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36TH INTERNATIONAL CONFERENCE ON COASTAL ENGINEERING 2018

Baltimore, Maryland | July 30 – August 3, 2018

The State of the Art and Science of Coastal Engineering

Consideration of Storm Surge Caused by Hurricane Irma Based on STOC-WRF Coupling Model

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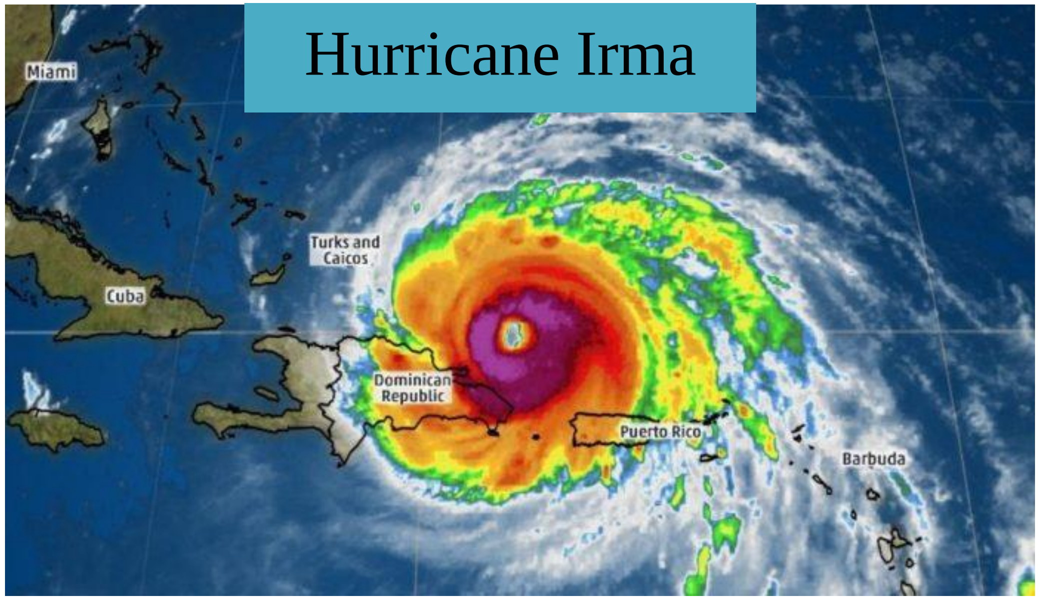
1. Introduction



There was serious damage at Caribbean Islands because of the storm surge and rain fall caused by Hurricane Irma.

British Virgin Islands
(Above : Before, Below : After)
REFERENCE : AccuWeather

To estimate storm surge, it is necessary to evaluate the wind and atmospheric pressure.

1. Introduction

	Empirical Atmospheric pressure model	Provided data by Metrological Agency (GPV)	Mesoscale Weather model (WRF)
Cost	○	×	△
Resolution	Optional setting	×	Optional setting
Accuracy	×	○	○

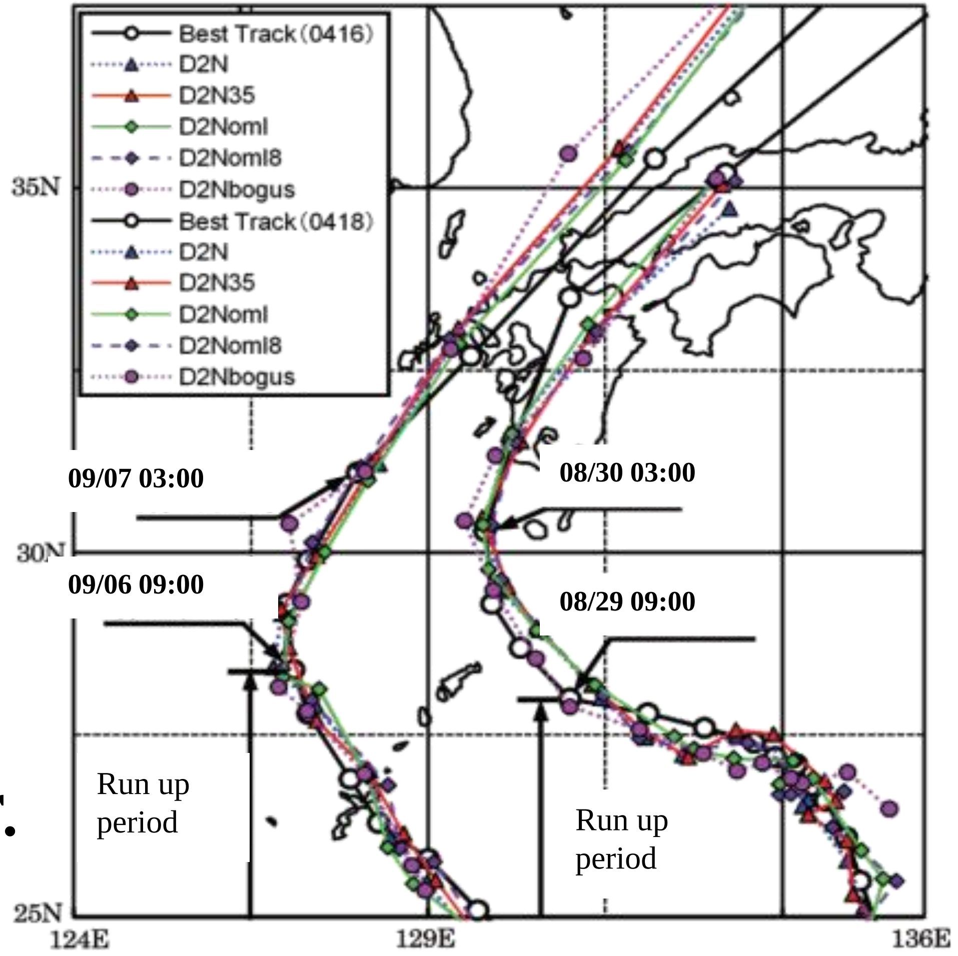
➡ Mesoscale weather model is high accuracy, however there are a lot of choices in numerical conditions (grid size, physics model, and boundary condition, etc.) .

1. Introduction

Previous research

Suzuyama *et al.* (2011) : Study of some characteristics of WRF calculation

・Domain size (moving nests)…700 to 1000km including typhoon margin
・Ocean mixed layer ⇒ maximum wind speed
・Thompson model (Micro physics)
⇒ underestimation can be suppressed



It is said WRF still depends on the experience of the model user.

1. Introduction

Previous researches on hurricane and typhoon by WRF

Author	Target	mp	bl_pbl	cu	ra_sw	ra_lw
Suzuyama *et al.*(2012)	T5115	Thompson	YSU	Kain-Fritsch	Old Goddard	RRTM
Tanemoto *et al.* (2012)	Typhoon (10 years)	Eta	MYJ	Kain-Fritsch	Dudhia	RRTM
Ninomiya *et al.*(2012)	T0918	WSM6	MYJ	Kain-Fritsch	Dudhia	RRTM
Nakamura *et al.*(2016)	T1115	WSM6	YSU	-	RRTMG	RRTMG
Ninomiya *et al.*(2015)	T5915	WSM6	YSU	Kain-Fritsch	RRTMG	RRTMG
Shigeta *et al.*(2014)	T0416, T0418	WSM6	MYJ	Kain-Fritsch	RRTM	RRTM

mp : Micro Physics, bl_pbl :Planetary Boundary Layer Physics, cu : Cumulus Parameterization, ra_sw and ra_lw : Shortwave and Longwave Radiation

1. Introduction

In this study…

- ✓ Evaluate the impact of different model conditions on the reproducibility, performance

- ✓ Estimate storm tide using storm surge prediction model and wave prediction model by applying meteorological fields calculated by mesoscale model(verification of WRF to STOC, SWAN)

1. Introduction –Numerical Model

WRF[1)](Weather Research and Forecasting model)

➡ 3 dimensional fully compressible non-hydrostatic model

STOC-ML[2)](Storm surge and Tsunami simulator in Oceans and Coastal areas)

➡ Quasi 3 dimensional model using hydrostatic approximation in z direction

SWAN[3)](Simulating WAves Nearshore)

➡ Calculate wave propagation in time and space based on spectral action Balance equation

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[1)]Skamarock *et al.* (2008) : A Description of the Advanced Research WRF Version3

[2)]Tomita *et al.* (2005) : Development of numerical simulator of seawater flow and Application to Tsunami Analysis

[3)]Ris *et al.* (1999) : A third-generation wave model for coastal regions: Part 2. Verification

2. Application Method

How to apply WRF to STOC and SWAN

WRF(Lat-Lon coordinate system)

PSFC
HGT
T2

Mean-sea-level barometric pressure (SLP)

U10
V10

*extract every 1h

Interpolate
SLP, U10, V10

Coordinate transformation

Interpolate
U10, V10

STOC(Orthogonal coordinate system)

Storm surge

Wave set up $(\eta = 0.1 H_{1/3})$

Significant wave height

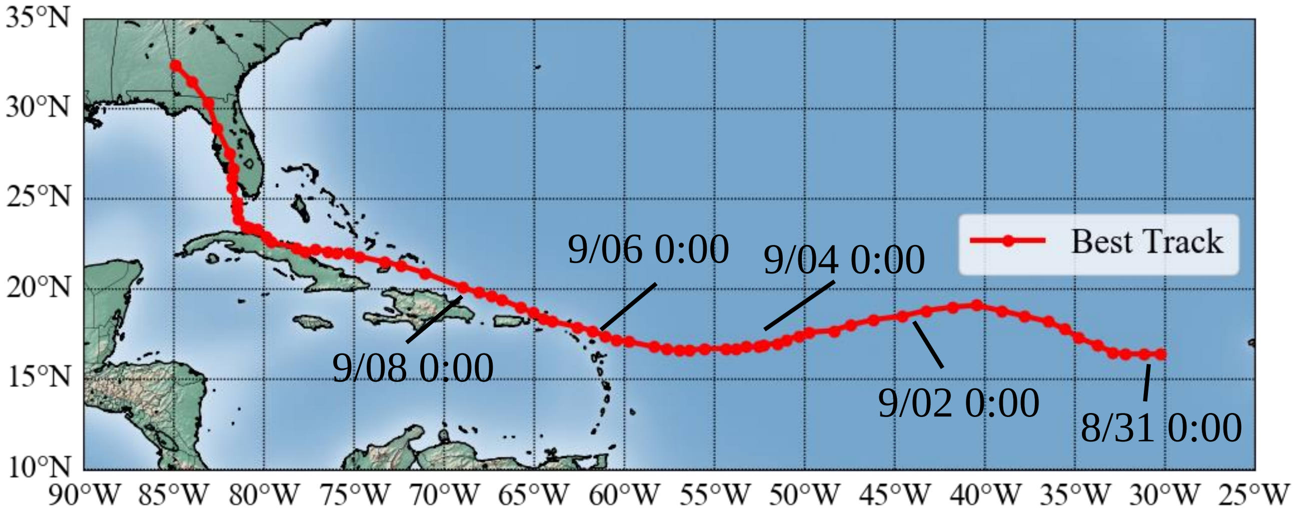
Significant wave period

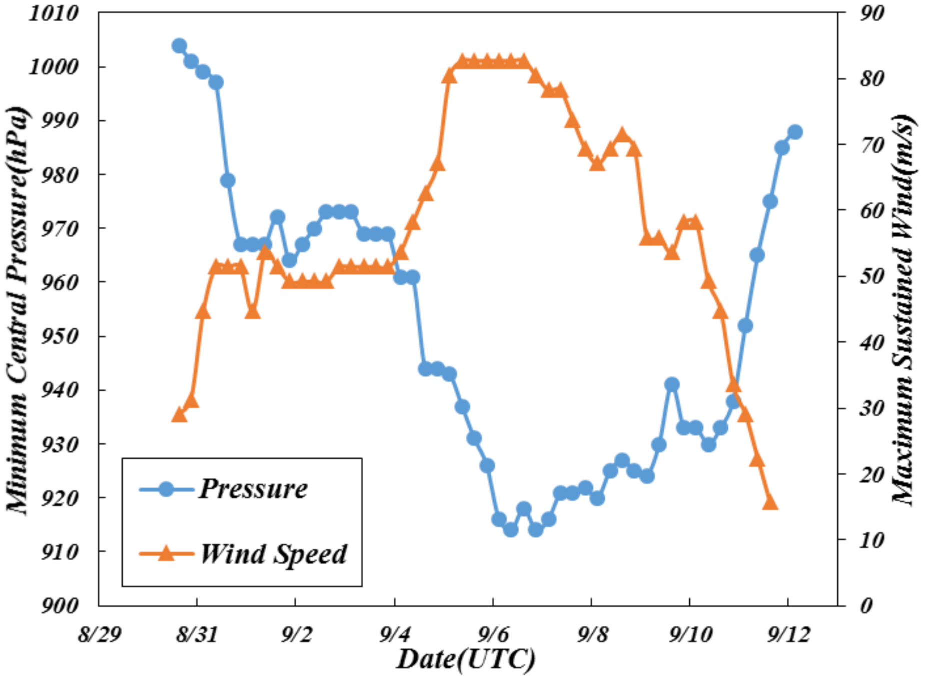
SWAN(Orthogonal coordinate system)

