Modelling of Dispersion from Direct Injection of Carbon Dioxide in the Water Column

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The Ocean in a High CO_2 World

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International Council for Science
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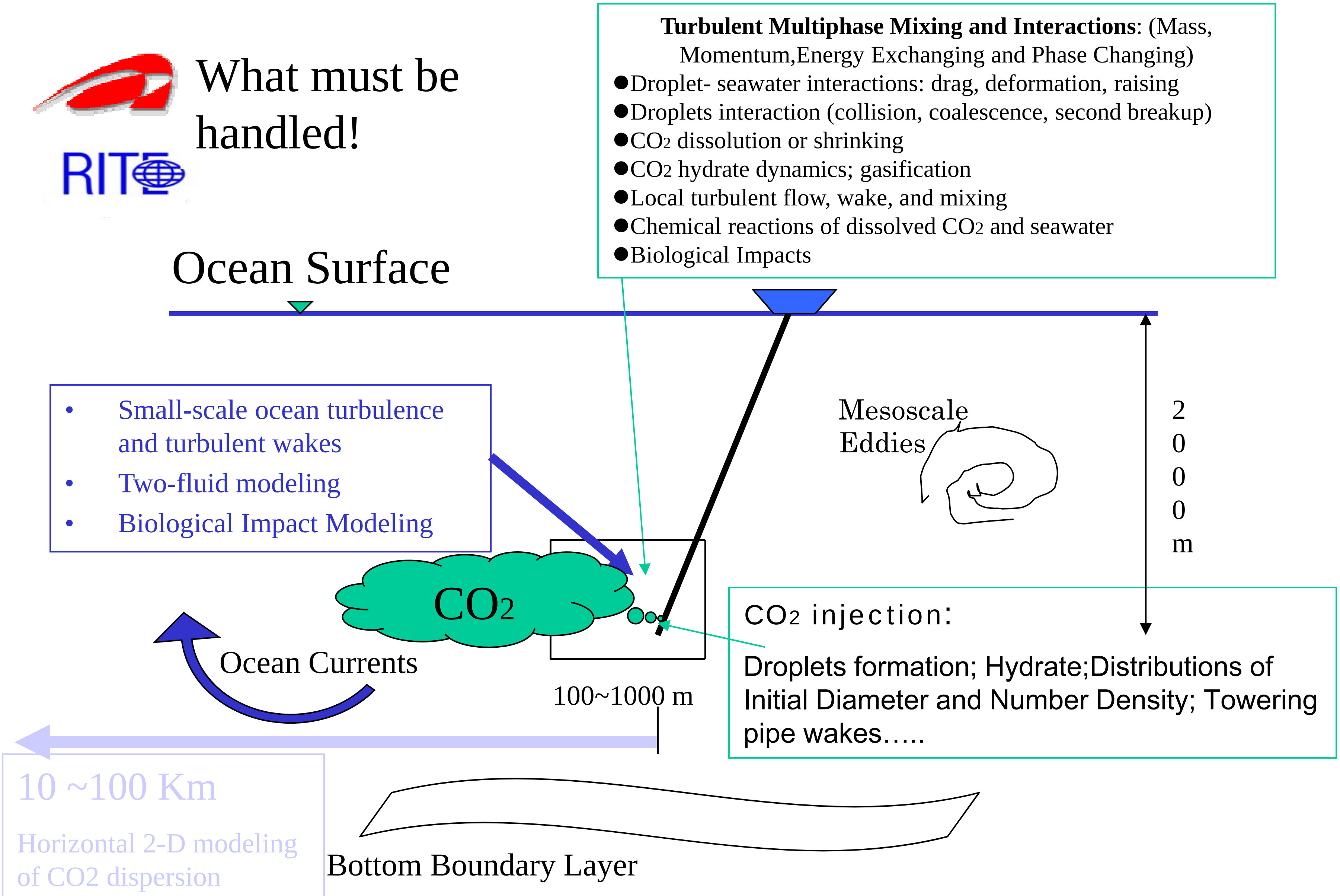
What must be handled!



Models developed

- Alendal et al. (NERSC Technical Report,1998; JGR-ocean, 2002)
- Sato et al. (RITE report, 1998;ASME,2000; GHGT-6, 2002)
- Chen et al.(RITE report, 1999; ASME,2000; Tellus, 2003)

Outline

- Introduction of the model developed
- Case investigation:

  Release of CO_2 from fixed port

  Release of CO_2 from a towered pipe

- Conclusions

A Near-field Physical & biological impact model of CO_2 Ocean Sequestration

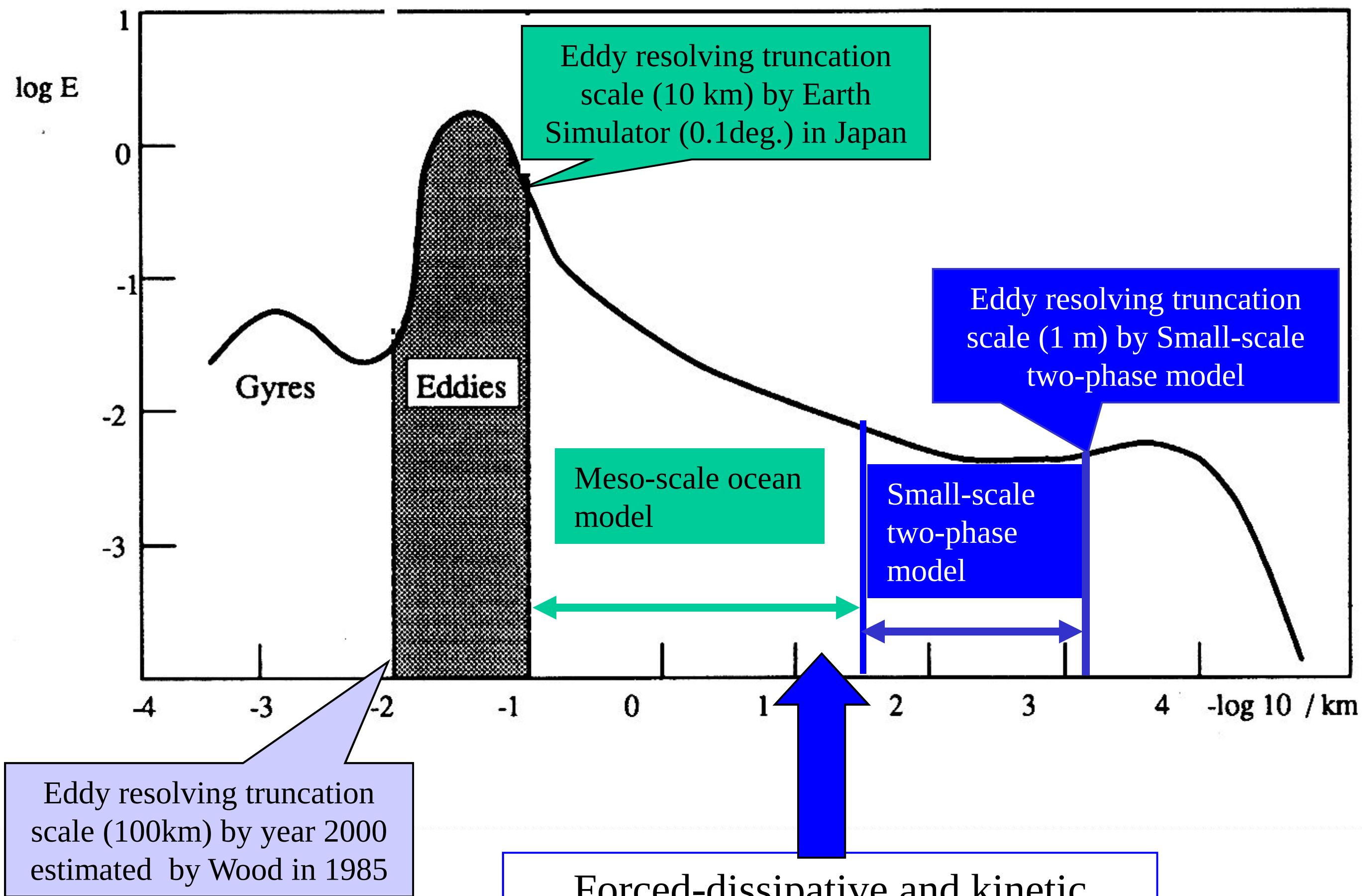
- 1. Modeling of Small scale ocean turbulent flow (Re-construction)
  - Forced-dissipative ocean turbulent flow model
  - CO_2 enrich-seawater dynamic model
- 2. Modeling of momentum and mass transfer between CO_2 droplets and seawater
  - Sub-model of CO_2 droplet drag coefficient
  - Sub-model of CO_2 droplet deformation
  - Sub-model of CO_2 solubility
- 3. Modeling of biological impacts of floating-orgms.
  - Conservative variables: Mass or Number density of organism *k*
  - Non-conservative variables: Degree of Damage/Activity Index, A_k.
  - Sub-models of Damage Degree /Activity Index

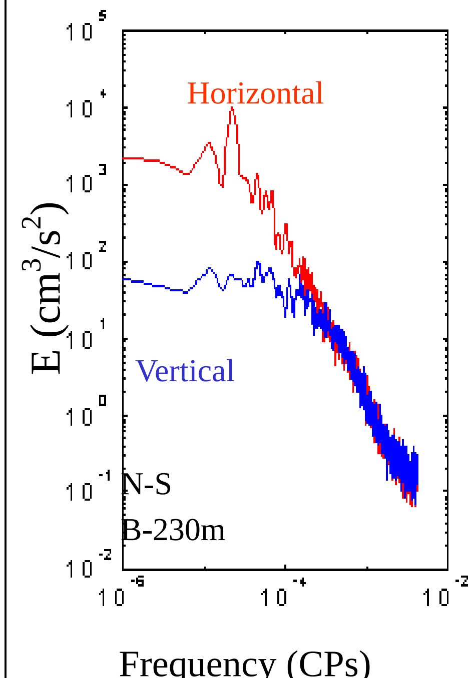
Supported by Lab. and field Exp.

