# Investigation of the Impact of Ocean Waves on Development of Explosive Cyclone with a Coupled Model

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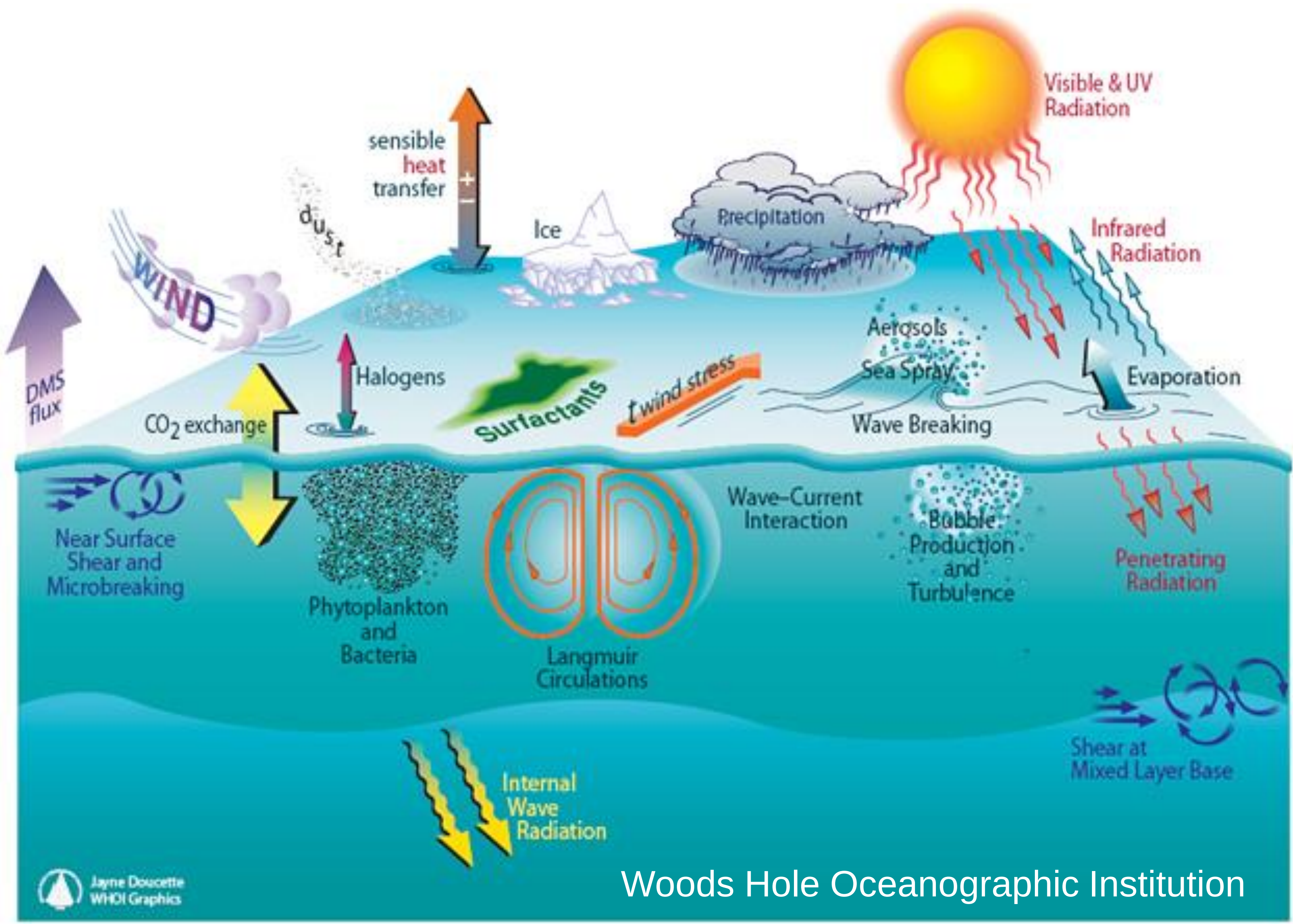
# Interactions among Atmosphere, Ocean, & Wave

## Ocean - Atmosphere
- SST feedback to heat flux
- Current feedback to momentum
- Water flux takes rainfall into account

## Atmosphere - Wave
- Surface roughness
- Sea spray affects water and heat

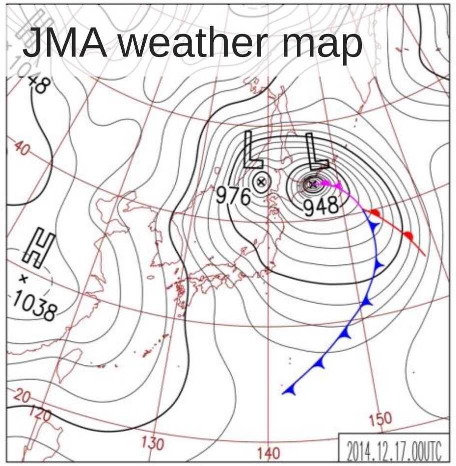
## Ocean - Wave
- Wave-induced current and turbulence (Stokes drift, Langmuir circulation)
- Enhanced mixing due to wave breaking
- Wave setup
- Wave-induced pressure



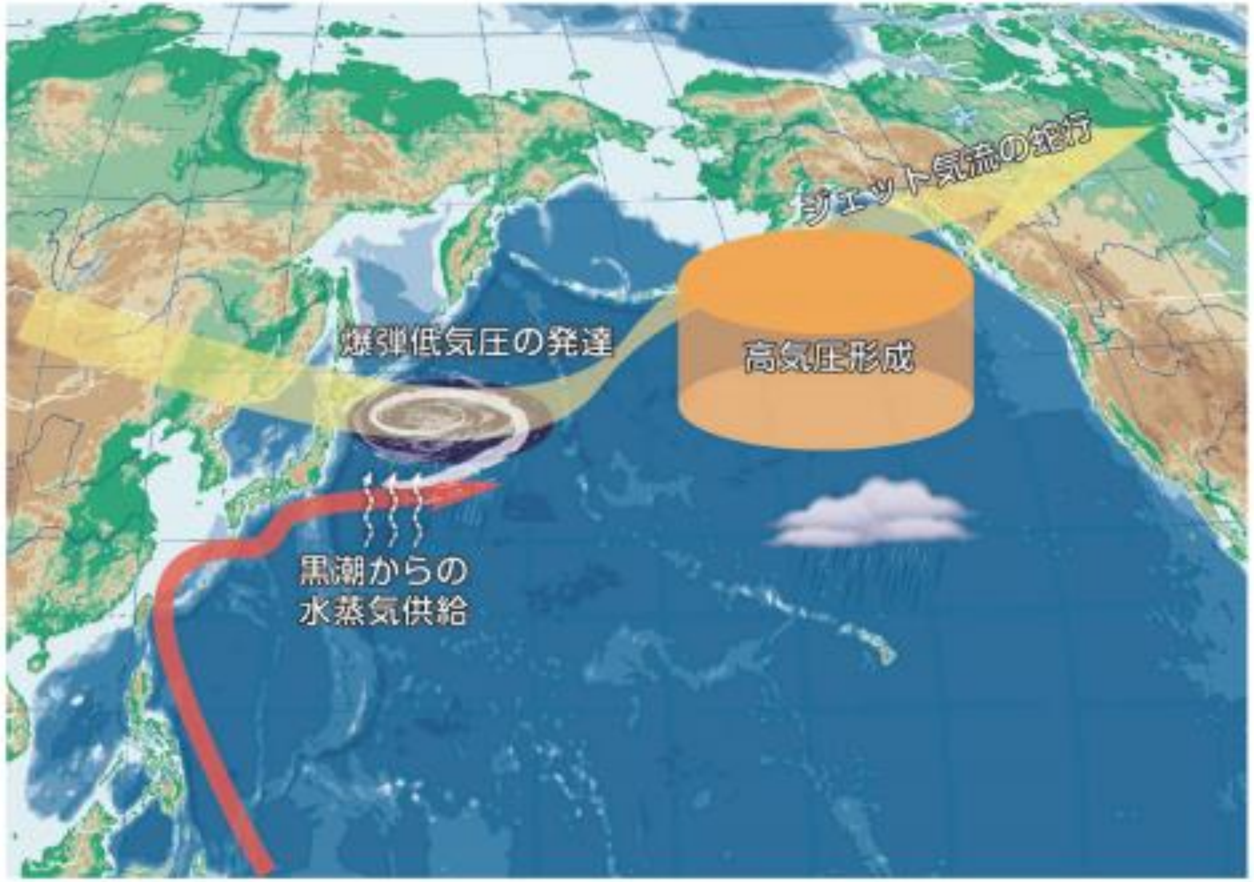
# Explosive Cyclone (EC)

- An **explosive cyclone** is generated in the area of high baroclinicity in winter and spring. Its definition is that its central SLP drops over 24hPa within a day. The explosive cyclone is hard to predict accurately and causes sever disasters in broad areas.
- Marine disasters caused by ECs
  - Coastal facility damages (Toyama, 2008)
  - Downfall and stranding of vessels (Ibaraki, 2006)
- Main factors of the development
  - Large anomaly of potential vorticity in upper layer
  - Inflow of latent heat and vapor from ocean
  - Latent heat release from cloud and rain generation


December, 2014 (Asahi Shimbun)



JMA weather map



Influence of Kuroshio on explosive cyclone (Nonaka et al., 2016)

# Research Overview

## ■ Motivation

- The Atmospheric and ocean model cannot resolve ocean wave effect explicitly.
- The effects of ocean wave on an meso-scale phenomenon in atmosphere and ocean are remain to be clarified for the sake of accurate weather forecast.

## ■ Objective

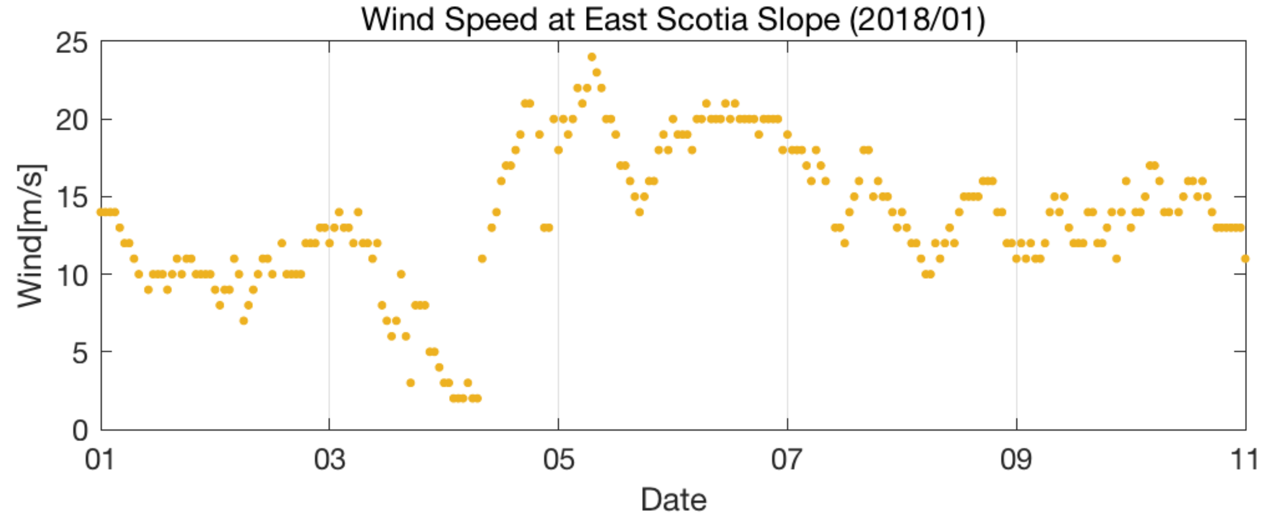
**To clarify ocean wave effects on the boundary layer turbulence in both atmosphere and ocean and on the development of a winter explosive cyclone.**

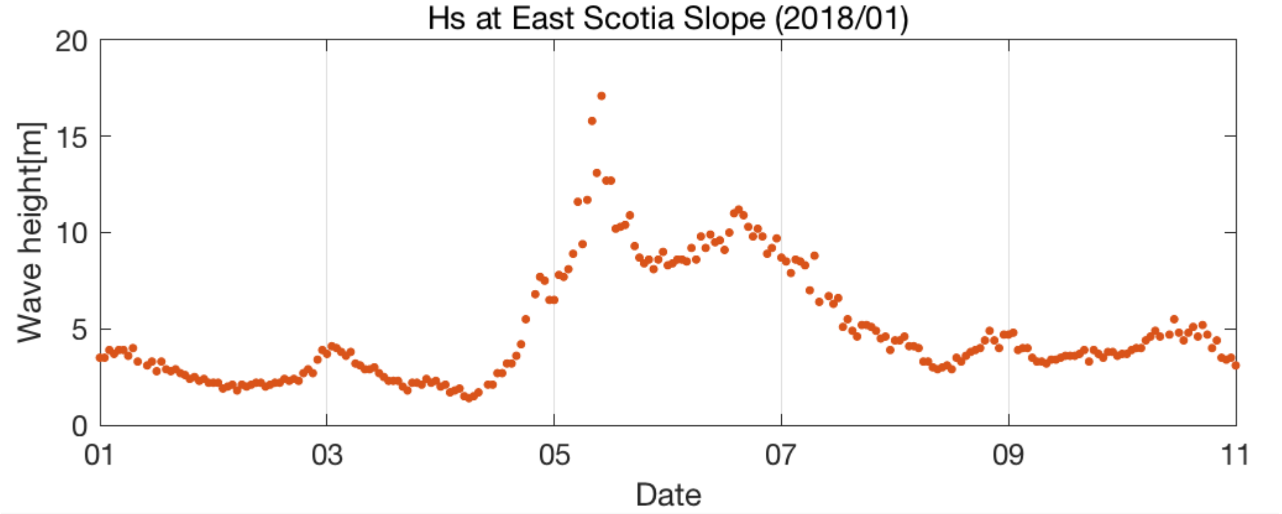
## ■ Methodology

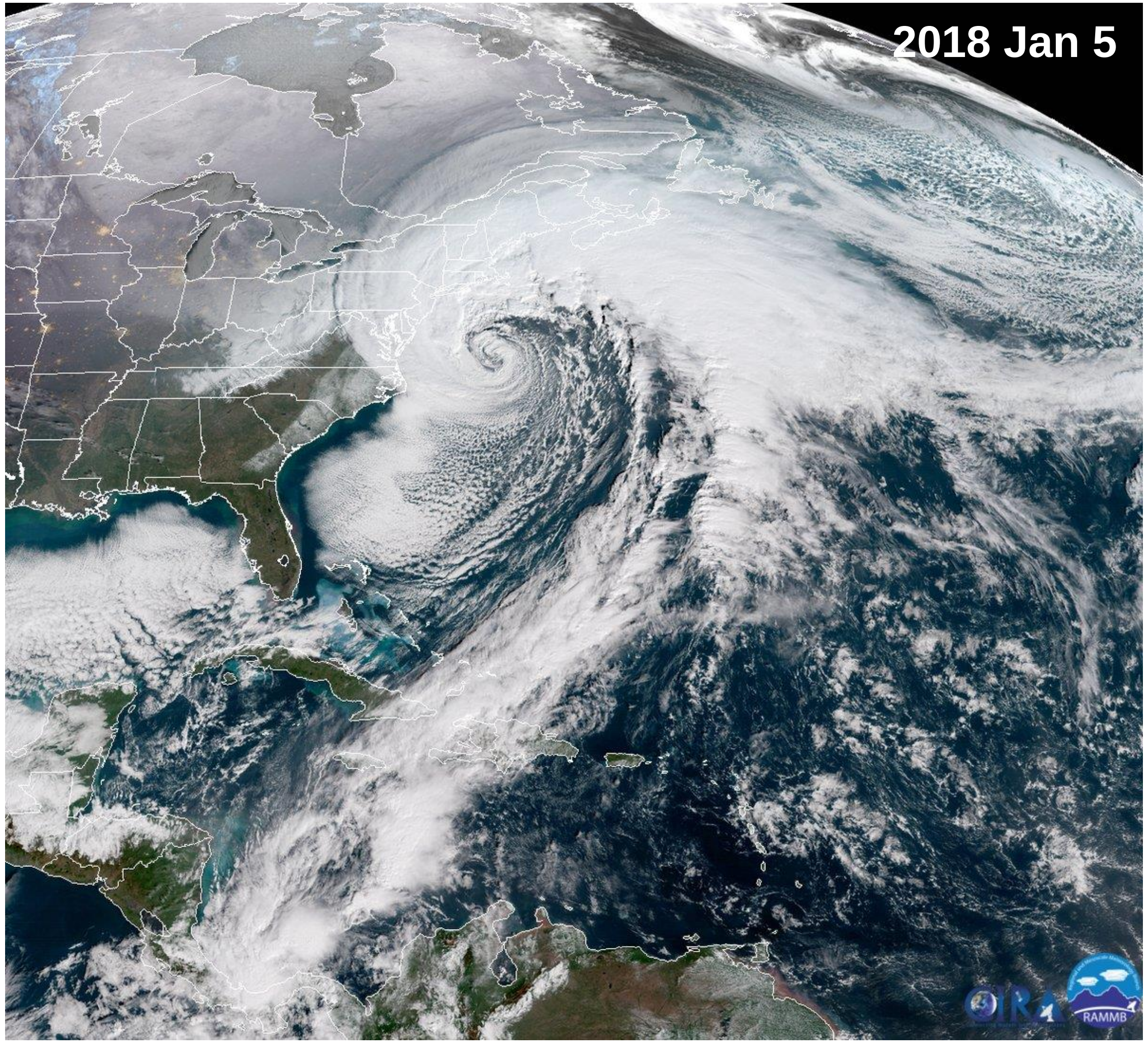
- **An atmosphere-ocean-wave coupled model** simulates an explosive cyclone considering ocean wave effects.

# Explosive Cyclone in Northwestern Atlantic in 2018 Jan

- In 2018 January, an explosive cyclone emerged in Northwestern Atlantic and developed as much as **949hPa** in its central SLP. It caused enormous blizzard and damages of $11 billion.



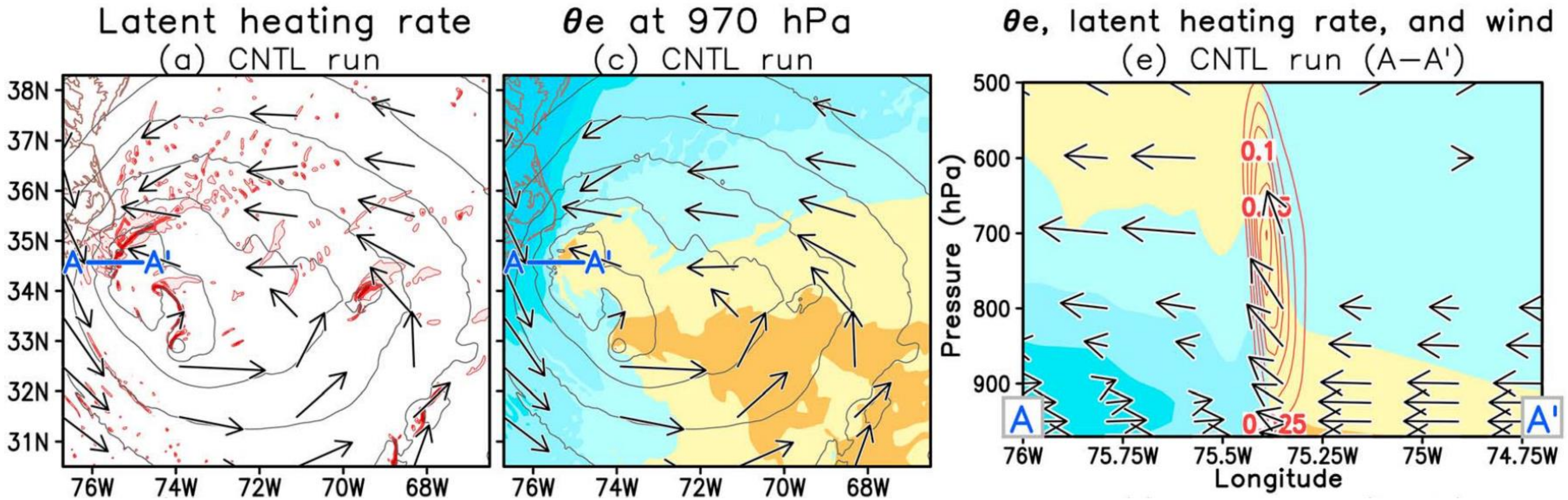




NOAA GOES-16 satellite

# Mechanism of Explosive Development

- The explosive cyclone was intensified by the latent and sensible heat flux supplied from Gulf Stream.
- The heat flux flowing into **cold conveyor belt (CCB)** enhances the bent-back front, resulting in enhancement of the convective instability.




