LES of Geophysical Turbulence and its Application

노 의 근
(연세대 대기과학과)

LES of Geophysical Turbulence and its Application

Yign Noh
Dept. Atmospheric Sciences, Yonsei Univ.
Seoul, Korea

1. Why LES?

2. Application to Oceanography

2.1 the ocean mixed layer model

2.2 the ocean mixed layer under the heat flux

2.3 particle settling in the ocean mixed layer

2.4 open-ocean deep convection

3. Application to Meteorology

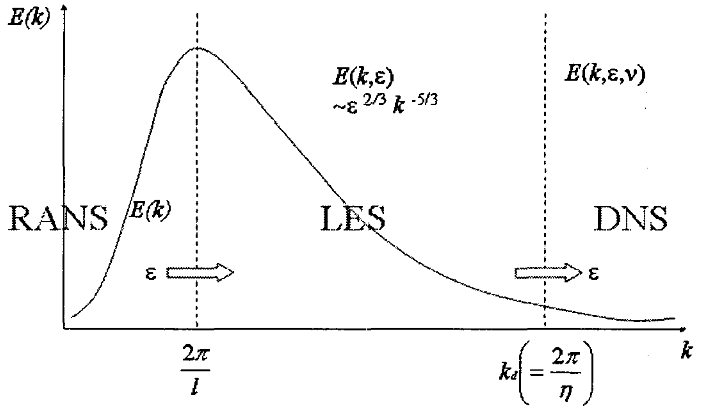
2.1 the PBL model development

2.2 heterogeneous effects in the PBL

2.3 a cumulus cloud

4. Further Application at RIAM

What is LES?



-simulate most of turbulent eddies
-parameterized turbulent eddies in the inertial subrange

We can use LES

1. **to understand the fundamental physics of turbulence**

   ex) cascade process, turbulent mixing, particle dispersion

2. **to investigate the 3-dimensioanl structure of turbulence**

   ex) coherent structure, vortices, plumes, Langmuir circulation, horizontal inhomogeneity

3. **to investigate the motion of suspended particles in tutbulent eddies simulated by LES**

4. **to provide the 'pseudo' observational data**

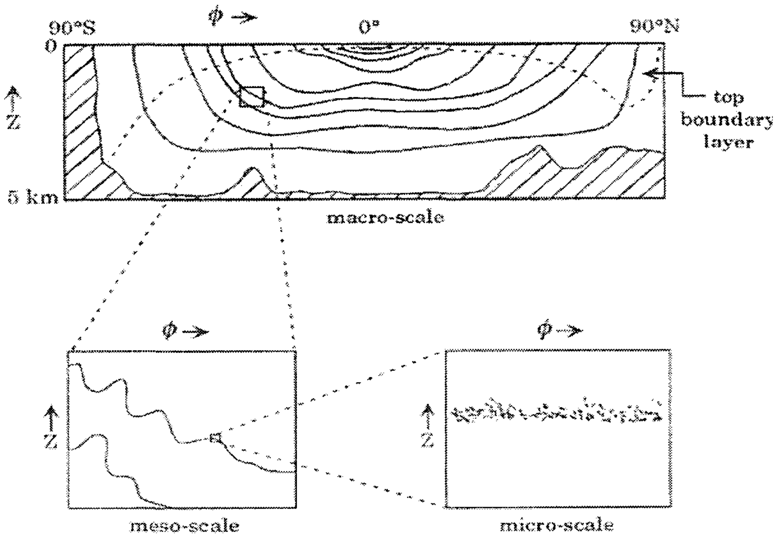
   - obtained under the ideal condition
   - provide the whole spectrum of information

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.

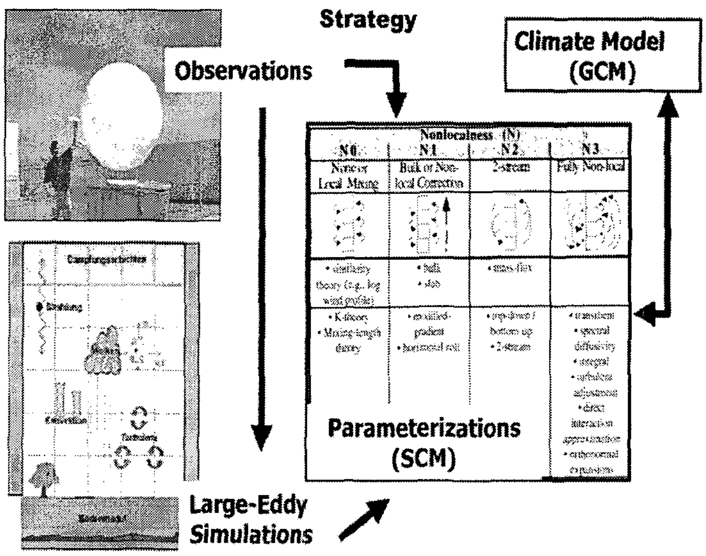
ex) OGCM - ocean mixed layer, ocean deep convection,
meso-scale eddies,
AGCM – atmospheric boundary layer, cumulus convection,
cloud microphysics,
Biogeochemical Model
- particle flux and biogeochemical process in the ocean
- aerosol and chemical process in the atmosphere



Verification of the SGS Parameterization (e.g., Ocean Mixed Layer)

1. Comparison with the observation data
2. Improvement of the OGCM results with a new mixed layer model
3. Analysis of more realistic turbulence simulation results,i.e., LES
   - *One can examine not only the performance of the model, but also the hypotheses used in the model.*
   - *One can examine the model under the ideal condition.*

Max-Planck-Institut für Meteorologie



Parallel Large eddy simulation Model (PALM)

(*Univ. Hannover, Germany/Yonsei Univ., Korea*)

- **equation**

$$\frac{\partial \overline{u_i}}{\partial t}+\overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j}=-\varepsilon_{ijk}f_{ijk}\overline{u_k}+g\frac{\overline{\theta}-\theta_0}{\theta_0}\delta_{i3}-\frac{1}{\rho_0}\frac{\partial p}{\partial x_j}-\frac{\partial}{\partial x_j}\overline{u_i'u_j'}$$

$$\frac{\partial \overline{u_j}}{\partial x_j}=0$$

$$\frac{\partial \overline{\theta}}{\partial t}+\overline{u_i}\frac{\partial \overline{\theta}}{\partial x_j}=-\frac{\partial}{\partial x_j}\overline{u_j'\theta'}$$

- **SGS parameterization (Deardorff scheme)**

$$\frac{\partial \overline{e}}{\partial t}+\overline{u_j}\frac{\partial \overline{e}}{\partial x_j}=-\left(\overline{u_i'u_j'}\right)\frac{\partial u_i}{\partial x_j}+\frac{g}{\theta_0}\overline{u_j'\left(e'+\frac{p'}{\rho_0}\right)}-\varepsilon$$

$$\overline{u_i'u_j'}=K_m\left(\frac{\partial \overline{u_i}}{\partial x_j}+\frac{\partial \overline{u_j}}{\partial x_i}\right)-\frac{2}{3}\overline{e}\delta_{ij}$$

$$\overline{u_i'\theta'}=-K_h\frac{\partial \overline{\theta}}{\partial x_i}$$

$$\overline{u_i'\left(e'+\frac{p'}{\rho_0}\right)}=-2K_m\frac{\partial \overline{e}}{\partial x_j}$$

$$K_m=-0.10l\sqrt{e}$$

$$K_h=\left(1+\frac{2l}{\Delta s}\right)K_m$$

$$l=\Delta s=(\Delta x\Delta y\Delta z)^{\frac{1}{3}}$$

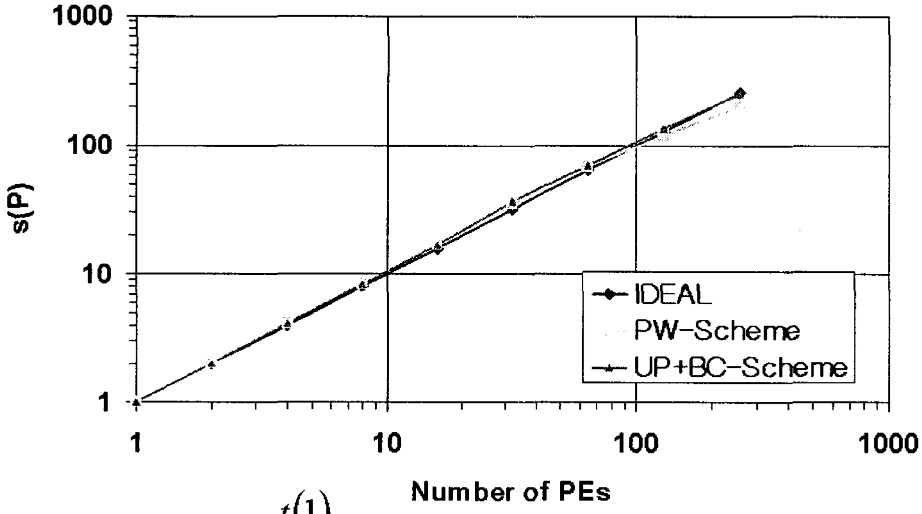
$$l=\min\left[\Delta s, 0.76\sqrt{e}\left(\frac{g}{\theta}\frac{\partial \overline{\theta}}{\partial z}\right)^{-\frac{1}{2}}\right]$$