Part – I : Reconstruction of small scale turbulent ocean with basis on observation data

- Theories and physical model
- Observation data analysis and implement

Turbulent kinetic energy spectrum in the ocean (J. D. Wood in Nature 1985 and CREIPI at Keahole Pt. Offing,1999)





CREIPI at Keahole Pt. Offing,1999

Forced-dissipative and kinetic energy cascade theories applied?

Theories and Techniques Applied

Large-scale information from Boundaries :

•Mean properties (X,t)

•Turbulent properties at $K > K_f$

Data analysis

Field Obs. Data

Inside of the ocean:

- N-S based 3-D unsteady Governing Eq.s
- Forced-dissipative Energy cascade theories
- Adjusted by observation spectrum

Governing Equations for simulating small-scale ocean turbulence

a. Forced-dissipative system of small-scale ocean:

$$\frac{\partial \overline{\rho}\hat{u}_i}{\partial t}+\frac{\partial \overline{\rho}\hat{u}_i\hat{u}_j}{\partial x_j}=-\frac{\partial \hat{p}}{\partial x_i}+\frac{\partial D_{ij}}{\partial x_j}+(\overline{\rho}-\rho_0)g_i+(\dot{F}_d)+F_f\delta_{ij}$$

Forced term:

$$F_f=\overline{\rho}\varepsilon u_0'(k,t)/\sum_{k\in k_f}u_0'(k,t)u_0'(k,t) \qquad k\in k_f$$

Dissipative term:

$$D_{ik}=2.0\rho\nu_t^k S_{ik}$$

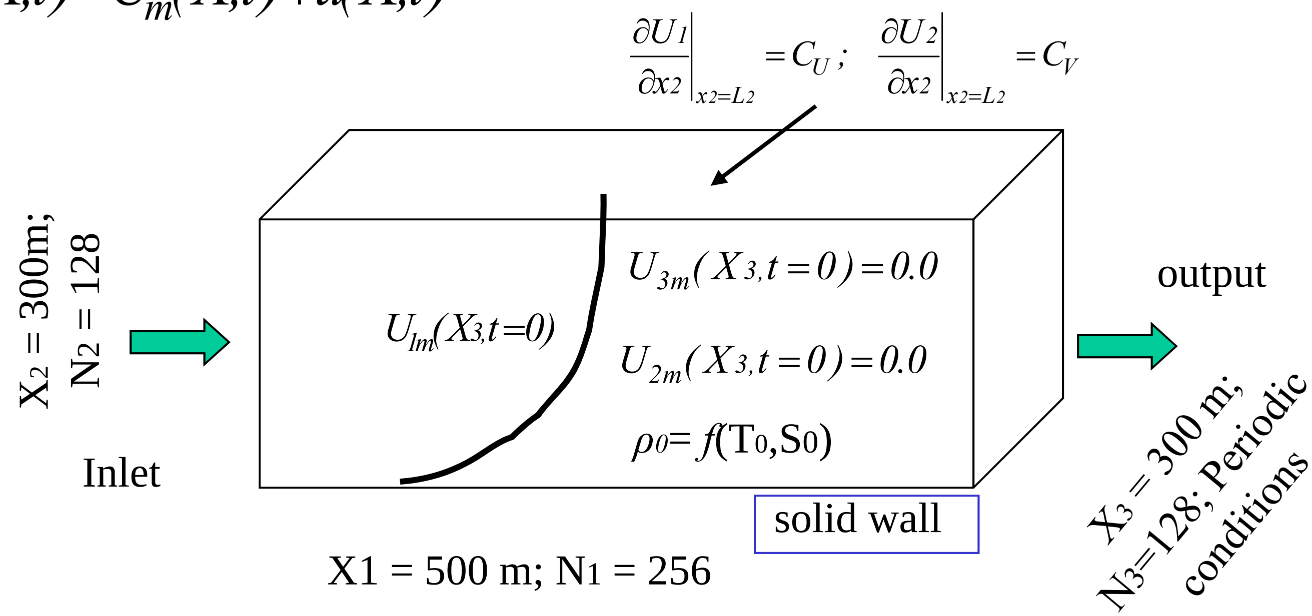
b. Structure-function Turbulent viscosity model:

$$\nu_t^k(x_k,\Delta x_k)=0.15C_k^{-3/2}\Delta x_k[F_2^k(x_k,\Delta x_k)]$$

$$F_2^k=0.25\sum(u_k(x_k)-u_k(x_k-\Delta x_k))^2$$

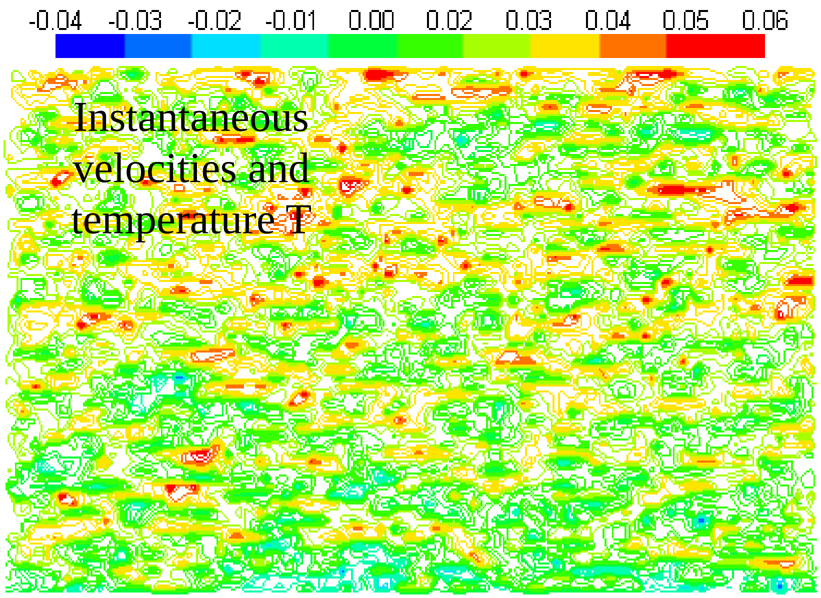
1-4. Example: Hawaiian Case (small-scale): Computational domain, initial &boundary conditions

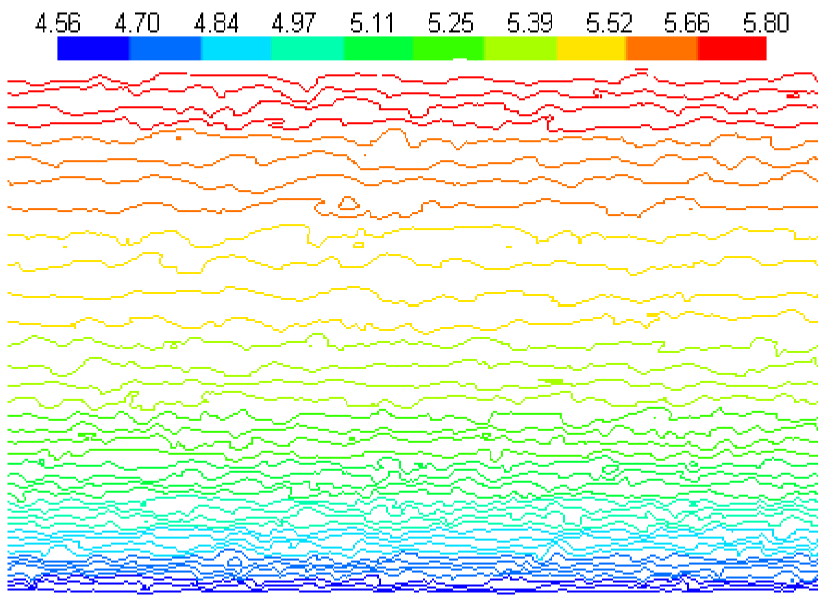
$$\vec{U}(X,t)=\vec{U}_m(X,t)+\vec{u}(X,t)$$