Latent heating rate owing to condensation
(cited from Fig.4 in Hirata et al., 2019)

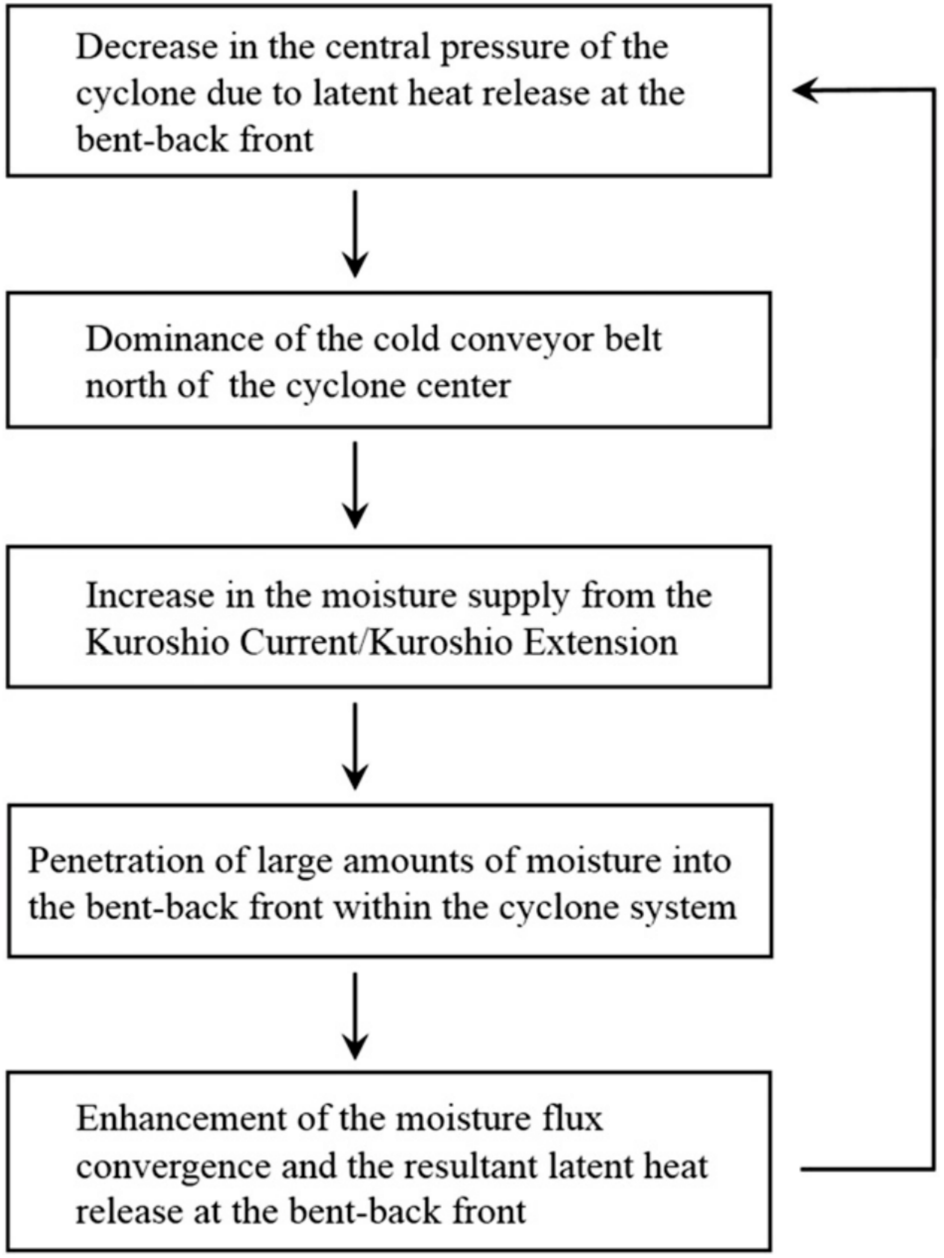
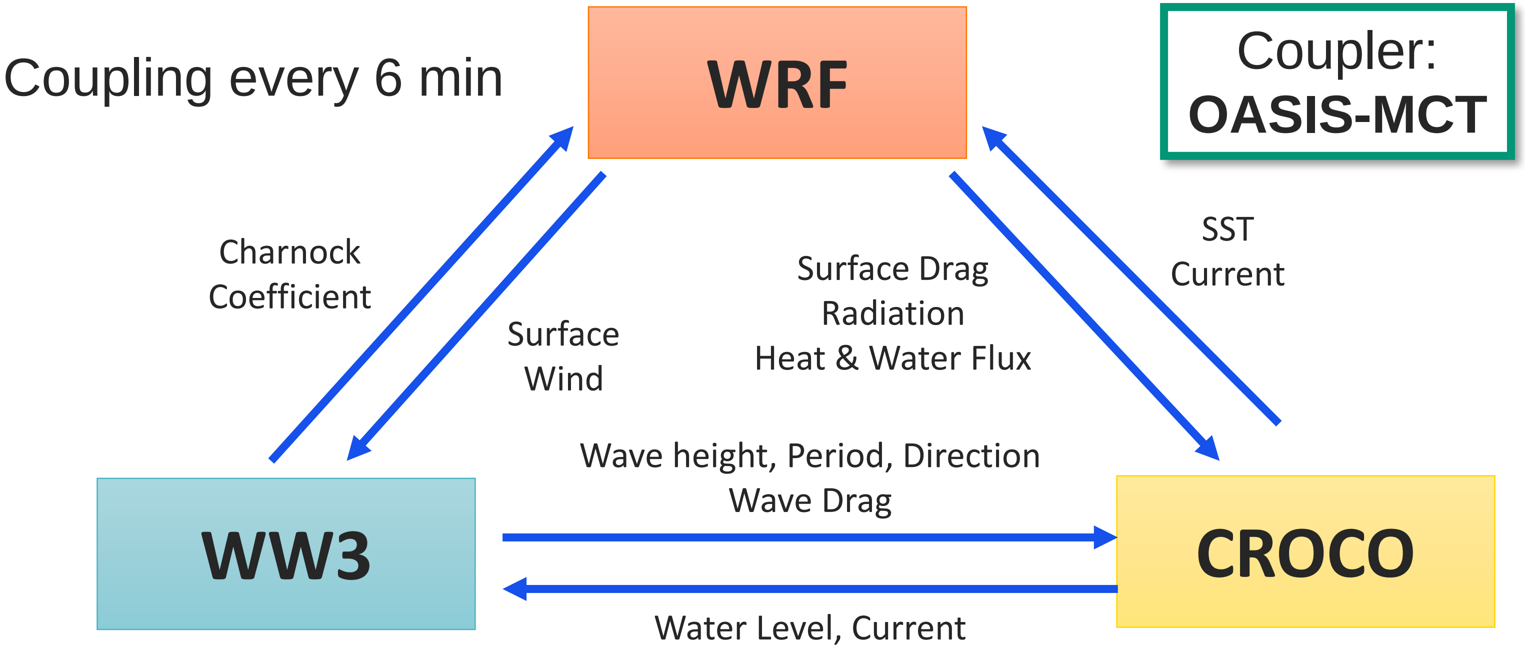


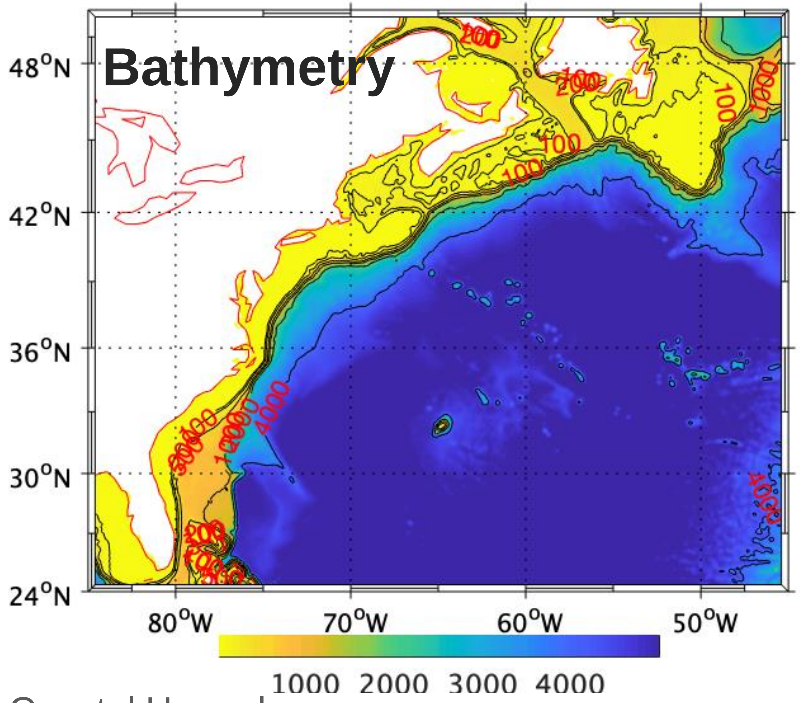

FIG. 18. Schematic diagram representing a positive feedback process in relation to the rapid intensification of an explosive cyclone over the Kuroshio/Kuroshio Extension.

(cited from Fig.18 in Hirata et al., 2015)

# Configuration of the Coupled Model

| | WRF | WAVEWATCH III | CROCO |
|---|---|---|---|
| Domain | $lon: 30°\sim 50°, \quad lat: -88°\sim -50°$ | | |
| Period | 2018/01/01 ~ 2018/01/10 | | |
| Resolution | 0.08° | 0.08° | 1/18° |
| Time Step | 30s | 360s (global) | 9s(2D), 360s(3D) |
| Grid | $lon\ 501 \times lat\ 326, 60\ layer$ | $lon\ 536 \times lat\ 349$ | $lon\ 729 \times lat\ 597, 45 layer$ |
| Others | Initial/boundary: CFSR<br>Boundary layer: MYNN scheme | Initial/boundary: Atlantic Model<br>wind, ice forcing: CFSR | Initial/boundary: HYCOM<br>No tide, σ coordinate |



# Configuration of Surface Physics

- Surface Stress: $\tau_{tot} = \rho_a u_*^2 = \rho_a C_d U^2$
- Surface Sensible Heat Flux: $H_S = -\rho_a c_p u_* \theta_* = -\rho_a c_p C_h U(\theta_a - \theta_s)$
- Surface Latent Heat Flux: $H_L = L_e \rho_a u_* q_* = L_e \rho_a M C_q U(q_s - q_a)$
- Charnock Parameter: $\alpha = 0.01(1 - \tau_w/\tau_{tot})^{-1/2}$ (Janssen 1991)
- Surface Roughness: $z_0 = z_{0\nu} + z_w = \frac{0.11\nu}{u_*} + \alpha \frac{u_*^2}{g} = \frac{0.11\nu}{u_*} + \frac{0.01}{\sqrt{1-\tau_w/\tau_{tot}}} \frac{u_*^2}{g}$

  ($z_{0,max} = 2.85mm$; Davis et al. 2008)

- Wave-induced Stress: $\tau_w = \rho_w \int_0^\infty \int_{-\pi}^{\pi} f^2 S_{in} \frac{\vec{k}}{k} d\theta df$
- Friction Velocity: $u_{*a} = kU[\ln(z/z_0) - \psi_m(z/L)]$, $u_{*w} = u_{*a}(1 + \gamma w_{age}[1 - \cos\phi])$

  $\phi$: angle between wind – wave, $\gamma = 0.007$, $w_{age} = C_p/u_{*a}$

  (Patton et al., 2019)

Surface roughness reflects wave development
Friction velocity reflects misalignment of wave-wind direction

# Governing Equations of CROCO (new ROMS-AGRIF)

- Make use of the wave-current Interactions configuration in **Uchiyama et al. (2010)**.
- Stokes Drift: $(u^{st}, v^{st}, w^{st})$, Vortex force: $(V_x, V_y, V_z)$, Bernoulli head: $\phi_B$, Unpreserved force: $F$
  Reynolds-averaged governing equations are:

Momentum:

$$\frac{\partial u}{\partial t} + u_j \frac{\partial u}{\partial x_j} - fv = -\frac{\partial(\phi + \phi_B)}{\partial x} - \frac{\partial}{\partial x_j}\left(\overline{u_j' u} - \nu \frac{\partial u}{\partial x_j}\right) + V_x + F_x + F_x^w$$

$$\frac{\partial v}{\partial t} + u_j \frac{\partial v}{\partial x_j} + fu = -\frac{\partial(\phi + \phi_B)}{\partial y} - \frac{\partial}{\partial x_j}\left(\overline{u_j' v} - \nu \frac{\partial v}{\partial x_j}\right) + V_y + F_y + F_y^w$$

Scalor:

$$\frac{\partial c}{\partial t} + u_j \frac{\partial c}{\partial x_j} = -u_j^{st} \frac{\partial c}{\partial x_j} - \frac{\partial}{\partial x_j}\left(\overline{u_j' c} - \nu_c \frac{\partial c}{\partial x_j}\right) + F_c \qquad (T, S)$$

Pressure:

$$\frac{\partial \phi}{\partial z} + \frac{g\rho}{\rho_0} = -\frac{\partial \phi_B}{\partial z} + V_z$$

Continuity:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

$$(V_x, V_y) = -\hat{\mathbf{z}} \times \mathbf{u}^{\mathbf{st}}[(\hat{\mathbf{z}} \cdot \nabla_\perp \times \mathbf{u}) + f] - w^{st} \frac{\partial \mathbf{u}}{\partial z},$$

$$V_z = \mathbf{u}^{\mathbf{st}} \cdot \frac{\partial \mathbf{u}}{\partial z}$$

$$\phi_B = \frac{1}{4} \frac{\sigma A^2}{k \sinh^2[kD]} \int_{-h}^{z} \frac{\partial (\mathbf{k} \cdot \mathbf{u})^2}{\partial \zeta^2} \sinh[2k(z - \zeta)] d\zeta$$

$\mathbf{F^w}$ = breaking + roller acceleration + bottom drag

$h$: batymetry, $D = h + \eta$, $k$: wave number

$A$: wave amplitude, $\sigma$: wave freqency

# Turbulence Parameterization: *k-kl* model (MY25)

- In the CROCO model, several **GSL** (generic length scale) approaches are provided (Umlauf and Burchard, 2003): e.g., $k-kl, k-\varepsilon, k-\omega$ model. They are two-equation models which diagnose two turbulence values explicitly.
- Here, Mellor–Yamada level 2.5 (**MY25, $\boldsymbol{k-kl}$**) scheme is selected, which is originally proposed in Mellor and Yamada (1974).
- For turbulent kinetic energy: $\boldsymbol{E}=\frac{1}{2}\left(\overline{u'^2}+\overline{v'^2}+\overline{w'^2}\right)$ and turbulent length scale: $\boldsymbol{l}$,

$$\frac{\partial E}{\partial t}+u_j\frac{\partial E}{\partial x_j}=\frac{\partial}{\partial z}\left(K_Q\frac{\partial E}{\partial z}\right)+P+B-\varepsilon$$

$$\frac{\partial (El)}{\partial t}+u_j\frac{\partial (El)}{\partial x_j}=\frac{\partial}{\partial z}\left[K_Q\frac{\partial (El)}{\partial z}\right]+l(c_1P+c_3B-c_2\varepsilon F_{wall})$$

$$\text{shear production: } P=-\overline{u'w'}\frac{\partial u}{\partial z}-\overline{v'w'}\frac{\partial v}{\partial z}, \text{buoyancy production: } B=-\frac{g}{\rho_0}\overline{\rho'w'}, \text{dissipation: } \varepsilon$$

$$K_Q=\sqrt{2k}lS_q;\ S_q=0.2;\ c_1=0.9, c_3=0.9, c_2=0.5$$

- Parameter used here is proposed by Umlauf et al. (2003) and Canuto et al. (2001).

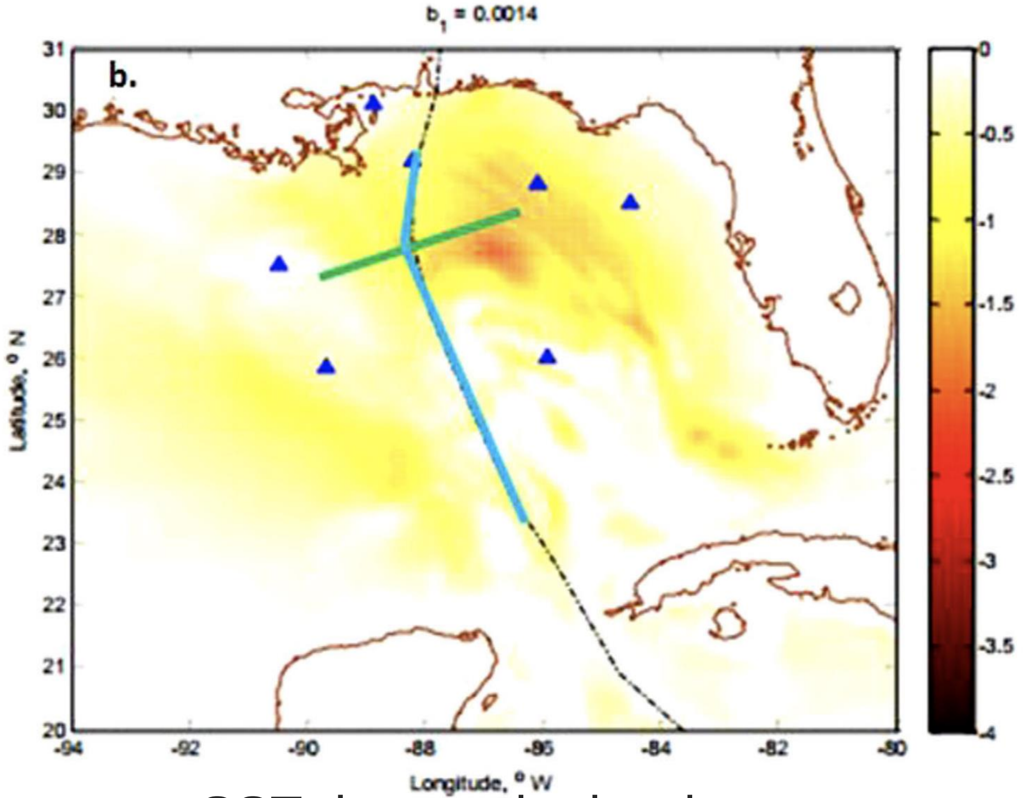
# Wave-induced Mixing Parameter in MY25 scheme

- Babanin (2011) suggested non-breaking wave-induced mixing formula, like:

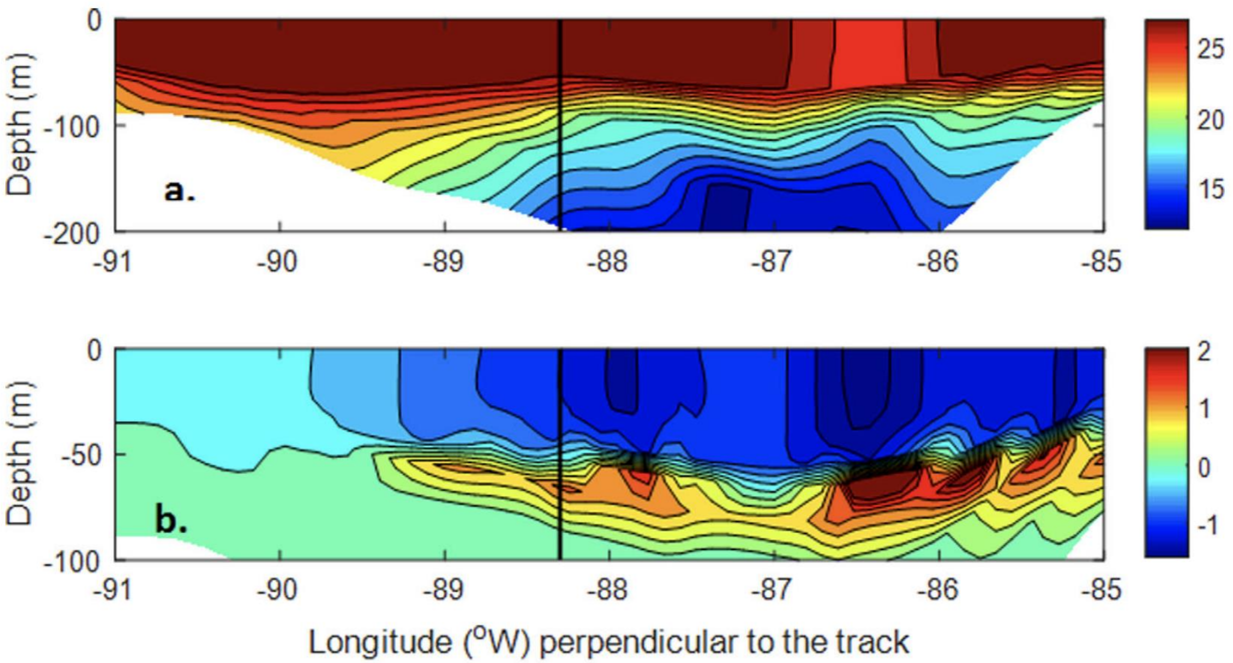
$$\text{shear production}: P \rightarrow P + P_w = -\overline{u'w'}\frac{\partial u}{\partial z} - \overline{v'w'}\frac{\partial v}{\partial z} + bk\left(\frac{\omega H_s}{2}e^{kz}\right)^3$$

$$b = 0.0014, \omega: \text{angular frequency}, H_s: \text{significant wave height}, k: \text{wave number}$$

- Aijaz et al. (2017) examined this $P_w$ impacts under a tropical cyclone condition.