*PSFC: Surface pressure
HGT: Terrain Height
T2: Temperature at 2m
U10, V10: 10m-elevation wind speed

Overview of Hurricane Irma

Basic Information	
Formed Date	August 30, 2017, at 3:00 p.m. (UTC)
Dissipated Date	September 12, 2017, at 3:00 a.m. (UTC)
Minimum Central Pressure	914 (hPa)
Maximum Sustained Wind	82 (m/s)

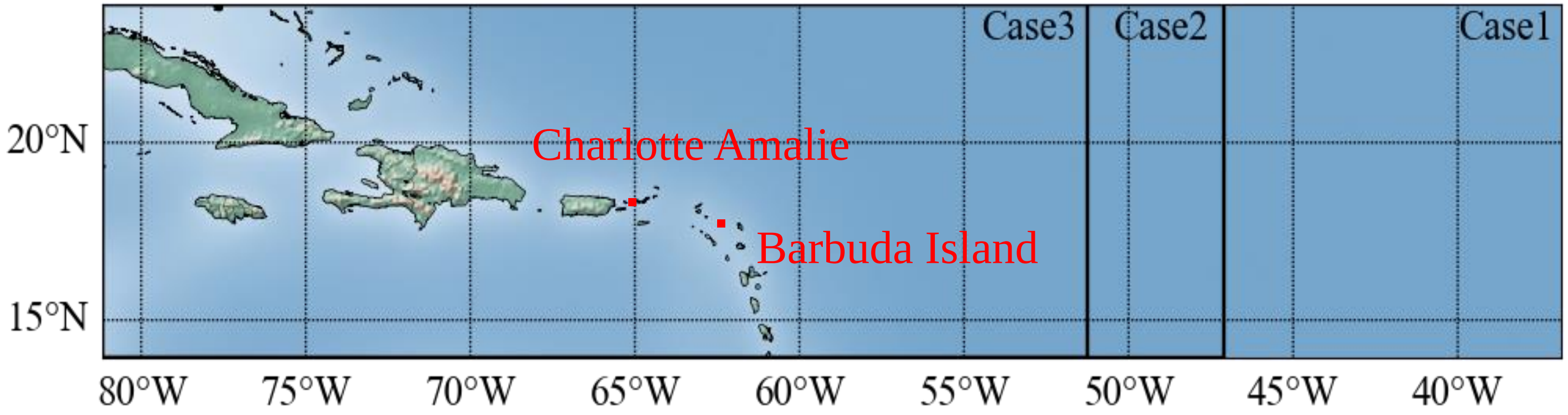




REFERENCE : NOAA

3. Consideration of WRF

WRF



Physics	Scheme
Microphysics(mp)	Thompson (2008)
Longwave Radiation(ra_lw)	RRTMG (2008)
Shortwave Radiation(ra_sw)	RRTMG (2008)
Planetary Boundary Layer(bl_pbl)	Mellor-Yamada-Janjic (1994)
Cumulus Parameterization(cu)	New Simplified Arakawa-Schubert (2011)
Surface Layer(sf_sfclay)	Eta Similarity (2002)
Land Surface(sf_surface)	Unified Noah (2004)

Input and nudging data is NCEP 0.25 × 0.25 provided from July 2015.

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3. Consideration of WRF

Model condition

*D.A. : Data assimilation

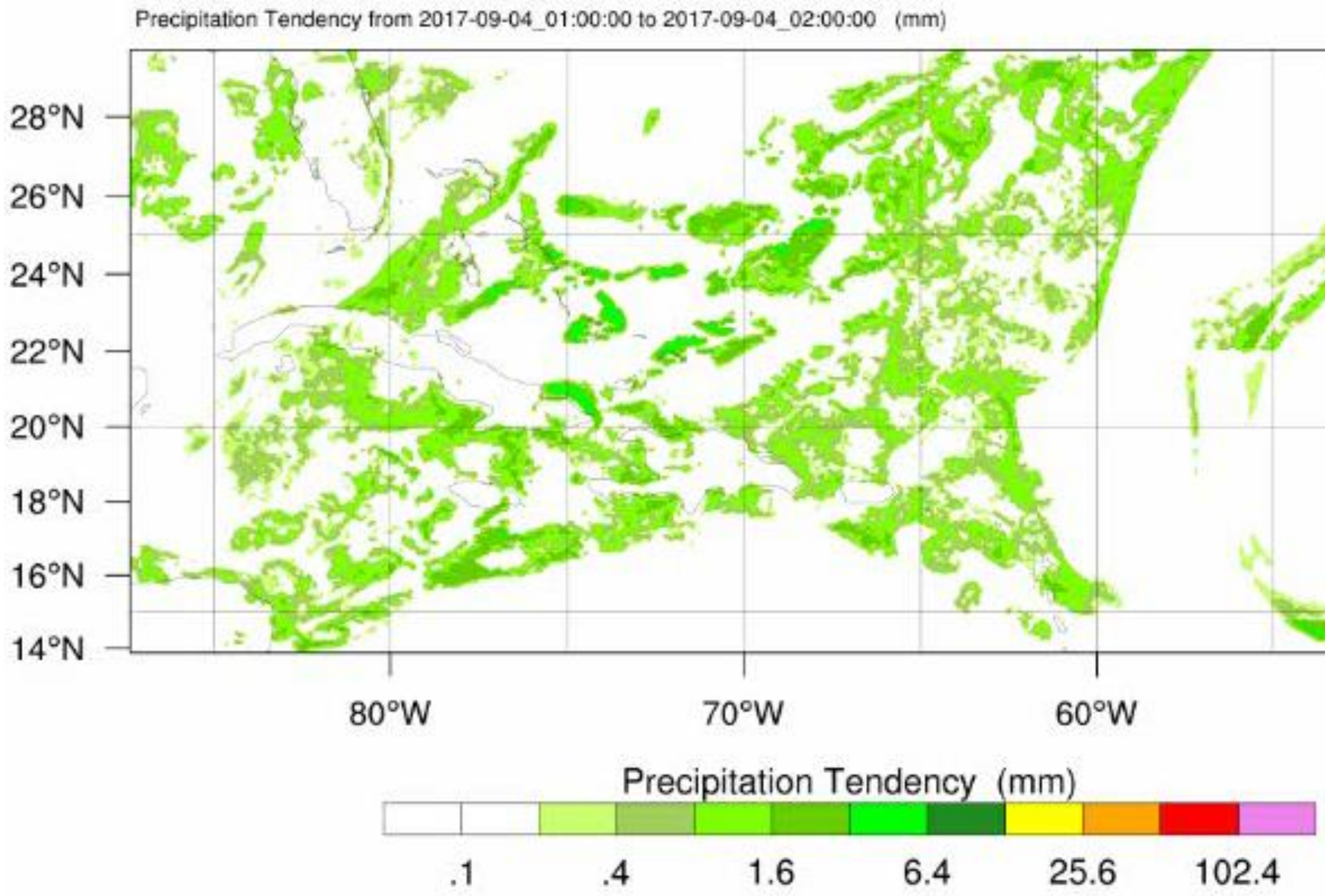
Case	Nesting	D.A.*	Cumulus Parameterization	Calculation Period
Case1	Moving Nest (Vortex following)	No D.A.	New Simplified Arakawa-Schubert	02/Sep./2017 ~ 09/Sep./2017
Case2				04/Sep./2017 ~ 09/Sep./2017
Case3				05/Sep./2017 ~ 09/Sep./2017
Case2-nonest	No Nesting			04/Sep./2017 ~ 09/Sep./2017
Case2-Cu_0	Moving Nest (Vortex following)		No Option (for D2)	
Case2-O		Obs. Nudging	New Simplified Arakawa-Schubert	
Case2-G		Grid Nudging		
Case2-G-Air				
Case2-S600		Spectral Nudging		
Case2-S2000				

Base case

- Nesting
- D.A.
- Cumulus Parameterization

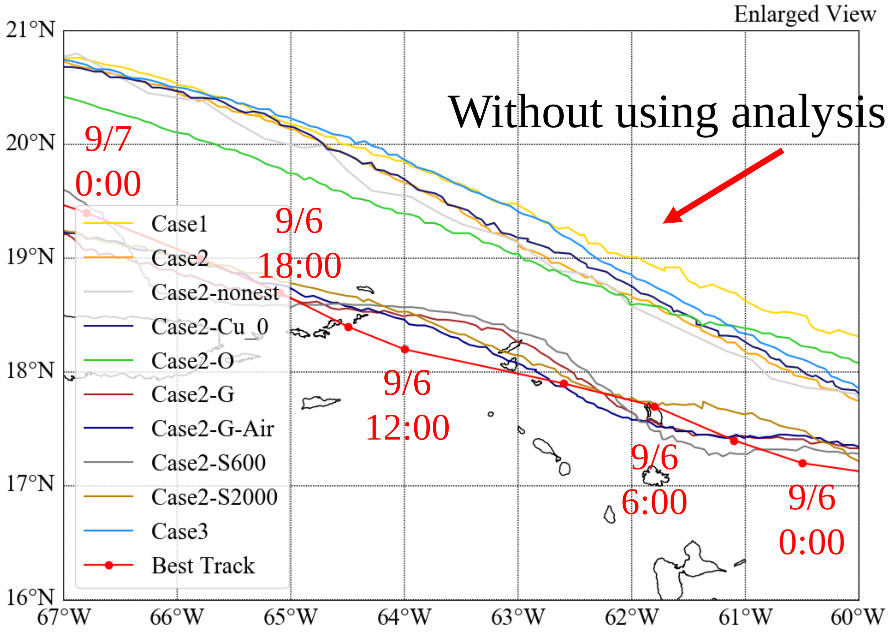
3. Consideration of WRF

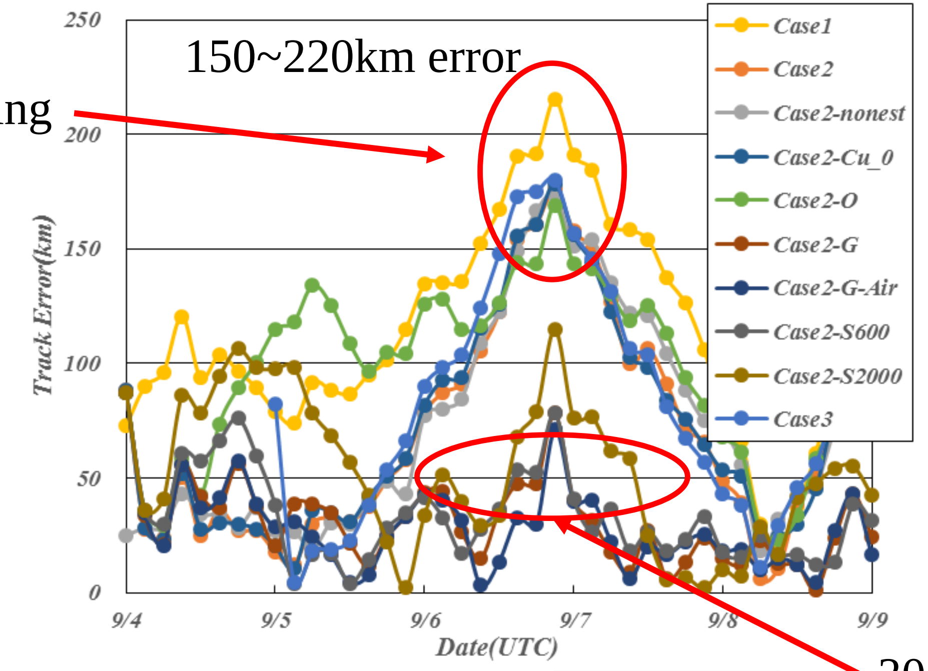
Precipitation Tendency (mm/h)