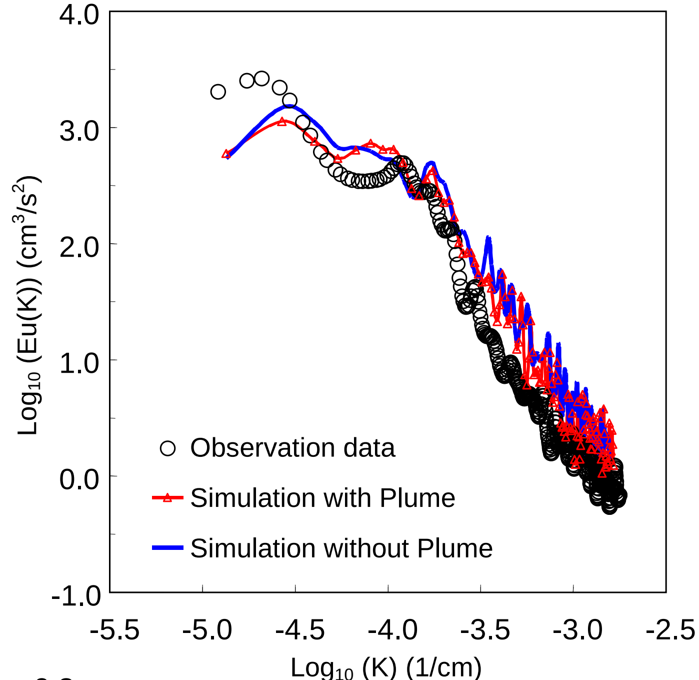


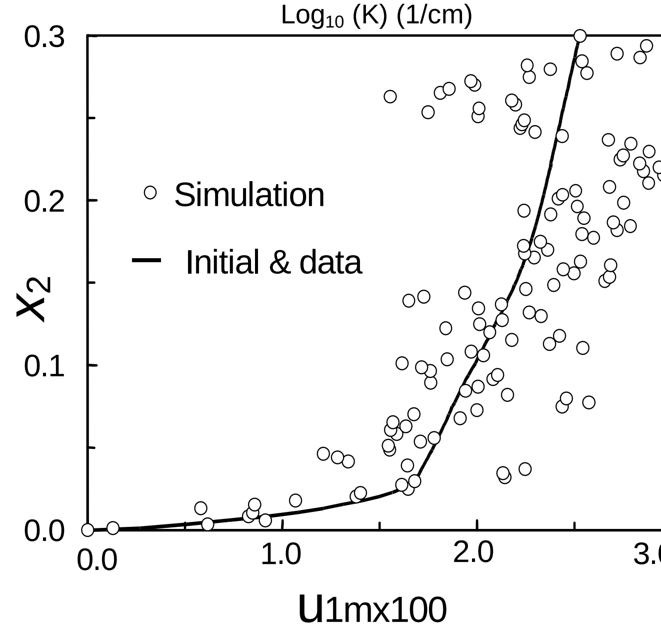
$U_{1m}(x_3)$, $T_0(x_3)$ S_0 $(x_3)$are the observation data

Simulations of small-scale ocean turbulence



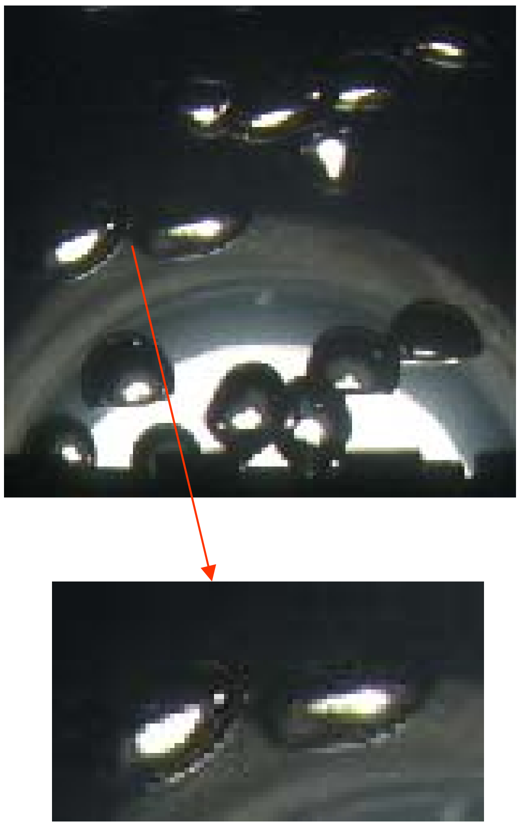






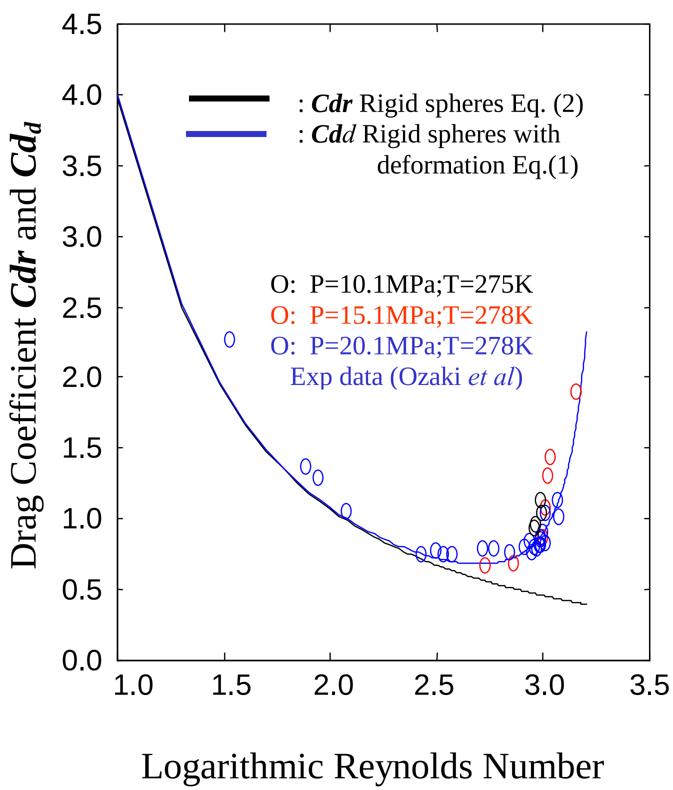
Part-II: CO_2 droplet dynamics

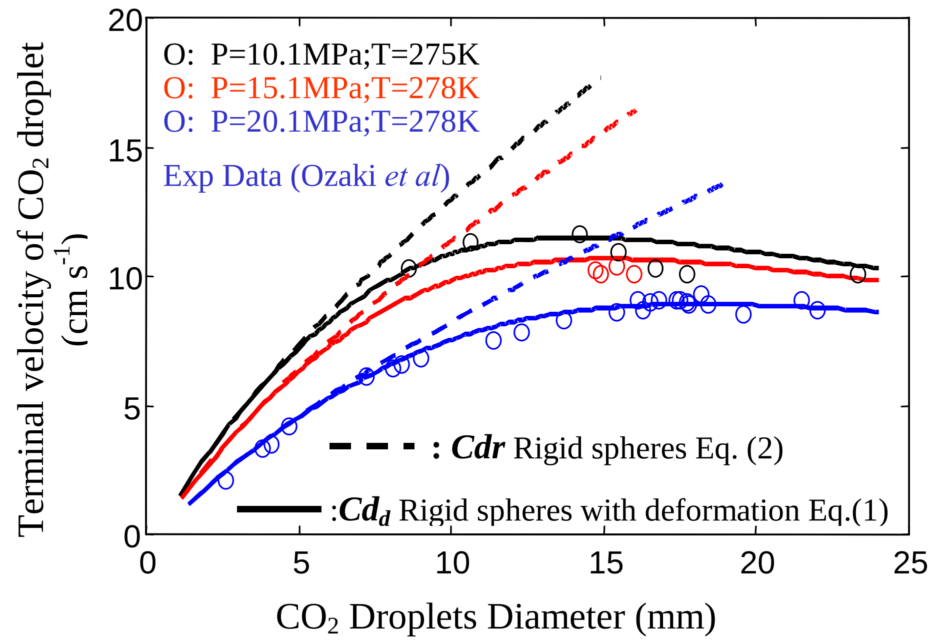
Experimental Observations and Modeling Assumptions



- Assumption: CO_2 droplet with hydrate covered is a Deformable rigid droplet with Permeable Surface
- Experimental data adopted are those from Stewart(1970) and Kimuro (1994) for CO_2 solubility, and from Ohgaki (1993) for phase diagram.
- Experiment data dealing with momentum transfer between droplets and seawater are from the experiments of Dr. Ozaki (1999)

