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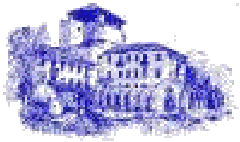

# Wave Effect on the Gas Fluxes at Ocean Surface


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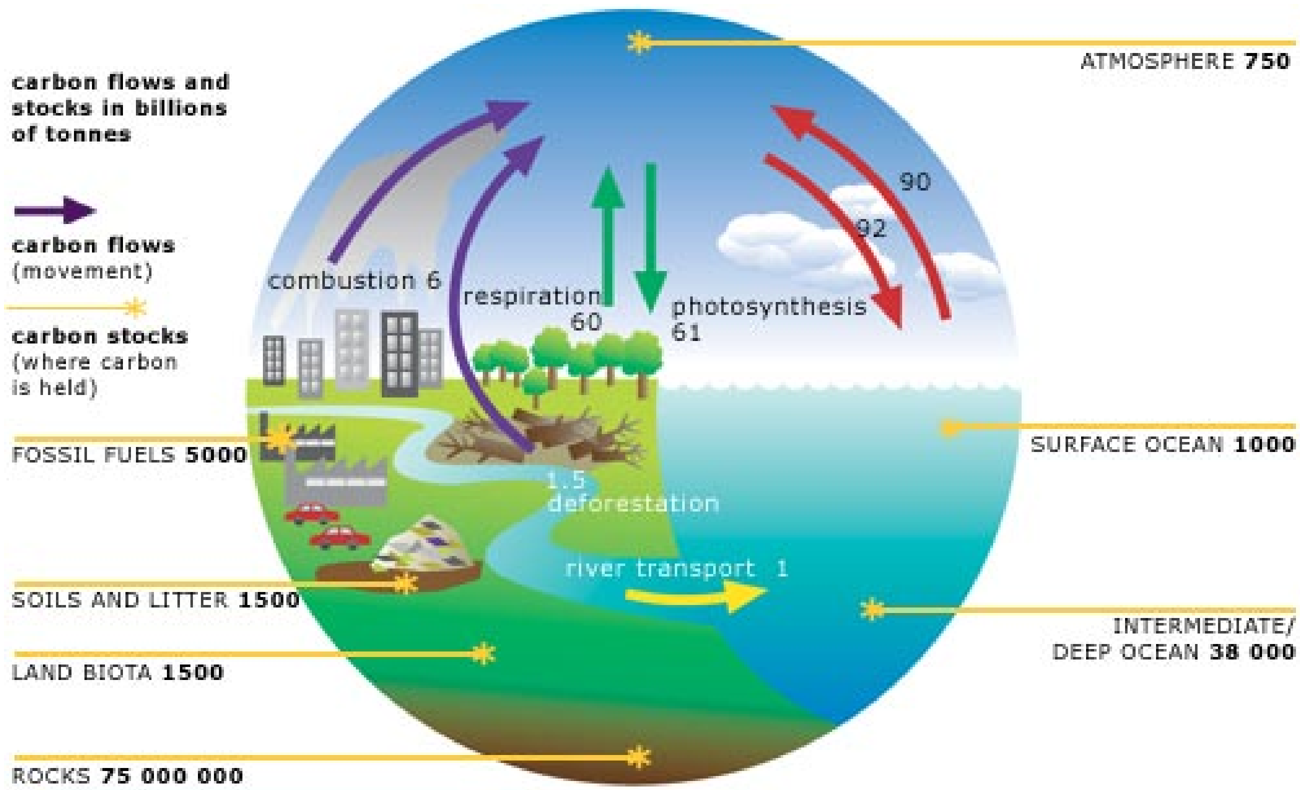
# Gas Transfer



# Flux Parameterization Issues (Fairall el al. 2005)

- Representation in GCM
  - Most observations are point time averages
  - Concept of gustiness sufficient?
  - Mesoscale variable?  Precip, convective mass flux, …
- Strong winds
  - General question of turbulent fluxes, flow separation, wave momentum input
  - Sea spray influence
- Waves
  - Stress vector vs wind vector (2-D wave spectrum)
  - $z_o$ vs wave age & wave height
- Breaking waves
  - Gas and particle fluxes
  - Distribution of stress and TKE in ocean mixed layer
- Gas fluxes
  - Bubbles
  - Surfactants (physical vs chemical effects)
  - Extend models to chemical reactions

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# Gas Deposition Velocity

$$v_d = \langle w'c' \rangle / (c - c_s) = (r_a + r_b)^{-1}$$

Two parameters: $r_a$ ~ aerodynamic resistance

$r_b$ ~ surface resistance

$$\frac{1}{r_a} = C_D \bar{u}$$

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# Surface Resistance

The surface resistance $r_b$ depends on

- Roughness length: $z_0$
- Roughness Reynolds number: $Re = u^* z_0/\nu$
- Schmidt number: $Sc = \nu/D_i$
- $\nu$ is the molecular viscosity, $D_i$ is the diffusion coefficient

# Examples

$$r_b = \int_{z_0}^{z_s} (D_i + K)^{-1}\, dz = \frac{\left(u_{z0} + B_i^{-1}\right)}{u_*}$$

Kramm & Dlugi (1994)

