LES of the Ocean Mixed Layer with its Application to the Parameterization in a Climate Model

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Parameterization of SGS Turbulence in the Climate Model

- Grid sizes of the climate model (*even at Earth Simulator*) are still much larger than the eddy size of turbulence

  ~ 10-100 km (horizontal)

  ~ 10-100 m (vertical)

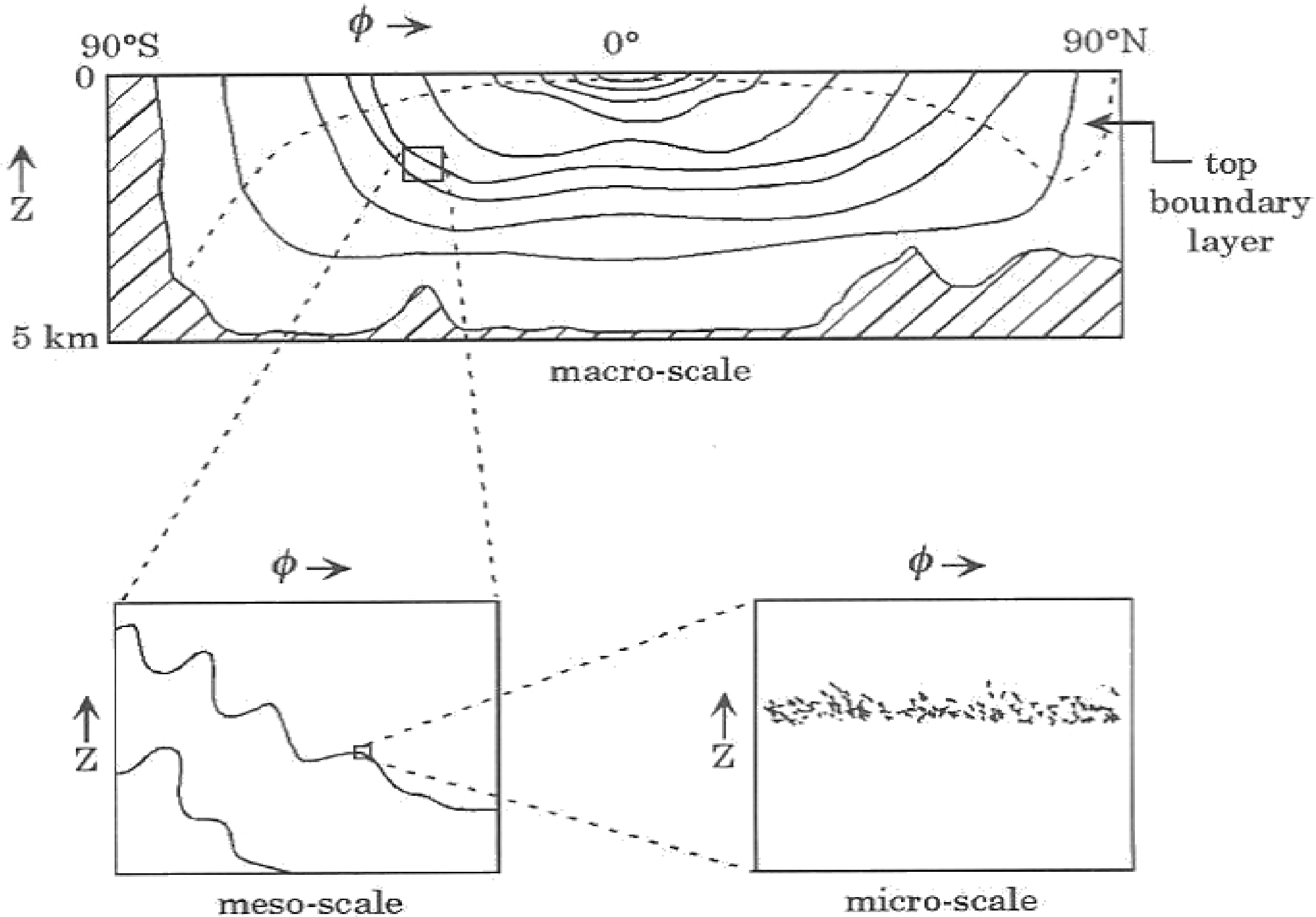
⇒ *We have to parameterize the turbulence within the grid.*

ex) OGCM - ocean mixed layer, ocean deep convection,
meso-scale eddies,

AGCM – PBL , cumulus convection, cloud

Biogeochemical Model

- particle flux, aerosol, biogeochemical process



φ →
90°S
0°
90°N
0
Z
5 km
top boundary layer
macro-scale
φ →
Z
meso-scale
φ →
Z
micro-scale

How is the SGS parameterization of turbulence developed currently ?

• A new parameterization based on intuitive (or *arbitrary*) hypotheses

→ Show that the new parameterization performs better in a certain case

- comparison with observation data
- examination of the performance of a climate model

→ Claim to improve the parameterization (and *publish*).

• There is no guarantee that

- *We are really moving to the right direction for the realistic representation of nature ultimately.*

(Driving without a map)

- *The hypotheses really represent correct physics.*

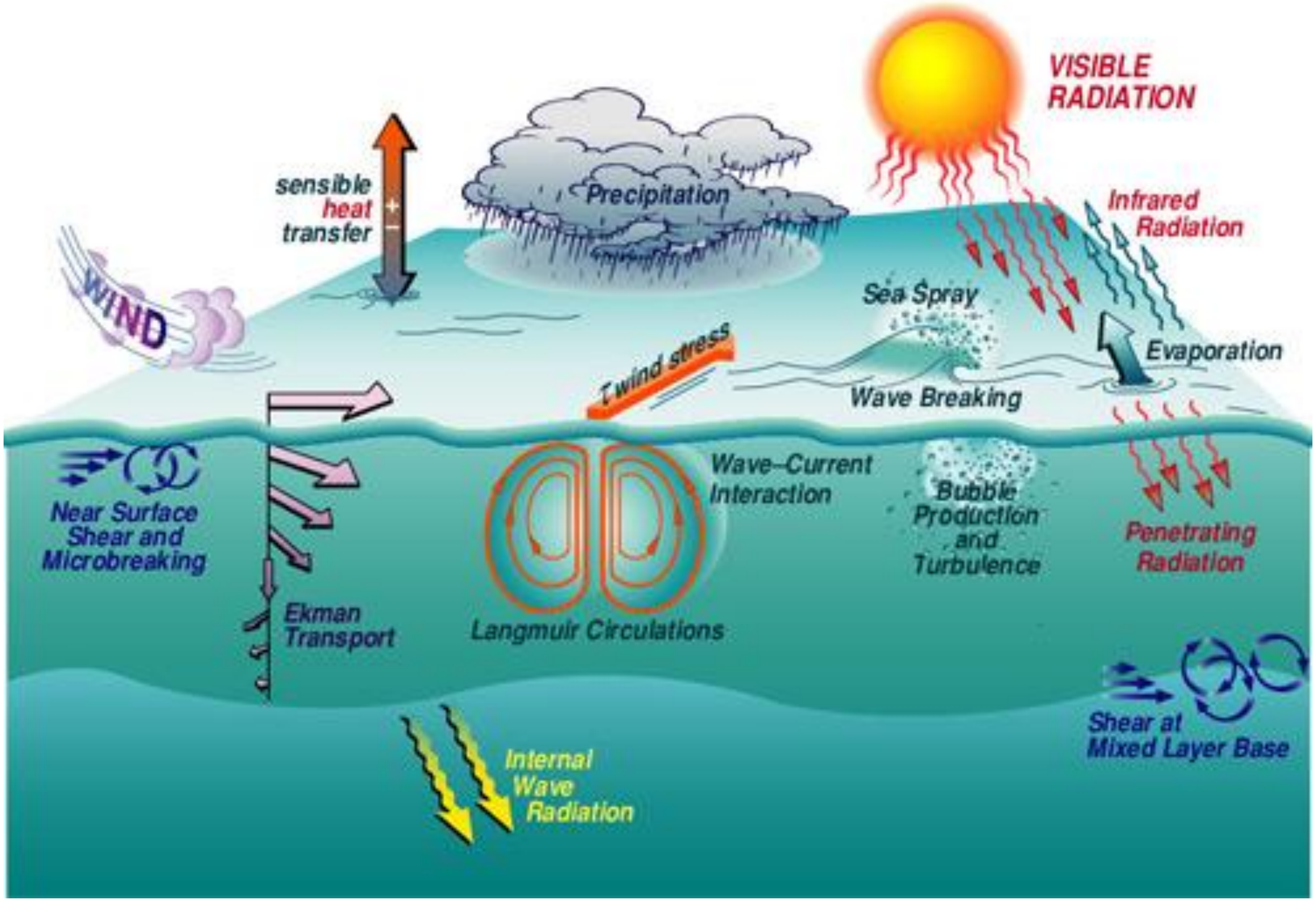
LES (large eddy simulation), which reproduces realistic 3-D structure of turbulence,

provides a powerful tool for the development of the SGS parameterization of turbulence

by examining

- not only *the performance of the parameterization*
- but also *the hypotheses* used in the parameterization.

Ocean Mixed Layer



LES of Ocean Mixed Layer

- Parallel Large Eddy Simulation Model (PALM)
- Inclusion of the effects of ***Langmuir circulation*** and ***wave breaking***

