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

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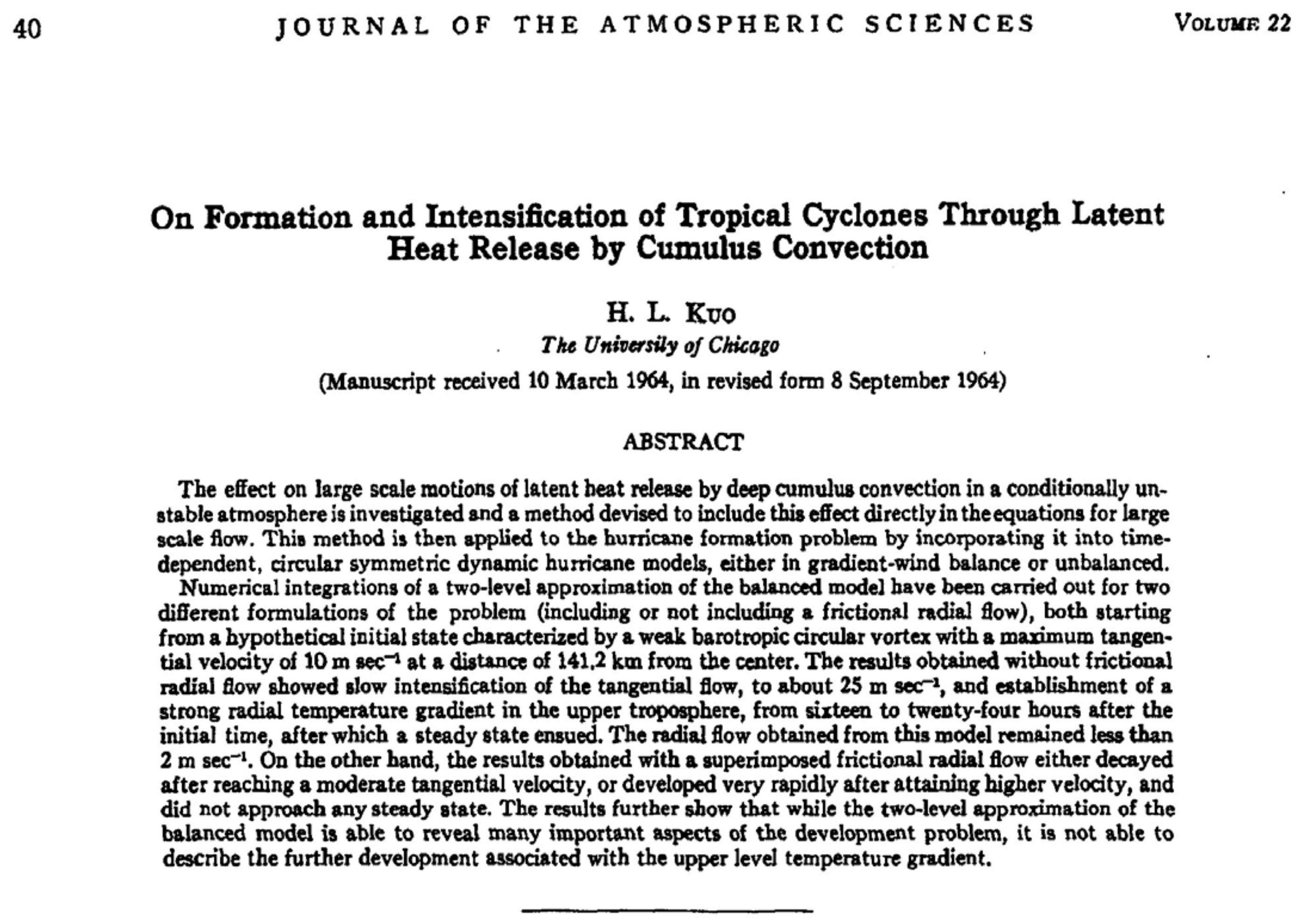
Following Prof. Kuo’s Milestone Paper on Tropical Cyclone

504 citations



40 JOURNAL OF THE ATMOSPHERIC SCIENCES VOLUME 22

On Formation and Intensification of Tropical Cyclones Through Latent Heat Release by Cumulus Convection

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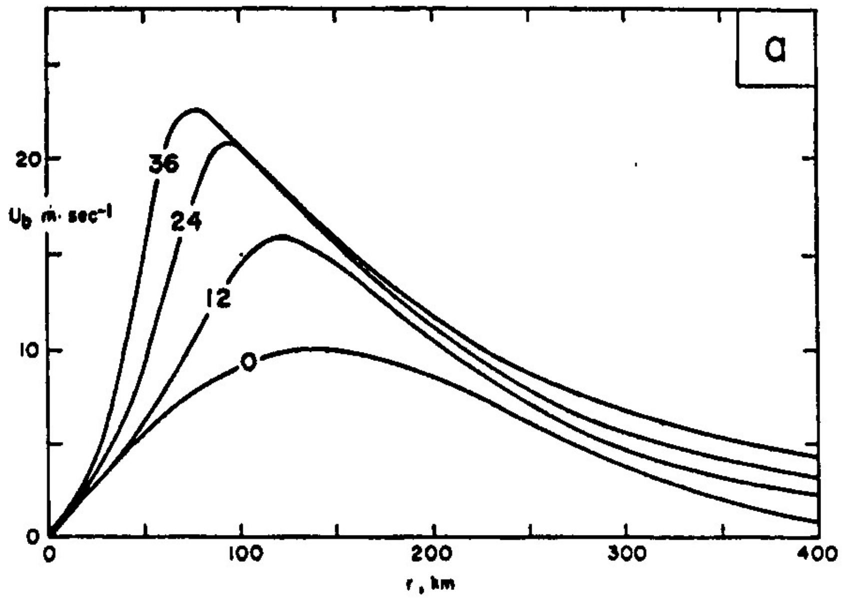
ABSTRACT

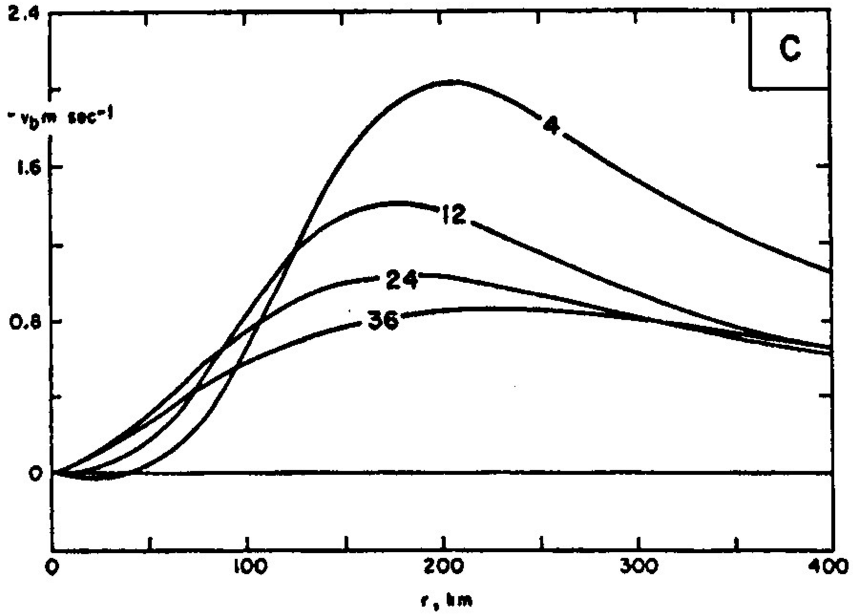
The effect on large scale motions of latent heat release by deep cumulus convection in a conditionally unstable atmosphere is investigated and a method devised to include this effect directly in the equations for large scale flow. This method is then applied to the hurricane formation problem by incorporating it into time-dependent, circular symmetric dynamic hurricane models, either in gradient-wind balance or unbalanced.

Numerical integrations of a two-level approximation of the balanced model have been carried out for two different formulations of the problem (including or not including a frictional radial flow), both starting from a hypothetical initial state characterized by a weak barotropic circular vortex with a maximum tangential velocity of 10 m sec^{-1} at a distance of 141.2 km from the center. The results obtained without frictional radial flow showed slow intensification of the tangential flow, to about 25 m sec^{-1}, and establishment of a strong radial temperature gradient in the upper troposphere, from sixteen to twenty-four hours after the initial time, after which a steady state ensued. The radial flow obtained from this model remained less than 2 m sec^{-1}. On the other hand, the results obtained with a superimposed frictional radial flow either decayed after reaching a moderate tangential velocity, or developed very rapidly after attaining higher velocity, and did not approach any steady state. The results further show that while the two-level approximation of the balanced model is able to reveal many important aspects of the development problem, it is not able to describe the further development associated with the upper level temperature gradient.

