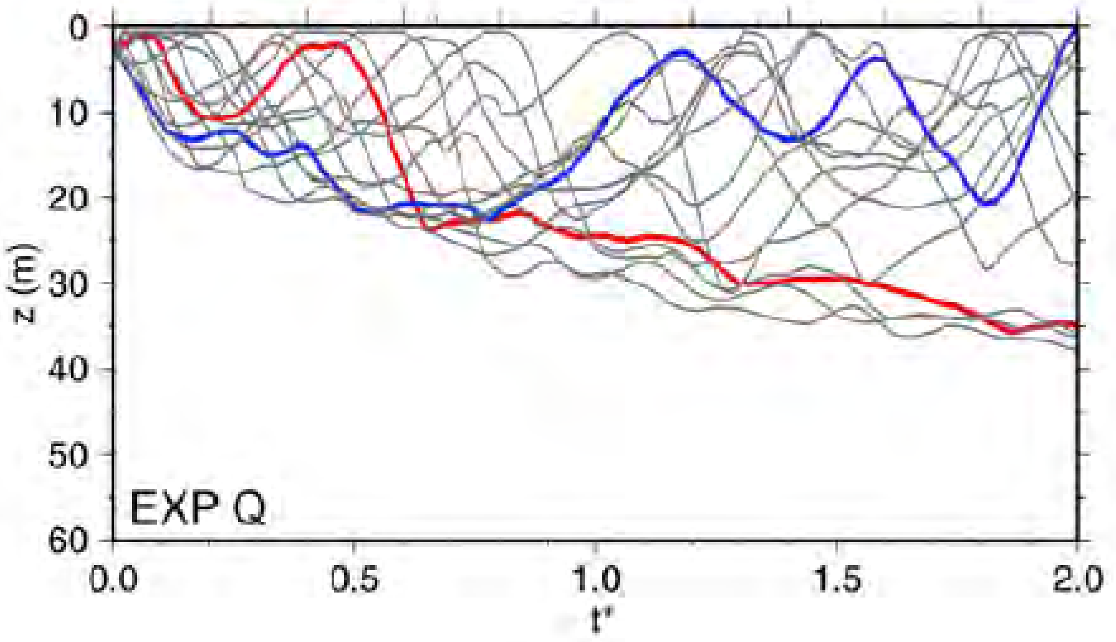
$$W/w_s = 1, \text{ if } w_s > w_d$$

$$= 0, \text{ if } w_s < w_d$$

*W = sedimentation velocity
w_s = terminal velocity of a particle
w_d = entrainment velocity
(mixed layer deepening velocity)



$$W / w_s = \exp[-1.4(w_d / w_s)]$$



Tracks of the vertical positions of particles

Escape of particles from the mixed layer occurs stochastically, and its probability is determined by turbulence at the MLD and by the mixed layer deepening, both of which are represented by wd/ws.

Lagrangian Plankton Model and its Application

Simplified 1-D Plankton Model

(Hodges and Rudnick 2004)

$$\frac{\partial N}{\partial t} = -GNPe^{\Gamma z} + DP + K\frac{\partial^2 N}{\partial z^2}$$

$$\frac{\partial P}{\partial t} = GNPe^{\Gamma z} - DP + K\frac{\partial^2 N}{\partial z^2} - W\frac{\partial P}{\partial z}$$

$GNP\mathrm{e}^{\Gamma z}$ = the rate of total phytoplankton growth minus all losses
DP = grazing, respiration, and other modes of physiological death
W = settling velocity
Γ = radiation penetration depth

Lagrangian Plankton Model

- A Lagrangian superplankton represents a plankton group that move and grow together.

$$\boxed{\begin{aligned}&\frac{\partial N}{\partial t}+\frac{\partial}{\partial x_j}\left(u_j N\right)=-\frac{\partial}{\partial x_j}\overline{u_j' N'}-M+DP\\&\frac{dp_i}{dt}=\mu_i-Dp_i\end{aligned}}$$

$$P=\frac{1}{\Delta V}\sum_{i=1}^{m}p_i \qquad M=\frac{1}{\Delta V}\sum_{i=1}^{m}\mu_i$$

$p_i(t)$ = plankton population represented a superplankton

m = the number of superplanktons within a grid

$\mu_i = GNe^{-\Gamma z}p_i$

$$\rightarrow \quad \frac{\partial P}{\partial t}+\frac{\partial}{\partial x_j}\left(u_j P\right)=-\frac{\partial}{\partial x_j}\overline{u_j' P'}+M-DP-W\frac{\partial P}{\partial z}$$

- equivalent to Hodges and Rudnick (2004)

- motion of a particle

$$\frac{dX_i}{dt} = V_i$$

$$V_i = u_i + u_i^{'} + W\delta_{i3}$$

- temperature with the radiation penetration modified by phytoplanktons (self-shading effect)

$$\frac{\partial T}{\partial t} + \frac{\partial}{\partial x_j}\left(u_j T\right) = -\frac{\partial}{\partial x_j}\overline{u_j^{'} T^{'}} - \frac{\partial R}{\partial z}$$