  (Noh et al. , *JPO* 2004)

$$\frac{\partial u_i}{\partial t} + (u_j + u_{sj})\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j}$$

$$-\varepsilon_{ijk} f_j \;\; u_k + u_{sk}$$

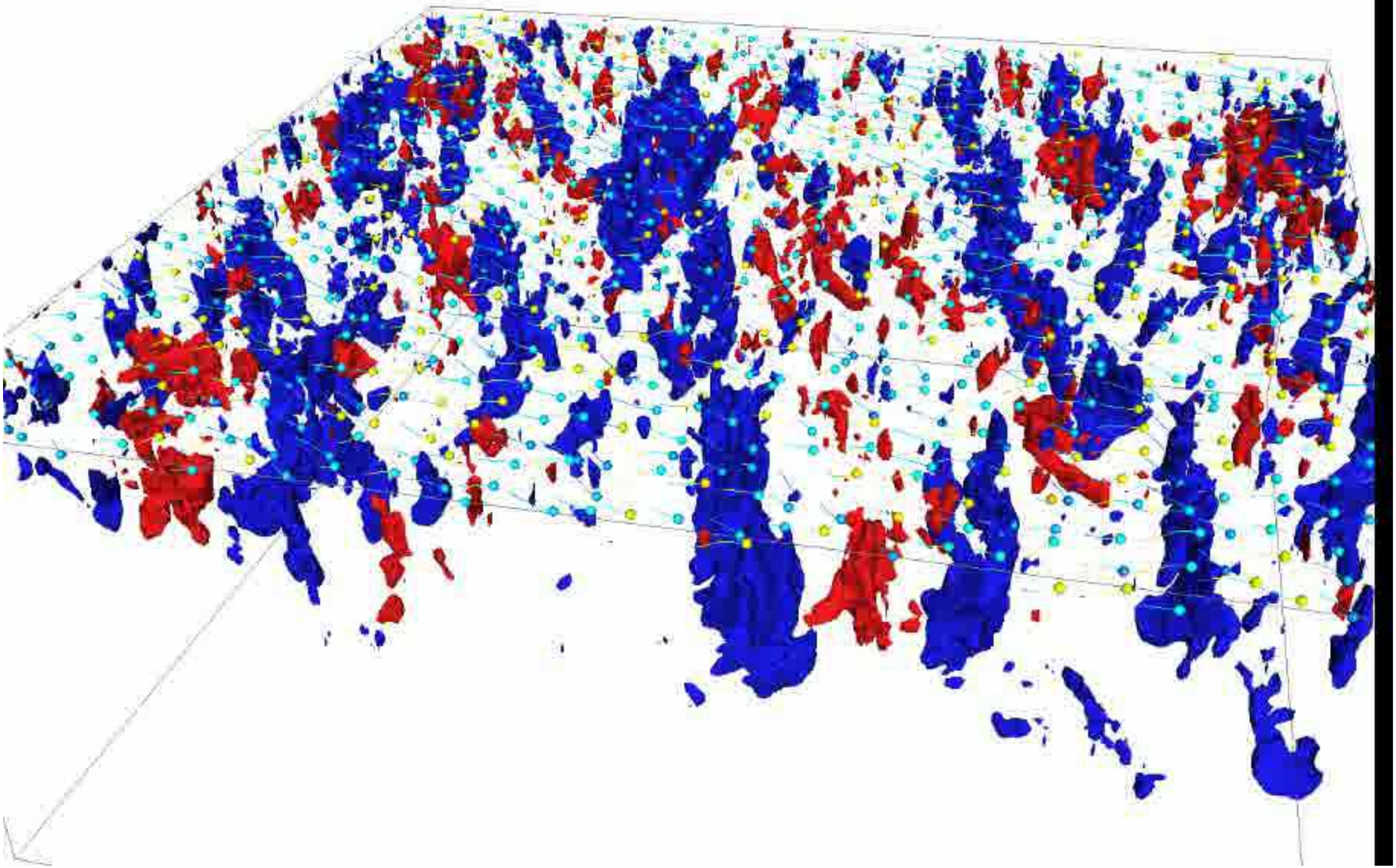
$$+\varepsilon_{ijk} u_{sj} \omega_k$$ ← vortex force to generate LC

$$+F_i(\mathbf{x}, t)$$ ← stochastic forcing to generate wave breaking

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

$$u_s = U_s \exp(-4\pi z/\lambda)$$

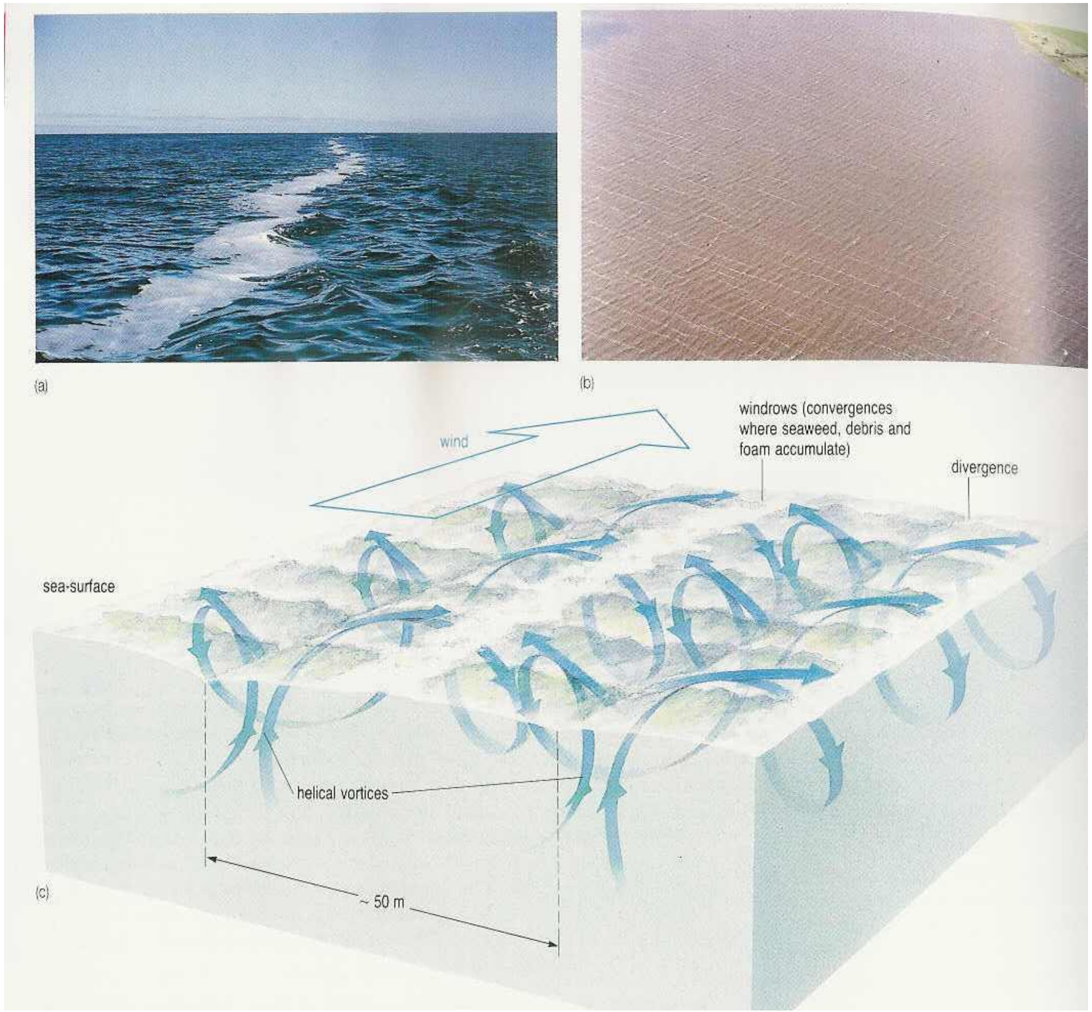
$$U_s = (2\pi a/\lambda)^2 (g\lambda/2\pi)^{1/2}$$



1. *What is the Role of* ***Langmuir Circulation*** *in the Mixed Layer Deepening ?*

2. *What is the Role of* ***Wind Stress*** *in the Convective Deepening of the Mixed Layer*

1. *What is the Role of* ***Langmuir Circulation*** *in the Mixed Layer Deepening ?*



Langmuir circulation observed in the ocean

Influence of LC on Vertical Mixing

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

- The role 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.

Consideration of LC in the Mixed Layer Model

- Li et al. (1995), Smith (1998)
  - modification of the PWP model

  *Mixing occurs, if

$$h\Delta B/(\Delta U)^2 < 0.65 \qquad \leftarrow \text{PWP model}$$

$$h\Delta B/v_L^2 < C \qquad (C = 9.8)$$

$$v_L = (U_s u_*^2)^{1/3} \qquad \text{: velocity scale of LC}$$

- McWilliams & Sullivan (2000), Smyth et al. (2002)
  - modification of the KPP model

$$w = \frac{\kappa u_*}{\phi(z,t)} \quad \rightarrow \quad w = \frac{\kappa u_*}{\phi(z,t)}\left[1 + \frac{C_w(u_*, w_*)}{La^4}\right]^{1/2}$$

$$-\overline{uw} = K_m \frac{\partial U}{\partial z} \quad \rightarrow \quad -\overline{uw} = K_m\left(\frac{\partial U}{\partial z} + \gamma_u\right)$$

$$K(z,t) = h(t)w(z,t)G(z,t)$$

- D’Alescio et al. (1998)

  - modification of TKE equation and BC at the MLD

$$\frac{\partial E}{\partial t} = F + P_s - P_b - \varepsilon + P_L$$

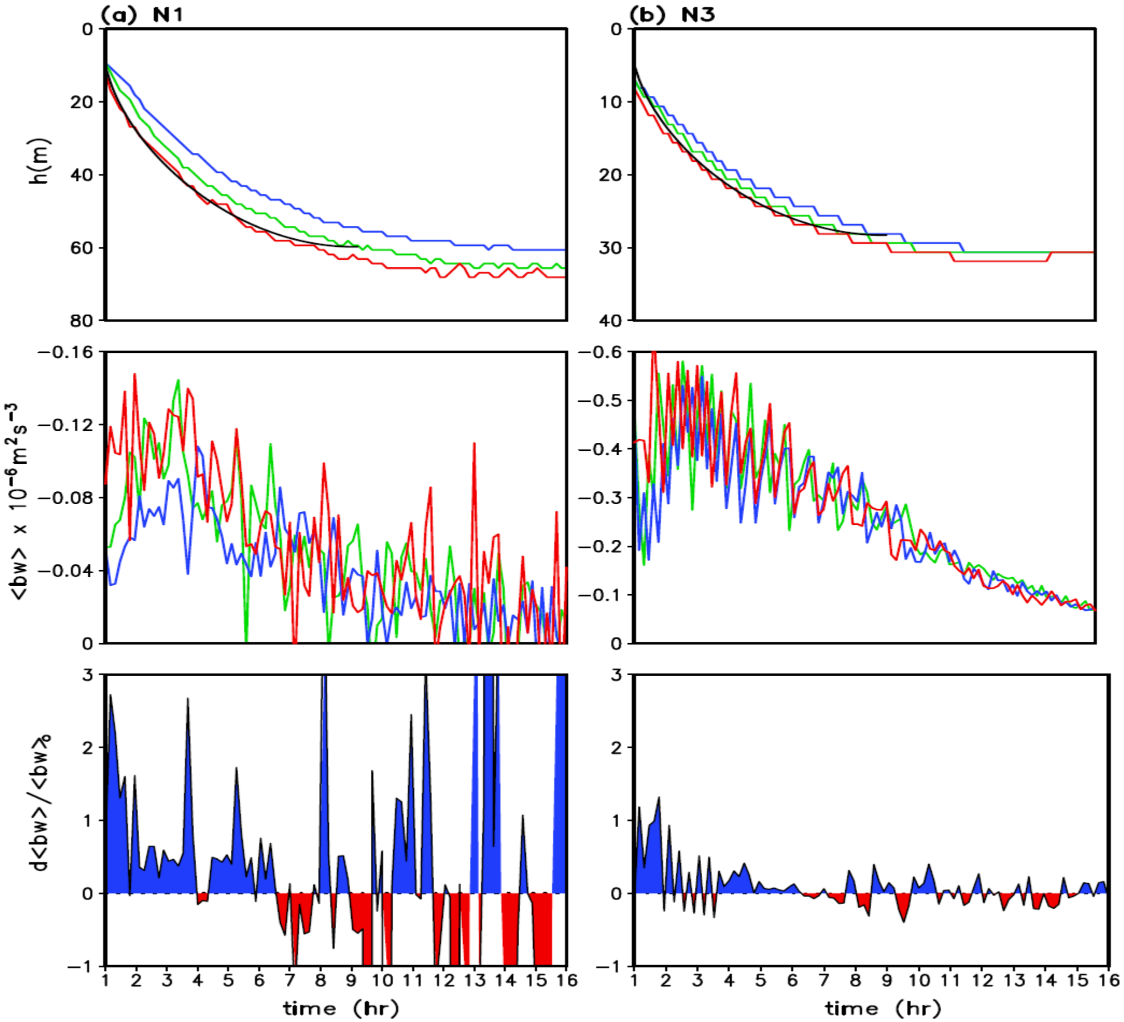
$P_L = u_s \partial(\overline{u'w'}) / \partial z$: additional TKE production by the vortex force