$$\varepsilon=C\frac{e^{-2/3}}{l}$$

$$C=0.19+0.51\frac{l}{\Delta s}$$

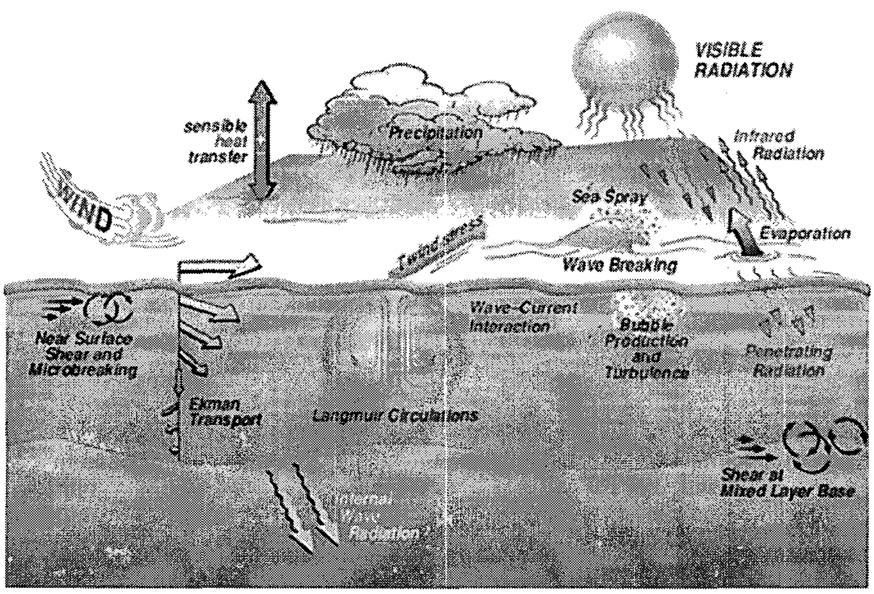
Scalability and performance

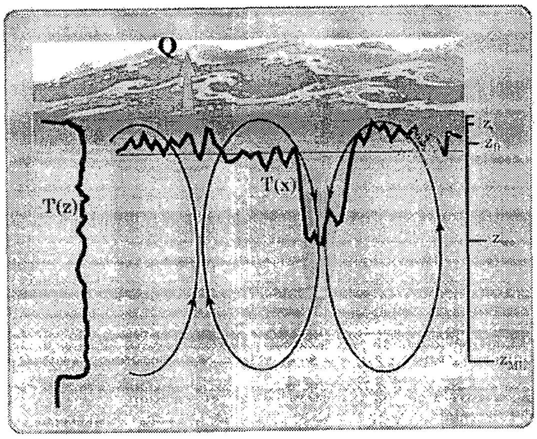
✓ Results for SGI/Cray-T3E (160*160*64 gridpoints)



speedup: $s(P) = \dfrac{t(1)}{t(P)}$

2.1 Ocean Mixed Layer





Sketch of processes relevant for near-surface temperature fine structure

What are the roles of wave breaking and Langmuir circulation in the turbulent structure in the ocean mixed layer?

LES of the Ocean Mixed Layer

- Parallel Large Eddy Simulation Model (PALM; Hannover/Yonsei)
- Inclusion of the effects of Langmuir circulation and wave breaking
- Noh et al. (JPO 2004)

♣ Equation

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho_0}\frac{\partial p_i}{\partial x_i} + g\frac{\rho - \rho_0}{\rho_0}\delta_{i3} - \frac{\partial}{\partial x_j}\overline{u_i' u_j'} - \varepsilon_{ijk} f_j (u_k + v_{sk})$$

$$+ \varepsilon_{ijk} v_{sj} w_k + F(k, z, u_*)$$

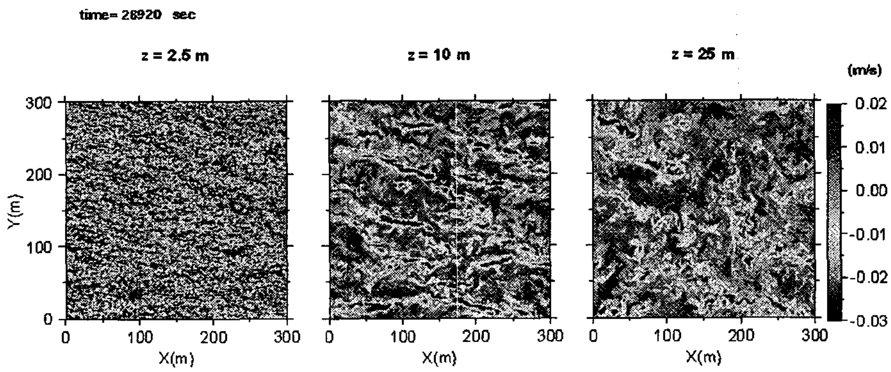
$$\# \quad F(k, z; u_*) = \frac{\alpha u_*}{\tau} G(x, y, t)\delta(k - 2\pi / z_0)\delta(z)\delta(1 - \delta_{i3}),$$

$G(\mu;\sigma)$ = Gaussian random function with mean μ and variation σ^2

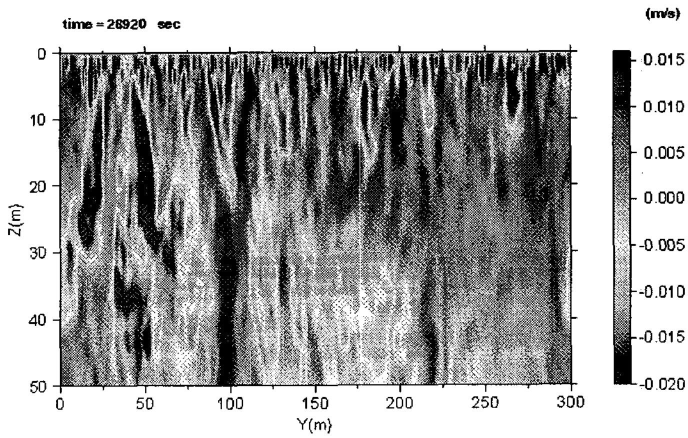
z_0 = length scale of eddy at z = 0 (= 1.25 m)

❖$_s$ = Stocks velocity

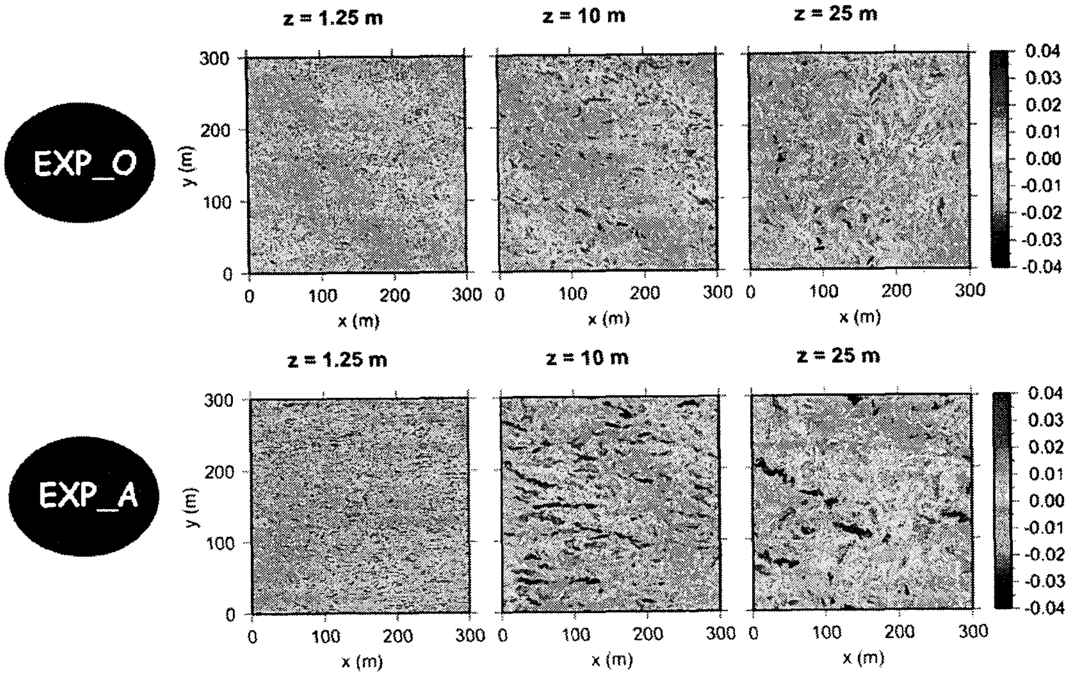
= $\left(\pi \frac{h}{\lambda}\right)^2 \sqrt{\frac{g\lambda}{2\pi}} \exp\left(-\frac{4\pi z}{\lambda}\right)$ (h = wave height, λ = wave length)



