The 5th workshop on waves and wave-coupled processes in ECMWF, 10-12 April of 2024

Wave coupling effects in regional and global atmosphere-ocean modeling

Disaster Prevention Research Institute (DPRI), Kyoto University

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Collaboration with

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R. Mizuta (MRI) and other researchers

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Contents

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2. Wave coupling effects in regional atmosphere-ocean modeling
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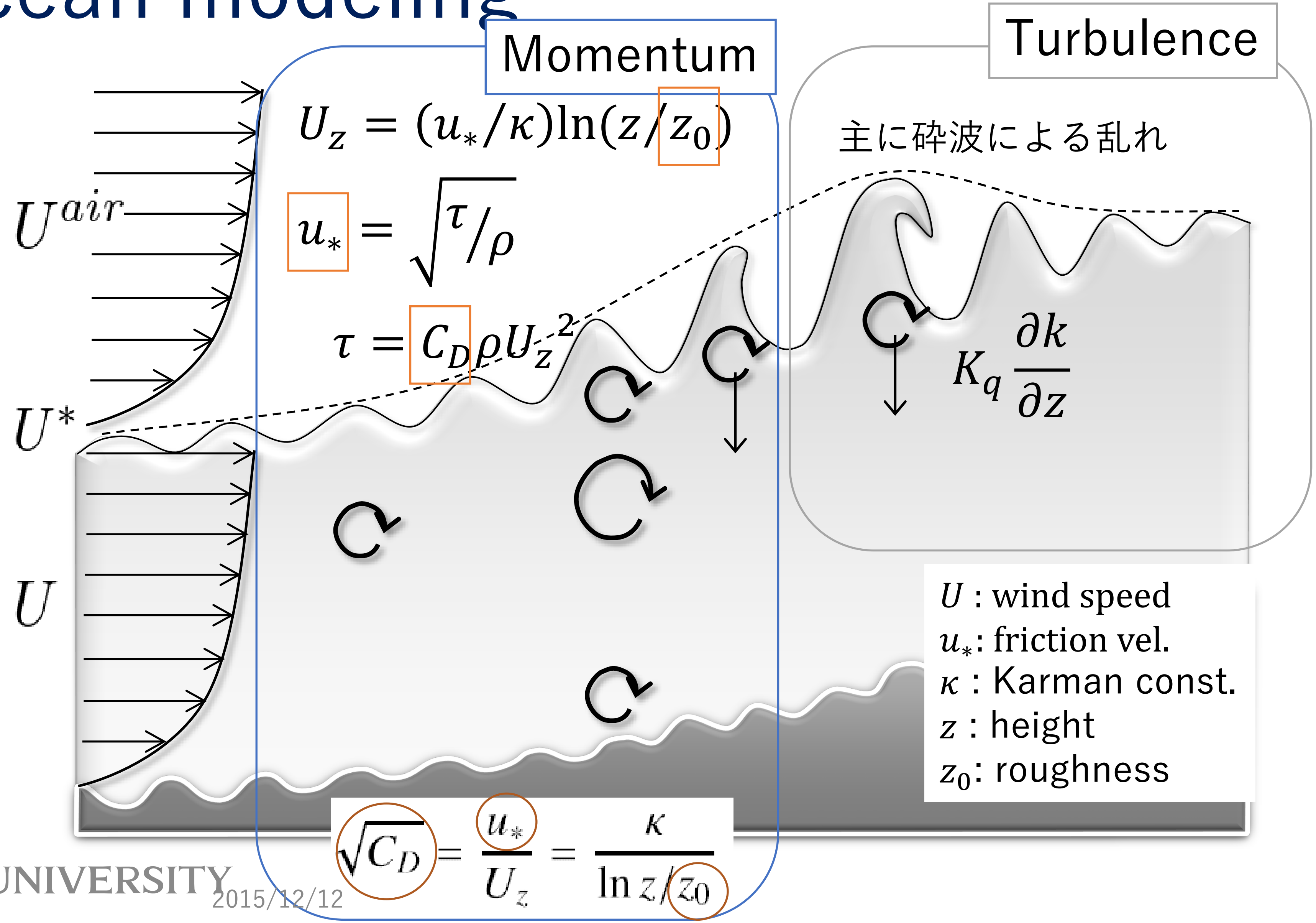
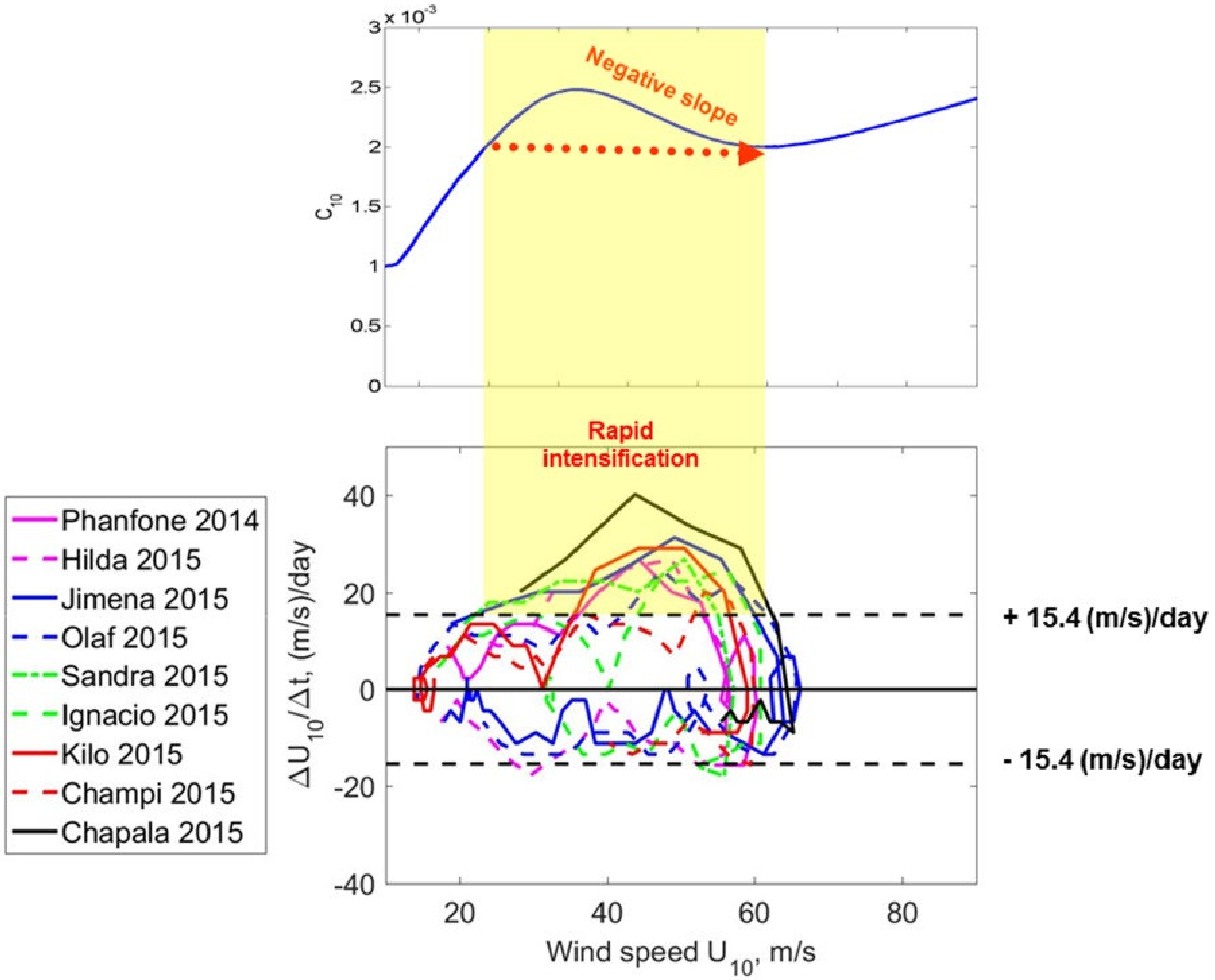
Role of air-sea interaction in ocean modeling



Balance between Cd and Ch is also important

- (Top) The air-sea drag coefficient as a function of wind speed for open ocean hurricanes and tropical cyclones that reached Category 4
- (Bottom) observed rate of wind speed as a function of wind speed 1.



Soloviev et al. (2017)JGR

Coupling models have been developed,
however,
physics of interface has not been improved

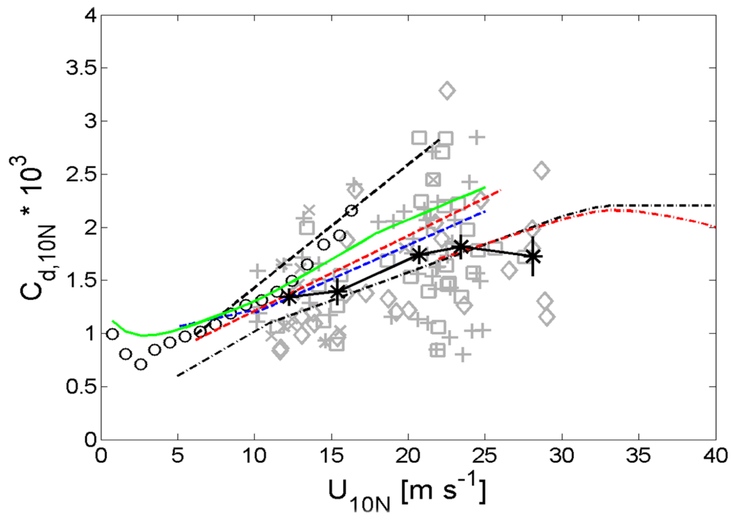
Atmosphere-Ocean boundary
atmospheric side z0

- High speed wind condition (after 2000s)
  - Powell et al. (2003)
    - decreasing Cd over 30m/s
  - Moon et al. (2003), Makin (2005), Babanin and Makin (2008)

$$z_0 = \frac{0.0185 u_*^2}{g} \qquad U_{10} \leq 12.5$$

$$z_0 = (0.085 C_1 - 0.58) \times 10^{-3} \qquad 12.5 < U_{10}$$

$$C_1 = -0.56 u_*^2 + 20.255 u_* + 2.45$$



Atmosphere-Ocean boundary
atmospheric side z0

- Charnock (1955)：Friction Velocity

$$z_0 = max\left(\frac{\alpha_{CH}}{g}(u_*)^2, z_{0_{min}}\right) \quad \alpha_{CH} = 0.018$$

Modified
by Fairall et al. (2003)

- Including wave information (after 2000s)
  - Taylor and Yelland (2001)

$$\frac{z_0}{H_s} = A\left(\frac{H_s}{L_p}\right)^B \quad A = 1200, B = 4.5$$

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$$\frac{z_0}{H_s} = E(u_*/C_p)^F \quad E = 3.35, F = 3.4$$

Atmosphere-Ocean boundary
ocean side TKE flux at sea surface

- TKE flux
  - Craig and Banner (1994)

$$K_k \frac{\partial k}{\partial z} = \alpha_{CB} {u_*}^3$$

  - Mellor and Blumberg (2004)

$$K_k \frac{\partial k}{\partial z} = 2\alpha_{CB} {u_*}^3$$

  - Feddersen and Trowbridge (2005)

$$K_k \frac{\partial k}{\partial z} = \alpha_{wdiss} \epsilon_{wdiss}$$

Wave coupling effects in regional atmosphere-ocean modeling

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Revised parameterization of wave induced turbulent kinetic energy for upper ocean surface mixing

Wave breaking induced TKE

- 1-D equation for turbulent kinetic energy(TKE) with k- ε model is assumed to be used

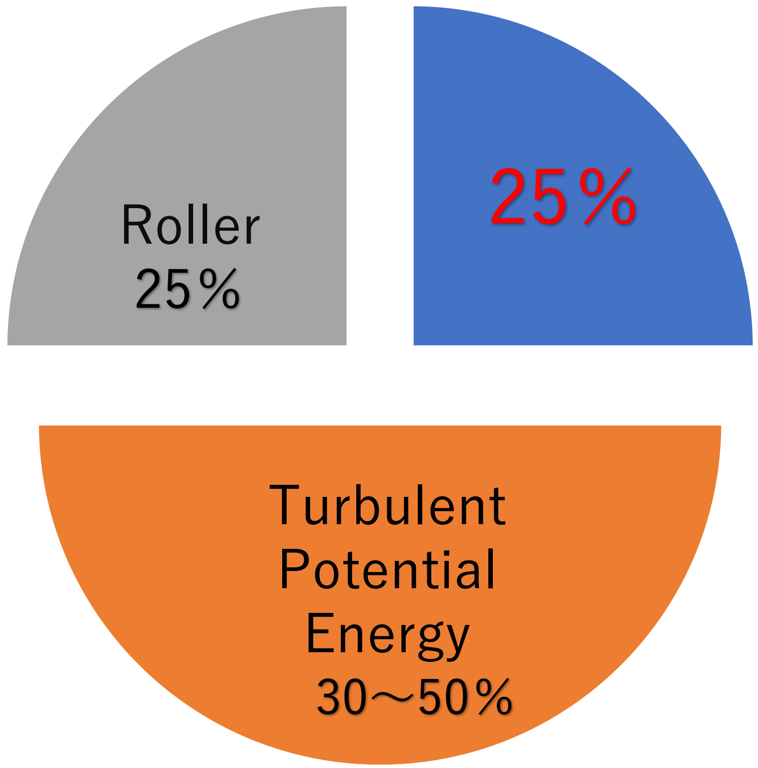
$$\frac{\partial k}{\partial t} = \frac{\partial}{\partial z}\left(\frac{K_v}{\sigma_k}\frac{\partial k}{\partial z}\right) + K_v S^2 - \varepsilon$$

- Boundary condition at MWL is needed to supply k
- Feddersen and Trowbridge (2005)

$$\frac{K_v}{\sigma_k}\frac{\partial k}{\partial z} = \alpha\overline{\varepsilon_w} \quad at\, z=0$$