Experiments

- $u_* = 0.02$ m/s
- $h_0 = 5$ m
- $f = 10^{-4}$ s^{-1}

-LC: a (m) = 0 (L0), 0.5 (L1), 1 (L2)

-Stratification: N^2 (s^{-2}) = 10^{-5} (N1), 5 x 10^{-5} (N2), 2 x 10^{-4} (N3)



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 (lower). Here = , and is the buoyancy flux in the absence of LC (). (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).

Dimensional Analysis

$$w_e = f(h, \Delta B, u_*, U_s, \lambda, f)$$

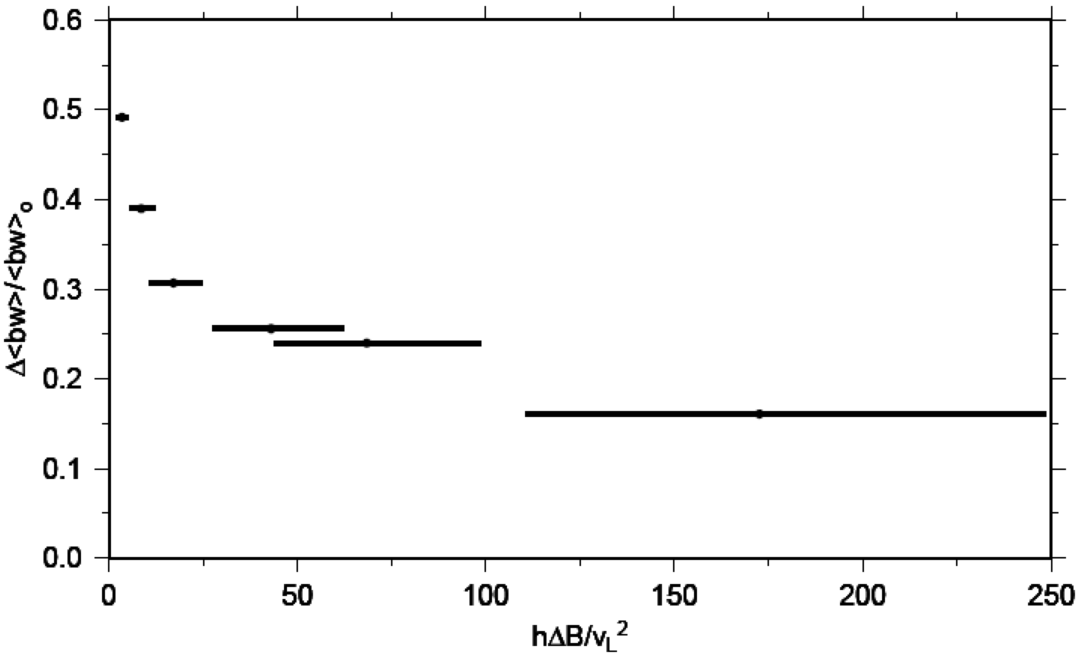
$$\frac{w_e}{u_*} = f\left(\frac{h\Delta B}{u_*^2}, \frac{h\Delta B}{v_L^2}, \frac{h}{\lambda}, \frac{h}{u_* / f}\right) \quad \leftarrow \quad v_L = (U_s u_*^2)^{1/3}$$

$$h\Delta B / v_L^2 = (h\Delta B / u_*^2)(u_* / v_L)^2$$

i) If h/λ and $h/(u_*/f)$ remain invariant,

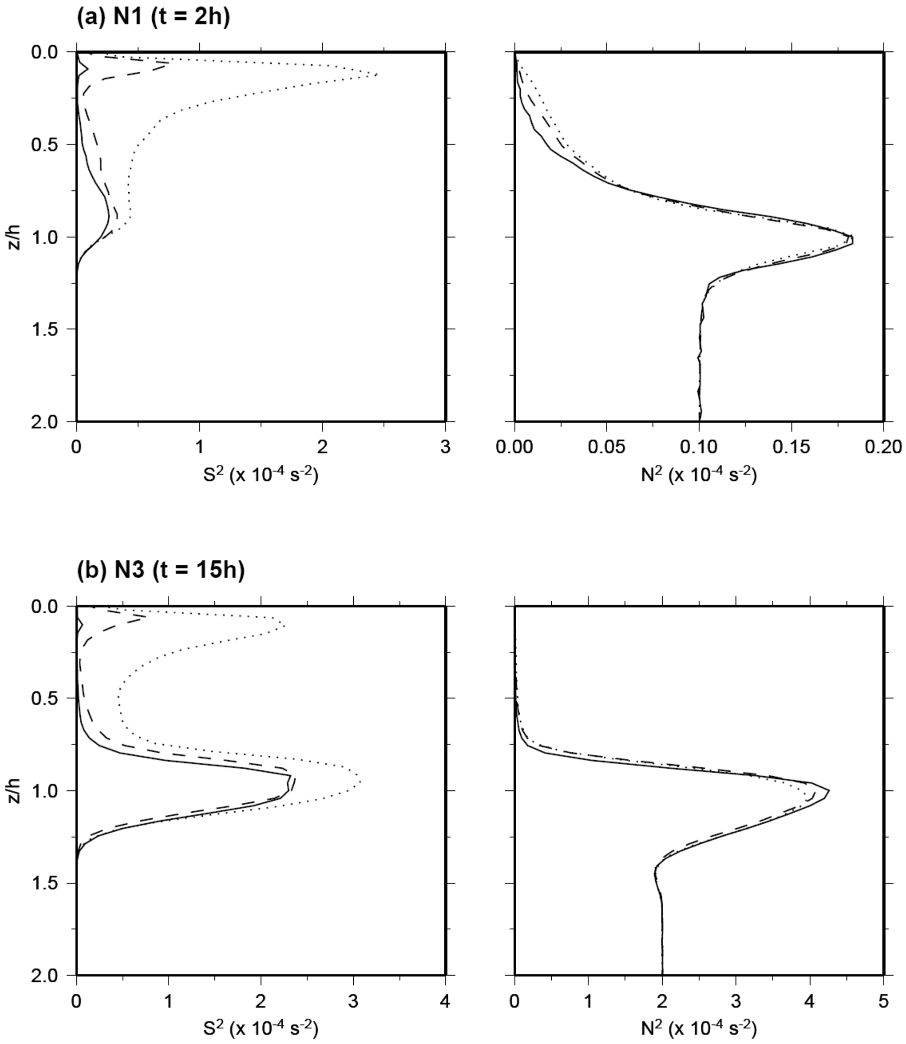
ii) If $w_e / u_* = f_1(h\Delta B / u_*^2)[1 + f_2(h\Delta B / v_L^2)]$

$$\frac{\Delta \overline{bw}(h)}{\overline{bw}(h)_0} = f_2\left(\frac{h\Delta B}{v_L^2}\right) \quad \leftarrow \quad \Delta \overline{bw}(h) = \Delta w_e \Delta B$$



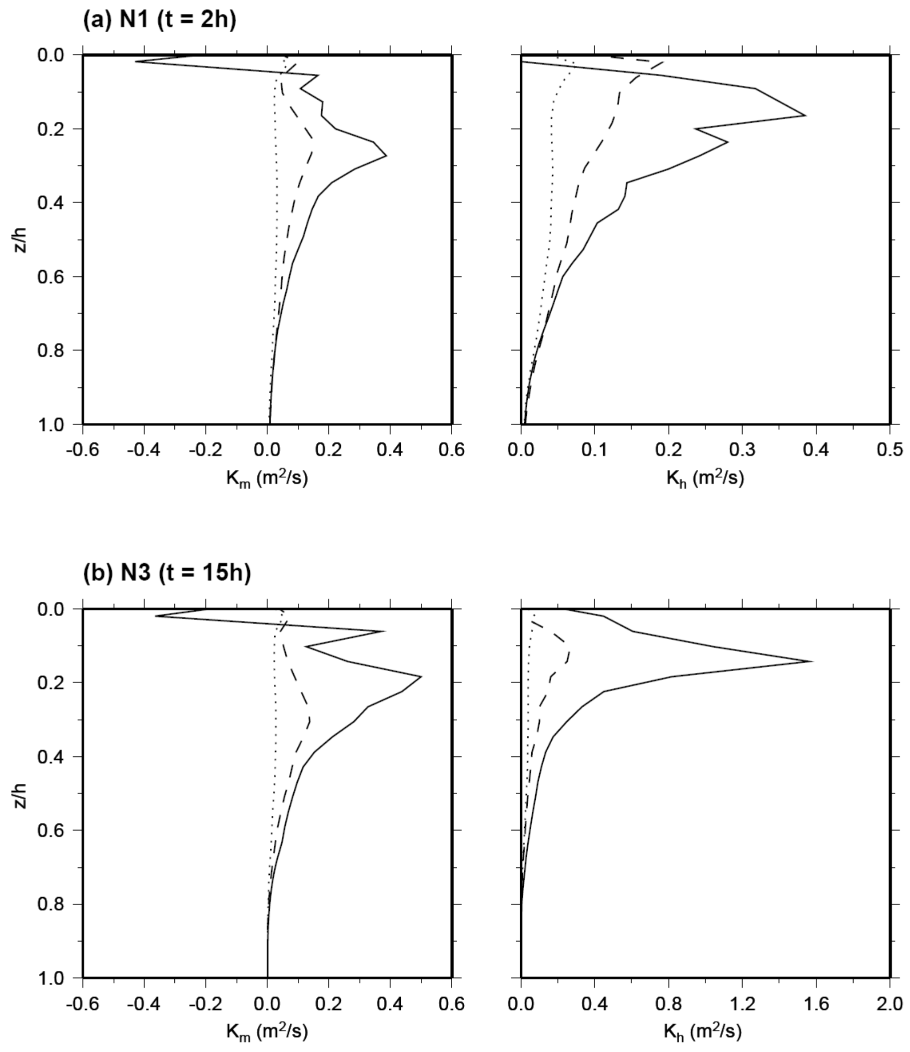
Variation of $\Delta\overline{bw}(h)/\overline{bw}_0(h)$ with $h\Delta B/v_L^2$