Low-level Velocity in Tropical Cyclone (Kuo 1965) → Theoretical Base for Surface Wind Field

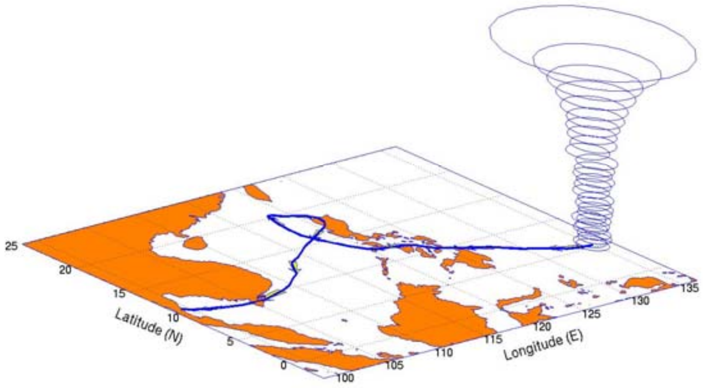


Tangential



Radial

What are tropical cyclone's effects on oceans and regional seas?



With Prof. Kuo (1965)'s milestone paper, high-resolution surface winds can be produced, and in turn to study the tropical cyclone's effect on oceans becomes feasible.

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.

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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

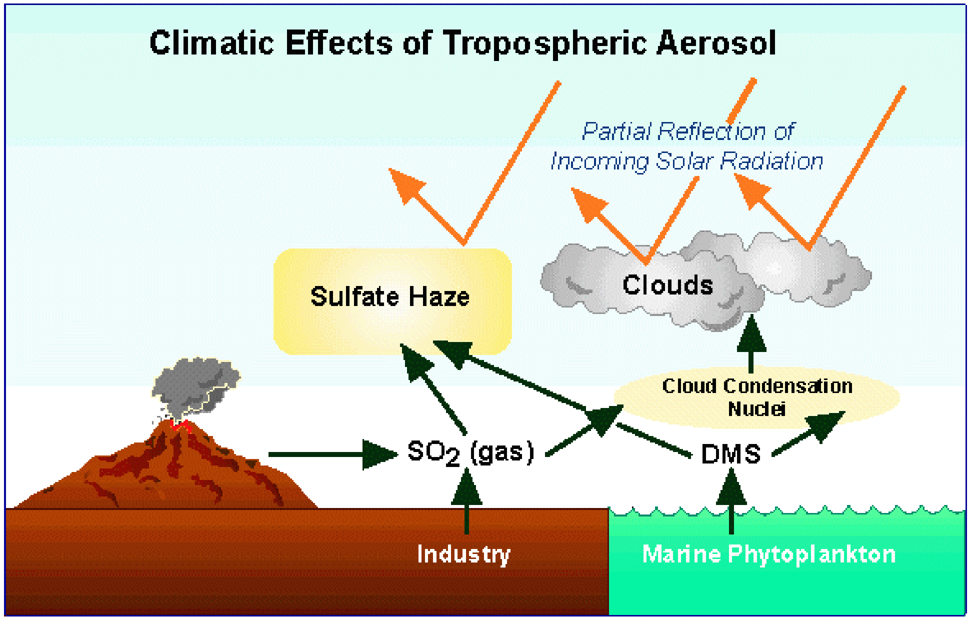
Outlines

- (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

Dimethylsulfide (DMS) Cycle
Ocean and Atmosphere Exchange

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



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

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

2. Sea-to-Air DMS Flux

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 ^{o}K

Sea-to-Air DMS Flux (*H*)
(McGillis et al., JGR 2000)

Eliminating $C_{s,w}$ →

$$H = \frac{k_w}{1 + \alpha k_w / k_a}(C_w - \alpha C_a)$$

Airside DMS Transfer Velocity k_a

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

M → molecular weight of DMS → 129.075

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

$u_\mathrm{r} = u(z_r) \rightarrow k_a$

$z_r = 10$ 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)

$$D = 1.1\times 10^{-2}\exp\left[-\frac{1896}{T}\right] \quad (\text{unit: cm}^2/\text{s})$$

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

Roughness Reynolds

Number

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

Nondimensional Roughness Length

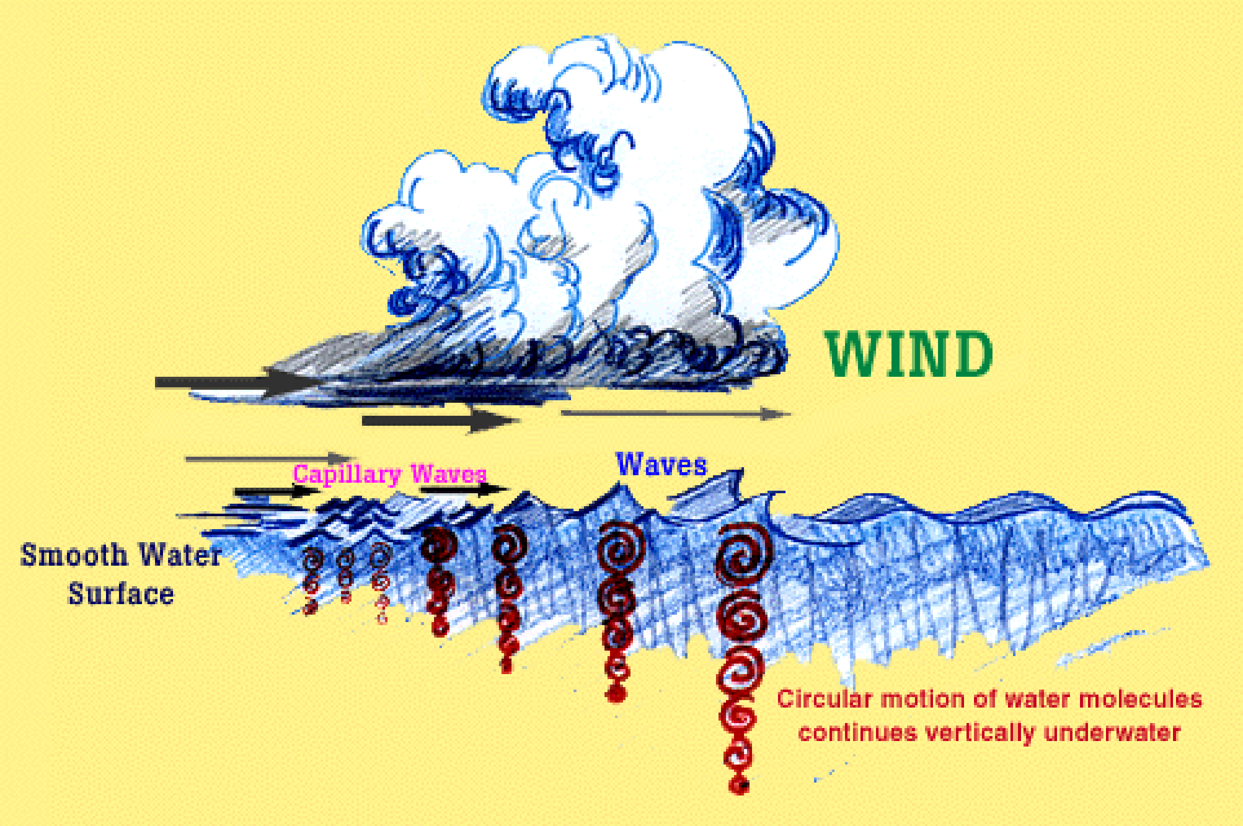
z_0 is roughness length

Nondimensional → $z_{0*} = z_0 g / u_*^2$

- $u_r \rightarrow k_a$
- $(\mathrm{z}_0 \; , \mathrm{u}_*) \rightarrow k_w$

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

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



3. Tropical Cyclone Wind Profile Model

Wind Decomposition

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

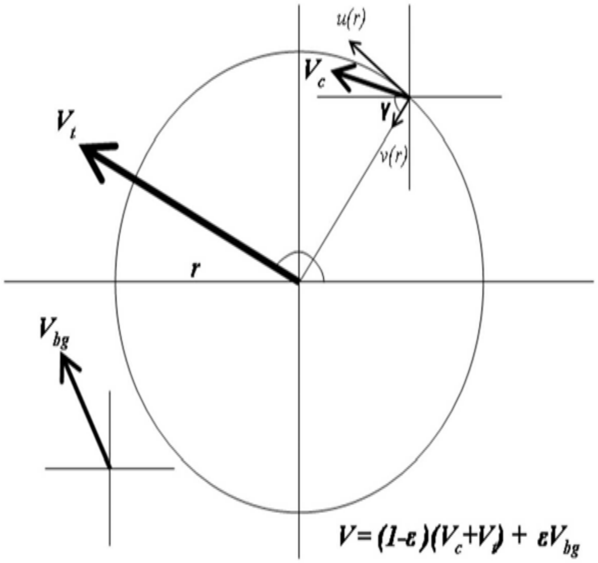
$$\varepsilon = \frac{c^4}{1+c^4}, c = \frac{r}{0.9R_0}$$