where $\alpha = 1/4$

- 1/4 of wave breaking dissipation will be used for TKE



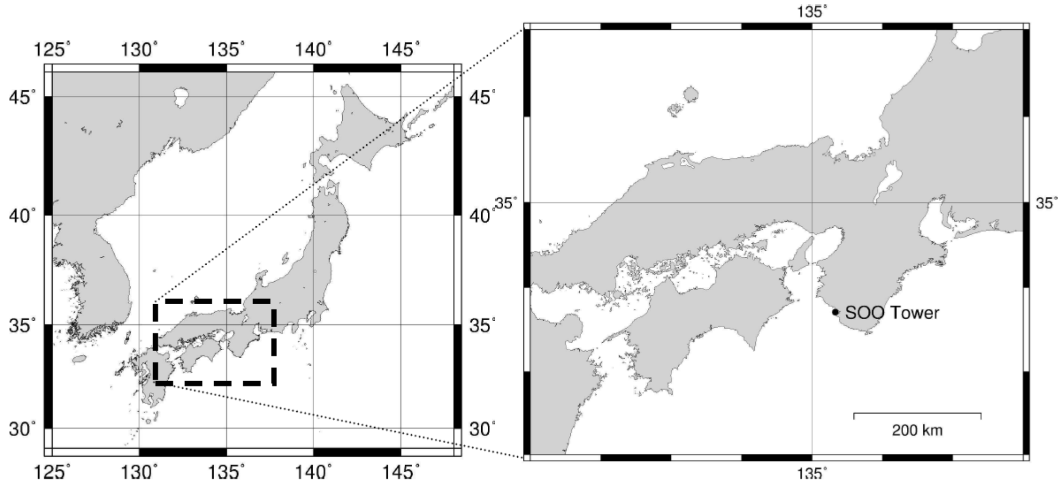
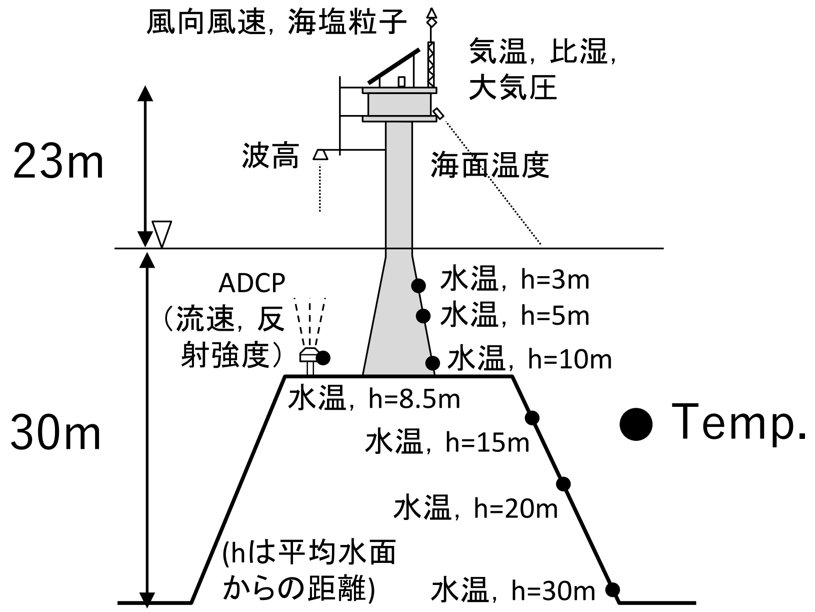
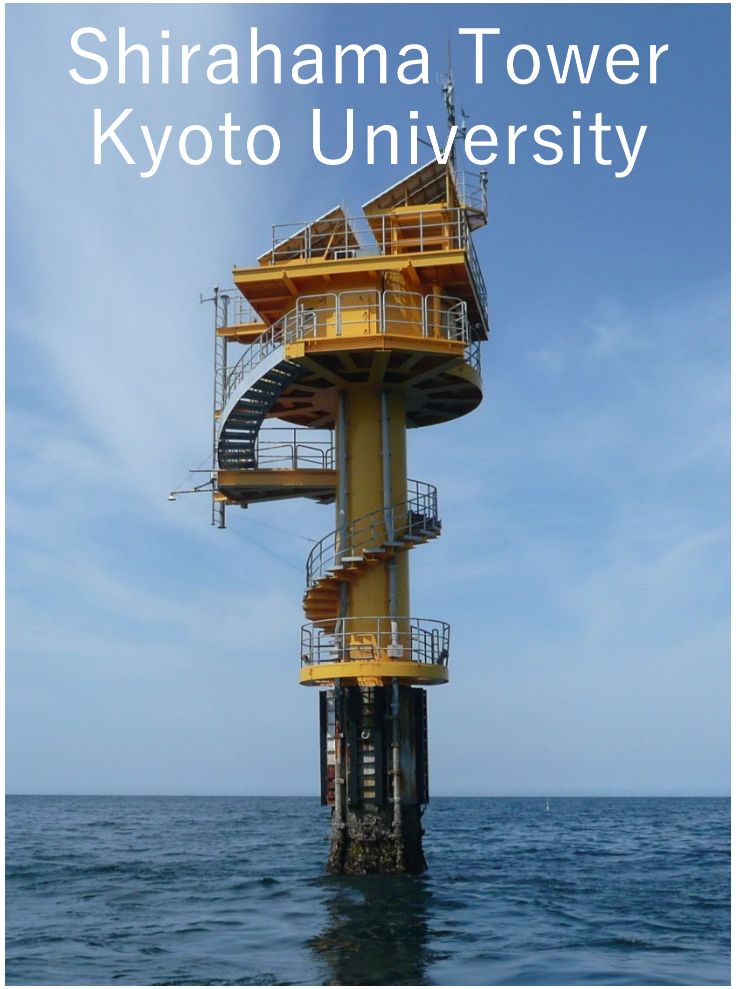
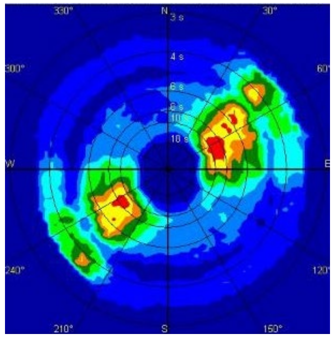


Figure 1 Shirahama Oceanographic Observatory

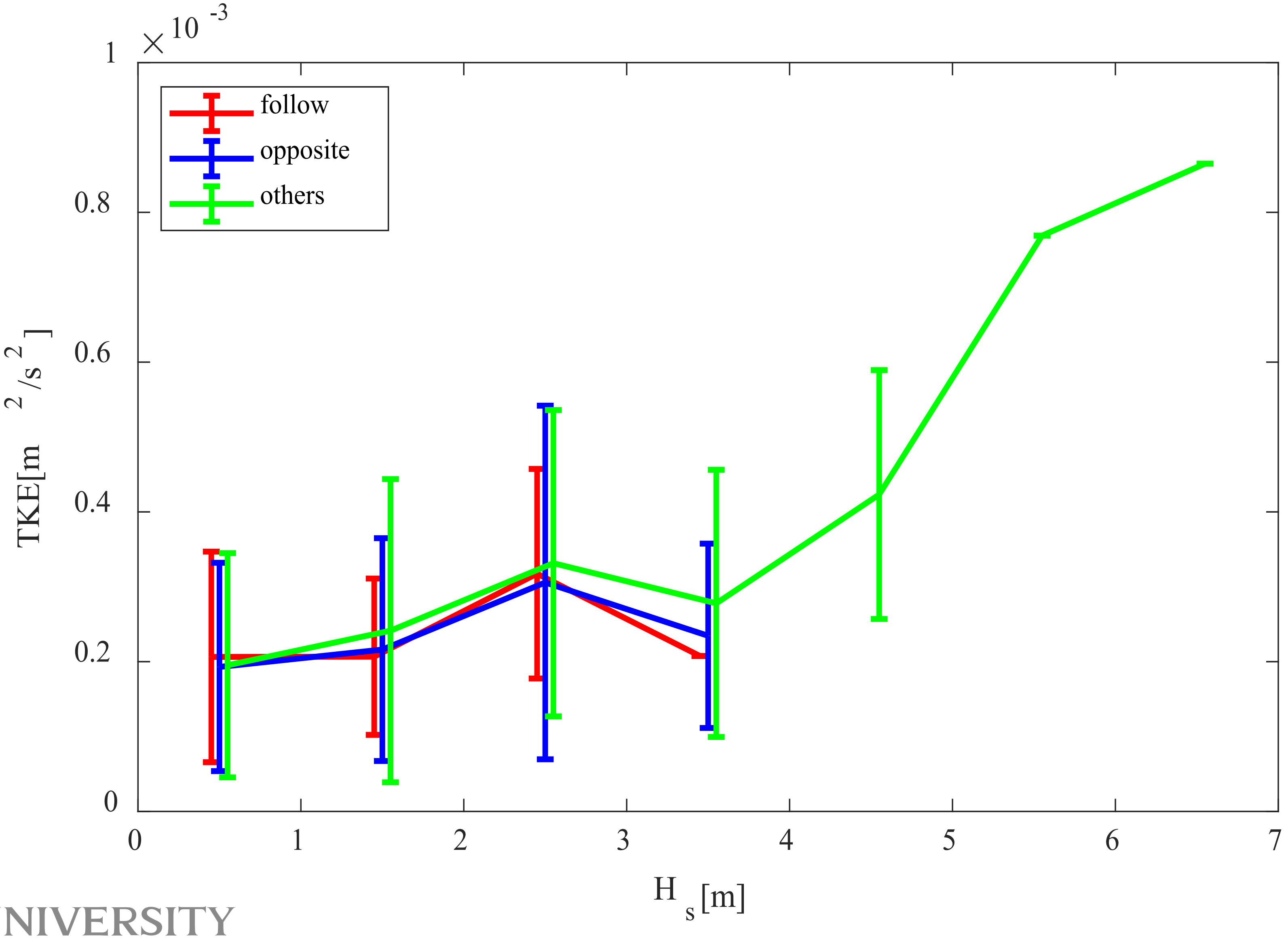


Field experiments for typhoons since 2009

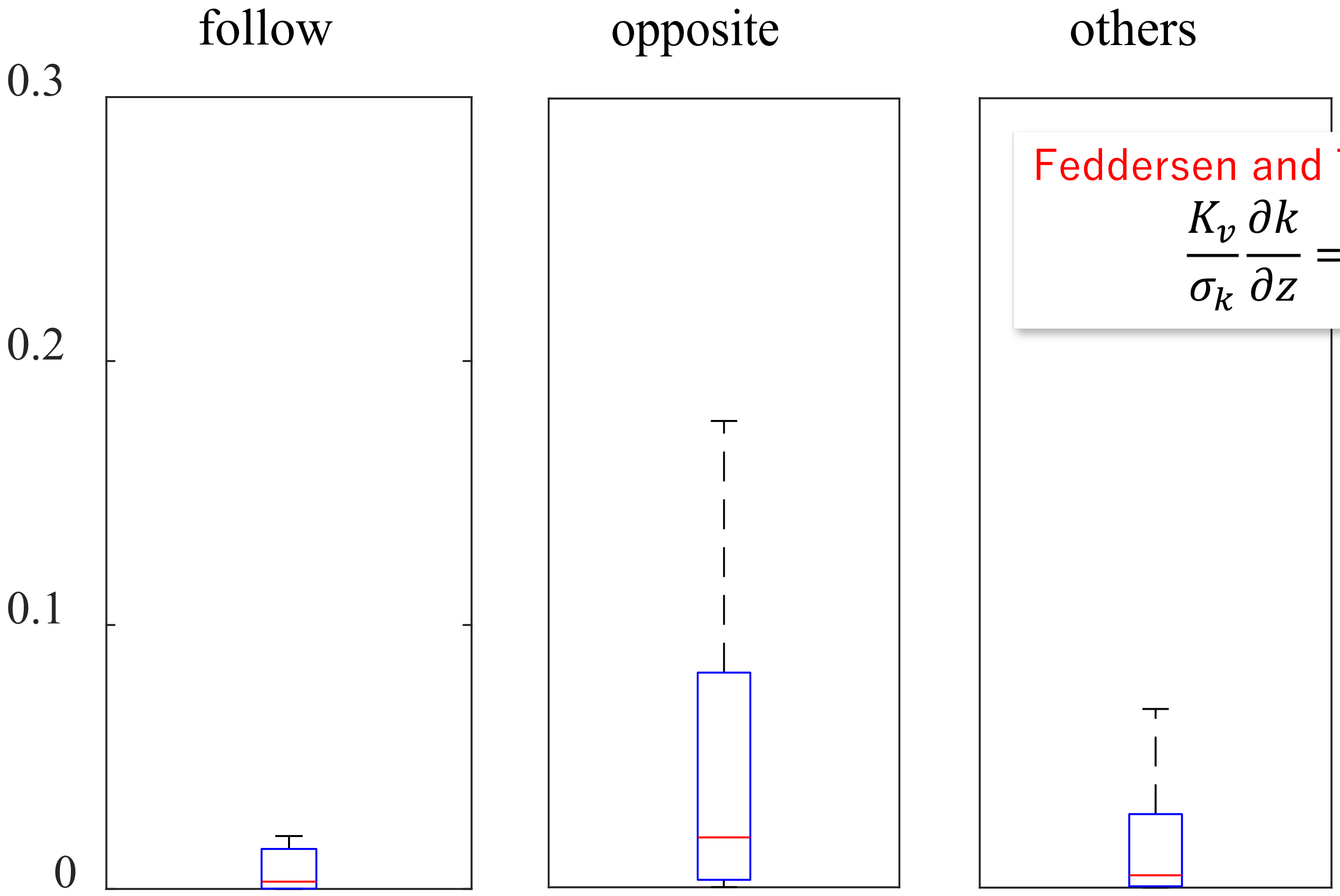




TKE at surface vs Hs



Result of tuning parameter α



Feddersen and Trowbridge

$$\frac{K_v}{\sigma_k}\frac{\partial k}{\partial z} = \alpha\overline{\varepsilon_w}$$

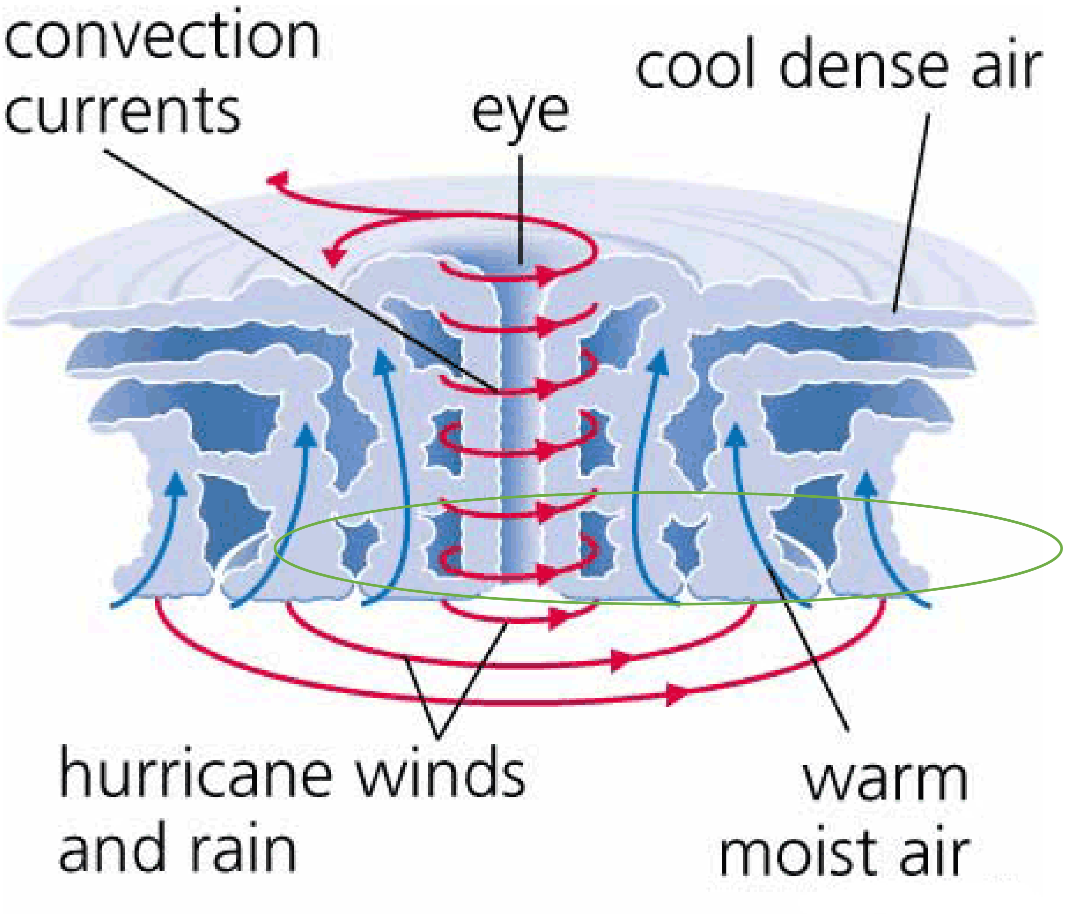
follow<others<opposite

In case “follow”, the correlation coefficient between the inverse number of wave steepness and α is 0.45

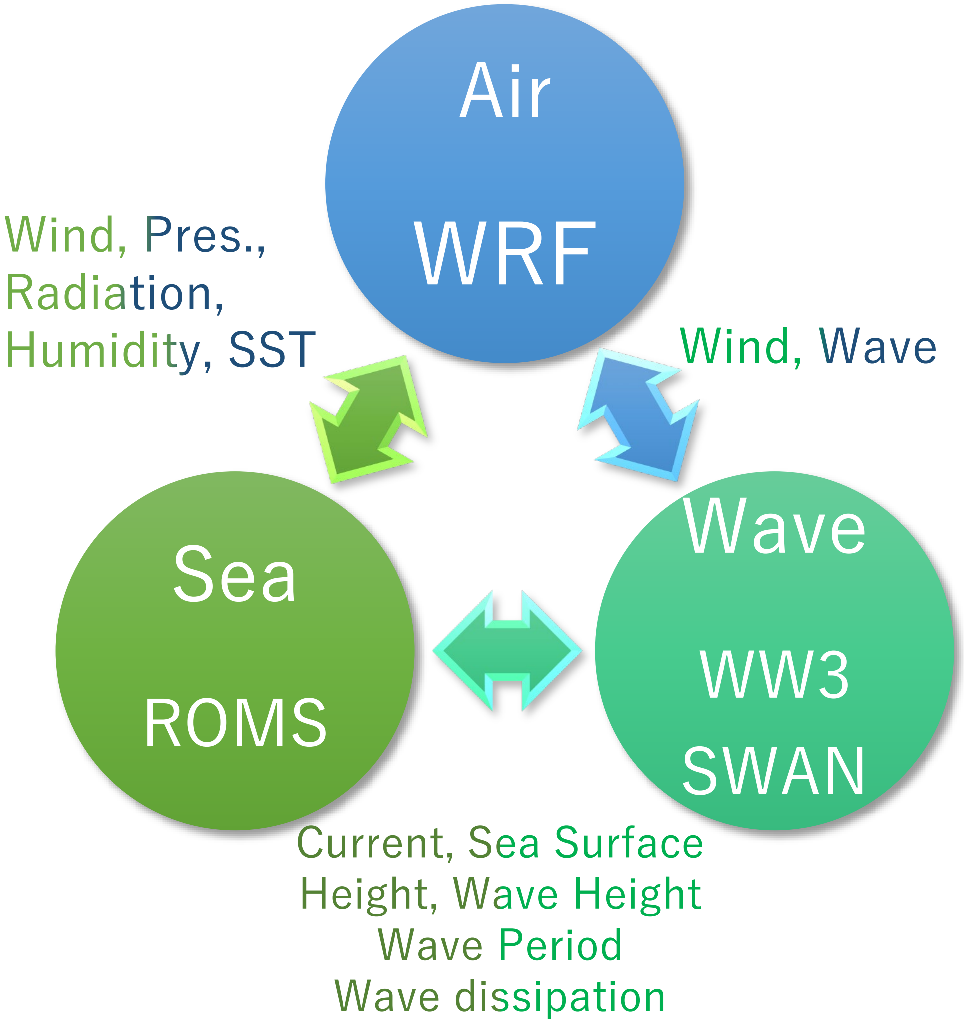
-->weak dependency on wave steepness

COAWST Model Setup

Warner et al.(2009)