⇒ ***LC induces a significant enhancement of the ML deepening, only if stratification is weak and MLD is shallow.***



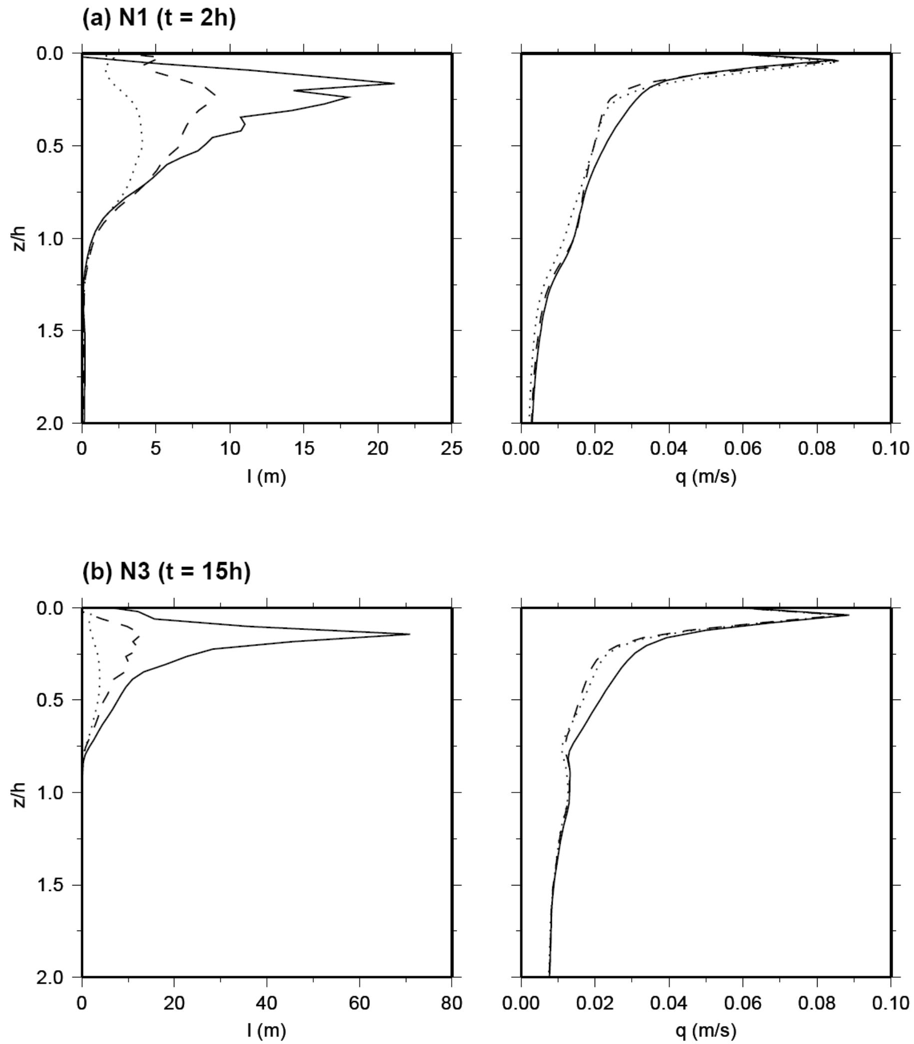
Profiles of S^2 and N^2 (dotted: L0, dashed: L1, solid: L2)

⇒ ***much weaker S^2 in the presence of LC***



Profiles of K_m and K_h (dotted: L0, dashed: L1, solid: L2)

⇒ ***much larger K_m and K_h within the ML in the presence of LC***

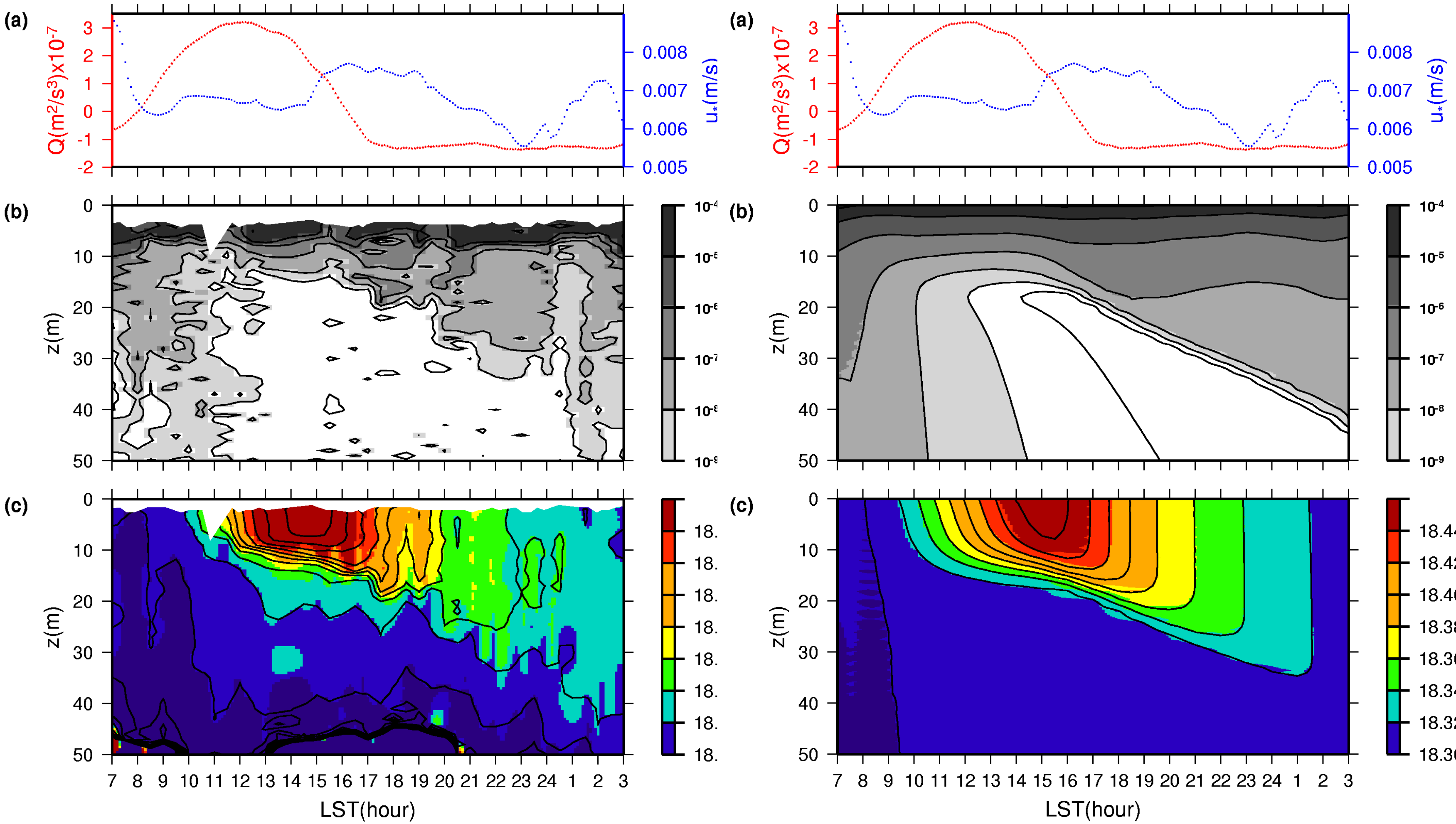


Profiles of l and q (dotted: L0, dashed: L1, solid: L2)

⇒ ***Much larger K_m and K_h under LC is due to much larger l ($K \sim ql$).***

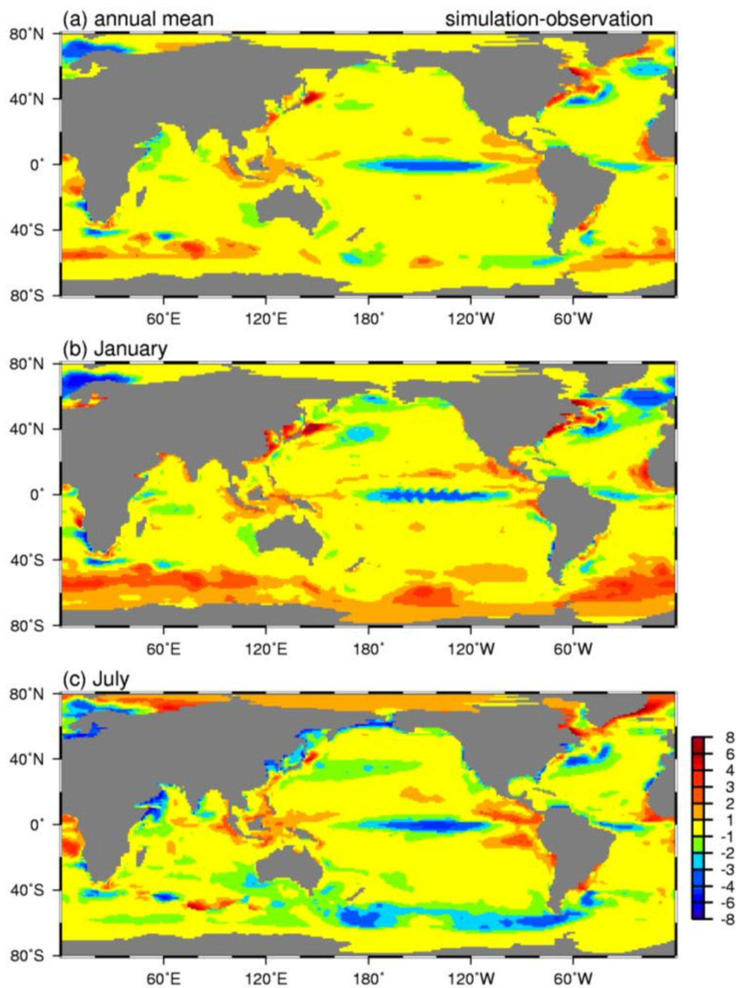
Noh Mixed Layer Model

(Noh et al., *JGR* 1999, *JPO* 2002, *GRL* 2005)