$\mathbf{V}_t$ → Translation velocity

$\mathbf{V}_\mathrm{c}$ → relative velocity to storm center

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

(R_0, R_m) → zero and maximum tangential velocities



Continuation of Kuo’s (1965) Work →

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

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

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

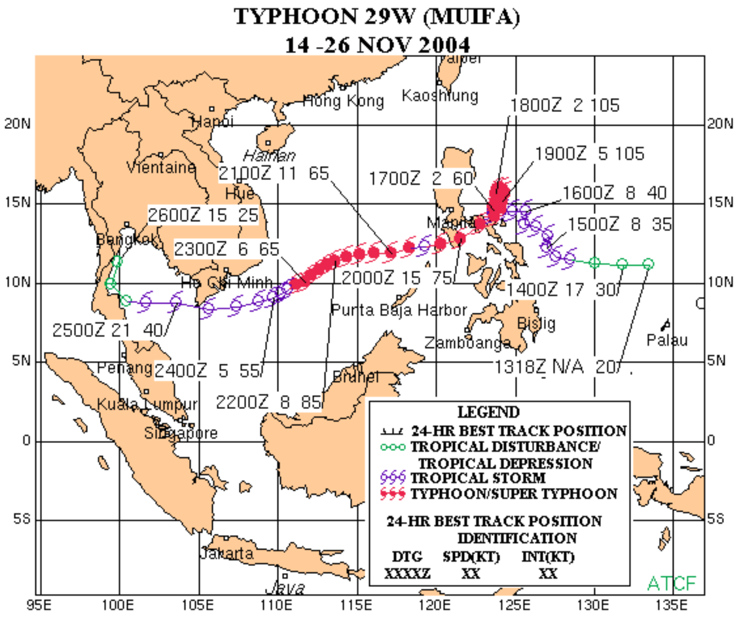
$$a = \frac{r}{R_m}$$

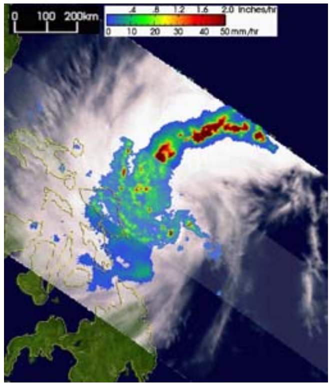
γ → inflow angle of air as it spirals into the typhoon center

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


TYPHOON 29W (MUIFA)
14 -26 NOV 2004



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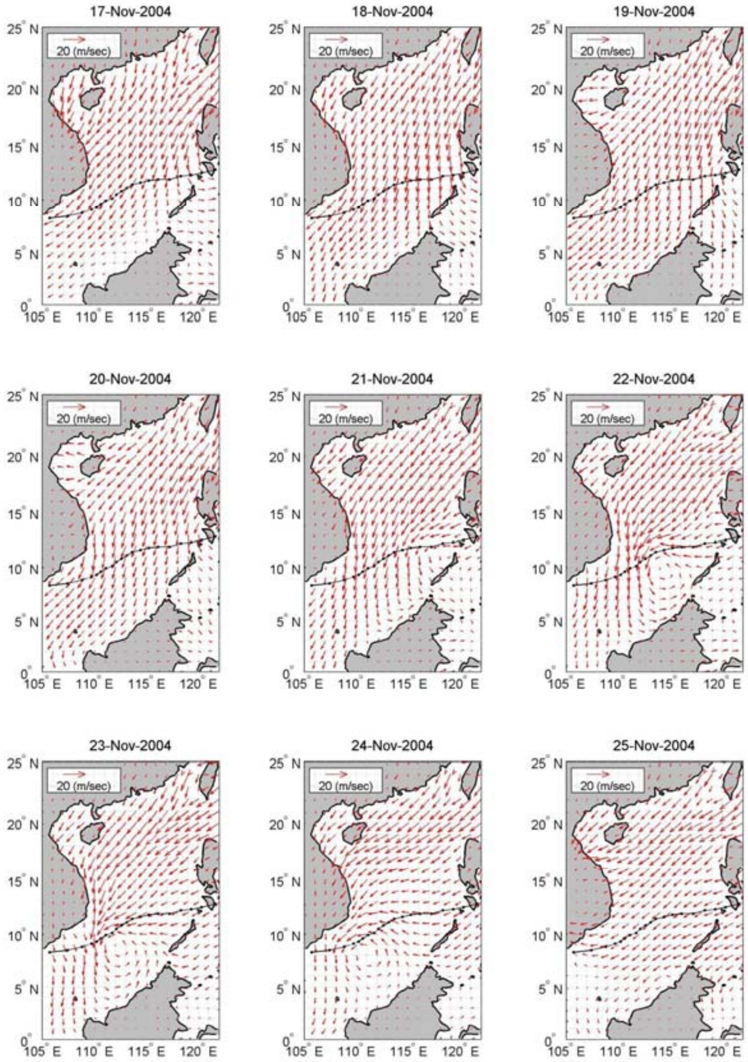
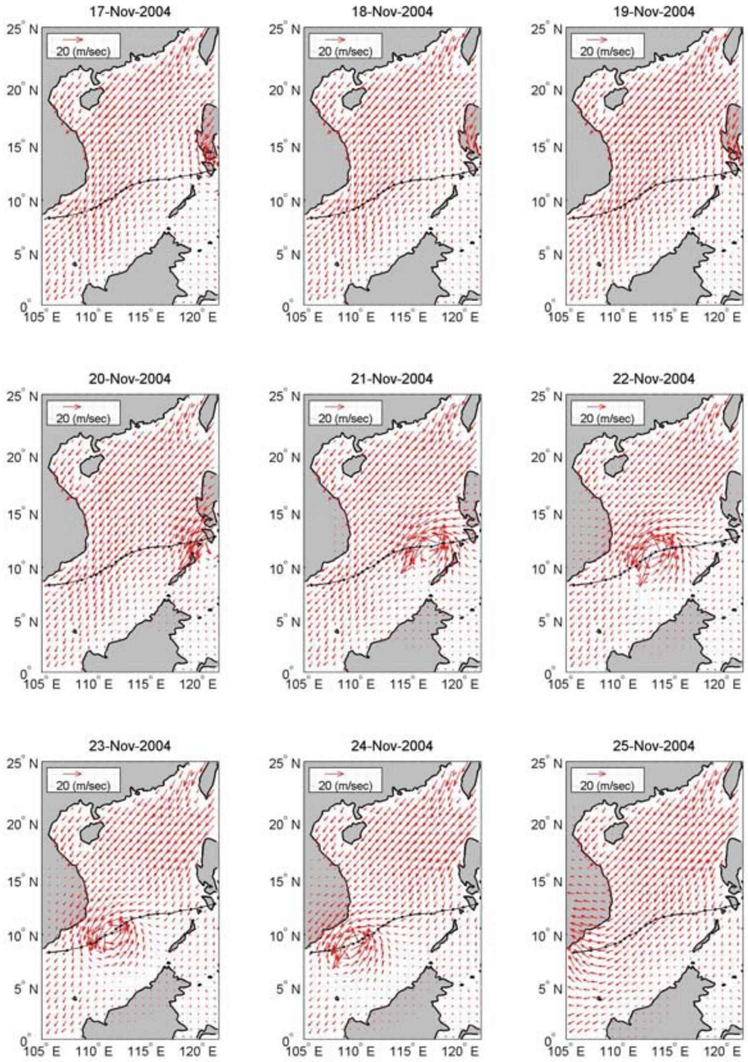
Comparison between NCEP and QSCAT-TCWPM (QTCWPM) Winds