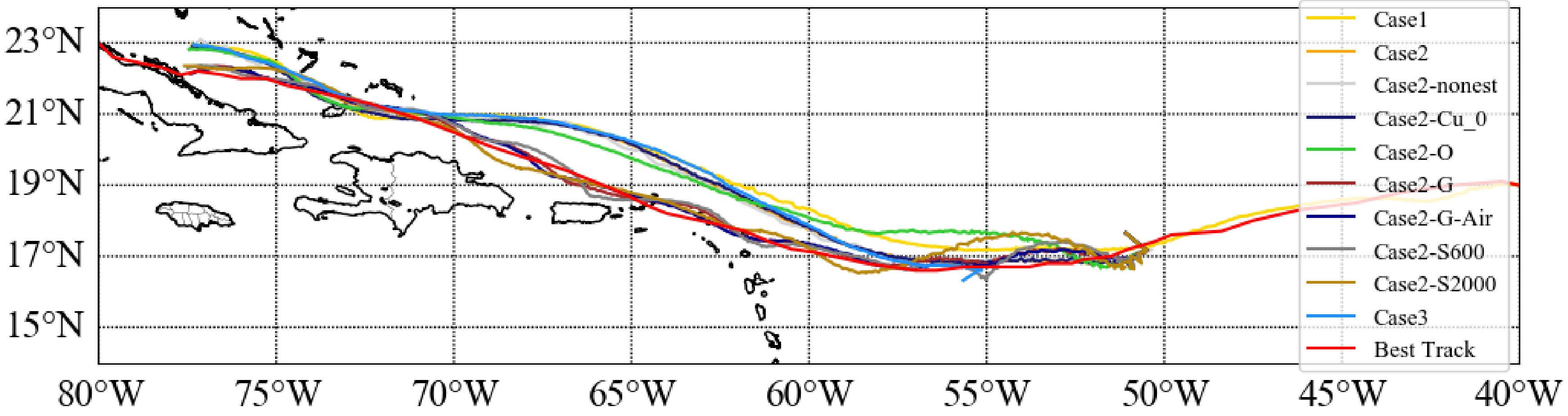


3. Consideration of WRF

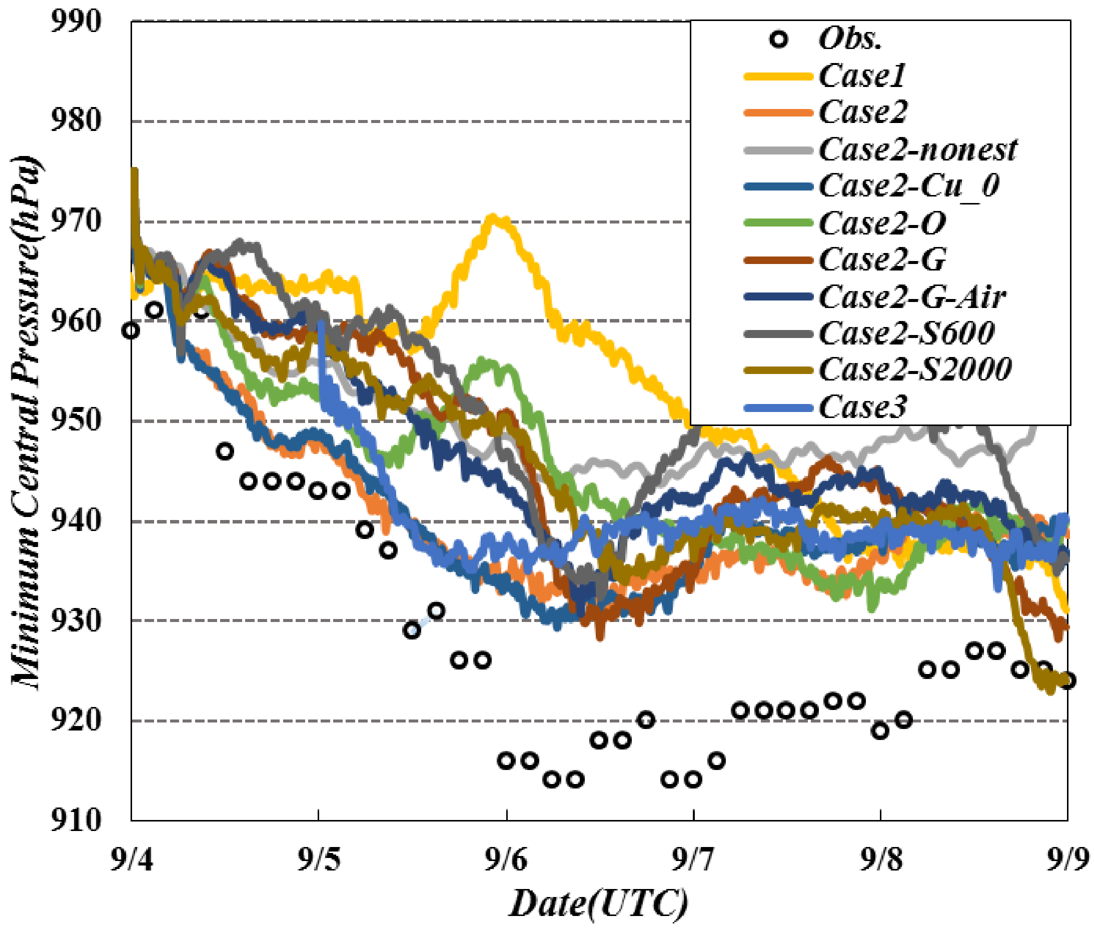
Comparison of track

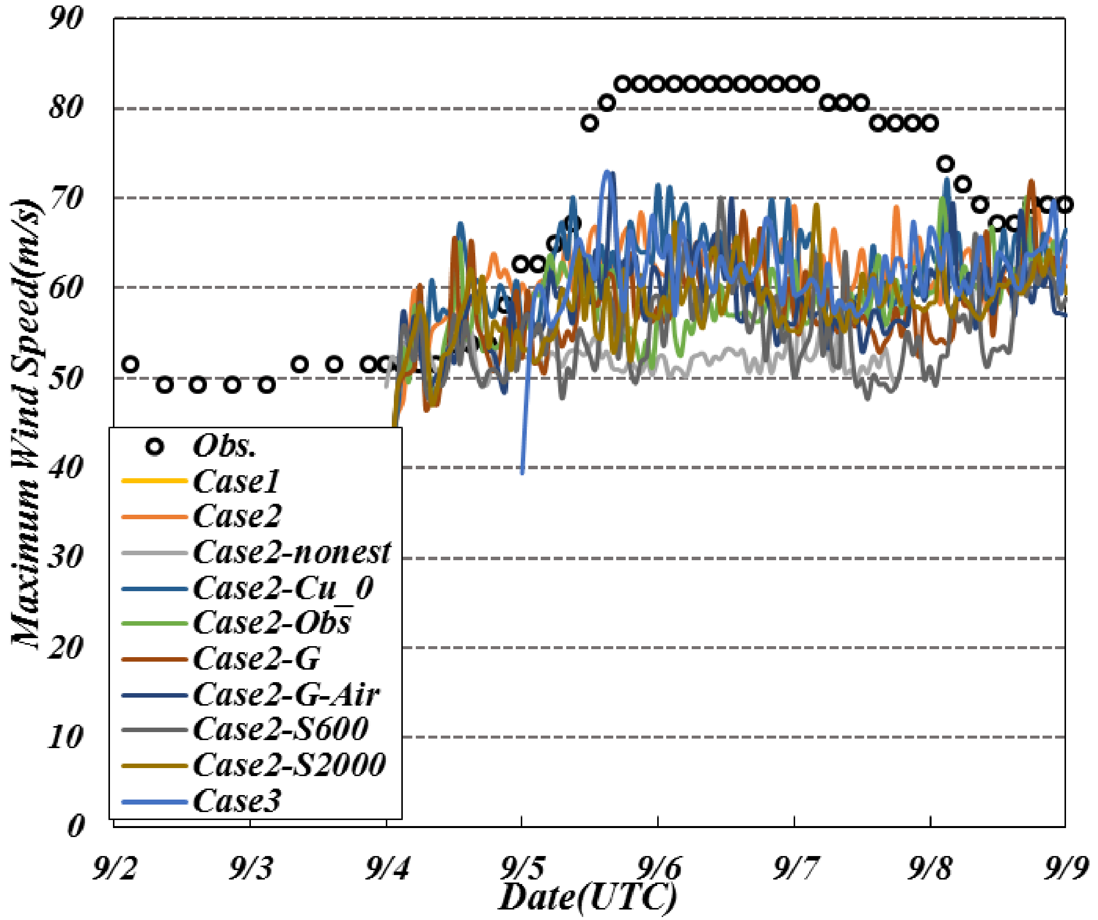






Comparison of the intensity





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Mean Error

$ME = \sum(F(i) - A(i)) \div N$, F:Calculation, A:Observation

Case	Location(km)	Pressure(hPa)	Wind Speed(m/s)
Case1	112.395	19.913	-13.205
Case2	69.890	11.783	-10.007
Case2-nonest	71.909	21.583	-20.577
Case2-Cu_0	71.172	11.800	-10.623
Case2-O	96.252	16.480	-13.704
Case2-G	30.983	17.558	-13.416
Case2-G-Air	28.524	18.288	-14.554
Case2-S600	33.786	23.195	-16.560
Case2-S2000	52.758	16.325	-13.837
Case3	82.672	16.377	-14.712