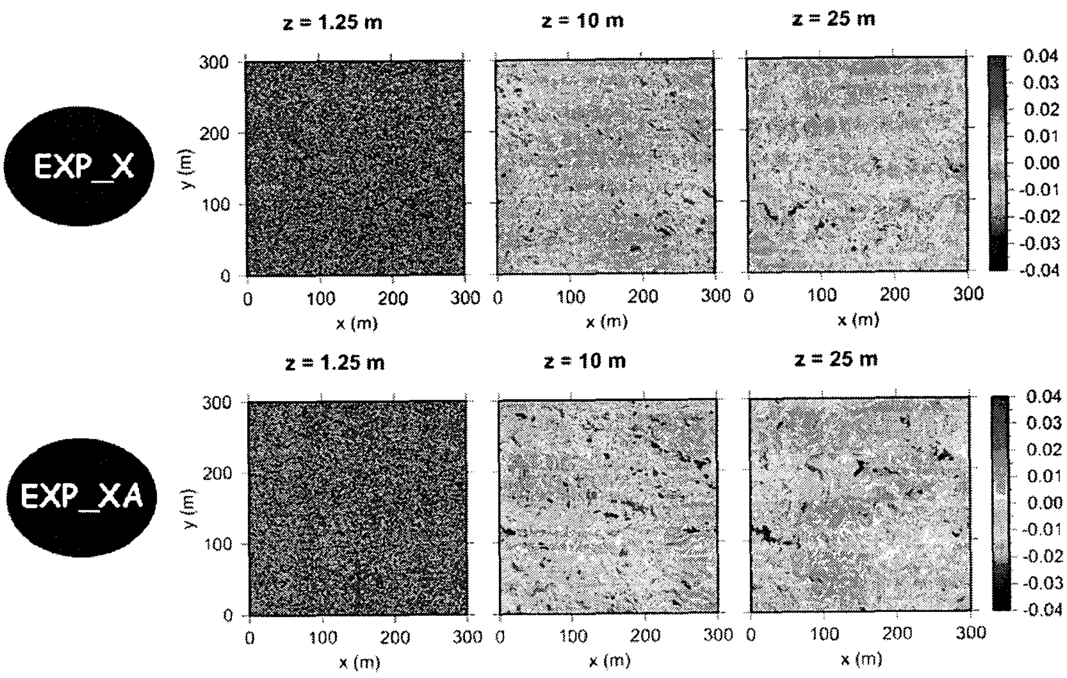
SBH_homo; w (H= 1.0, α = 0.8, u_* = 0.01, Q_0 =0)



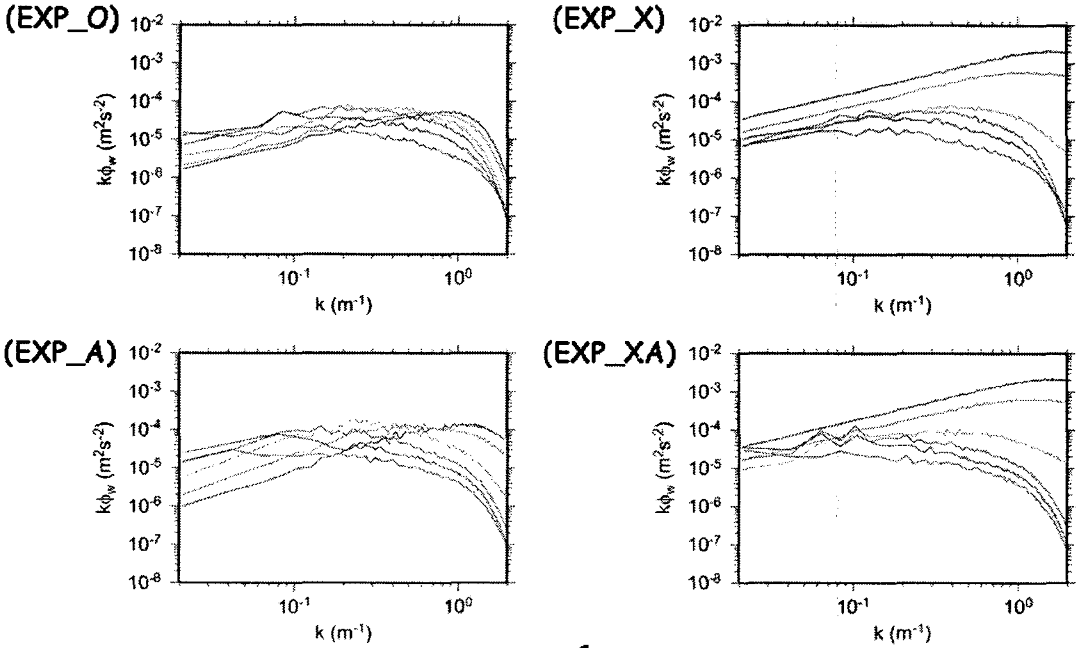
SBH_homo; w (H= 1.0, α = 0.8, u_* = 0.01, Q_0 =0)



Horizontal cross-section of vertical velocity(W) (m/s);
EXP_O (no WB & LC), EXP_A (LC only)

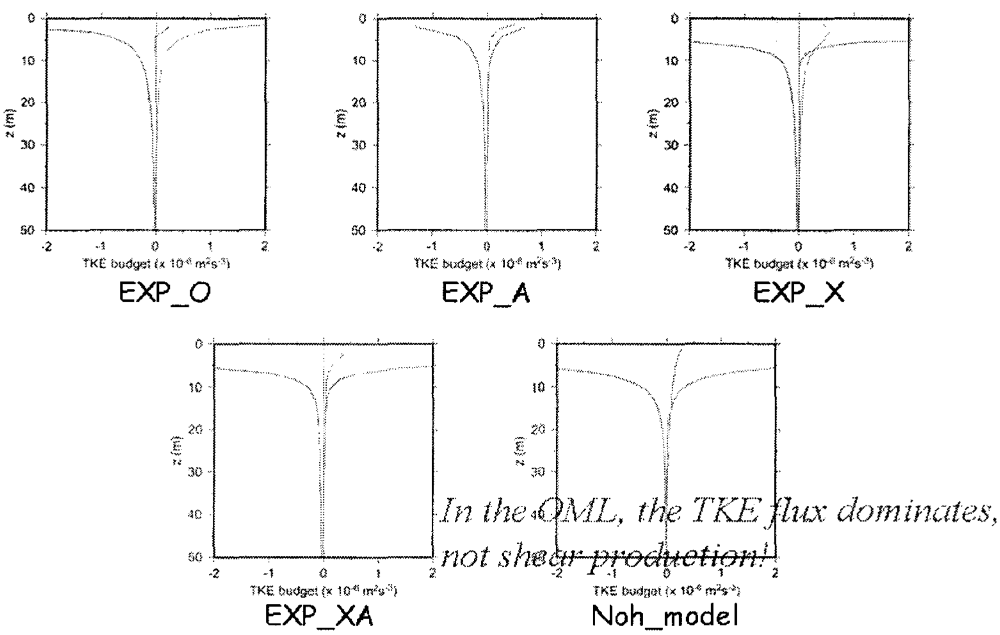


Horizontal cross-section of vertical velocity(W) (m/s);
EXP_X (WB only), EXP_XA (both WB & LC)



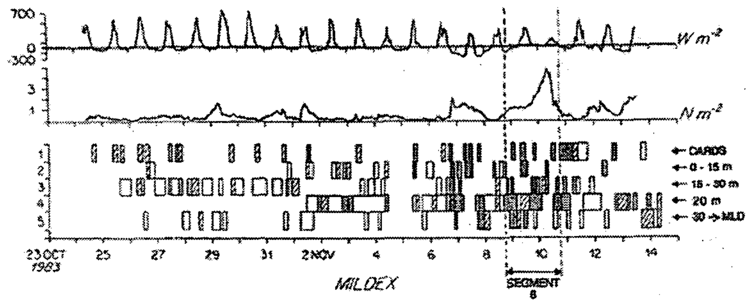
y-component of spectrum

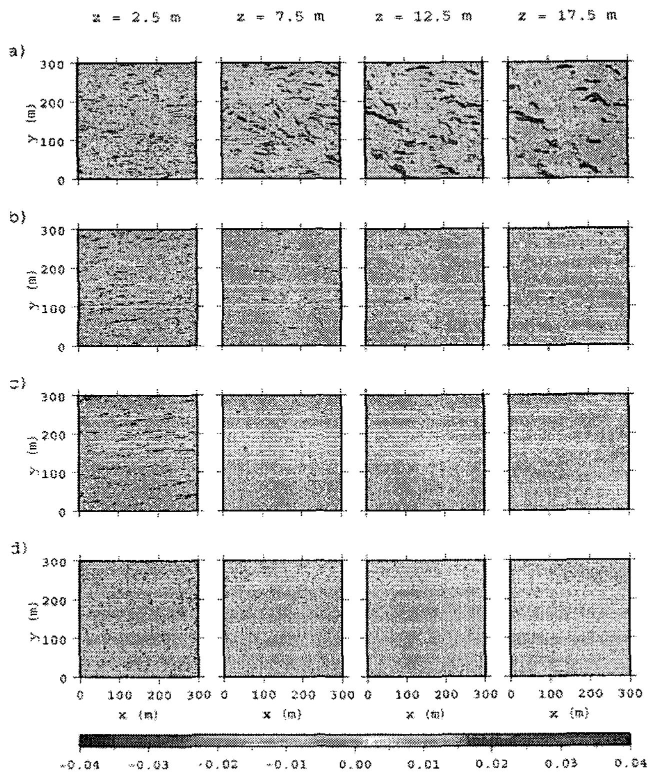
(1.25 m, 2.5 m, 7.5 m, 12.5 m, 25 m, 50 m)