NCEP Wind Fields

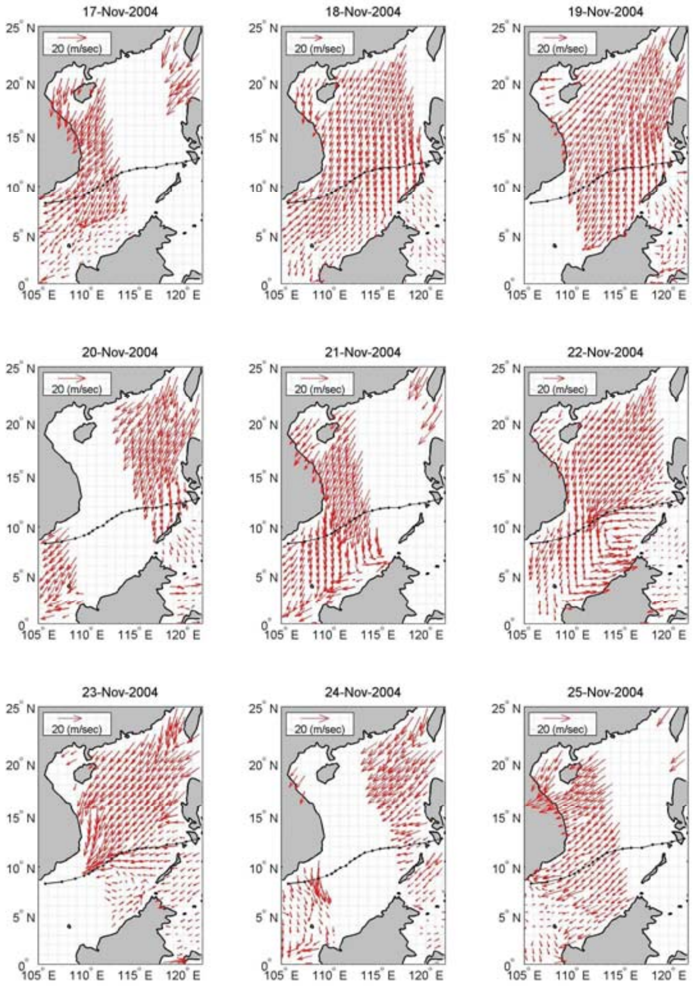


QSCAT-TCWPM Wind Fields

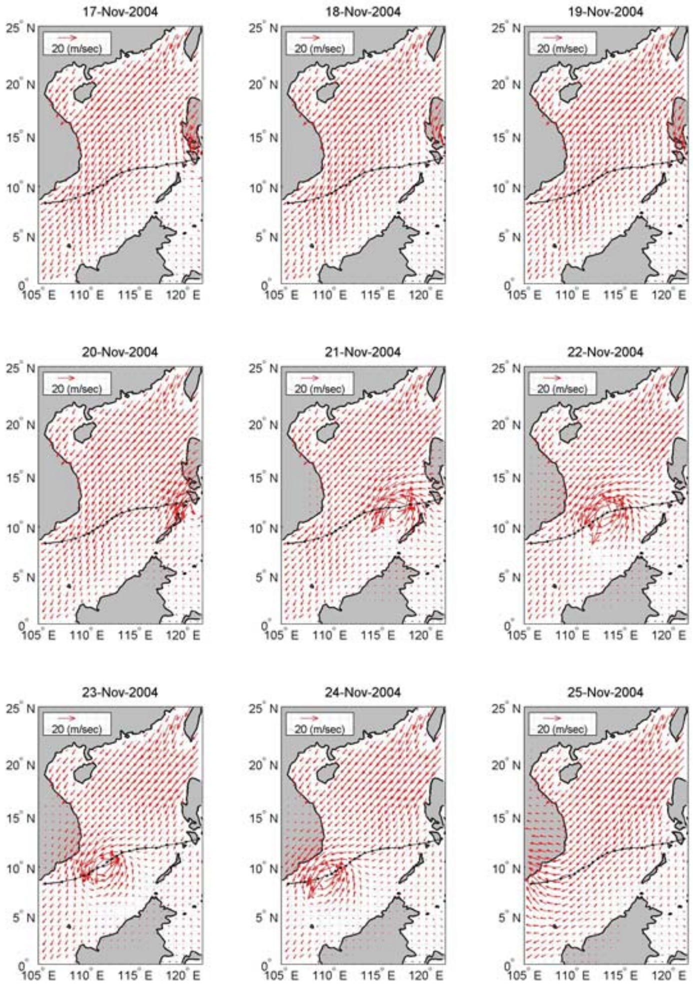


Comparison between QSCAT and QTCWPM Winds

QuikSCAT Wind Fields



QTCWPM Wind Fields



4. Wave Effects on Air-Sea Fluxes

Drag Coefficient without Ocean Waves

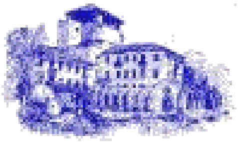
$$C_D = (u_*/u_r)^2$$

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

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

$z_r = 10$ 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)

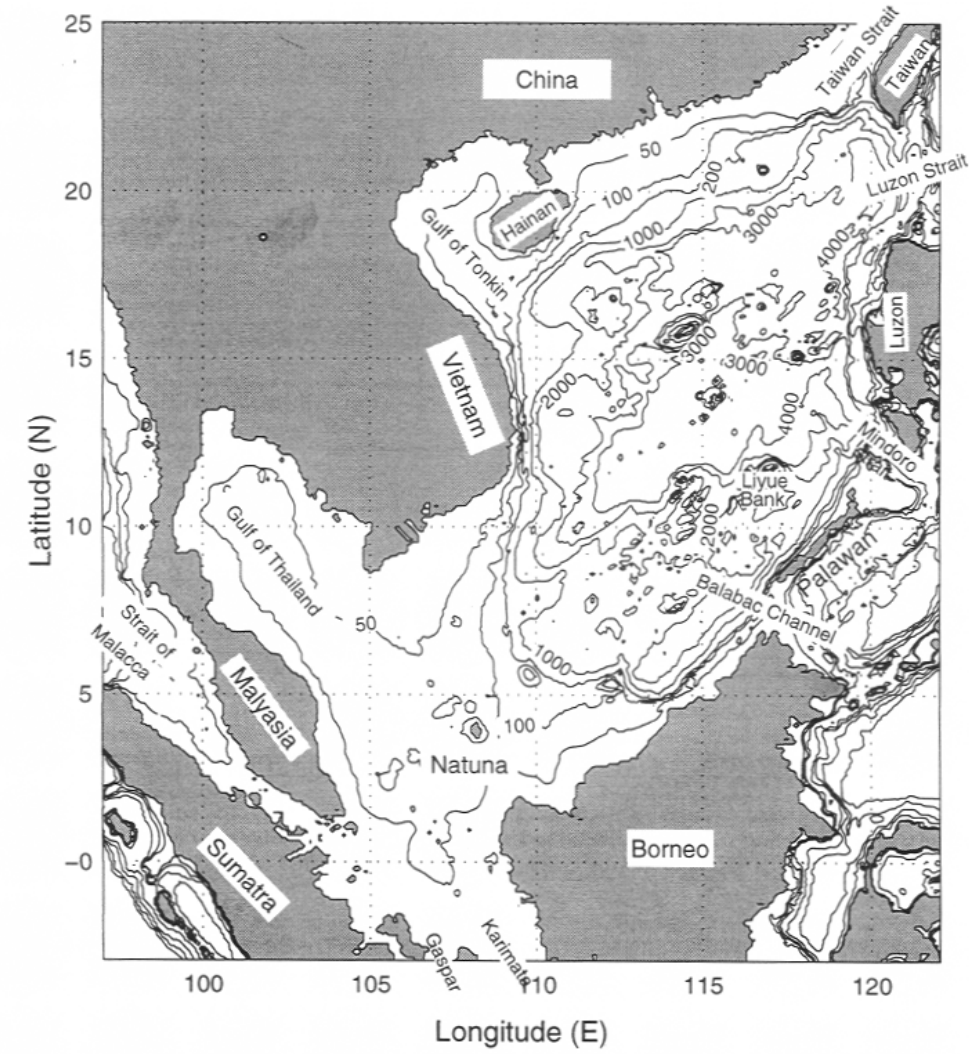
$$\frac{\partial N}{\partial t} + \frac{1}{\cos\phi}\frac{\partial}{\partial \phi}\dot{\phi} N \cos\theta + \frac{\partial}{\partial \lambda}\dot{\lambda} N + \frac{\partial}{\partial k}\dot{k} N + \frac{\partial}{\partial \theta}\dot{\theta}_g N = \frac{S}{\sigma}$$