SST drop under hurricane
(cited from Fig.6 in Aijaz et al., 2017)



Cross-section of temperature under hurricane
(cited from Fig.8 in Aijaz et al., 2017)

# Experiment Conditions

1. Examine Atmosphere-Wave Interactions

| | | |
|---|---|---|
| **A**<br>WRF | ⟺ | **AW**<br>WRF-WW3 |

2. Examine Ocean-Wave Interactions

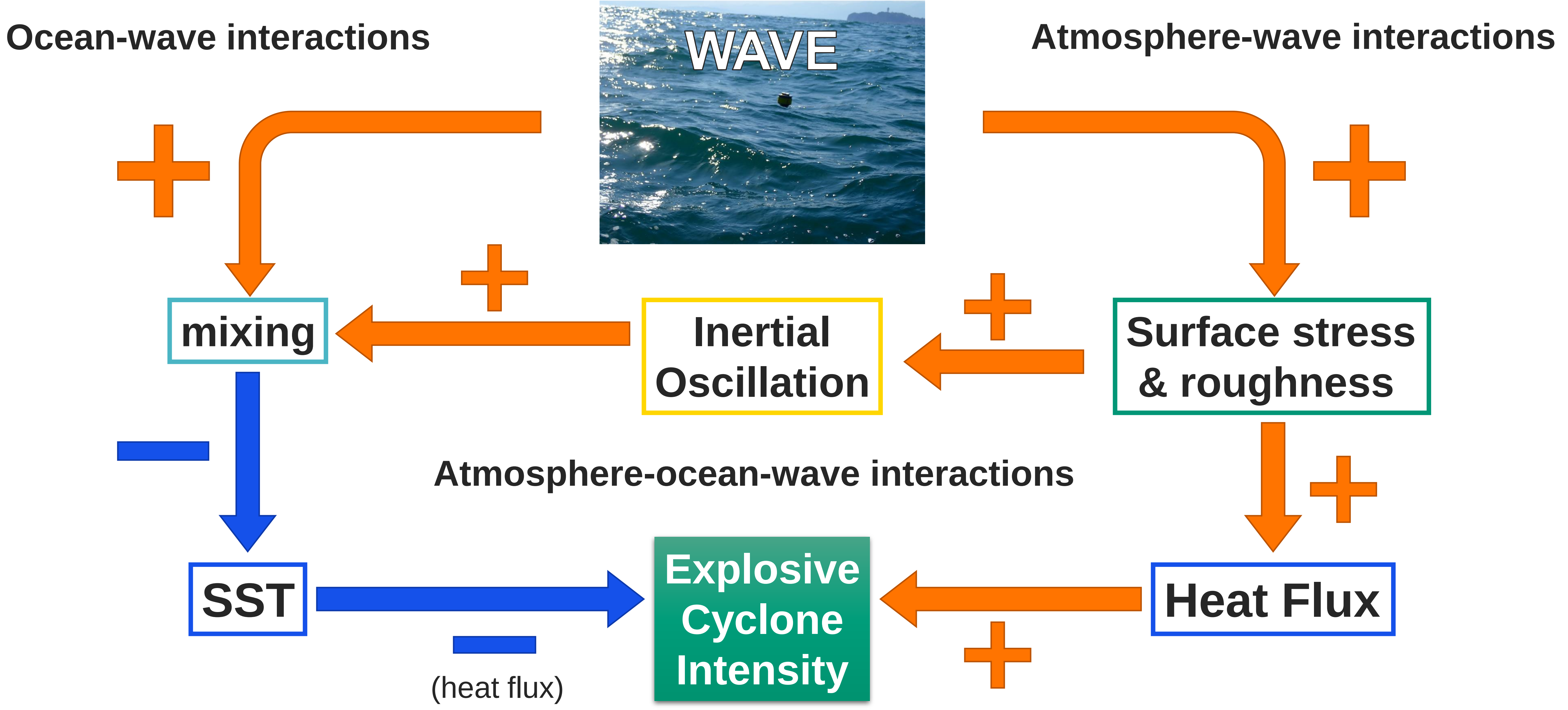
| | | |
|---|---|---|
| **AO**<br>WRF-CROCO | ⟺ | **AWO.naw**<br>WRF-CROCO-WW3 |

without wave-atmosphere coupling

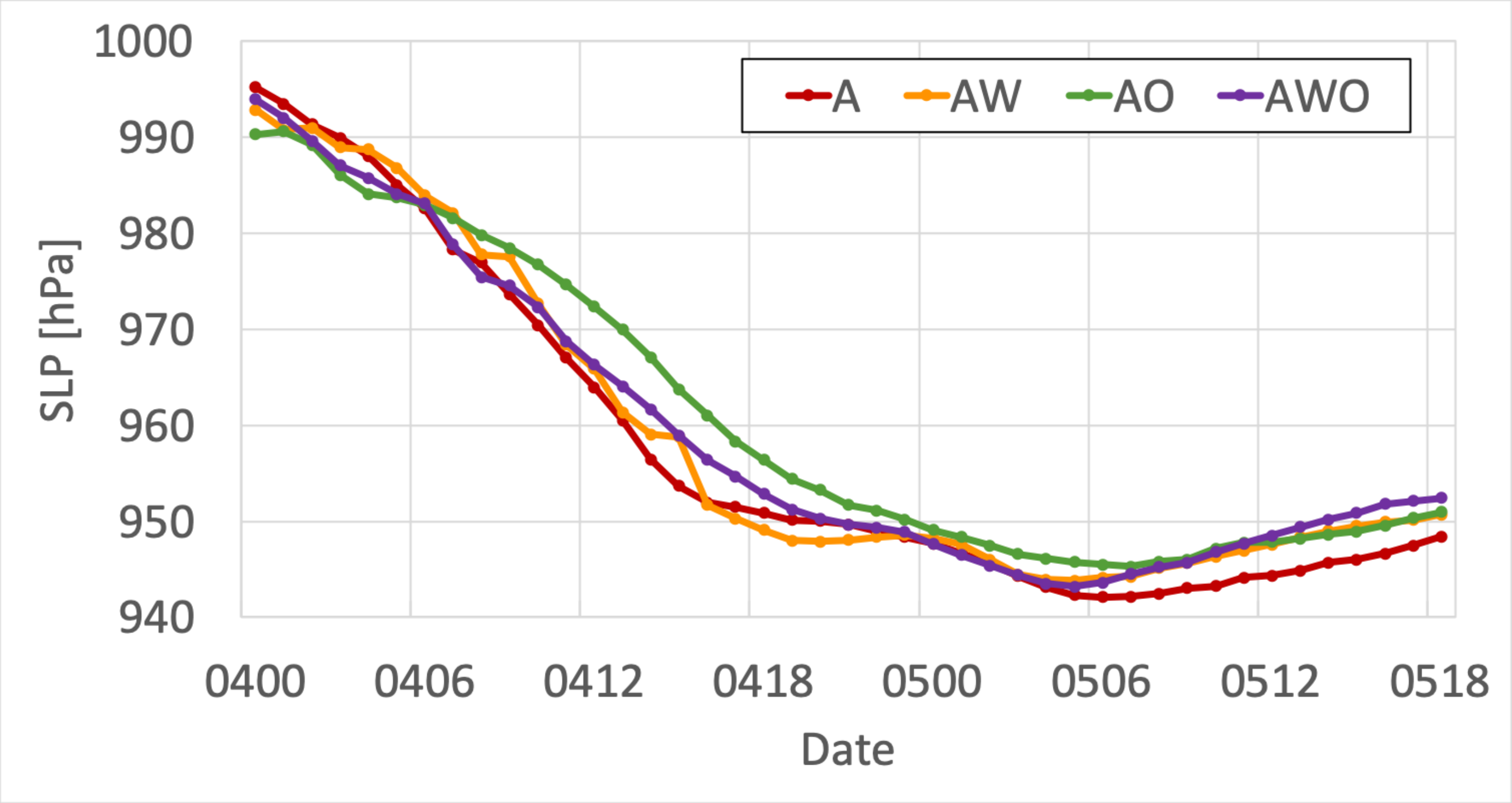
3. Examine Atmosphere-Ocean-Wave Interactions

| | | |
|---|---|---|
| **AO**<br>WRF-CROCO | ⟺ | **AWO**<br>WRF-CROCO-WW3 |

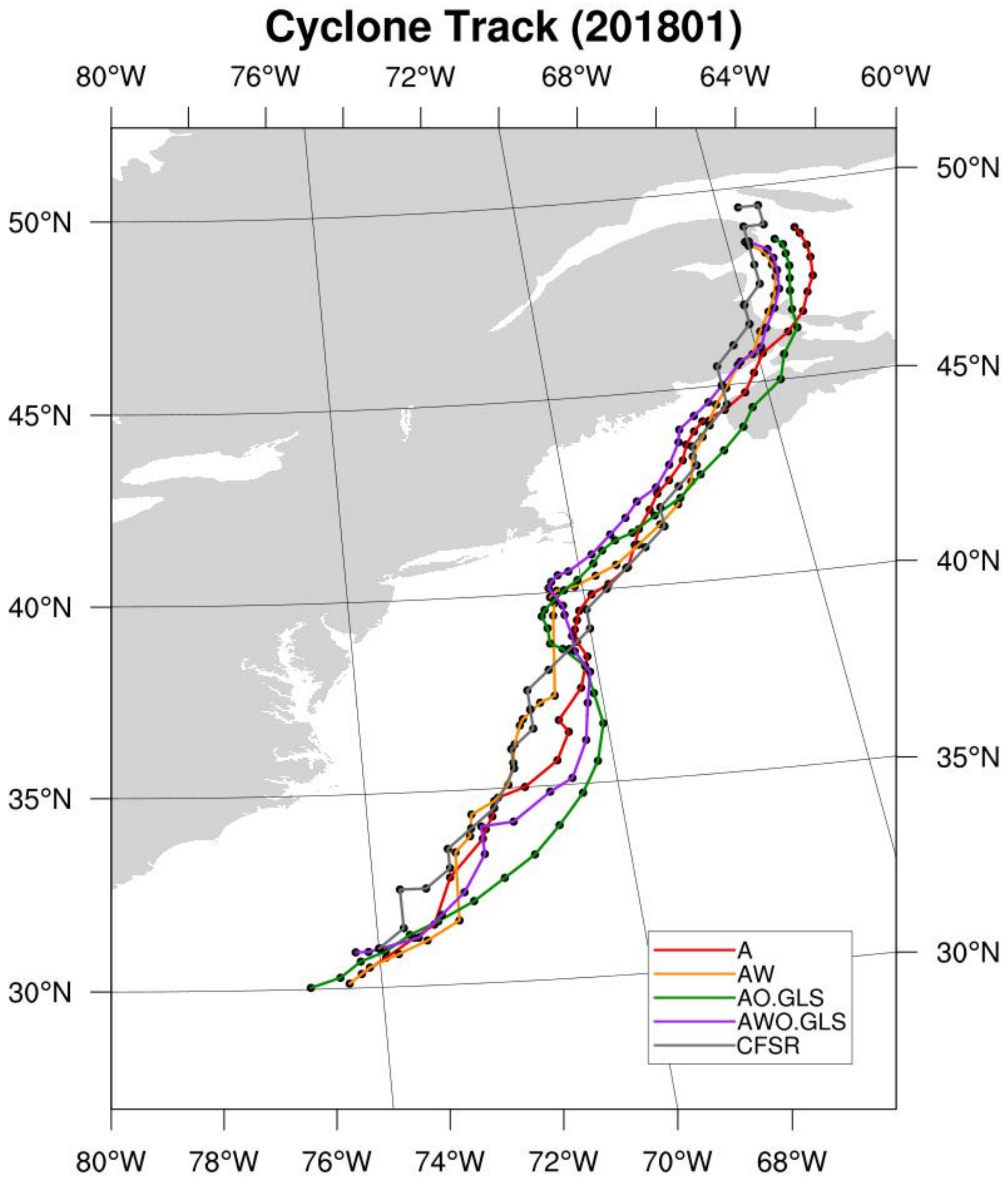
# Overview of Wave Coupling Effects



# Cyclone Track & Central SLP



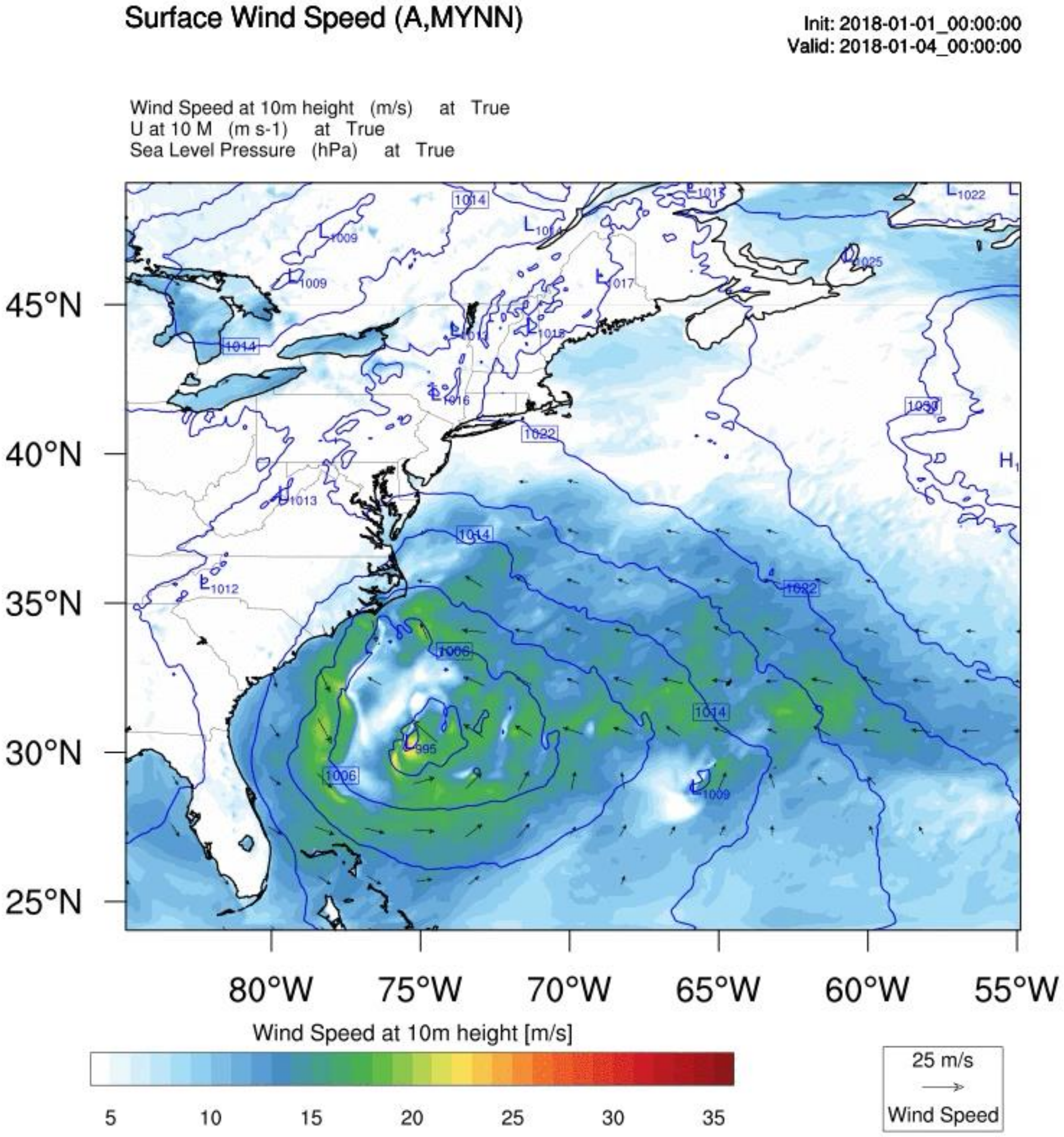

Time-series of the central sea level pressure (SLP)



