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Effect of Typhoon-Driven Ocean Waves on Sea-to-Air Transfer of Dimethylsulfide (DMS)

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- Ever notice the salty sea smell when you're out on or near the ocean?

  →

- Gases diffuse across the air-sea interface, many of which are synthesized and emitted by micro-algae. One of them is DMS.

- **DMS (CH_3SCH_3)**



References

- Chu, P.C., J. M. Veneziano, and C.W. Fan, 2000: Response of the South China Sea to tropical cyclone Ernie 1996. Journal of Geophysical Research, 105, 13991-14009.

- Chu, P.C., Y. Qi, Y.C. Chen, P. Shi, and Q.W. Mao, 2004: South China Sea wave charcteristics. Part-1: Validation of wavewatch-III using TOPEX/Poseidon data. Journal of Atmospheric and Oceanic Technology, 21 (11), 1718-1733.

- Chu, P.C., and K.F. Cheng, 2007: Effect of wave boundary layer on the sea-to-air dimethylsulfide transfer velocity during typhoon passage. Journal of Marine Systems, 66, 122-129.

- Chu, P.C., and K.F. Cheng, 2008: South China Sea wave characteristics during Typhoon Muifa passage in winter 2004. Journal of Oceanography, inpress.



Outlines

- (1) DMS and Climate
- (2) Sea-to-air DMS transfer
- (3) Tropical cyclone wind profile model
- (4) Wave effects (Wavewatch-3 Modeling)
- (5) Typhoon effects on sea-to-air DMS transfer
- (6) Summary





1. DMS and Climate

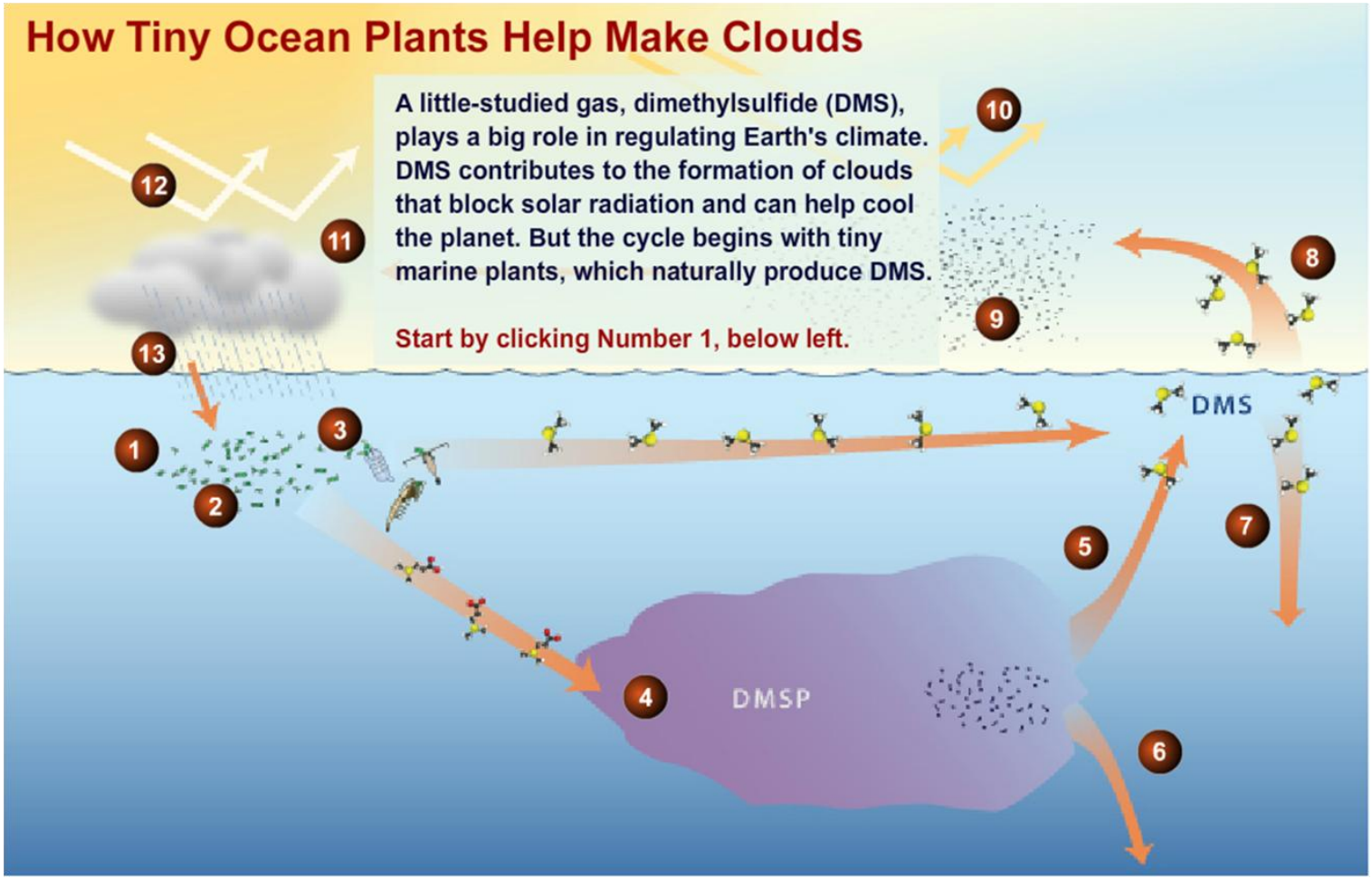




The dominant natural source of sulfur (S) to the atmosphere is the oceanic DMS

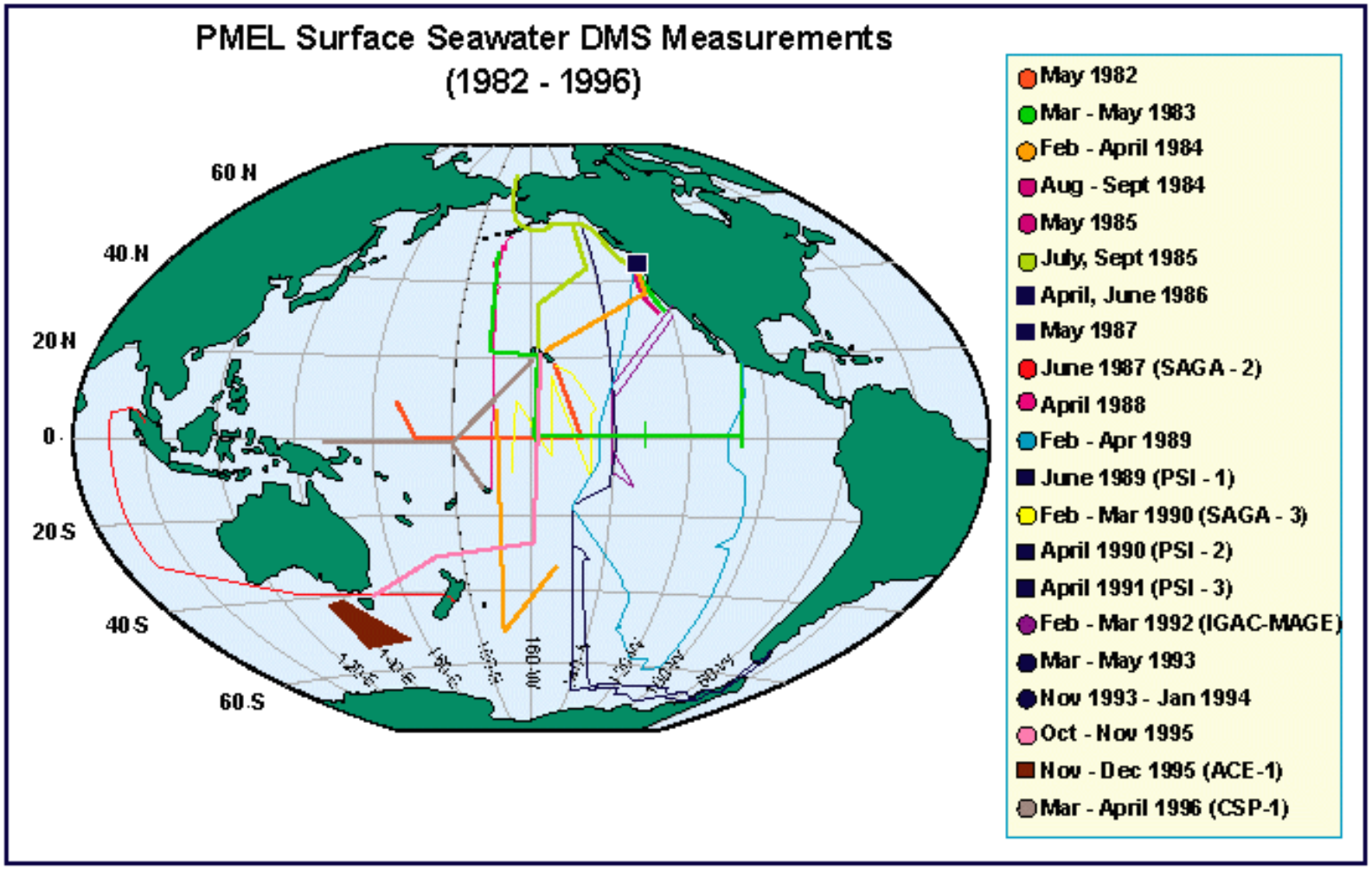
(Bates et al., 1992; Gondwe et al., 2003).