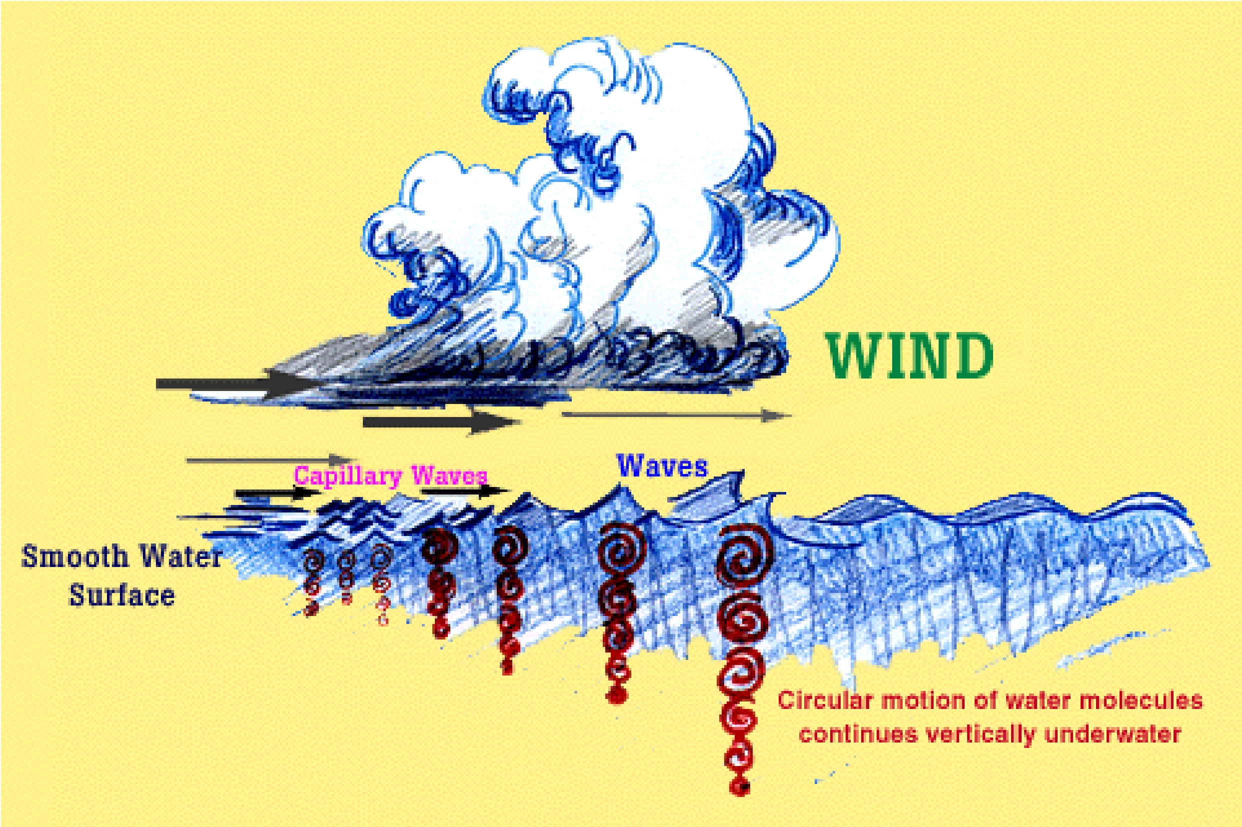
$$r_b = \frac{1}{k u_*} \ln \frac{z0}{z0c}$$

Asman (1994)

$$z_c = 30\,(\nu/u_*)\,\exp\left(-13.6\,k\,S_c^{2/3}\right) \quad ;\ \text{for } R_e<0.13$$

$$z_c = 20\,z_o\,\exp\left(-7.3\,k\,R_e^{1/4}\,S_c^{1/2}\right) \quad ;\ \text{for } R_e>0.13$$

# Waves


WIND
Capillary Waves
Waves
Smooth Water Surface
Circular motion of water molecules continues vertically underwater

# Wave Effects

- Waves $\rightarrow$ $z_0$ $\rightarrow$ $C_D \rightarrow r_a$
- Waves $\rightarrow$ $z_0$ $\rightarrow$ (Re, Sc) $\rightarrow r_b$
- WaveWatch-3 for the South China Sea as an example

# Nondimensional Roughness Length

$$z_0^* \equiv g z_0 / u_*^2 = f(c_p / u_*)$$

Cp = phase speed at peek frequency

# Without Wave Effects
# Charnock (1955)

$$z_0^* = \beta_*$$

$\beta_* = 0.0185$ (Wu 1980)

0.035 (Kitaigorodskii and Volkov 1965)

0.0144 (Garratt 1977)

0.0192 (Geernaert et al. 1986)

# With Wave Effect (1)

Kitaigorodskii (1968)

$$z_0^2 = A^2 \int_0^\infty F(k) \exp\left(-\frac{2\kappa c}{u_*}\right) dk$$

$$c = c(k)$$

Kitaigorodskii with $F(\omega) = \beta g^2 \omega^{-5}$, $\beta = 0.012$

$$z_0^* = 0.012\Phi(x_0)$$

$$\Phi(x_0) \equiv \left[1 - \mathrm{e}^{-x_0}\left(1 + x_0 + \frac{x_0^2}{2} + \frac{x_0^3}{6}\right)\right]^{1/2}$$

$$x_0 \equiv 2\kappa c_\mathrm{p} u_*$$

Kitaigorodskii with $F(\omega) = \alpha_s g u_* \omega^{-4}$, $\alpha_s = 0.062$

$$z_0^* = 0.014\Phi(x_0)$$

$$\Phi(x_0) \equiv \left[1 - \mathrm{e}^{-x_0}\left(1 + x_0 + \frac{x_0^2}{2} + \frac{x_0^3}{6}\right)\right]^{1/2}$$

$$x_0 \equiv 2\kappa c_\mathrm{p} u_*$$

Kitaigorodskii (1970)

$$z_0^* = 0.068\left(\frac{u_*}{c_\mathrm{p}}\right)^{-3/2} \exp\left(-\kappa \frac{c_\mathrm{p}}{u_*}\right)$$

# With Wave Effect (2)

| | |
|---|---|
| Hsu (1974) | $z_0^* = 0.144\left(\frac{u_*}{c_p}\right)^{1/2}$ |
| Toba and Koga (1986) | $z_0^* = \Omega\left(\frac{u_*}{c_p}\right)^{-1}$ <br> $\Omega = 0.025$ (Toba and Koga 1986) <br> 0.015 (Toba et al. 1990) |
| Huang et al. (1986) | $z_0^* = 0.085\left(\frac{u_*}{c_p}\right)^{1/2}\Phi(x_0)$ <br> $\Phi(x_0) \equiv \left[1 - e^{-x_0}\left(1 + x_0 + \frac{x_0^2}{2} + \frac{x_0^3}{6}\right)\right]^{1/2}$ <br> $x_0 \equiv 2\kappa c_p/u_*.$ |
| Geernaert, Larsen and Hansen (1987) | $z_0^* \equiv \frac{10g}{u_*^2}\exp\left(-3.65\left(\frac{u_*}{c_p}\right)^{1/3}\right)$ <br> $C_D = 0.012\left(\frac{u_*}{c_p}\right)^{2/3}$ |