$$R = I_{RED} e^{-\Gamma_R z} + I_{BLUE} e^{-\Gamma_B z}$$

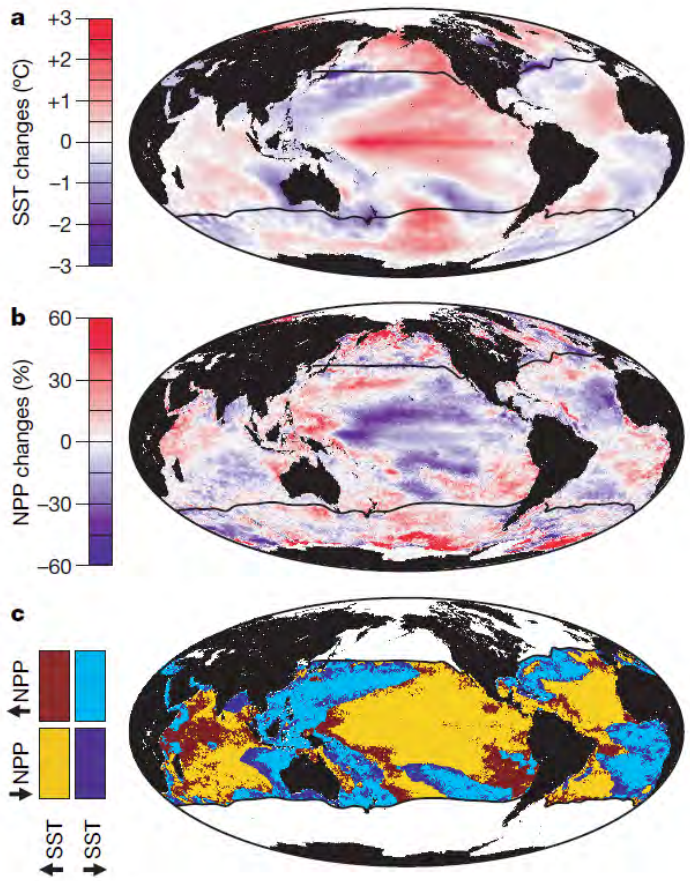
$$\Gamma_i z = \Gamma_{i0} z + k_i \int_0^z P(z')dz'$$ ← Manizza et al. (2005)

*** Advantage of the Lagrangian plankton model**

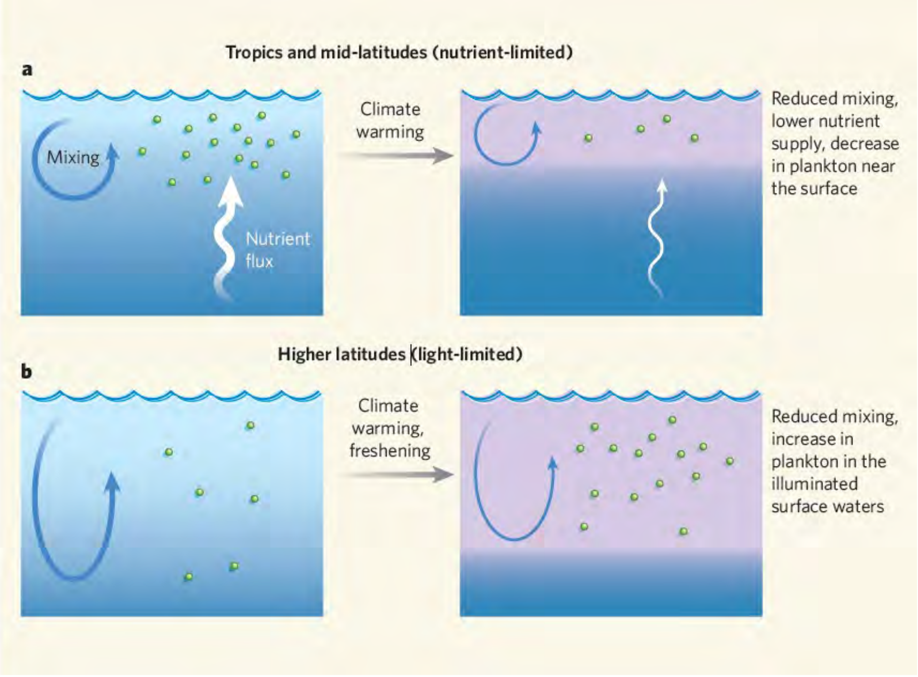
- ability to trace the location and growth of individual planktons
- ability to distinguish the growth of plankton population between dynamical (m) and biological (p_i) mechanisms

$$P = \frac{1}{\Delta V} \sum_{i=1}^{m} p_i$$

- natural dispersion and sedimentation of plankton (no eddy diffusivity for planktons)
- naturally extended to include sedimentation, preferential concentration, and aggregation and grazing by zoo plankton



Negative correlation between the variations of SST and NPP (Behrenfeld et al. 2006)



Predicted phytoplankton responses to increased temperature in the upper ocean (Doney 2006)

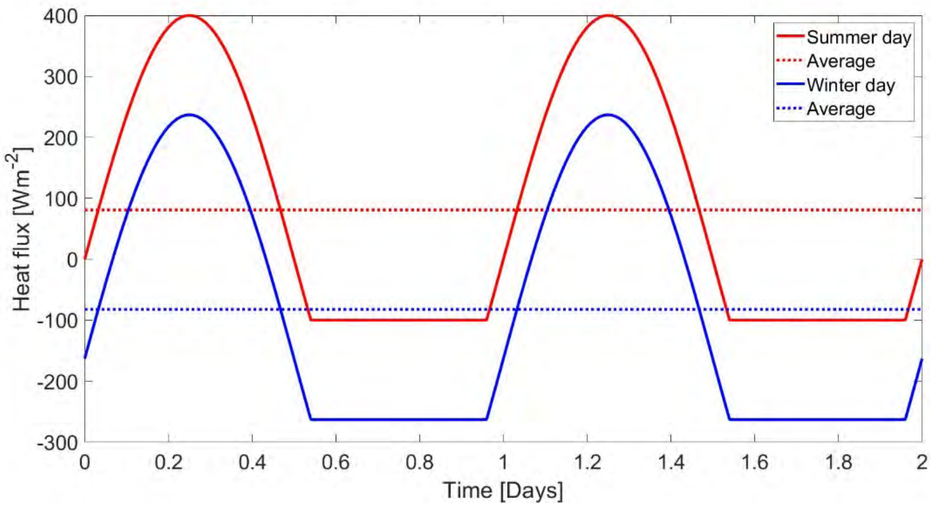
Surface heat flux affects plankton concentration.