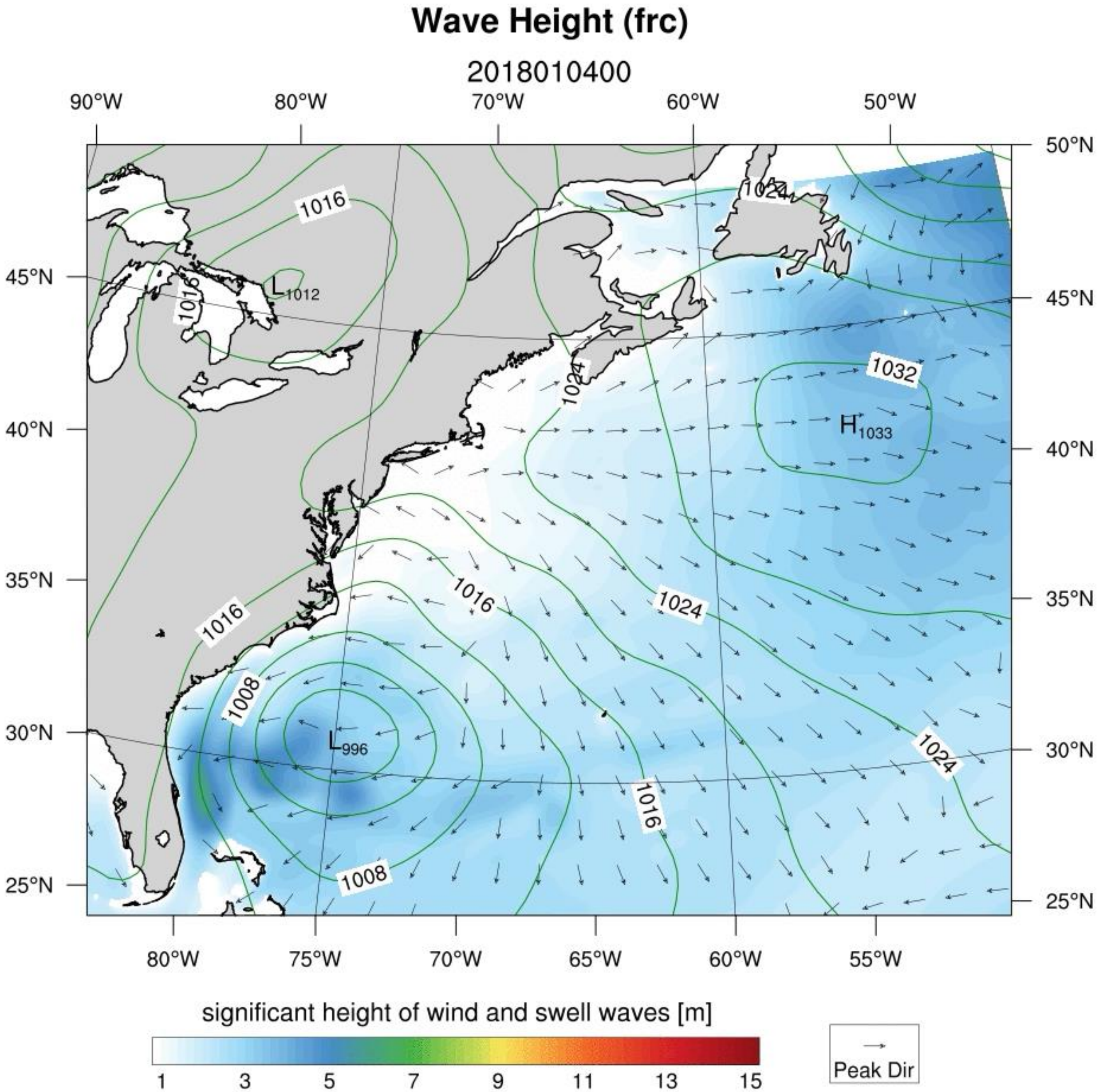

Tracks of the cyclone centers

# Overview of the Simulation Results

## Surface Wind (10m height)

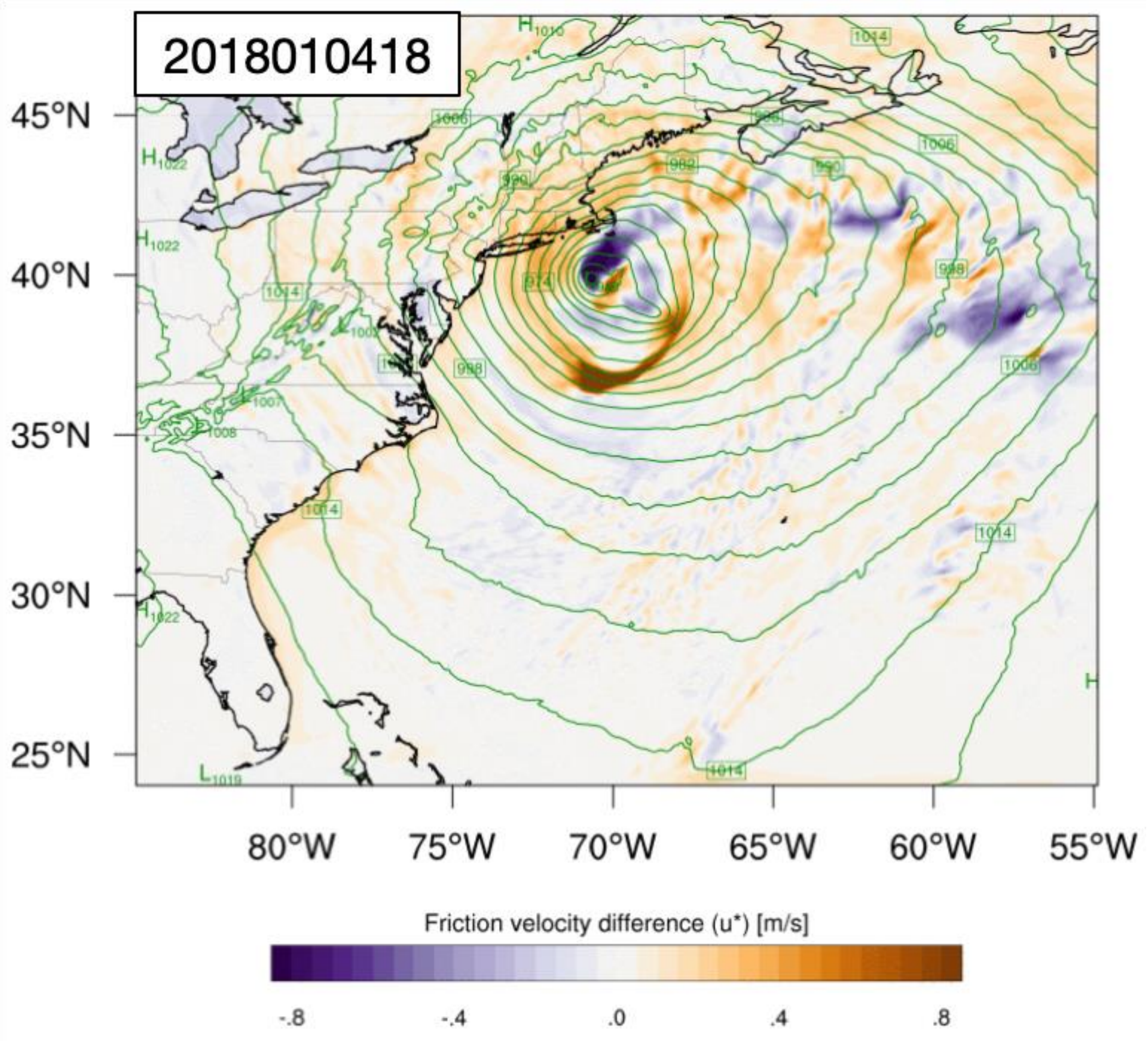



## Significant Wave Height

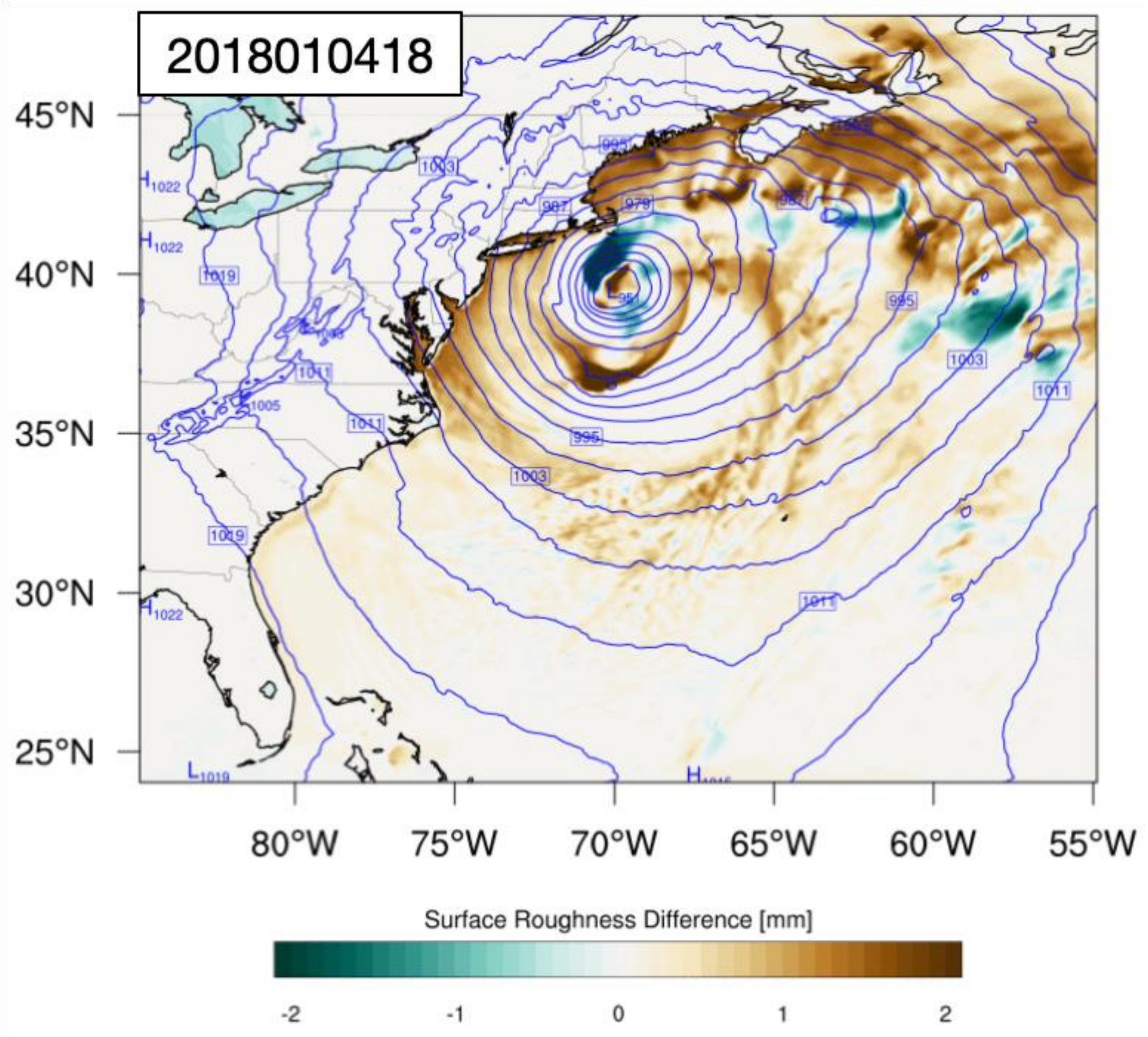


# Atmosphere-Wave Coupling Effects $(\mathbf{AW}-\mathbf{A})$

## Friction Velocity $u_*$



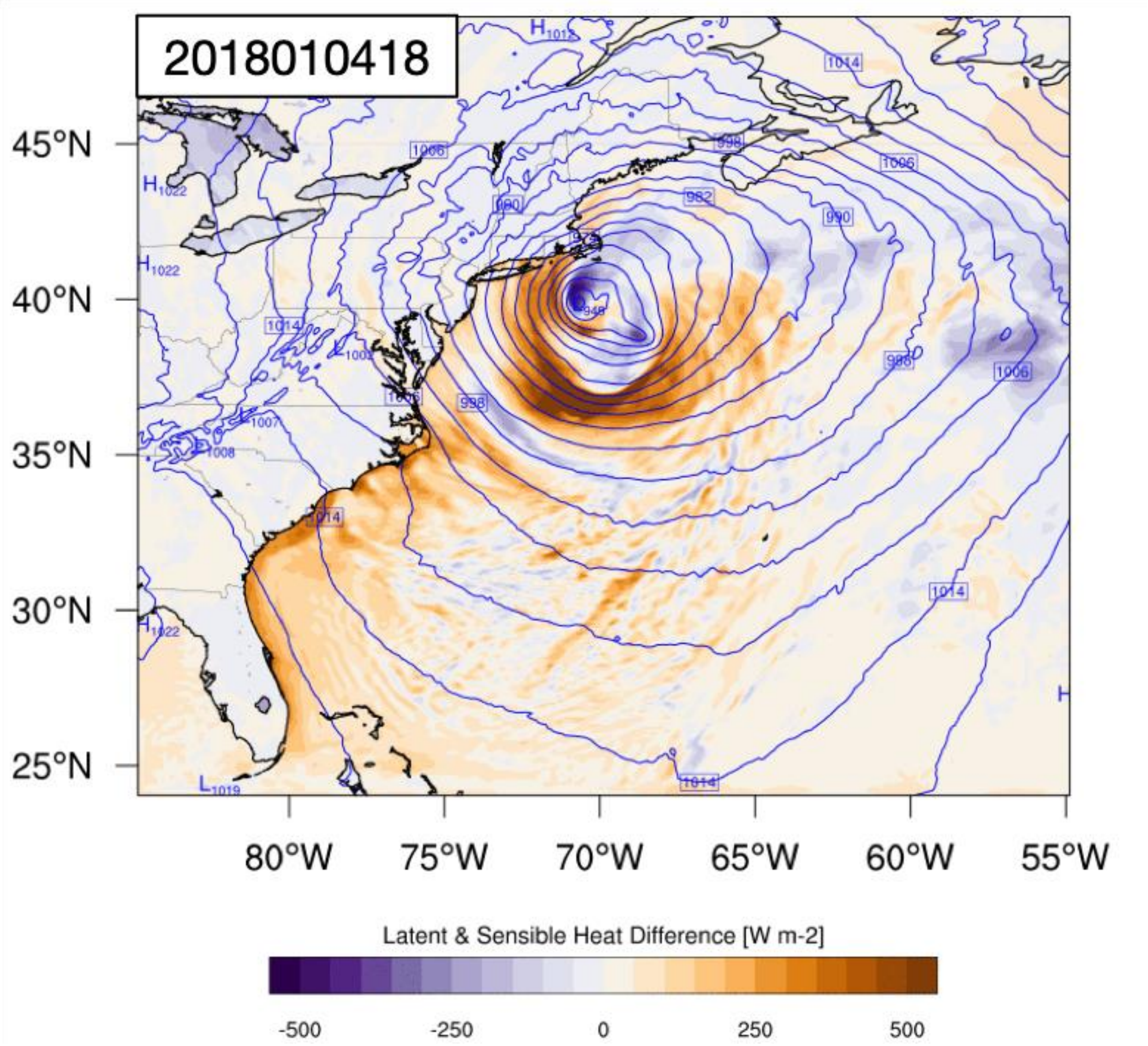

## Surface Roughness $z_0$



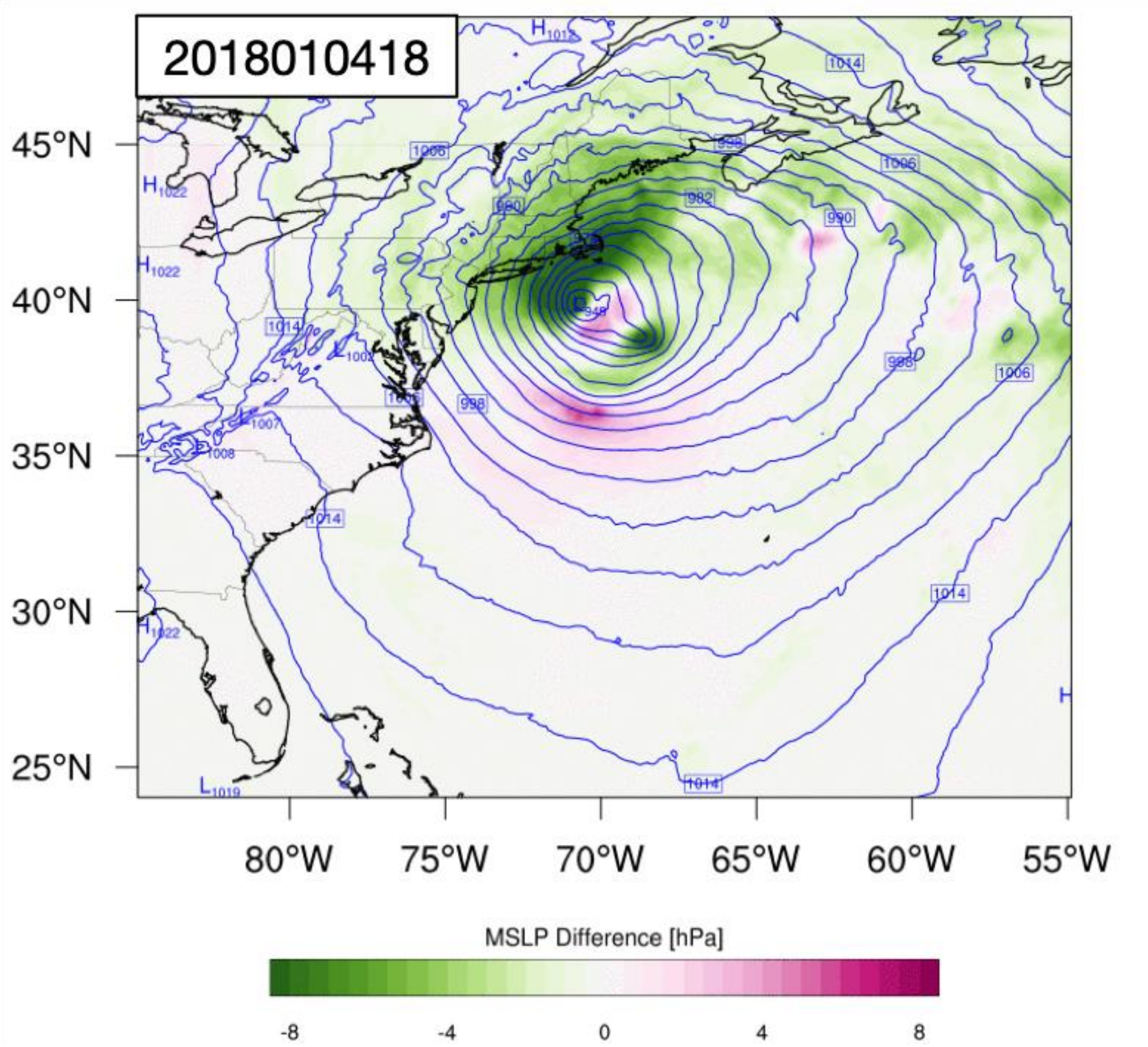

$u_*$ and $z_0$ are intensified by the modified parameterization in the atmosphere-wave coupling

# Atmosphere-Wave Coupling Effects $(AW - A)$

## Surface Heat Flux

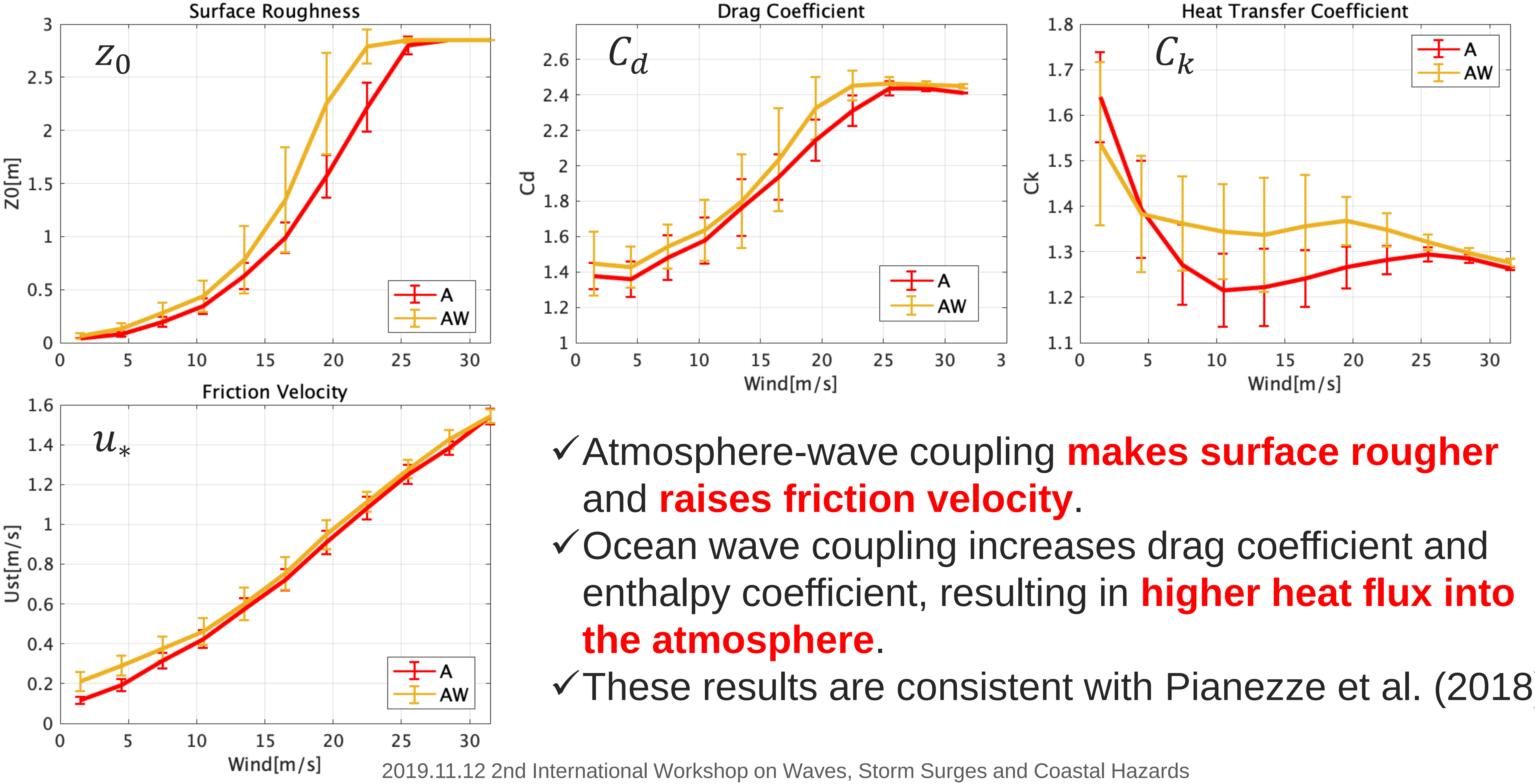



## Sea Level Pressure (SLP)



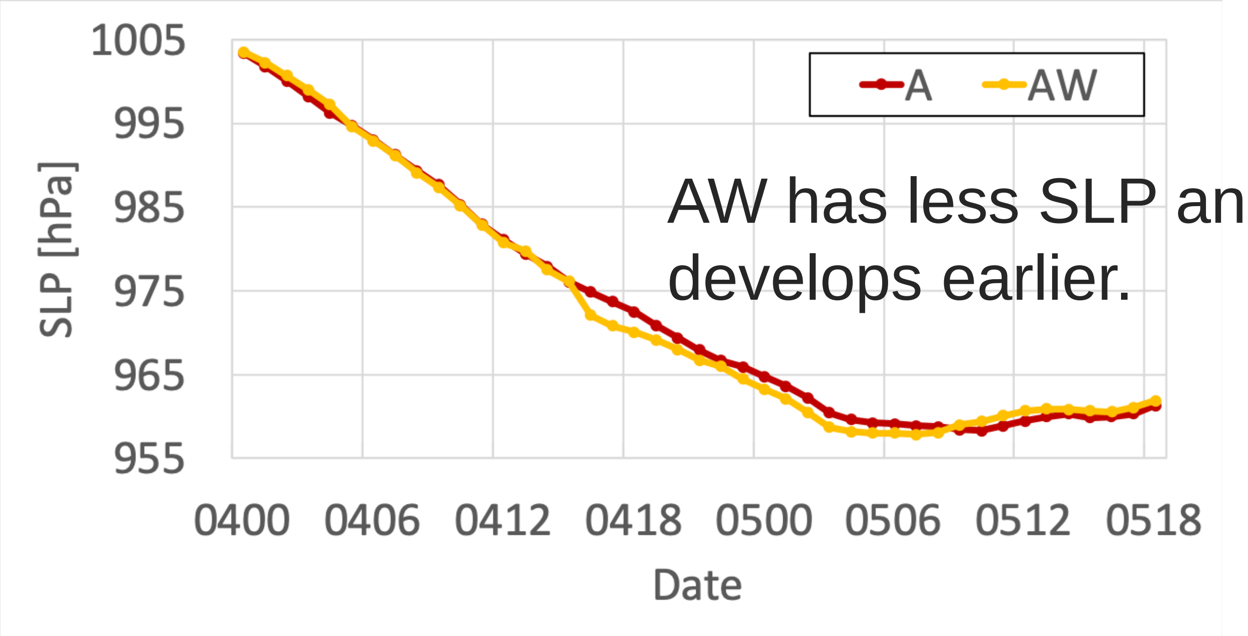

Surface heat flux raises with modified $z_0$ and $u_*$, and SLP drops more deeply in AW