# With Wave Effect

| | |
|---|---|
| Masuda and Kusaba (1987) | $z_0^* = 0.0129\left(\frac{u_*}{c_p}\right)^{1.10}$ |
| Donelan (1990) Field | $z_0^* = 0.42\left(\frac{u_*}{c_p}\right)^{1.03}$ |
| Donelan (1990) Lab | $z_0^* = 0.047\left(\frac{u_*}{c_p}\right)^{0.68}$ |
| Toba et al. (1990) [TIKEJ] | $z_0^* = 0.020\left(\frac{u_*}{c_p}\right)^{1/2}$ |
| Mast, Kraan and Oost (1991) | $z_0^* = 0.8\left(\frac{u_*}{c_p}\right)$ |
| Nordeng (1991) | $z_0^* = 0.11\left(\frac{u_*}{c_p}\right)^{3/4}\Phi(x_0)$ <br> $\Phi(x_0) \equiv \left[1 - e^{-x_0}\left(1 + x_0 + \frac{x_0^2}{2} + \frac{x_0^3}{6}\right)\right]^{1/2}$ <br> $x_0 \equiv 2\kappa c_p/u_*$ |
| Smith et al. (1992) | $z_0^* = 0.48\left(\frac{u_*}{c_p}\right)$ |

# NOAA WaveWatch-III
# Third Generation Wave Model
# (Tolman 1999)

$$\frac{\partial N}{\partial t} + \frac{1}{\cos\phi}\frac{\partial}{\partial\phi}\dot{\phi}N\cos\theta + \frac{\partial}{\partial\lambda}\dot{\lambda}N + \frac{\partial}{\partial k}\dot{k}N + \frac{\partial}{\partial\theta}\dot{\theta}_g N = \frac{S}{\sigma}$$

$$S = S_{in} + S_{nl} + S_{ds} + S_{bot}$$

$$\dot{\phi} = \frac{c_g\cos\theta + U_\phi}{R} \qquad \dot{\lambda} = \frac{c_g\sin\theta + U_\phi}{R\cos\phi}$$

$$\dot{\theta}_g = \dot{\theta} - \frac{c_g\tan\phi\cos\theta}{R}$$

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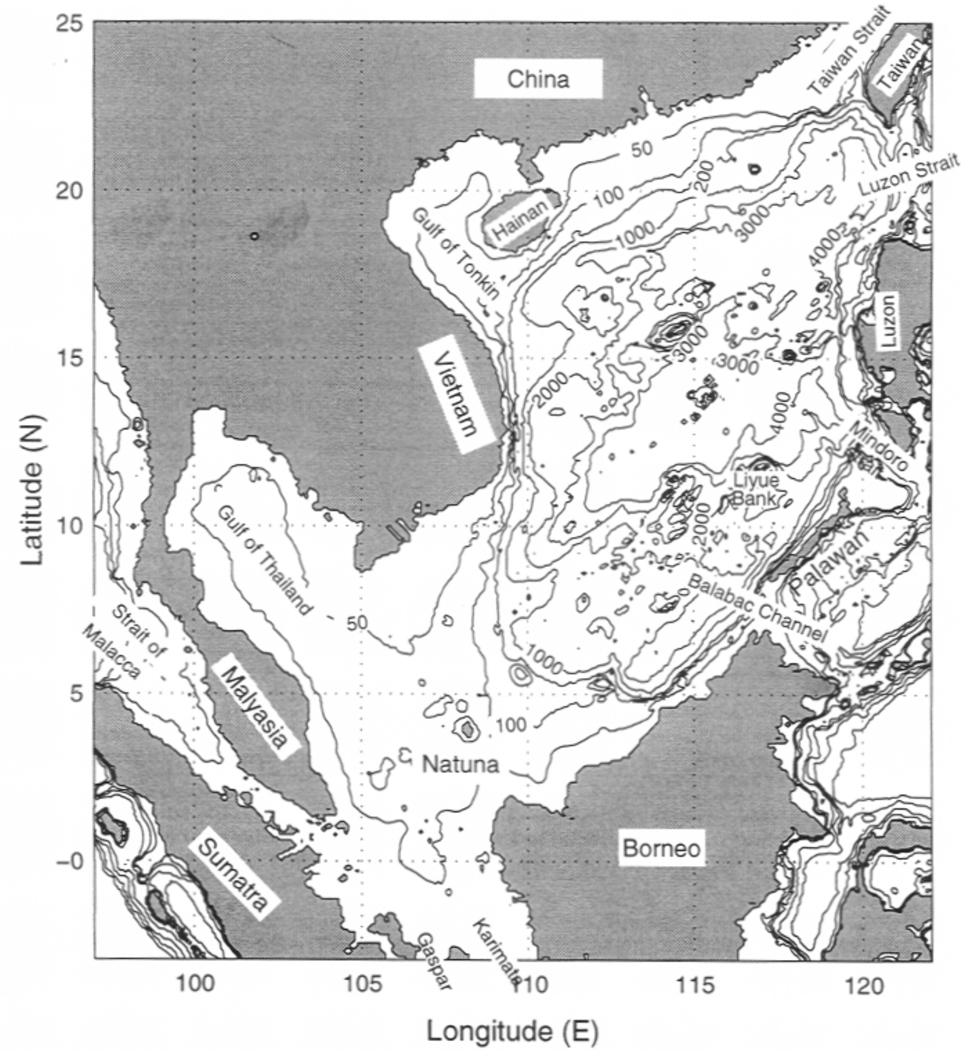
# South China Sea