Simulation

- LES model - PALM

- model domain
  - Lx = Ly = 300 m & H = 300m or 160 m
  - Δx = Δy = Δz = 1.25 m with nx = ny = 240 & nz = 240 or 128

- forcing
  - heat flux



$$Q_0 = \max(A\sin(\omega t), -B)$$

$$\overline{Q_0} = 81/\text{-}81\ \mathrm{Wm}^{-2}$$

A = 400 Wm^{-2},
B = 100/263 Wm^{-2}
(summer/winter)

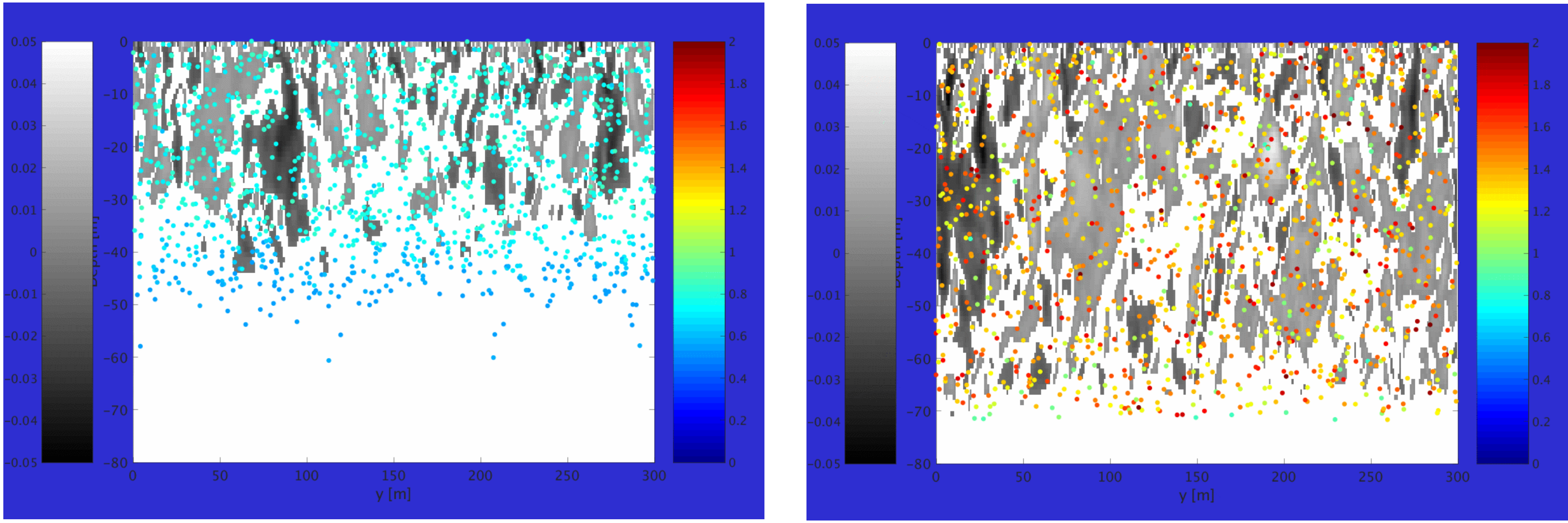
  - wind stress : u* = 0.01 m/s

- integration: 10 days
- h_0 = 60 m
- below MLD ($z > h_0$),
  - $N/N_0 = 2$
  - N^2 (stratification) = 5×10^{-5} s^{-2}
- total number of particles = 10^6
- Particles are released at z = 5 m, and mixed by convection before the onset of surface heating
- latitude: $\phi = 40^o$
- penetration depth of solar radiation: $\Gamma_0 = 20$ m^{-1}
- settling velocity: $W = 0$ ms^{-1}
- growth rate: G = 10 day^{-1}
- death rate: D = 0.1day-1

Experiments

- summer, winter

- with and without radiation modification by self-shading



summer

winter

Particles with plankton population of a superplankton (color) and vertical velocity (shade) at the vertical cross-section