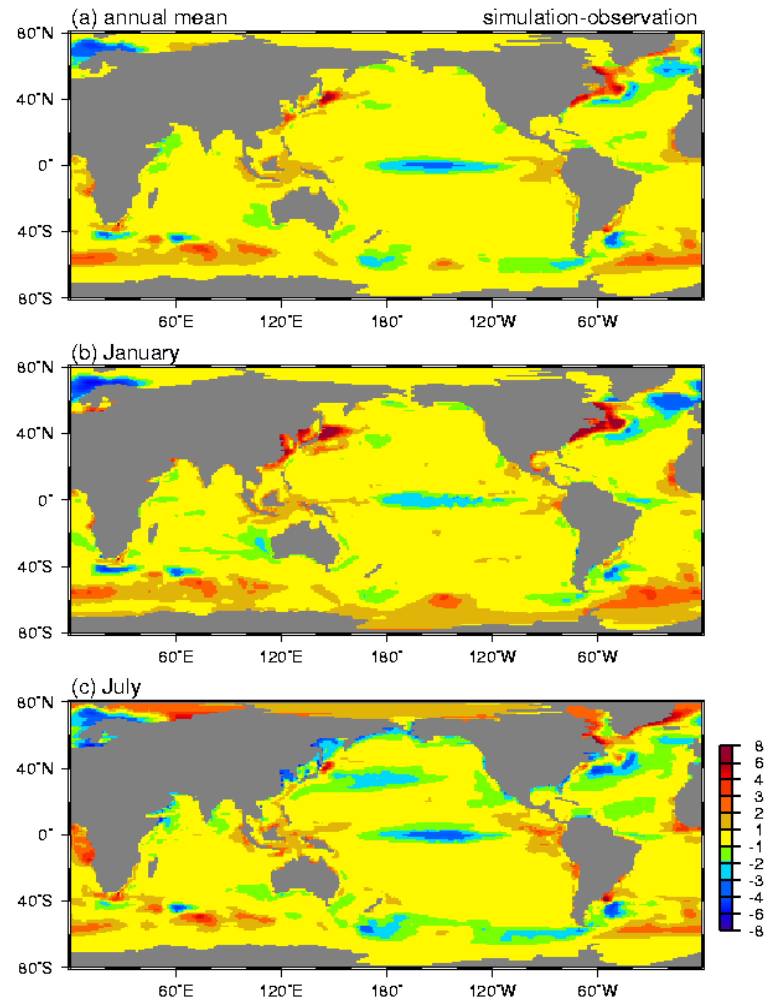


Evolution of the OML from the observation (PATCHEX) (left) and simulation (right): (a) surface forcing, (b) dissipation rate (m^2 s^{-3}) and (c) temperature (^0C)

SST anomaly



PP mixing



a new mixed layer model

Basic Concept of the Noh Model

- **TKE flux at the surface;**

$$K_E \partial E / \partial z = A u_*^3 \qquad \text{with } A = 100$$

**Mellor & Yamada (1982): A = 0 m - neglect wave breaking*

- **effects of stratification;**

$$l / l_0 = (1 + \alpha \mathrm{Rt})^{-1/2} \qquad \leftarrow \qquad K \sim ql$$

$$\mathrm{Rt} = (N l_0 / q)^2$$

**Mellor & Yamada (1982), Pacanowski & Philander (1981)*

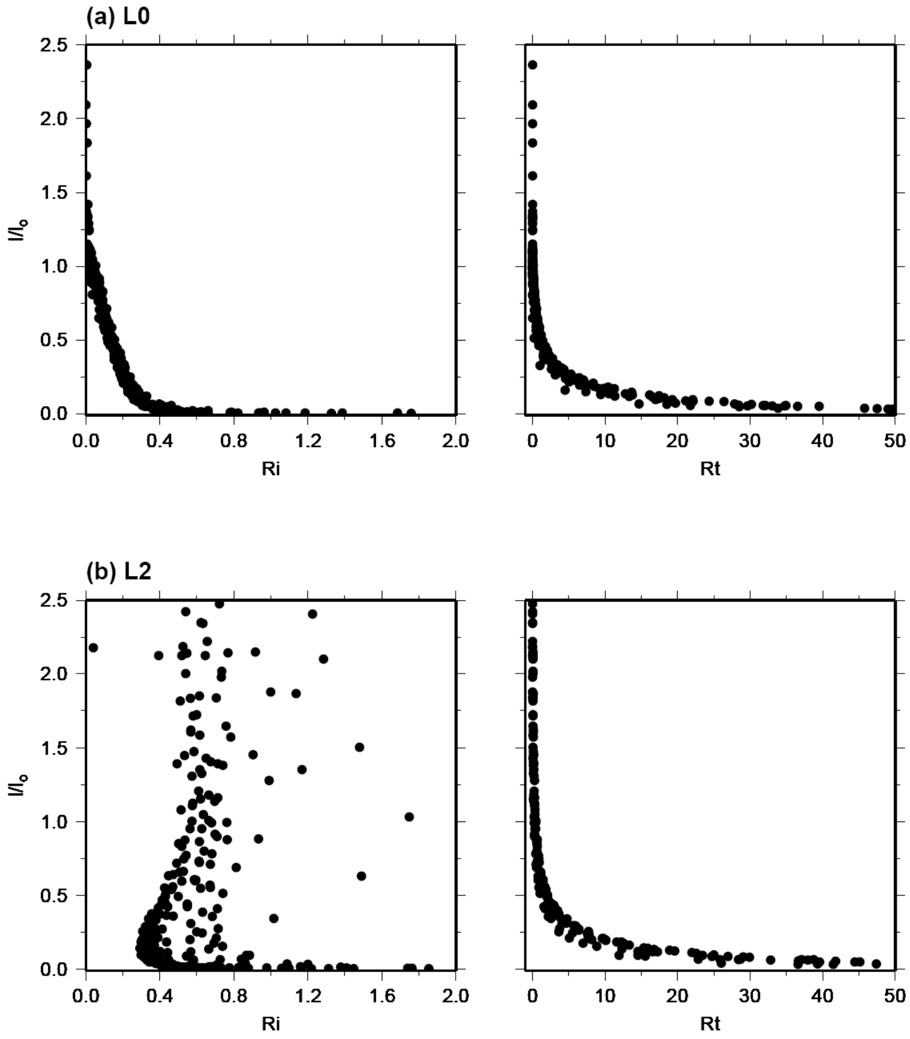
$$l / l_0 = f(\mathrm{Ri}) \qquad \mathrm{Ri} = (N / S)^2$$

- *TKE production is dominated by shear production* ($P_s - P_b - \varepsilon = 0$).

- **length scale;**

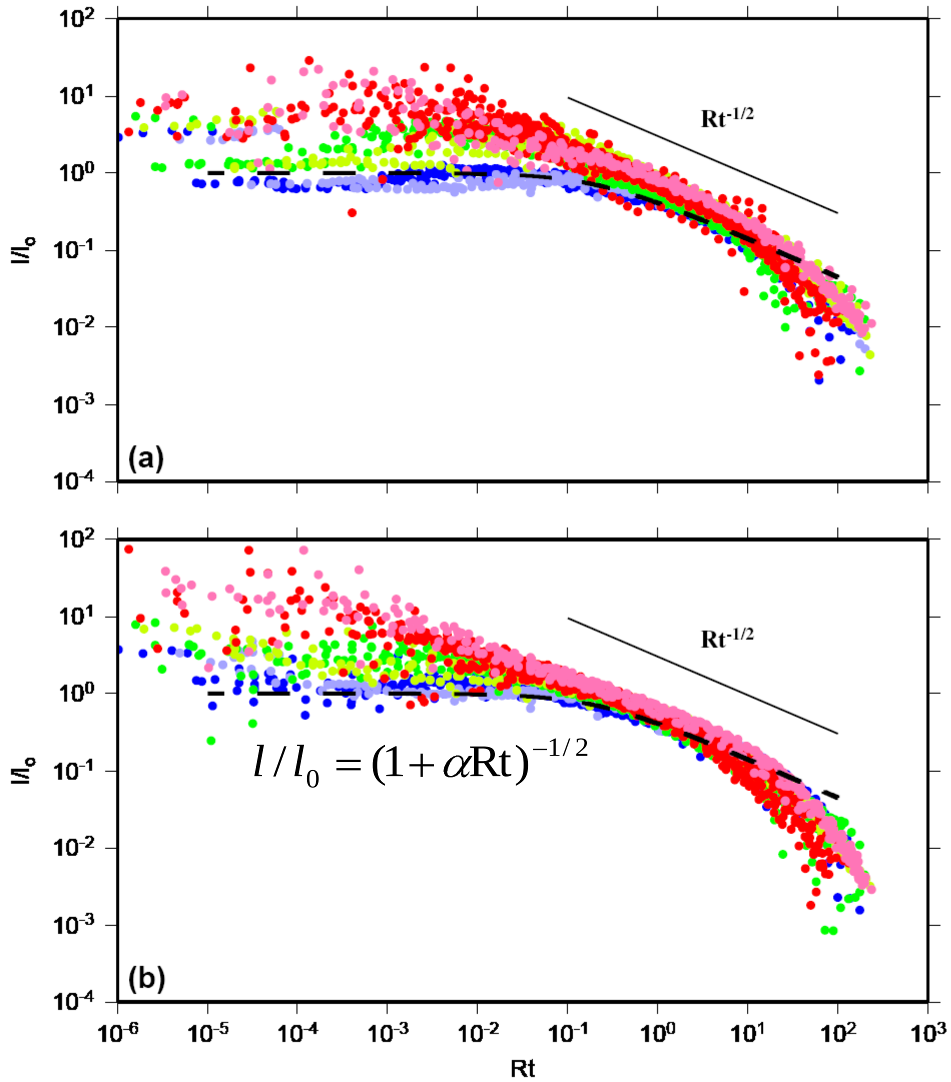
$$\frac{1}{l_0} = \frac{1}{\kappa(z + z_0)} + \frac{1}{h} \qquad \text{with } z_0 = 1 \text{ m}$$

**Mellor & Yamada (1982): z_0 = 0 m - neglect wave breaking*



Scatter plots l/l_0 vs. Ri and Rt (N3): (a) L0, (b) L2

⇒ ***Ri cannot be a parameter in the presence of LC***



L0: blue, L1: green, L2: red

Conclusion

• LC induces a significant enhancement of the mixed layer deepening, only if stratification is weak and MLD is shallow.

• Stronger vertical mixing within the ML in the presence of LC is due to much larger *l*.

• Vertical mixing must be parameterized in terms of Rt instead of Ri in the presence of LC.