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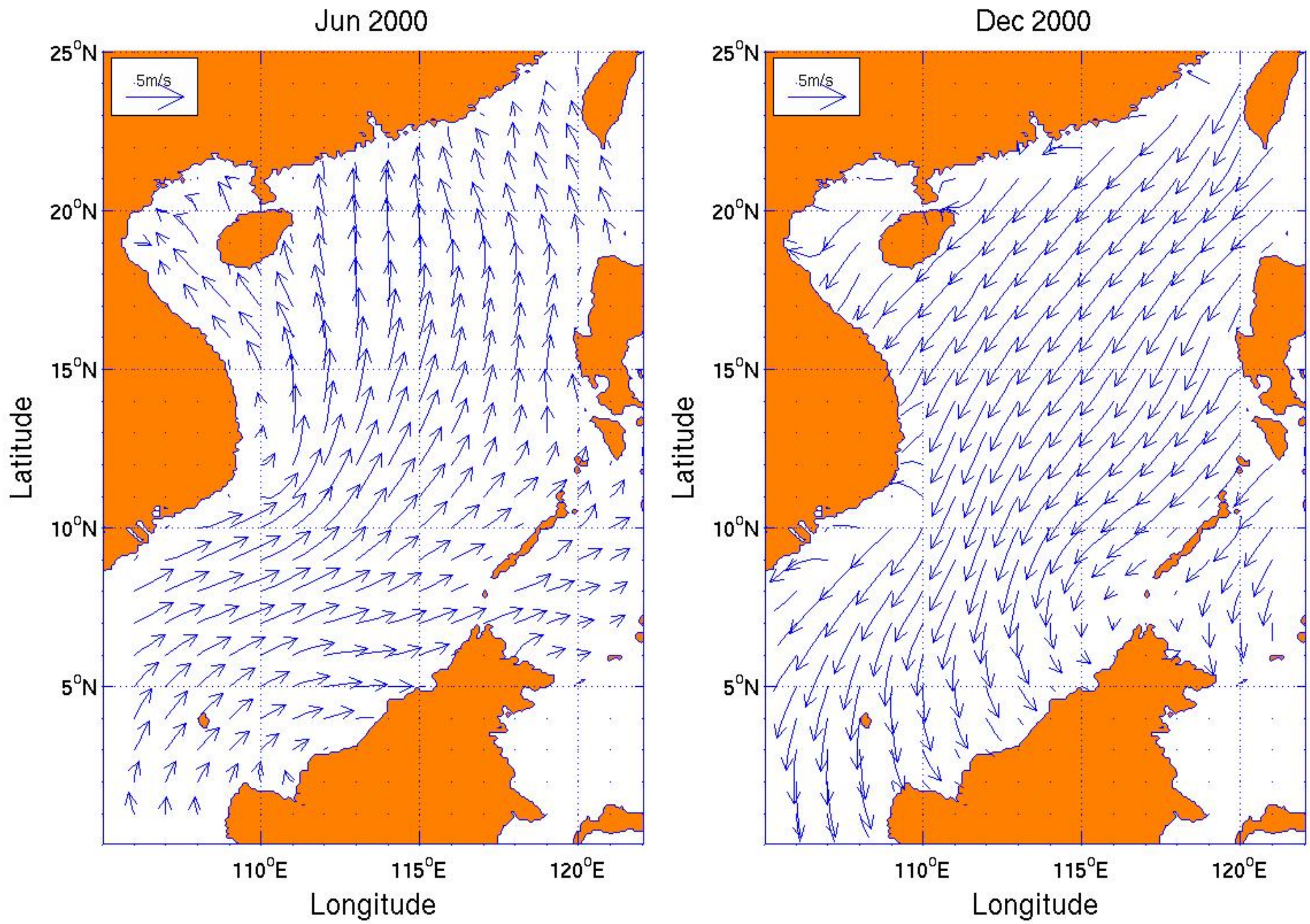
