EERA DeepWind CONFERENCE 2025

2024/1/15 (Wed.) 14:20-14:35

Session 1B) Met-ocean conditions

Prediction of typhoon-induced extreme wave height using mesoscale model and tropical cyclone best track data

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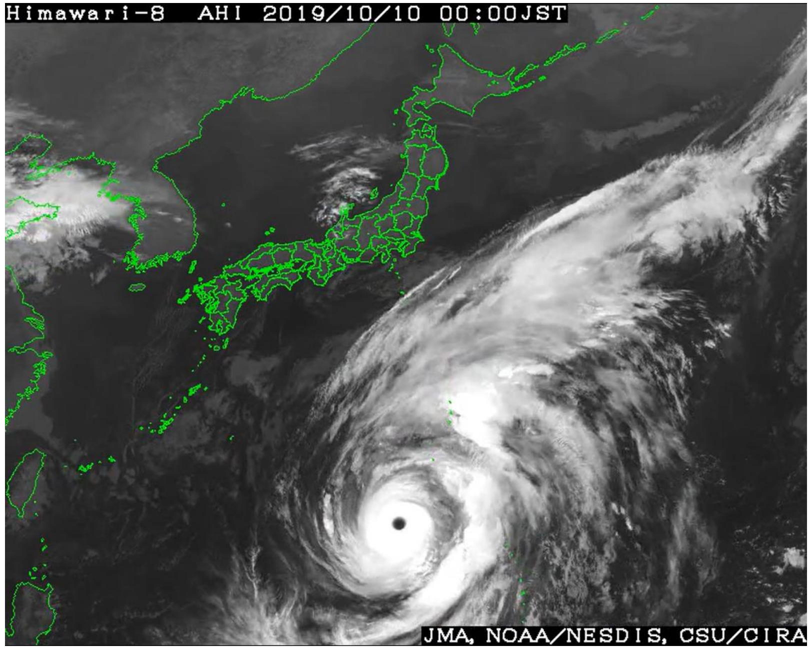
Background

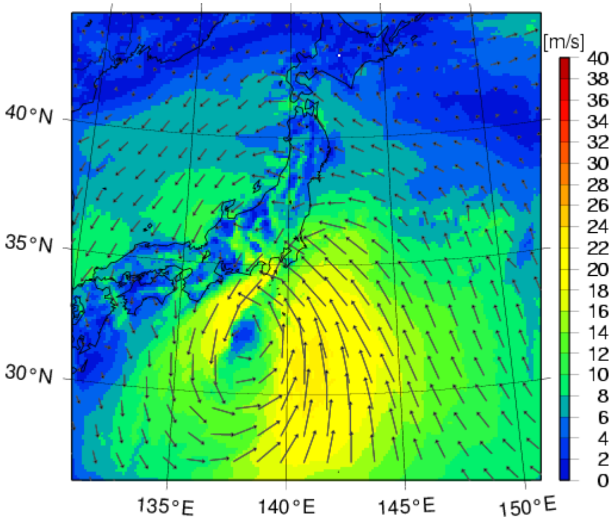
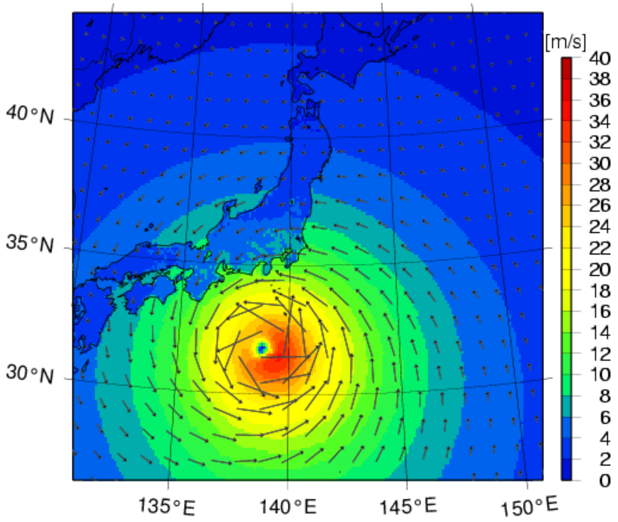
- Typhoons have a significant impact on extreme wave heights in the Northwest Pacific, which makes their accurate prediction vital for the design of offshore wind turbines.
- Hindcasting techniques are necessary for predicting extreme wave heights due to the lack of long-term offshore observations.
- Since swells play an important role in open seas such as the Pacific Ocean, it is essential to accurately predict wind speeds both inside and outside a typhoon.



Accurate prediction of typhoon-induced wind fields is important.

Mesoscale and Typhoon Models

- Mesoscale models can well predict normal wind conditions (Kikuchi et al., 2020) however they tend to underestimate wind speeds near the typhoon center.
- Typhoon models can well predict wind speeds near the center however they underestimate them far from the center.