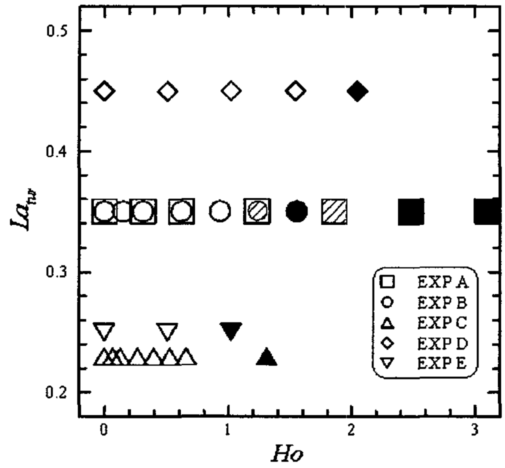
Fig; TKE budget (TKE flux, shear production, dissipation)

2.2 Ocean Mixed Layer under the Surface Heating



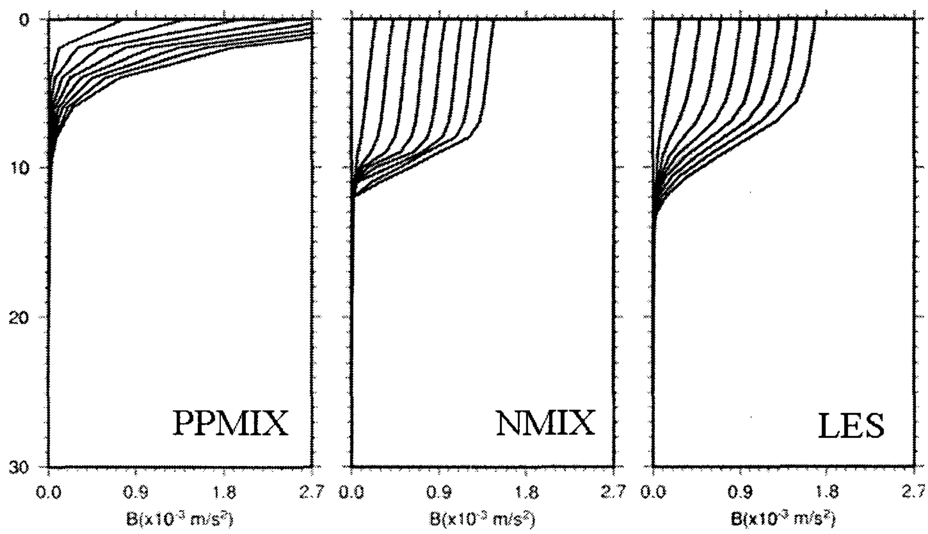


Destruction of LC with increasing heating

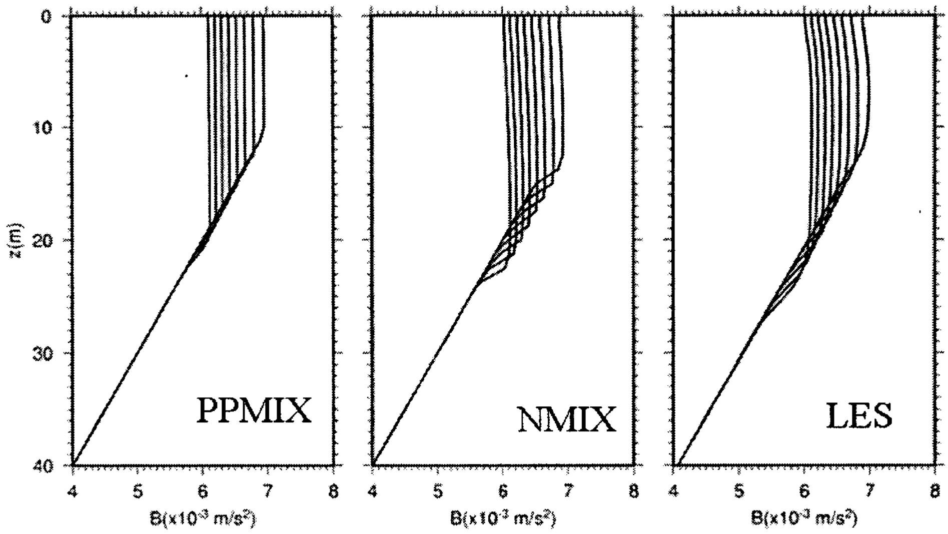


A regime diagram for the breakdown of LC

⇨ $Ho_c\ (= 2B_0/kU_s u_*^2) \sim 1 - 2$



Evolution of temperature profiles under the heating

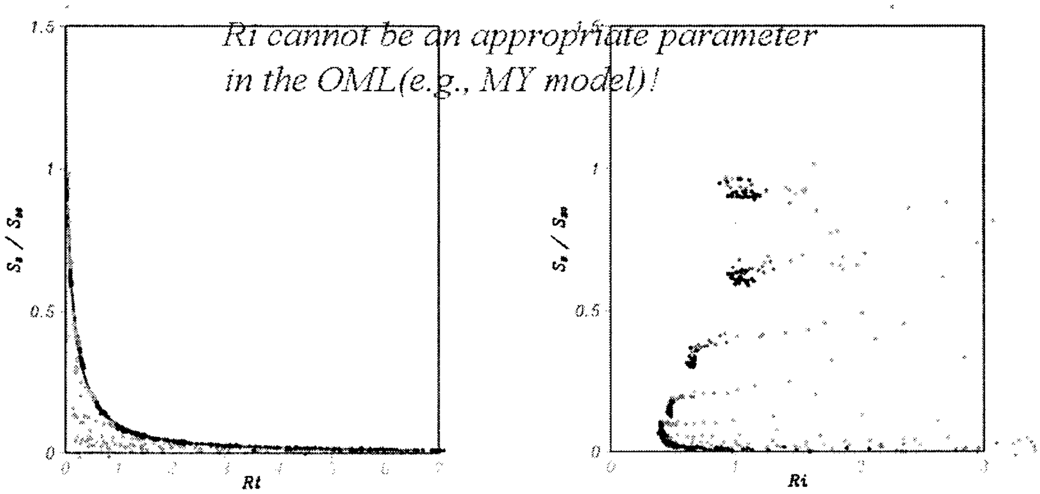


Evolution of temperature profiles under the cooling

- •PPMIX - convective adjustment only
- •NMIX- convective adjustment + entrainment

Effects of Stratification on K_h

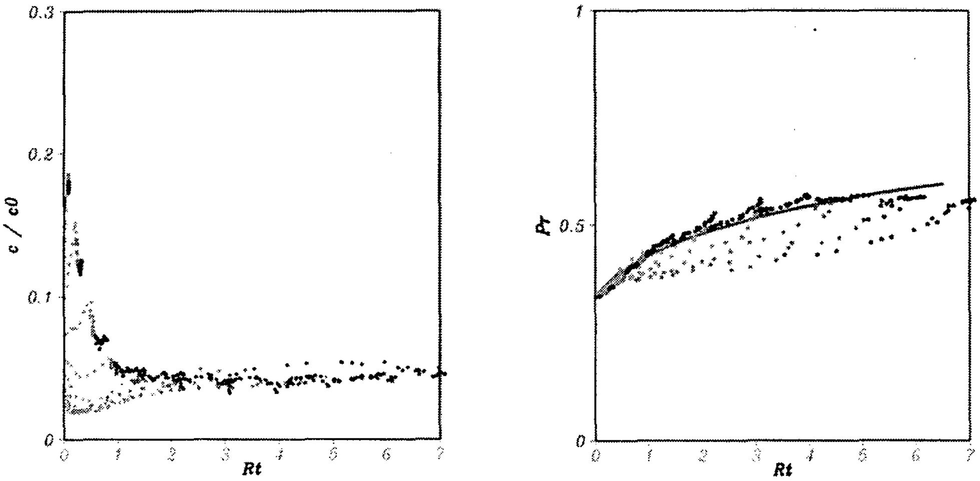
Ri cannot be an appropriate parameter in the OML(e.g., MY model)!