# Surface Parameters: $\mathbf{AW}, \mathbf{A}$

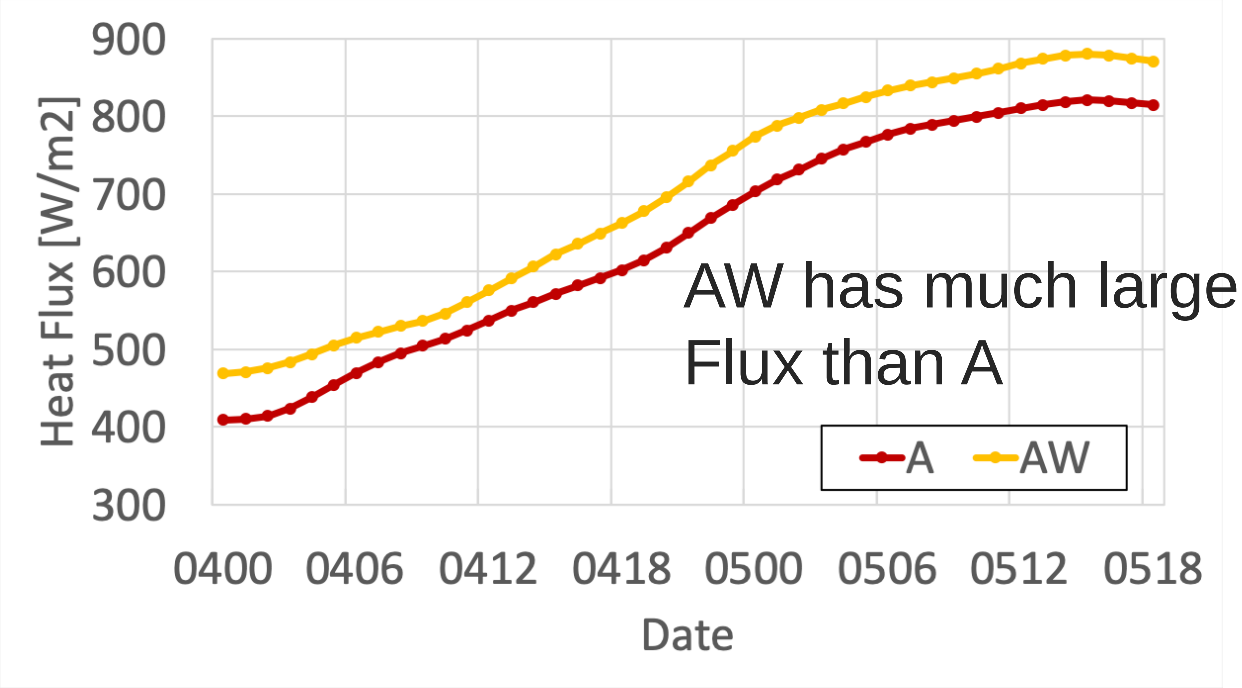



- ✓Atmosphere-wave coupling **makes surface rougher** and **raises friction velocity**.
- ✓Ocean wave coupling increases drag coefficient and enthalpy coefficient, resulting in **higher heat flux into the atmosphere**.
- ✓These results are consistent with Pianezze et al. (2018)

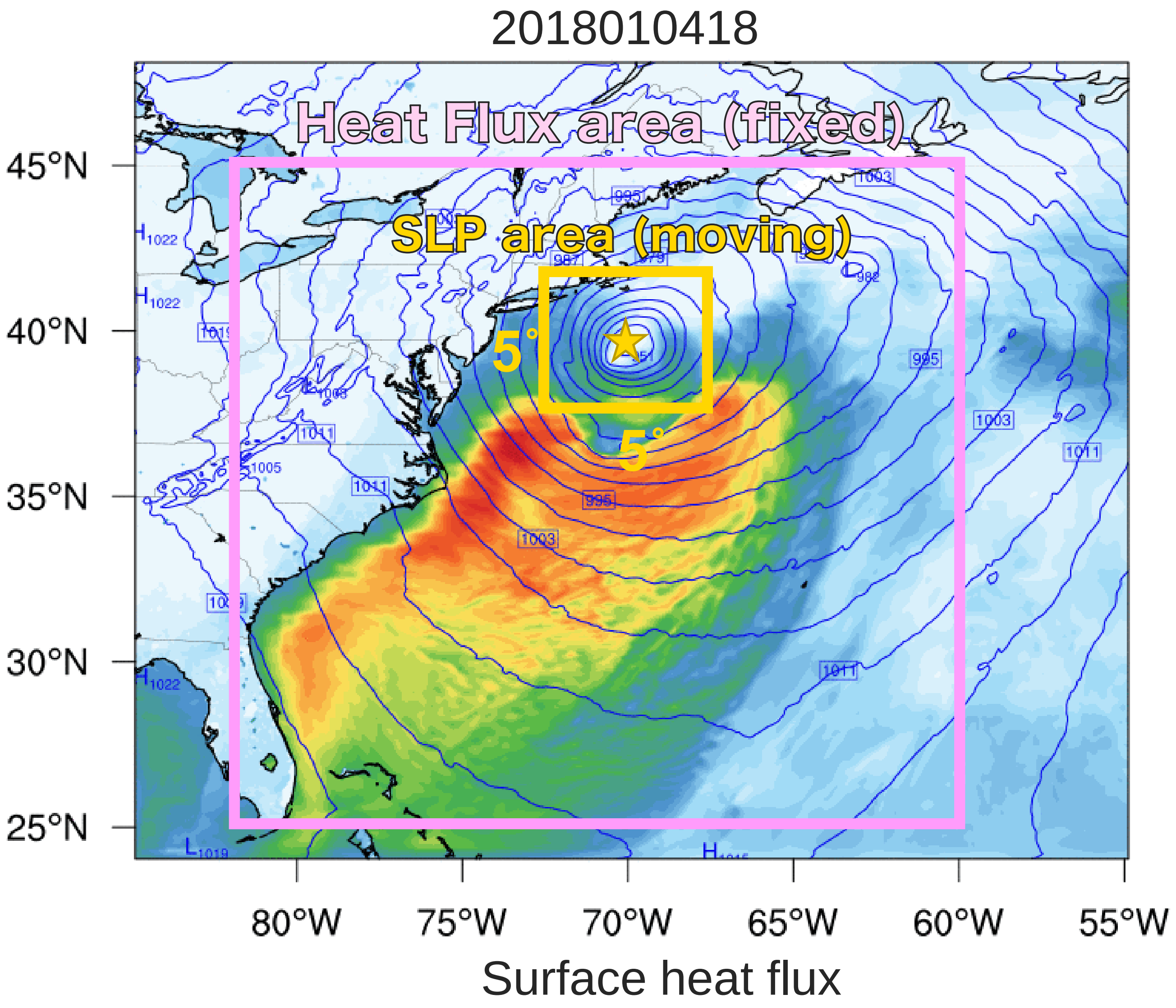
# Area-Averaged Sea Level Pressure & Heat Flux ($\mathbf{AW}, \mathbf{A}$)




AW has less SLP and develops earlier.




AW has much larger heat Flux than A

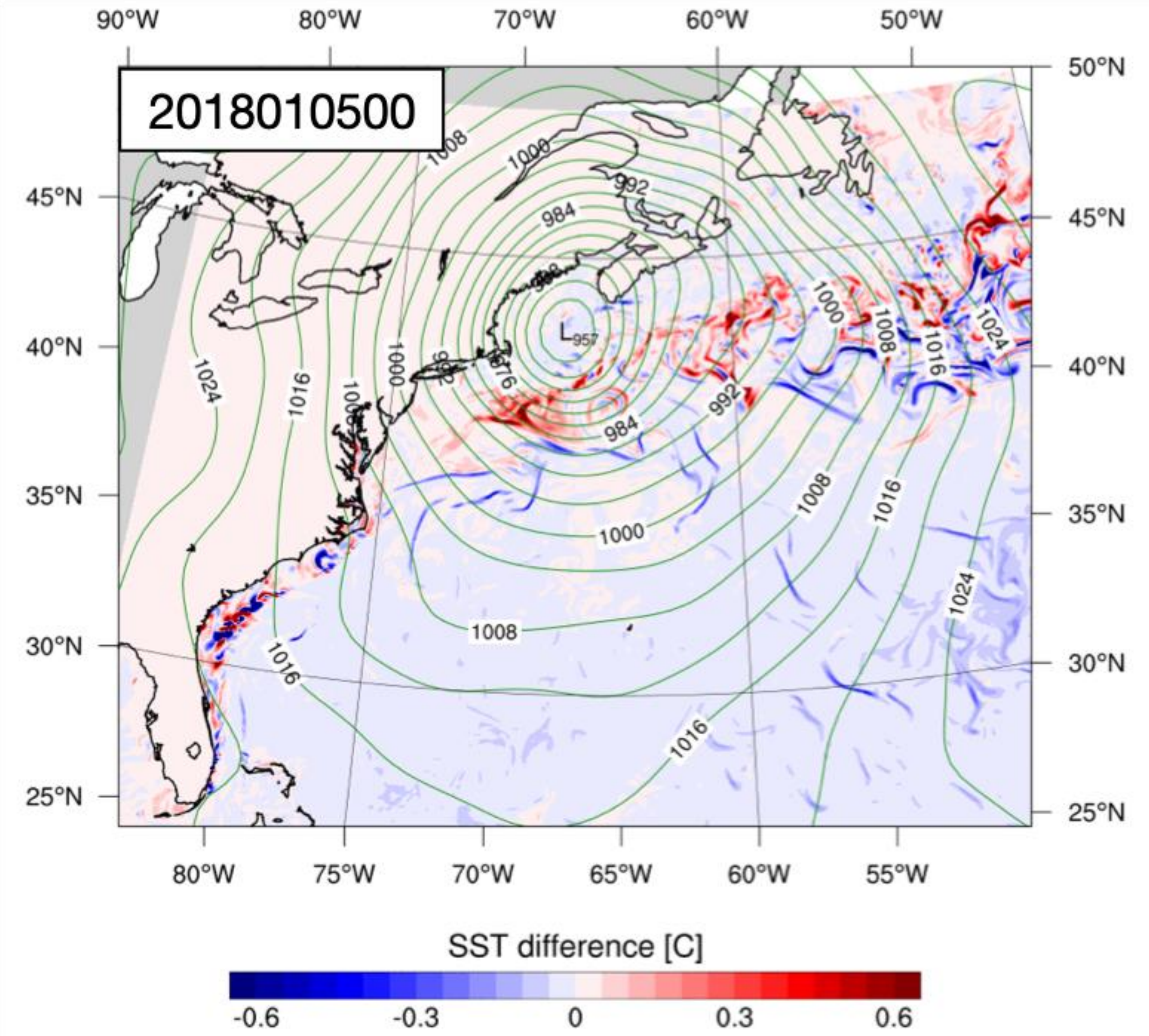



Wave-coupling increases $u_*$, $z_0$, and heat flux, which develops the cyclone stronger.

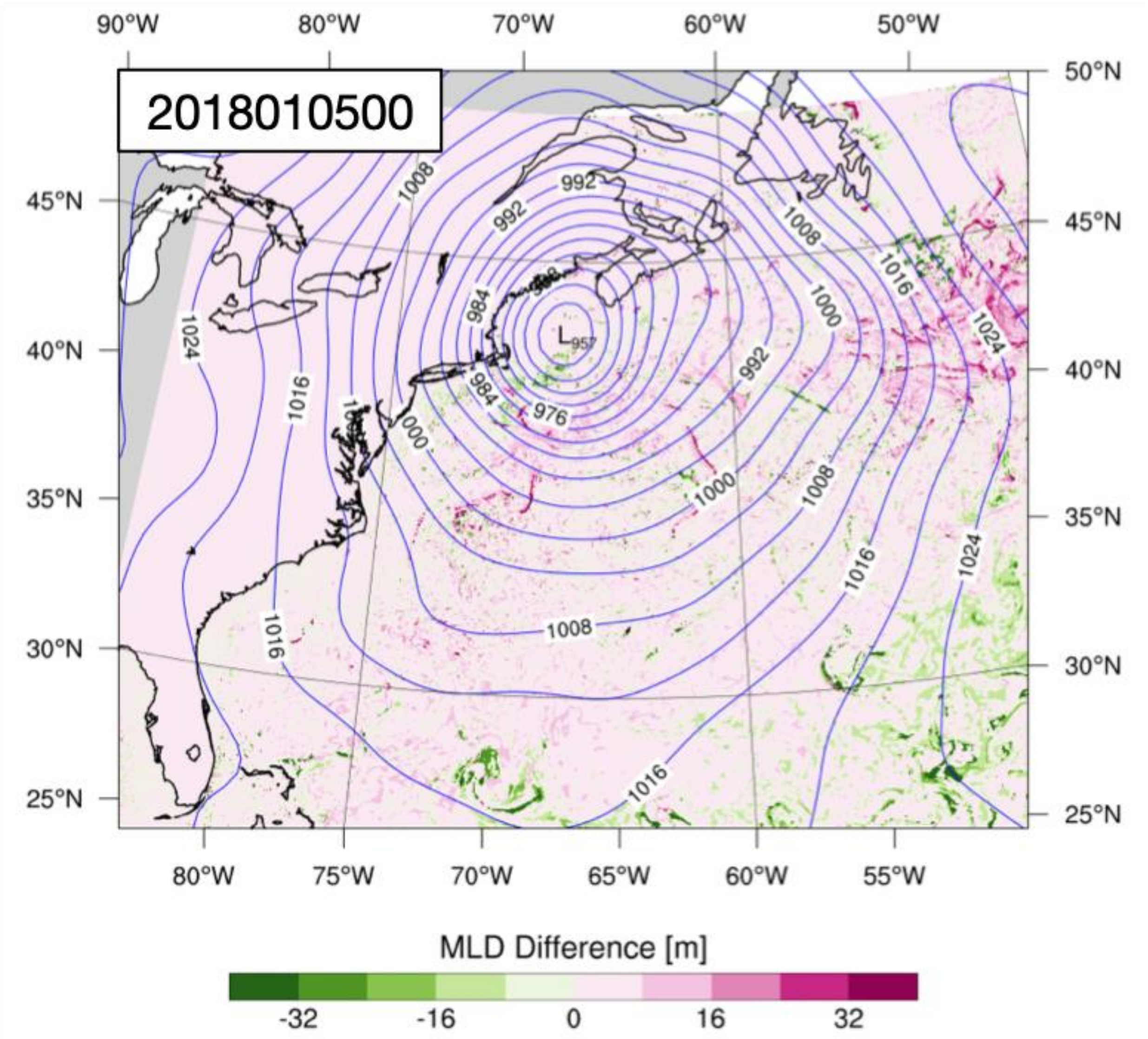
# Ocean-Wave Coupling Effects $(AWO.naw - AO)$

* Defined as the depth whose buoyancy frequency is the largest

## Sea Surface Temperature (SST)



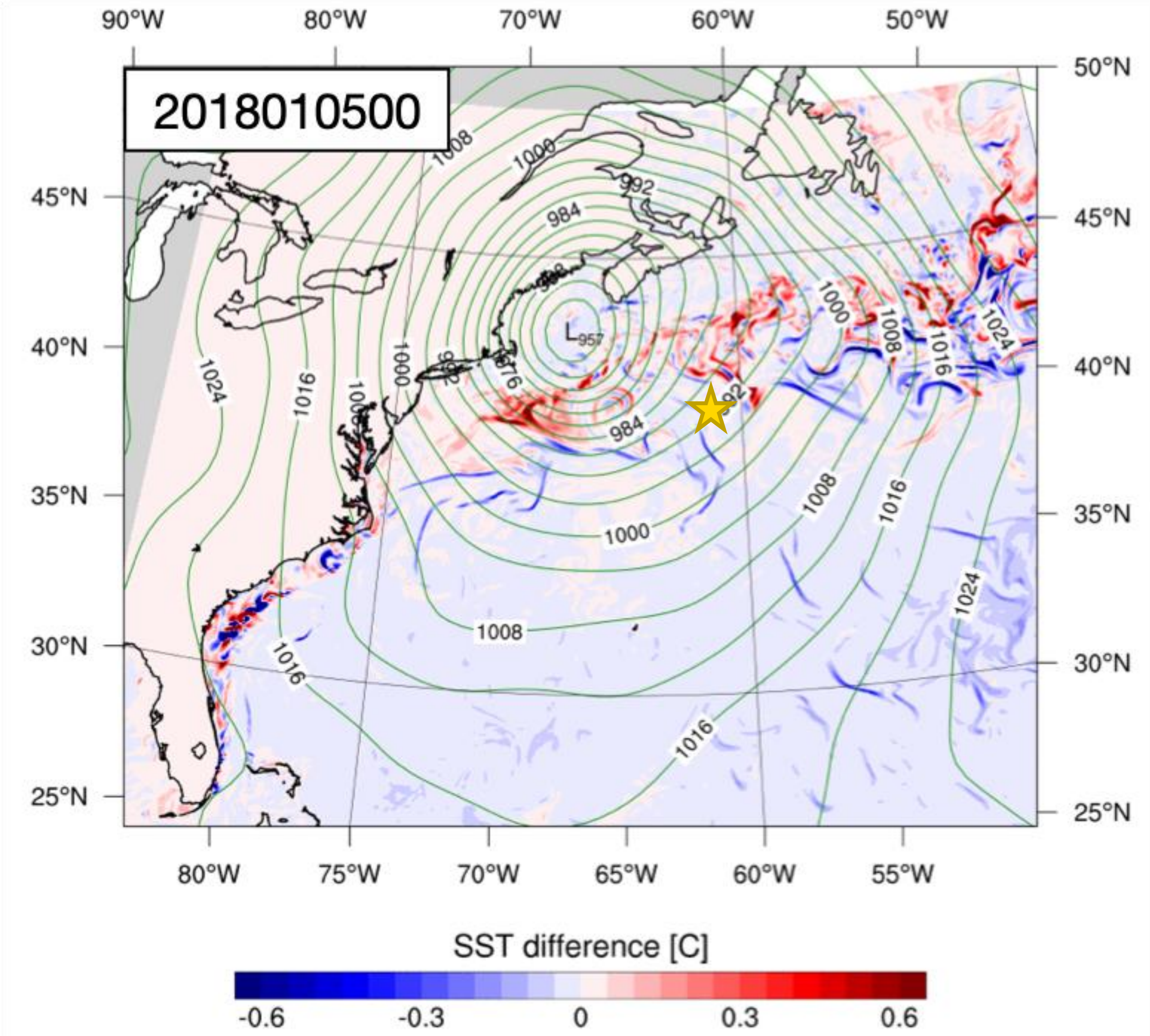

## Mixed Layer Depth (MLD)*

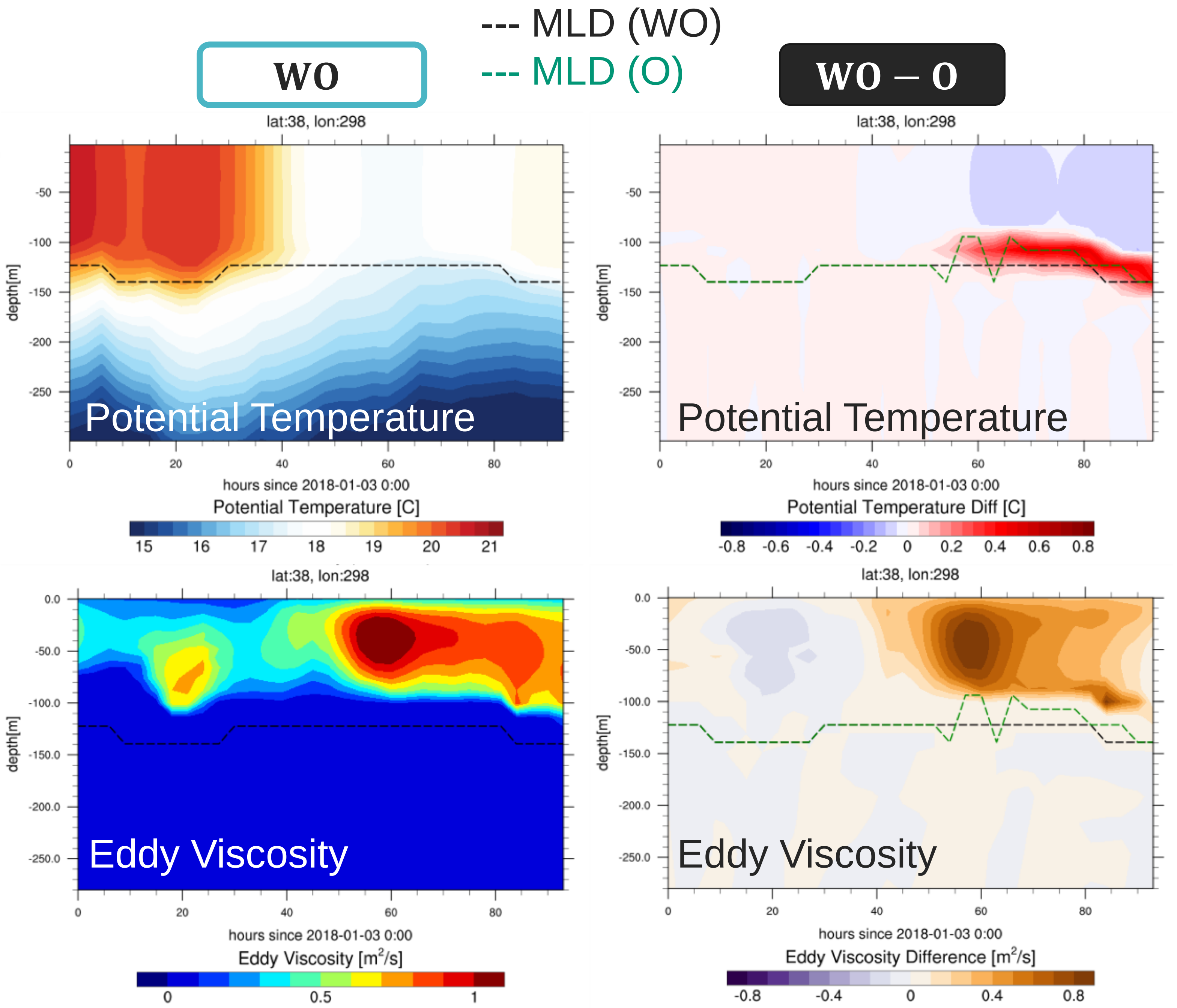



With wave-induced mixing, MLD and SST drops more than independent ocean model.