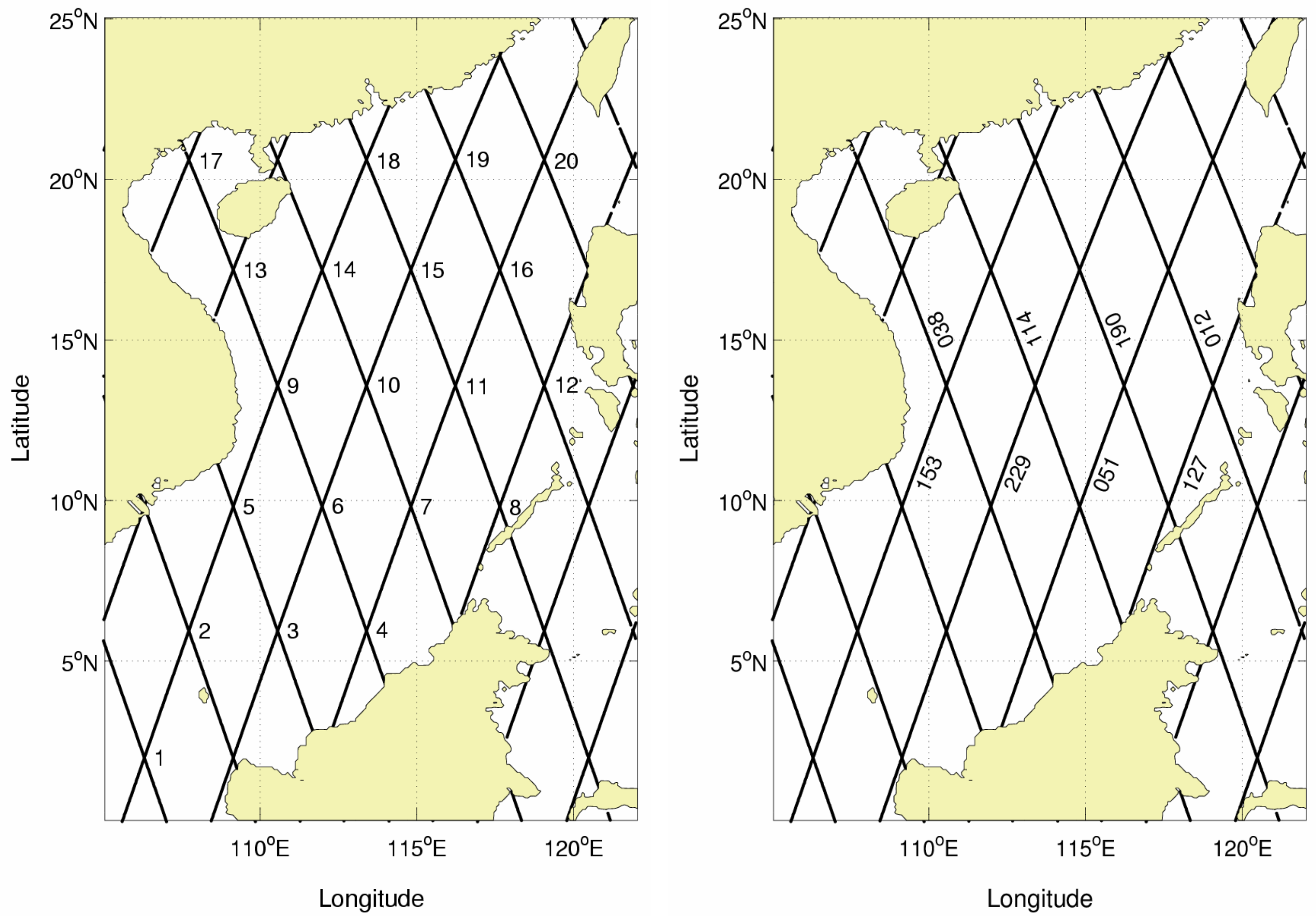
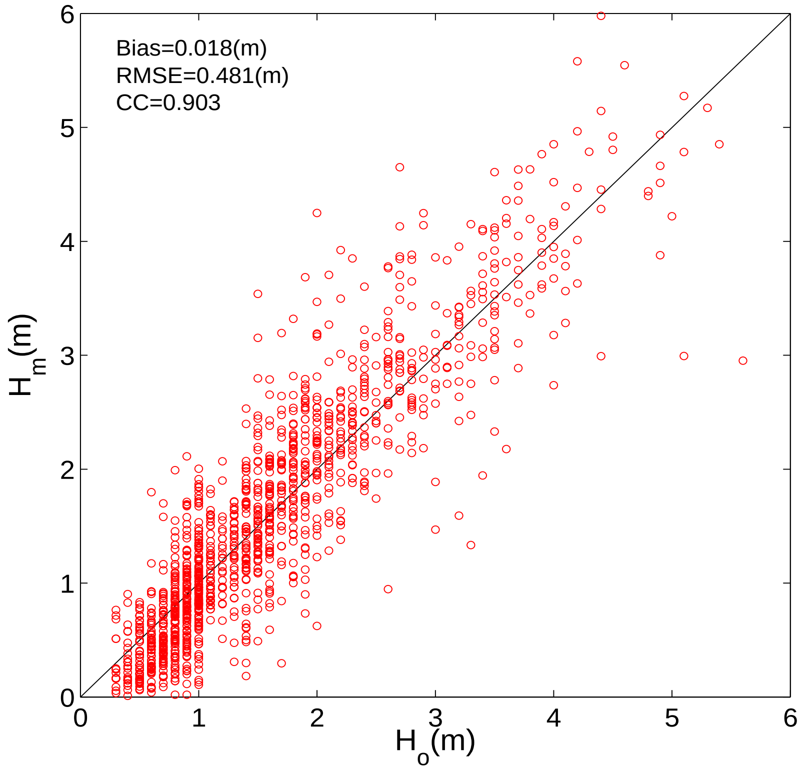
# Monsoon Winds (from QuikScat Data)