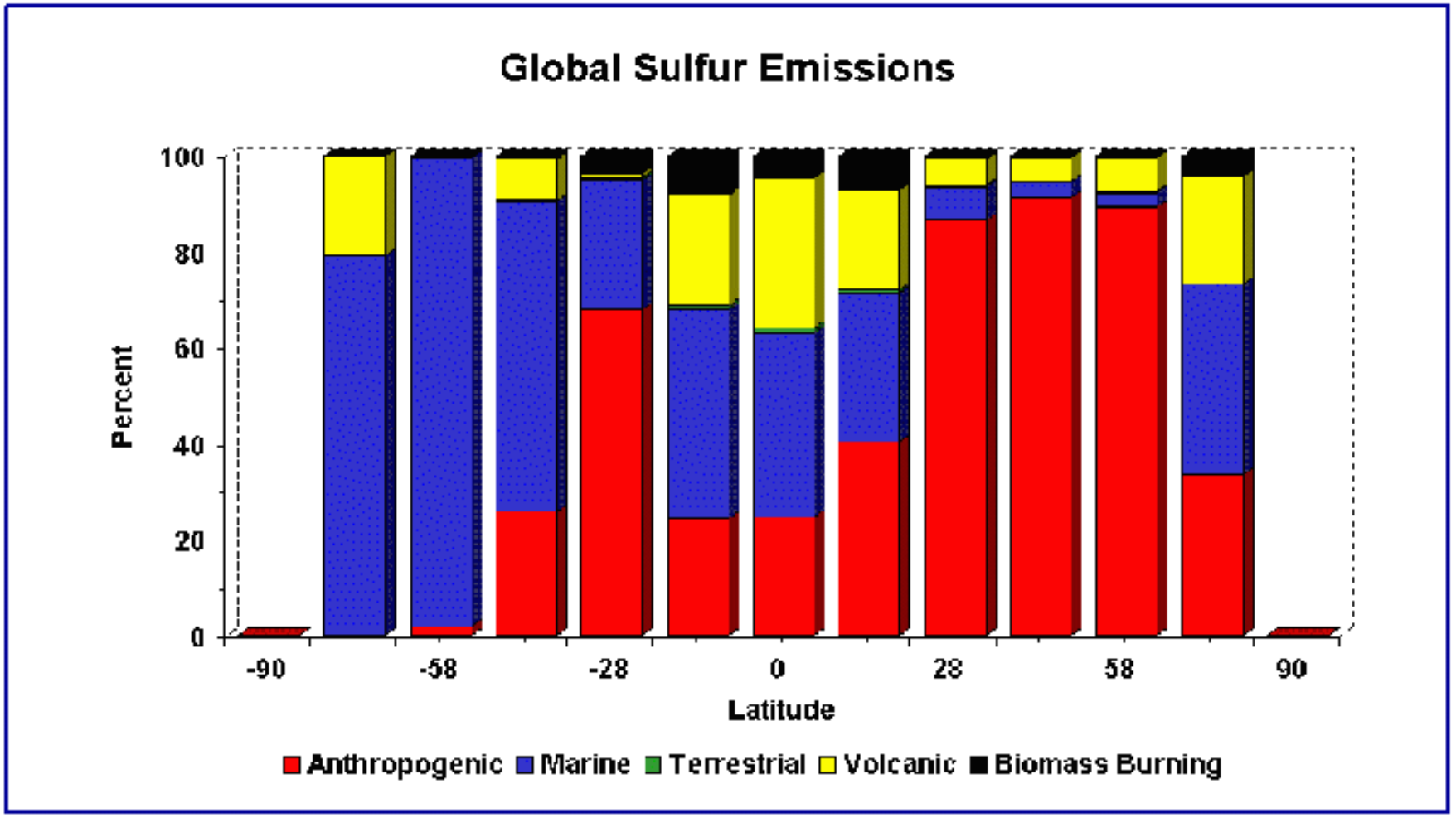


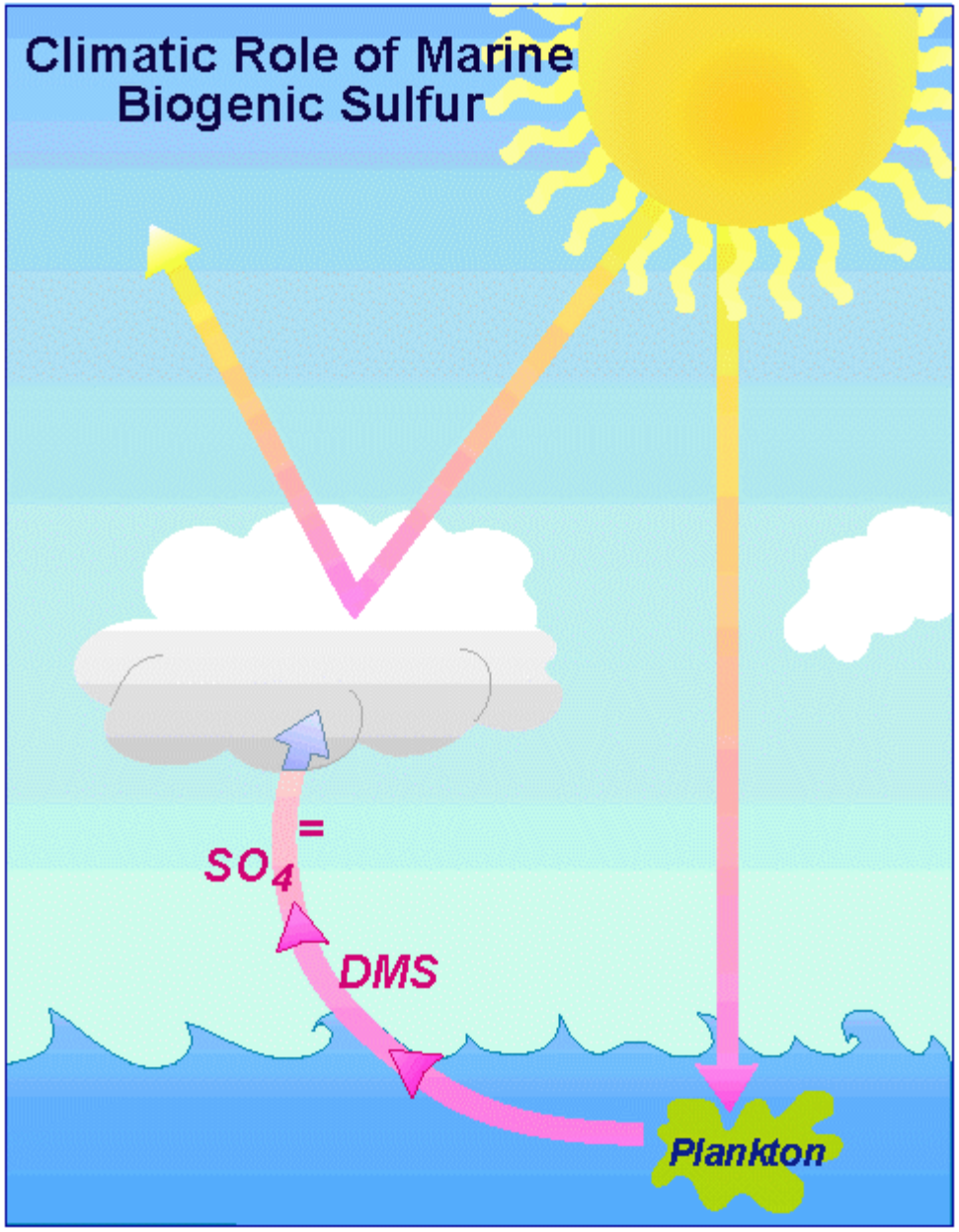
From:
http://www.whoi.edu/oceanus/viewFlash.do?fileid=40305&id=28372&aid=45946

Sea Surface DMS Measurements



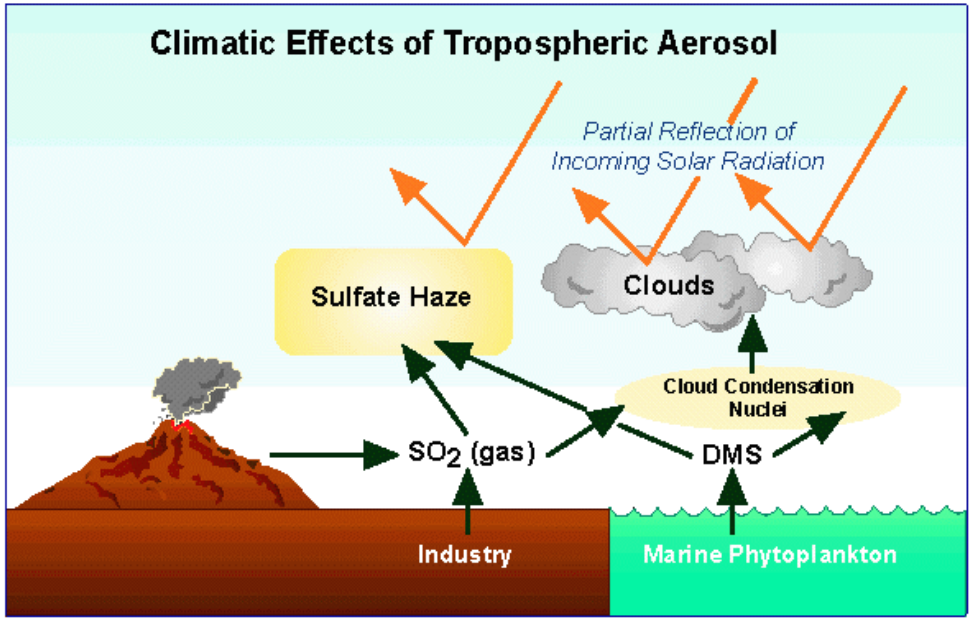
Global Sulfur (S) Emissions



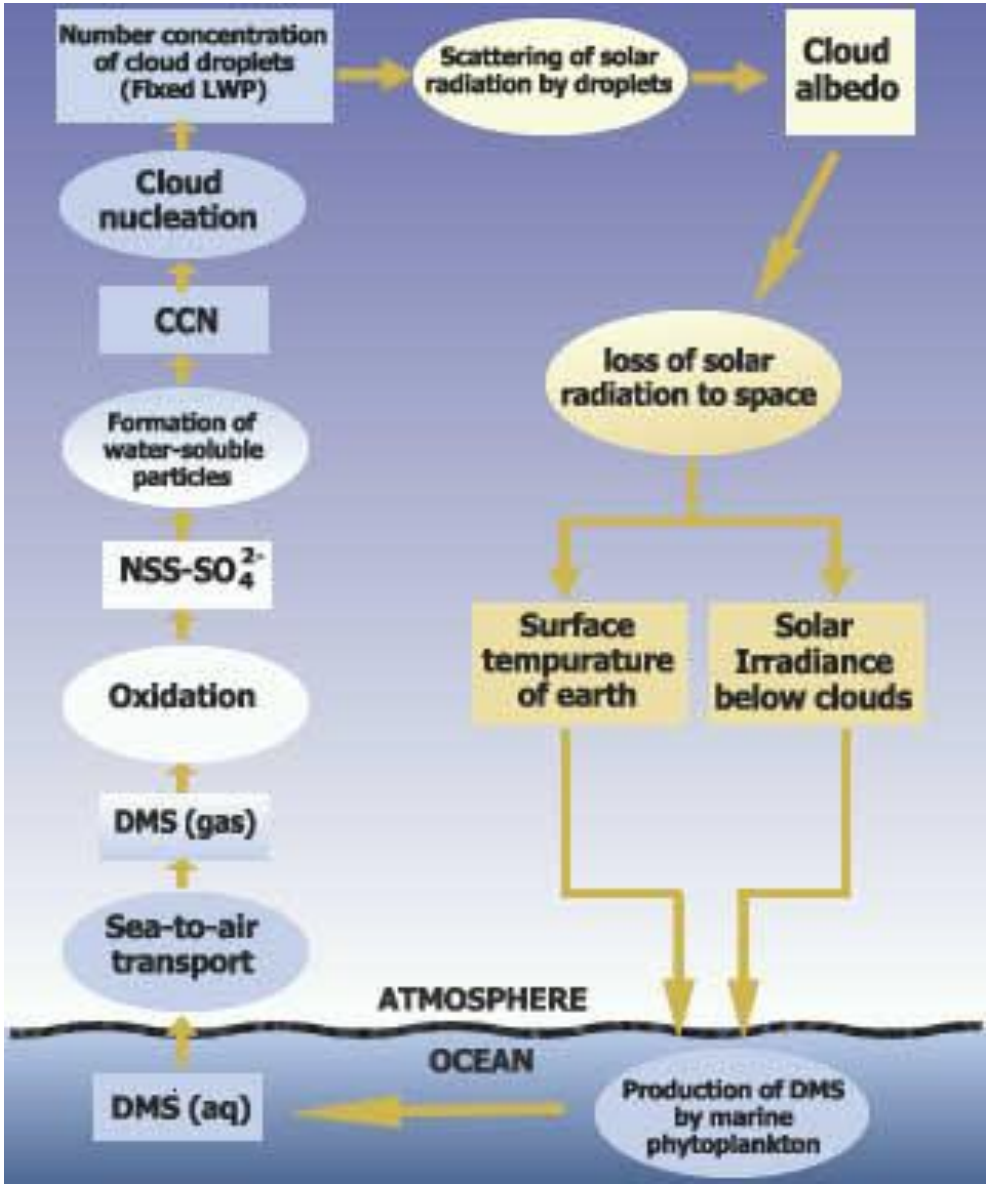

Climatic Role of Marine Biogenic Sulfur
$SO_4^=$
DMS
Plankton

Dimethylsulfide (DMS) Cycle

- **DMS (CH_3SCH_3) changes the radiation budget in the atmosphere and in turn changes the climate.**