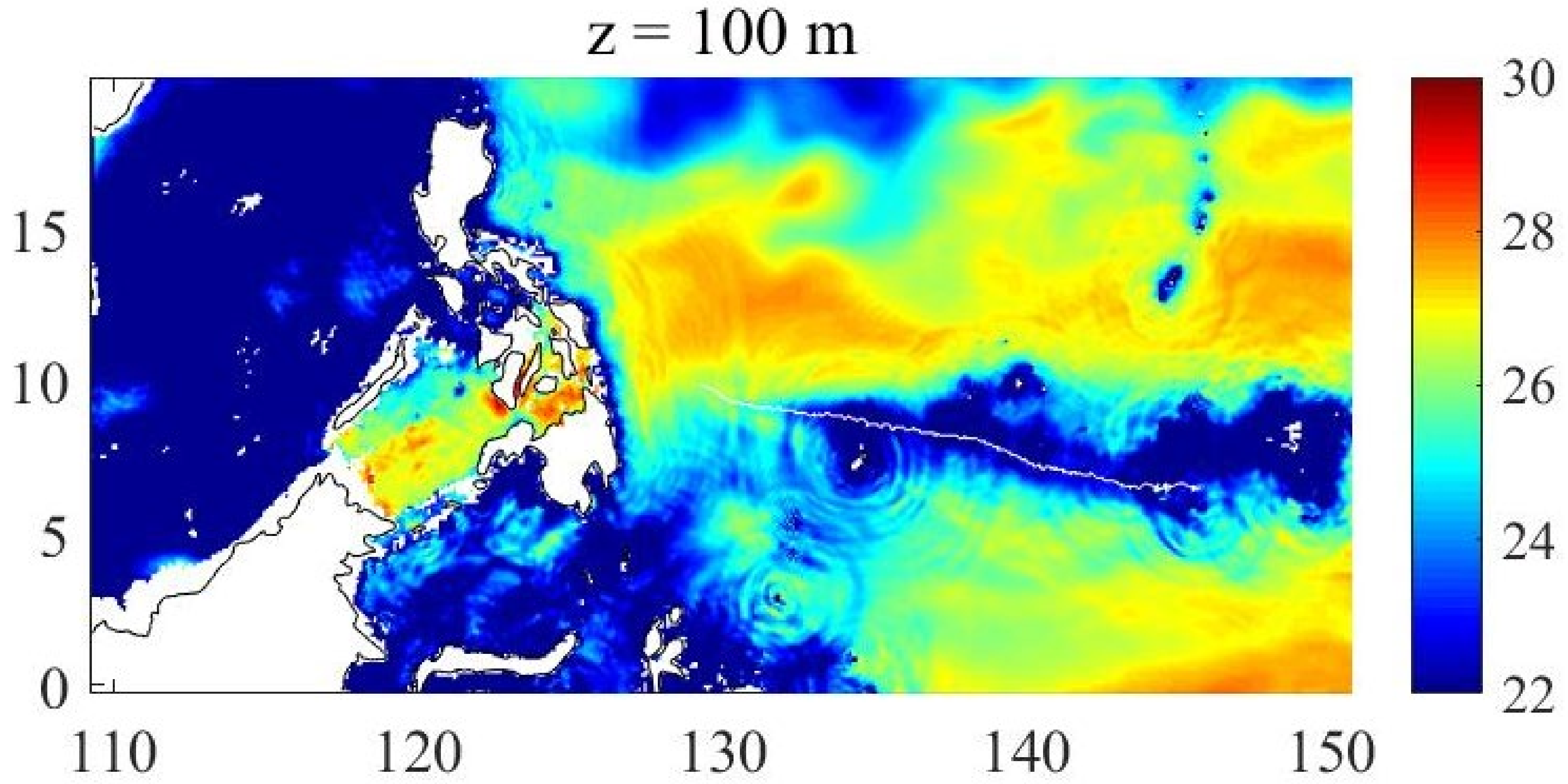


AOW Model



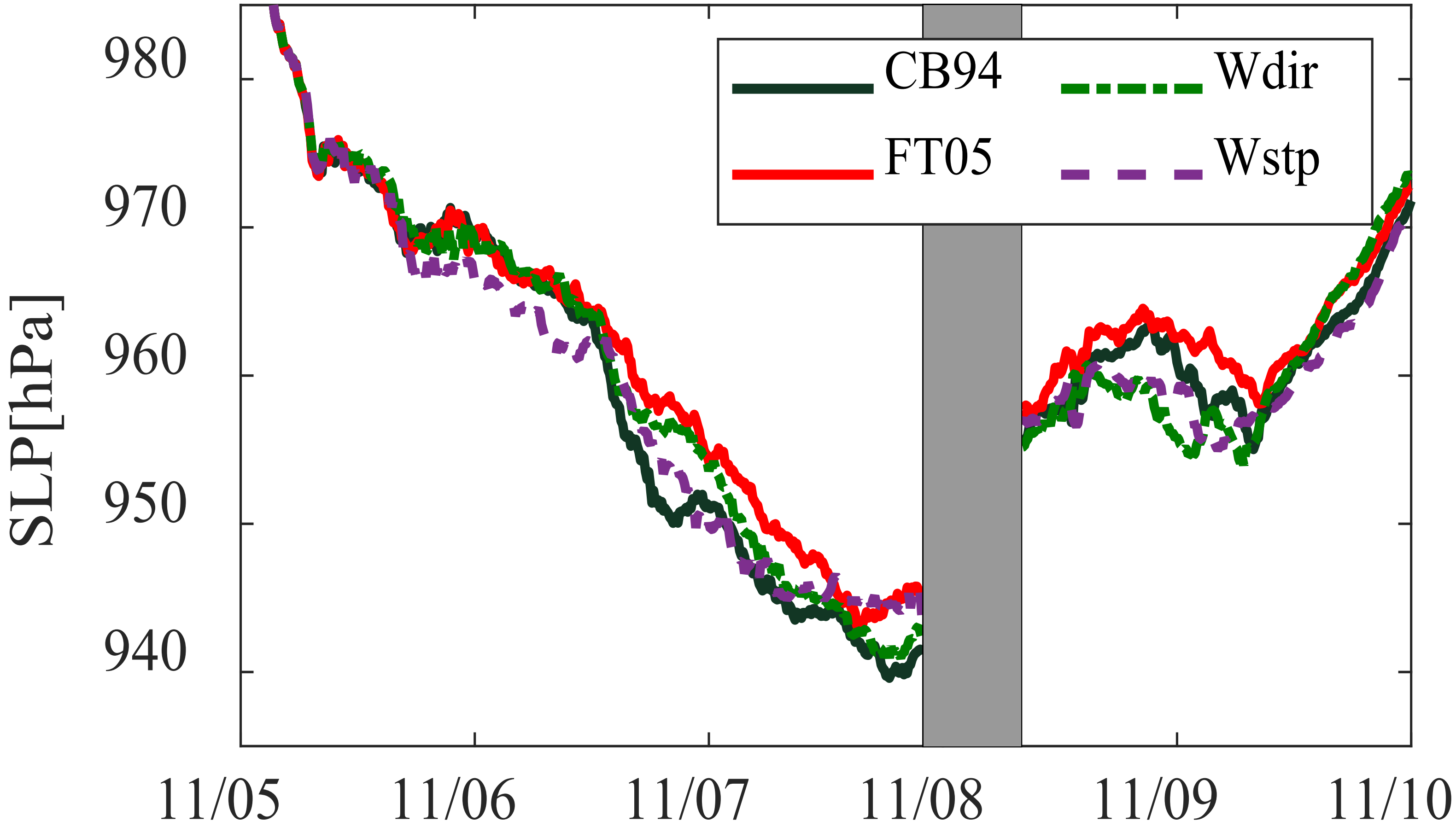
Resolution WRF=1km, ROMS, SWAN=3km

Changes of temperature at h=100m
TC Haiyan 2013



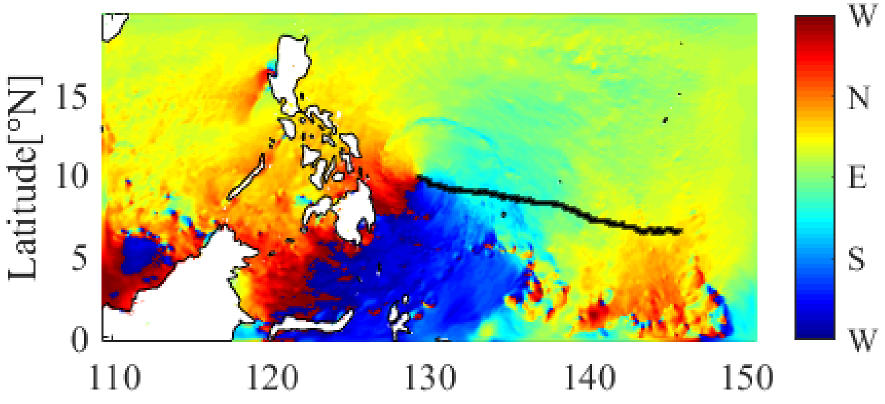
7 November UTC12:00

Time series of min central pressure

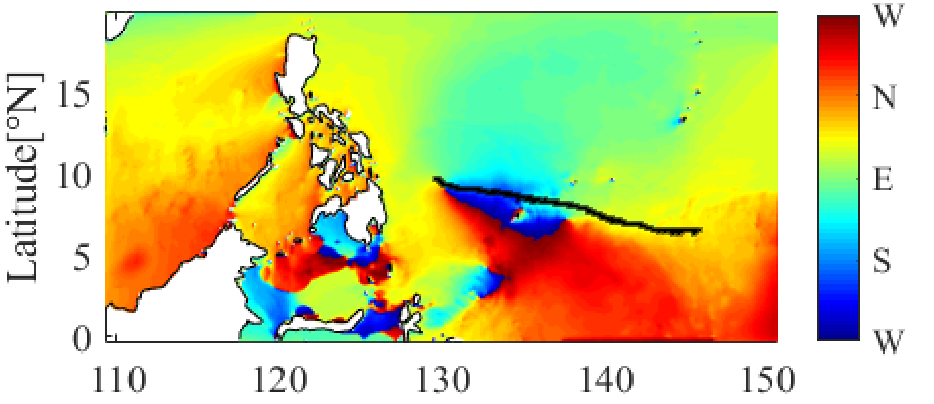


Maximum difference of SLP is 8hPa

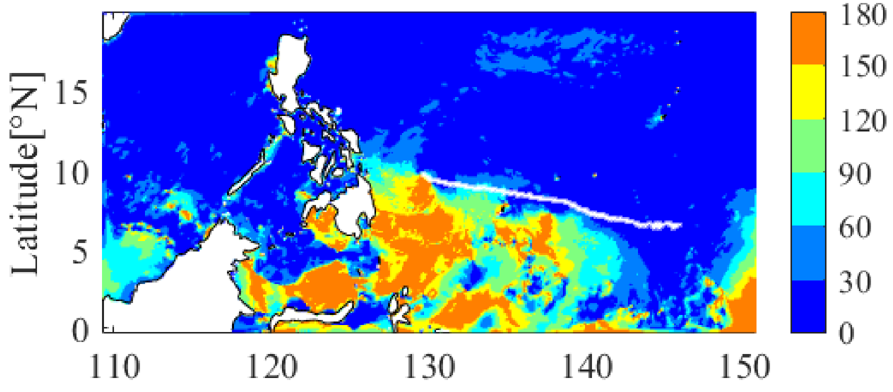
Snapshot: directions, steepness



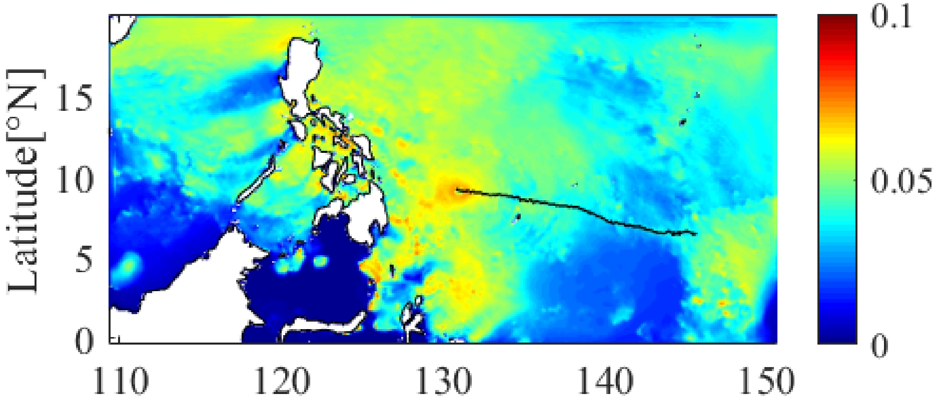
Wind direction



Wave direction

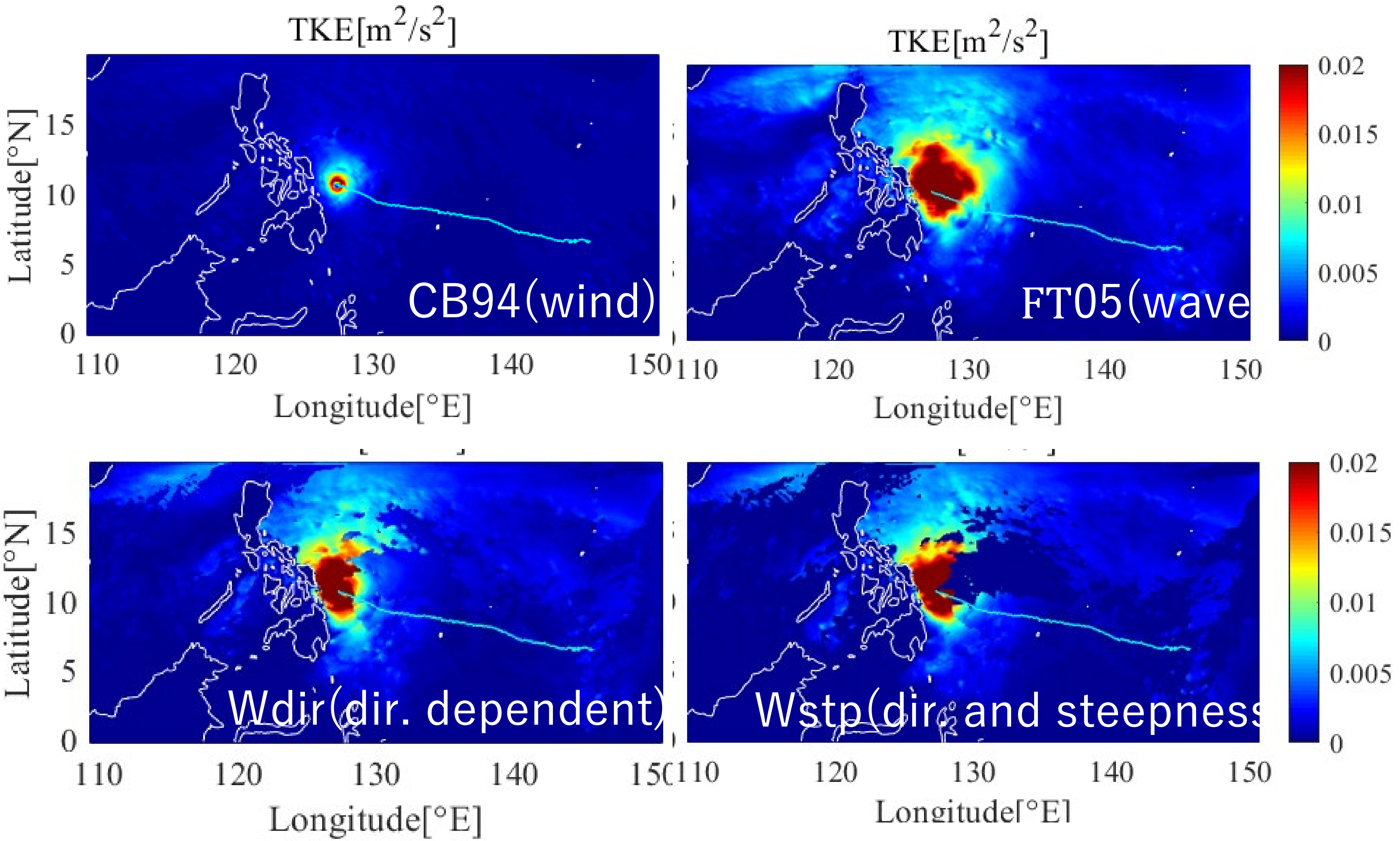


Difference of wind and wave direction

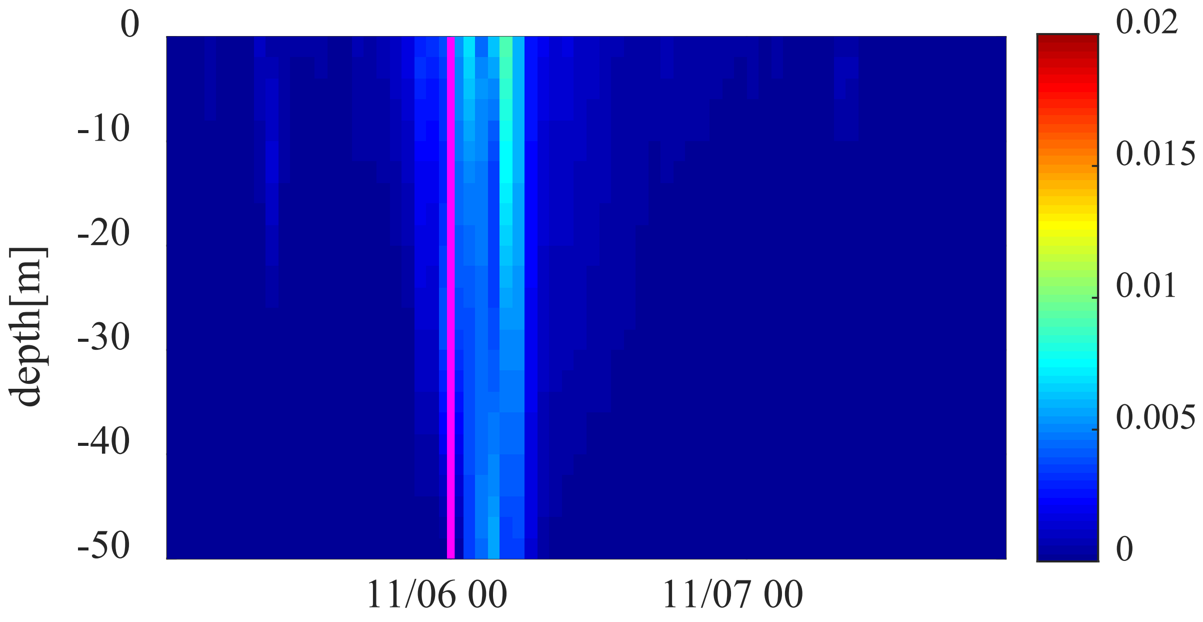


wave steepness

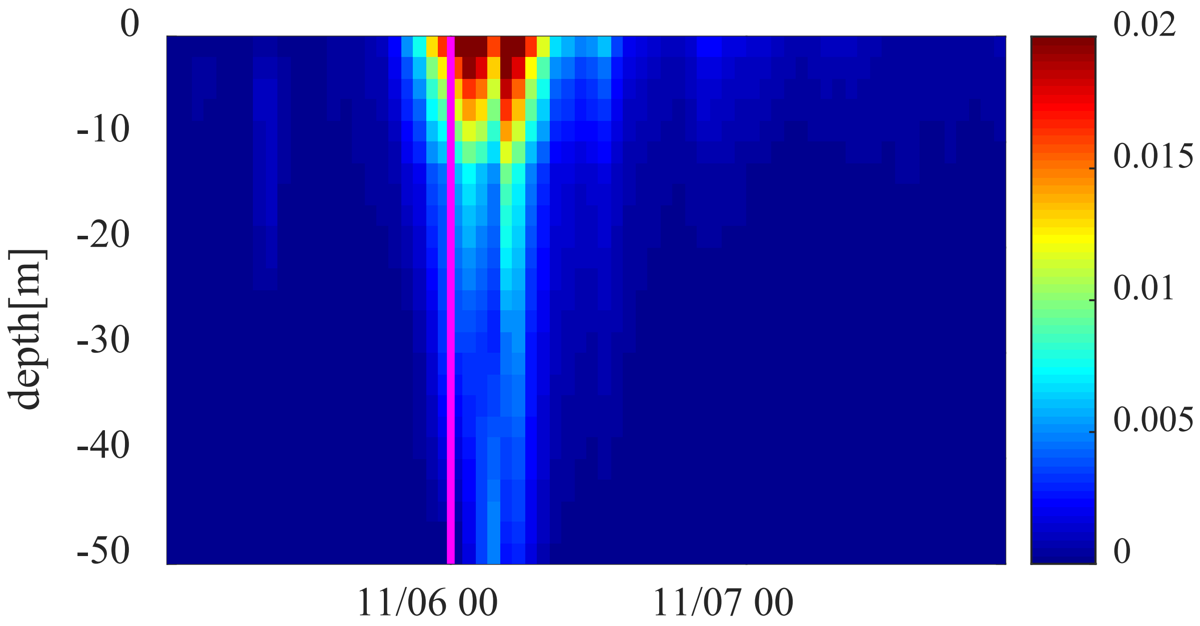
Snapshot: TKE