Sub-models of drag coefficient and terminal velocities

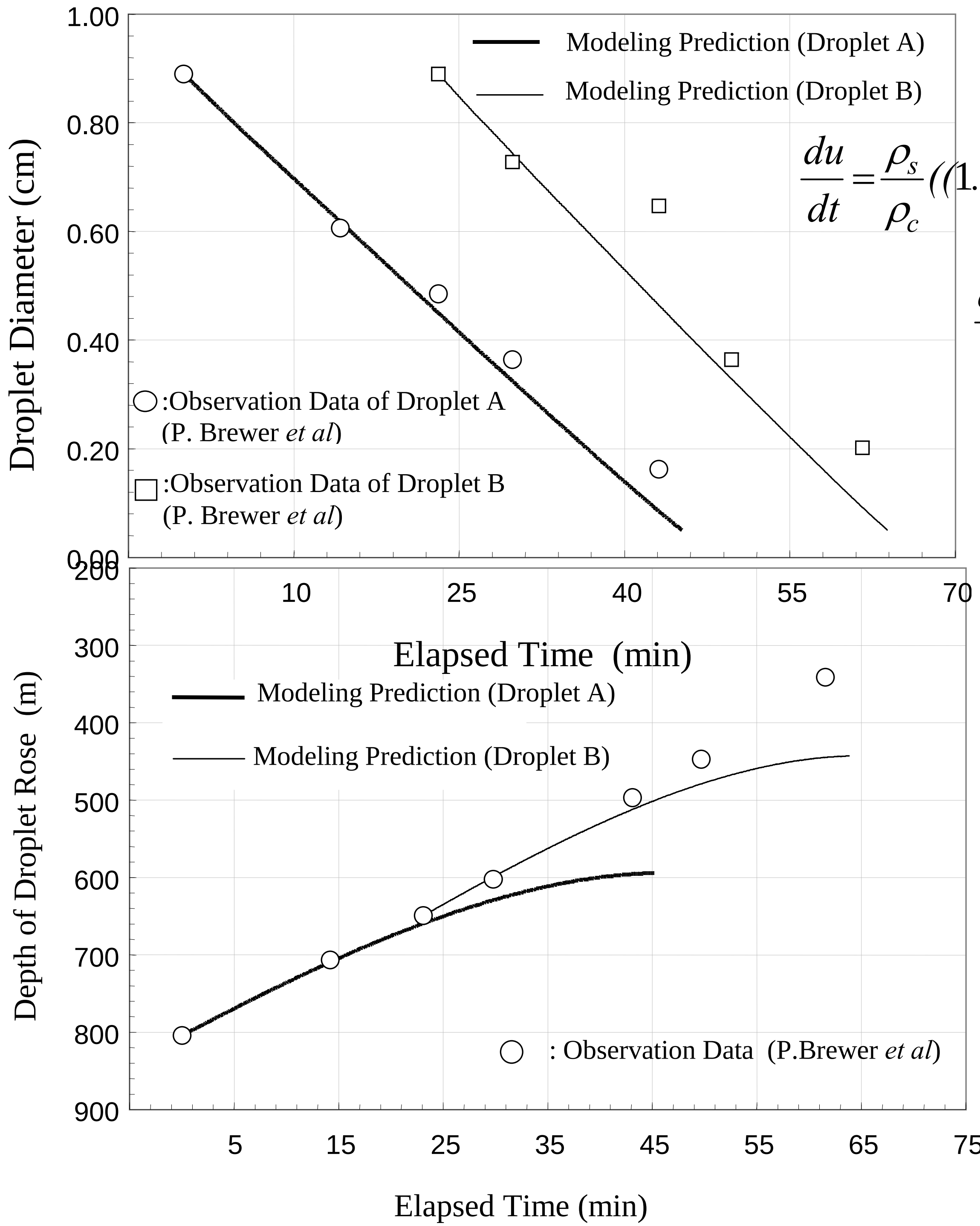




$$Cd_d = Cd_r(A_{eff} / A_{eq})_{Cd} \qquad (1)$$

$$Cd_r = 24(1+0.125\, Re^{0.72}) / Re \qquad (2)$$

$$(A_{eff} / A_{eq})_{Cd} = 1.0 + (5.6419 - 8.3484 \times 10^{-3}\, Re + 1.4596 \times 10^{-6}\, Re^2) \times 10^{-4}\, Re$$



$$\frac{du}{dt}=\frac{\rho_s}{\rho_c}((1.0-\frac{\rho_c}{\rho_s})g-\frac{3u^2}{4D}C_d)-u\frac{d\ln(m_c)}{dt}$$

$$\frac{dD}{dt}=-\frac{1}{\rho_c}(\frac{D}{3}\frac{d\rho_c}{dt}+\frac{2Sh\alpha D_f C_s}{D})$$

Key Parameters:

C_d: Drag coefficient

Sh: Sherwood Number

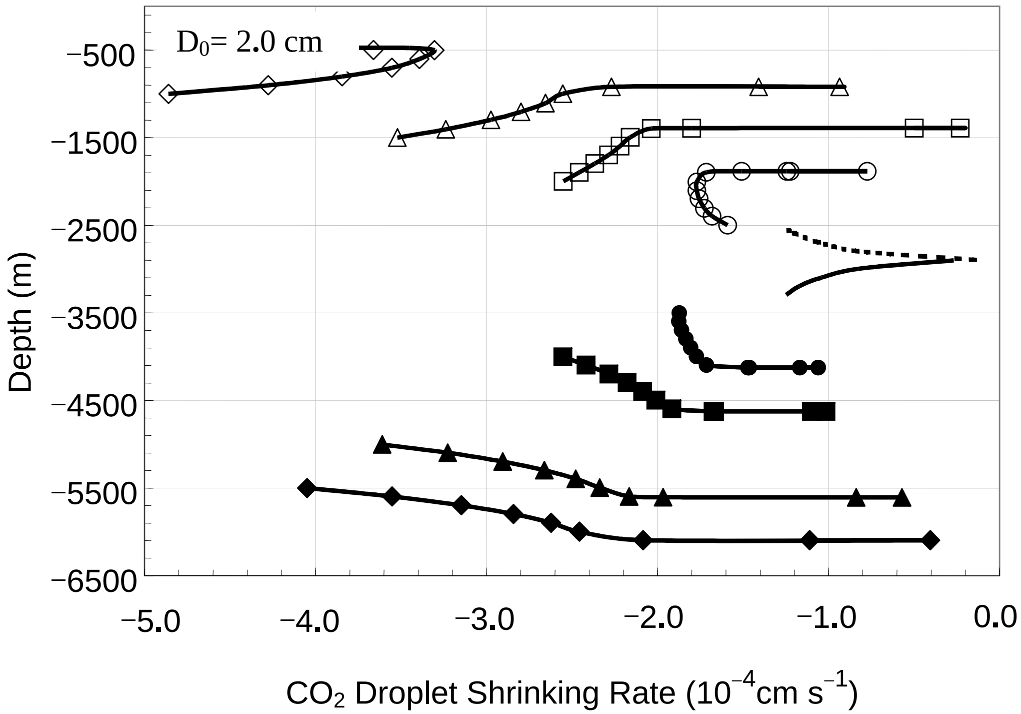
C_s: The solubility

α : The effective area coefficient

Model prediction of an individual droplet dissolution *(model calibration)*

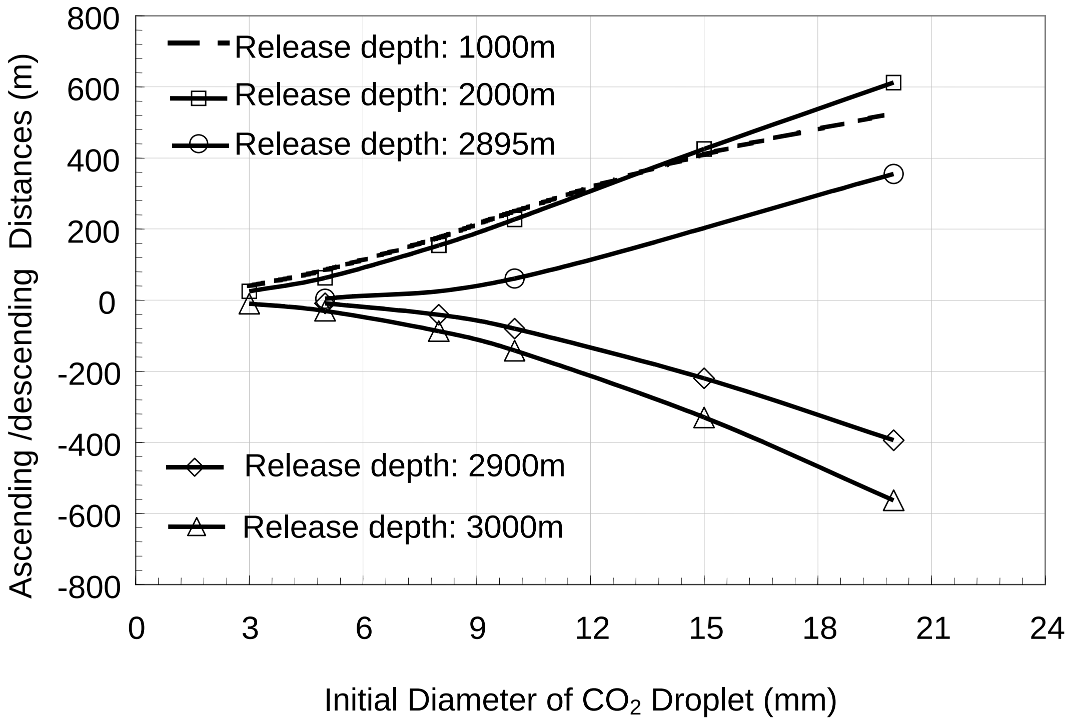
(CO_2 droplet Diameter vs Exp data by P. Brewer et al)

CO_2 droplet dissolution at variant depth



Release depth(m)	Density Ratio	Elapsed time(min)	Release depth (m)	Density Ratio	Elapsed time(min)
1000	0.93144	84.5	2900	1.0001	240.0
1500	0.95462	113.0	3500	1.0164	180.2
2000	0.97233	142.0	4000	1.0287	151.7
2500	0.98832	187.0	5000	1.0503	122.6
2890	0.99997	240.0	5500	1.0597	113.8