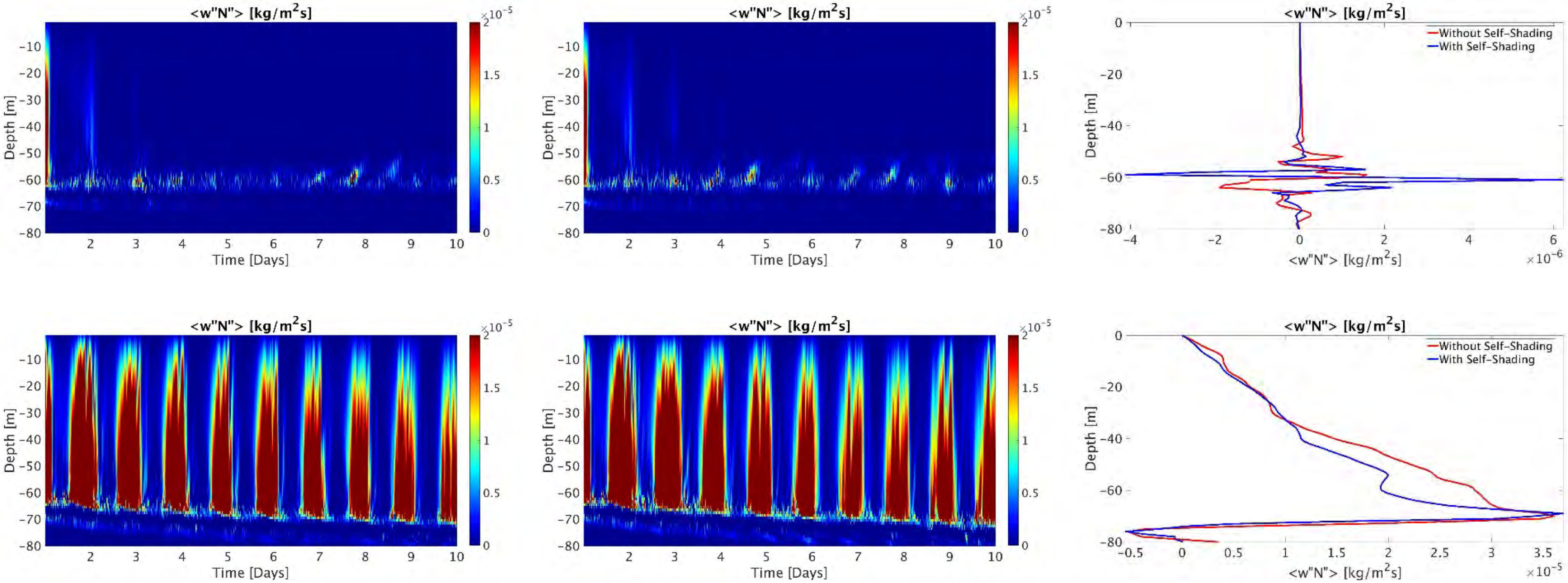
Nutrient flux

Self-Shading

No Self-Shading

Summer

Winter



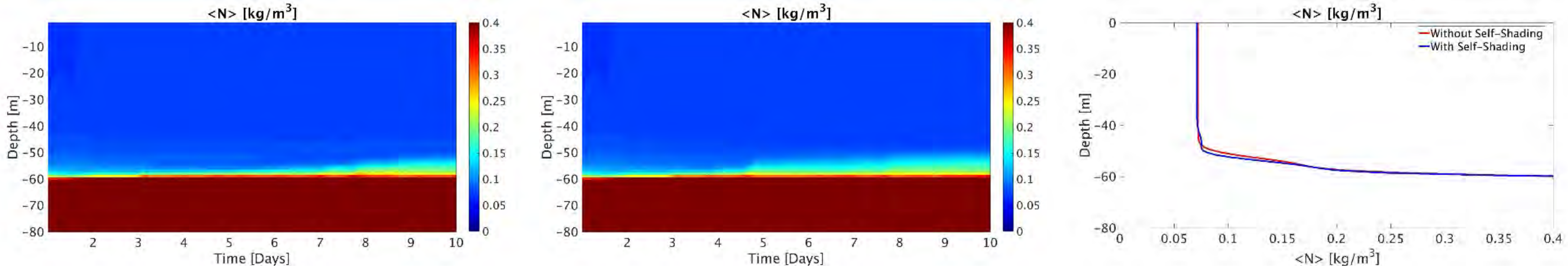
Nutrient flux is shut off in summer.