Vertical distribution of TKE along TC center

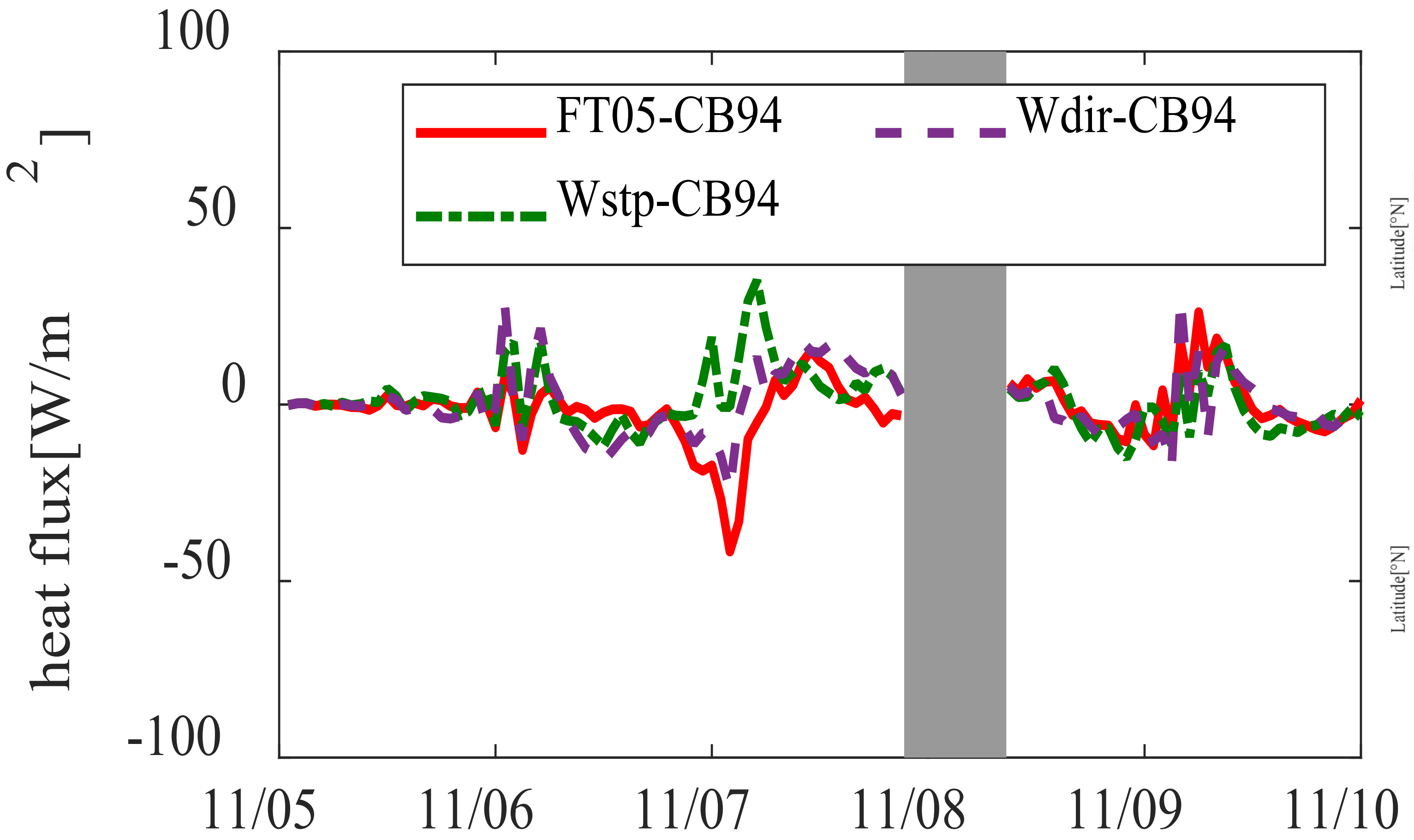


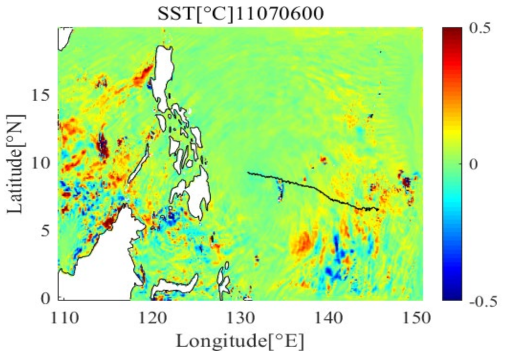
CB94

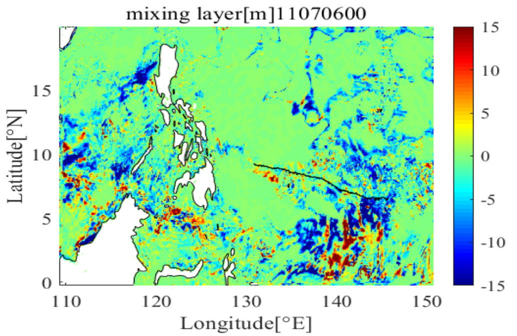


FT05

Difference of heat flux

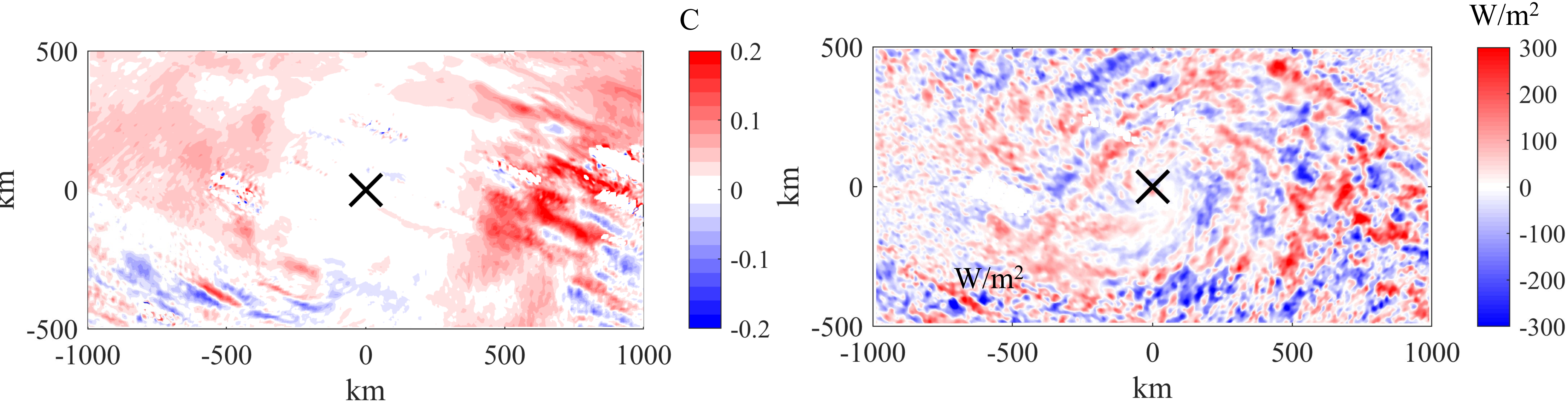






Total difference of heat flux is 6~9%

Snapshot of SST and SW radiation

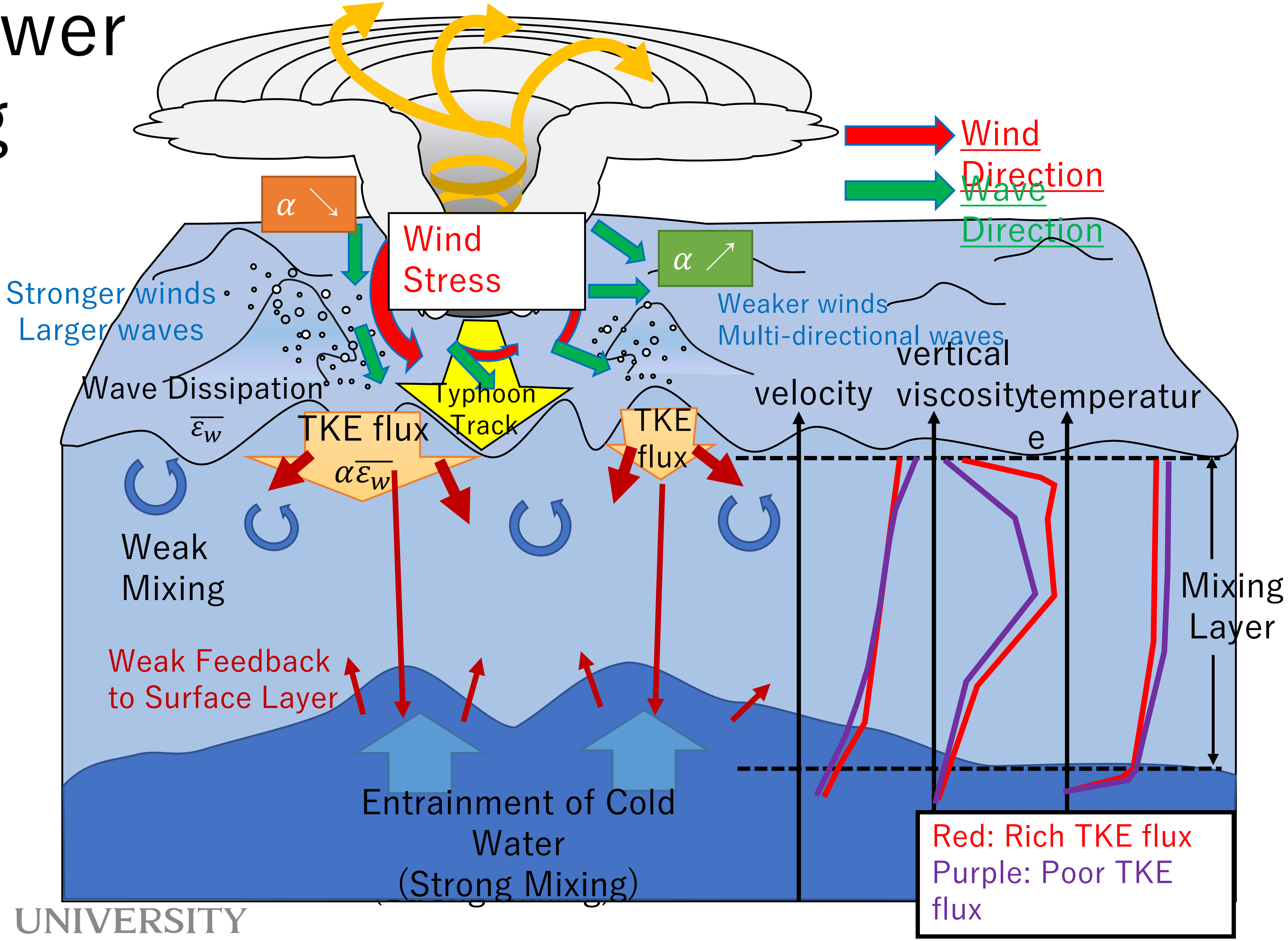


SST

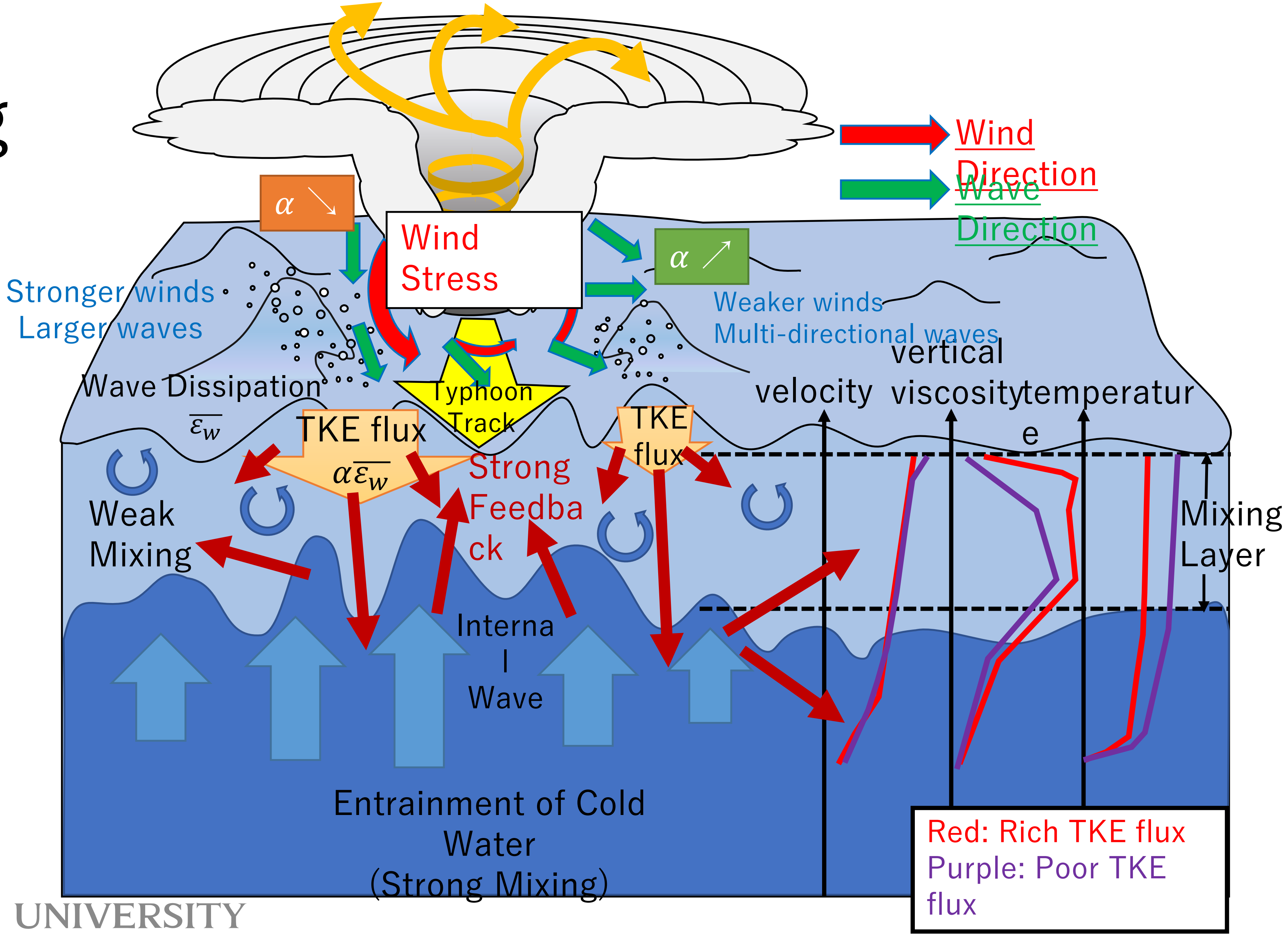
SW rad

CB94-FT05

Shallower mixing layer

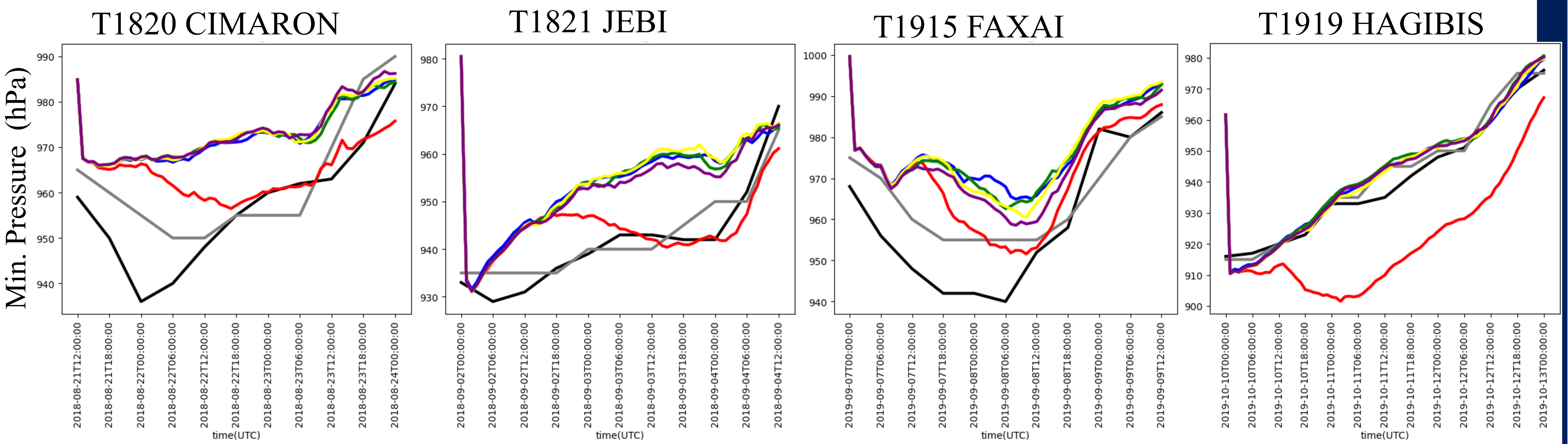


Thin mixing layer



Impacts of Waves for Typhoon Intensity

PBL Scheme of WRF is MYJ

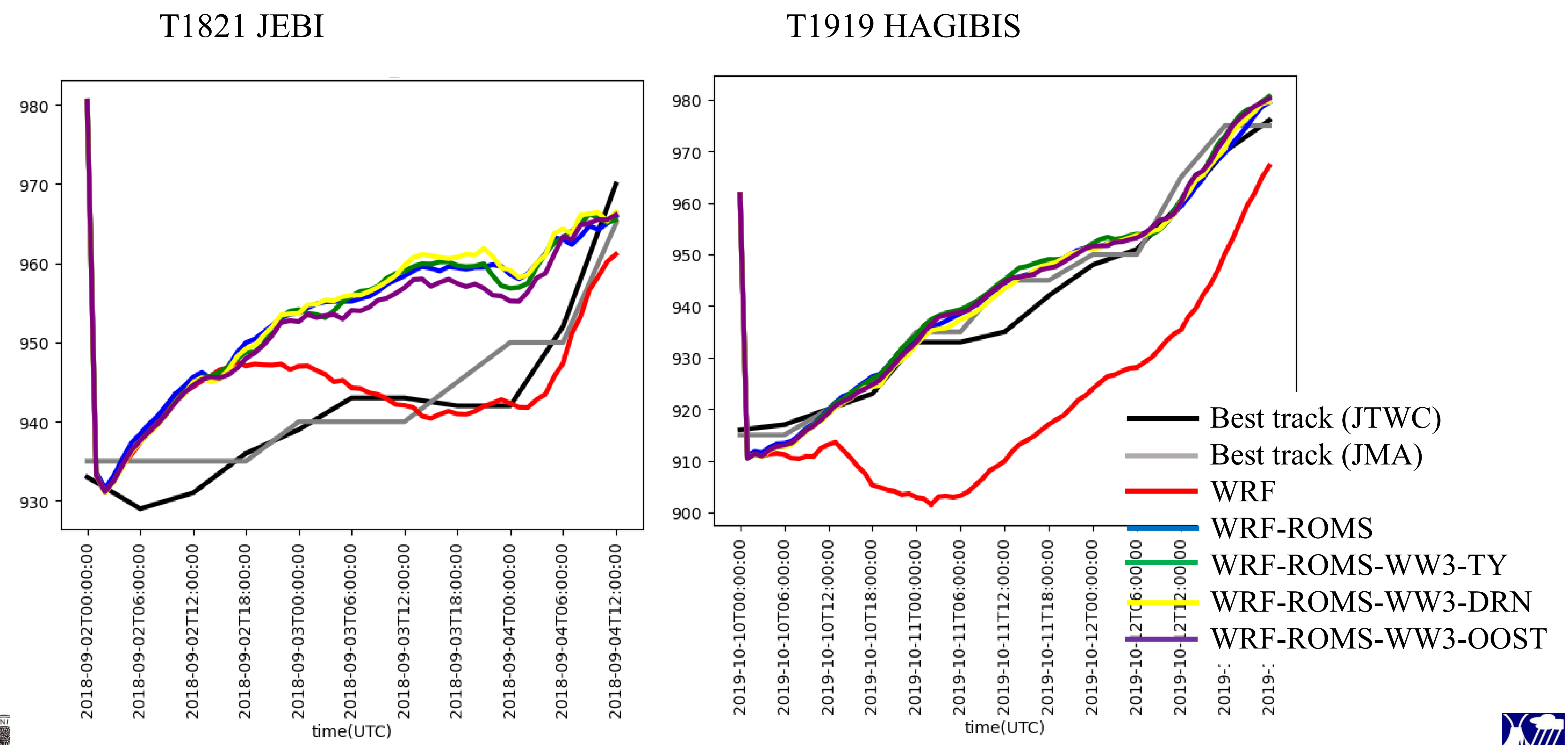


- Cimaron, Jebi and Faxai are underestimated while Hagisbis is corresponded in coupled model