# T/P (a) crossover points and (b) tracks in the SCS.

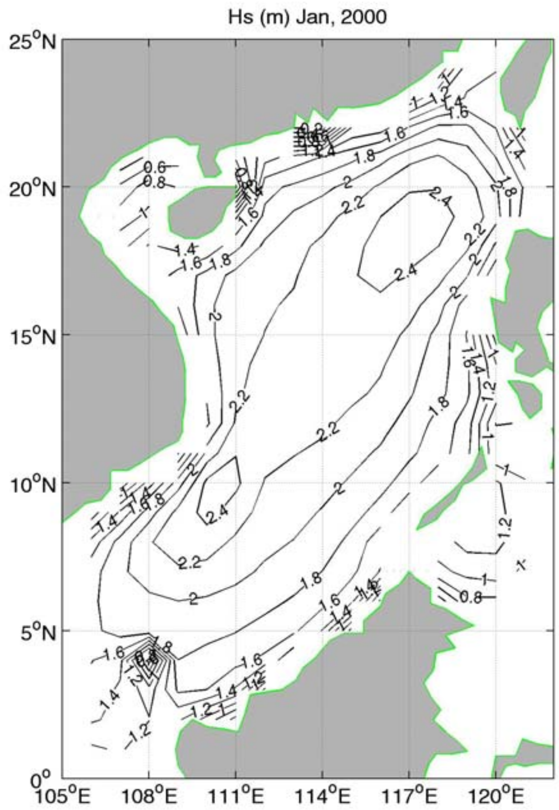


# STATISTICAL EVALUATION OF WAVEWATCH-3

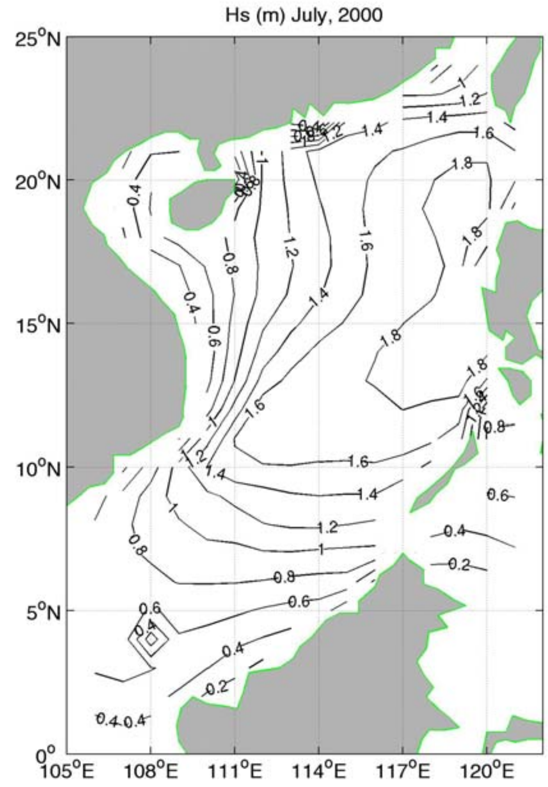


# Significant Wave Height (2000)

January

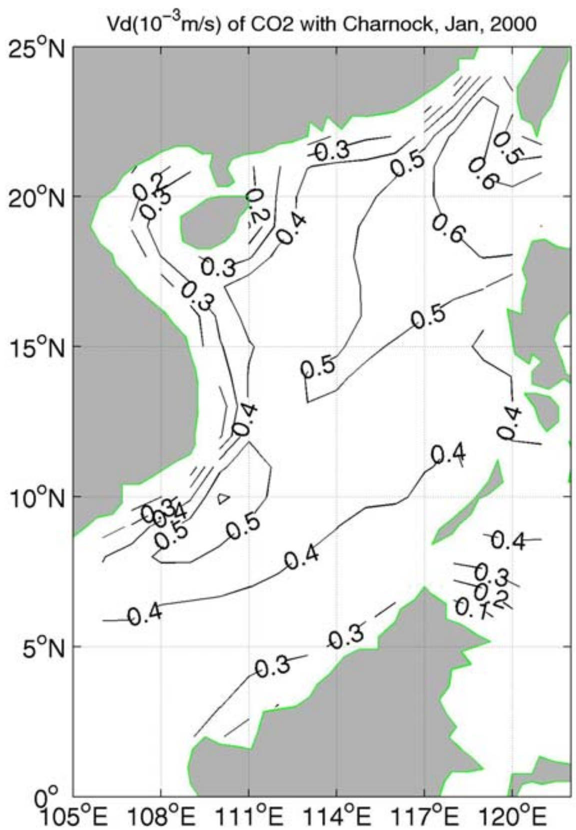



July

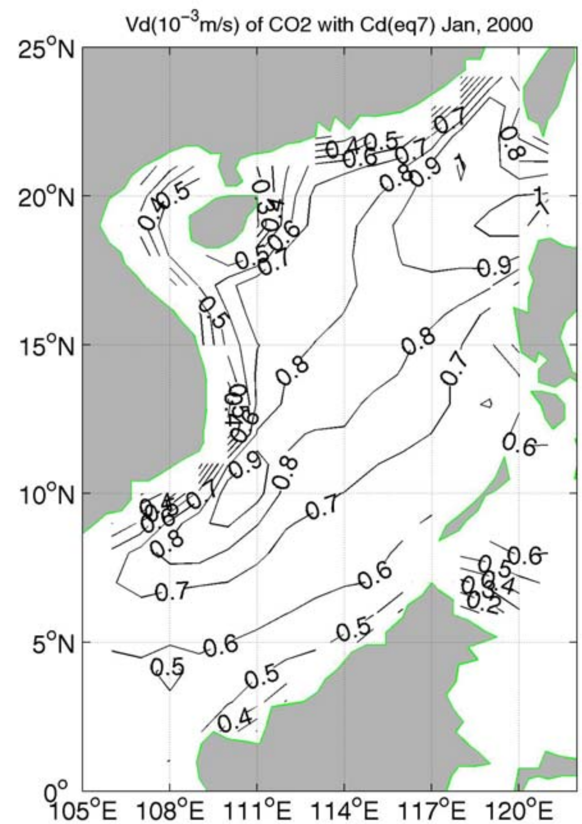


# Total Deposit Velocity of $CO_2$ in January 2000

Without Wave Effect
(Charnock 1955)




With Wave Effect
(Toba & Koga 1986)



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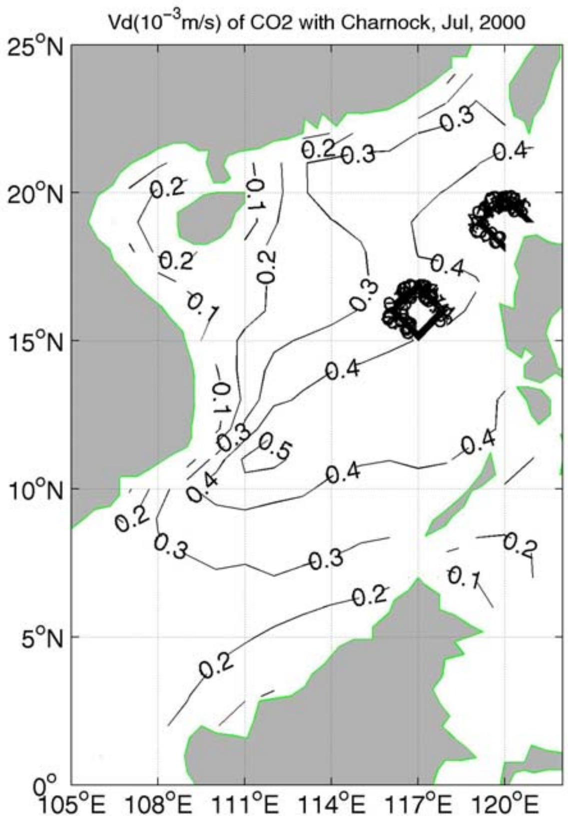
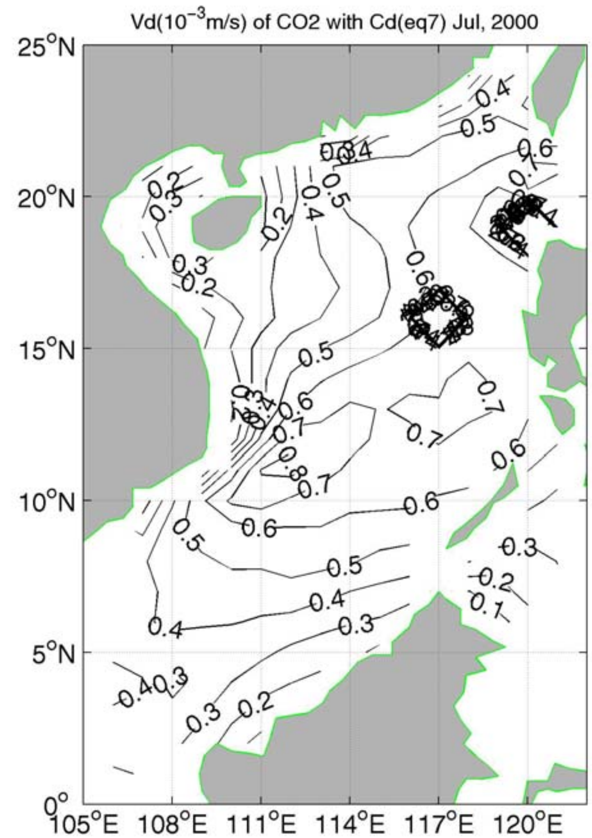