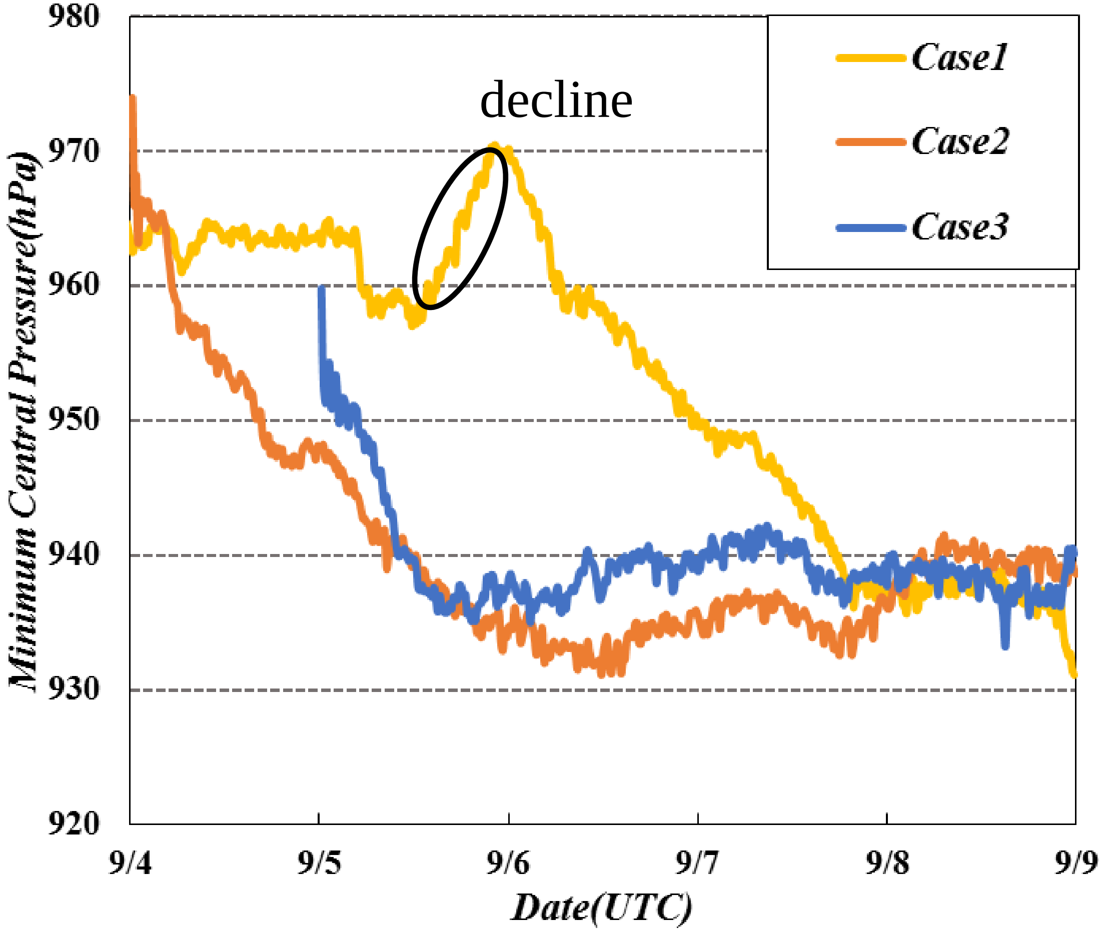
Case2 – Case2-G: 40km, 6hPa, 3m/s

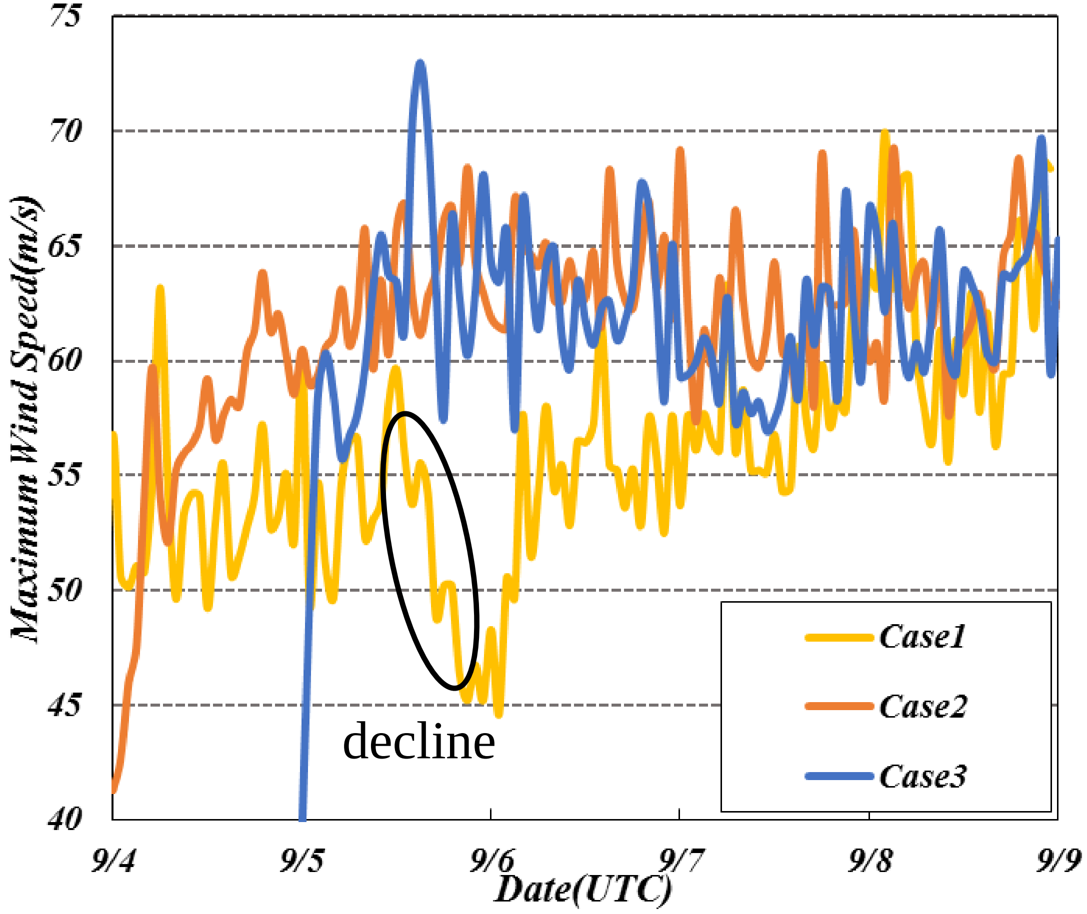
Case2-G – Case2-S2000: 20km, 1hPa, 0.4m/s

*Blue : apply to STOC and SWAN

3. Consideration of WRF

Starting date of calculate





Case2 is most reproduced the strength

→ Start calculation when we confirm the eye of Hurricane Irma

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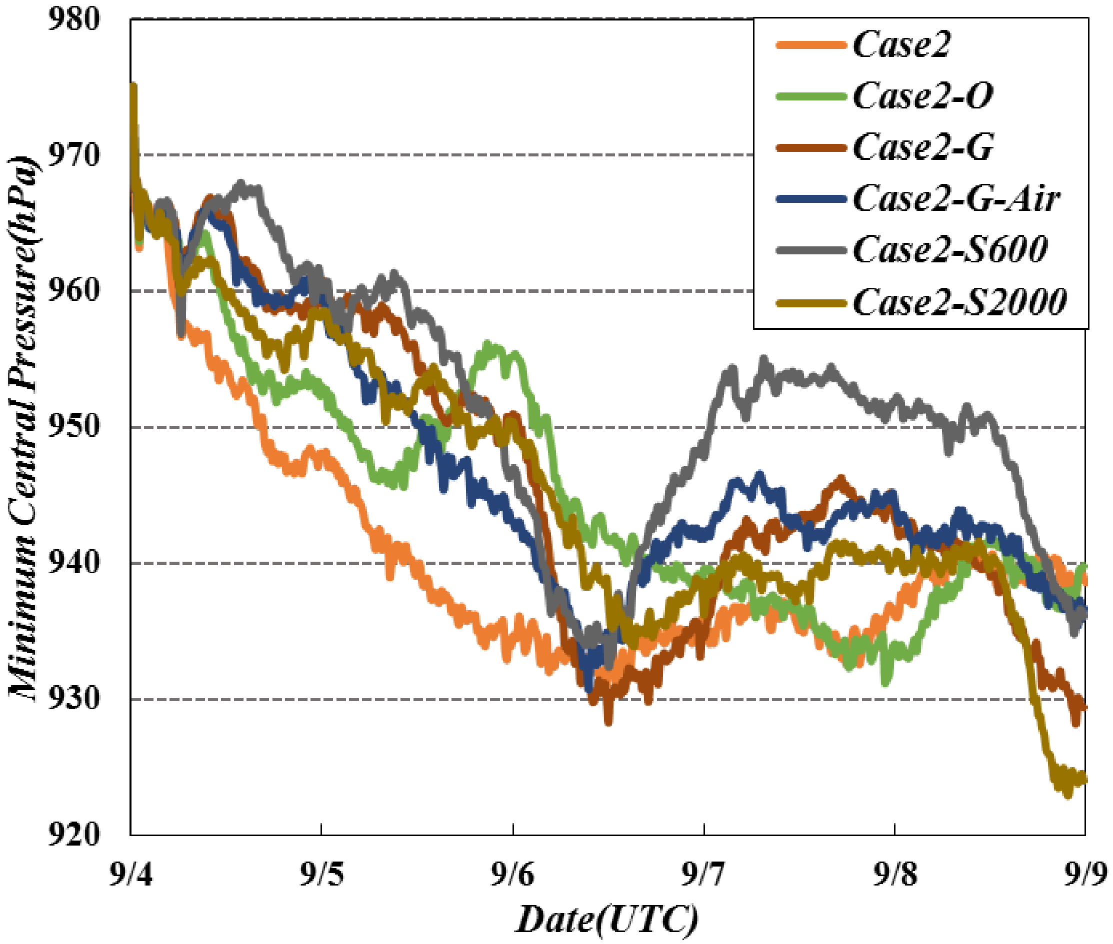
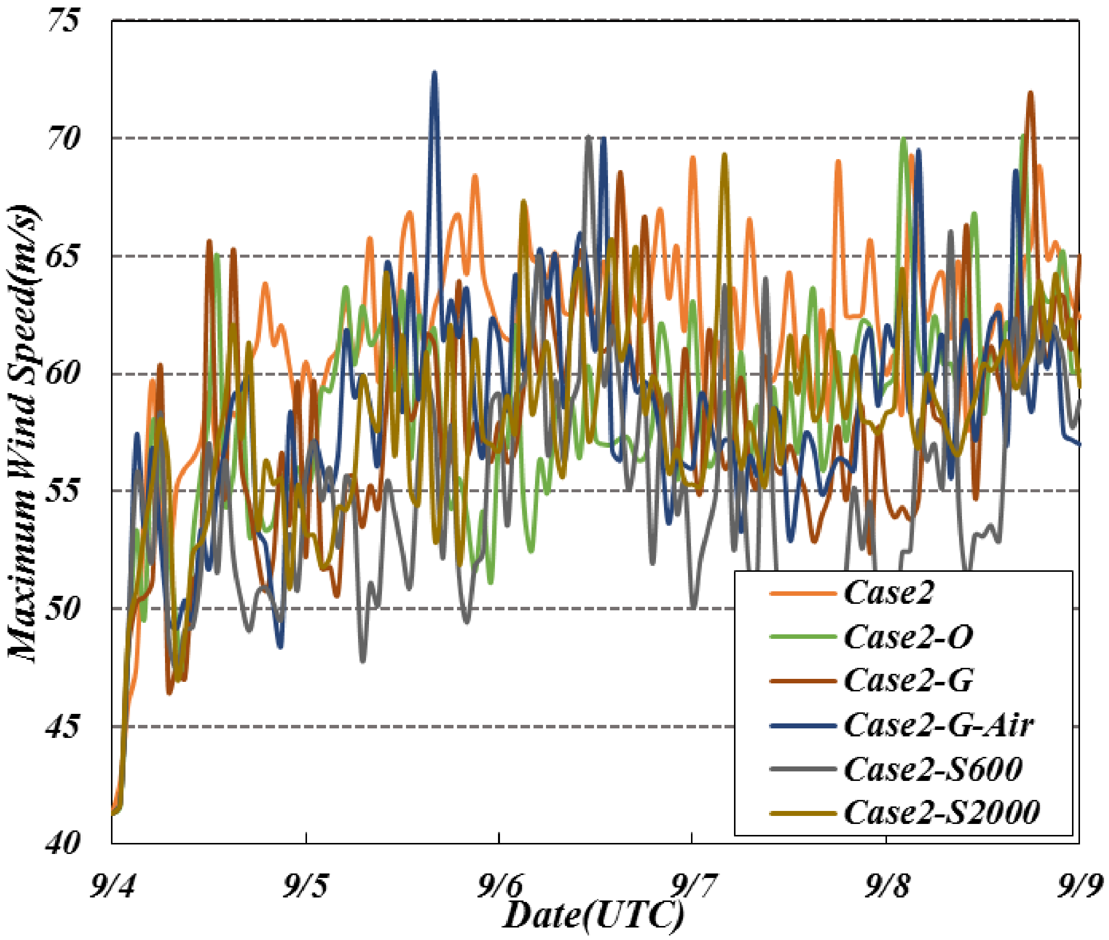
3. Consideration of WRF