- The ocean-wave coupled model suppressed the decrease in intensity more than the ocean-only coupled
- Impacts of waves have a small effects in case Cimaron and Hagibis
- Difference of bulk formulas affect Jebi and Faxai

Best track (JTWC)
Best track (JMA)
WRF
WRF-ROMS
WRF-ROMS-WW3-TY
WRF-ROMS-WW3-DRN
WRF-ROMS-WW3-OOST

Impacts of Waves for Typhoon Intensity

PBL Scheme of WRF is MYJ



Summary

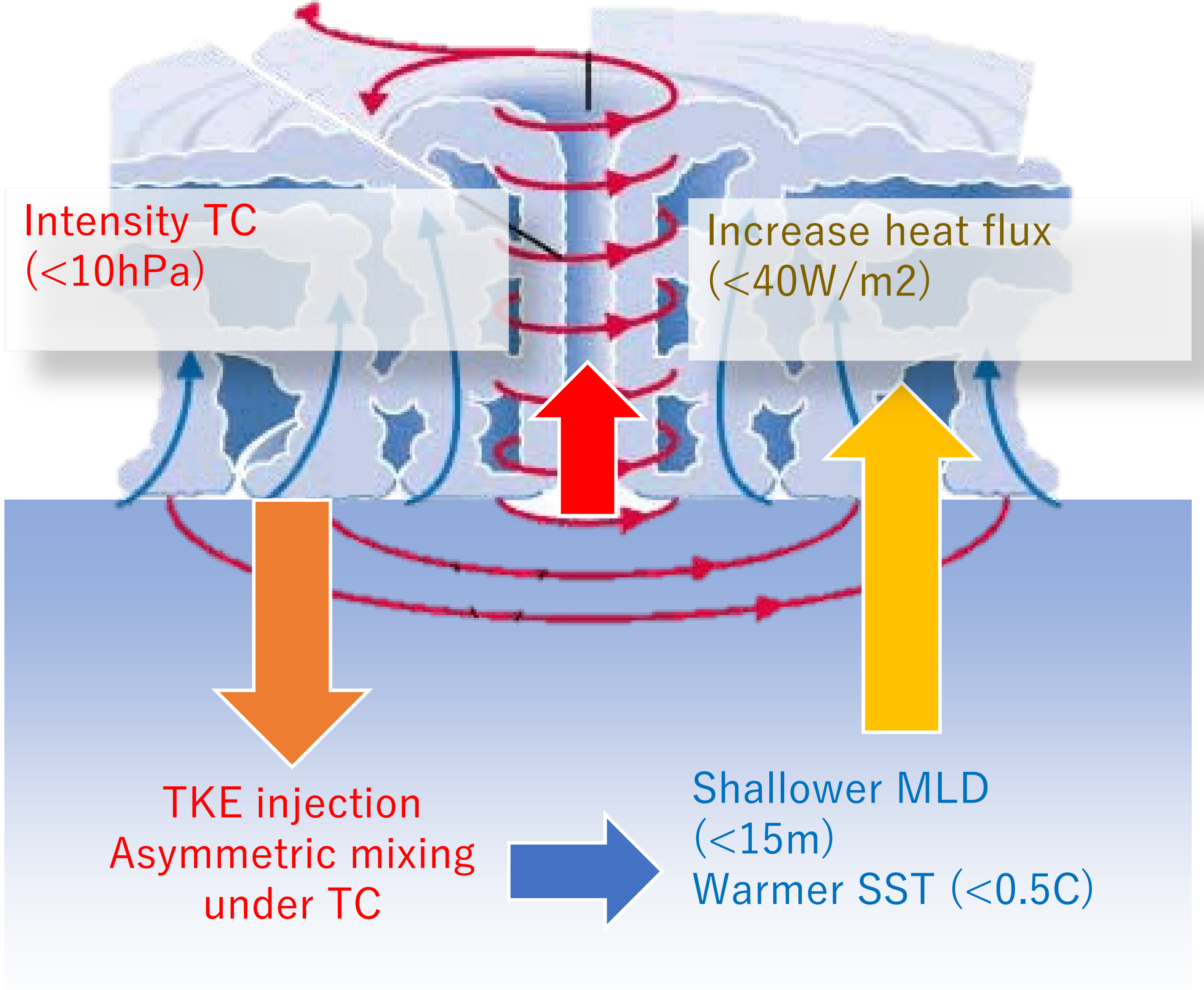
• MLD is important

Parameterization

TKE flux

Cd

Wave field



Wave coupling effects in global atmosphere-ocean modeling

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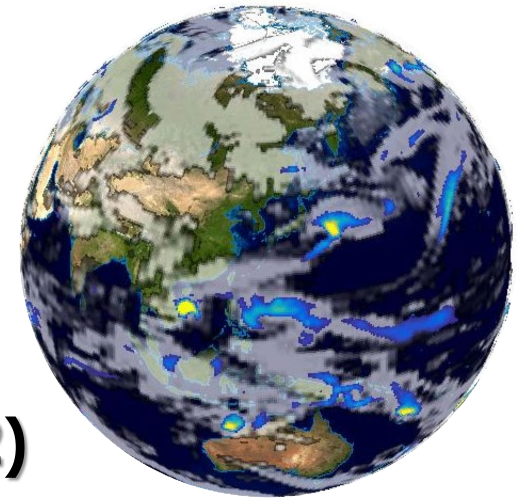
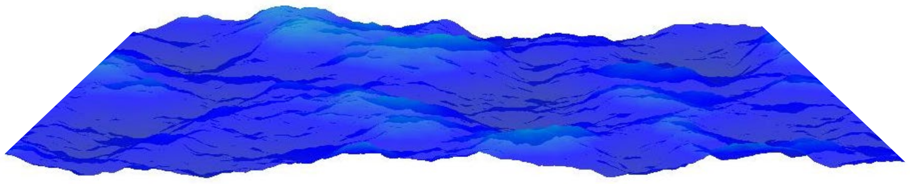
Background