$$K_B = S_B q l$$

$$S_B = S_{B0}(1 + \alpha Rt^2)^{-1/2}$$

$$-\overline{bw} = K_B \frac{\partial B}{\partial z}$$

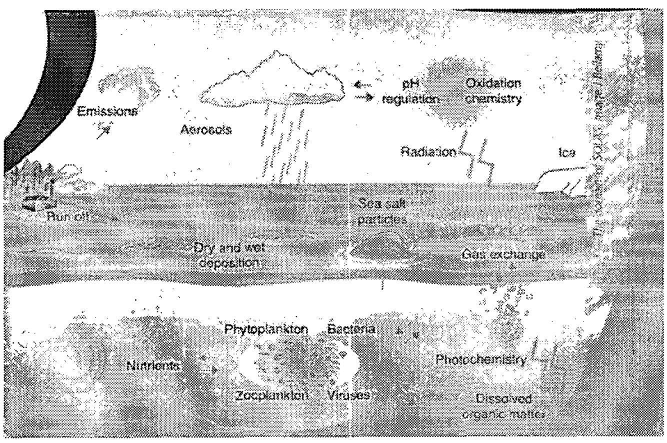


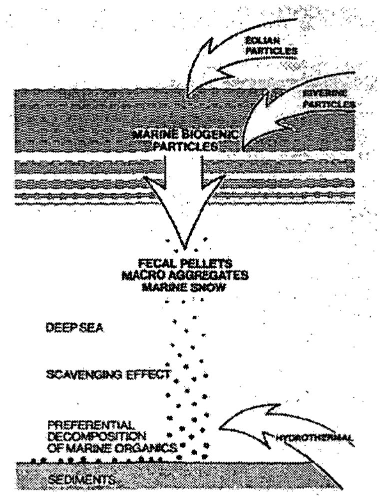
$$\mathrm{Pr} = \mathrm{Pr}_0(1+\alpha_p Rt)^{1/2} \qquad \alpha_p \cong 0.5$$

Effects of Stratification on ε and Pr

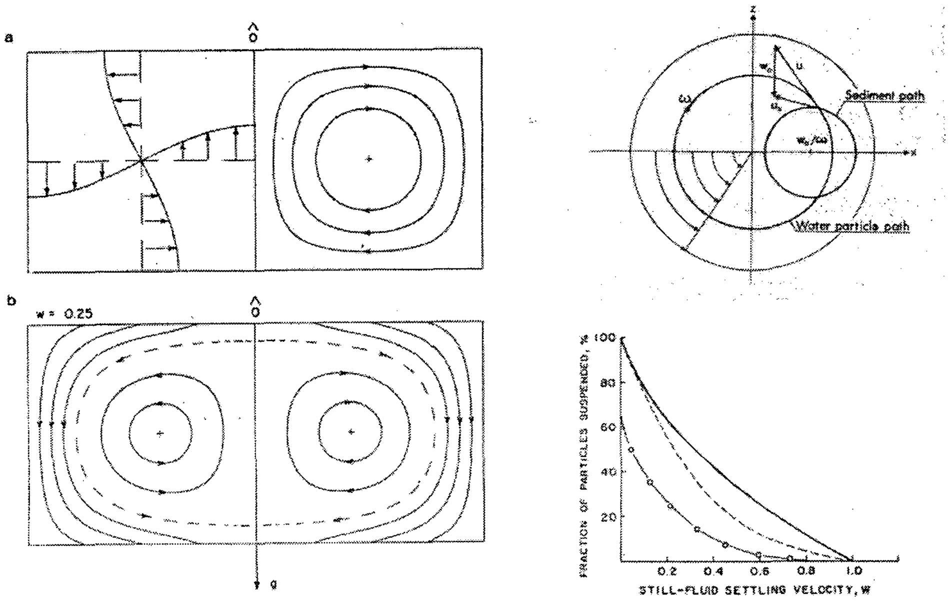
2.4 Particle Settling in the Ocean Mixed Layer

(Noh et al. *JFM*, submitted)





biological pump by particle flux



Stommel (1949), Maxey and Riley (1986);
- Partilces can be suspended indefinitely in the presence of large vortices

◆ Motion of a Particle

$$\frac{dV_i}{dt} = \frac{1}{\tau_p}(u_i - V_i) + g'\delta_{i3}$$

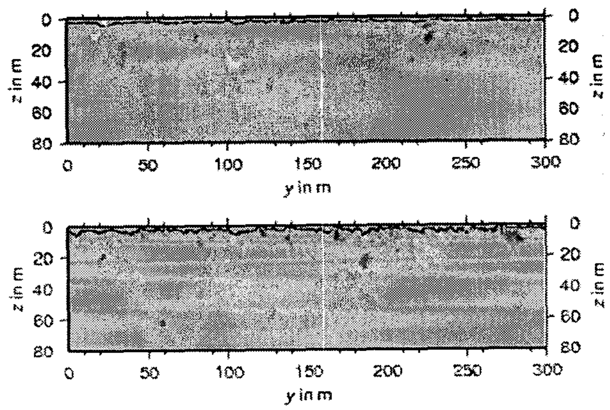
$$\tau_p = \frac{2\rho_p a^2}{9\rho_f \nu}$$: responding time scale (Re << 1)

$$g' = \frac{\rho_p - \rho_f}{\rho_p} g$$: reduced gravity

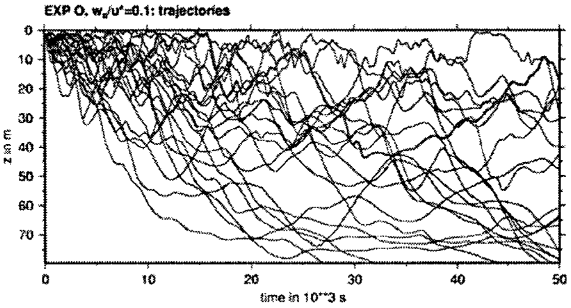
V_i: Lagrangian velocity of a particle
u_i: Eulerian velocity of a fluid
a: the radius of a particle
ρ_p : density of a particle
ρ_f : density of a fluid

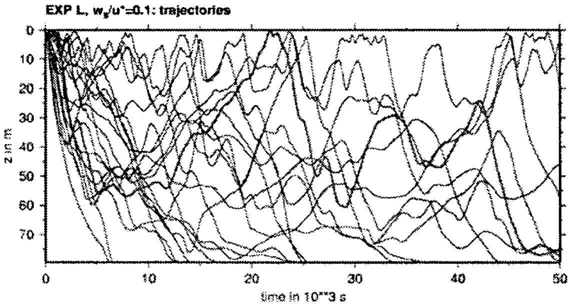
In the still fluid ($u_i = 0$),

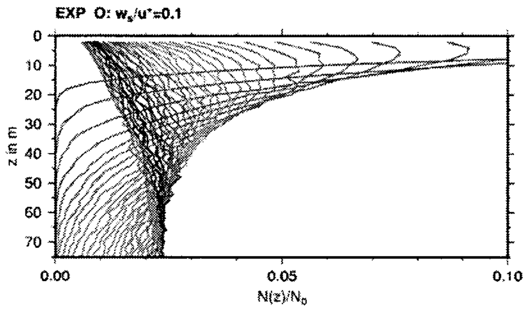
$$W = w_s (= \tau_p g')$$

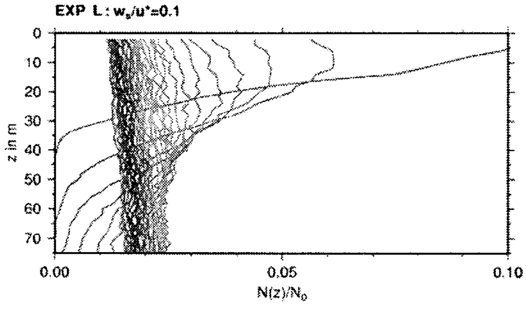


(a) EXP O, (b) EXP L (Langmuir circulation)