• Vertical mixing in the presence of LC can be parameterized by

$$\Rightarrow \qquad l / l_0 = \gamma (1 + \alpha \gamma^2 \mathrm{Rt})^{-1/2} \qquad (\alpha \sim 5, \gamma \sim 10)$$

2. What is the Role of ***Wind Stress*** *in the Convective Deepening of the Mixed Layer ?*

Parameterization for convective deepening

- NK model [Niiler and Kraus, 1977]

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

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

- PWP model [Price et al., 1986]

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

- KPP model [Large et al., 1994]

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

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

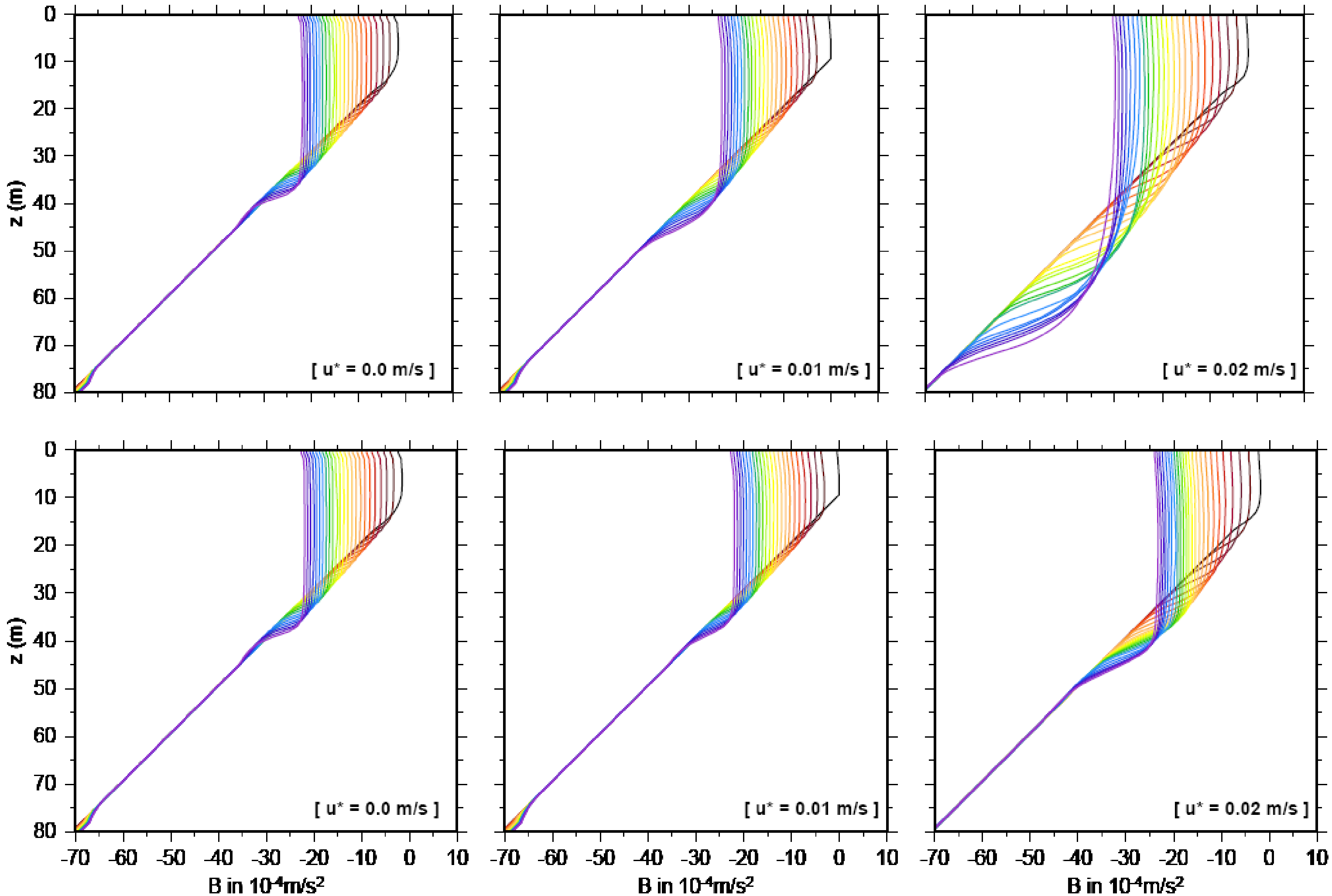
Simulations

- model domain
  - $L_x = L_y = 300$ m & $H = 80$ m
  - $\Delta x = \Delta y = \Delta z = 1.25$ m with nx = ny = 240 & nz = 64
- forcing
  - $Q_o = 1.25, 2.5, 5 \times 10^{-7}\ m^2/s^3$
  - for rotation effect : $\varphi = 0^o, 30^o, 55^o$
  - for wind stress : $u^* = 0.0, 0.01,$ & 0.02 m/s
- 12 hours integration

Buoyancy

φ = 0°

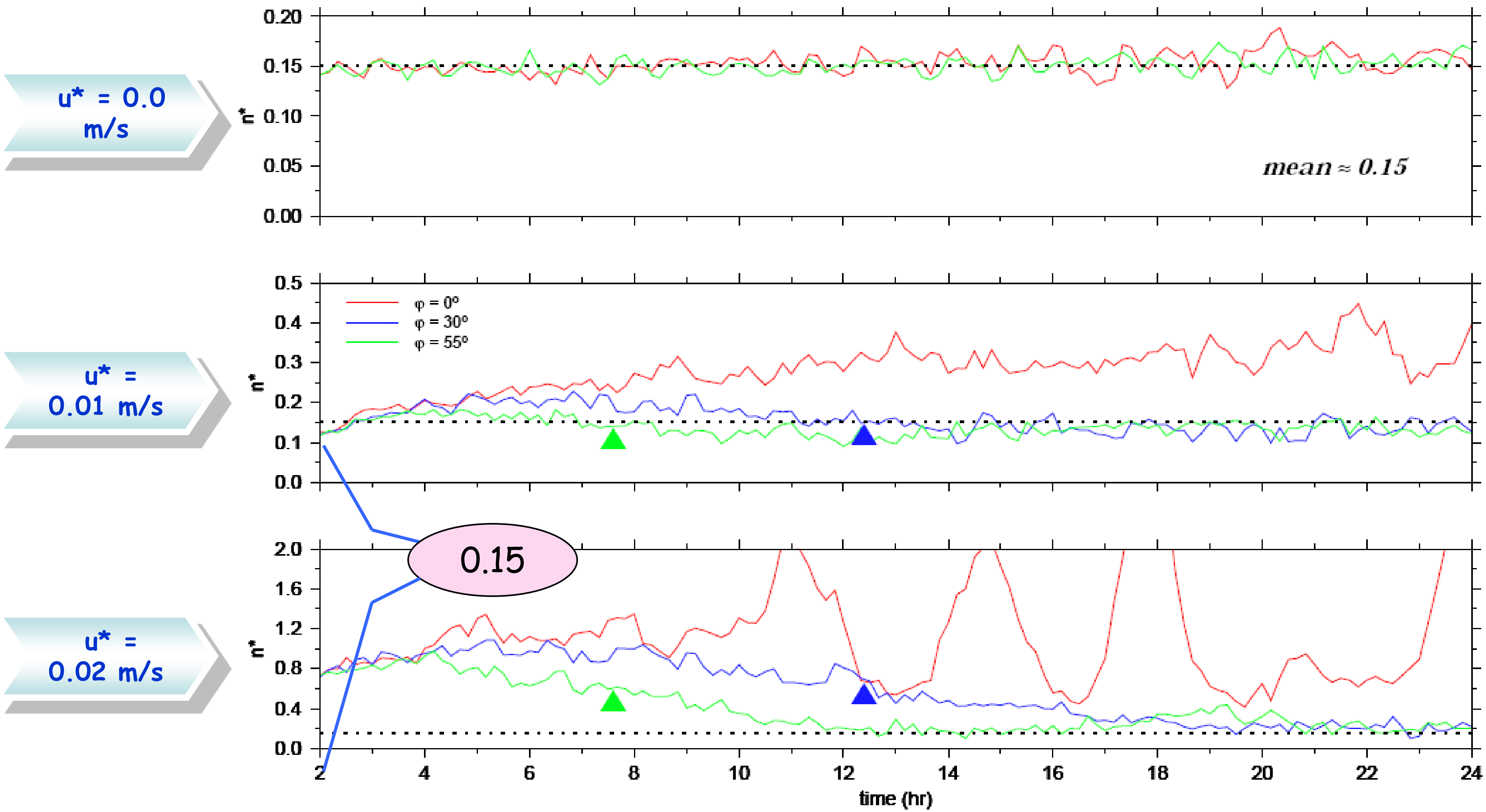
φ = 55°



$$-\overline{bw_h} = -nQ_0 + 2m_0 u_*^3/h + m_s w_e (\Delta U)^2/h \quad \text{(NK model)}$$