MRI-AGCM3.2
(Mizuta et al., 2012)

Wind (U_{10})

Roughness length
(z_{0m})



WAVEWATCH III
ver.4.18
(Tolman, 2014)

Bulk transfer relation

・Momentum

$$u_*^2 = \boldsymbol{C_d} U^2$$

・Heat

$$\overline{w'\theta} = \boldsymbol{C_h} |U| (\theta_a - \theta_g)$$

Experimental configuration

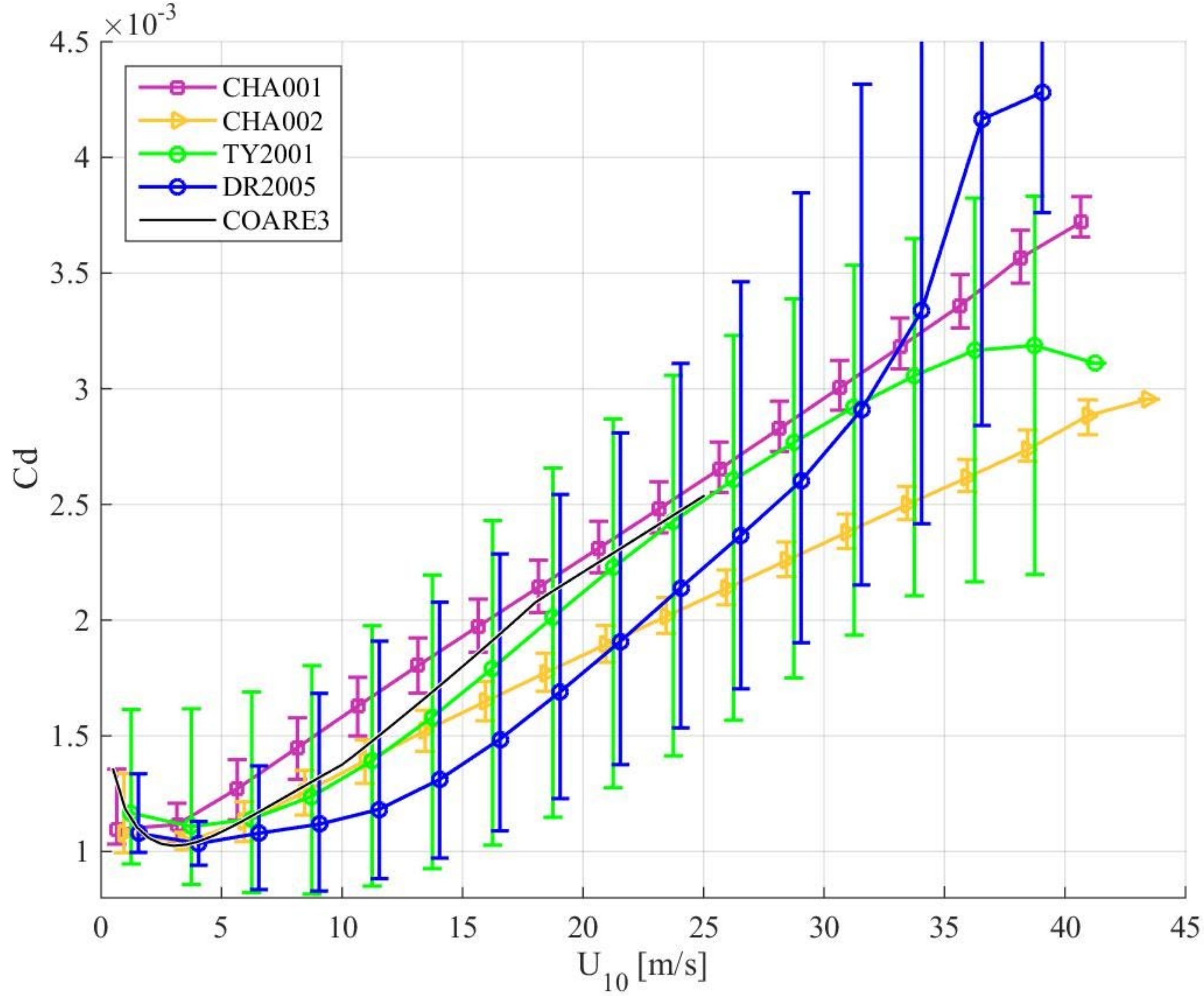
Climate simulations

- Uncoupled simulations
  - CHA002 ($\alpha = 0.020$)
  - CHA001 ($\alpha = 0.010$)
- Coupled simulations
  - TY2001
    - Wave steepness (Taylor and Yelland 2001)
  - DR2003
    - Wave age (Drennan et al., 2003)

- Period
  - 1990 – 2014 (25 years)
- Boundary condition
  - Observed sea Surface Temperature (SST) and Sea ice
    - HadISST1 (Rayner et al., 2003)
- Reference
  - Reanalysis and observation combined dataset
    - OAFlux and CMAP
  - Reanalysis dataset
    - ERA-Interim and JRA-55

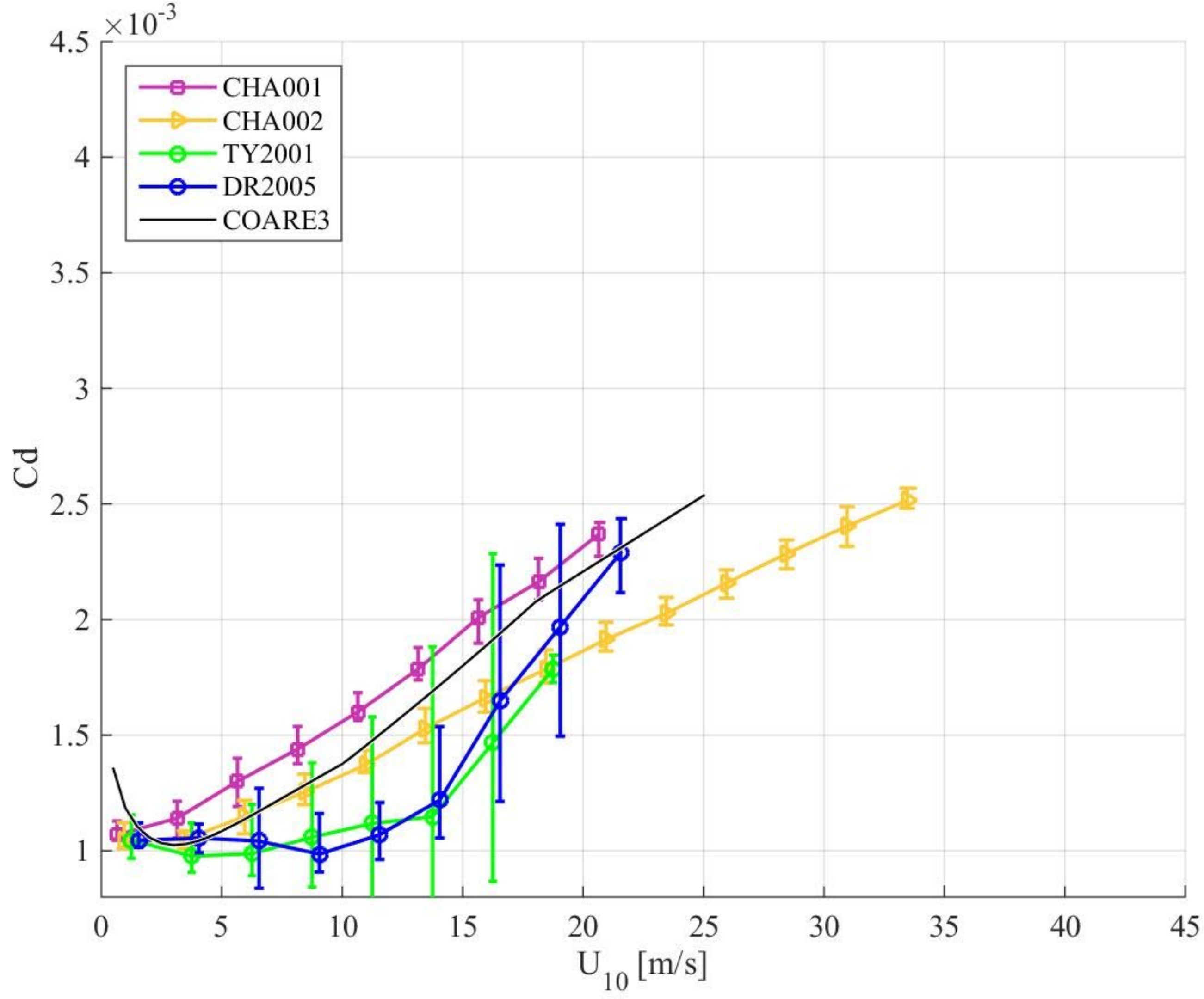
U10 vs Cd

(NP)180E-140W, 40N-50N



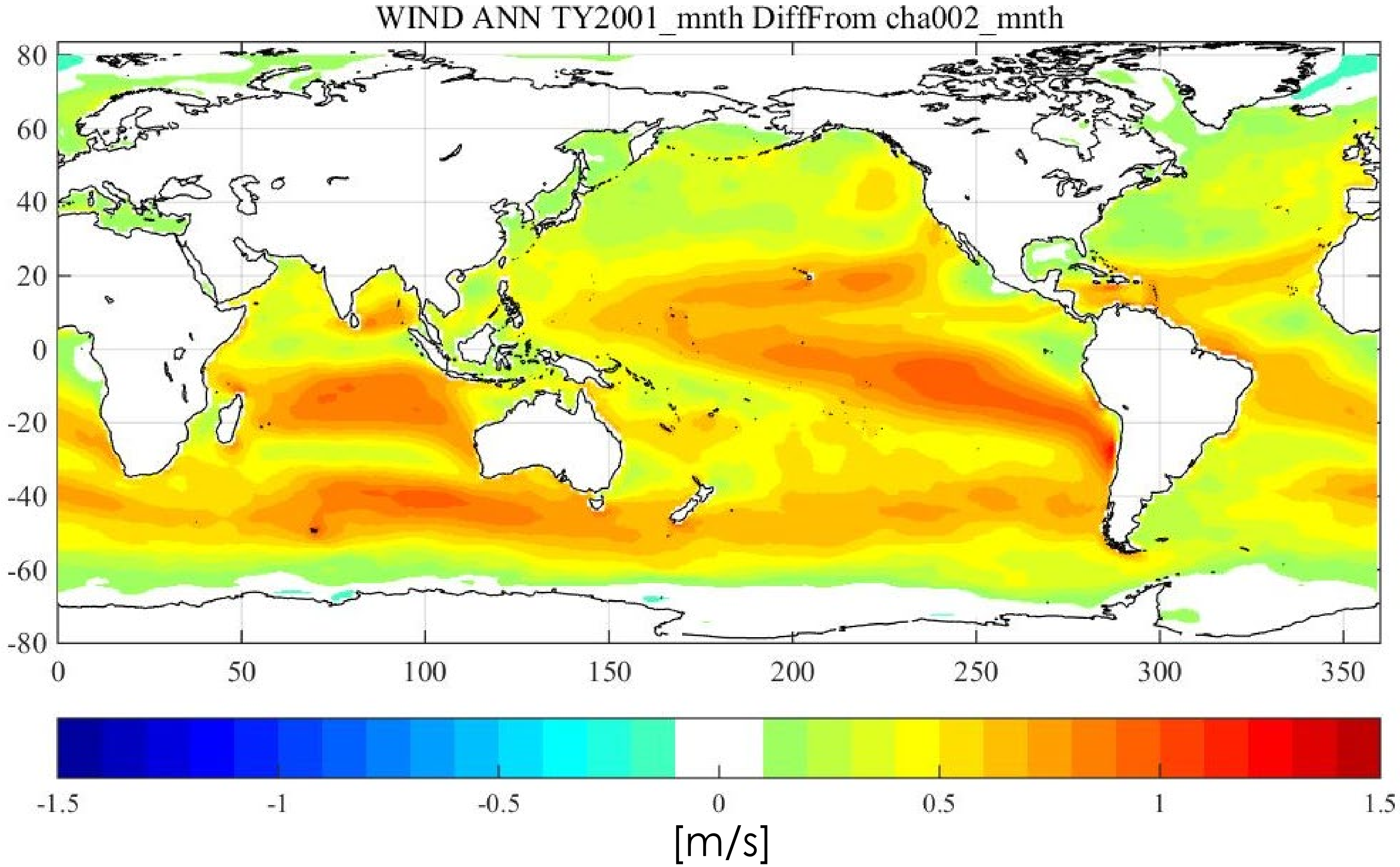
Shimura et al. (2017) JGR

U10 vs Cd
Equator (180E-140W, 5S-5N)



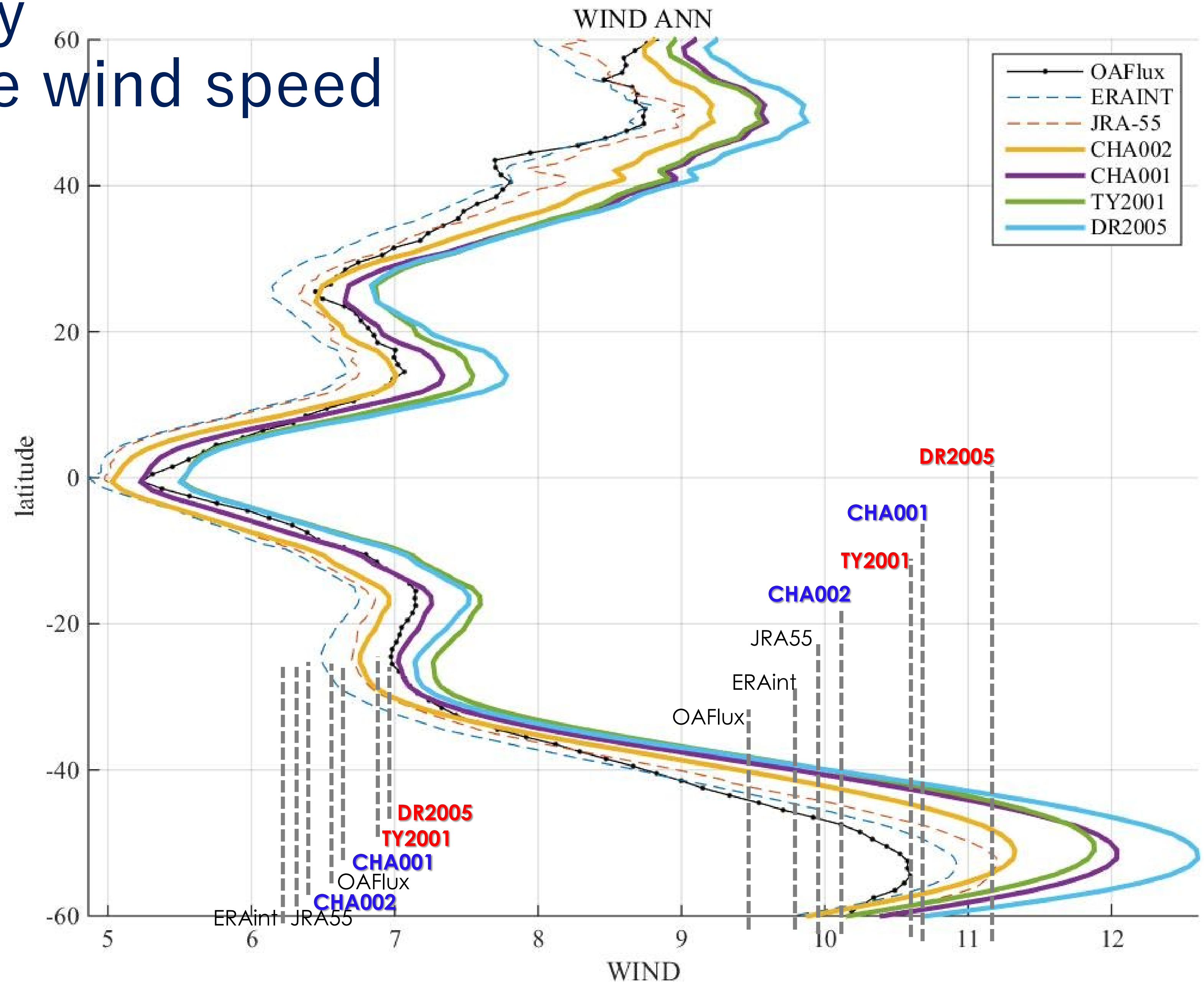
Shimura et al. (2017) JGR

Climatology: sea surface wind speed



TY2001 – CHA002

Climatology
sea surface wind speed

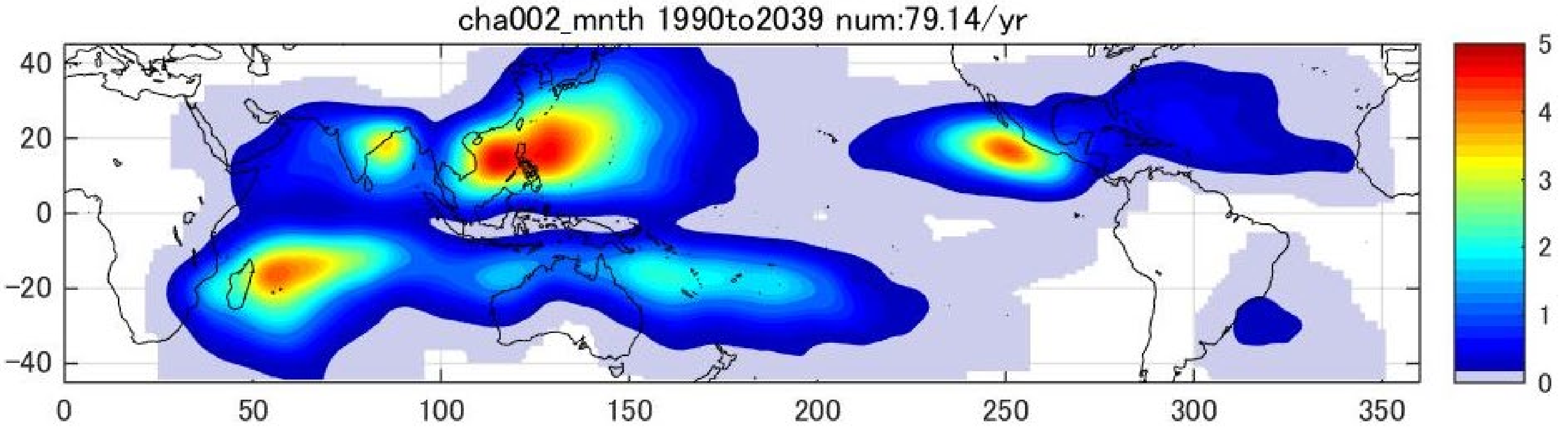


[m/s]