Impact of data a assimilation

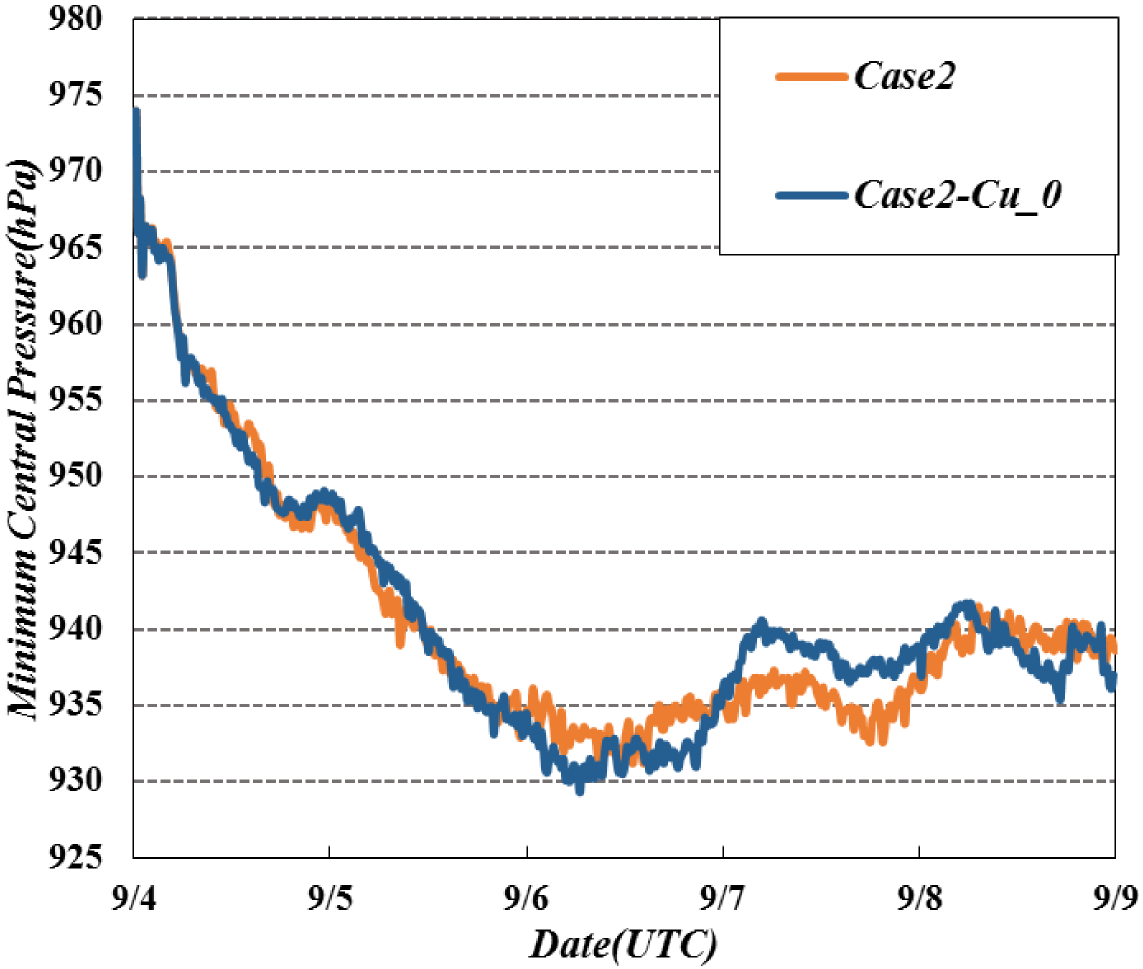


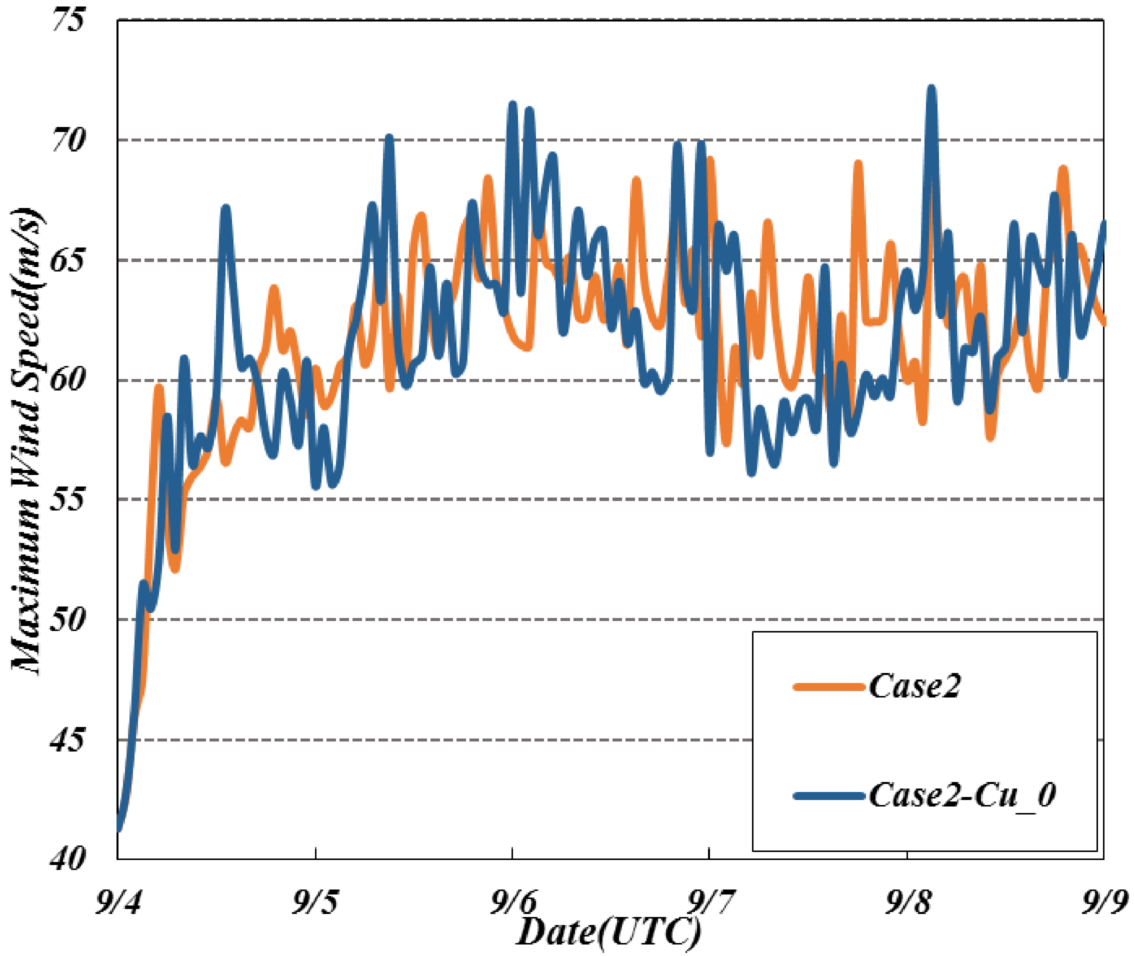


In any case, the result was underestimated because datasets can't reproduce accurately
The intensity reproducibility of Grid nudging is better way than another nudging

3. Consideration of WRF

Impact of cumulus parameterization

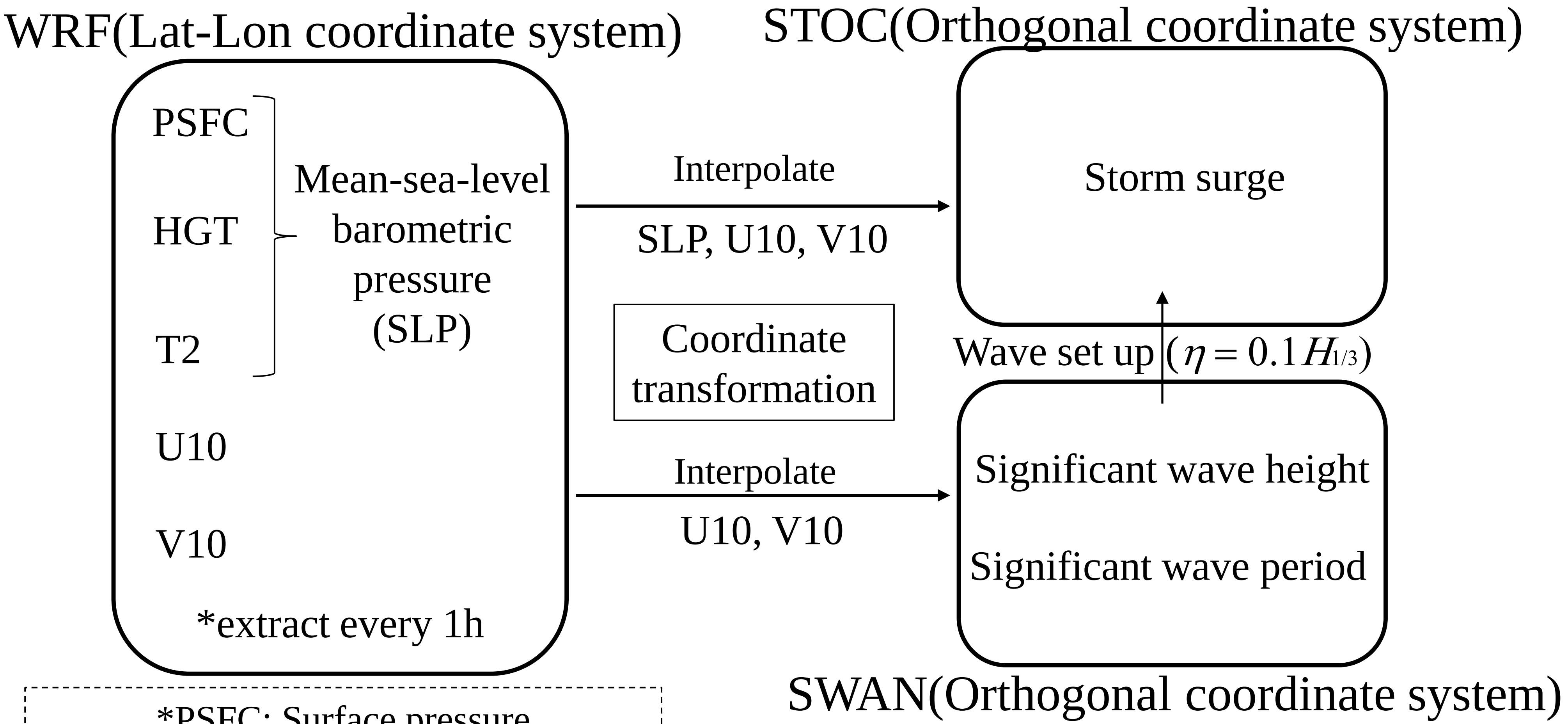




There aren't much difference when focus on meteorological fields and track

4. Application Method

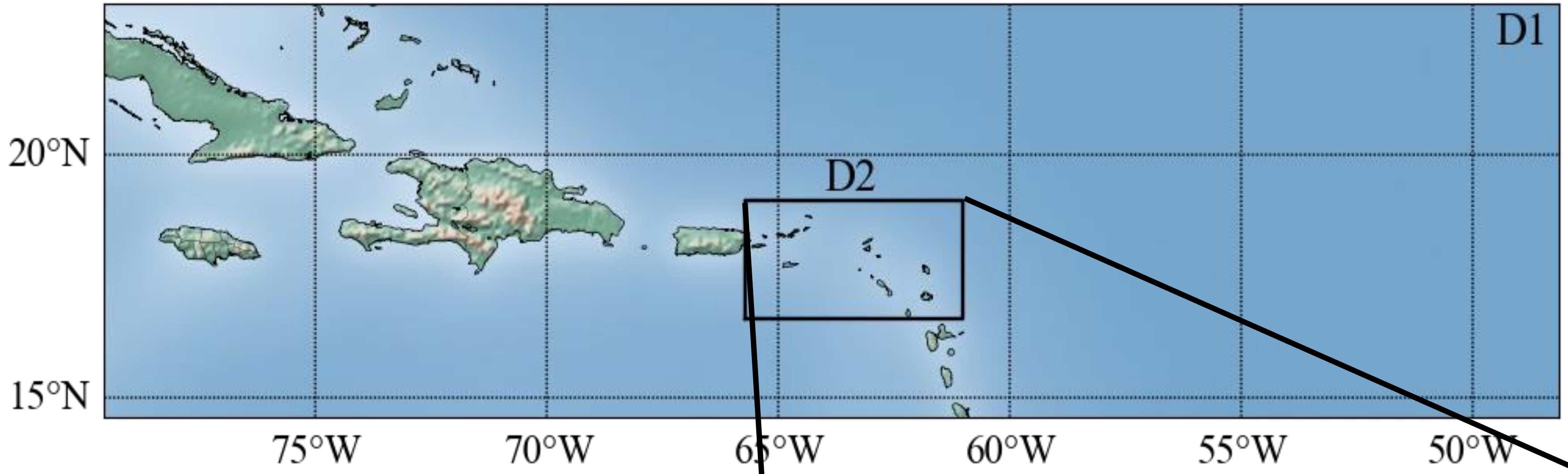
How to apply WRF to STOC and SWAN



*PSFC: Surface pressure
HGT: Terrain Height
T2: Temperature at 2m
U10, V10: 10m-elevation wind speed