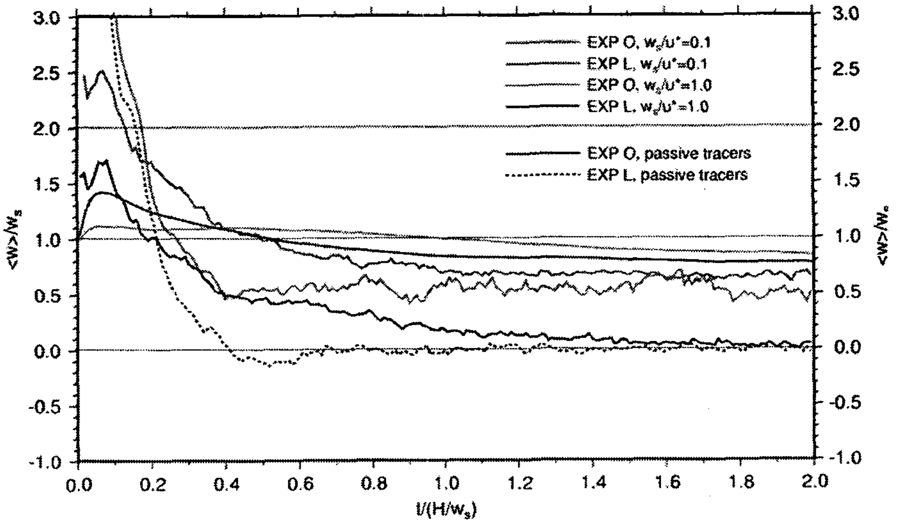

EXP O, w_s/u^*=0.1: trajectories
z in m
time in 10**3 s


EXP L, w_s/u^*=0.1: trajectories
z in m
time in 10**3 s


EXP O: w_s/u^*=0.1
z in m
$N(z)/N_0$

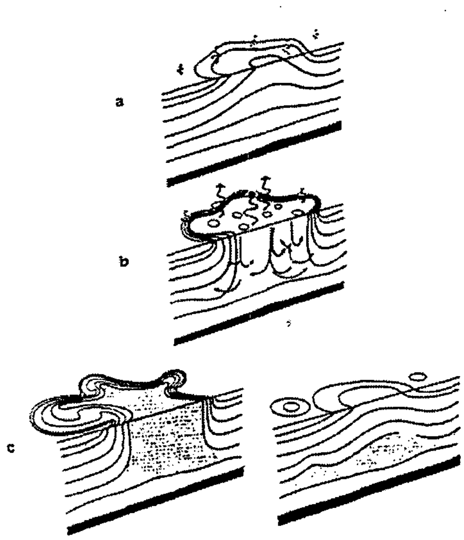

EXP L : w_s/u^*=0.1
z in m
$N(z)/N_0$

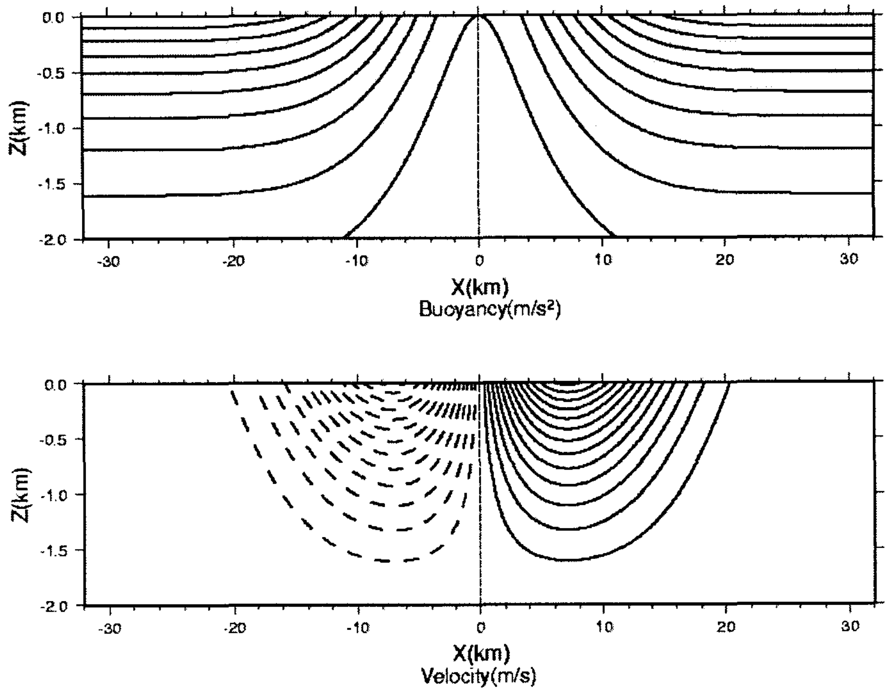
EXP O/L: <w>/w_s



2.3 Open-Ocean Deep Convection

(Noh et al. *JPO* 2003)





Preconditioning for the onset of the open-ocean Deep Convection

Experiment

- preconditioning

$$b = Ae^{-\beta z}\left[1 - \mathrm{R}e^{-(r/l)^2}\right]$$

$$u_\theta = 2\frac{AR}{f\beta l^2}re^{(r/l)^2}\left(e^{-\beta z} - e^{-\beta H}\right)$$

$\beta = 10^{-3}m^{-1}$ $\quad l = 10^4 m$

❖ L = eddy size
R = intensity of eddy
A , β → background stratification

- surface buoyancy flux;

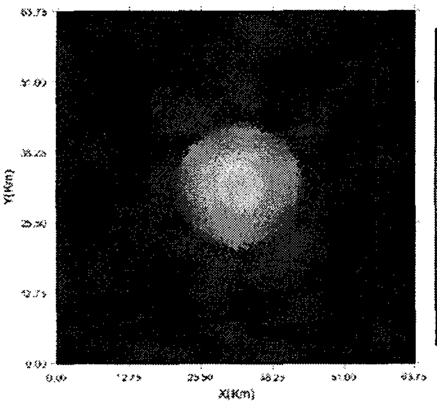
  $B = 10^{-7}$ m²s⁻³

- dimensions

  L = 64 km , H = 2km

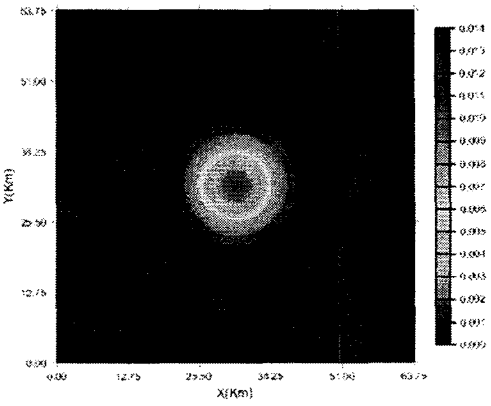
  Δx = 250 m , Δz = 100m (256×256×20)

$A = 0.3 \times 10^{-4} ms^{-2}$



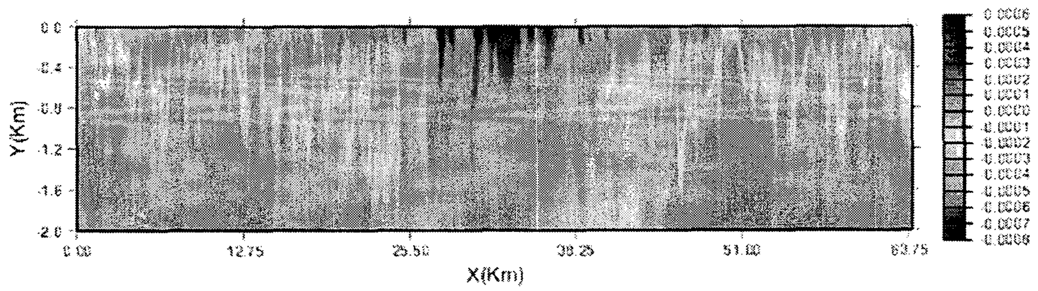
distributed convection

$A = 6.7 \times 10^{-4} ms^{-2}$

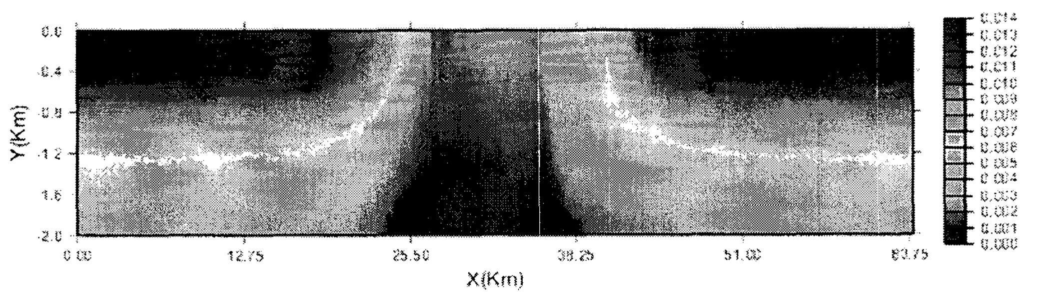


localized convection
- generation of baroclinic eddies

Horizontal cross section of potential temperature

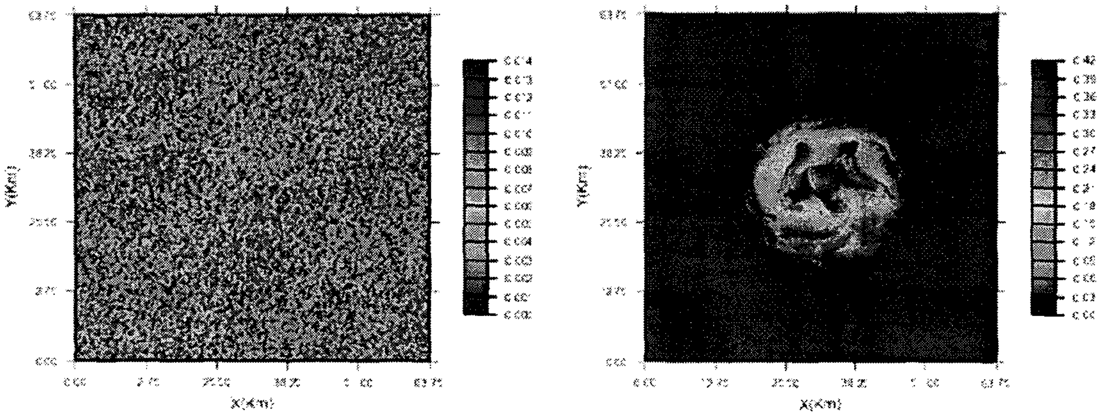


R = 0.9, A = 0.3 × 10^{-4}



R = 0.9, A = 6.7 × 10^{-4}

Fig. Vertical cross-section of potential temperature (θ-300K)