Effects of DMS







2. Sea-to-Air DMS Flux Computation





C_a (DMS concentrations at airside)

Air

$m_a = k_a(C_a - C_{s,w}/\alpha)$

$\leftarrow m_a$ (flux in airside)

$C_{s,w}$ (concentration at the interface)

$m_a = m_w$

$m_w = k_w(C_{s,w} - C_w)$

$\leftarrow m_w$ (flux in waterside)

Ocean

C_w (DMS concentrations at waterside)



Ostwald Solubility Coefficient



$$\alpha = \exp\left[\frac{3525}{T} - 9.464\right]$$

→Representing ratio of C_w / C_a at equilibrium

T in ^oK



Airside DMS Transfer Velocity k_a

$$k_a = 659\ u_r\ (\mathrm{M_{H2O}/M})^{1/2}$$

M → molecular weight of DMS → 129.075

$\mathrm{M_{H2O}}$ → molecular weight of $\mathrm{H_2O}$ → 18

Winds → $u_r = u(z_r)$ → k_a

z_r = 10 m



Waterside DMS Transfer Velocity (Jahne et al., 1987)



- Waterside transfer velocity (n = 0.58)

$$k_w = \sqrt{\rho_a / \rho_w}\,\beta^{-1}\mathrm{Sc}^{-n}u_*$$

- Schmidt Number = 720 (DMS at 300 K)

$$\mathrm{Sc} \equiv \nu / D$$

- DMS Diffusion coefficient (Saltzman et al., 1993)

$$D = 1.1\times10^{-2}\exp\left[-\frac{1896}{T}\right] \quad \text{(unit: cm}^2\text{/s)}$$

$$\beta = 0.55\,\mathrm{Re}_r^{1/4}$$

Roughness Reynolds Number

$$\mathrm{Re}_r \equiv u_* z_0 / \nu$$

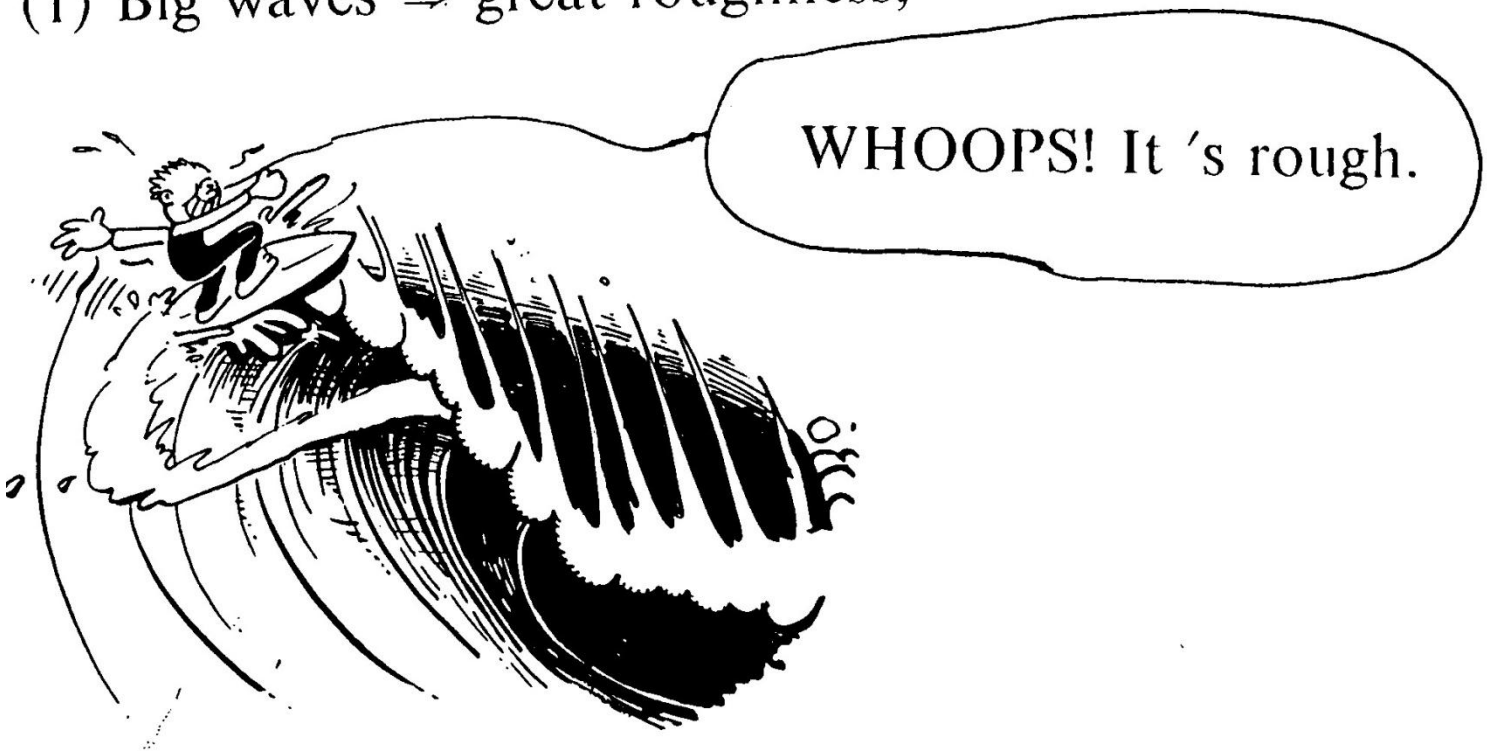




- $u_r \rightarrow k_a$

- $(z_0 , u_*) \rightarrow k_w$

(1) Big waves ⇒ great roughness,



Typhoon (Hurricane) → Big Waves → z_0

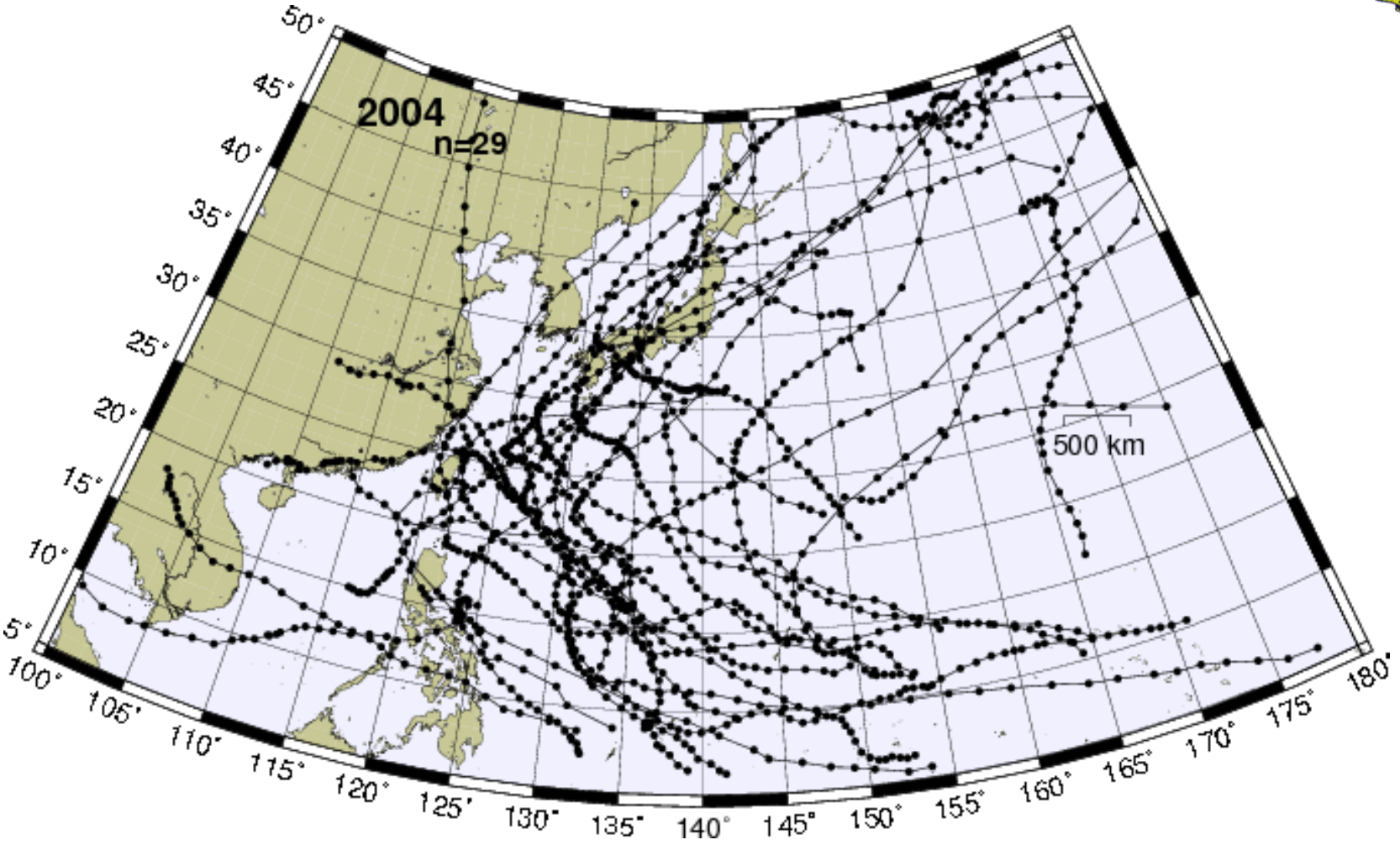




What is the effect of tropical cyclones on the sea-to-air DMS transfer?






2004
n=29
500 km
50°
45°
40°
35°
30°
25°
20°
15°
10°
5°
100°
105°
110°
115°
120°
125°
130°
135°
140°
145°
150°
155°
160°
165°
170°
175°
180°