Ascending /Descending of CO_2 droplet



Two-fluid ocean turbulent flow model

Governing Equations of Seawater

$$\frac{\partial \overline{\rho}}{\partial t} + \frac{\partial \overline{\rho}\hat{u}_i}{\partial x_i} = w_c$$

$$\frac{\partial \overline{\rho}\hat{u}_i}{\partial t} + \frac{\partial \overline{\rho}\hat{u}_i\hat{u}_j}{\partial x_j} = -\frac{\partial \hat{p}}{\partial x_i} + \frac{\partial \overline{\rho}\hat{\tau}_{ij}}{\partial x_j} + \underline{(\overline{\rho} - \rho_0)g_i} + \underline{(F_c)}$$

$$\frac{\partial \hat{p}}{\partial x_i} = \frac{\partial P^*}{\partial x_i} - \rho_0 g_i$$

$$\frac{\partial \overline{\rho}\hat{\phi}_k}{\partial t} + \frac{\partial \overline{\rho}\hat{\phi}_k\hat{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}(\overline{\rho}D_k\frac{\partial \hat{\phi}_k}{\partial x_j}) + \frac{\partial \overline{\rho}\hat{q}_k}{\partial x_j} + \underline{w_c\delta_{kl}}$$

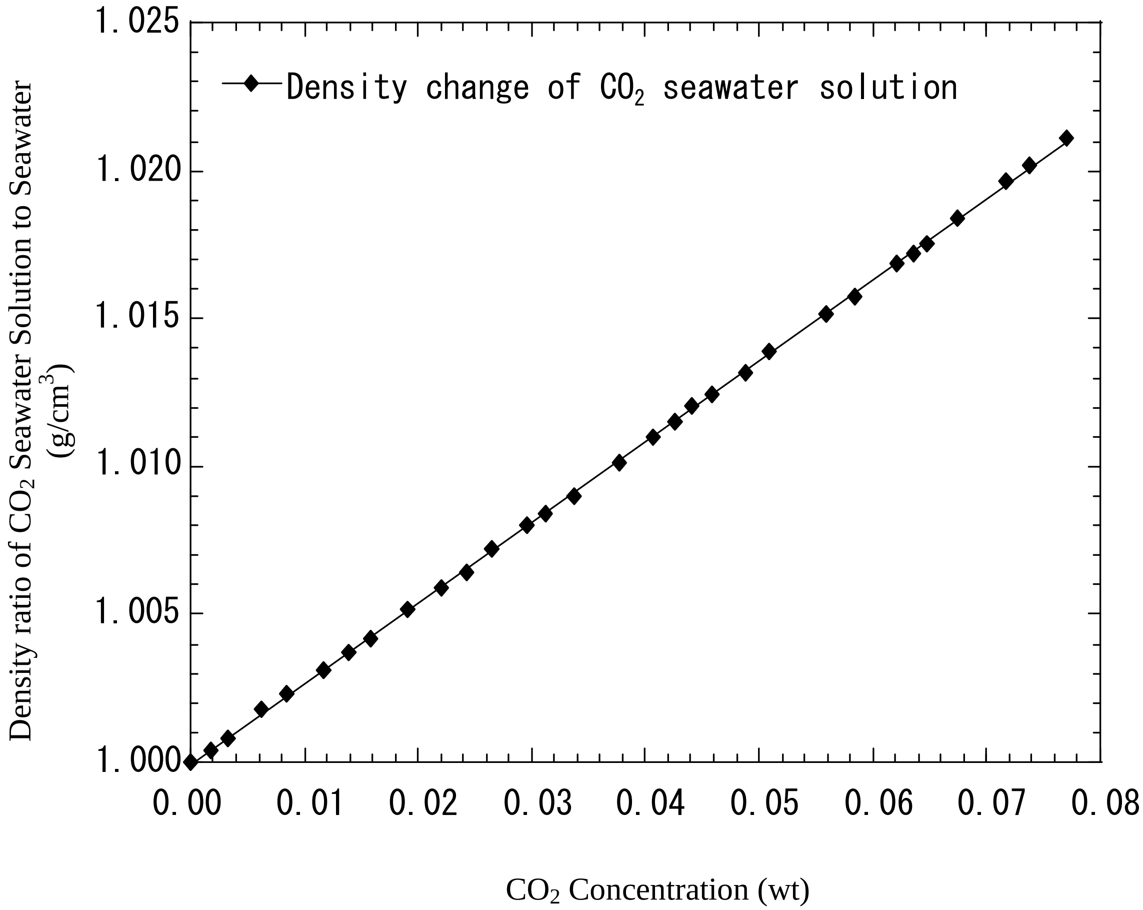
Governing Equations of LCO2

$$\frac{\partial \hat{n}}{\partial t} + \frac{\partial \hat{n}\hat{u}_{dj}}{\partial x_j} = \delta_{inj} w_{ninj}$$

$$\frac{\partial \hat{\alpha}}{\partial t} + \frac{\partial \hat{\alpha}\hat{u}_{dj}}{\partial x_j} = -\underline{w_c / \rho_c} + \delta_{inj} w_{\alpha inj}$$

$$\frac{\partial \hat{\alpha}\rho_c\hat{u}_{di}}{\partial t} + \frac{\hat{\alpha}\rho_c\hat{u}_{di}\hat{u}_{dj}}{\partial x_j} = \hat{\alpha}(\rho_c - \overline{\rho})g_i \underline{-F_c}$$

Density change of CO2 enriched seawater



$$\rho_s = \rho_w (1.0 + \alpha\chi)$$

ρ_s : CO_2 solution density

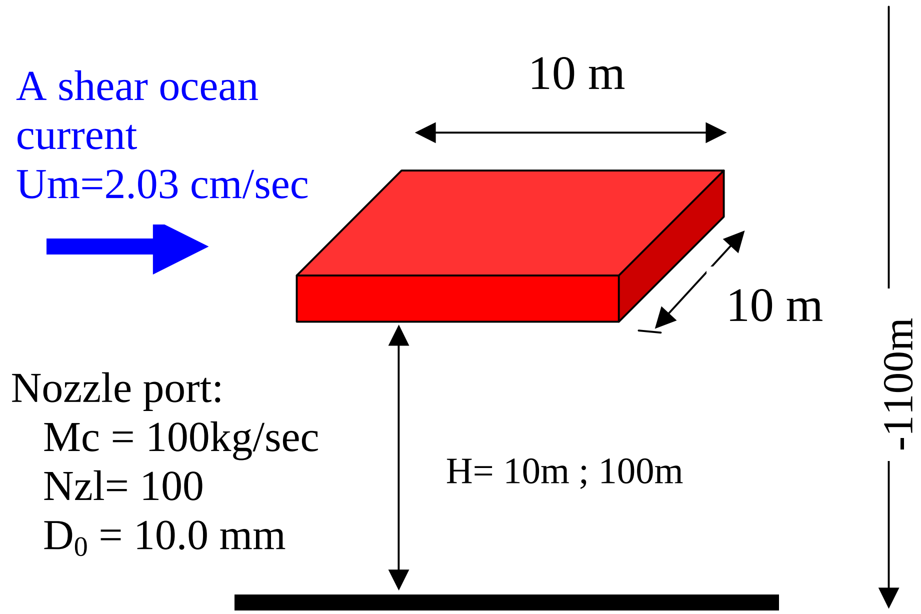
ρ_w : seawater density

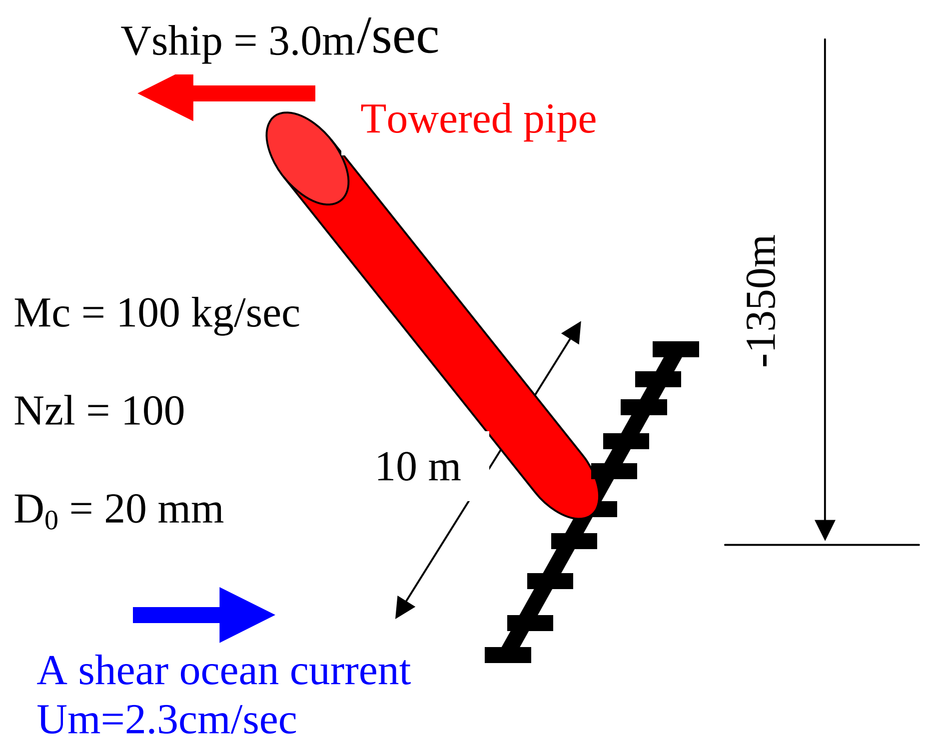
χ : CO_2 mass fraction

α=0.273 by Exp (Song *et al*. 2003)