Shimura et al. (2017) JGR

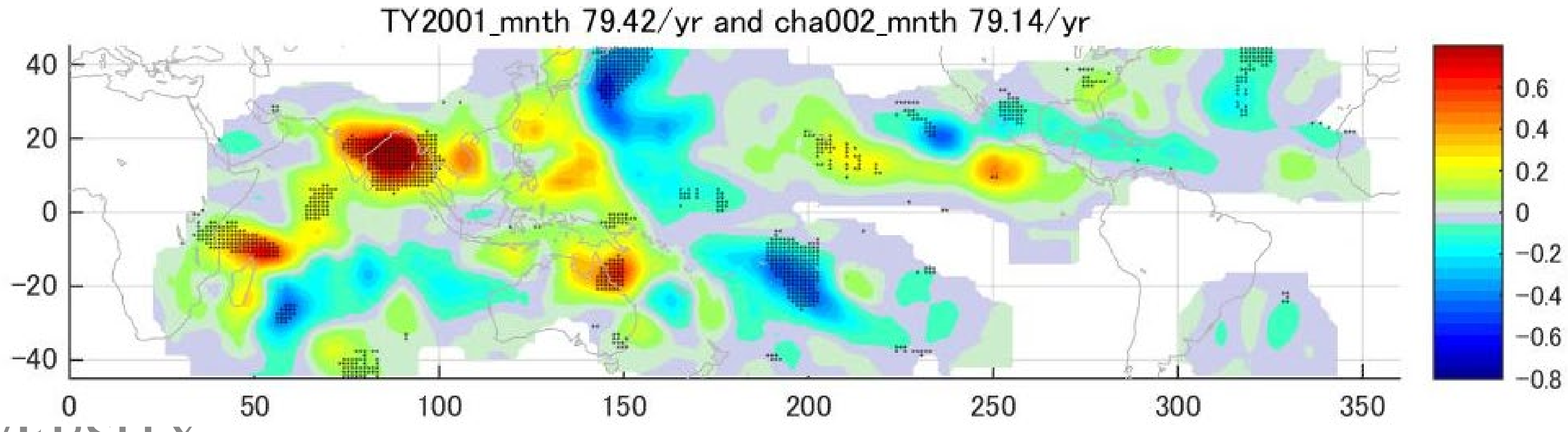
Climatology : tropical cyclone

Uncoupled: CHA002



TY2001 – CHA002

[#/yr]



On going research

Estimation of Cd in highspeed wind condition

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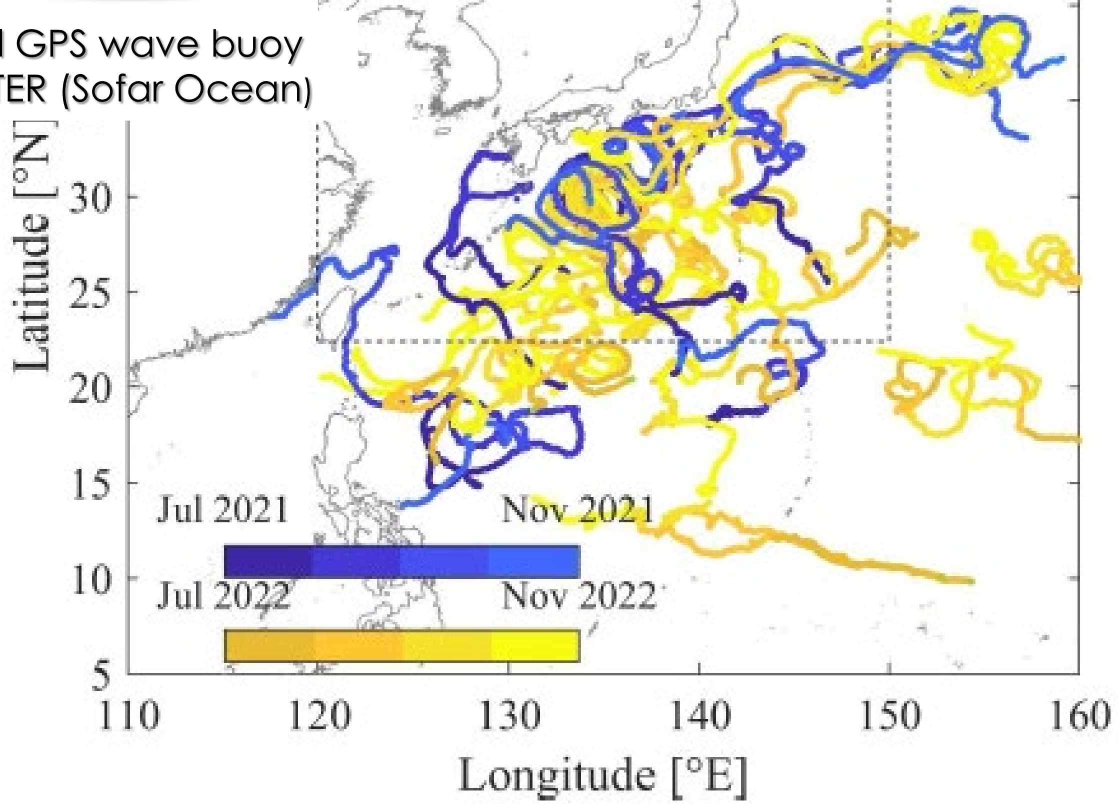
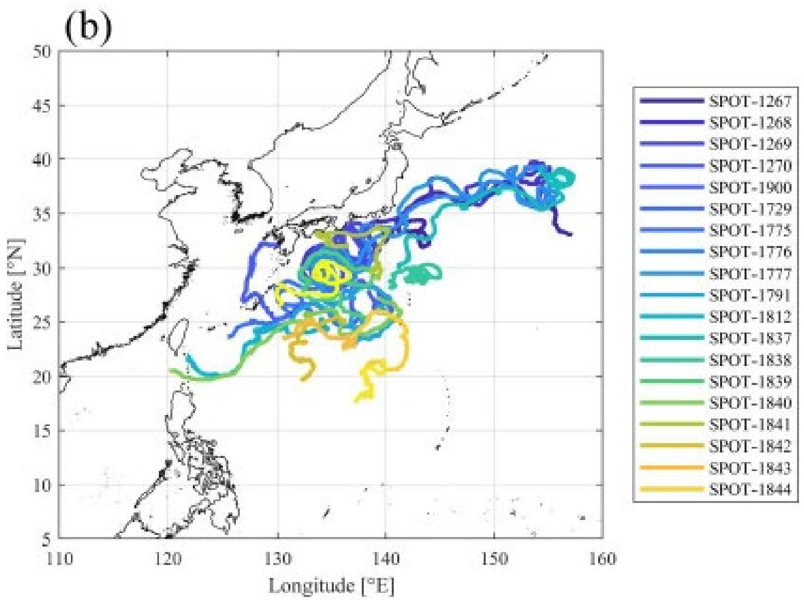
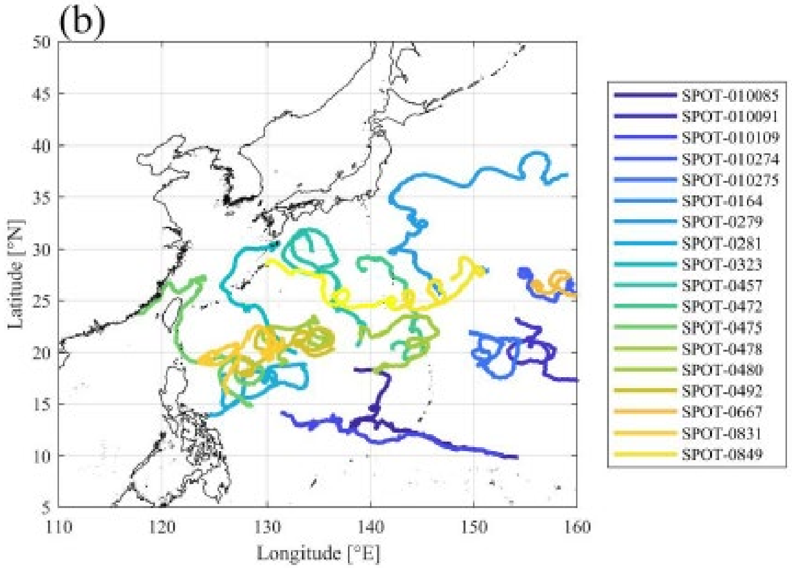
Small GPS wave buoy
SPOTTER (Sofar Ocean)