# Model Comparison (WO – O)

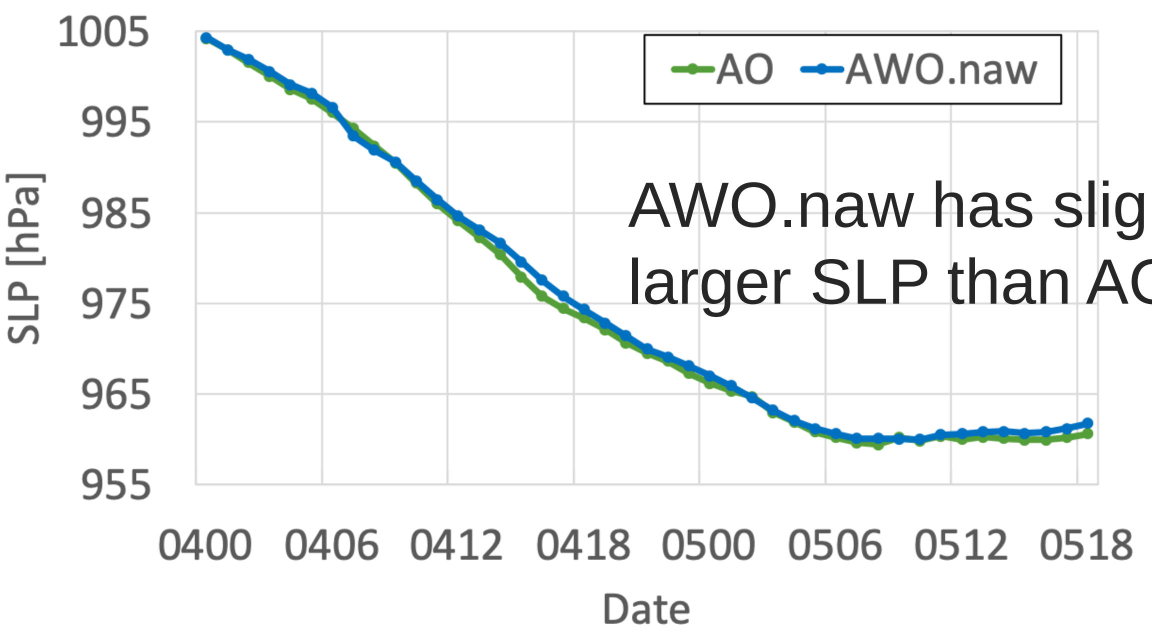
## SST Difference



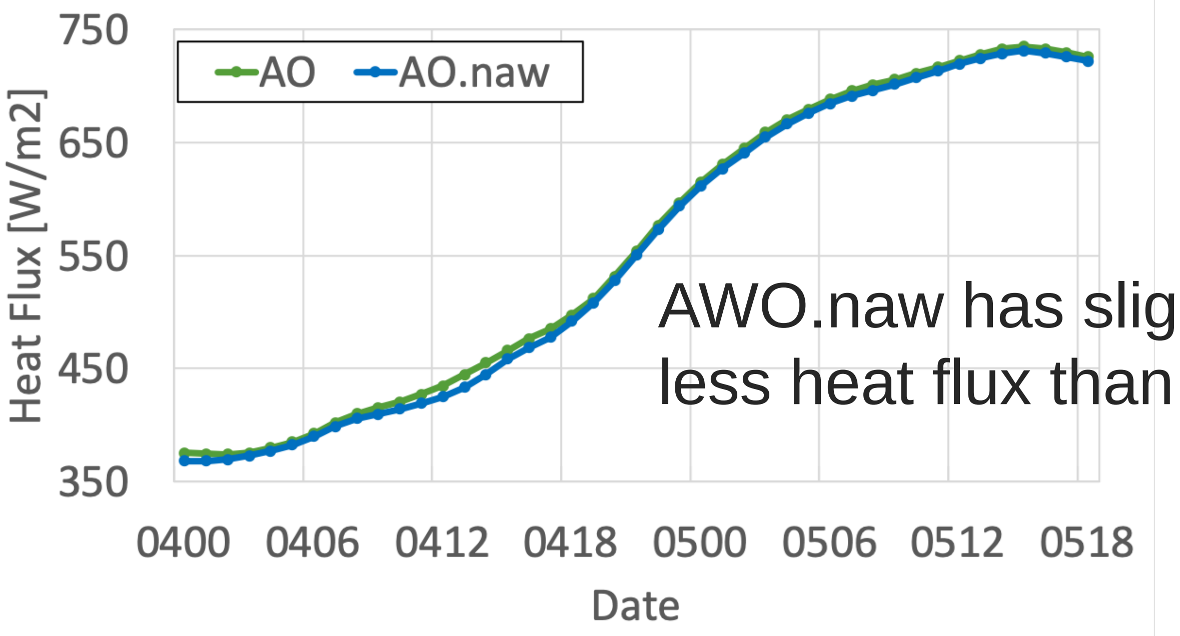




With wave-induced mixing, the eddy viscosity is amplified and mixed layer depth is deepened.

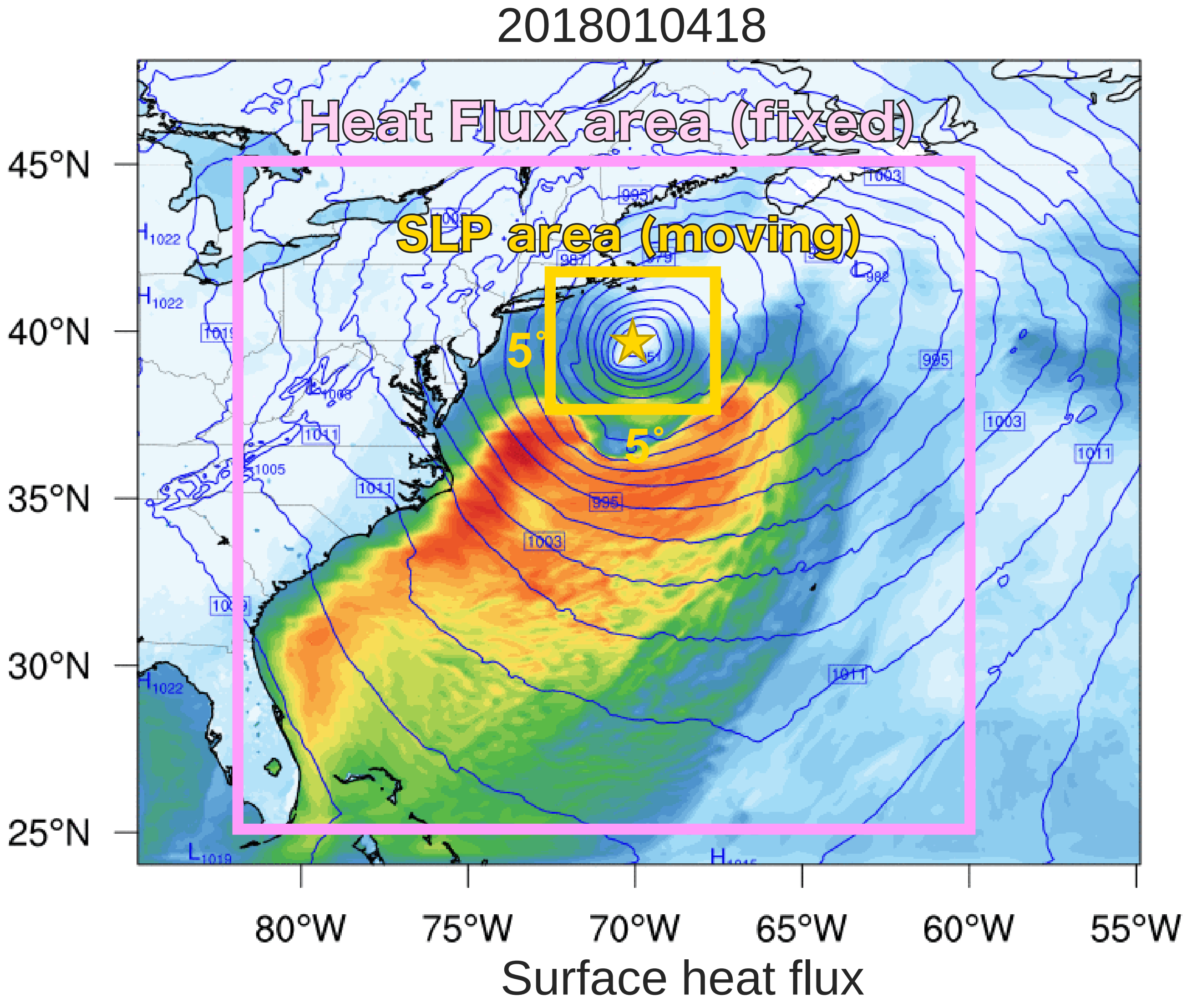
# Area-Averaged Sea Level Pressure & Heat Flux (AO, AWO. naw)




AWO.naw has slightly larger SLP than AO.

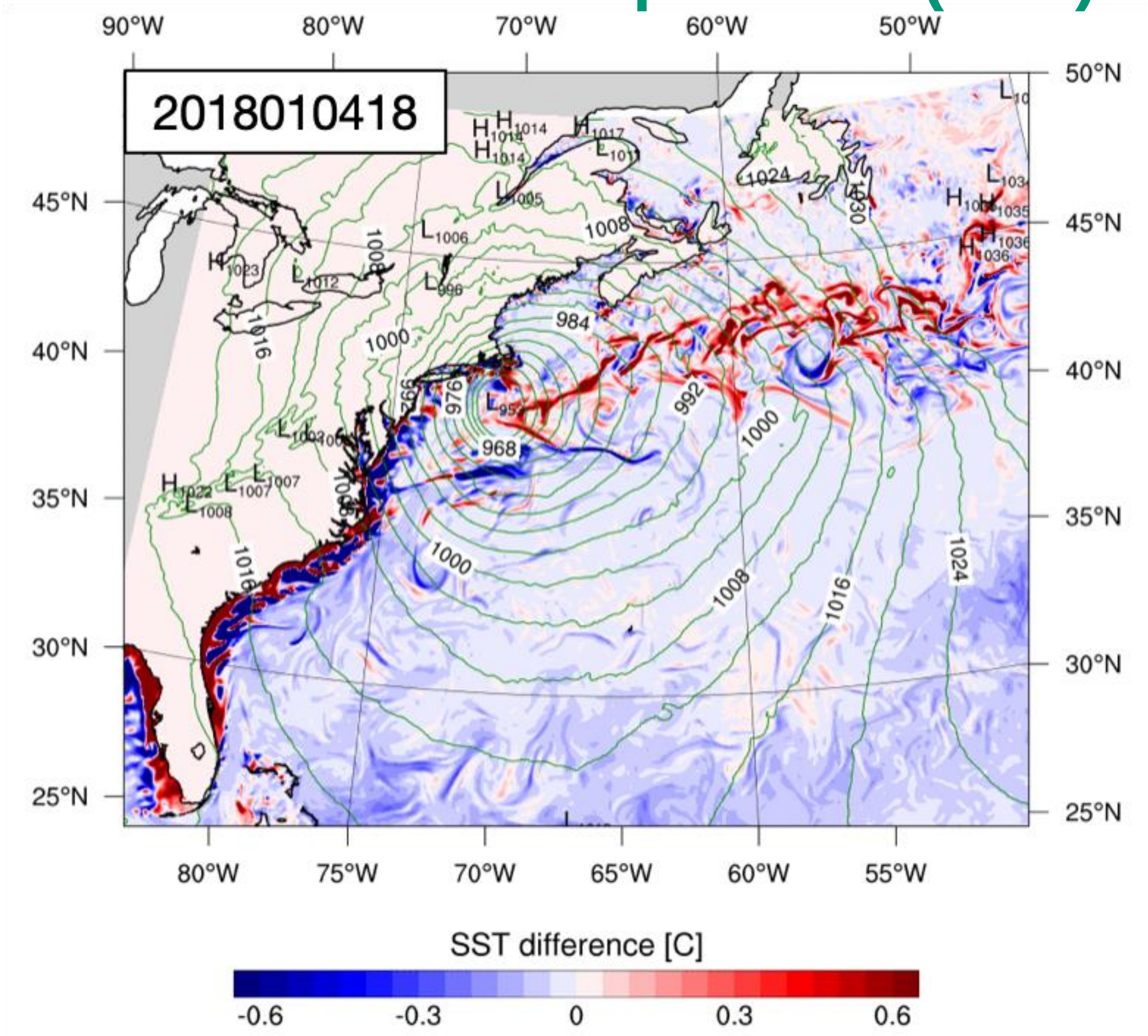


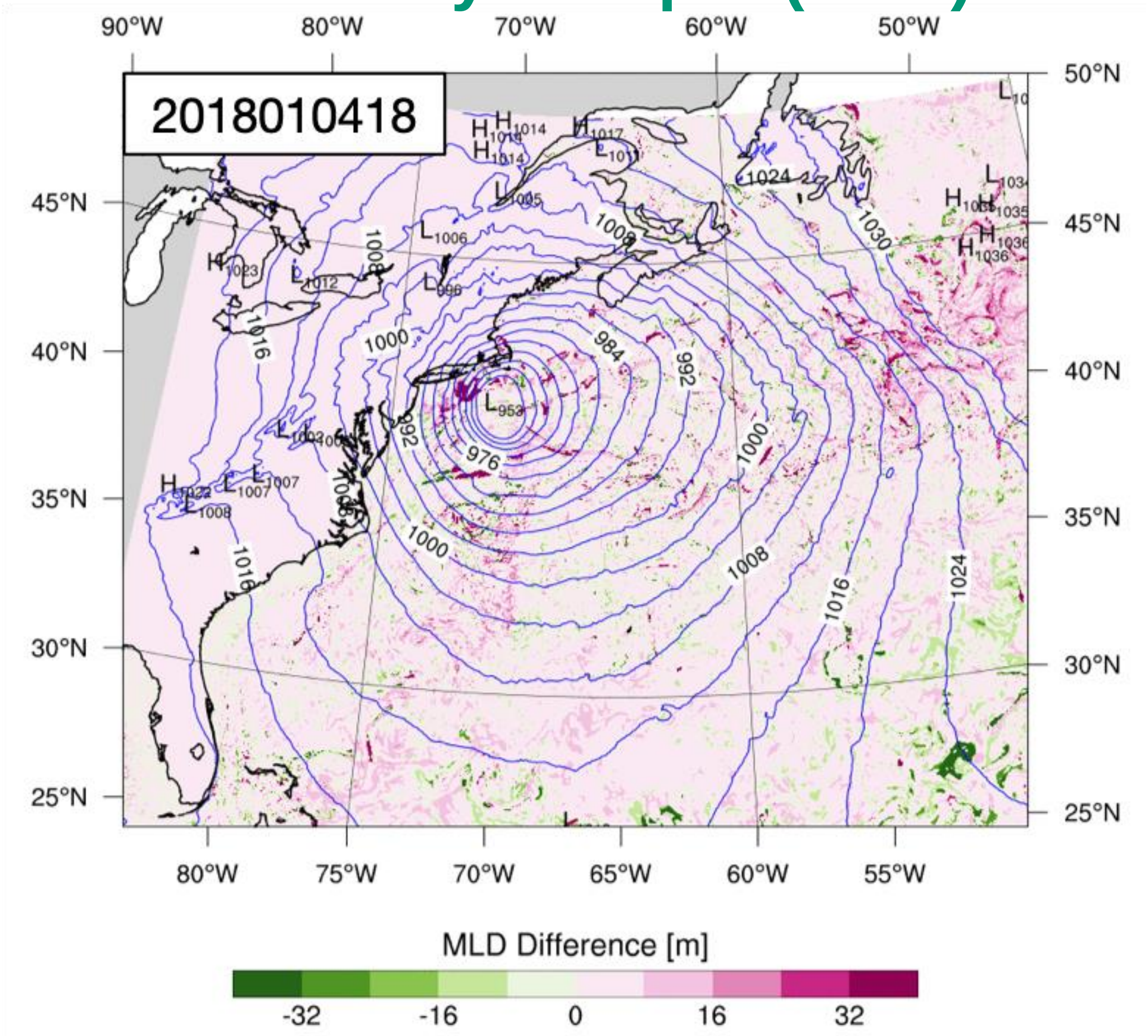

AWO.naw has slightly less heat flux than AO.




Wave-induced mixing decreases surface heat flux and inhibits the development of the explosive cyclone.

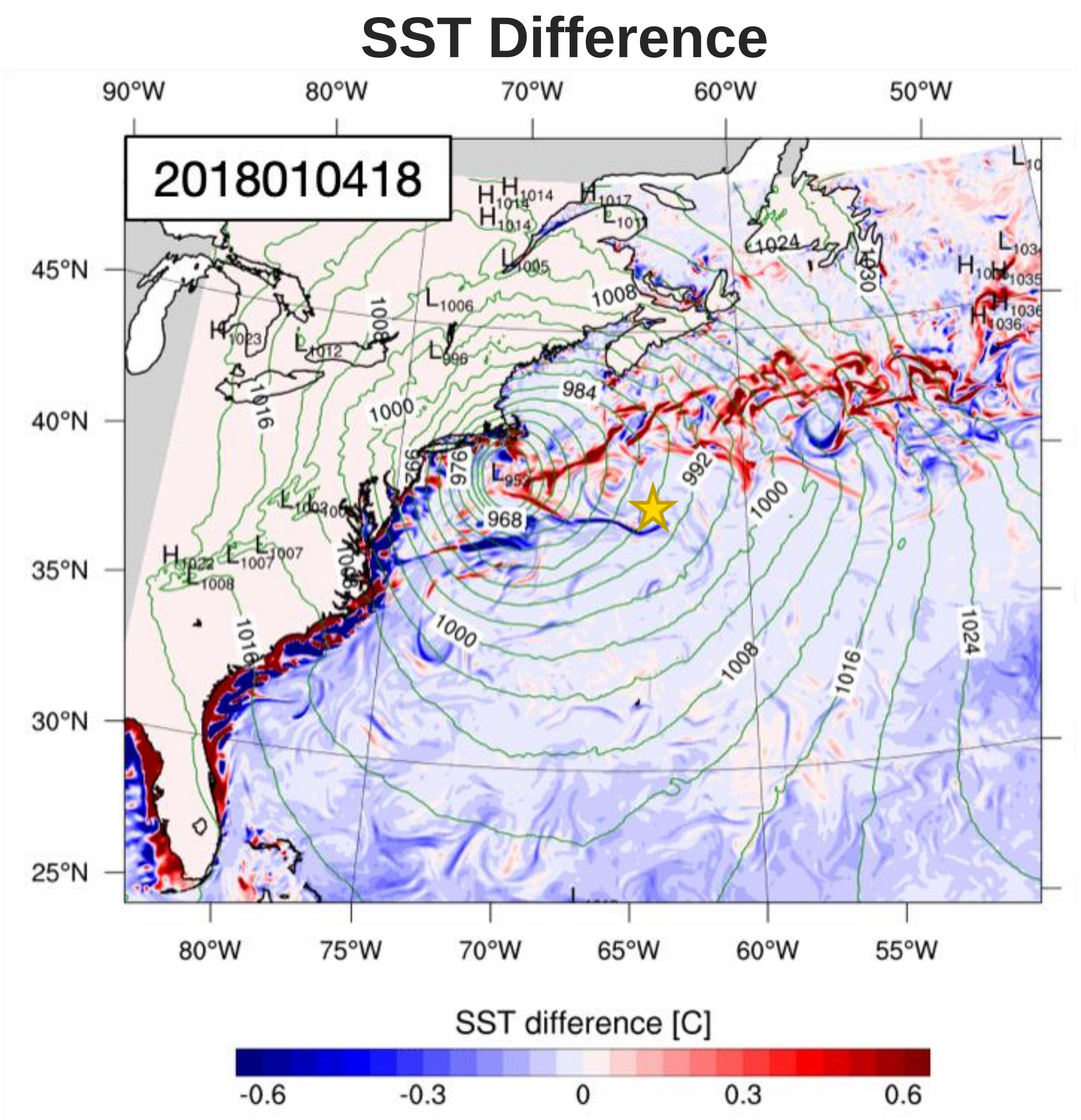
# Atmosphere-Ocean-Wave Coupling Effects $(\mathbf{AWO - AO})$

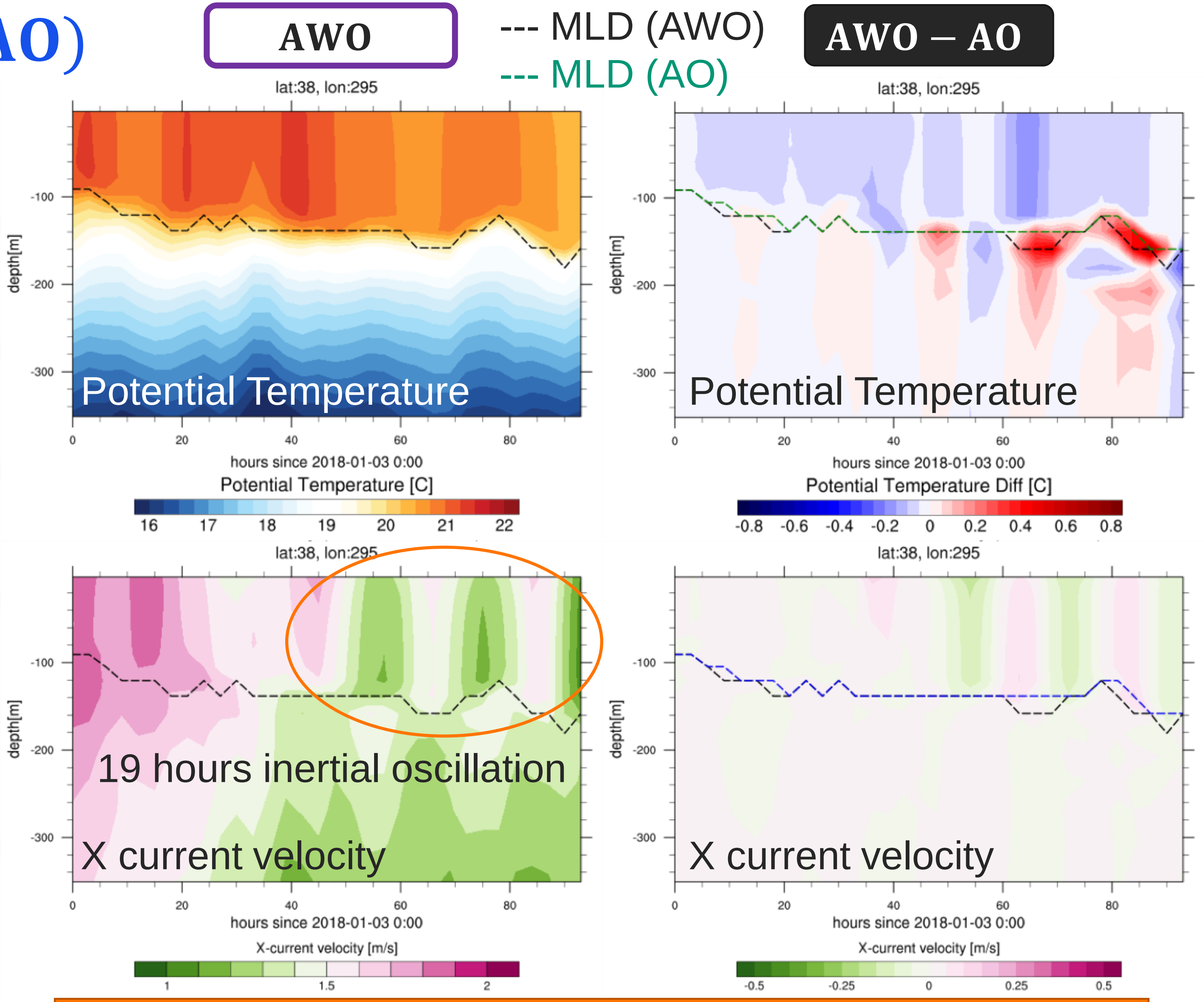



With atmosphere-ocean-wave interactions, SST and MLD drops more deeply.