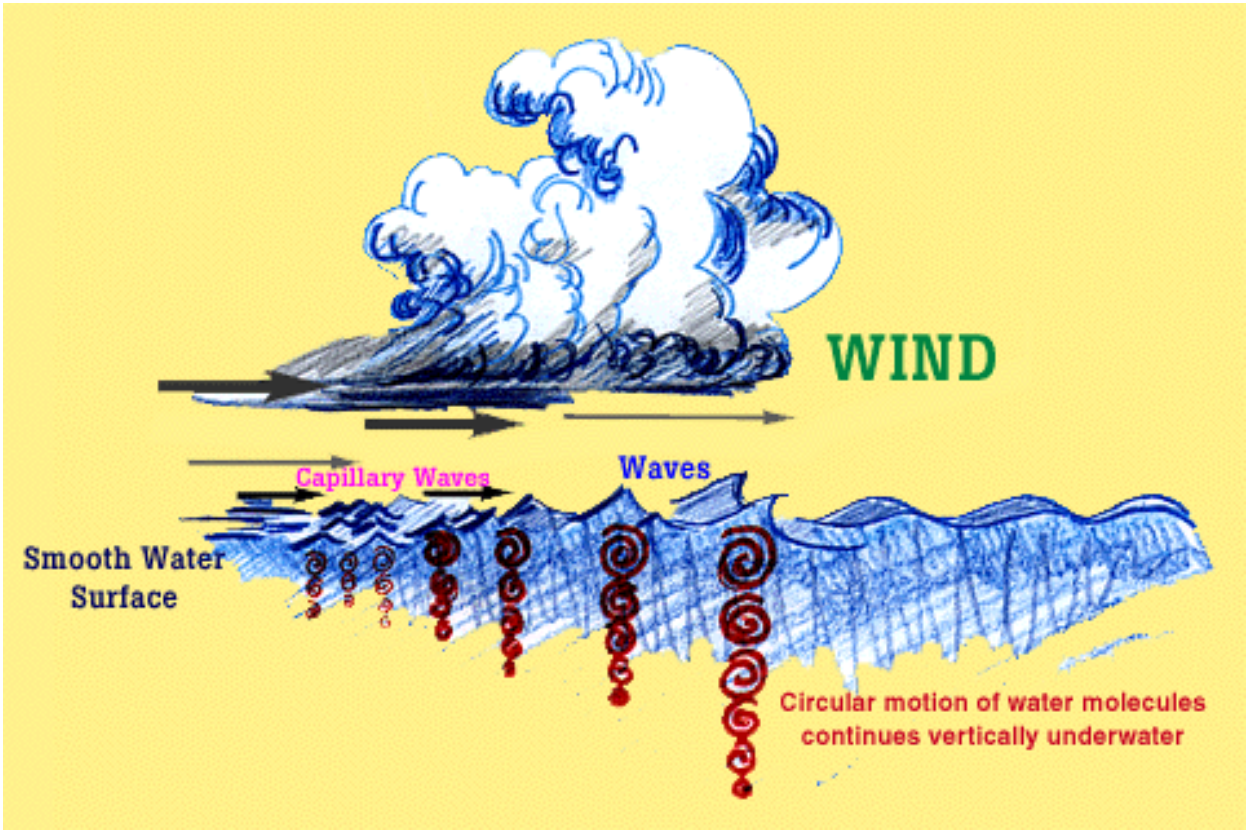
Tropical cyclone's effects on oceans

- Strong near-inertial, anticyclonic turning upper-ocean currents to the right of the storm track
- Maximum sea surface temperature cooling to the right of the storm track
- Air-sea fluxes
- Ocean surface wave boundary layer





Tropical Cyclones
→ Ocean Waves
→ $(z_0\ u_*)$ → k_w → Sea-to-Air DMS Flux







3. Tropical Cyclone Wind Profile Model



Wind Decomposition

$$\mathbf{V} = (1-\varepsilon)(\mathbf{V}_c + \mathbf{V}_t) + \varepsilon \mathbf{V}_{bg}$$

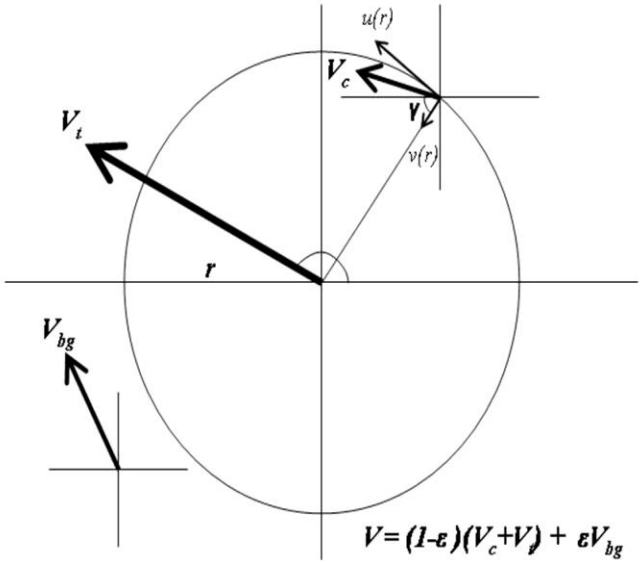
$$\varepsilon = \frac{c^4}{1+c^4}, c = \frac{r}{0.9R_0}$$

$\mathbf{V}_t$ → Translation velocity

$\mathbf{V}_c$ → relative velocity to storm center

$\mathbf{V}_{bg}$ → Background velocity

(R_0, R_m) → zero and maximum tangential velocities







Tropical Cyclone Wind Profile Model (TCWPM) (Carr and Elsberry 1997)

$$v_c(r) = \frac{f_0}{2}\left[R_0 \left(\frac{R_0}{r}\right)^X - r \right] \frac{a^4}{1-a^4}$$

$$u_c(r) = \tan(\gamma) v_c(r)$$

$$a = \frac{r}{R_m}$$

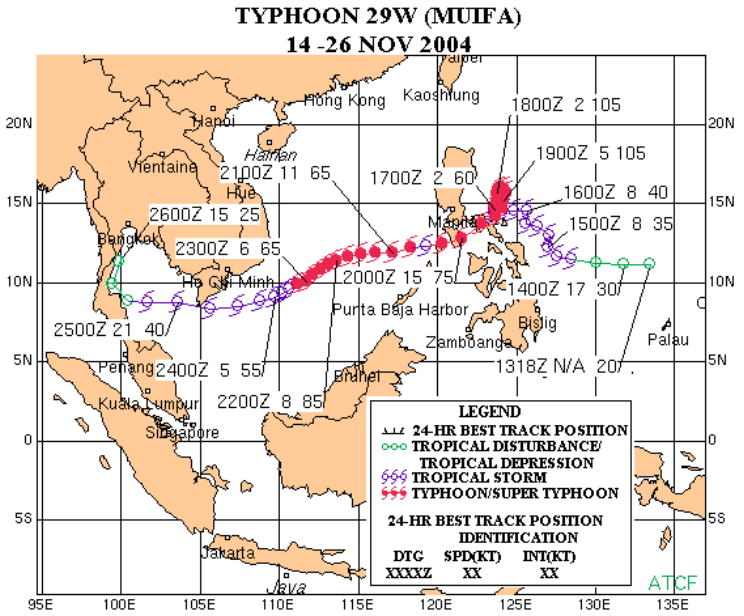
γ → inflow angle of air as it spirals into the typhoon center

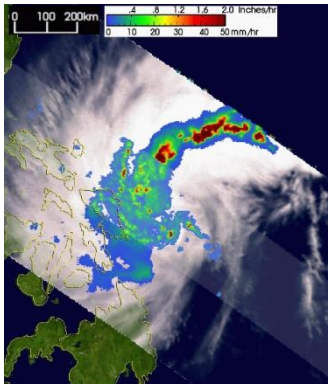
X → positive parameter (~ 0.4)



Typhoon Muifa (2004)

- Best Track Record from the JTWC (2005)
- Duration
  - 14 Nov. to 26 Nov.
  - 20 Nov. to 25 Nov. (in the SCS)
- Max. Wind Speed
  - 59.2 m/sec (115 kt)
  - 46.3 m/sec (in the SCS)
- Hurricane Translation Speed (HTS): 1~10 m/sec



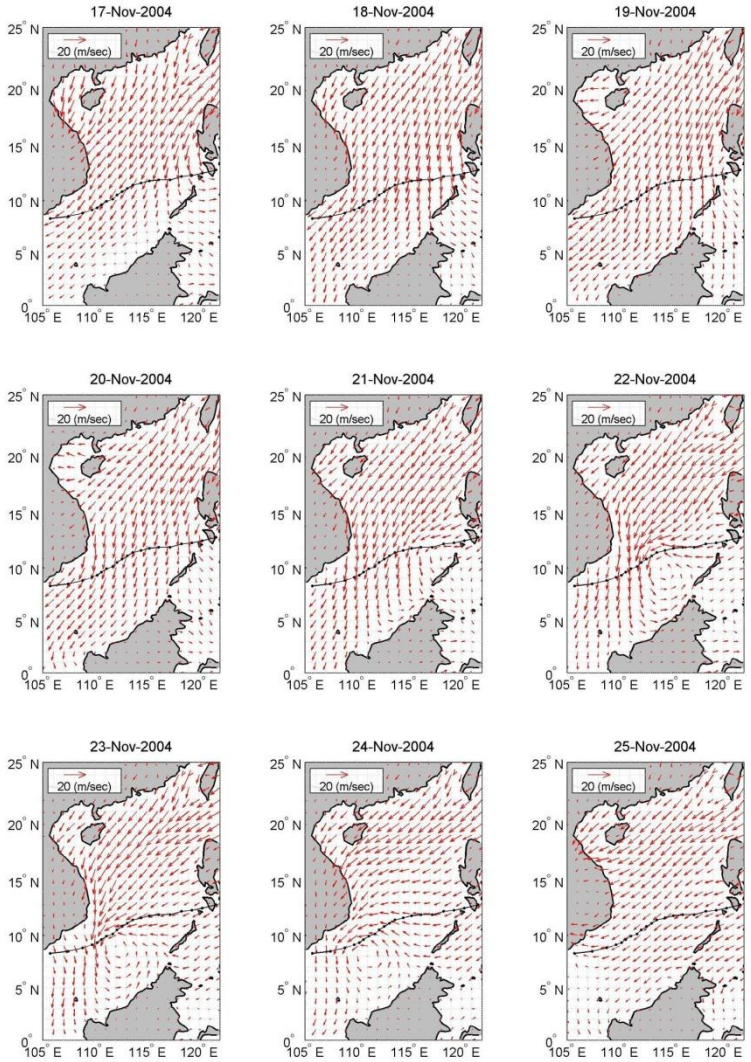




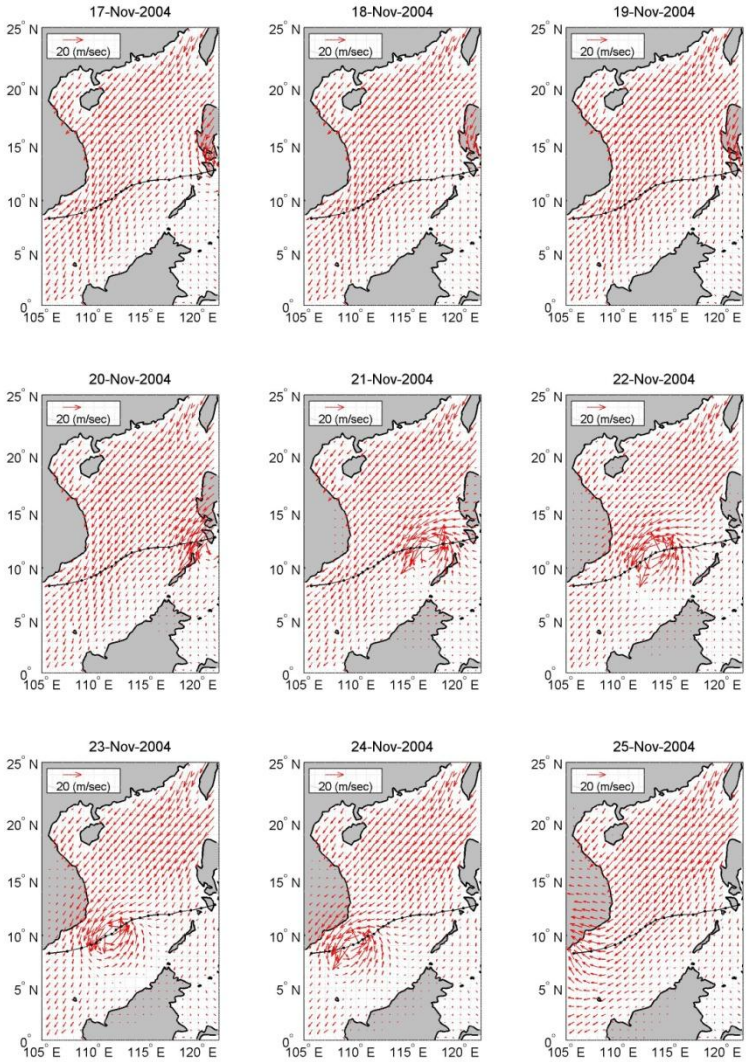
Comparison between NCEP and QSCAT-TCWPM (QTCWPM) Winds