## With Wave Effect (Toba & Koga 1986)



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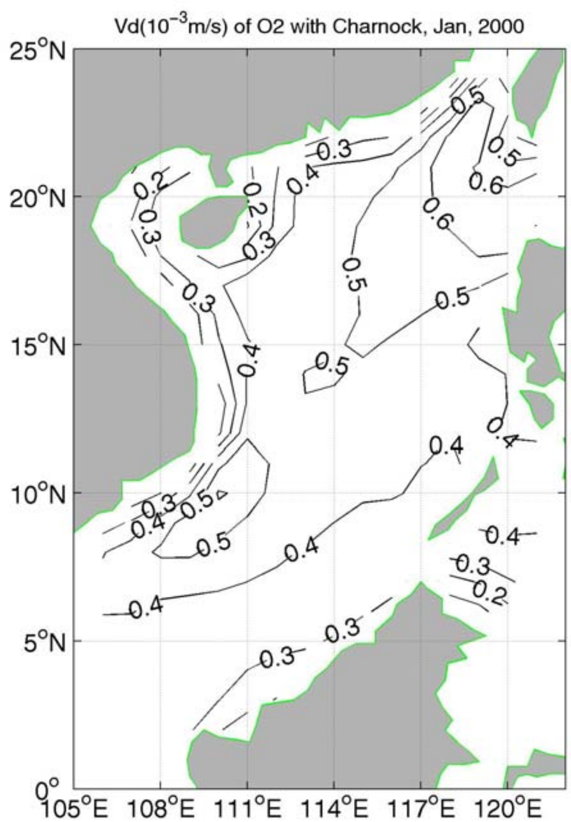
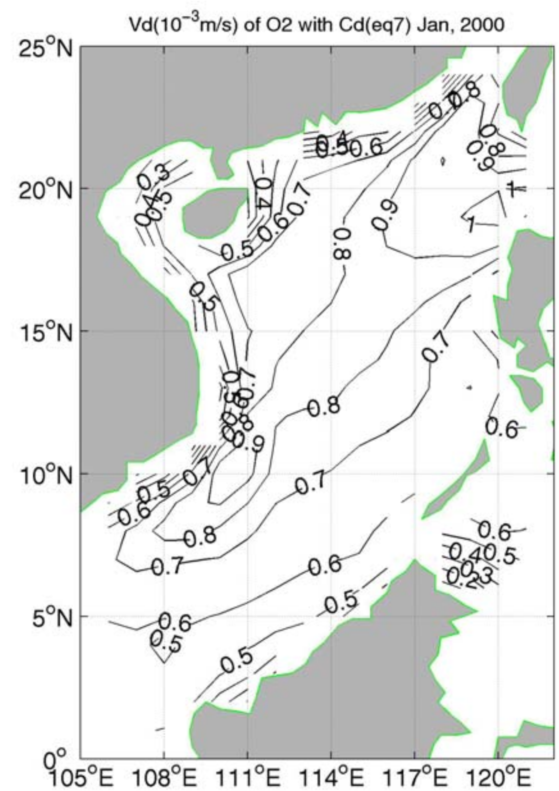



With Wave Effect
(Toba & Koga 1986)



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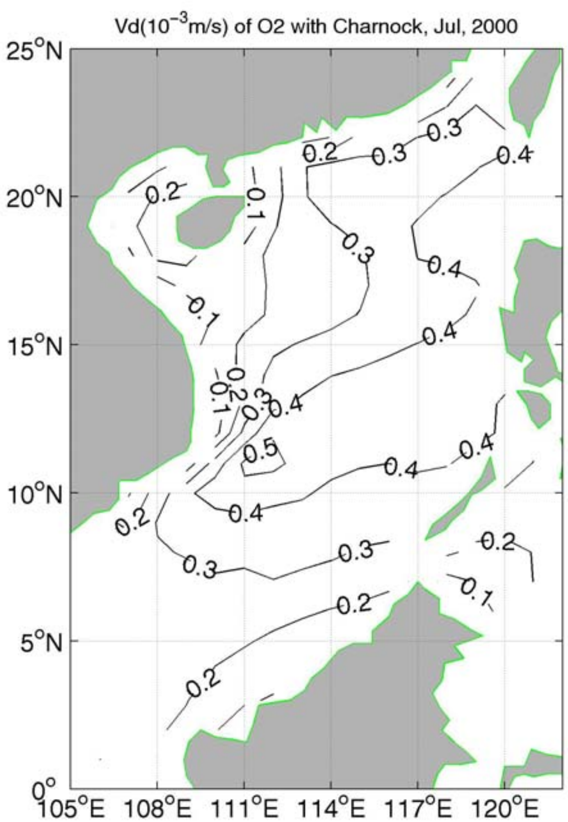
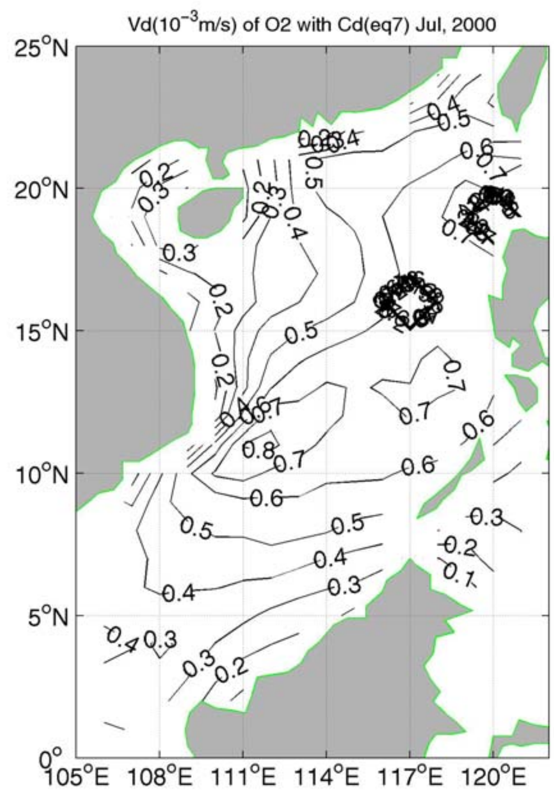



With Wave Effect
(Toba & Koga 1986)