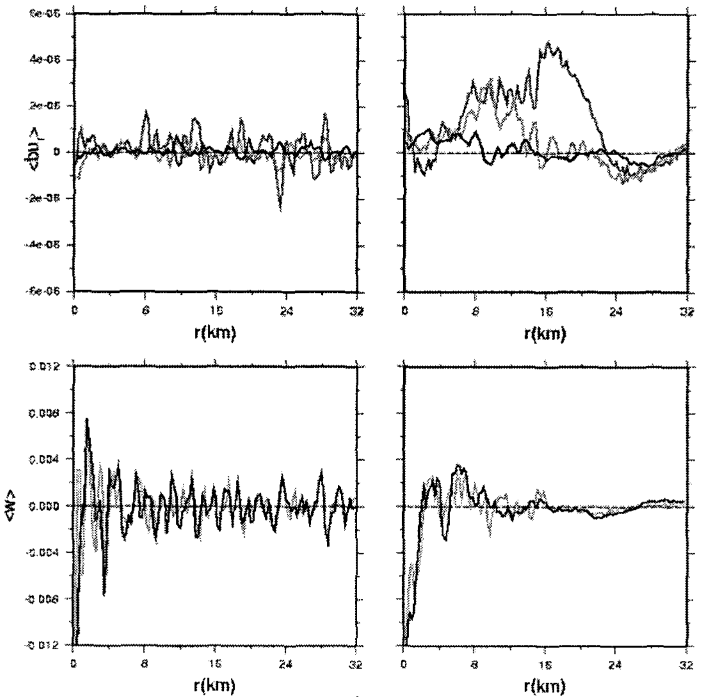


A = 0.9
R = 0.3 × 10^{-4}

A = 0.9
R = 6.7 × 10^{-4}

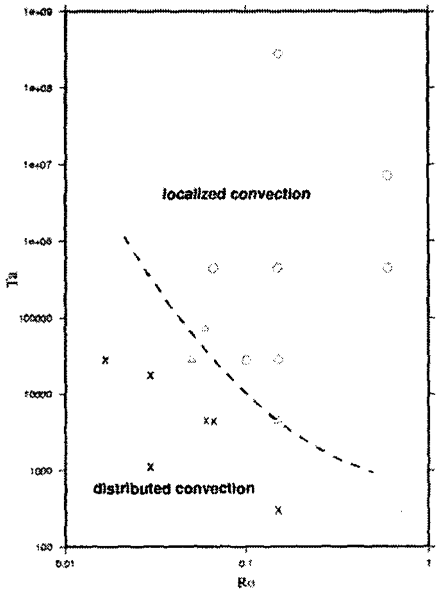
Fig. Horizontal cross section of $U^2 + V^2$

Fig; $<bu_r>$,$<w>$
at t = 4(day)



$R = 0.9$ $A = 0.3\times10^{-4}$ $R = 0.9$ $A = 6.7\times10^{-4}$

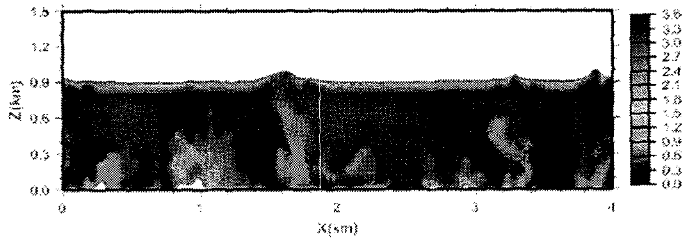
z = - 50m(red), z = - 450m(green), z = -950m(blue line)



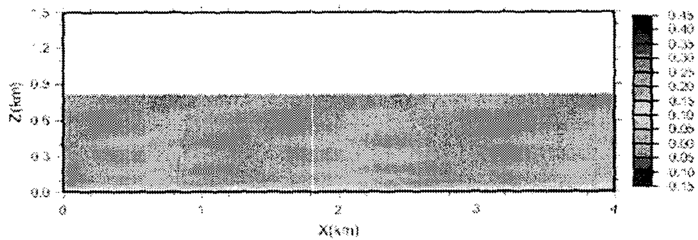
A regime diagram of convection pattern

3.1 PBL Modeling

(Noh et al. *BLM* 2003)



convective boundary layer



shear-driven boundary layer

Troen & Mahrt Model (*BLM*, 1986)

- ✓ K-profile model

  (KPP model for the ocean mixed layer)

- ✓ Non-local mixing

$$-\overline{w'u'} = K_m\left(\frac{\partial u}{\partial z} - \gamma_m\right) \qquad -\overline{w'\theta'} = K_h\left(\frac{\partial \theta}{\partial z} - \gamma_h\right)$$

$$K_m = w_s h k \frac{z}{h}\left(1 - \frac{z}{h}\right)^2, z > \varepsilon h \qquad K_h = \Pr^{-1} \times K_m$$

$$w_s = \left(u_*^3 + 7\varepsilon k w_*^3\right)^{1/3}$$ ⇒ by matching $K_m = u_* kz \Phi_m^{-1}(z/L)$ at z < εh (surface layer). (ε=0.1)

$\gamma_m = 0$ ⇒ no non-local mixing for momentum

$$\gamma_h = C\frac{\overline{w'\theta_0'}}{w_s h}$$

- ✓ Entrainment is given *by a critical Ri*

$$h = Ri\frac{T_0\left|\vec{u}(h)\right|^2}{g(\theta_v(h) - \theta_T)}$$

$$\theta_s = \theta(z_1) + \theta_T \qquad \theta_T = C\frac{\overline{w'\theta_0'}}{w_s}, (C \cong 6.5)$$

- ✓ $\Pr = \left[\frac{\Phi_h}{\Phi_m}\left(\frac{z}{h}\right) + k\frac{z}{L}C\right]^{-1}$

  (L : Monin-Obukhov length scale $= \frac{(\tau/\rho)^{3/2}}{k(g/\theta_0)(H_0/\rho c_p)}$)

❖ if unstable

$$\phi_m = (1 - 16z/L)^{-1/4}$$

$$\phi_h = (1 - 16z/L)^{-1/2}$$

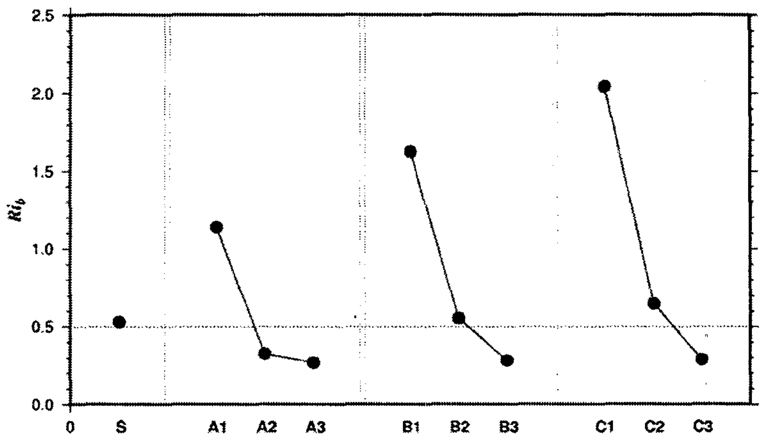


Fig.10; Variation of the bulk Richardson number at the inversion layer

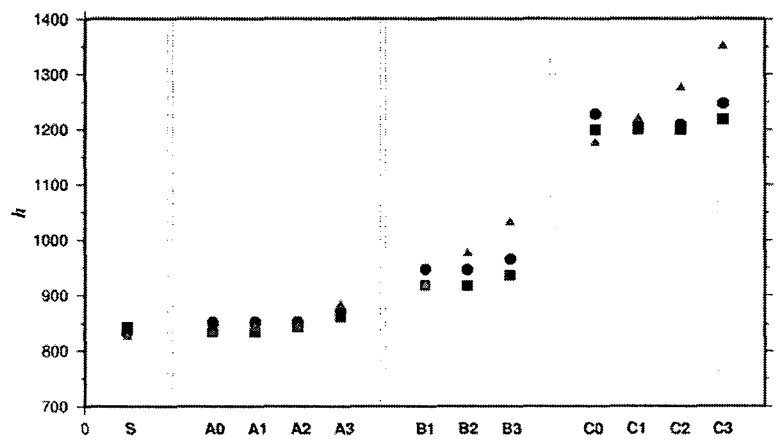
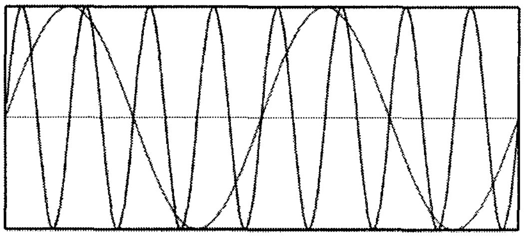