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

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

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

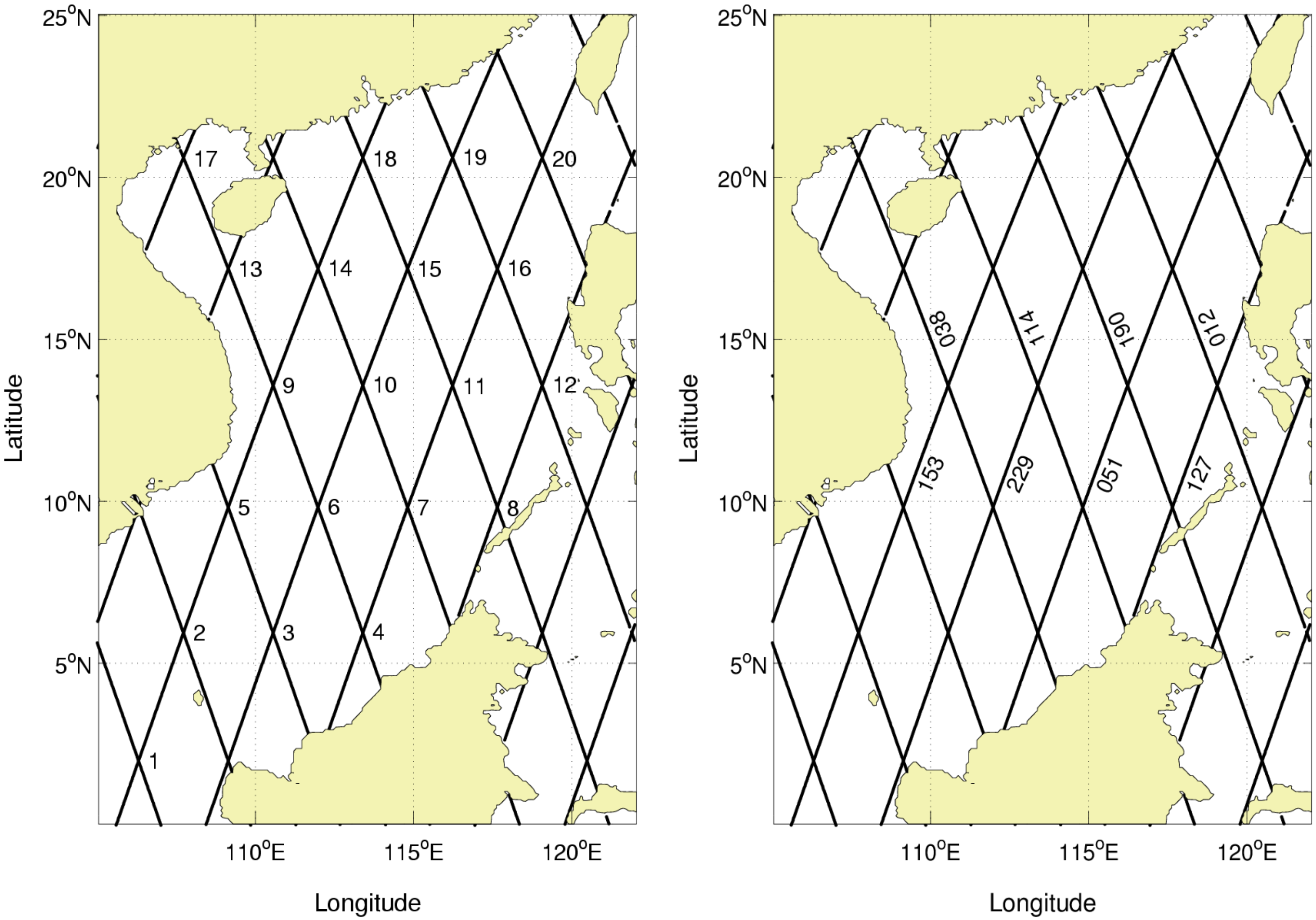
South China Sea



Numerical Integration

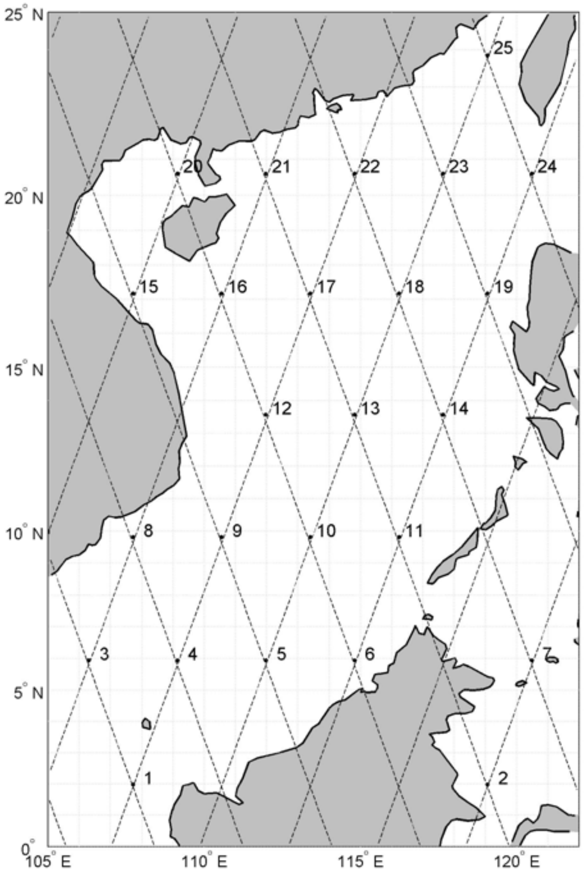
- Spatial grid
  - Latitude: 0° to 15°N, Longitude: 105° to 122°N
  - Spatial Interval: 1/4 ° X 1/4 °
- Energy spectra
  - 25 frequencies with logarithmic increment.
  - 24 directions (15° interval)
- Time step
  - Global step = Spatial step = Spectral step = 300 sec.
  - Source step = 100 sec.

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



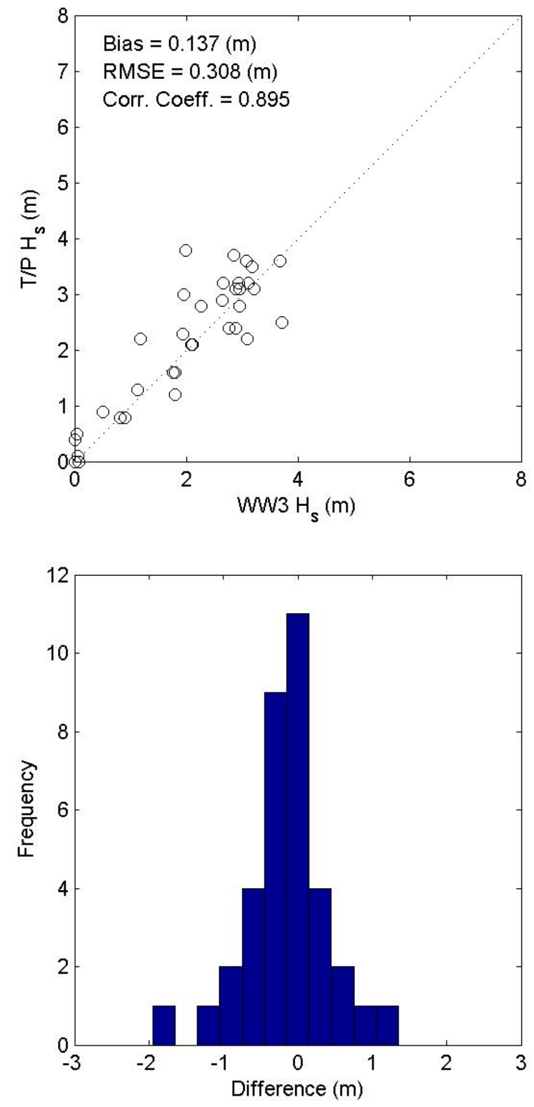
TOPEX/Poseidon Altimetry

- 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.

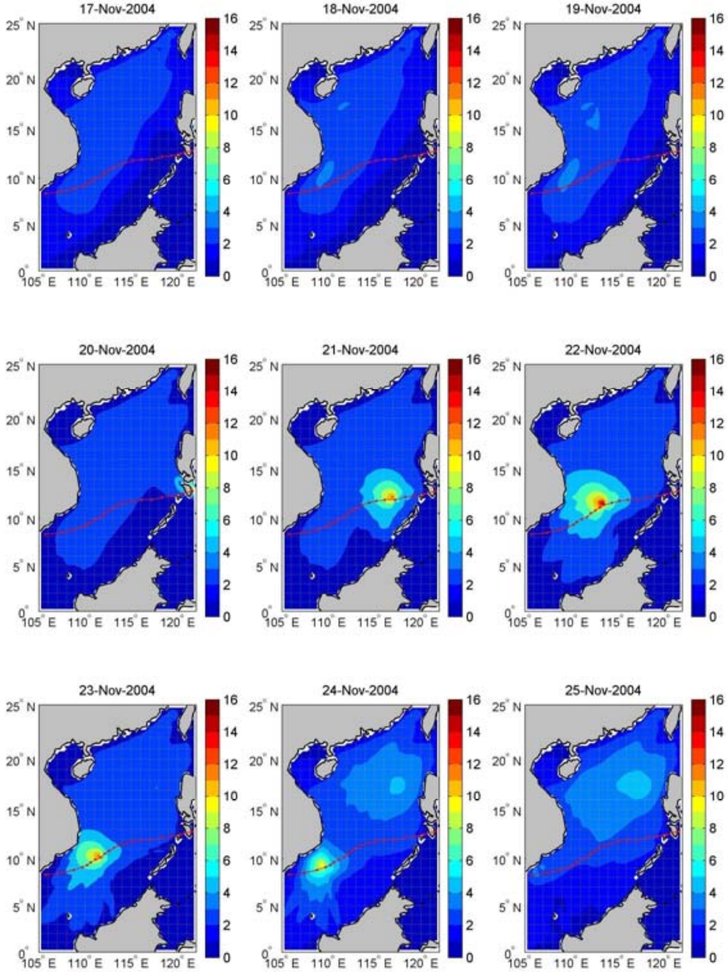


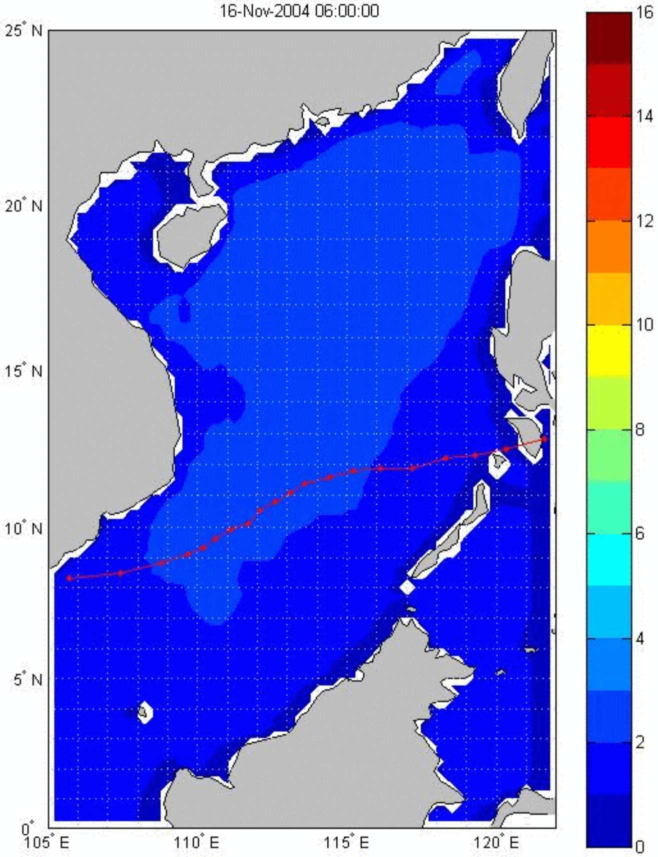
Evaluation Using Significant Wave Height (H_S)

- 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.