NCEP Wind Fields

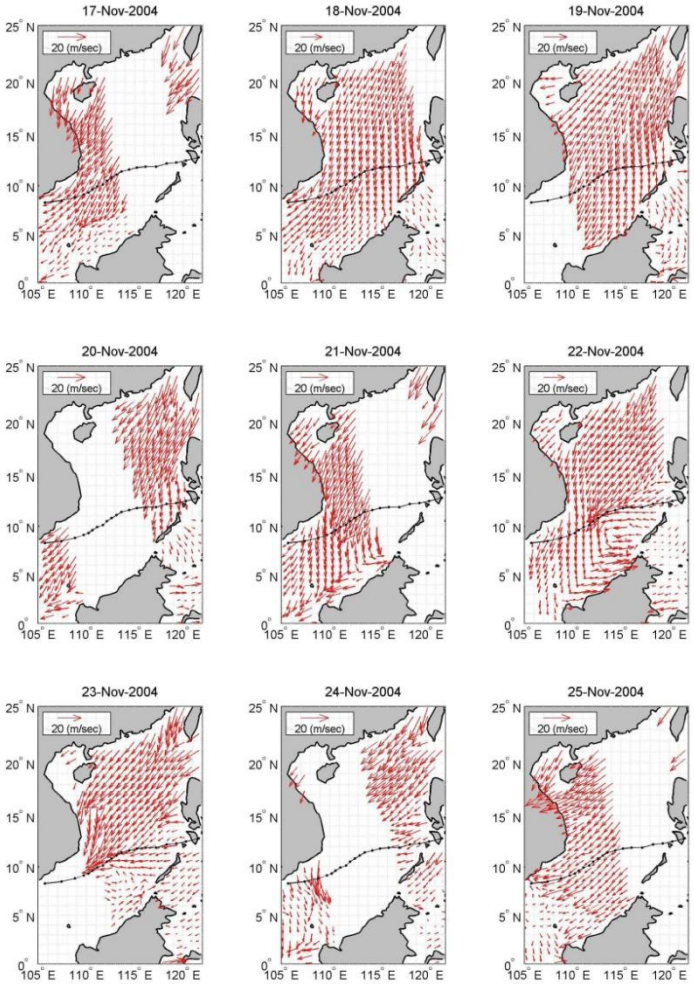


QSCAT-TCWPM Wind Fields

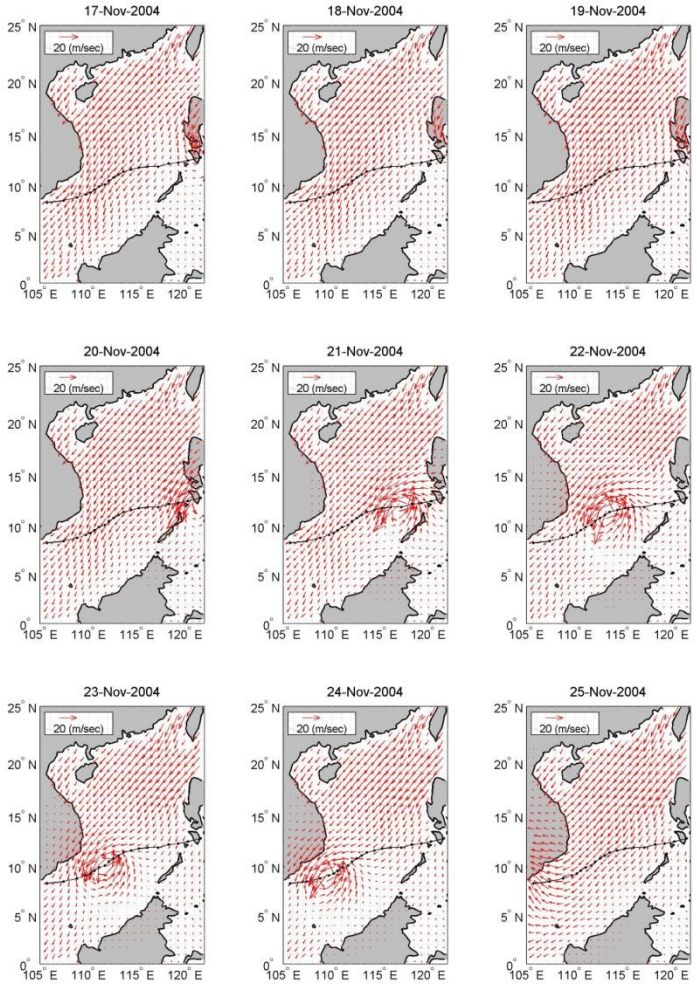


Comparison between QSCAT and QTCWPM Winds

QuikSCAT Wind Fields



QTCWPM Wind Fields







4. Wave Effects on Air-Sea Fluxes



Drag Coefficient without Ocean Waves



$$C_D = (u_*/u_r)^2$$

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

$$C_D = \frac{\kappa^2}{\left[\ln\left(\frac{z_r}{z_0}\right)\right]^2}$$

$z_r = 10$ m

$\kappa = 0.4$ (von Karman Constant)



Charnock (1955) Parameterization



Constant → $z_{0*} = 0.0144$

$$z_0 = 0.0144\, u_*^2/g$$

$$C_D = \frac{\kappa^2}{\left[\ln\left(\frac{z_r}{z_0}\right)\right]^2}$$





Drag Coefficient with Ocean Waves →
Chalikov (1995) parameterization

$$C_D = \kappa^2 \left[R - \ln C_D \right]^2$$

$$R = \ln\left(\frac{z_r g}{\gamma \sqrt{\mu_p u_r}} \right)$$

$$\mu_p = 0.57\ (u_*/C_p)^{3/2}$$

C_p is the peak phase speed.





NOAA WaveWatch-3
Third Generation Wave Model
(Tolman 1999)

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

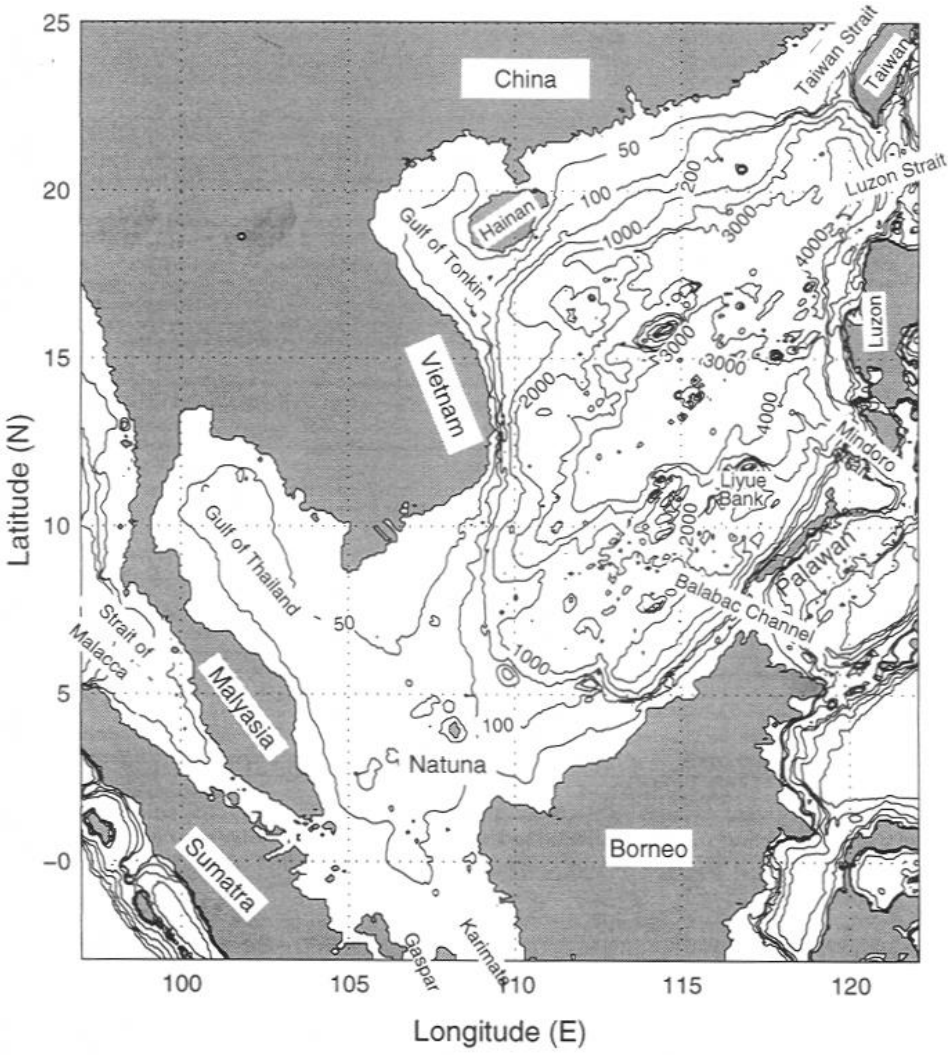
$$S = S_{in} + S_{nl} + S_{ds} + S_{bot}$$