4. Consideration of Storm Surge and Wave Height

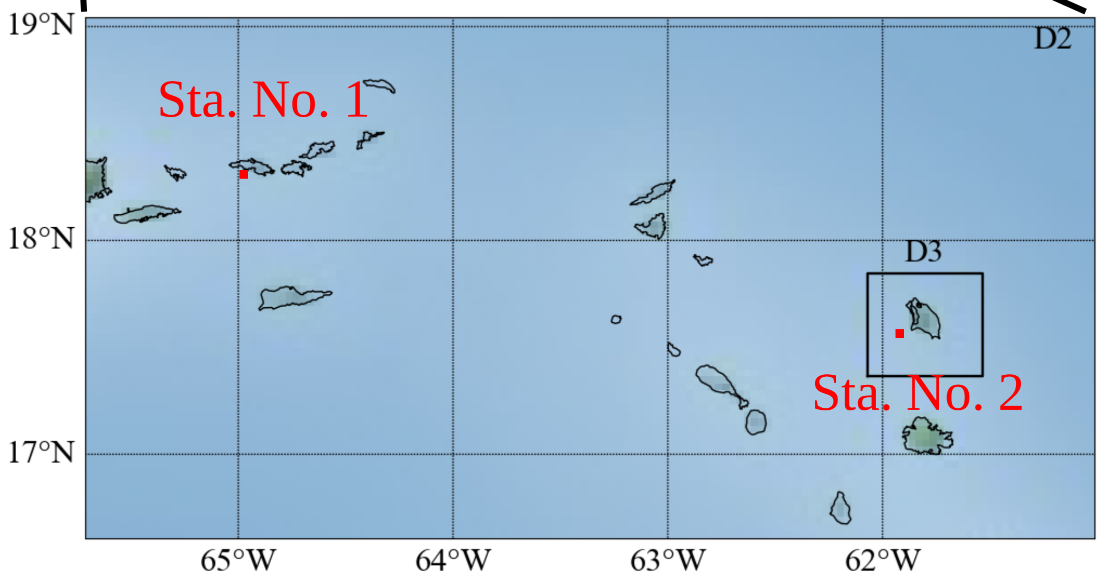
STOC, SWAN



Sta. No. 1 : Charlotte Amalie

Sta. No. 2 : Barbuda Island

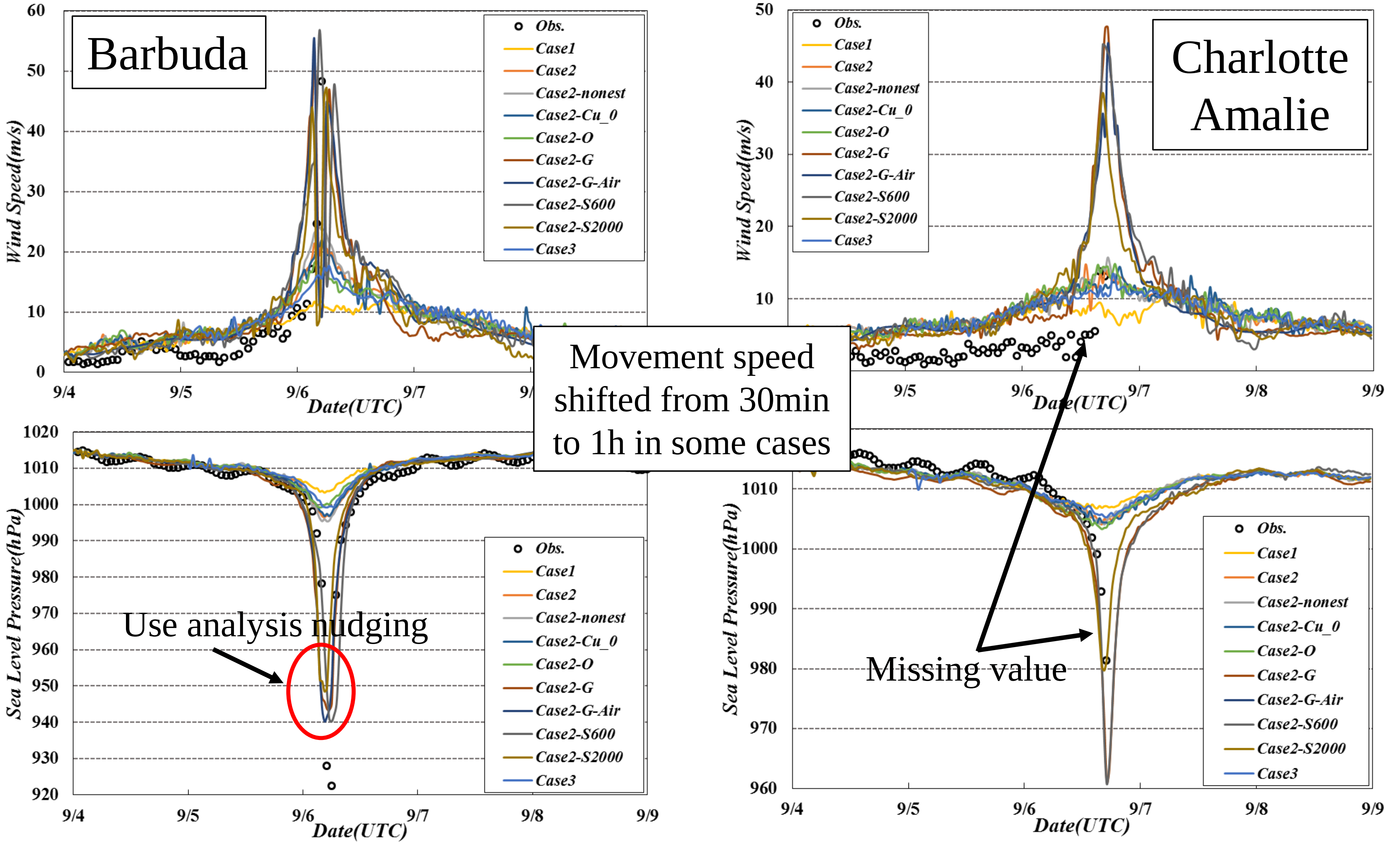
	Grid Size	Num. of Cell
D1	5000m	634*184
D2	1000m	500*275
D3	200m	300*300



4. Consideration of Storm Surge and Wave Height

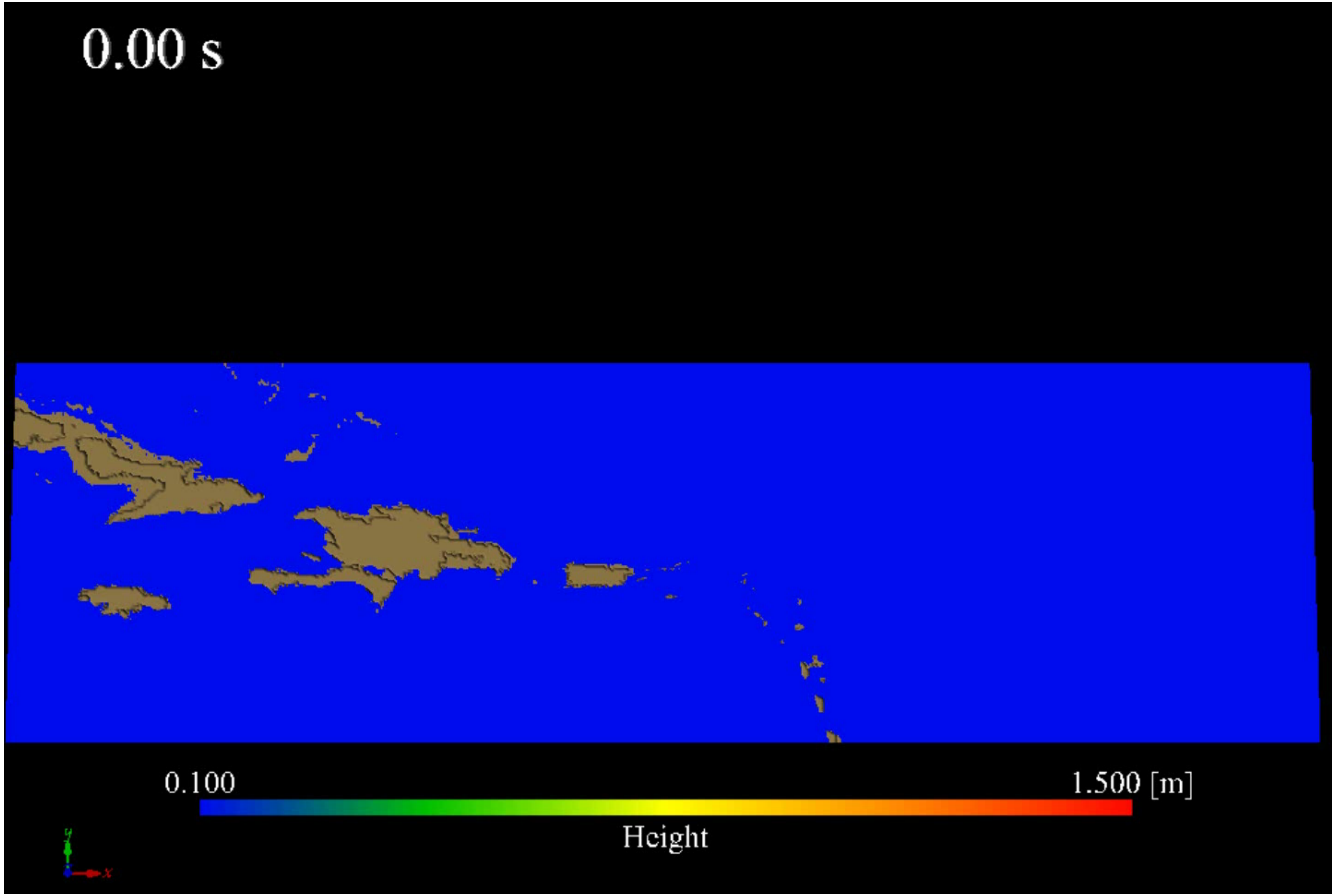
Comparison of the meteorological fields

Depend on track



4. Consideration of Storm Surge and Wave Height

Animation of calculation result about storm surge



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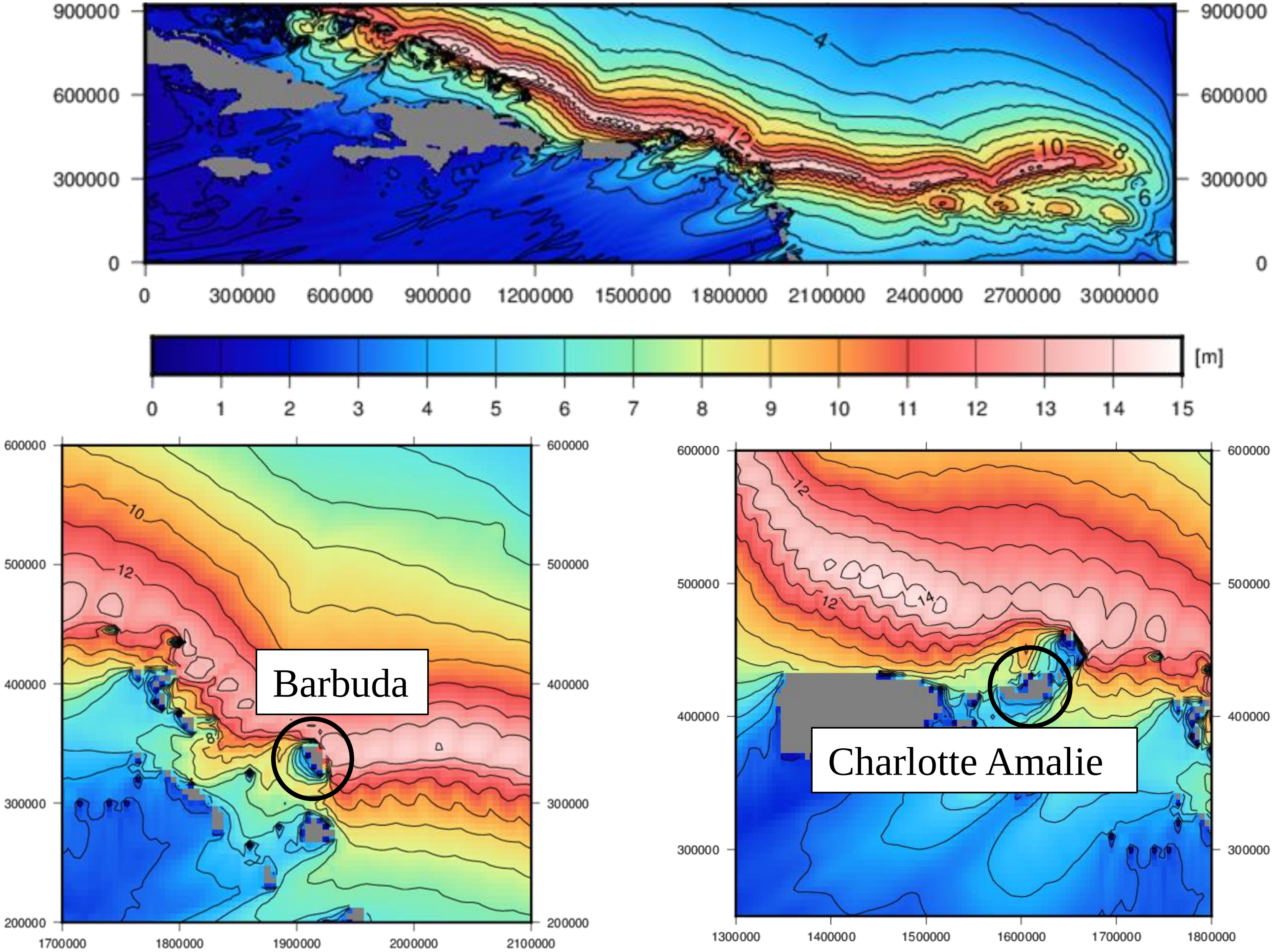
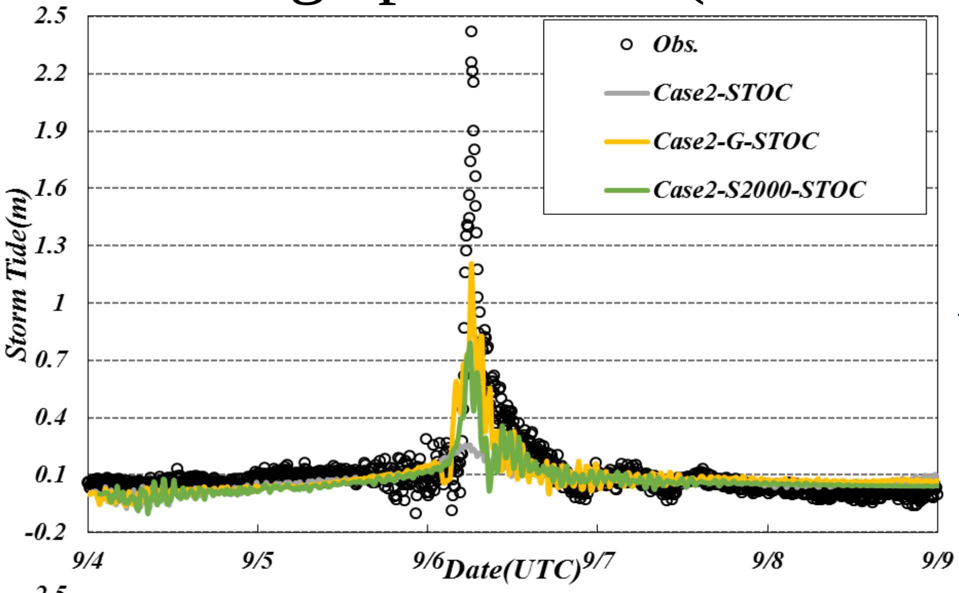
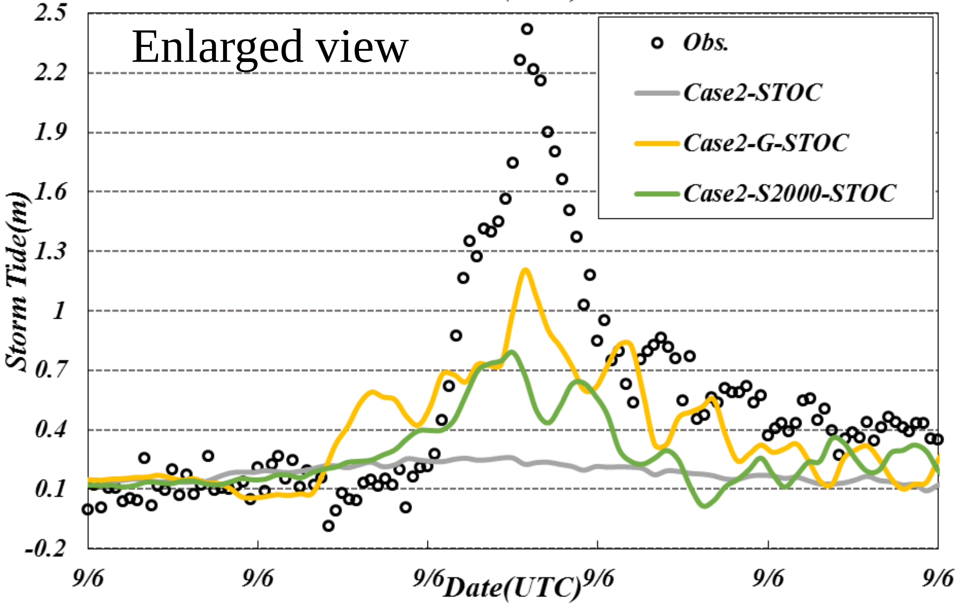
Maximum significant wave height distribution (Case2-G) using by SWAN