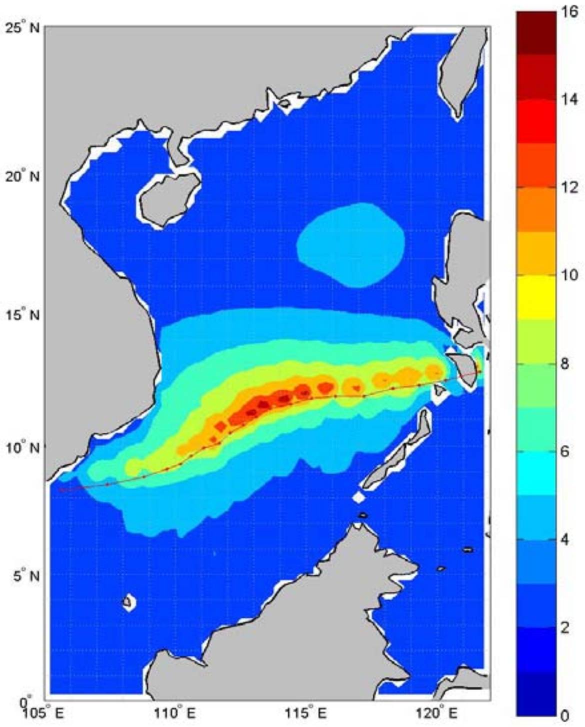
Effects of Tropical Cyclone on H_S



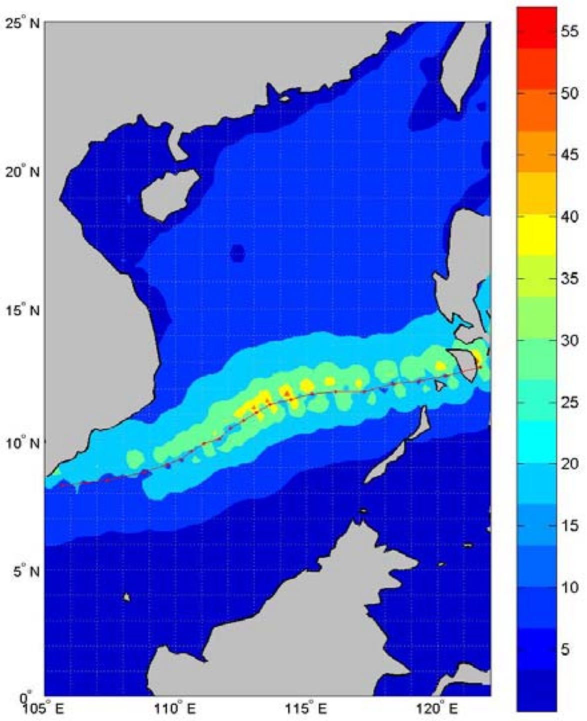


Comparison of Max. H_s and Winds

Maximum Wave Field



Maximum Wind Field

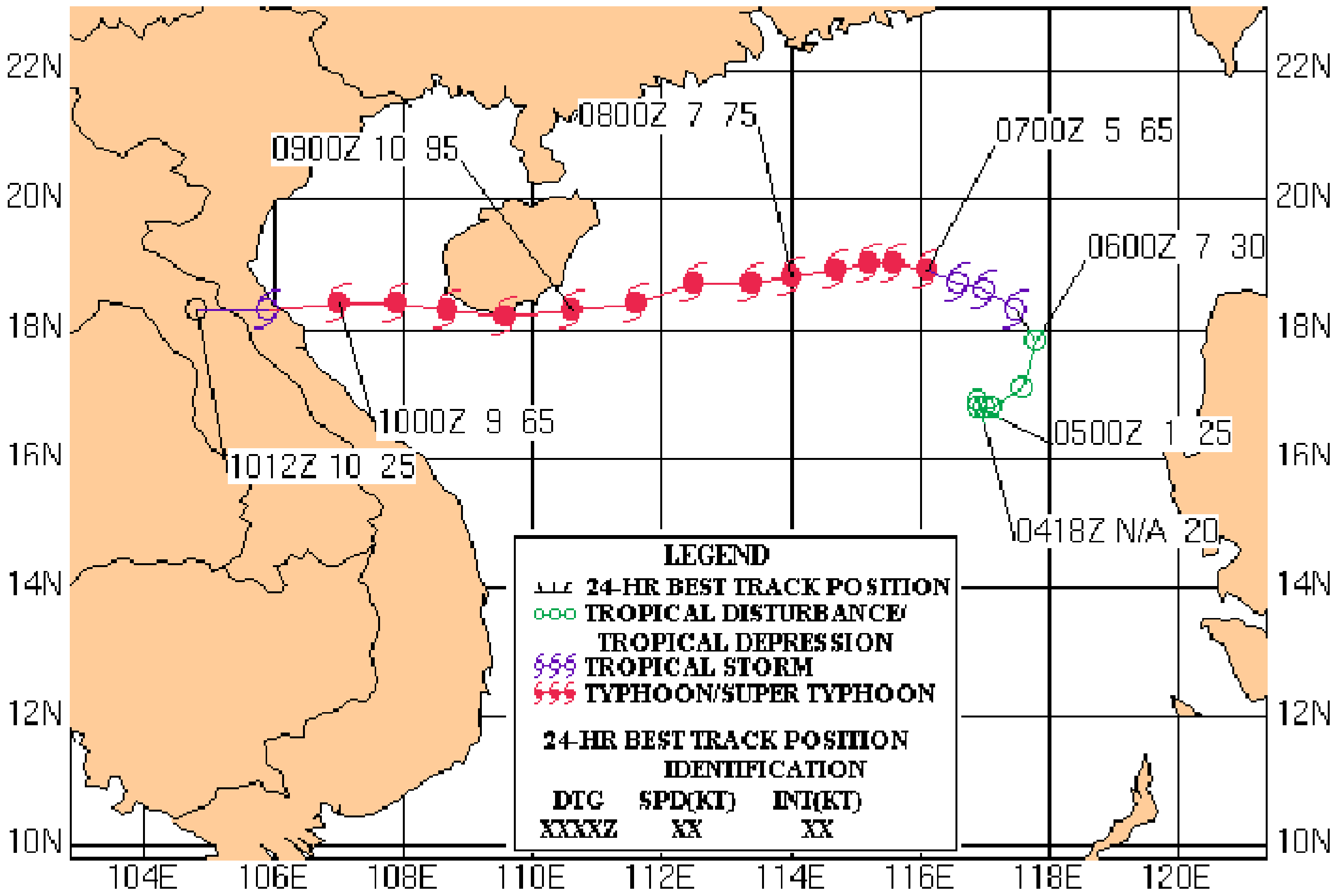


Along the typhoon track: to the right side;
expending wider to the right side.