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

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



South China Sea



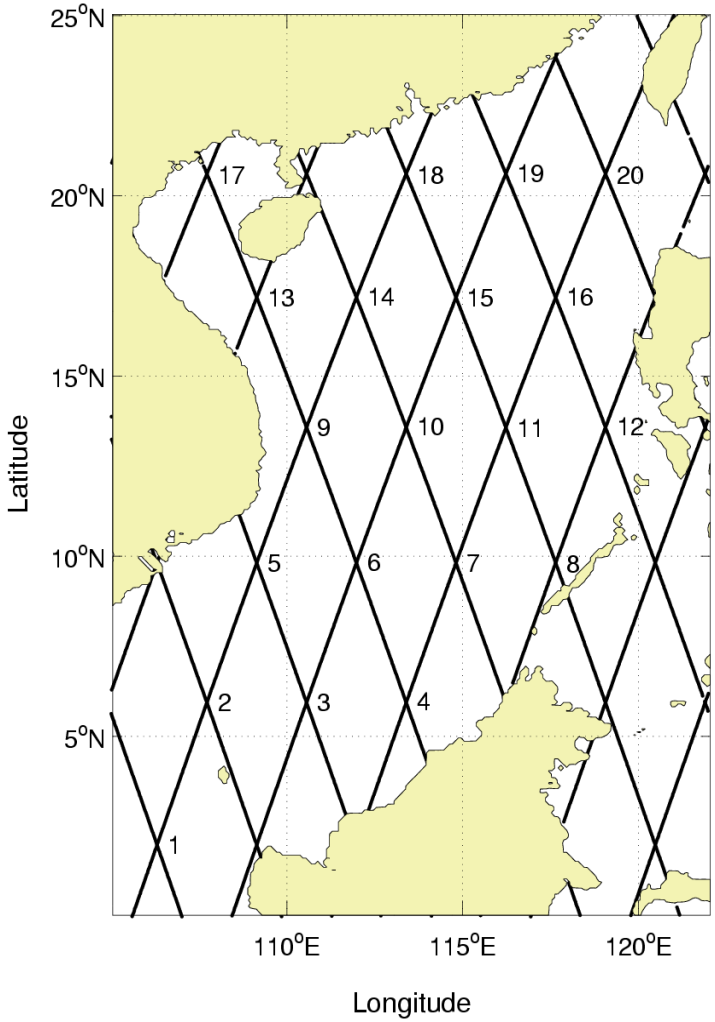


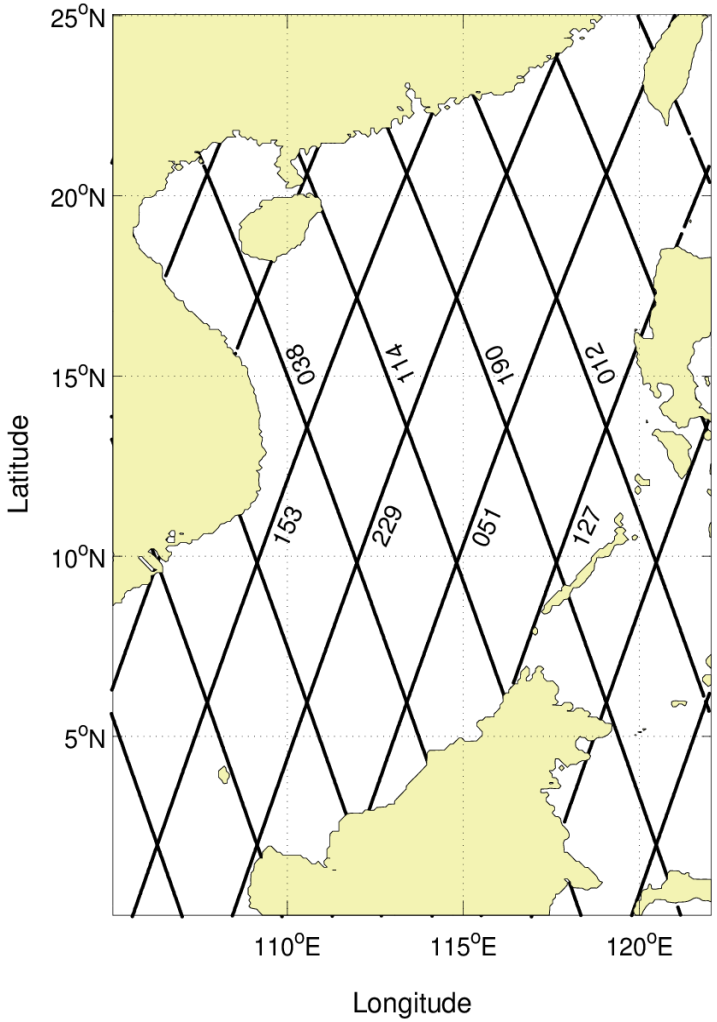
Numerical Integration

- Spatial grid
  - Latitude: 0º to 15ºN, Longitude: 105º to 122ºN
  - Spatial Interval: 1/4 º X 1/4 º
- Energy spectra
  - 25 frequencies with logarithmic increment.
  - 24 directions (15º interval)
- Time step
  - Global step = Spatial step = Spectral step = 300 sec.
  - Source step = 100 sec.



WaveWatch-3 was evaluated using T/P (a) crossover points and (b) tracks in the SCS (Chu et al., 2003, JTECH)

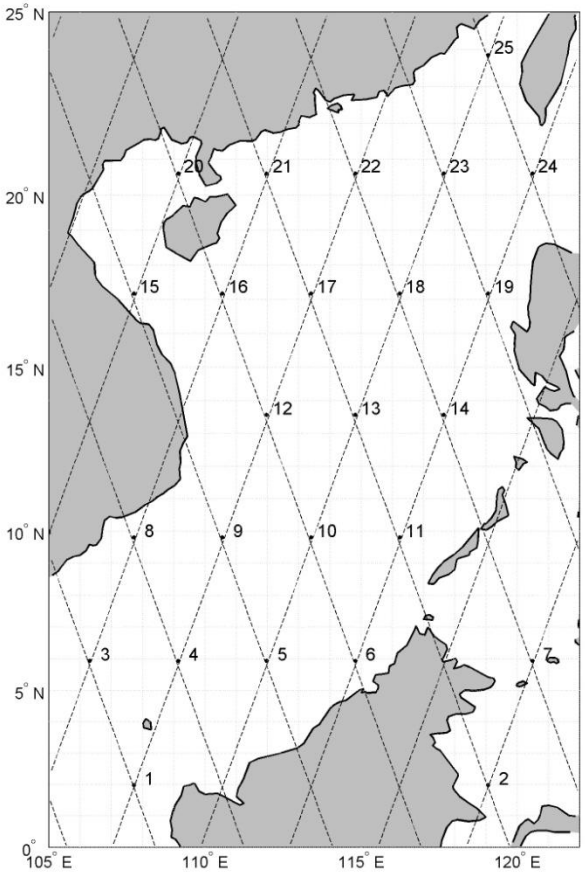






TOPEX/Poseidon Altimetry

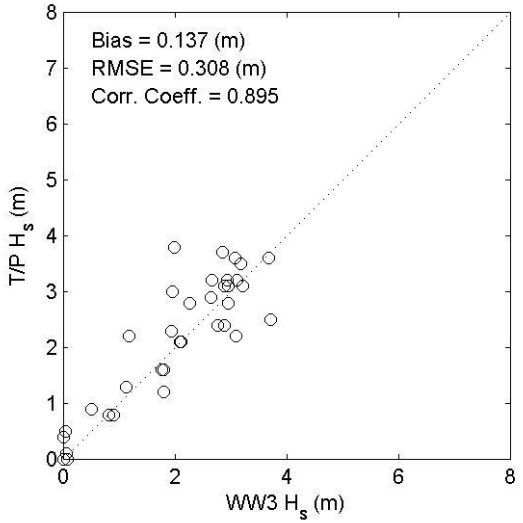
- T/P Satellite
  - NASA and CNES cooperation project.
  - August 1992 till now.
  - 9.916 days repeat period.
- Dataset in use
  - 00UTC 16 Nov. to 12UTC 25 Nov.
  - 2 Cycles: 448, 449.
  - 14 Passes: 001, 012, 051, 064, 077, 088 114, 127 ,140, 153, 164, 216, 229.
  - Total 25 crossover points.

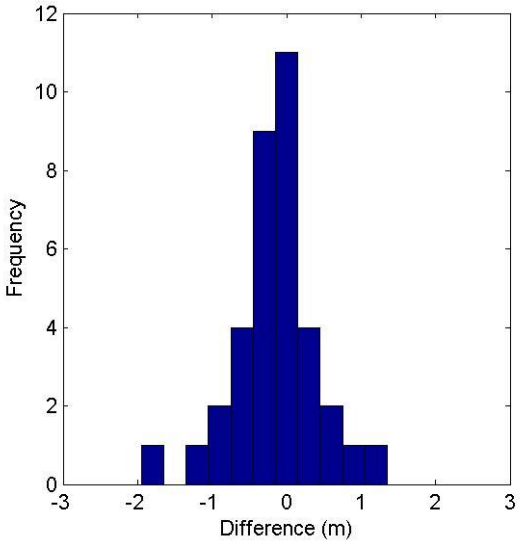




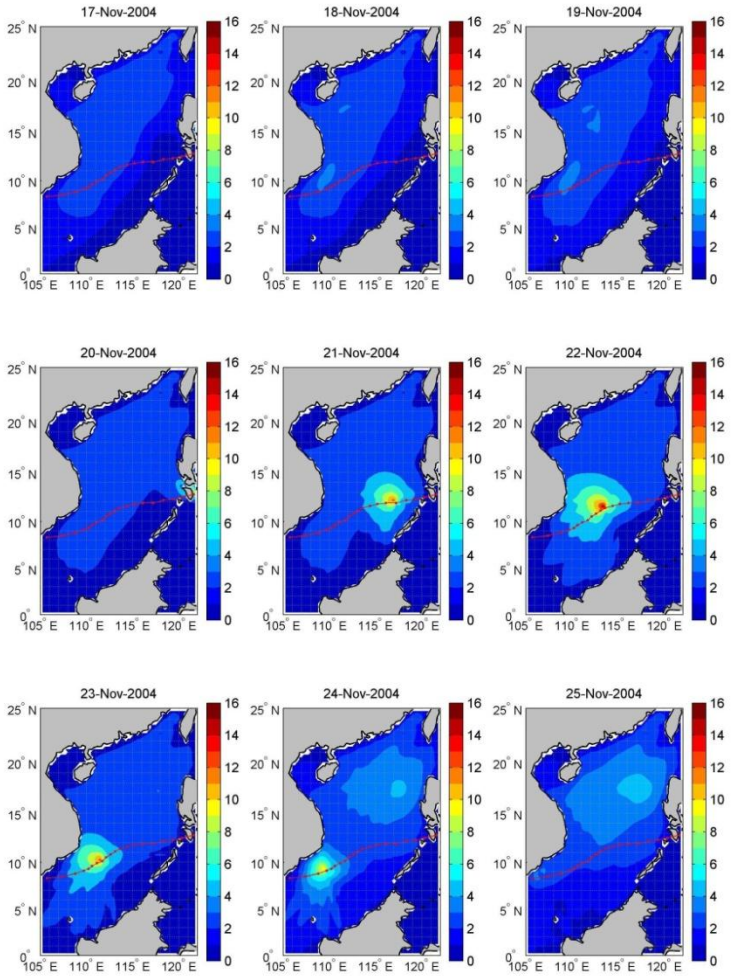
Evaluation Using Significant Wave Height (H_S)

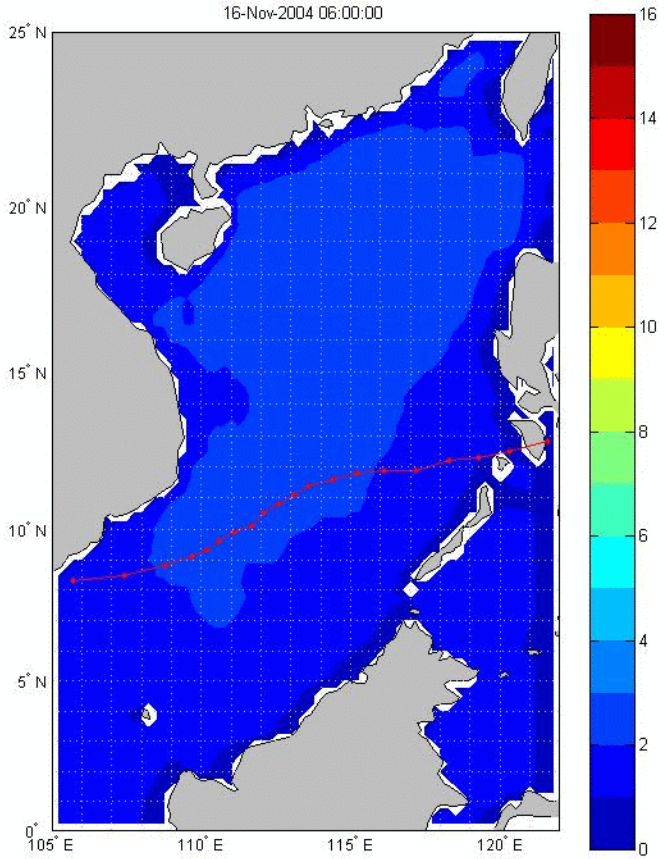
- Statistics
  - 38 data pairs (T/P vs. WW3).
  - BIAS = 0.137 m.
  - RMSE = 0.308 m.
  - Corr. Coeff. = 0.895.
- T/P observations and WW3 simulations are in a good agreement.
- WW3 simulation in the SCS is accurate and reasonable.