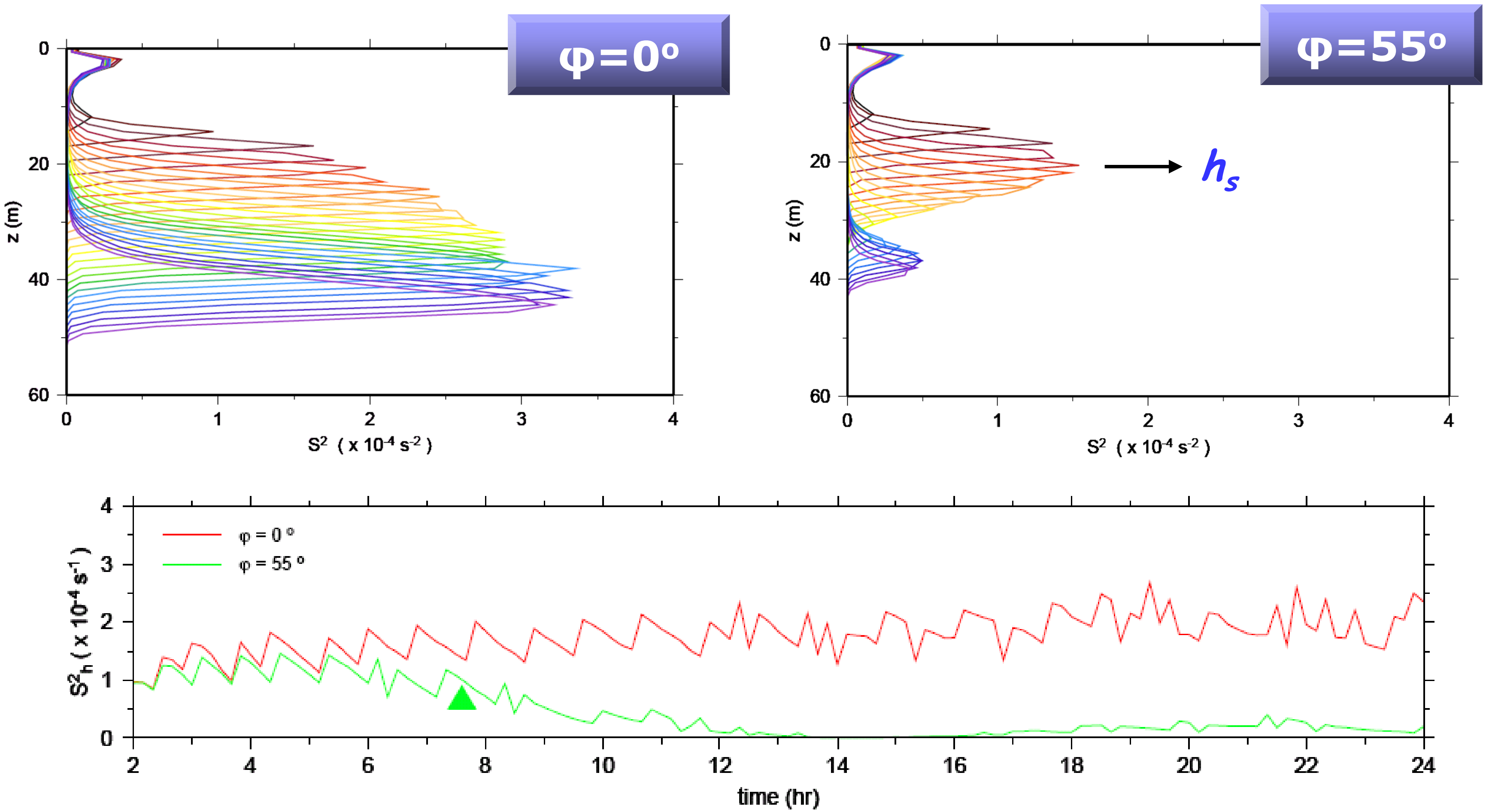
$$-\overline{bw_h} = -n^* w_*^3/h, \quad w_*^3 = Q_0 h$$

▲ : $t \sim \pi/f$

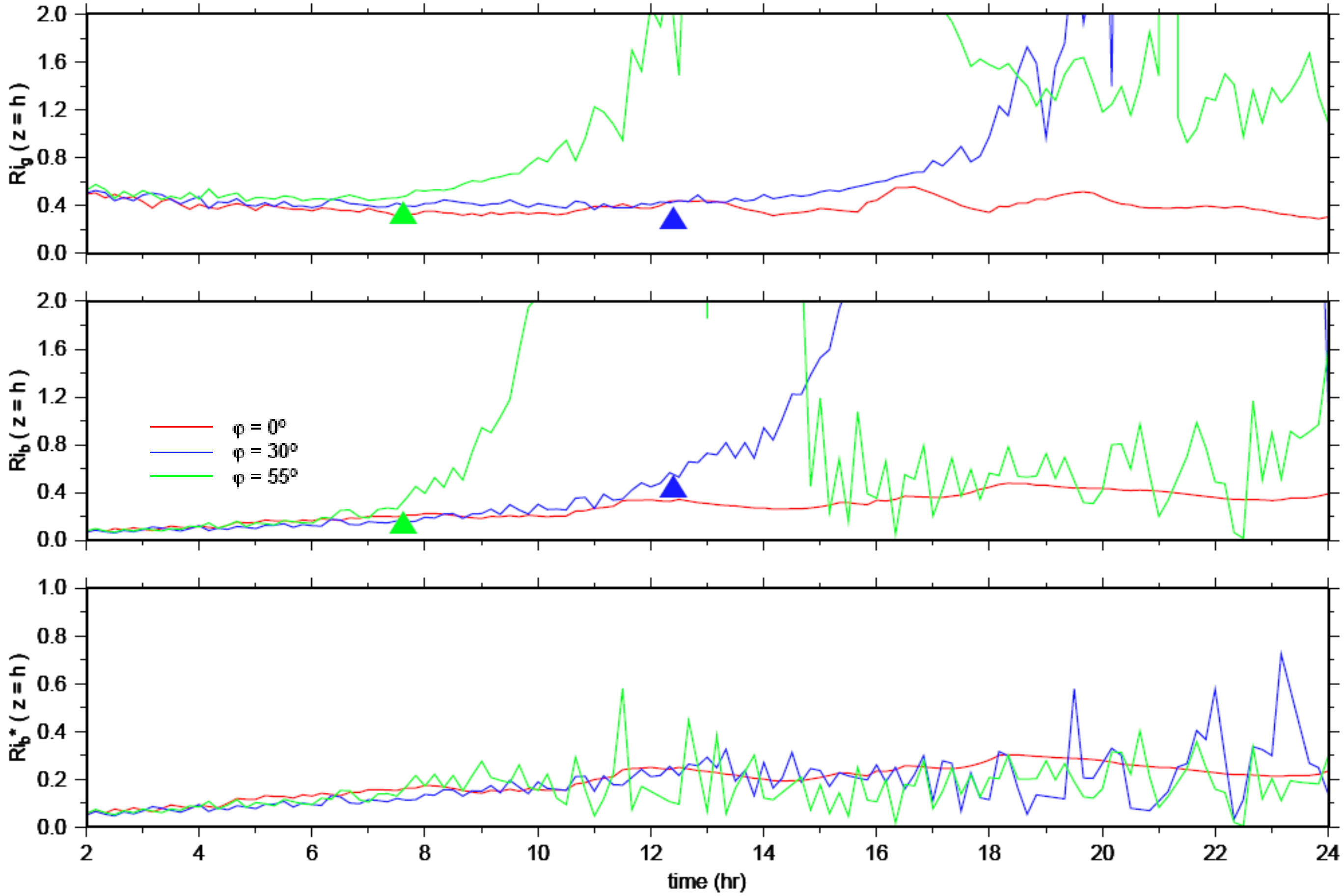


➔ *The effects of wind forcing m_0 in the NK model is overestimated in the high latitude!*

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

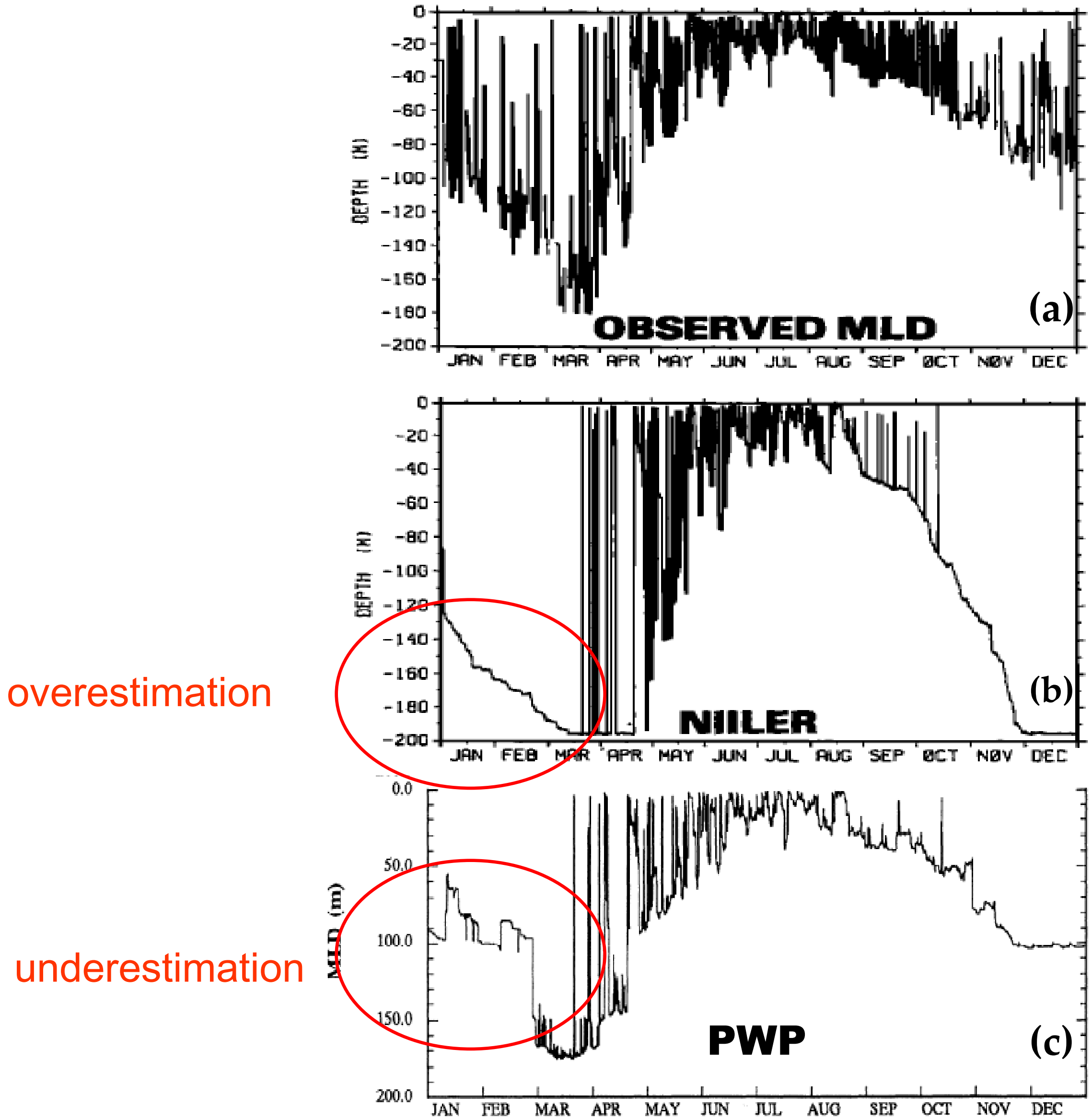


Ri_g, Ri_b, and Ri_b^* (z = h) for **u* = 0.02 m/s**



→ *The critical Ri_g and Ri_b are overestimated in the PWP model!*

The critibal Ri_b^* in the KPP model is OK!