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

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

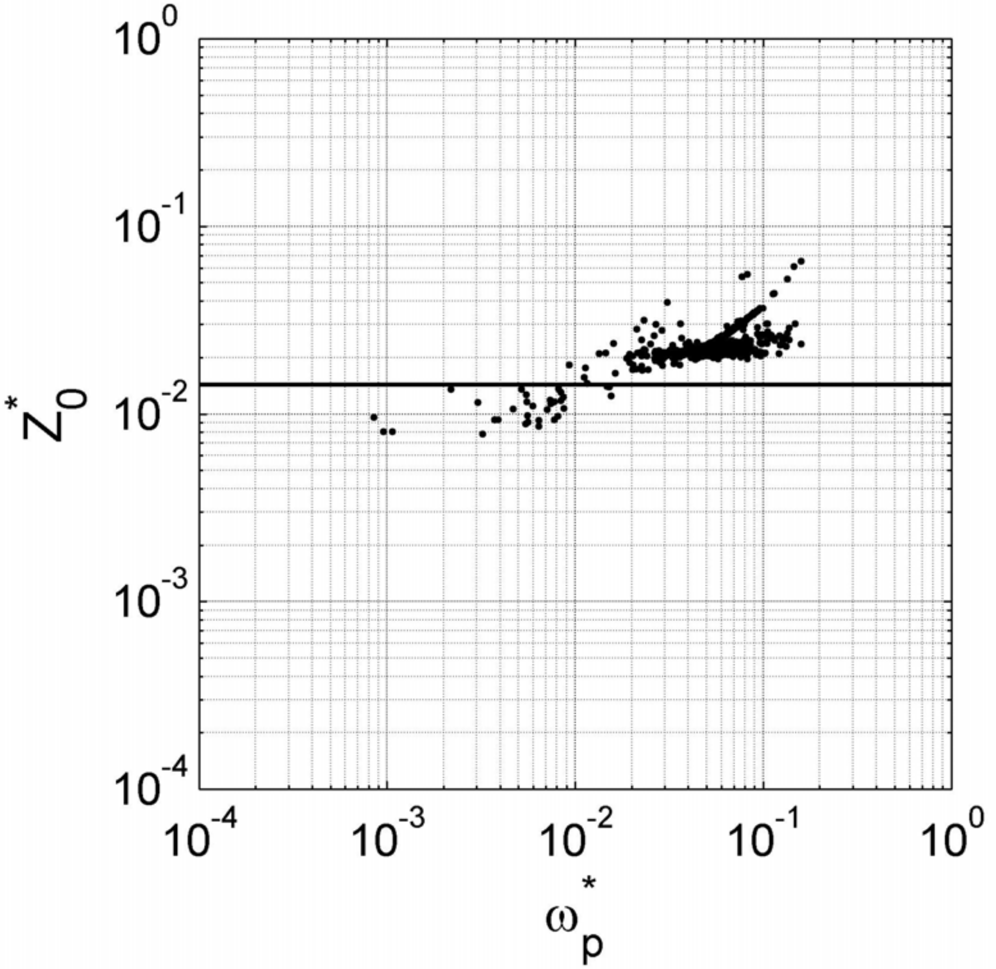
TYPHOON 23W (WUKONG)
05 - 10 SEPTEMBER 2000