Effects of Tropical Cyclone on H_S

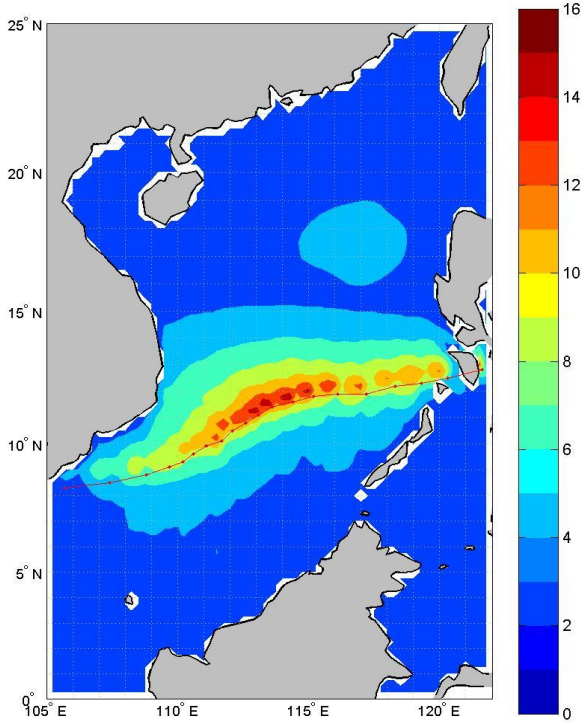




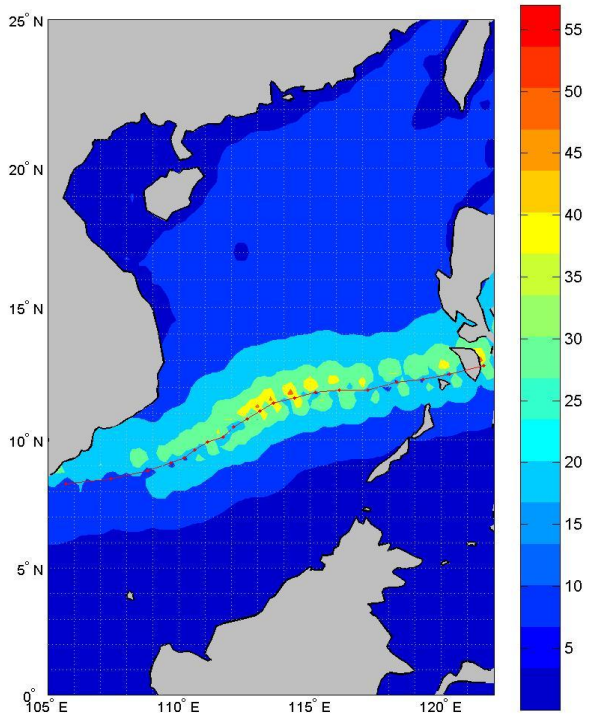


Comparison of Max. H_s and Winds

Maximum Wave Field



Maximum Wind Field



Along the typhoon track: to the right side;

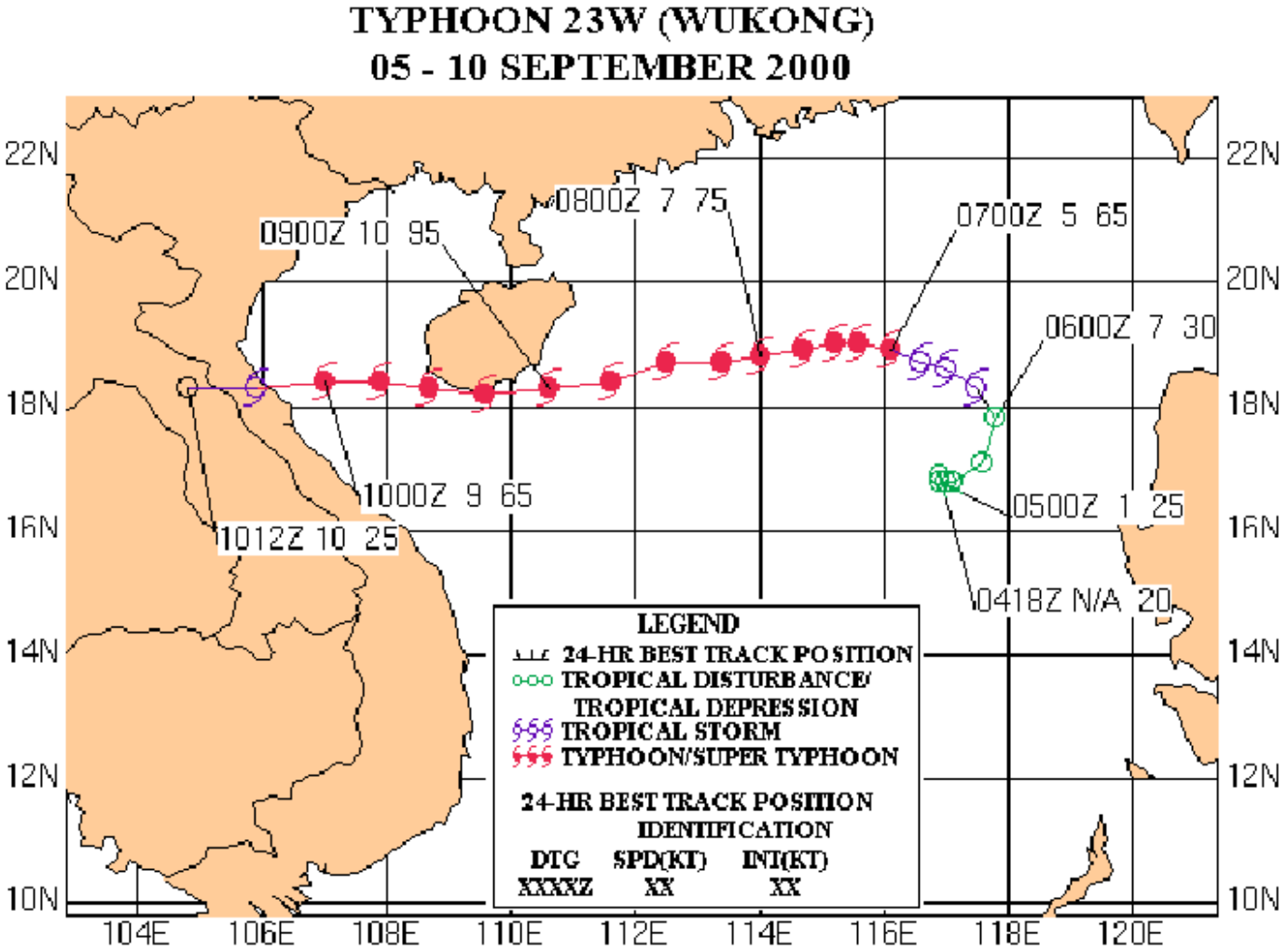
expending wider to the right side.





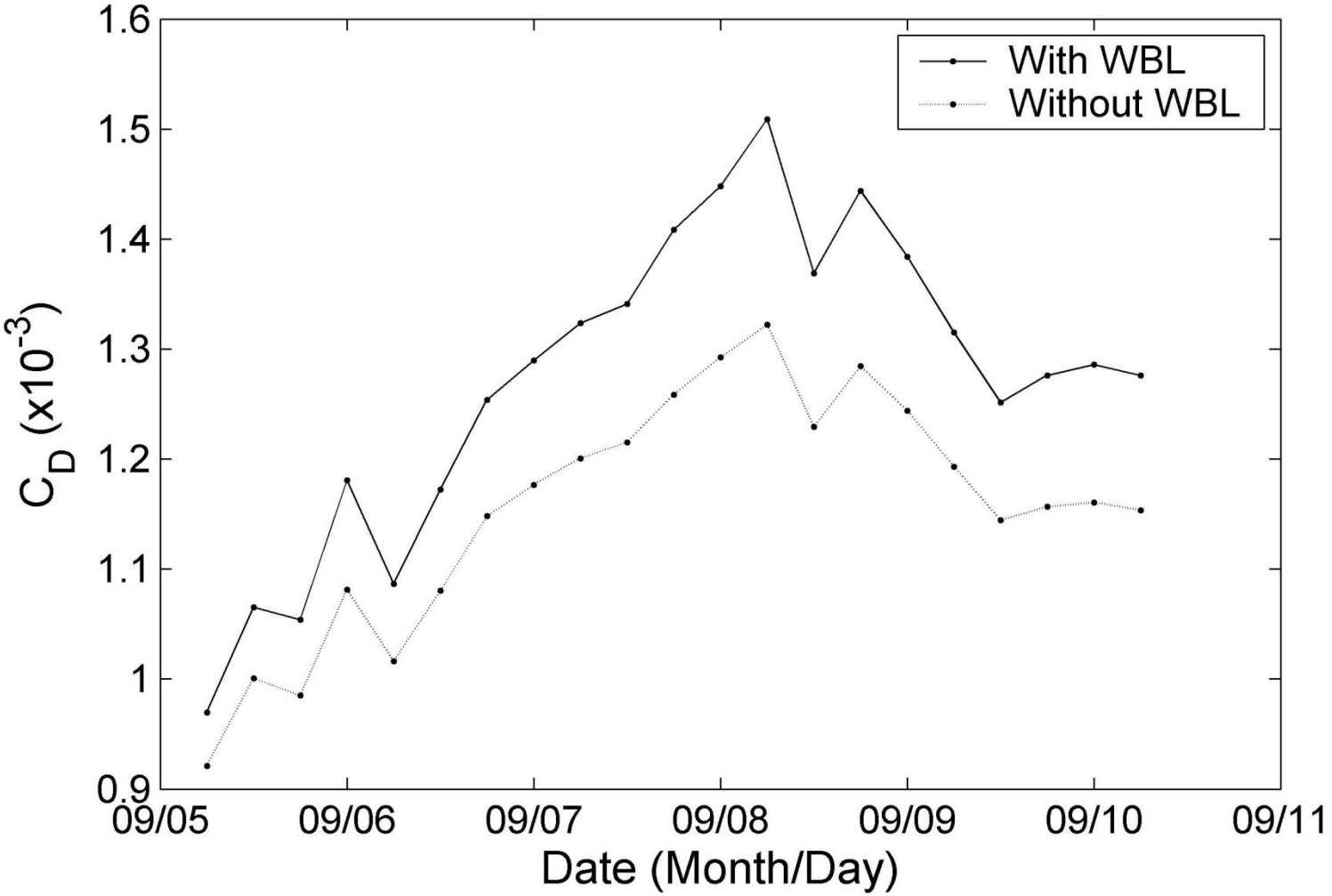
5. Typhoon Effect on Sea-to-Air DMS Transfer