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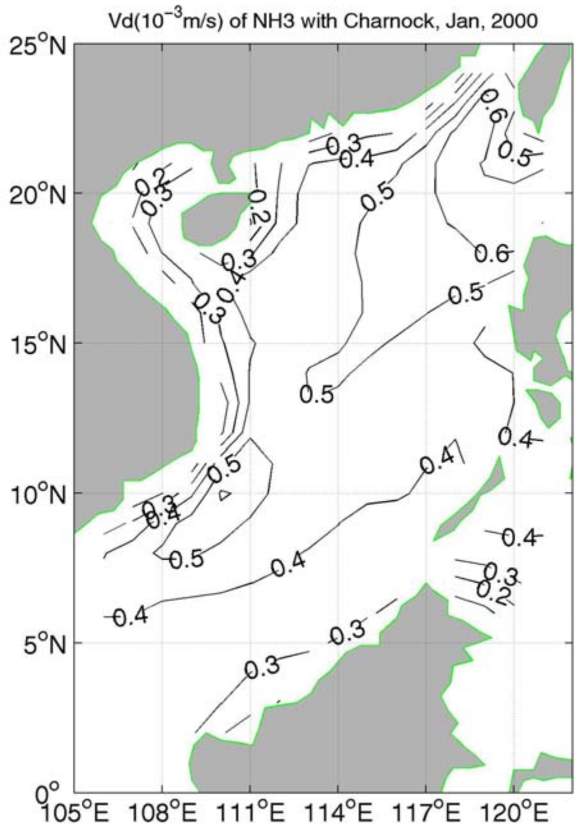
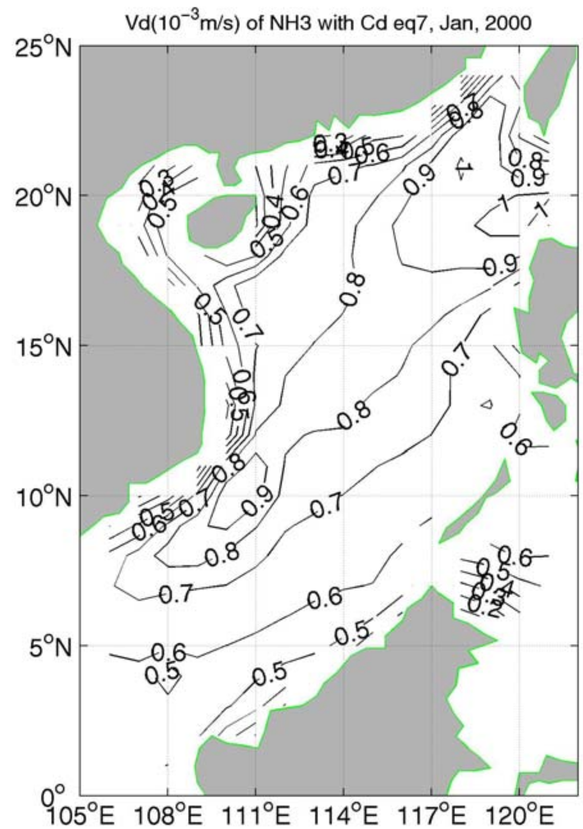
# Total Deposit Velocity of $NH_3$ in January 2000

Without Wave Effect (Charnock 1955)




With Wave Effect (Toba & Koga 1986)

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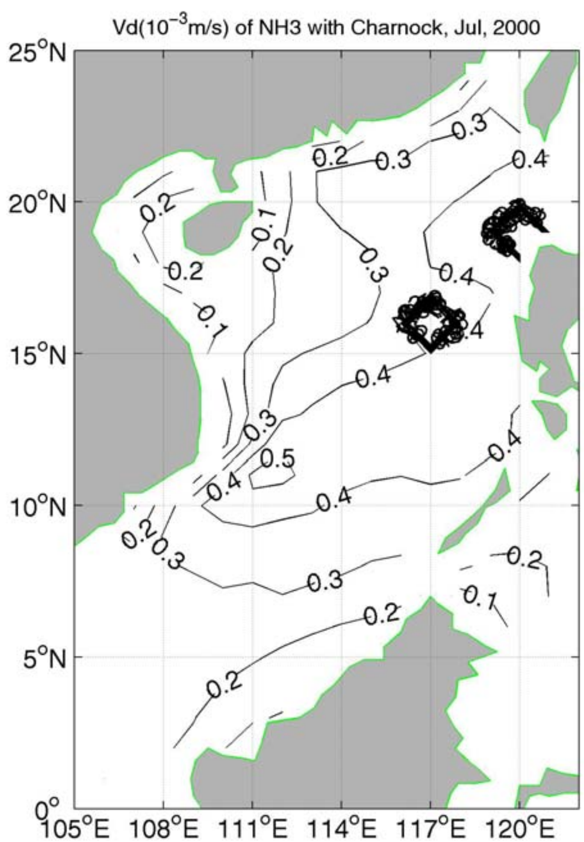
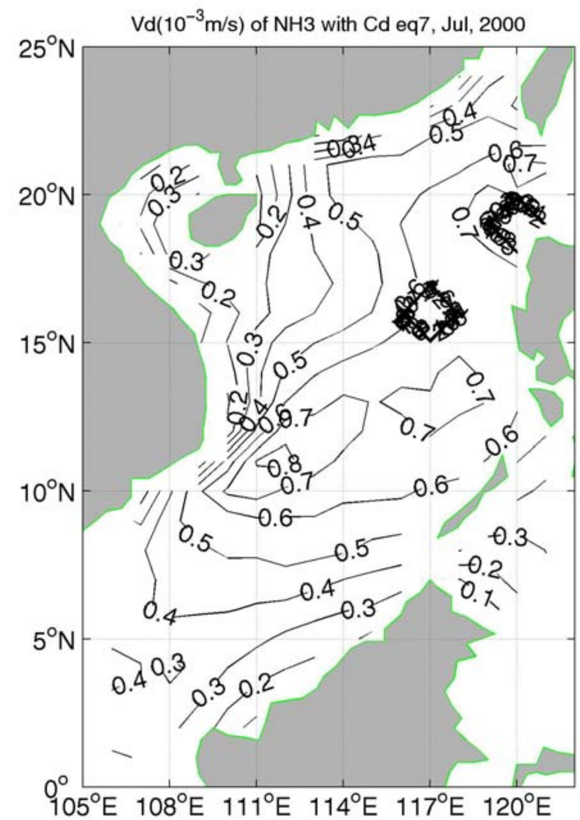
# Total Deposit Velocity of $NH_3$ in July 2000

Without Wave Effect (Charnock 1955)




With Wave Effect (Toba & Koga 1986)

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# Conclusions

- (1) Waves increase the gas deposit velocity $V_d$ (up to twice)
- (2) It is important to include a wave model into gas transfer model.