# Model Comparison (AWO – AO)

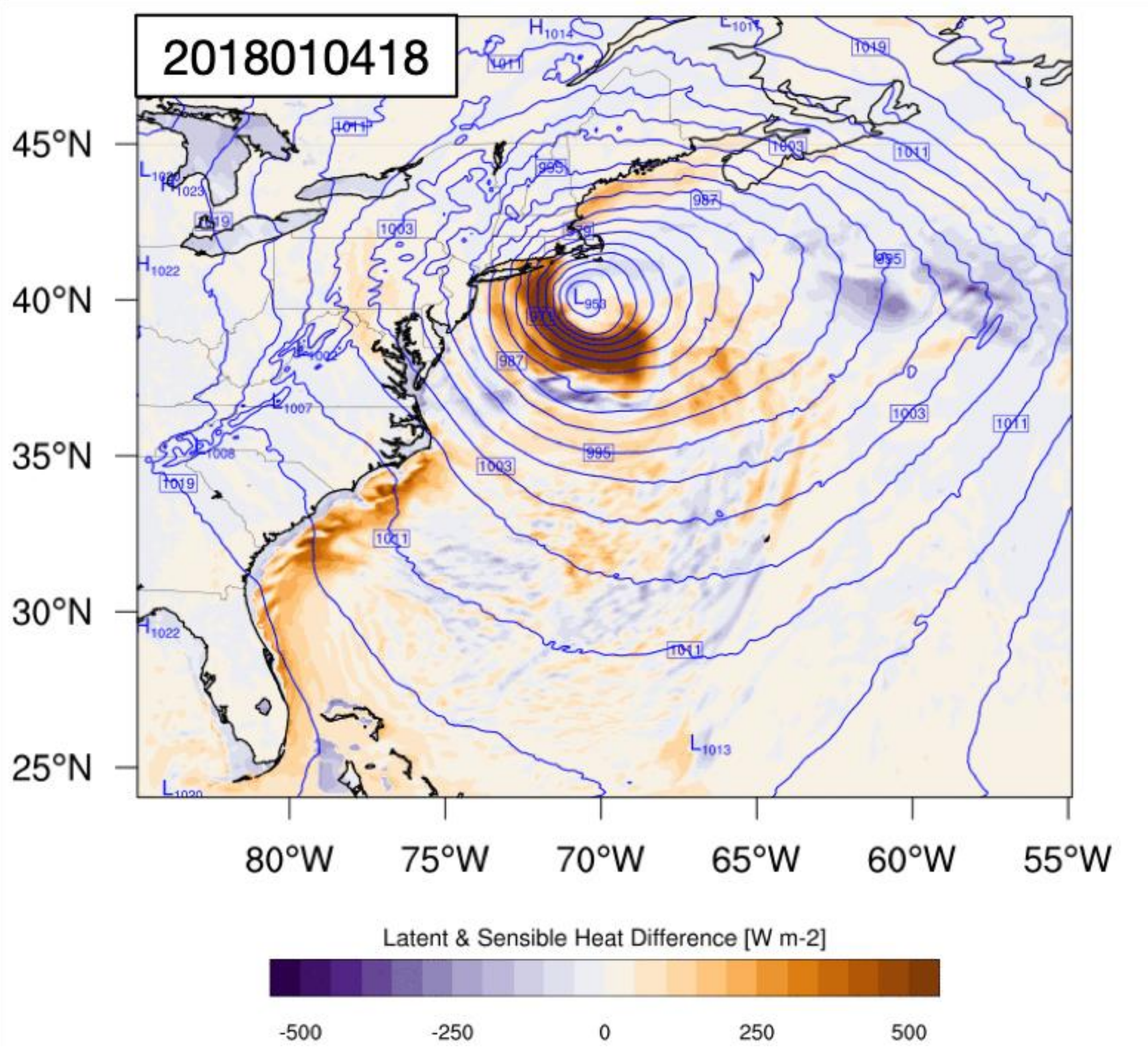


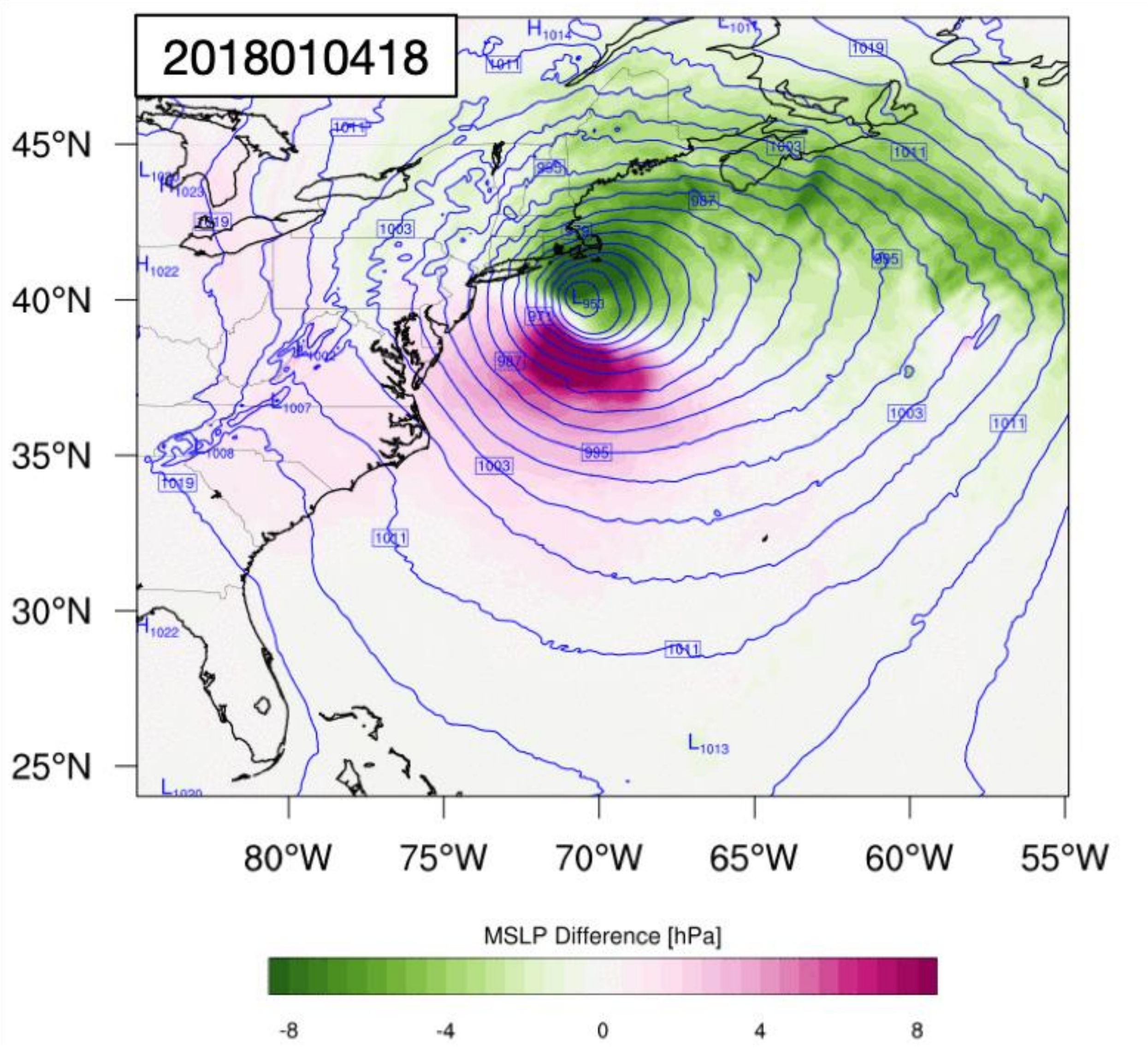

When atmosphere-ocean-wave interaction is active,
Increased $u_*$ enhances inertial oscillation under the cyclone

# Atmosphere-Ocean-Wave Coupling Effects $(\mathbf{AWO} - \mathbf{AO})$

## Surface Heat Flux

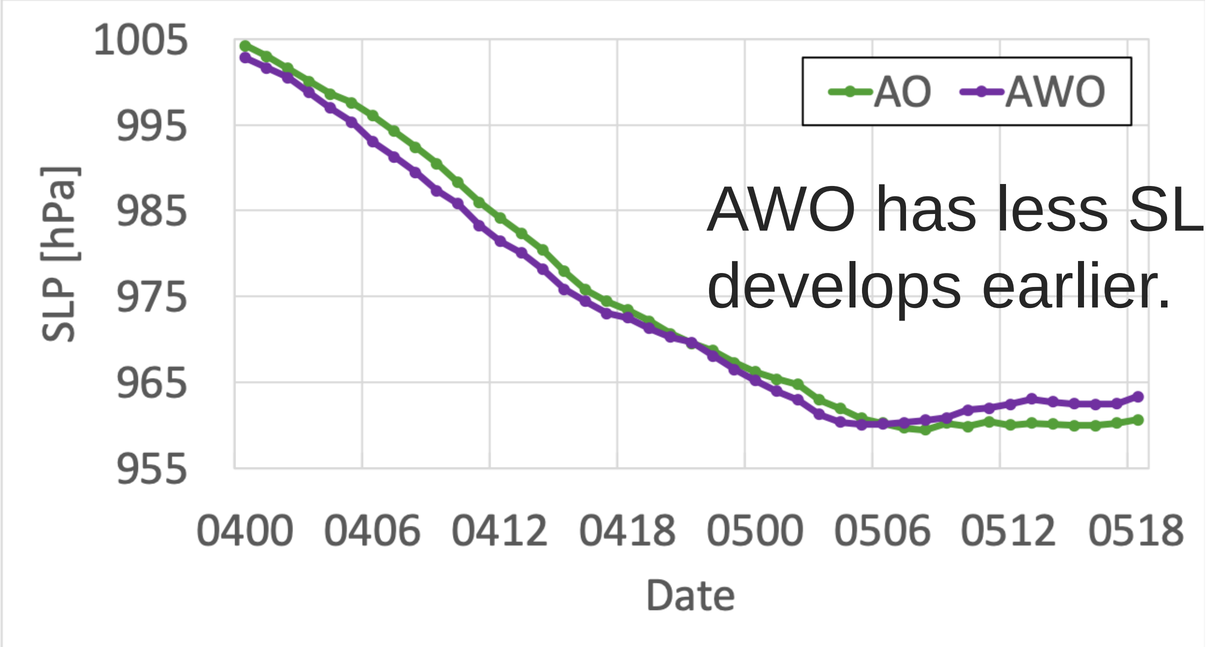



## Sea Level Pressure (SLP)

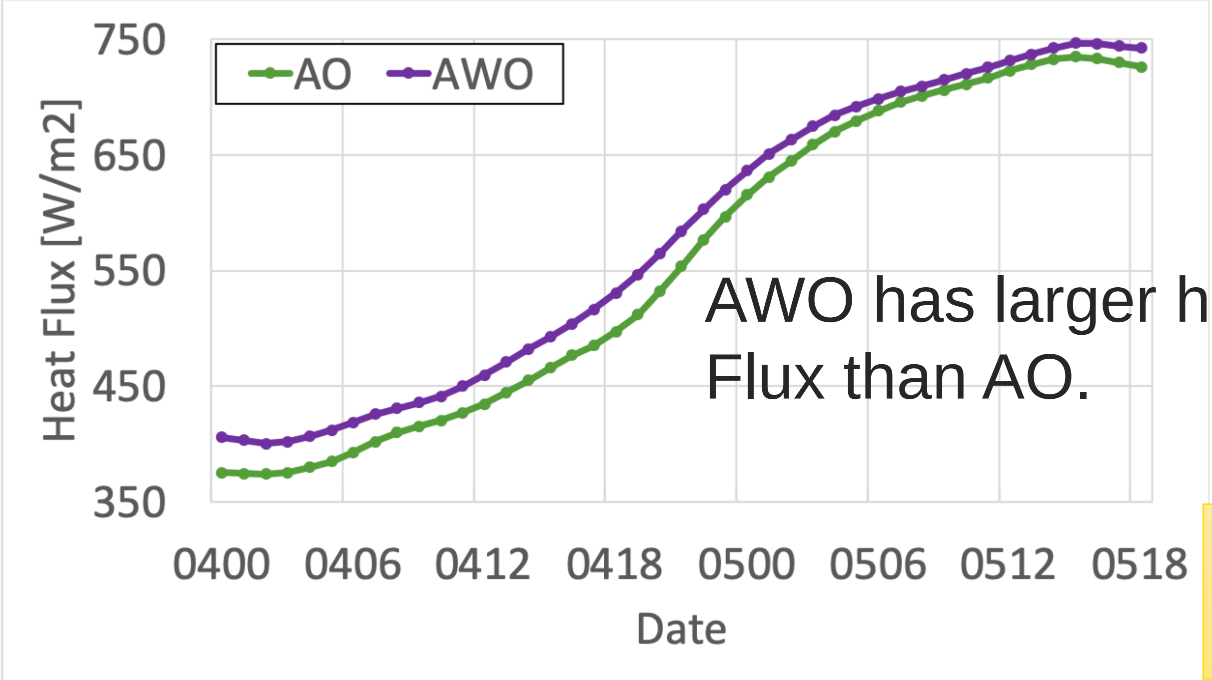



In fully coupled model, the surface hear flux is enhanced and SLP drops more deeply.

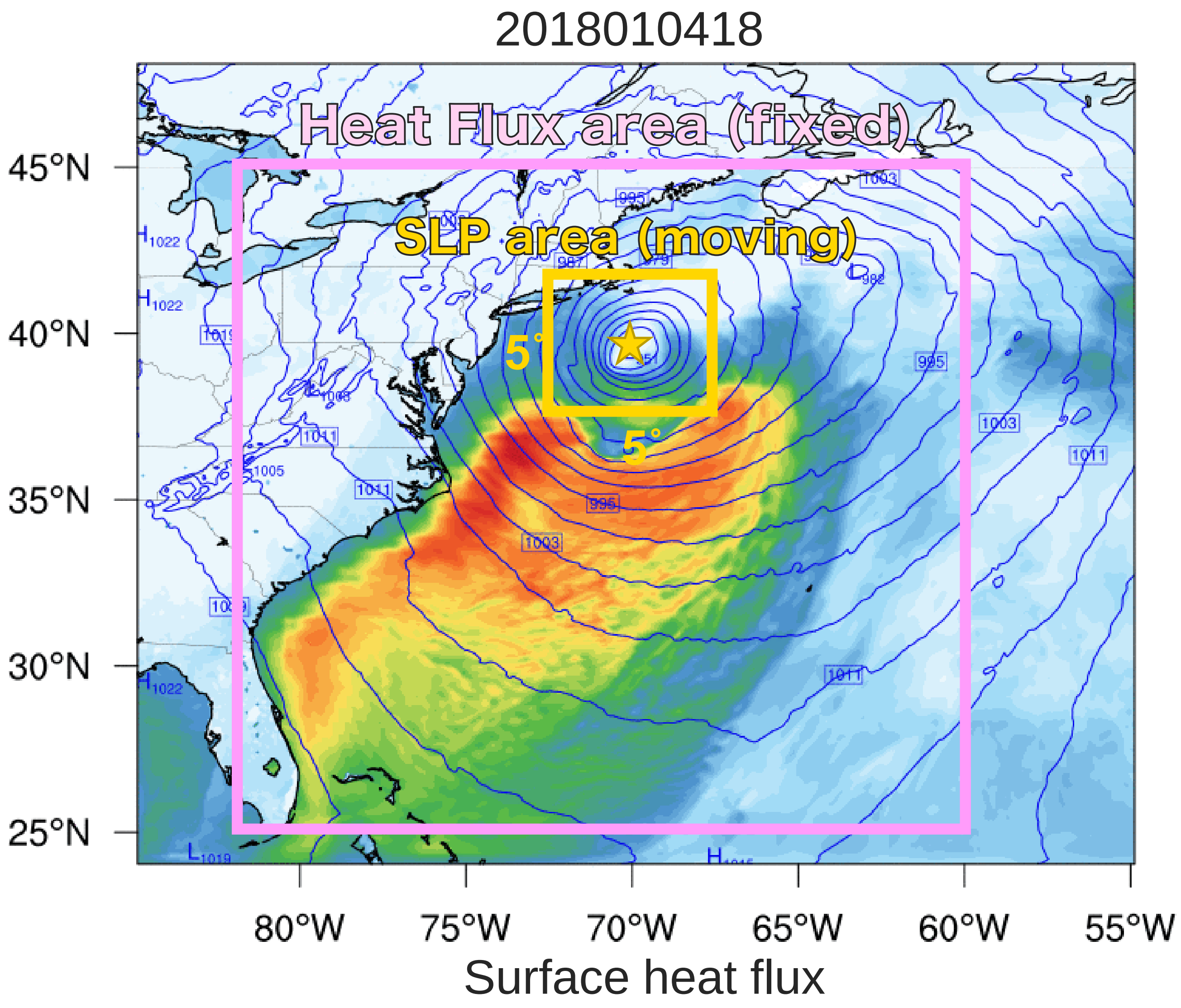
# Area-Averaged Sea Level Pressure & Heat Flux (AO, AWO)




AWO has less SLP and develops earlier.