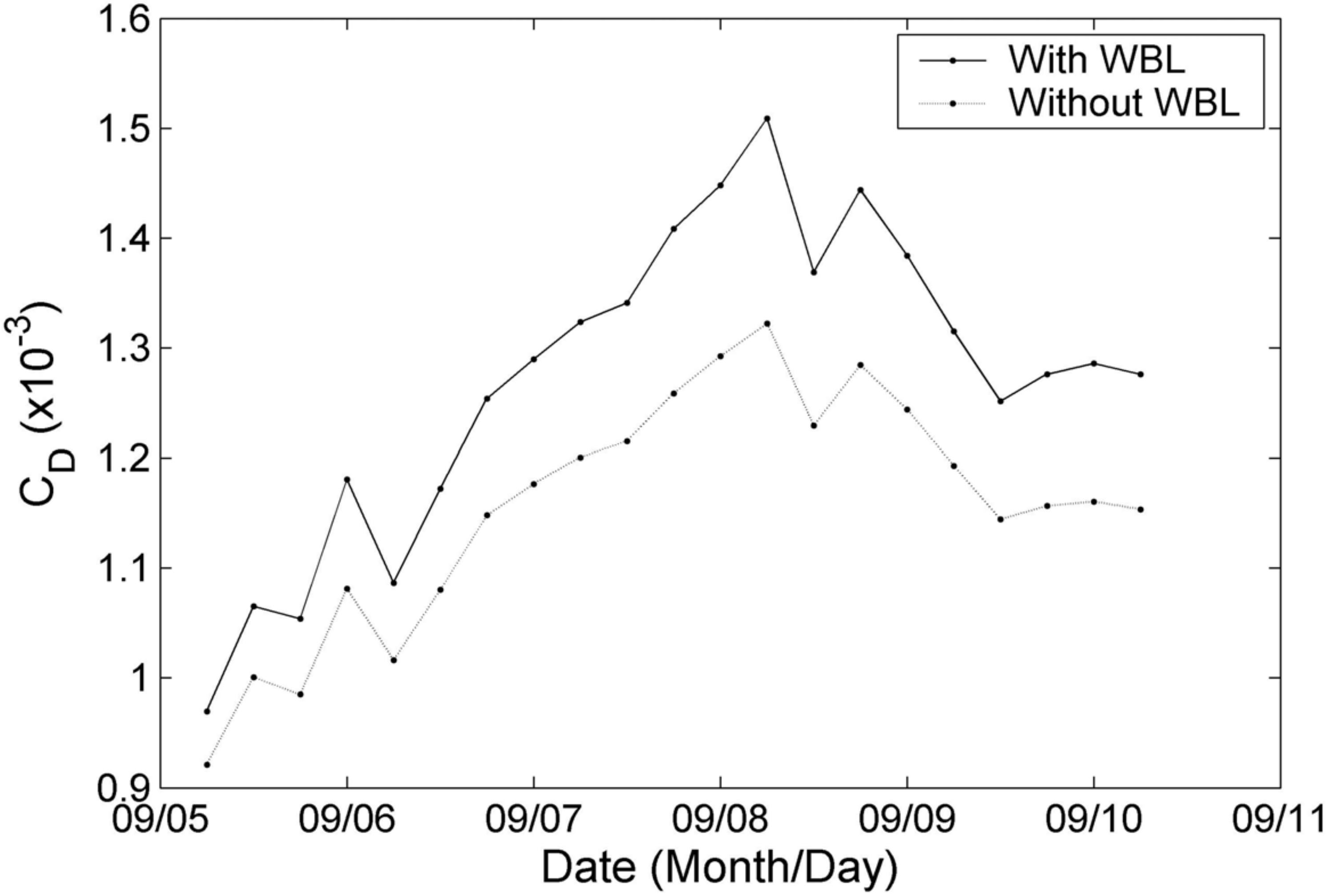
Effect of WBL on z_{0*}

Nondimensional Peak Wave Frequency

$$\omega_{p*} \equiv \omega_p u_* / g$$

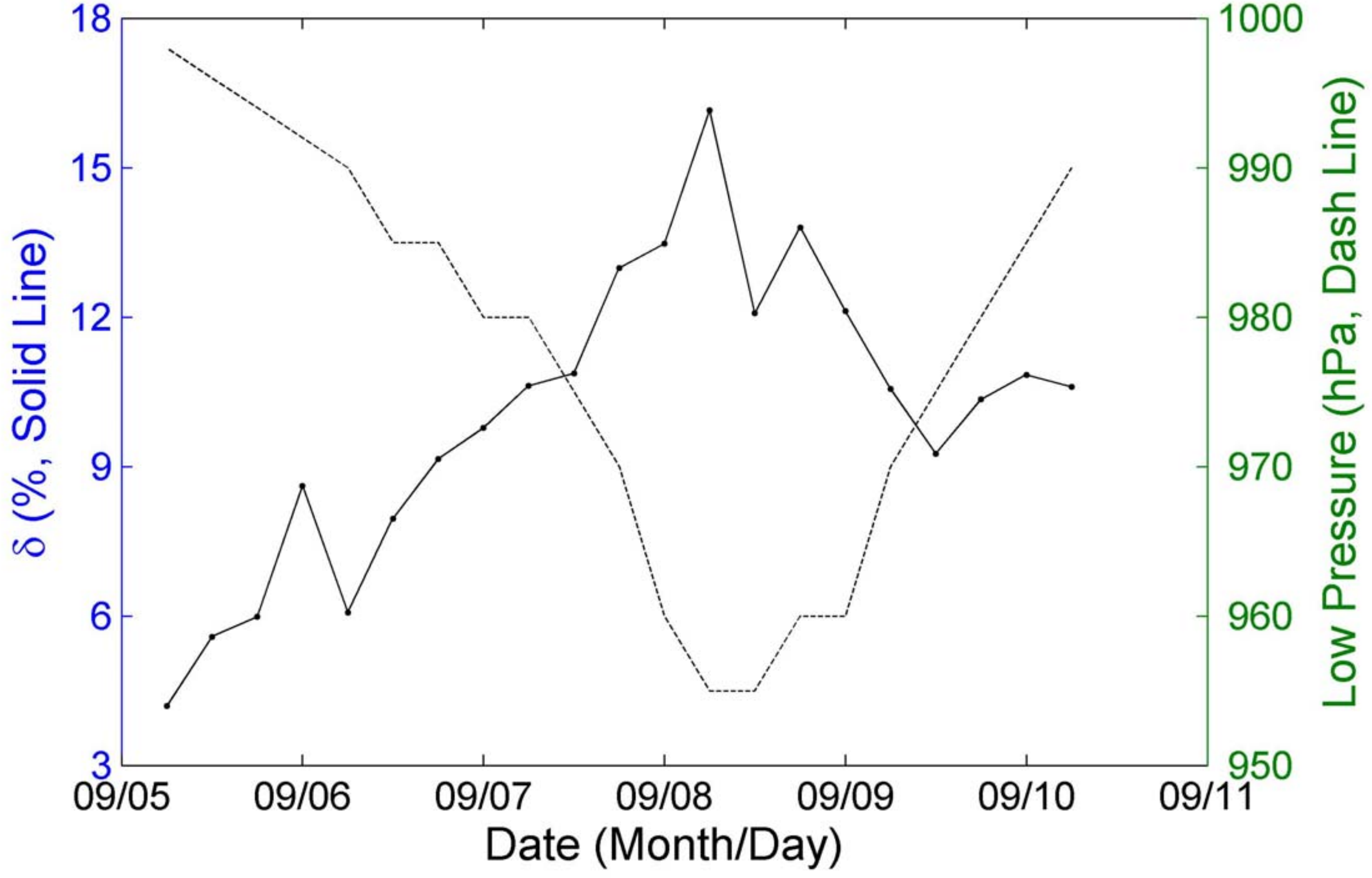


Effect on C_D

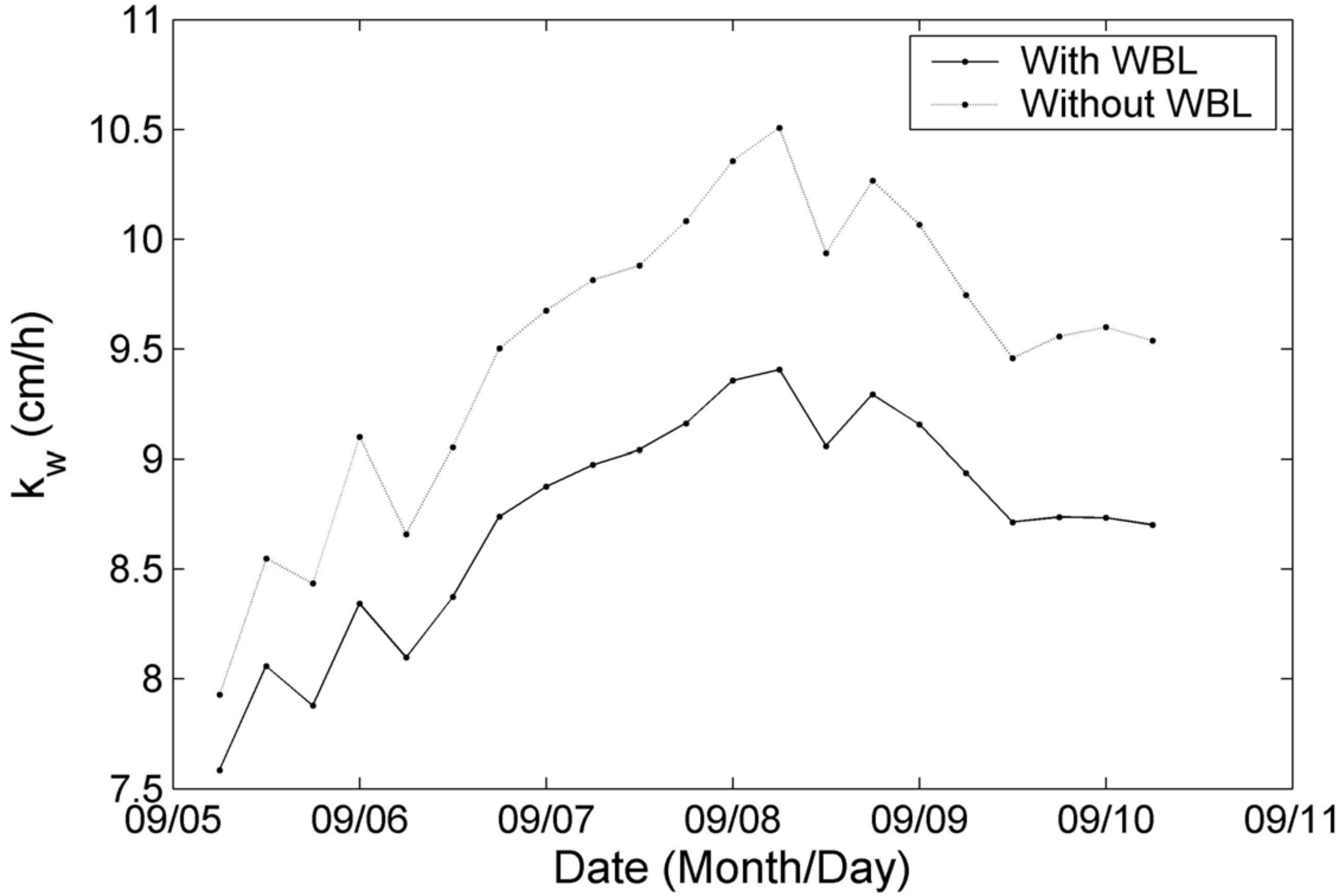

1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
C_D ($\times10^{-3}$)
09/05
09/06
09/07
09/08
09/09
09/10
09/11
Date (Month/Day)
With WBL
Without WBL

Relative Difference of C_D

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

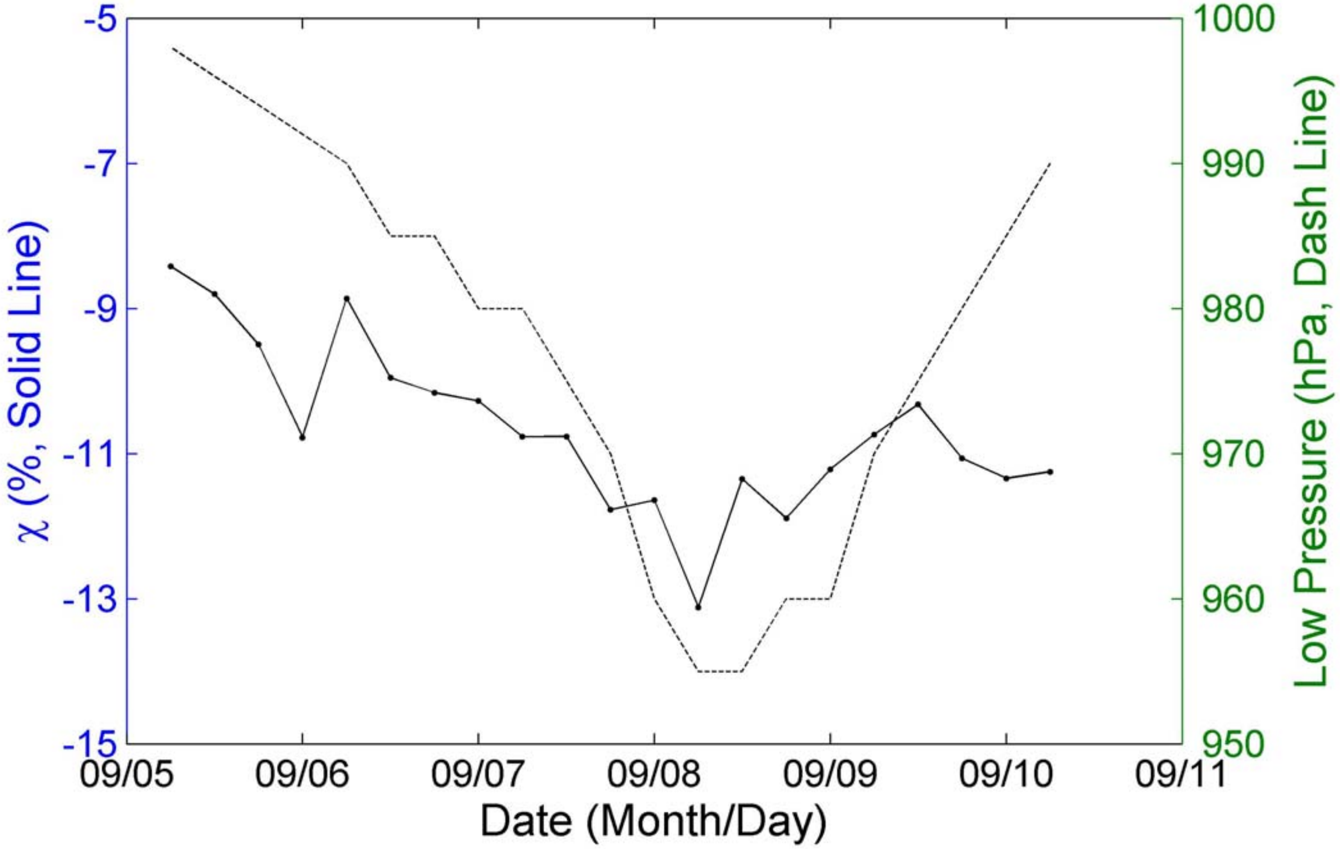


Effect on k_w


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

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



Conclusions

- (1) WBL increases C_D and in turn enhances the momentum flux → negative feedback.
- (2) WBL decreases k_w and in turn weakens the sea-to-air DMS transfer → less sulfate haze, CCN → 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.