	Mesoscale model u_M	Typhoon model u_T
Near	×	○
Far	○	×
Wind Field		

It is important to combine the strengths of mesoscale and typhoon models.

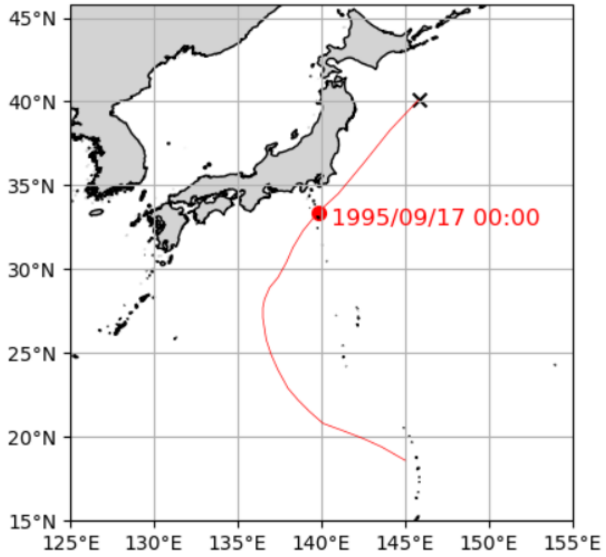
Problem 1. Identification of Tropical Cyclone (TC) Parameters

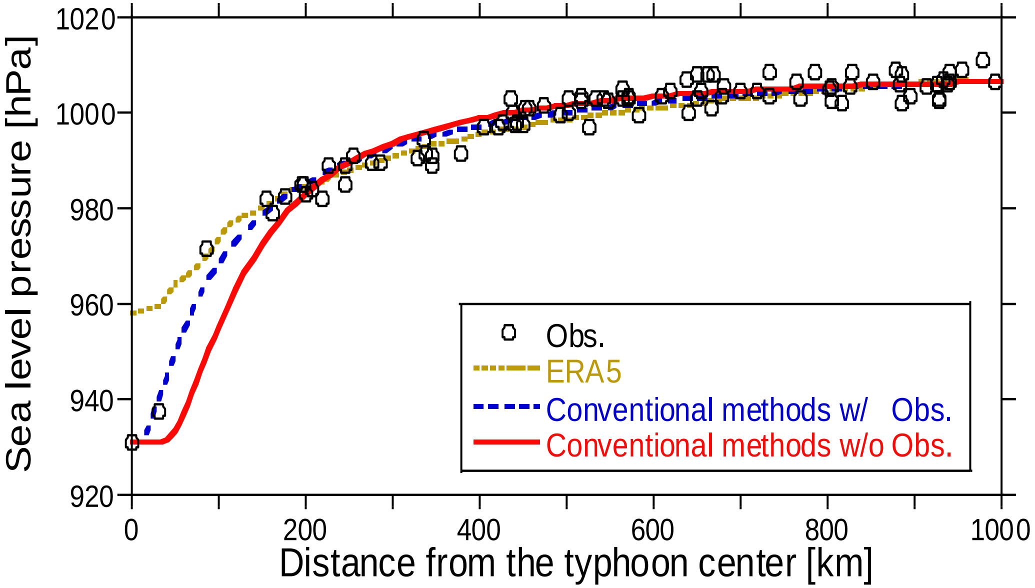
- Typhoon models require Tropical Cyclone (TC) parameters (p_∞, R_m, B) used in the Holland model.

$$p(r) = p_c + (\boldsymbol{p_\infty} - p_c) \cdot \exp\left[-\left(\frac{\boldsymbol{R_m}}{r}\right)^{\boldsymbol{B}}\right]$$

$p(r)$	Pressure distribution	r	Distance from the TC center	p_c	Central pressure
p_∞	**Ambient pressure**	R_m	**Radius at maximum winds**	B	**Shape parameter**

- Conventionally, TC parameters are identified using onshore observational data by the least square method.
- ERA5 pressure data can be used instead of observations, but its accuracy near the center is limited.





TC parameters identified by the conventional methods

	w/ Obs.	w/o Obs.
p_∞	84.2	78.2
R_m	79.4	111.4
B	0.9	1.5

A new identification method for offshore regions is needed.

Problem 2. Combined Model of Typhoon-induced Wind Fields

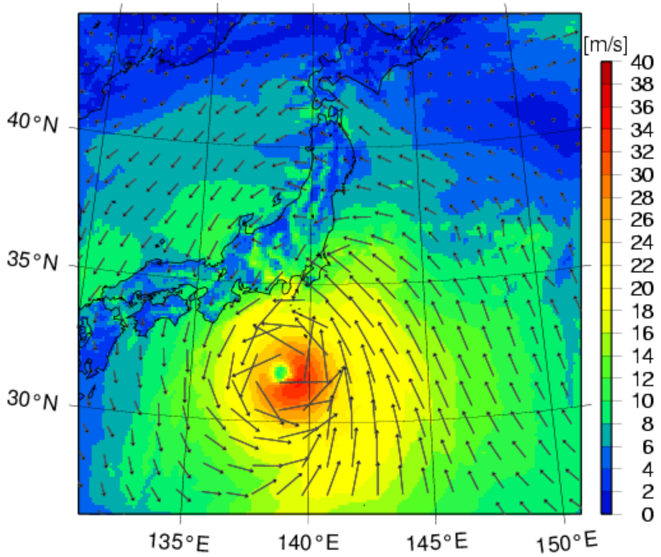
- The wind fields from mesoscale and typhoon models are typically combined using a weight function based on the radial distance from the typhoon center, as shown in Tanemoto and Ishihara (2013).