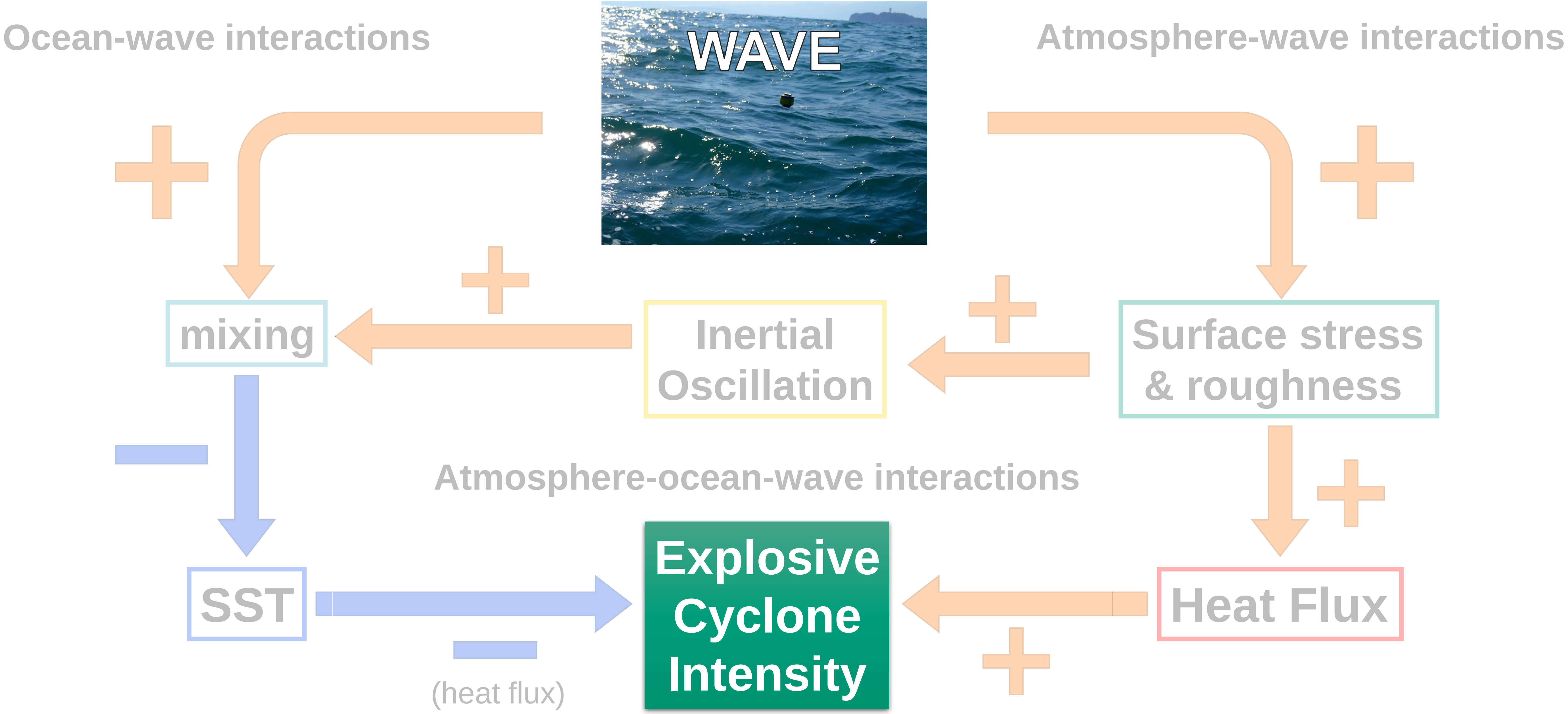



AWO has larger heat Flux than AO.




Wave-induced mixing cools SST, but wave-atmosphere coupling have more impacts on resultant heat flux.

# Ocean Wave Effects on the Development of Explosive Cyclone



# Summary

- The modification of $z_0$ and $u_*$ increases surface stress and roughness of the atmospheric surface, and **enhances the surface heat flux**.
- Introducing the wave-induced mixing in the ocean model **declines MLD more deeply and cools SST down**.
- The wave coupling to both atmosphere and ocean **intensifies the inertial oscillations** by the explosive cyclone, resulting in deeper MLD and cooler SST.
- These wave coupling effects influence the surface heat flux significantly and **make prominent changes in the development of the explosive cyclone**.

## Future work

- It remains to be clarified how the enhanced heat flux make changes in the development in the context of atmospheric dynamism.
- Feedbacks of the wave coupling to the wave development are still unclear.

# APPENDIX

# Turbulence Parameterization: KPP (LMD scheme)

- **KPP (K-Profile Parameterization)**
  - Parameterize 2nd-order fluxes with 1st-order value like:

$$\overline{u'w'} = -K_M \frac{\partial u}{\partial z}, \qquad \overline{v'w'} = -K_M \frac{\partial v}{\partial z}, \qquad \overline{w'\theta'} = -K_H \frac{\partial \theta}{\partial z}$$

  - In the KPP scheme, non-local term $\gamma_a$ is added to:

$$\overline{u'w'} = -K_M \left( \frac{\partial u}{\partial z} - \gamma_u \right), \overline{v'w'} = -K_M \left( \frac{\partial v}{\partial z} - \gamma_v \right), \overline{w'\theta'} = -K_H \left( \frac{\partial \theta}{\partial z} - \gamma_\theta \right)$$

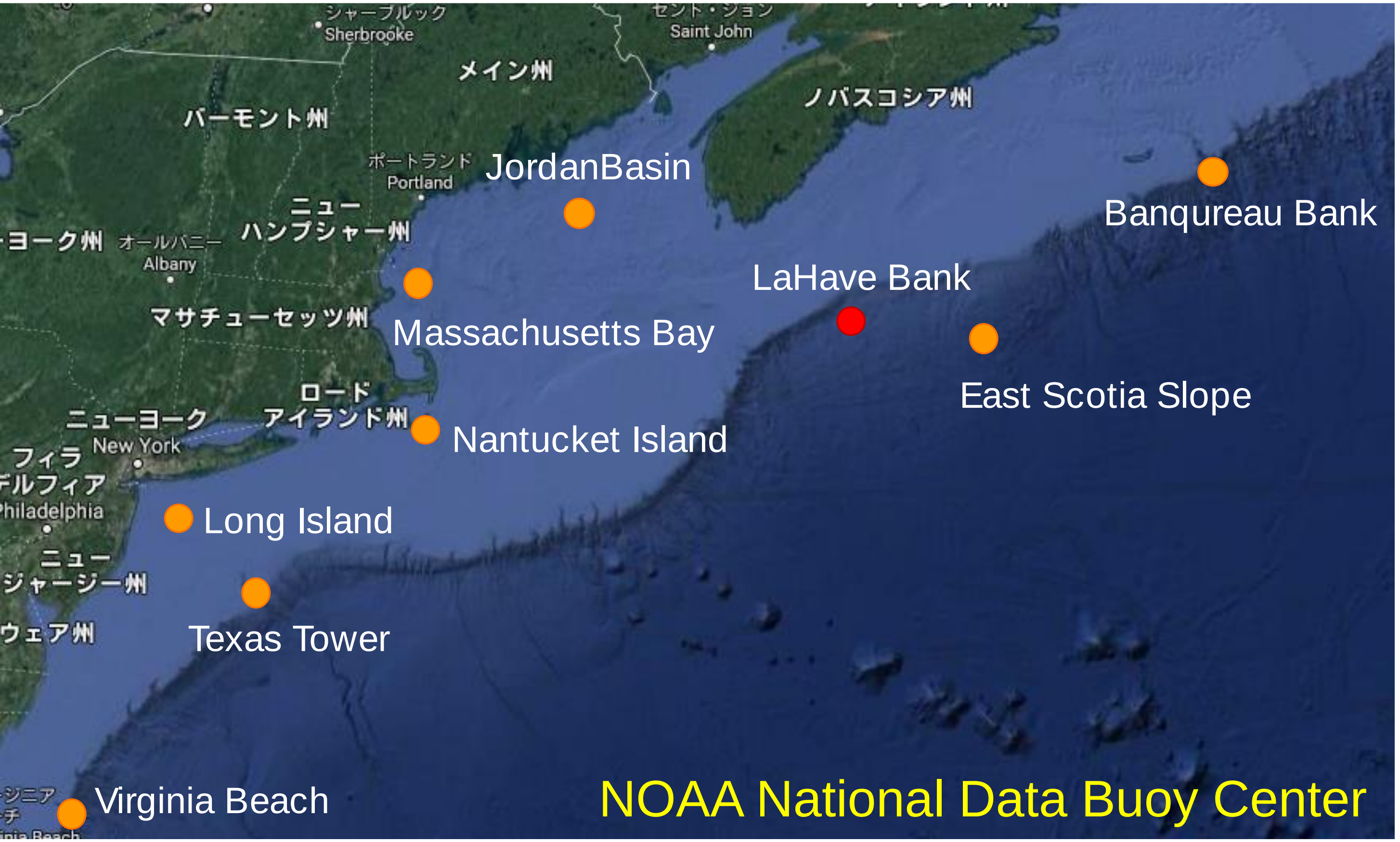
- In the CROCO model, **LMD (Large, McWilliams, Doney 1994)** scheme is used.

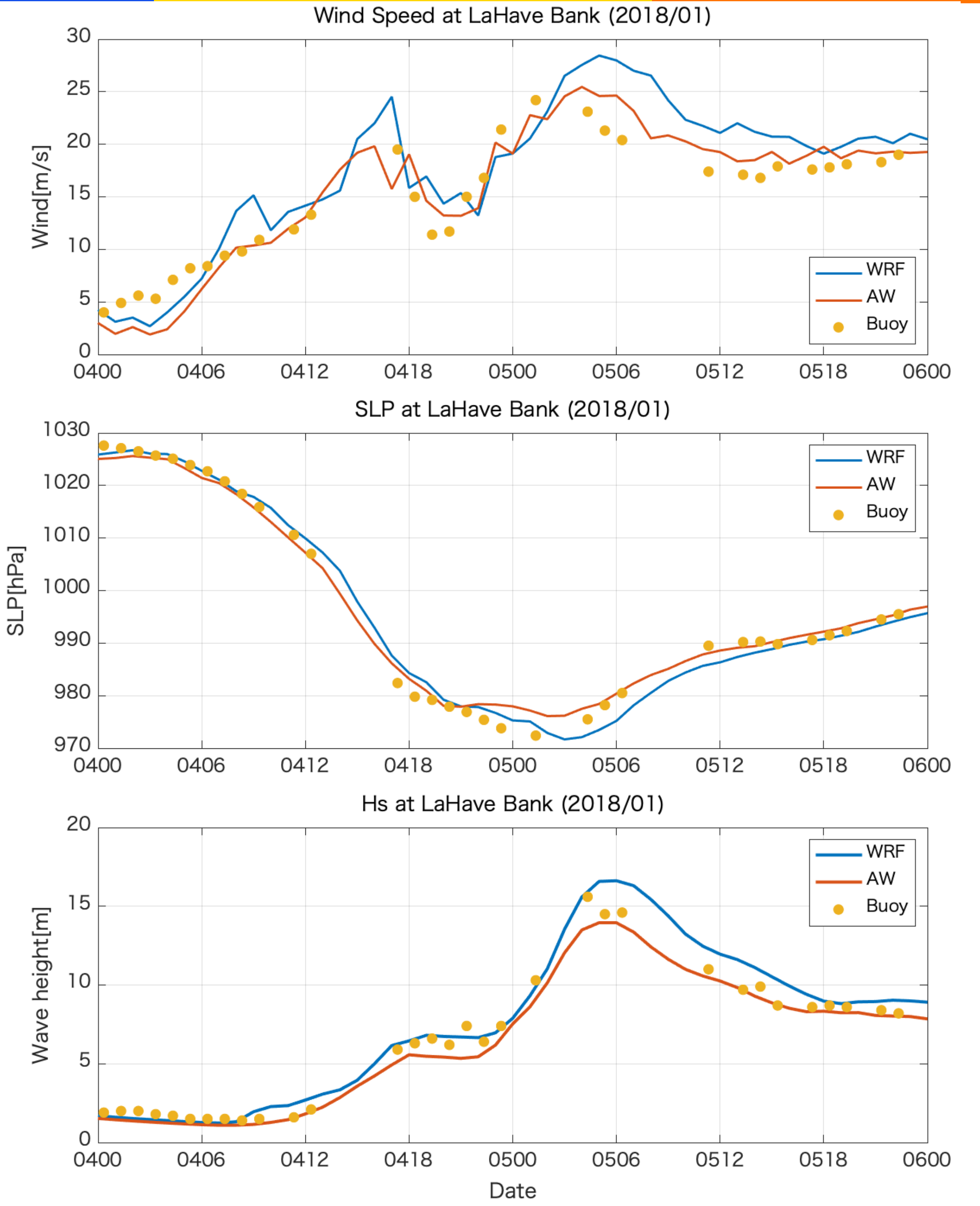
- In terms of wave-current interactions, Qiao et al. (2004) introduced nonbreaking wave-induced turbulence effect into the KPP scheme.

New $K_M \rightarrow K_M + B_v$, New $K_H \rightarrow K_H + B_v$

$$, where\ B_v = \alpha A^3 k \omega \left[ \frac{\sinh k(h+z)}{\sinh kh} \right]^3 \quad (\alpha = 0.1;\ \text{cf. Wang et al. 2010})$$

# Comparison with Marine Observations



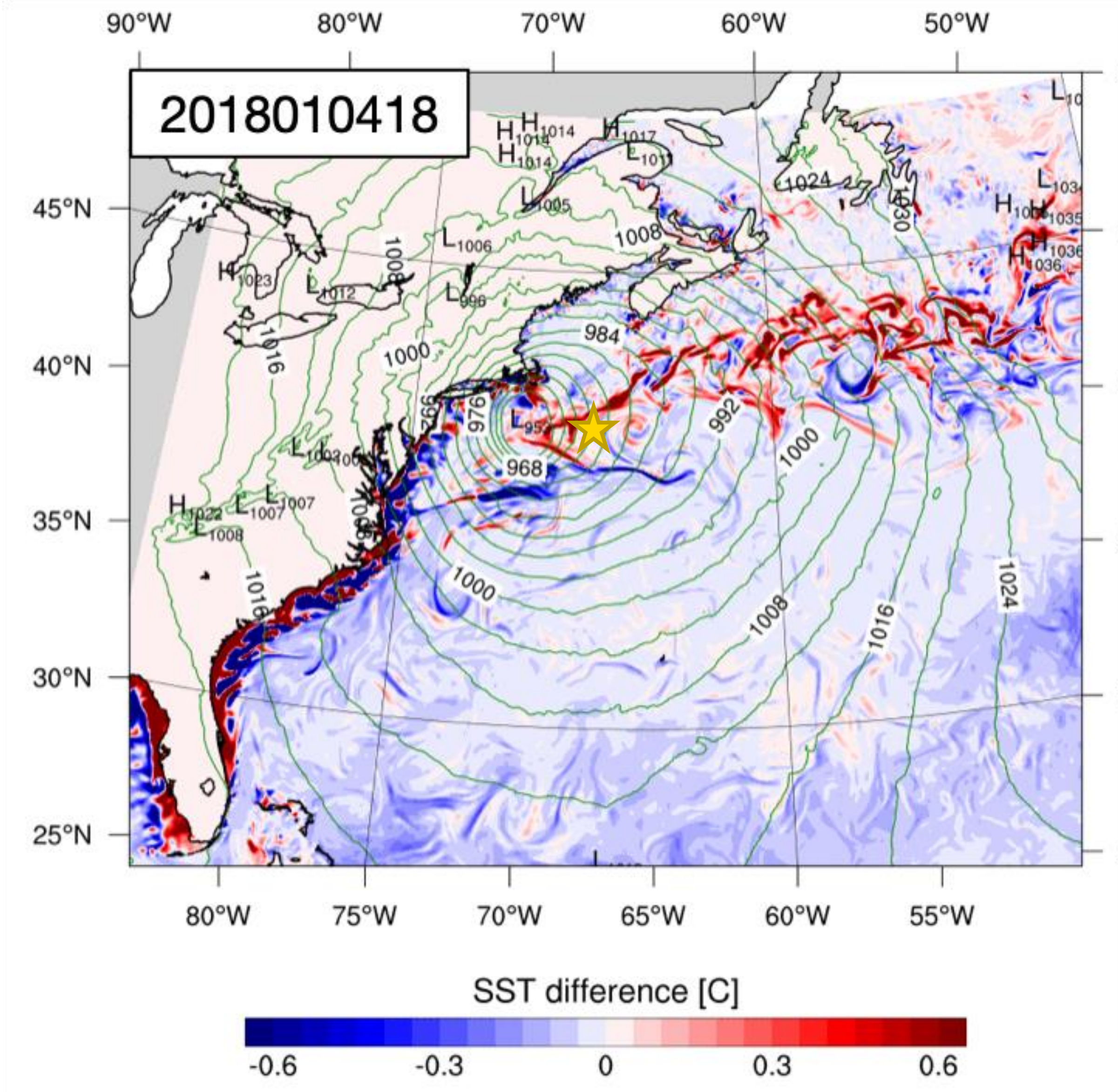



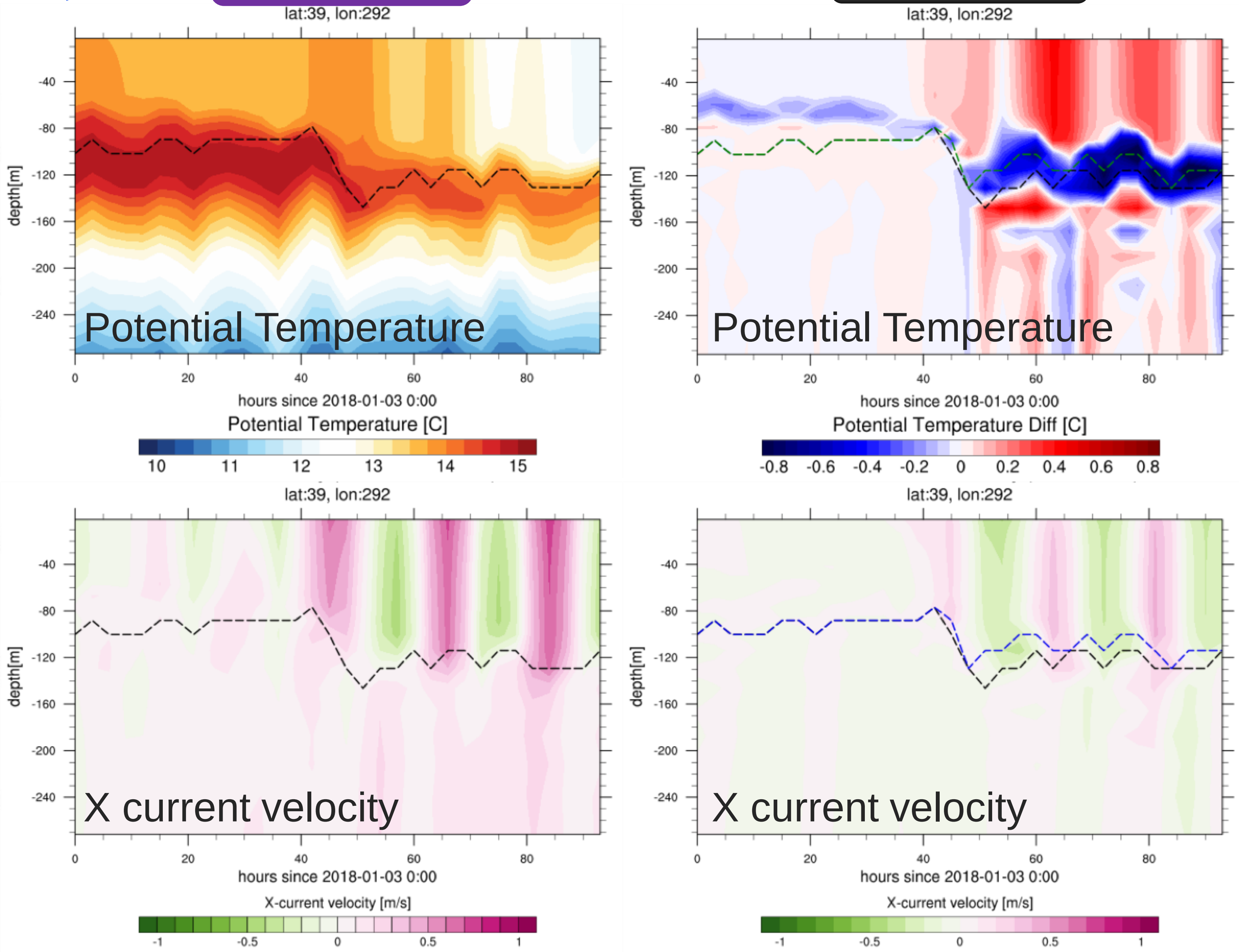
# Model Comparison (AWO – AO)

AWO

AWO – AO

SST Difference




When atmosphere-ocean-wave interaction is active,
Increased $u_*$ enhances inertial oscillation under the cyclone

# Pressure tendency equation (Fink et al., 2012)

$$\frac{\partial p_{sfc}}{\partial t} = \rho_{sfc}\frac{\partial \phi_{p_2}}{\partial t} + \rho_{sfc}R_d\int_{p_{sfc}}^{p_2}\frac{\partial T_v}{\partial t}d\ln p + g(E-P) + RES_{PTE}$$

Geopotential tendency of upper boundary

ITT: integrated virtual temperature tendency

Precipitation & evaporation

$$\rho_{sfc}R_d\int_{p_{sfc}}^{p_2}\frac{\partial T_v}{\partial t}d\ln p = \rho_{sfc}R_d\int_{p_{sfc}}^{p_2}\left(-\vec{v}\cdot\overrightarrow{\nabla_p}T_v\right)d\ln p$$

TADV: horizontal temperature advection

$$+\rho_{sfc}R_d\int_{p_{sfc}}^{p_2}\left(\frac{R_dT_v}{c_pp}-\frac{\partial T_v}{\partial p}\right)\omega d\ln p$$

VMT: vertical motions

$$+\rho_{sfc}R_d\int_{p_{sfc}}^{p_2}\frac{T_vQ}{c_pT}d\ln p$$

DIAB: diabatic processes

$$+RES_{ITT}$$

# ITT: integrated virtual temperature tendency