Drifting wave buoy paths
Target period: summer in 2021 and 2022



Kyoto Univ. deployed buoys



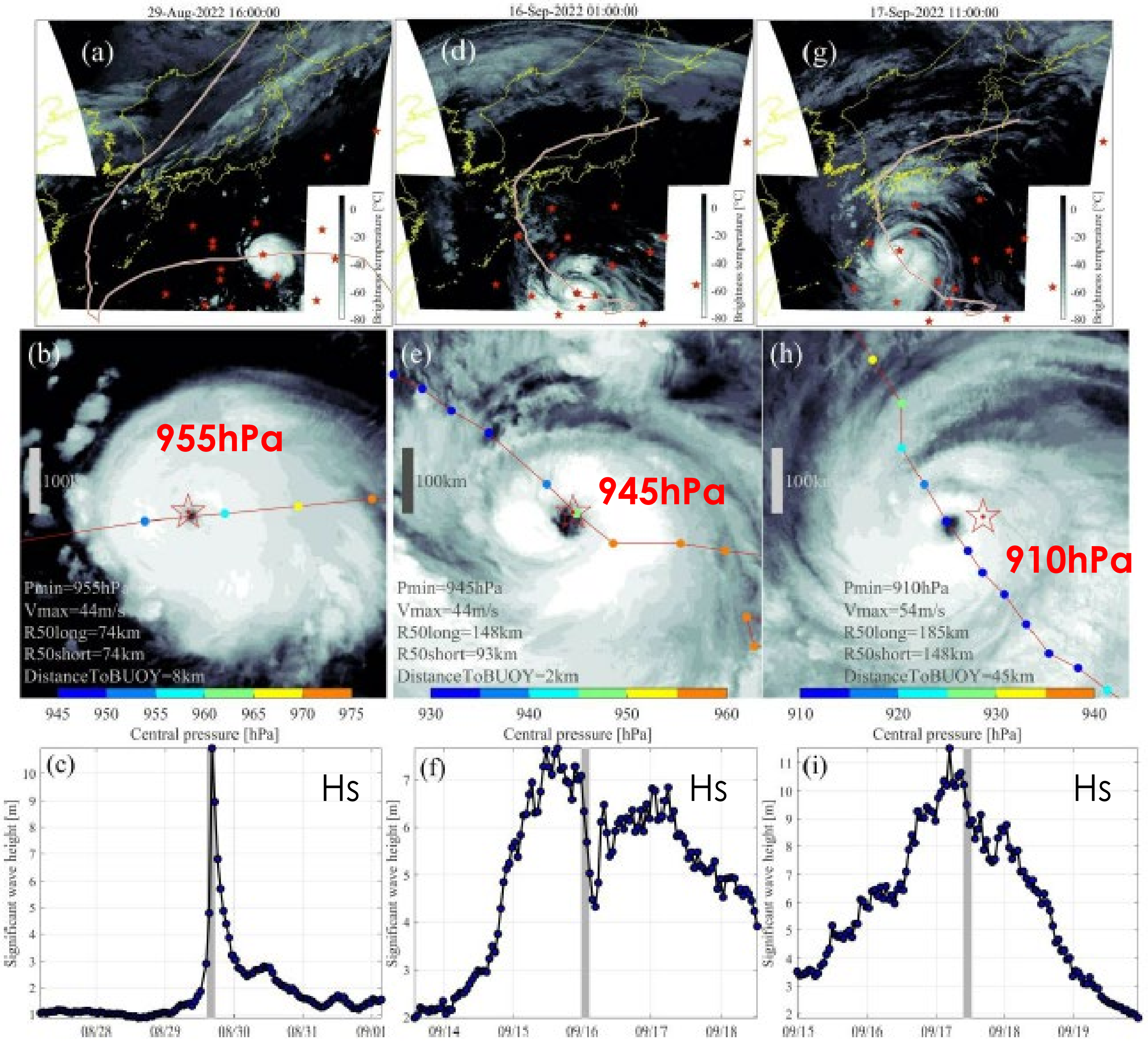
Sofar Ocean provided data

Representative observations of extreme Tropical cyclone

TC and buoys

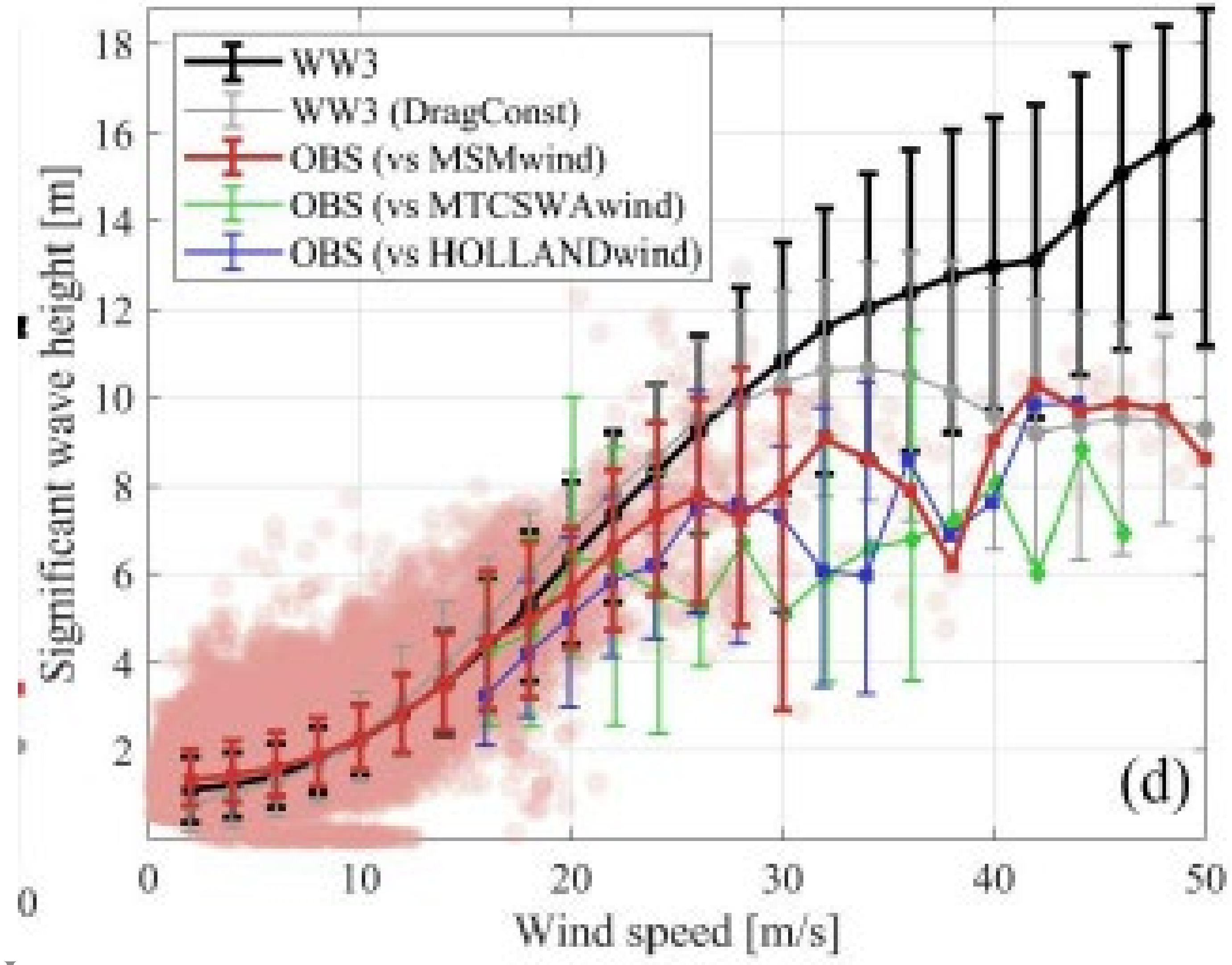
Zoom up to eyes

Hs time series

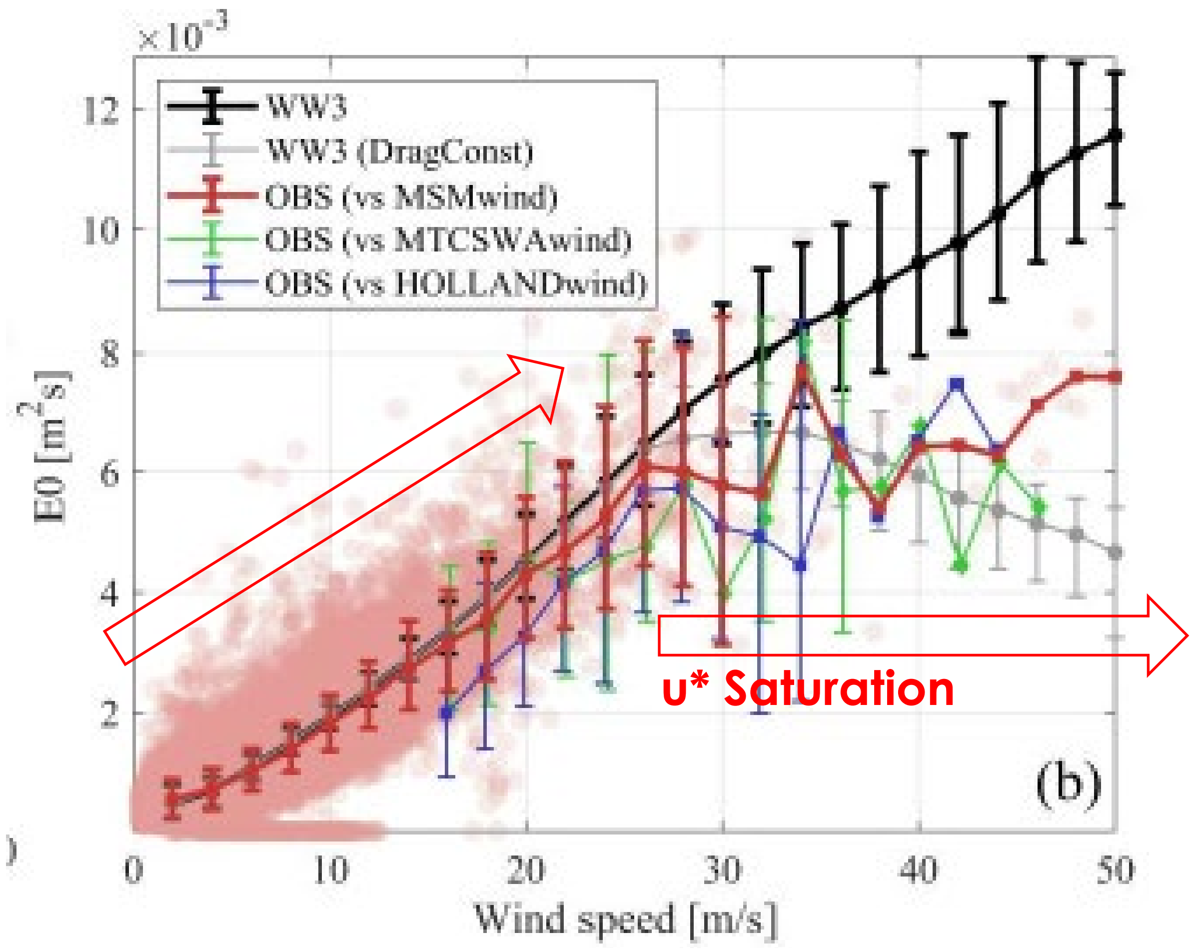


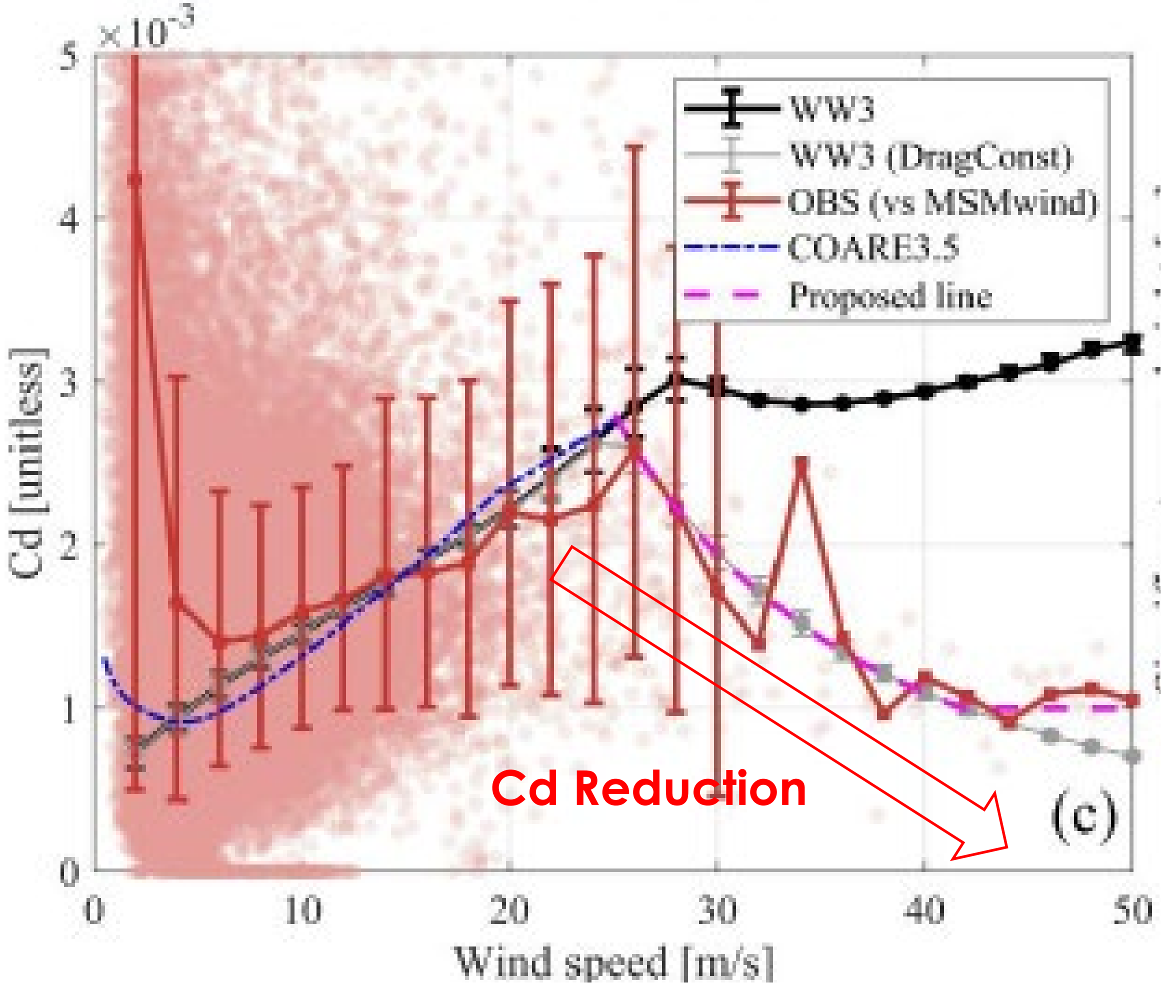
☆ Buoys

Wind speed vs Hs



Wind speed vs E0 and Cd



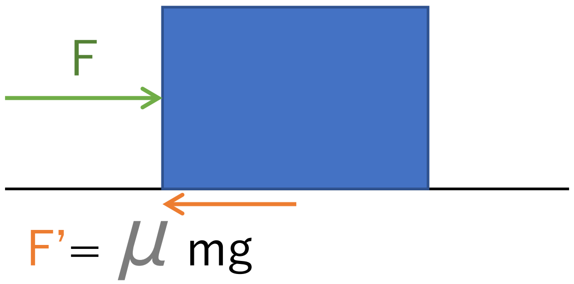


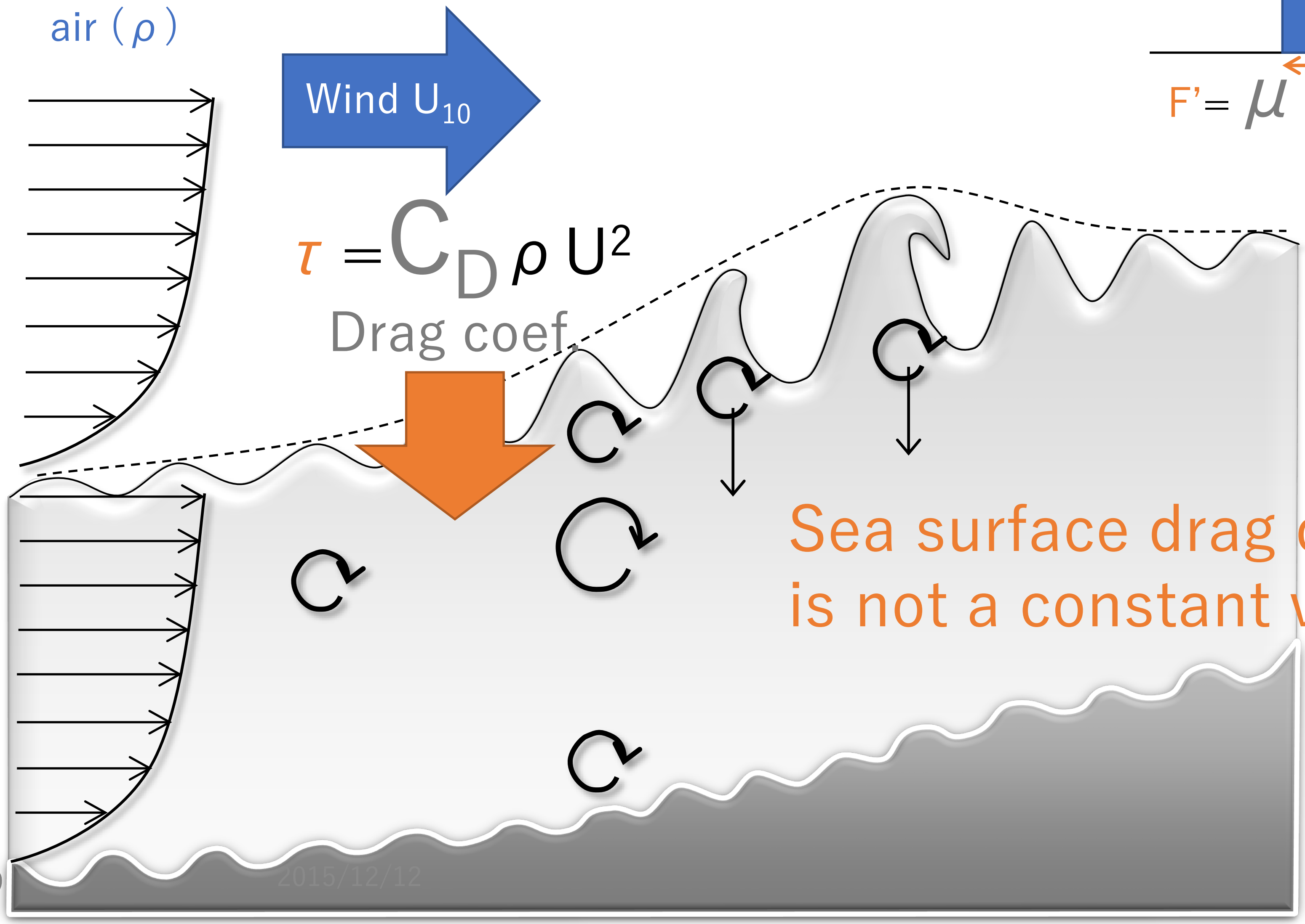
Summary

- Wave coupling effects in regional and global atmosphere-ocean modeling are
    - significant in sea surface climatology
    - marginal in short-term tropical cyclone modeling but not negligible
- Sea surface parameterizations including wave effects are old and need to update
    - Cd, Ch, z0, TKE flux and etc

Role of air-sea interaction in ocean modeling

Solid material





Sea surface drag coefficient is not a constant value

Atmosphere-Ocean boundary
atmospheric side z0

- High speed wind condition (after 2000s)
  - Powell et al. (2003)
    - decreasing Cd over 30m/s
  - Moon et al. (2003), Makin (2005), Babanin and Makin (2008)

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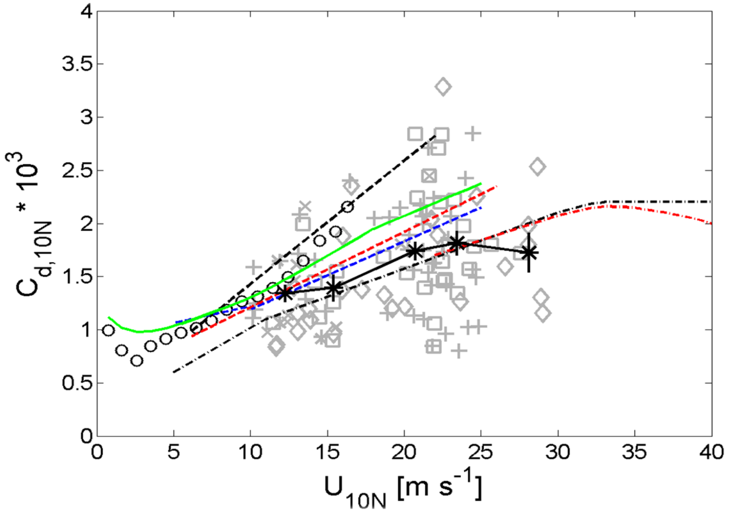

Atmosphere-Ocean boundary
atmospheric side z0

- Charnock (1955)：Friction Velocity

$$z_0 = max\left(\frac{\alpha_{CH}}{g}(u_*)^2, z0_{min}\right) \quad \alpha_{CH} = 0.018$$

Modified
by Fairall et al. (2003)

- Including wave information (after 2000s)
  - Taylor and Yelland (2001)

$$\frac{z_0}{H_s} = A\left(\frac{H_s}{L_p}\right)^B \quad A = 1200, B = 4.5$$

  - Oost et al. (2002)

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Atmosphere-Ocean boundary
ocean side TKE flux at sea surface

- TKE flux
  - Craig and Banner (1994)

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Short term wave impact on AGCM

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Summary

Wave roughness impact
on climatology