Nutrients

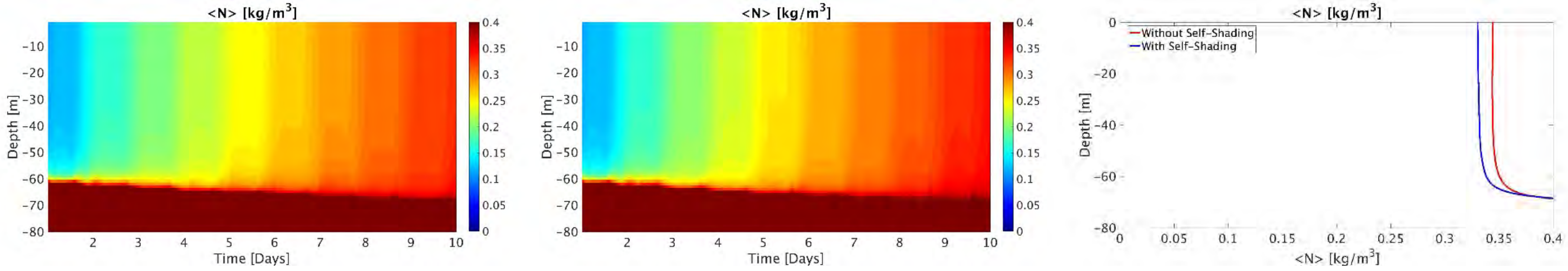
Self-Shading

No Self-Shading

Summer



Winter



Larger nutrients and stronger effect of self-shading in winter

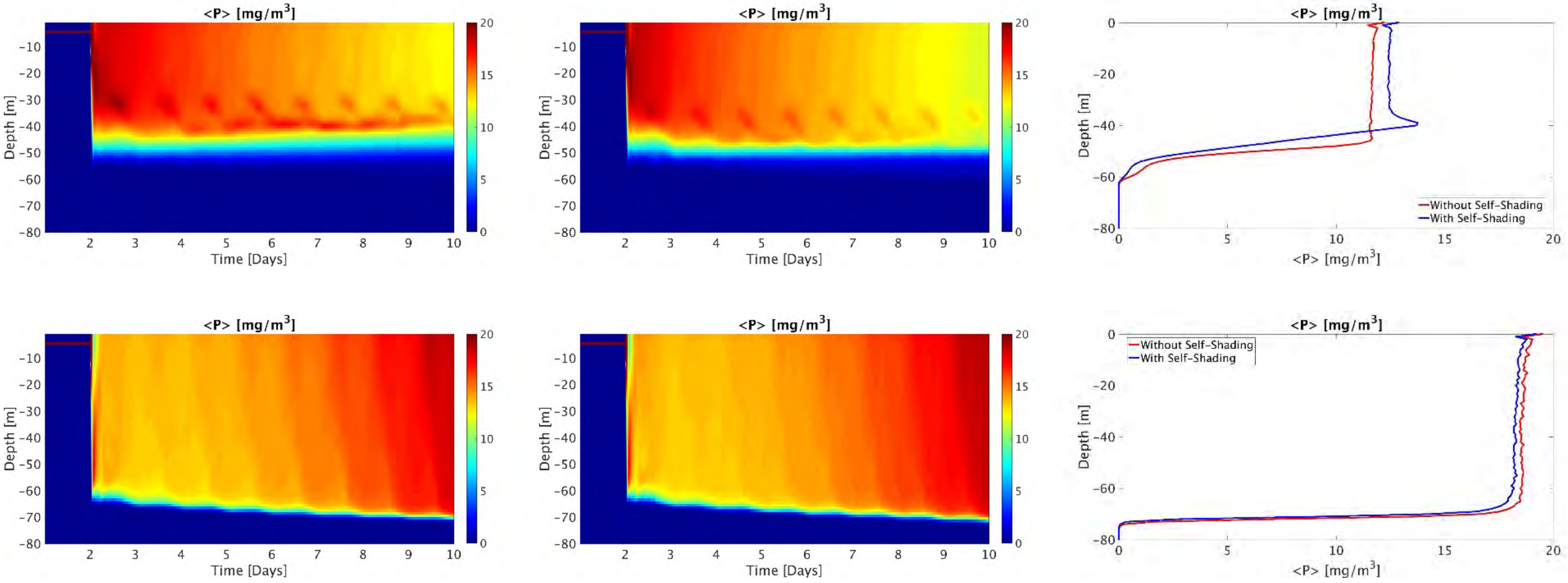
Phytoplankton

Self-Shading

No Self-Shading

Summer

Winter



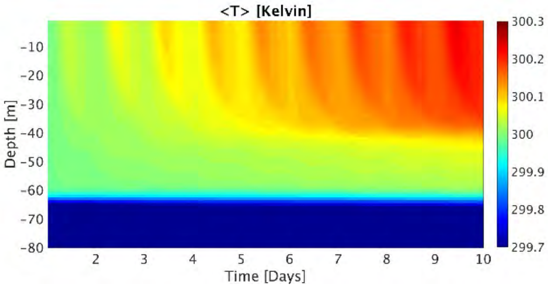
Phytoplankton concentration is increasing in winter, but decreasing in summer.