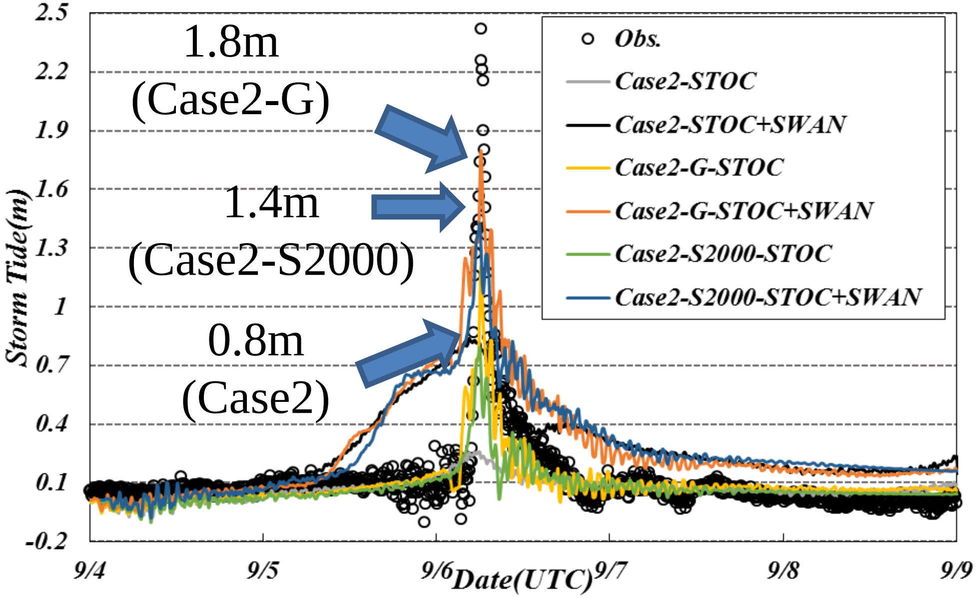
4. Consideration of Storm Surge and Wave Height

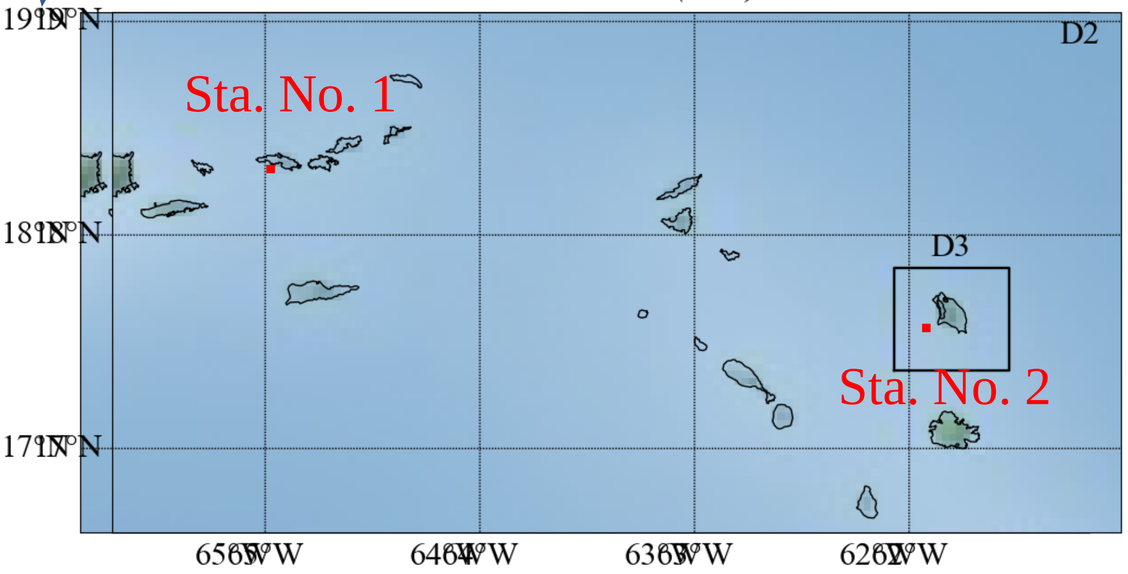
Storm surge prediction(Barbuda)





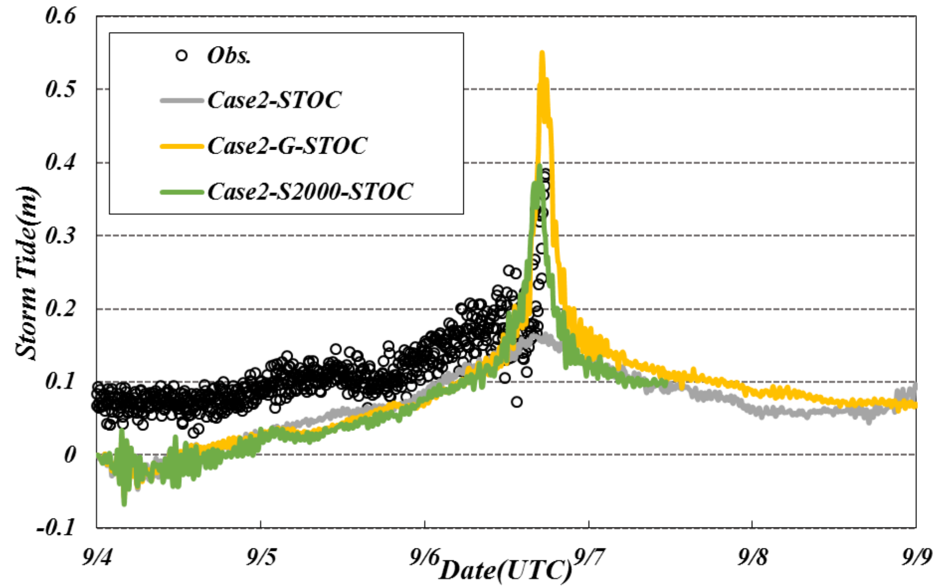
Wave set up



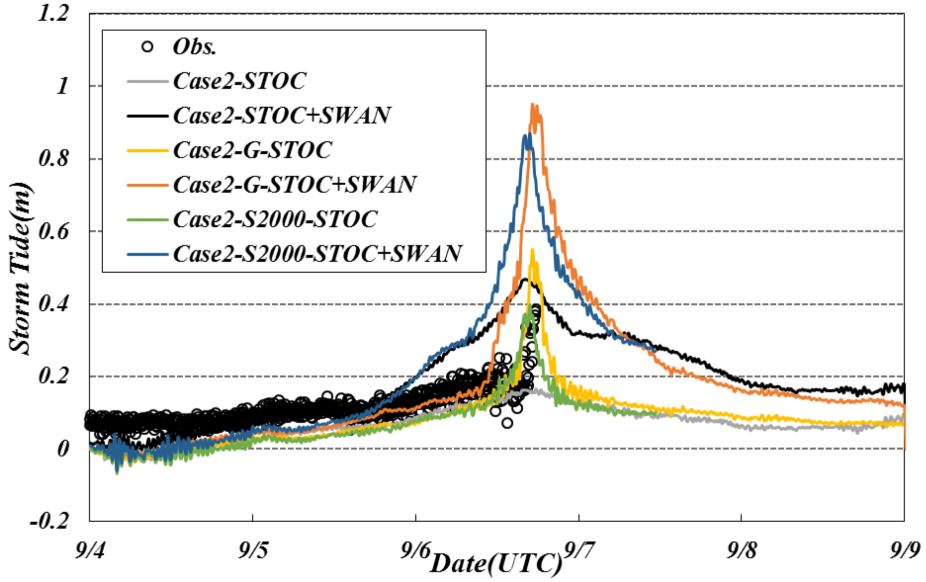


4. Consideration of Storm Surge and Wave Height

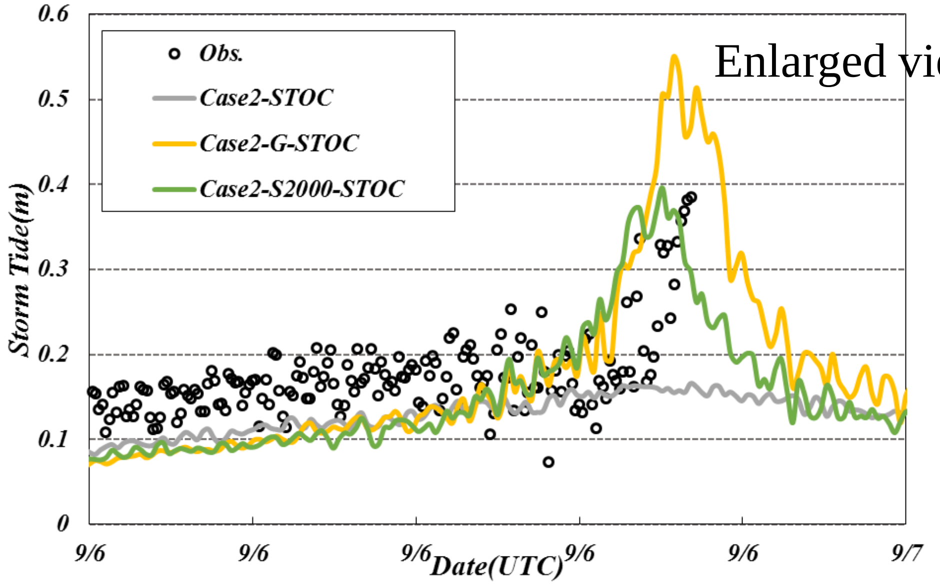
Storm surge prediction (Charlotte Amalie)

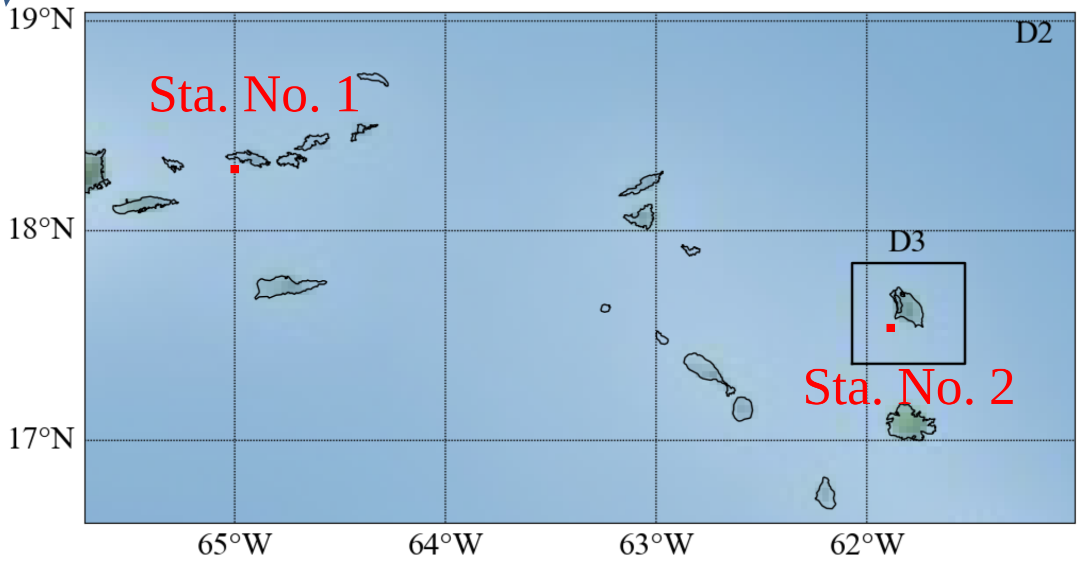


Wave set up



Enlarged view





5. Conclusion

1) By setting the initial time when the eye of Hurricane can be confirmed, the development of the strength can be reproduced well.