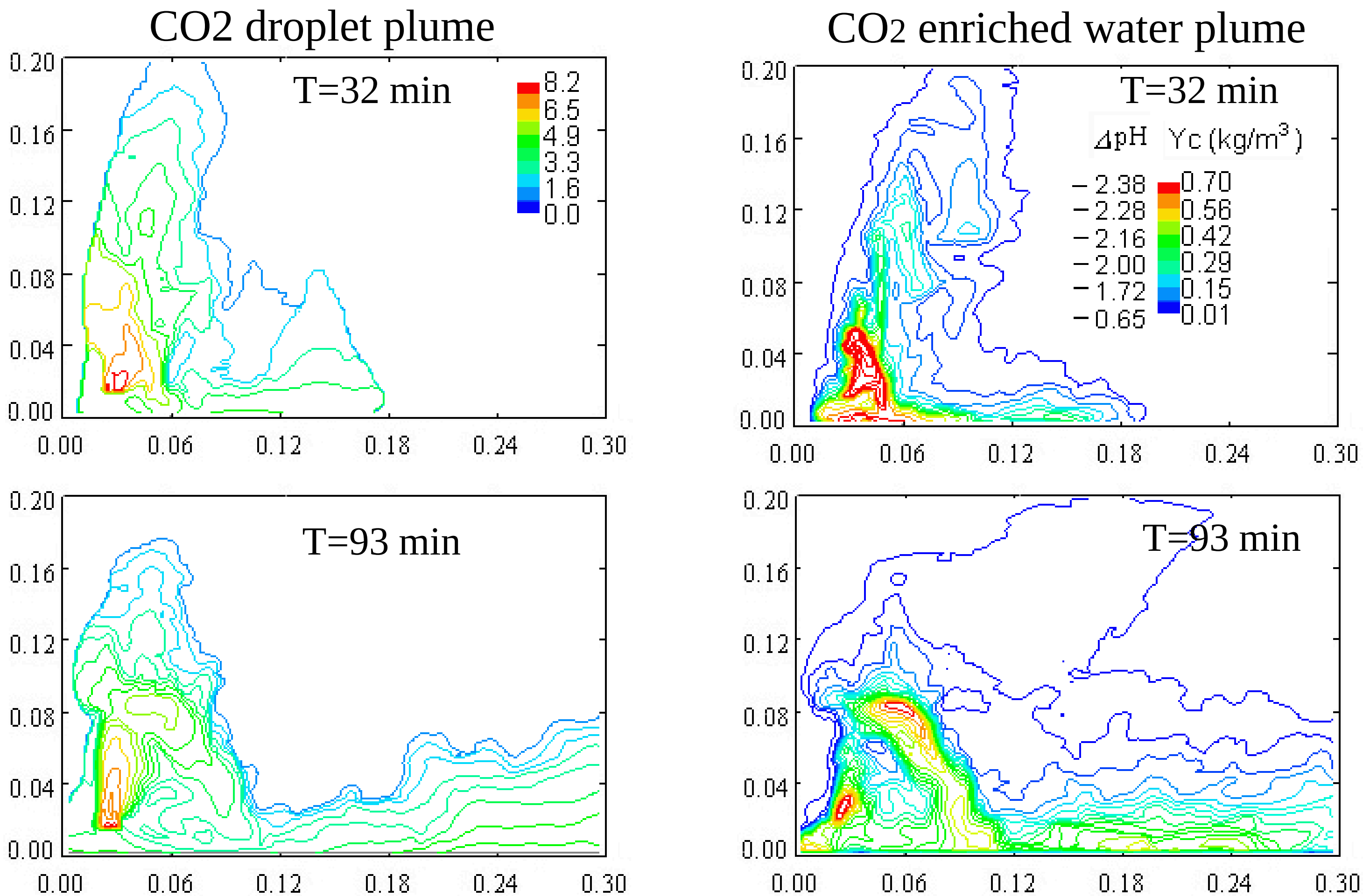
Part – III : Dispersion from Direct Injection of Carbon Dioxide in the Water Column