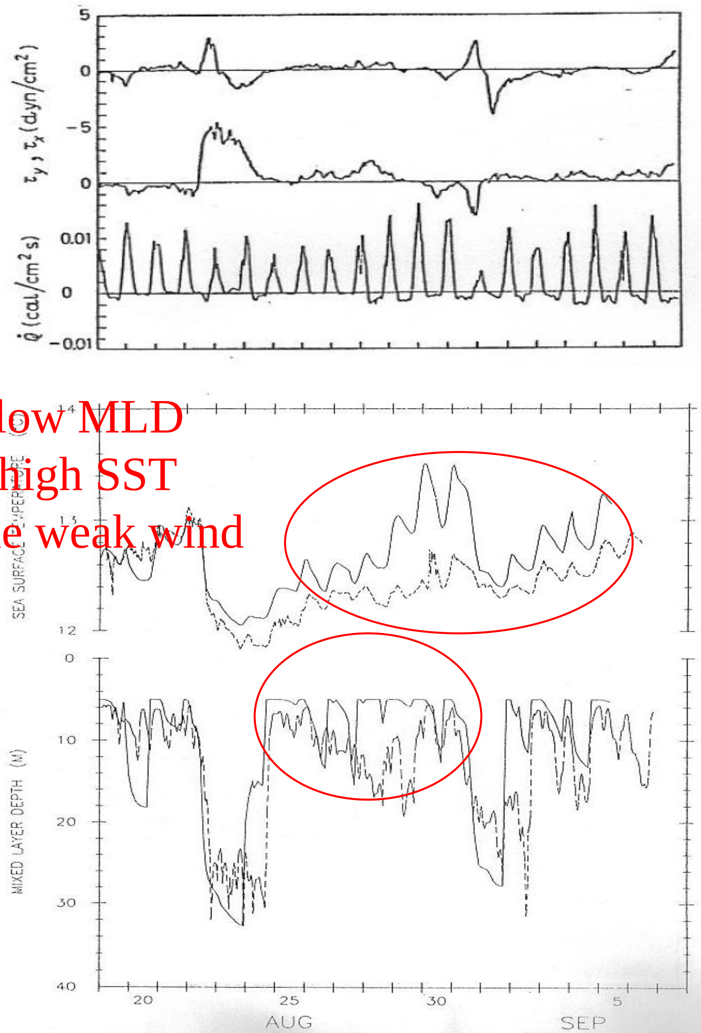


Seasonal variation of MLD simulated by NK and PWP model (Station PAPA 1961; 50 N)

Sensitivity Test of NK model

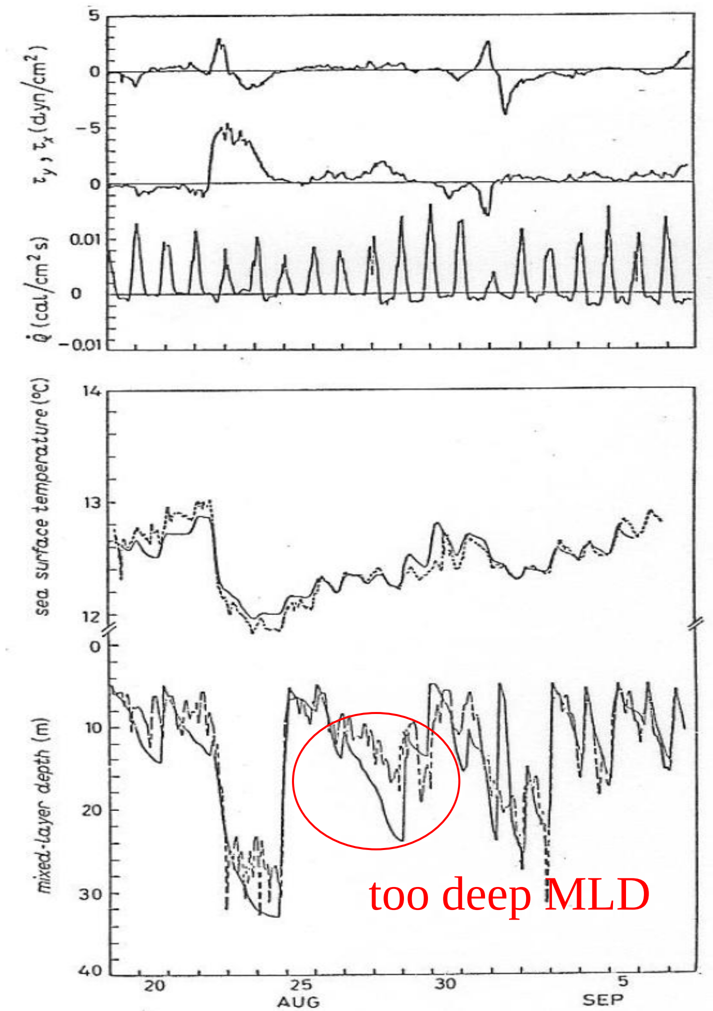
- NK model

[Davis et al., 1981]



too shallow MLD and too high SST under the weak wind

($m_0 = 0.13$, $m_s = 0.67$)



too deep MLD

($m_0 = 0.39$, $m_s = 0.48$)

Suggested Modification of NK model

$$-\overline{bw}_h = nQ_0 + \boxed{2m_0 u_*^3 e^{z/\delta} / h} + m_s w_e (\Delta \mathbf{U})^2 / h$$

effect of wave breaking and Lanmuir circulation in the near surface region

Conclusion

• In the extratropical ocean,

- the contribution from wind stress disappears after the inertial period
- the bulk and gradient Richardson number at the MLD increases rapidly with time.

→ NK model and PWP models cannot be applied.

• In the tropical ocean,

- the contribution from wind stress continues to increase until it reaches a critical value.

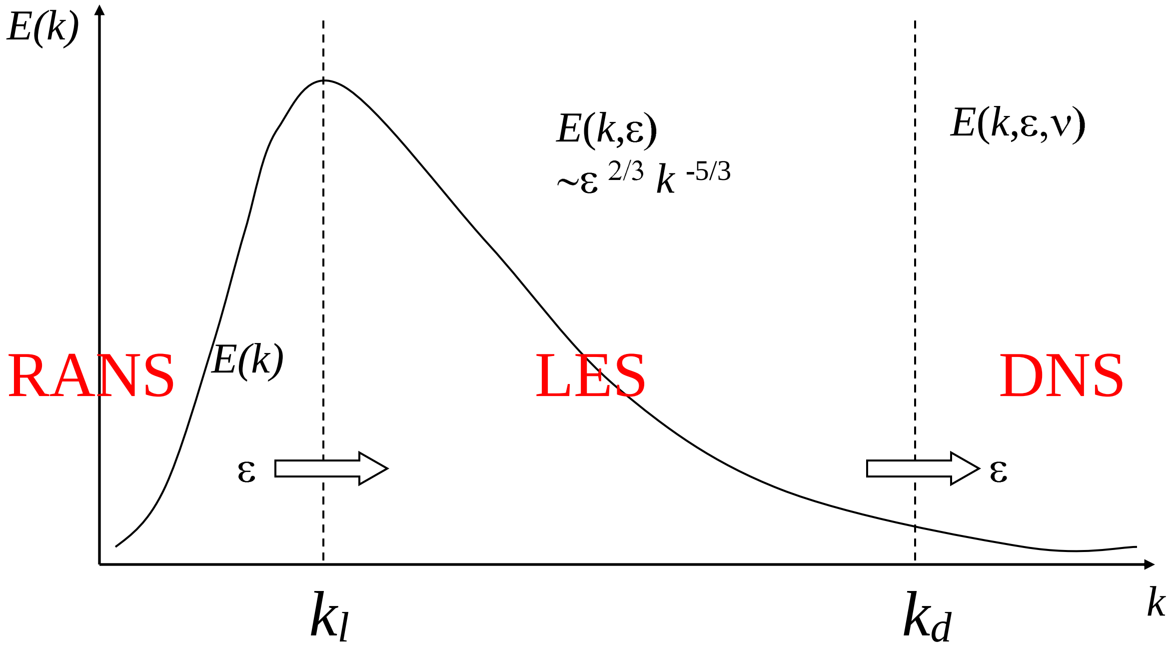
Numerical Ocean Circulation Modelling: Present Status and Future Direction (J. Willebrand & D.B. Haidvogel, in *Ocean Circulation and Climate*)

"The most pressing concern of the OGCM, particularly for global climate modeling, is the improvement of ***parameterization for SGS process****"*

"Especially, ***the surface mixed layer*** *has received special attention because of its important role in air-sea exchange"*

"A strong test of a SGS closure would involve a high-resolution simulation such as ***LES****, followed by a demonstration that a coarse resolution OGCM with the new parameterization gives qualitatively identical net results."*

What is LES?



- reproduces the realistic 3-D structure of fluctuating turbulent flows by utilizing strong computing power

- Most turbulence models of the OML apply the same assumptions and parameterizations used for the ABL.

- *Mellor and Yamada (1982), Kantha and Clayson (1994), Large et al. (1994), Klein and Coantic (1981), Andre and Lacarrere (1985), Mellor and Durbin (1975), Canuto (2001), Umlauf et al. (2004)*

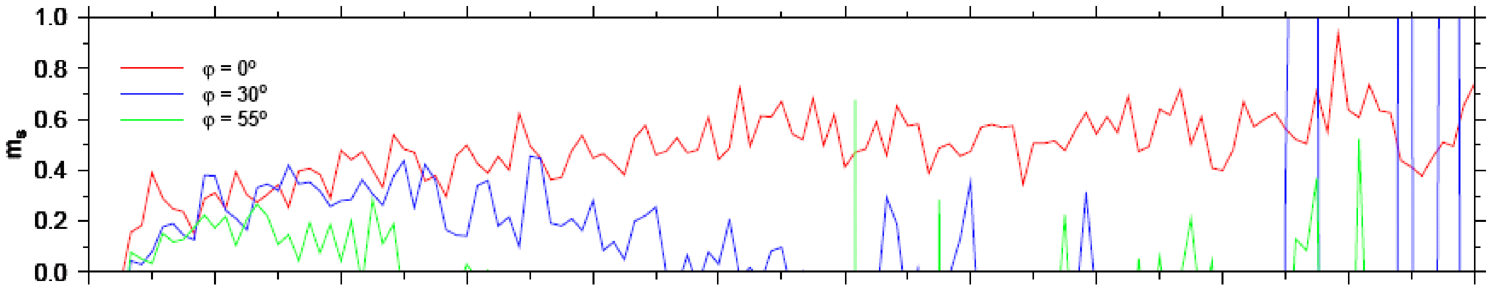
"In view of the fact that they do not explicitly incorporate the unique porcess occuring in the oceanic mixed layer, ***such as Langmuir circulation and wave breaking,*** *higher-order closure models of the oceanic mixed layer are* ***similar to geocentric pre-Copernican astronomy****, in which epicylces were added to epicycles to account for the apparent motions of the planetes"* (*E. Kunze, C. Garrett*)

$$-\overline{bw_h} = -nQ_0 + 2m_0 u_*^3/h + m_s w_e (\Delta U)^2/h$$

e.g., n = 0.21, m_o = 0.39, and m_s = 0.48 [Davis et al., 1981]

m_o = 0 with n = 0.15

u* = 0.01 m/s



u* = 0.02 m/s