2) By applying grid analysis nudging for D1, the reproducibility of the hurricane track improved, specifically the error falls within the range of 30 to 50km as a whole.

3) If we use 1km moving nests, it doesn’t significantly affect the reproducibility of meteorological fields without using cumulus parameterization because it is said to calculate vertical transport directly.

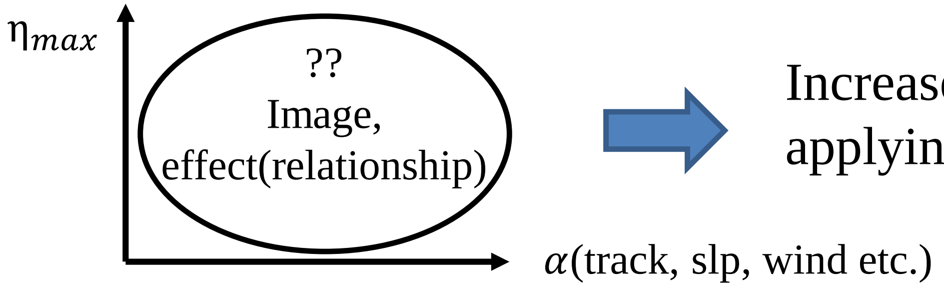
4) It is considered that if we accurate meteorological fields (WRF) to STOC, storm surge occurred at the points can be reproduced.

5. Conclusion

Future works

- Further consideration

  Ex.)apply to other weather disturbances, investigate the effect of WRF error to storm surge…



Increase the number of case applying to STOC, SWAN

- Calculate wave setup correctly

- Floods and river inundation

Eventually, want to make use to the evacuation

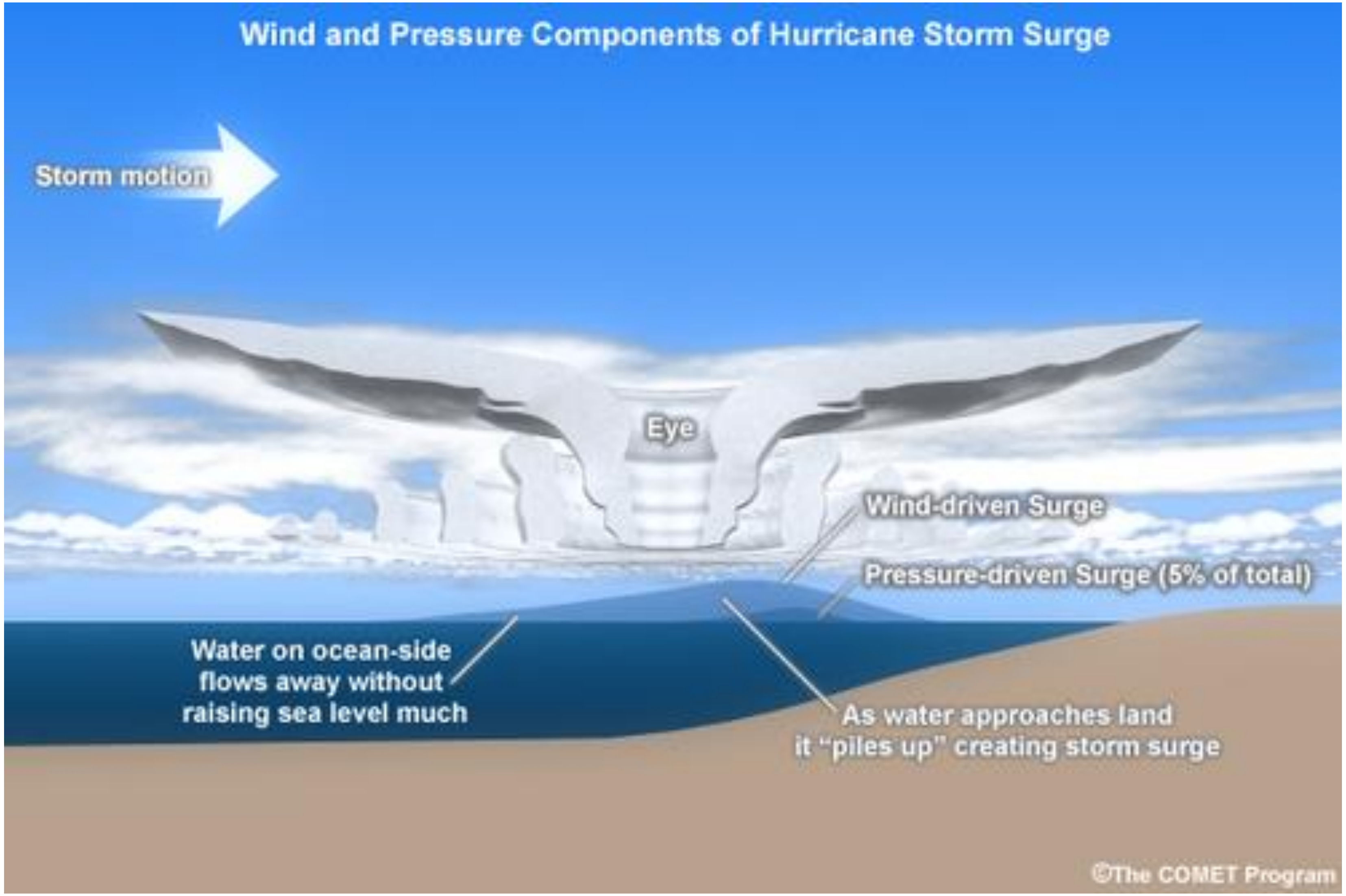
Thank you for your listening

2. Application Method

How to apply WRF to STOC and SWAN

WRF

STOC,
SWAN



REFERENCE : UCAR -What Causes Storm Surge- (https://scied.ucar.edu/what-causes-storm-surge)

Appendix -Consideration of WRF

Root Mean Square Error

$RSME = SQRT\{\sum(F(i) - A(i))^{\wedge 2} \div N\}$, F:Calculation, A:Observation

Case	Location(km)	Pressure(hPa)	Wind Speed(m/s)
Case1	121.146	25.199	17.959
Case2	83.547	13.429	13.245
Case2-nonest	85.094	23.053	22.786
Case2-Cu_0	83.969	13.515	14.586
Case2-O	103.065	18.585	17.140
Case2-G	35.783	19.082	17.008
Case2-G-Air	33.533	19.324	17.335
Case2-S600	39.283	24.706	19.631
Case2-S2000	61.282	18.246	16.663
Case3	96.418	17.342	16.637

Appendix

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WRF – Governing equation

η coordinate system : $\eta = \dfrac{(P_h - P_{ht})}{\mu}$, $where\ \mu = P_{hs} - P_{ht}$

(Conservation of momentum)

$$\begin{cases} \partial_t U + (\nabla . V_u) + \mu_d \alpha \partial_x p + (\alpha/\alpha_d)\partial_\eta p \partial_x \emptyset = F_U \\ \partial_t V + (\nabla . V_v) + \mu_d \alpha \partial_y p + (\alpha/\alpha_d)\partial_\eta p \partial_y \emptyset = F_V \\ \partial_t W + (\nabla . V_w) - g[\left(\dfrac{\alpha}{\alpha_d}\right)\partial_\eta p - \mu_d] = F_W \end{cases}$$

$, where\ \boldsymbol{V} = \mu_d \boldsymbol{v}, (\boldsymbol{V} = (U, V, W), \boldsymbol{v} = (u, v, w))$

(Conservation of mass)

$$\partial_t \mu_d + (\nabla . V\ ) = 0$$

P_h : hydrostatic component of the pressure, $P_{hs}\ and\ P_{ht}$: refer to values along the surface and top boundaries

Appendix

(Entropy mass conservation)

$$\partial_t \Theta + (\nabla . V\theta) = F_\Theta \quad ,\text{where } \Theta = \mu_d \theta$$

(Scalar mass conservation)

$$\partial_t Q_m + (\nabla . V q_m) = F_{Q_m} \quad ,\text{where } Q_m = \mu_d q_m$$

(Geopotential law)

$$\partial_t \emptyset + \mu_d^{-1}[(V.\nabla\emptyset) - gW] = 0 \quad ,\text{where } \emptyset = gz$$

(Diagnostic relations)

$$\partial_\eta \emptyset = -\alpha_d \mu_d$$

$$p = (R_d \theta_m / p_0 \mu_d \alpha_d)^\gamma$$

R :gas constant, α :specific volume, γ :ratio of c_p to c_v ($= c_p/c_v$), d :dry air, q_m :mixing ratio of water vapor, cloud water, snow, ice, hailstone, ω :vertical velocity, θ_m :virtual potential temperature($\theta_m = \theta[1 + \left(\frac{R_v}{R_d}\right) q_m] \approx \theta(1 + 1.61 q_m)$), R_v :gas constant(moist air), W :vertical flux

STOC – Governing equation

(Conservation of momentum)

x-direction: $$\gamma_v \frac{\partial u}{\partial t} + \frac{\partial}{\partial x}(\gamma_x uu) + \frac{\partial}{\partial y}(\gamma_y uv) + \frac{\partial}{\partial z}(\gamma_z uw) - \gamma_v f_0 v = -\gamma_v \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\gamma_x \nu_H 2\frac{\partial u}{\partial x}\right)$$
$$+ \frac{\partial}{\partial y}\left\{\gamma_y \nu_H \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right\} + \frac{\partial}{\partial z}\left\{\gamma_z \nu_V \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)\right\}$$

(Conservation of mass) $$\frac{\partial}{\partial x}(\gamma_x u) + \frac{\partial}{\partial y}(\gamma_y v) + \frac{\partial}{\partial z}(\gamma_z w) = 0$$

(Wind stress) $$\tau_{sx} = \rho_a \gamma_a^2 W_x \sqrt{W_x^2 + W_y^2}$$

$$\begin{cases} \gamma_a^2 = 0.001 \times (1.29 - 0.024\sqrt{W_x^2 + W_y^2} & \left(when \sqrt{W_x^2 + W_y^2} < 8.0m/s\right) \\ \gamma_a^2 = 0.001 \times (1.29 - 0.024\sqrt{W_x^2 + W_y^2} & \left(when \sqrt{W_x^2 + W_y^2} \geq 8.0m/s\right) \end{cases}$$

(Bottom friction) $$\tau_{bx} = \frac{\rho g n^2 u_b \sqrt{u_b^2 + v_b^2}}{h^{1/3}}$$

SWAN – Governing equation

(Spectral action balance equation)

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial x}\left(C_x N\right)+\frac{\partial}{\partial y}\left(C_y N\right)+\frac{\partial}{\partial \sigma}\left(C_\sigma N\right)+\frac{\partial}{\partial \theta}\left(C_\theta N\right)=S/\sigma$$

(Source term)

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

S_{in}: Energy transportation by wind

S_{ds}: Dissipation of wave energy

S_{nl}: Energy transportation by nonlinear wave-wave interactions

Appendix

What is Nudging method?

Assimilate observed values or objective analysis values as external force term

How to assimilate gridded data

$$\frac{\partial \mu \alpha}{\partial t} = F(\alpha, X, t) + \mu \cdot G_\alpha \cdot W_\alpha \cdot \varepsilon\alpha(X)(\hat{\alpha} - \alpha)$$

F: physical forcing terms of α, μ : dry hydrostatic pressure, X : independent spatial variable, t : specified time window, α : prediction variables (wind, temperature, water vapor), $\hat{\alpha}$: objective analysis values to the grid and interpolated linearly for α, G_α : timescale controlling the nudging strength applied to variable α, W_α : vertical weight, $\varepsilon\alpha$: horizontal weight for observation density

Appendix

How to assimilate obs. data

$$\frac{\partial \mu \alpha}{\partial t} = F(\alpha, X, t) + \mu \cdot G_{\alpha} \cdot \frac{\sum_{i=1}^{N} W_i^2(X,t)\,[\alpha_0(i) - \alpha_m(X_i, t)]}{\sum_{i=1}^{N} W_i(X,t)}$$

$$W_i(X,t) = w_{xy} \cdot w_{\sigma} \cdot w_t \quad \begin{cases} w_{xy} = \dfrac{R^2 - D^2}{R^2 + D^2}\ (0 \le D \le R) \quad , w_{xy} = 0\ (D > R) \\ w_t = 1\ (|t - t_0| < \frac{\tau}{2}) \quad , w_t = \dfrac{\tau - |t - t_0|}{\tau/2}\ (\frac{\tau}{2} \le |t - t_0| \le \tau) \end{cases}$$

N: total number of the observed points, i : index to the current observation, α_m : model value of α interpolated to the observation location, w_{σ}: vertical weight, R : radius of influence, D : distance from observation modified by difference of elevation

Appendix

- **Grid nudging**

  Assimilate objective analysis values for lattice points

- **Spectral nudging**

  For arbitrary scale disturbance
  This may be useful for controlling longer wave phases for long analysis-driven simulations

- **Observation nudging**

  Each grid point is nudged using a weighted average of differences from observations within a radius of influence and time window