- Injection of CO2 from fixed ports
- Injection of CO2 from towered pipe

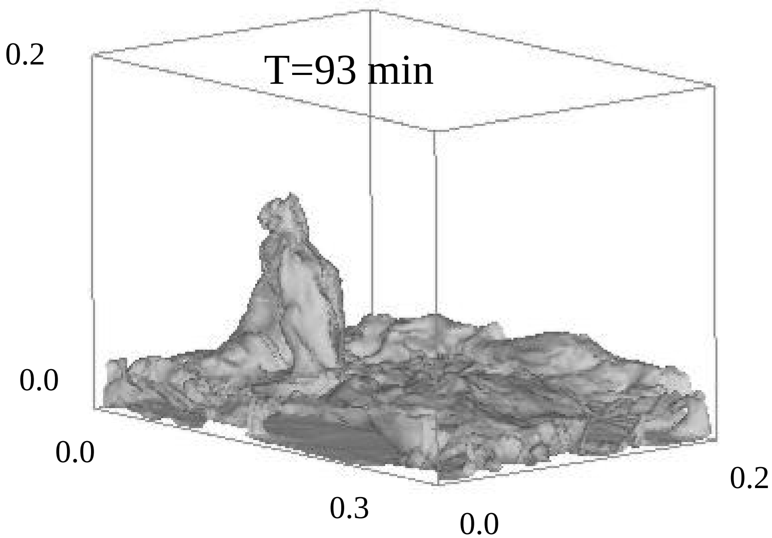


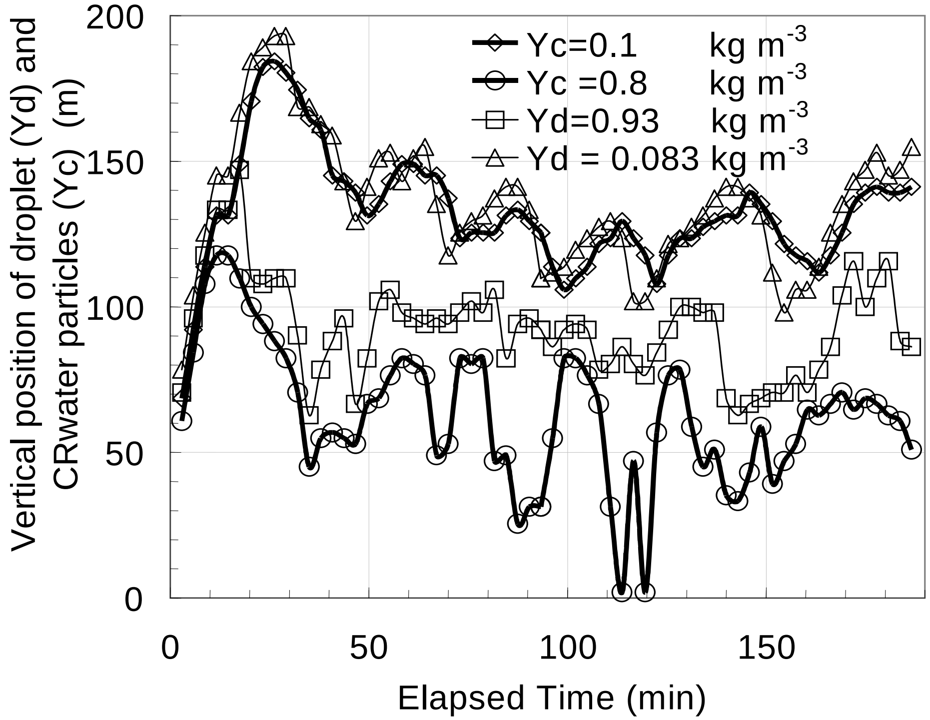


Dispersion from a fixed port release



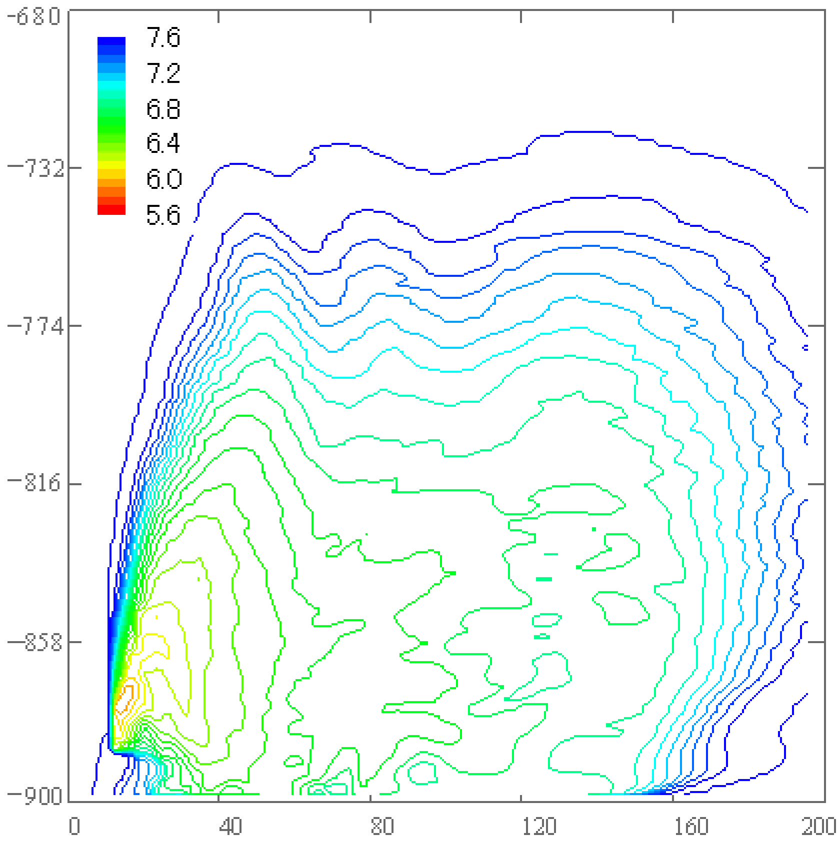
Plume characters from a fixed port



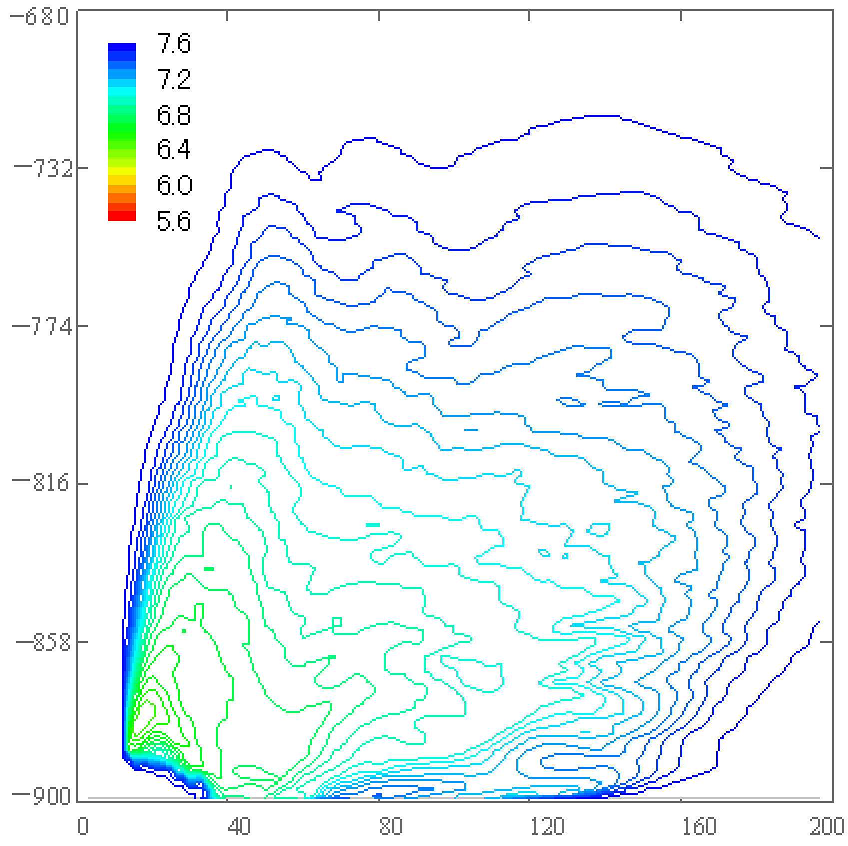


Lower Injection rate

(*p*H plume at middle depth)