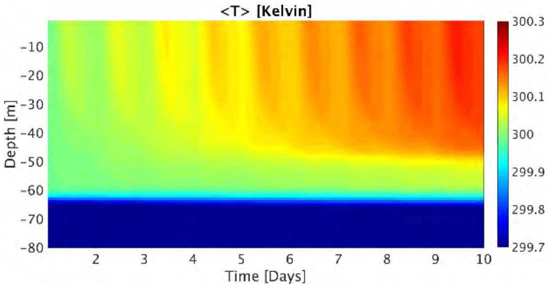
Temperature

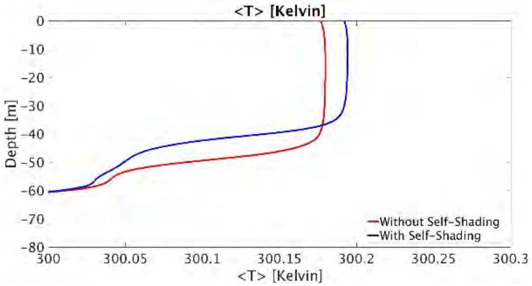
Self-Shading

No Self-Shading

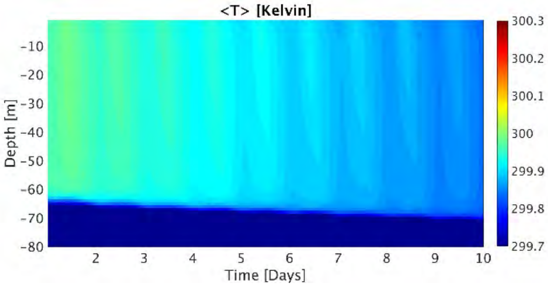
Summer

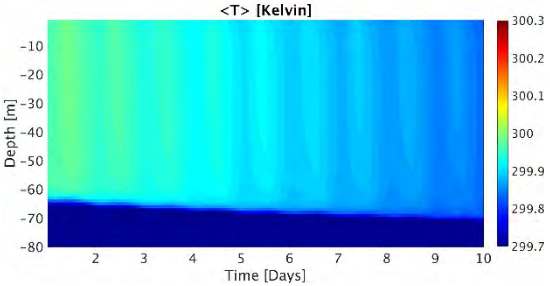