Typhoon 23W (Wukong) Sept 5-11, 2000
Maximum Sustained Wind: 38 m/s





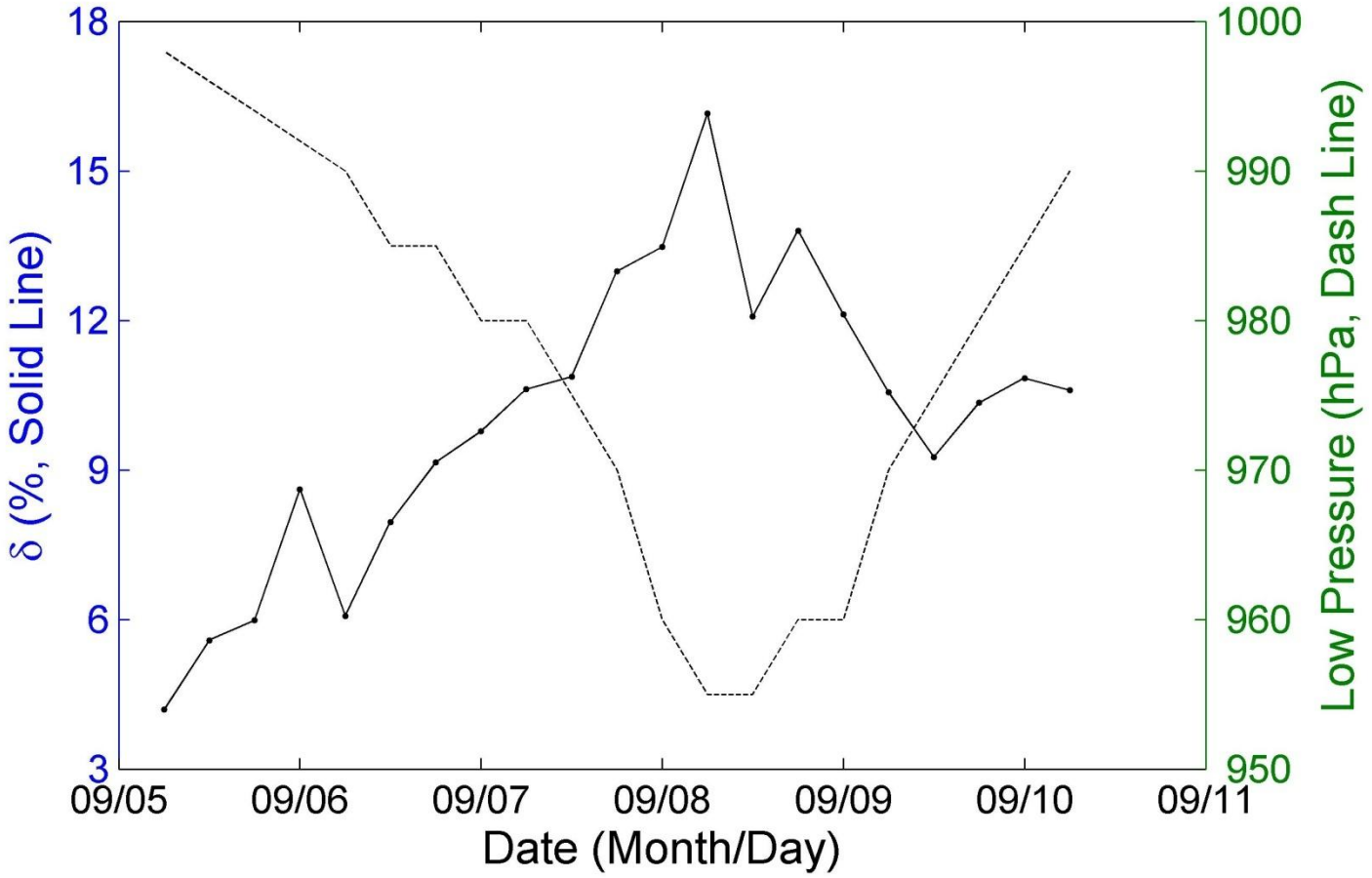
Effect on C_D


With WBL
Without WBL
C_D (x10^{-3})
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
09/05
09/06
09/07
09/08
09/09
09/10
09/11
Date (Month/Day)

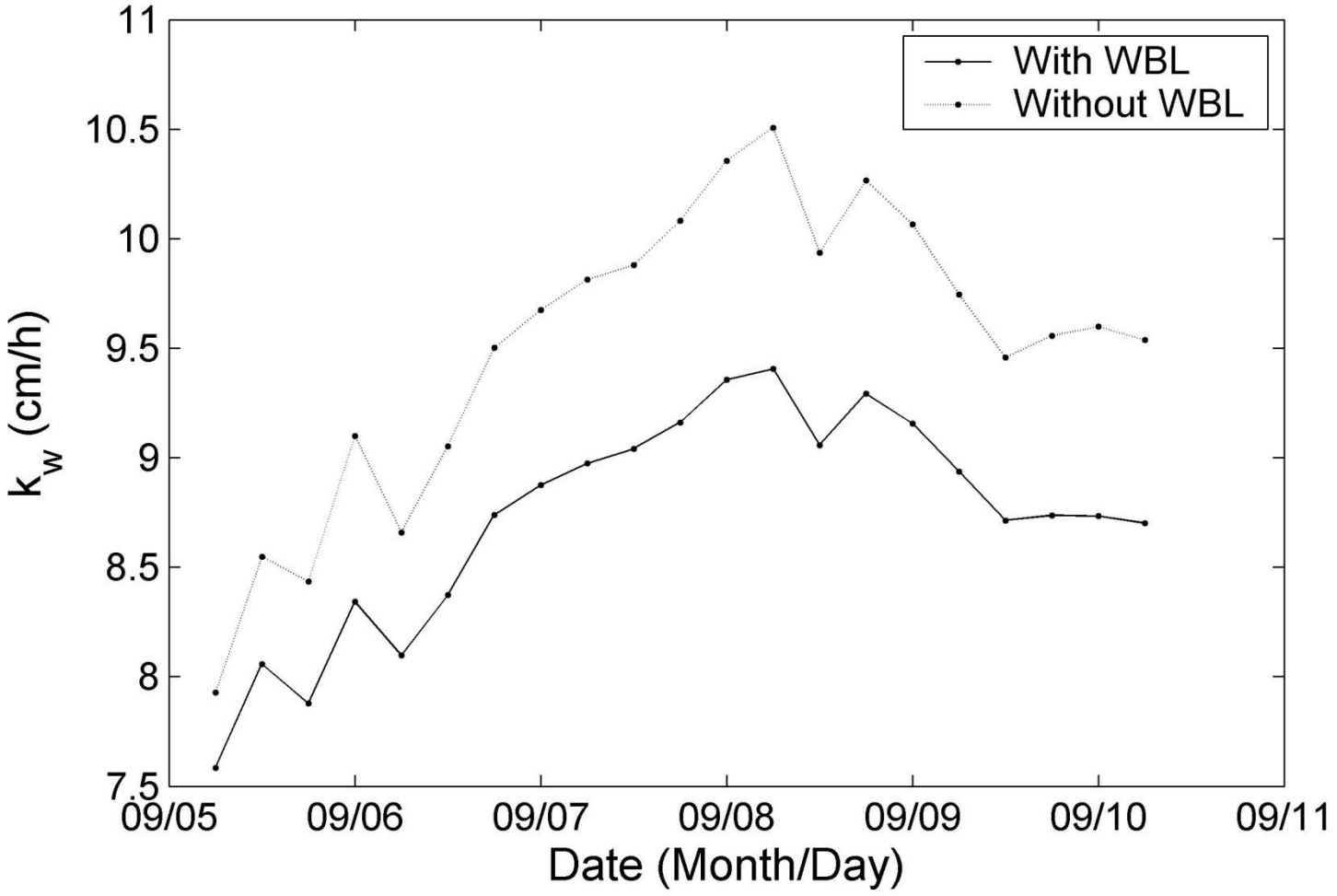


Relative Difference of C_D

$$\delta = \frac{\sum_i \sum_j \left[C_D^{(w)}(i,j) - C_D^{(n)}(i,j) \right]}{\sum_i \sum_j C_D^{(n)}(i,j)}$$



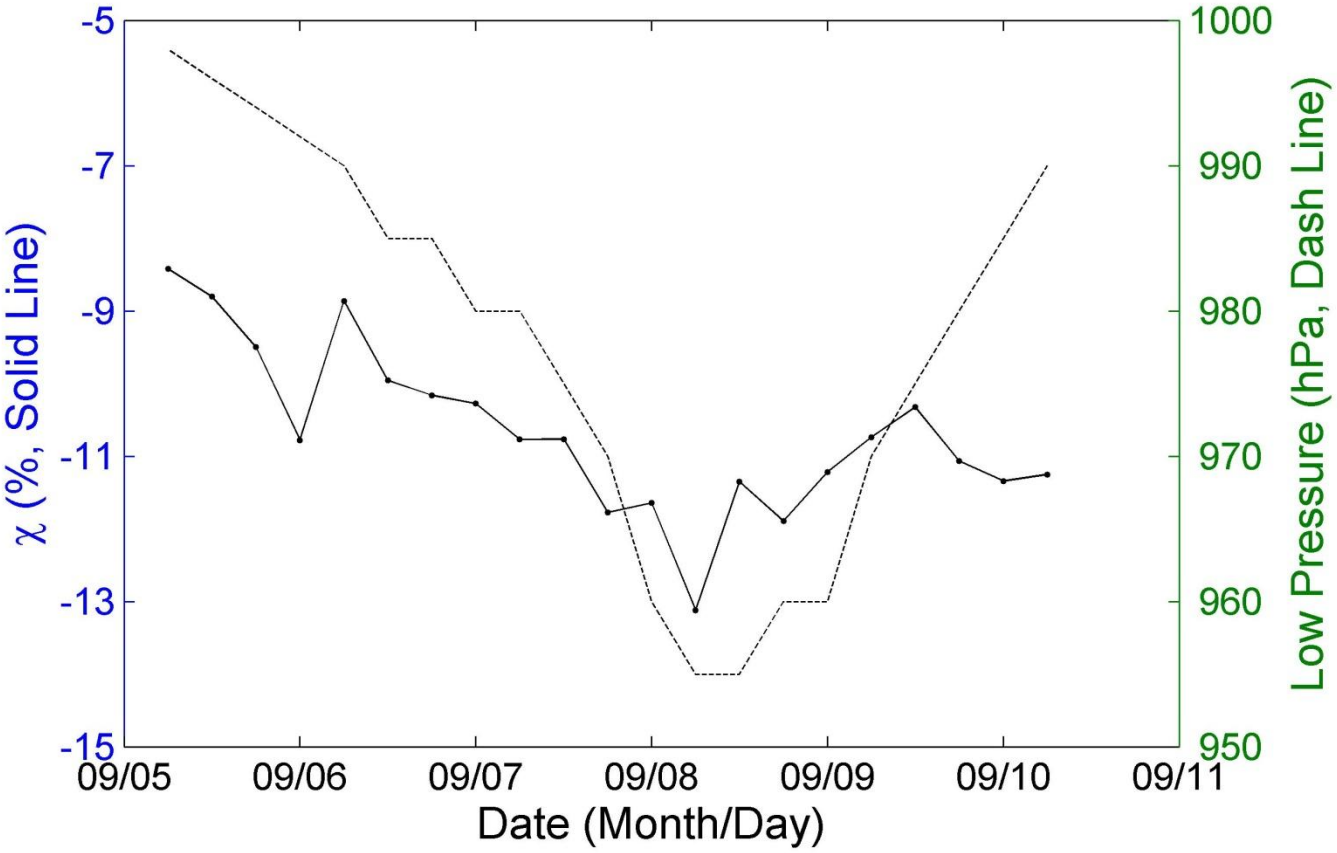
Effect on k_w


With WBL
Without WBL
11
10.5
10
9.5
9
8.5
8
7.5
k_w (cm/h)
09/05
09/06
09/07
09/08
09/09
09/10
09/11
Date (Month/Day)



Relative Difference of k_w

$$\chi = \frac{\sum_i \sum_j \left[k_w^{(w)}(i,j) - k_w^{(x)}(i,j) \right]}{\sum_i \sum_j k_w^{(x)}(i,j)}$$





Conclusions

- (1) WBL increases C_D → strengthens tropical cyclone → enhances the sea-to-air DMS transfer → more sulfate haze, CCN → more clouds

- (2) WBL decreases k_w → weakens the sea-to-air DMS transfer → less sulfate haze, CCN → less clouds→ air quality and climate

- (3) Such opposite WBL effects are evident for typhoon Wukong (max wind ~ 38 m/s) → 13% reduction in k_w

- (4) Such opposite WBL effects under tropical cyclones on the climate should be further investigated.