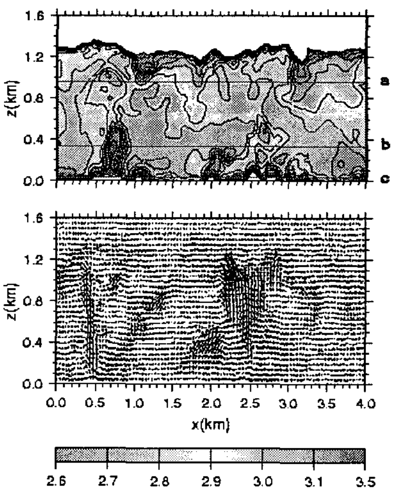
Fig.9; The comparison of the PBL height prediction at t= t_0 + 6000 s
h_{PBL}(blue square), h_{LES}(black circle), h_{TM}(red triangle)

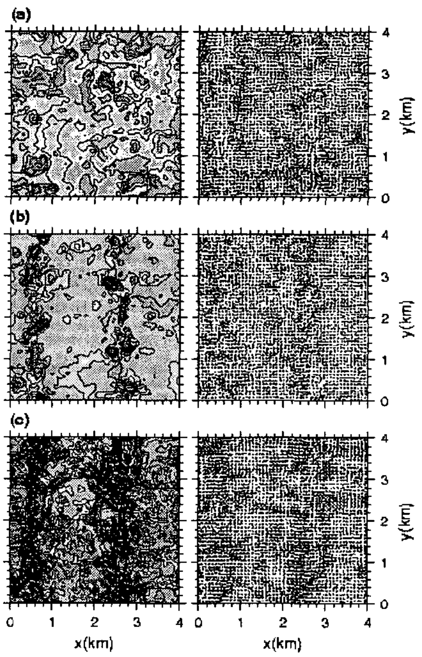
3.2 Heterogeneous Convection

(Kim et al., *BLM* 2004)

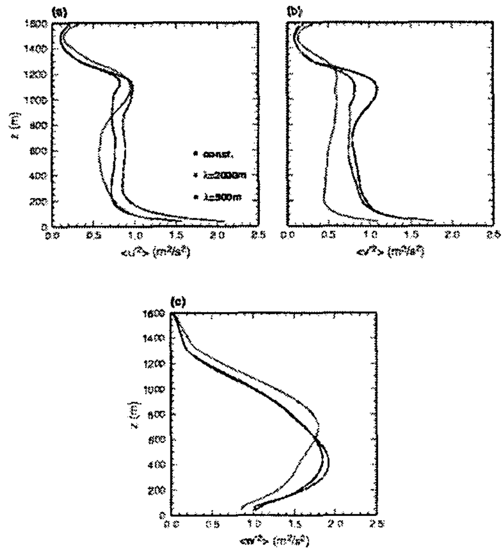
	Surface heat flux (K m/s)	Etc.
EXP1	Qo + Asin(2πx/λ)	Q0 = A = 0.2 λ = 2000 m
EXP2	Qo + Asin(2πx/λ)	Q0 = A = 0.2 λ = 500 m







The vertical cross section(left) and the horizontal cross section(right) of buoyancy and vector fields ; z = (a) 962.5, (b) 337.5, (c) 37.5 m for surface heat flux with scale 2000 m (t = 12000 sec.).



Horizontally averaged vertical profiles of (a) u-variance, (b) v-variance and (c) w-variance, for heat fluxes from an inhomogeneous surface with scale 2000 m (EXP2 ; red), 500 m (EXP6 ; blue), and from homogeneous surface (EXP0 ; black) (t = 12000 sec.).

3.3 LES of a Cumulus Cloud with Lagrangian Droplets

Cloud Microphysics with Lagrangian Droplets

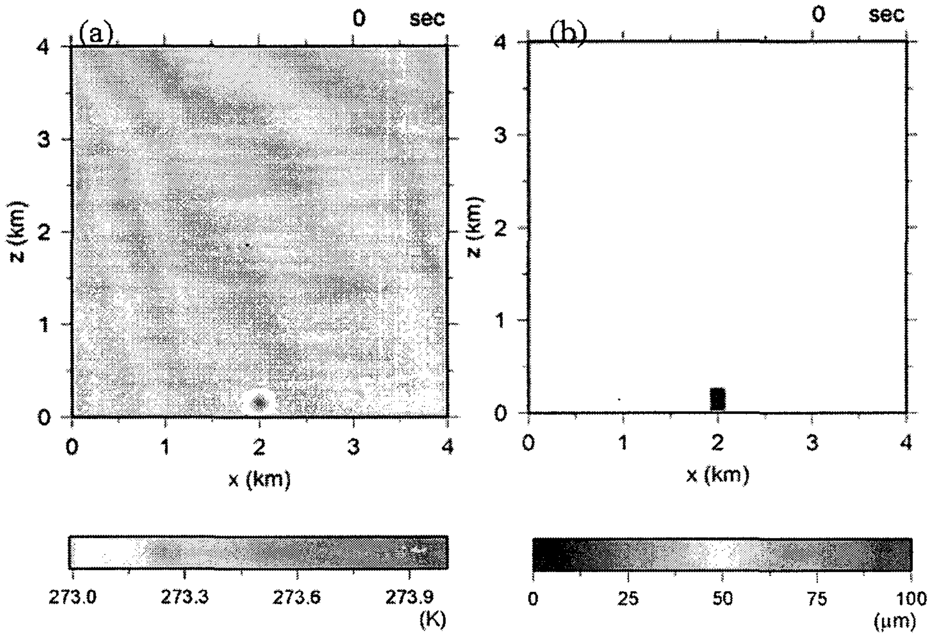
- ❑ $N = \sum_{p} N_p$ (N_p = number of droplets within a grid)
- ❑ $\frac{dr_i}{dt} = P + Q$ P : condensation - evaporation; Q : collision; * Every individual droplet has its own r_i
- ❑ $q_l = A_p \frac{1}{\rho}\left[\frac{\rho_L}{\Delta V}\sum_{i=1}^{N_p}\frac{4}{3}\pi r_i^3\right]$ A_p = weighting factor = $\frac{\text{mass of real droplets per unit volume}}{\text{mass of simulated droplet per unit volume}}$

❑ During one time step

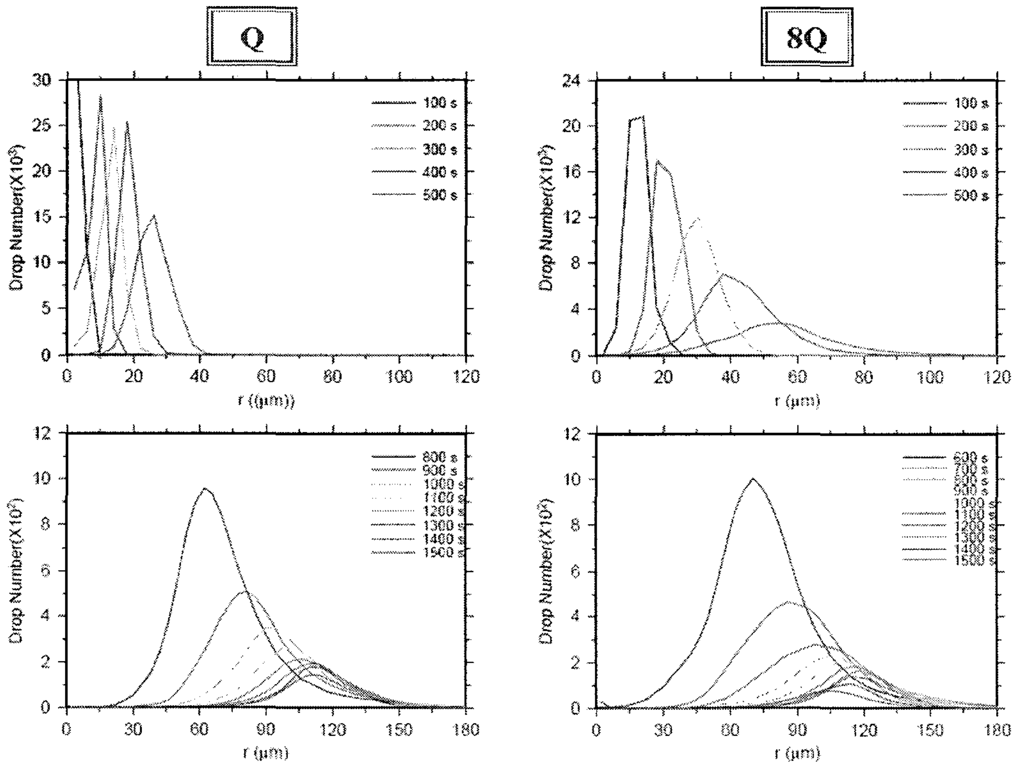
[1] condensation-evaporation

[2] collision

[3] advection



Evolutions of (a) potential temperature and (b) droplets position with radius



Evolution of droplets spectrum

A new Lagrangian LES cloud model can provied information automatically

- Convection from cloud water to rain.
- Effects of turbulence on condensation and collision.
- Mixing process (entrainment, internal mixing, etc)
- Evolution of the droplet spectrum.
- Spatial distribution of the droplet concentration.
- Time history of droplets.
- Interaction between droplets and turbulence

Conclusion

- LES is a highly effective tool to understand geophysical turbulence process and to develop its parameterization
- Much work is required, however, for more realistic simulation of turbulence by LES (e.g. SGS parameterization)