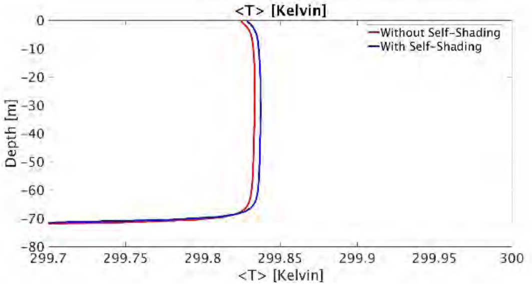




Winter



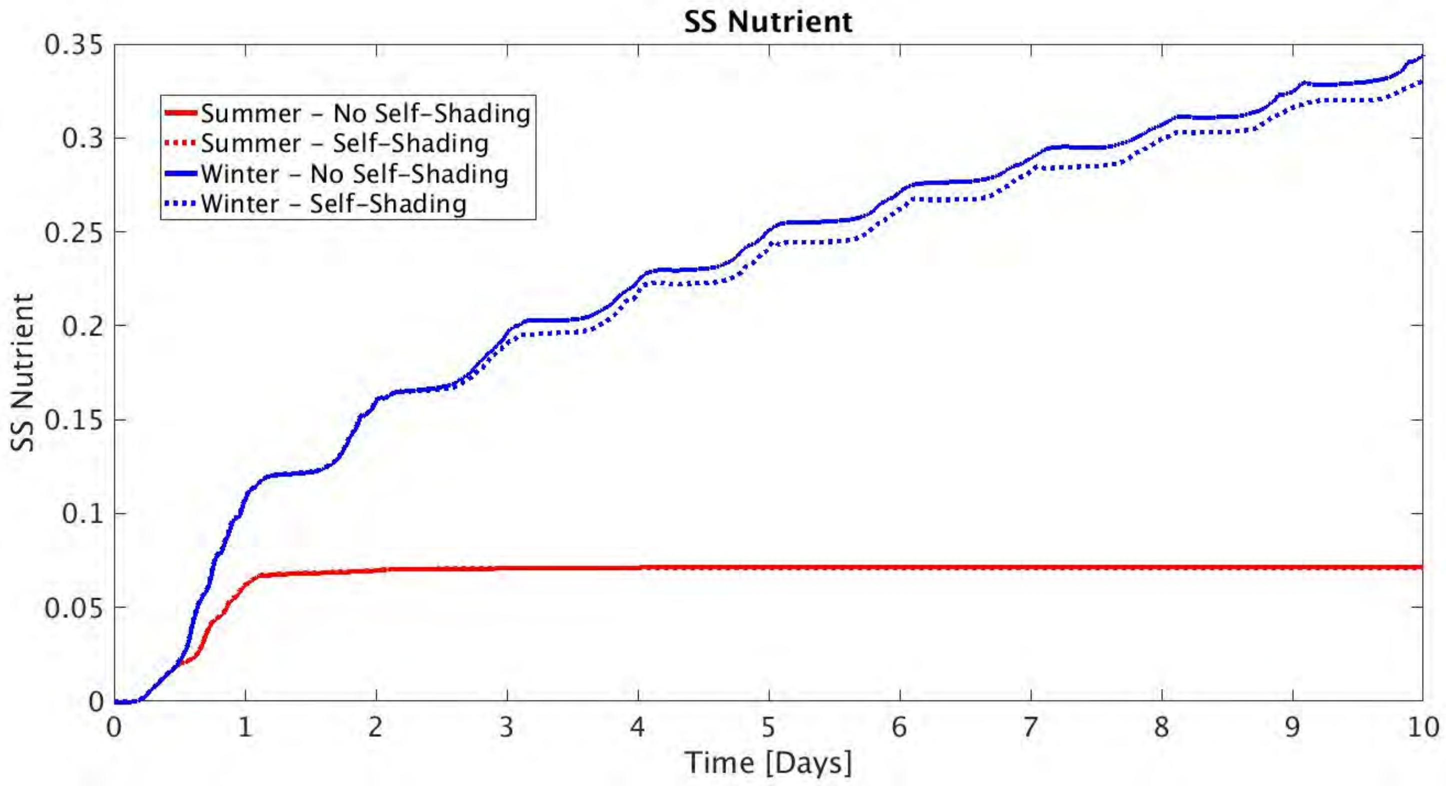




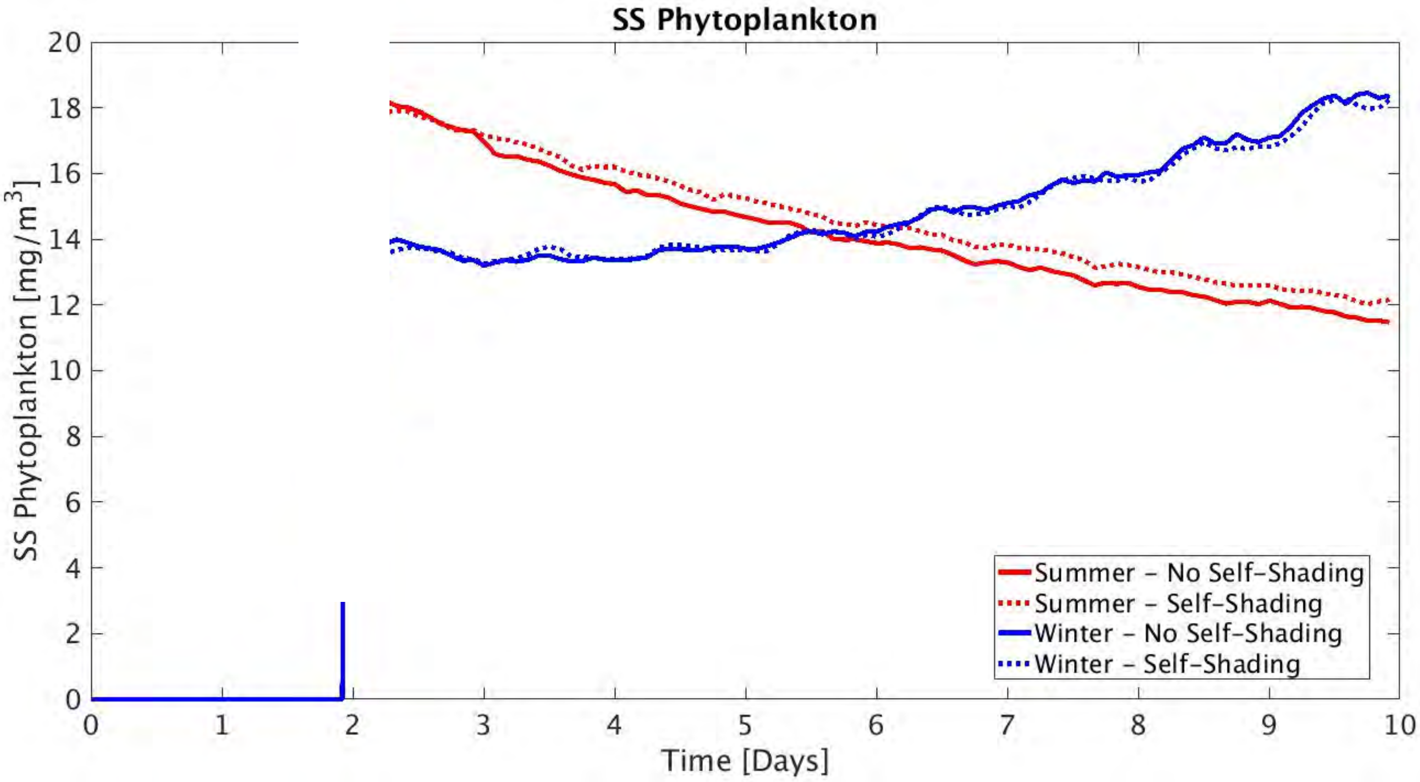
Self-shading effect is stronger in summer.

- Weaker turbulence is more sensitive to stratification.