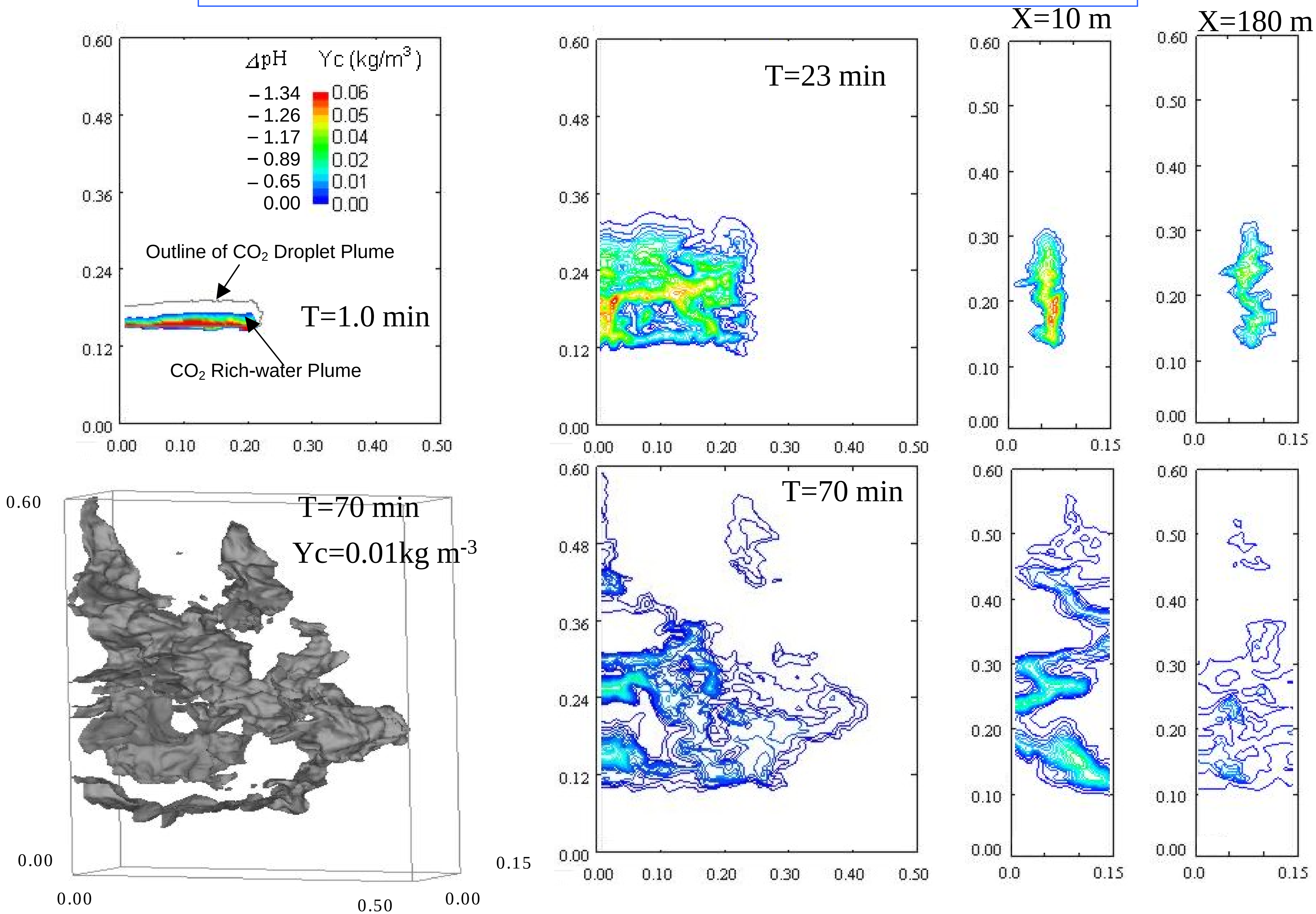
Mc=0.6kg/s; D_0 =8.0mm



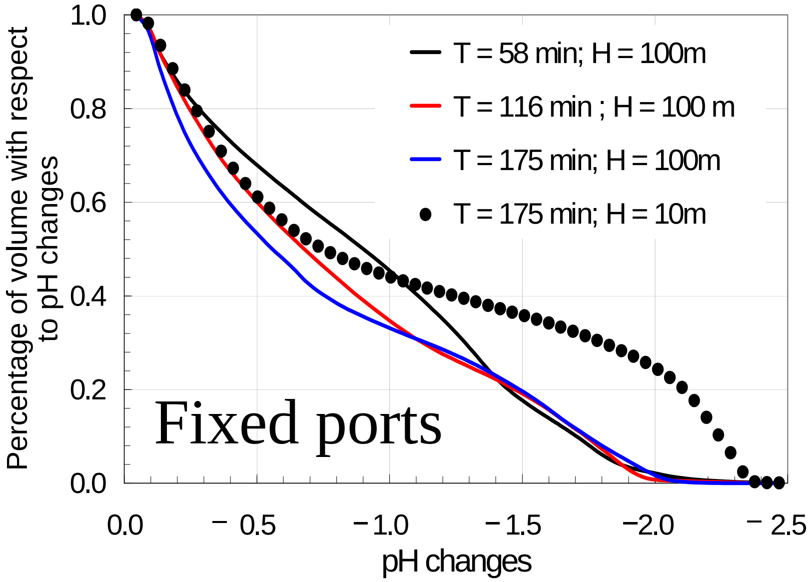
Mc=0.1kg/s; D_0 =8.0mm

T=100.3 min

Dispersion from a towered pipe release

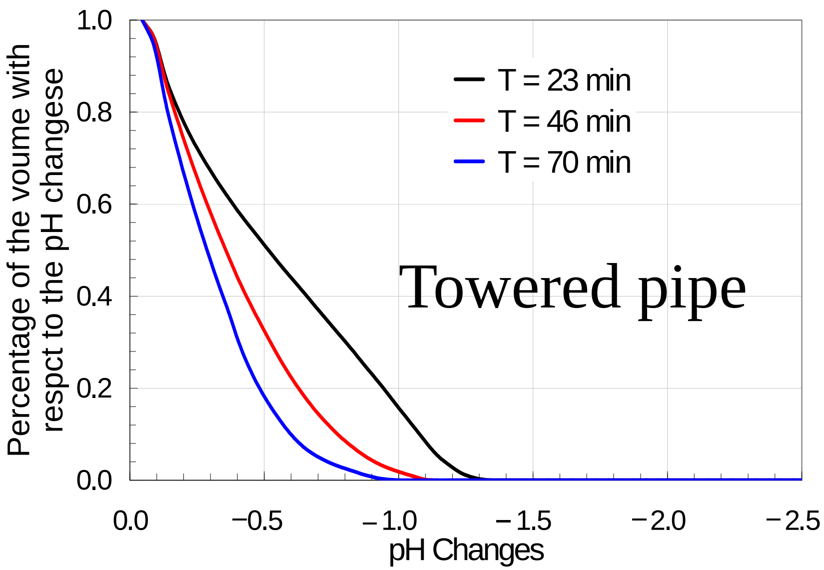


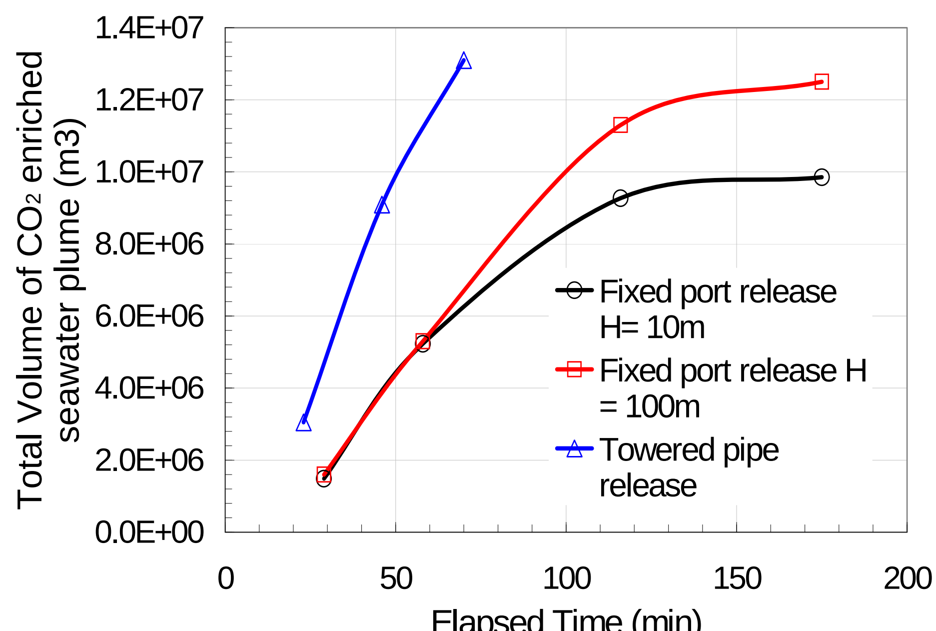
Statistical characteristics of CO_2 enriched seawater plume



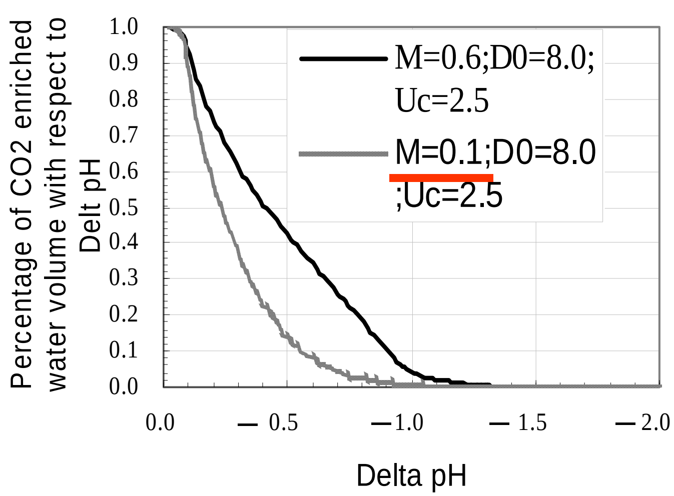
$$P(V_{X<X_k}) = \frac{\sum_{i=1}^{k} V_{X<X_k}}{V_{tot}}$$

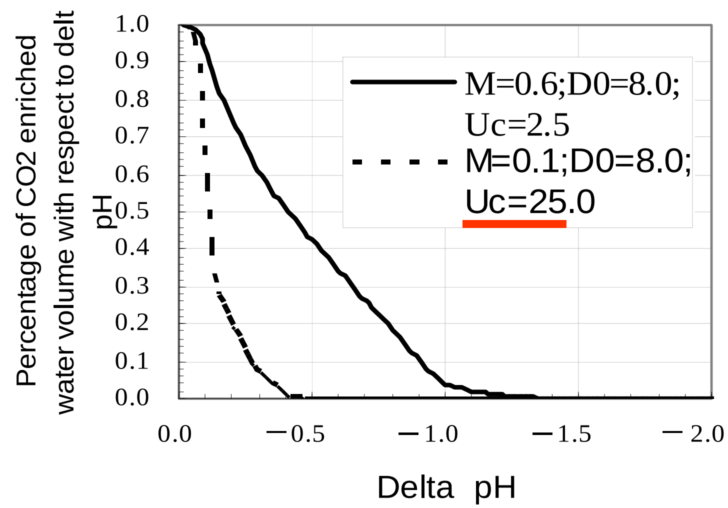
$$X = \Delta pH$$

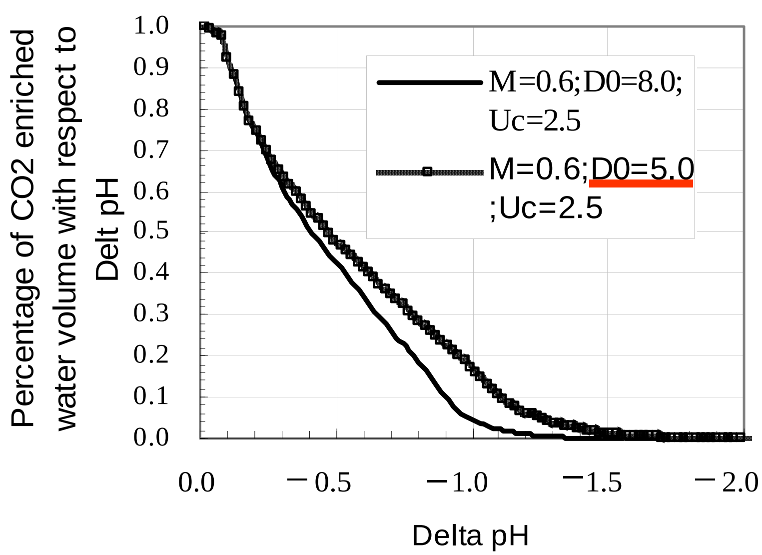


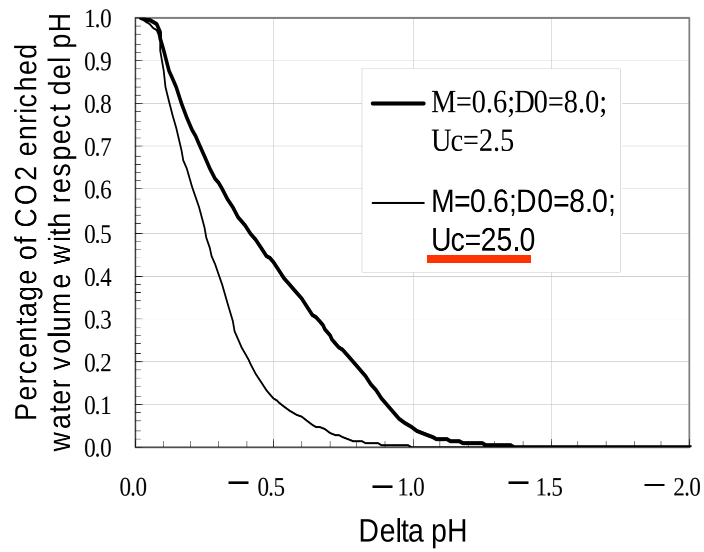


Statistical characteristics of CO2 enriched seawater plume









Conclusions

- Near-filed physical and chemical process created by directly injected LCO_2 into the ocean waters could be reasonably simulated.

- To engineering application, injection of LCO_2 from fixed ports should be carefully arranged to limit the local injection rate associated with the selection of an incline seafloor.

- In case of large injection rate (100kg/s) from fixed port on a flat seafloor, injected LCO_2 could yield a large pH change and an unsteady waving double-plume.

- Alternatively, release of LCO_2 from a towered pipe at middle-depth with a relatively large size droplets is an expectable option to practically performance of CO_2 ocean sequestration, which could be adjusted with the limitation of biological impact.

- Understanding of the effect of dissolved CO_2 on oceanic bio-organisms appeared to be urgently necessary for assessing the oceanic environmental impacts.

…. We still have more works to be done .

Acknowledgements

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