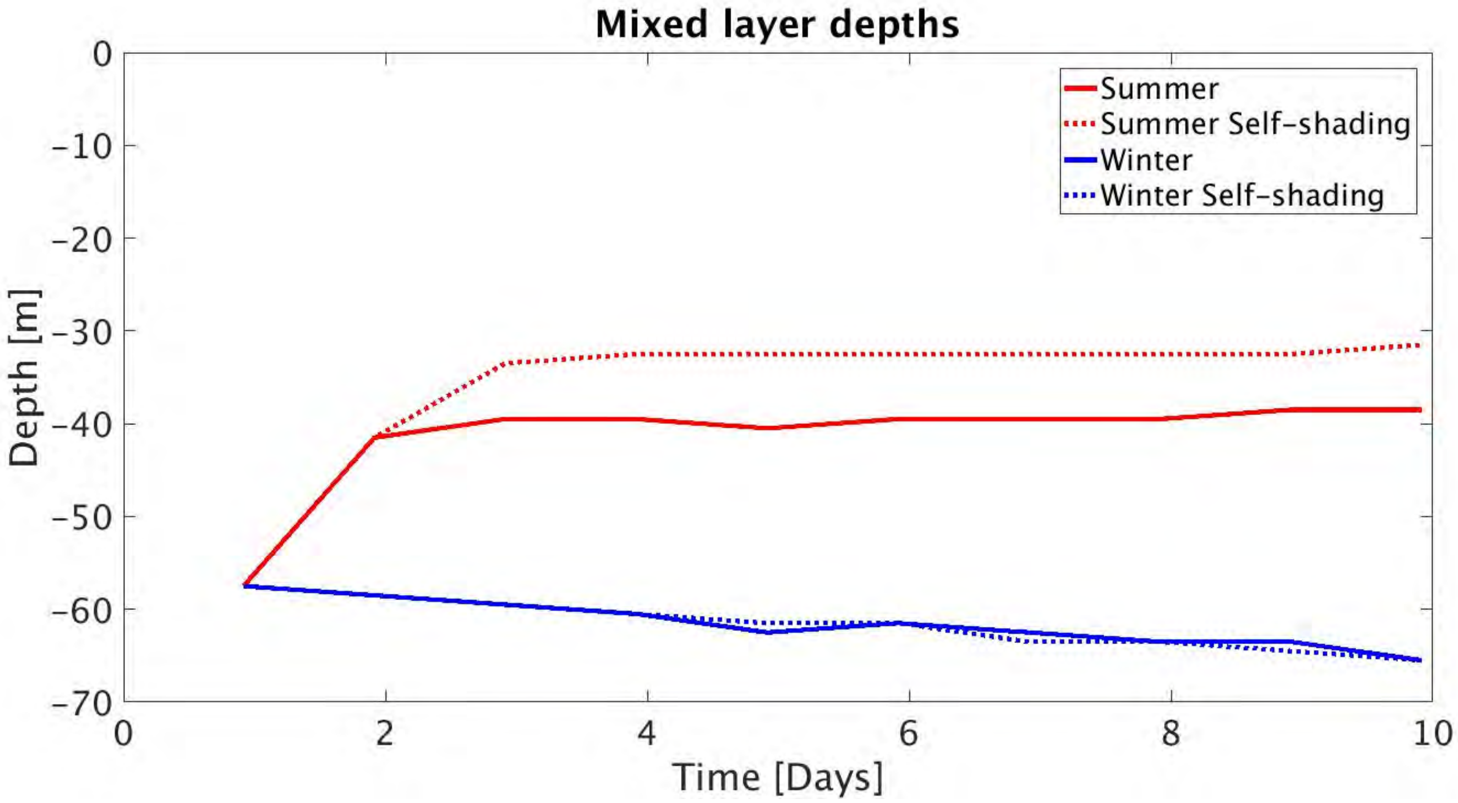
Sea Surface Nutrient



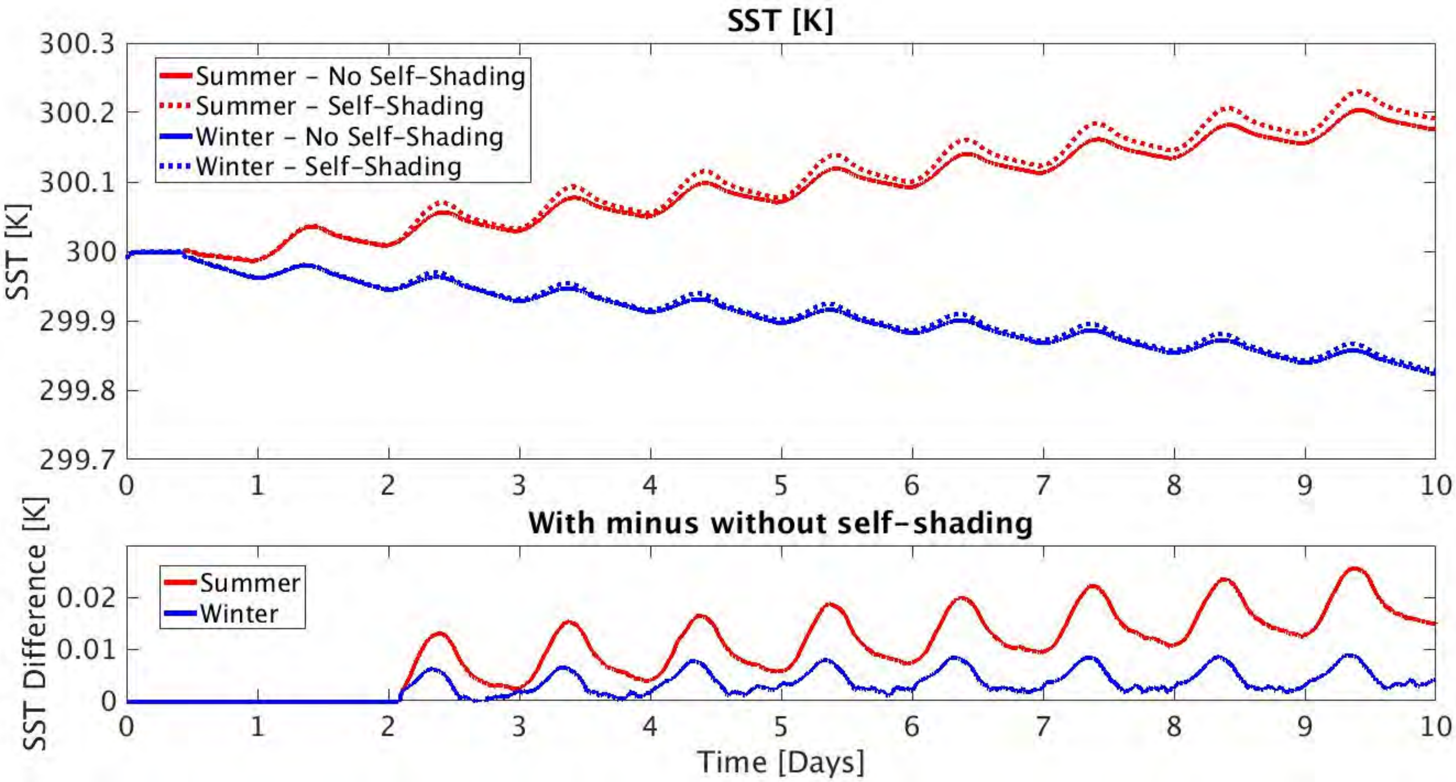
Sea Surface Plankton



Mixed Layer Depth



SST


SST [K]
300.3
300.2
300.1
300
299.9
299.8
299.7
SST [K]
Summer - No Self-Shading
Summer - Self-Shading
Winter - No Self-Shading
Winter - Self-Shading
0
1
2
3
4
5
6
7
8
9
10
With minus without self-shading
SST Difference [K]
0.02
0.01
0
Summer
Winter
Time [Days]

Conclusion

- Summer
  - decrease nutrients and phytoplankton concentration

    ← Nutrient flux is shut off from below
  - stronger self-shading effect on temperature

    ← Weaker turbulence is more sensitive to stratification.

- Winter
  - increase nutrients and phytoplankton concentration

    ← strong nutrient flux from below
  - weaker self-shading effect on temperature

    ← Stronger turbulence is less sensitive to stratification.