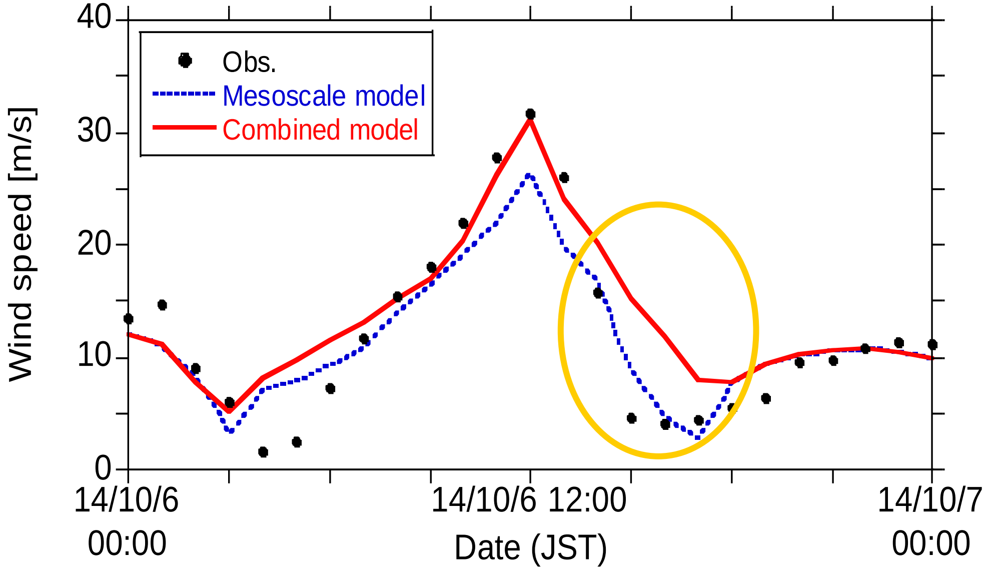
$$u_C = \boldsymbol{W}(\boldsymbol{r}) \cdot u_M + (1 - \boldsymbol{W}(\boldsymbol{r})) \cdot u_T$$

u_C	Combined wind field	u_M, u_T	Wind fields from mesoscale and typhoon models
W	Weight function	r	**Radial distance from the typhoon center**

- The combined model accurately captures the peak wind speeds but shows reduced performance compared to mesoscale model after the peak.

Combined model u_C





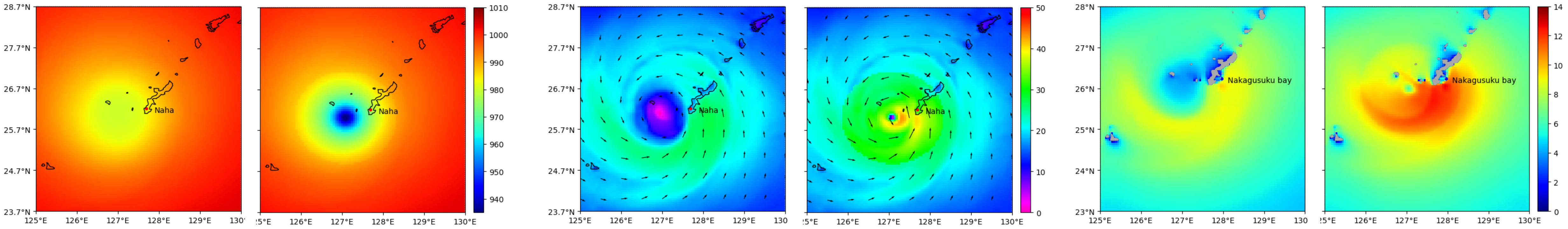
The combined model of typhoon-induced wind fields should be improved.

Problem 3. Model Validation

- Many studies, such as Tanemoto and Ishihara (2013), have proposed combined models however most have been validated using only a limited number of typhoon cases.
- IEC61400-3-1 (2019) requires at least 30-year hindcasting to estimate extreme wave heights during typhoons.

	Extreme wave height (IEC61400-3-1, 2019)
Method	Hindcasting
Period	**≧30 years**
Validation	Sea level pressure, Wind speed, Significant wave height

Sea level pressure | Wind speed | Significant wave height



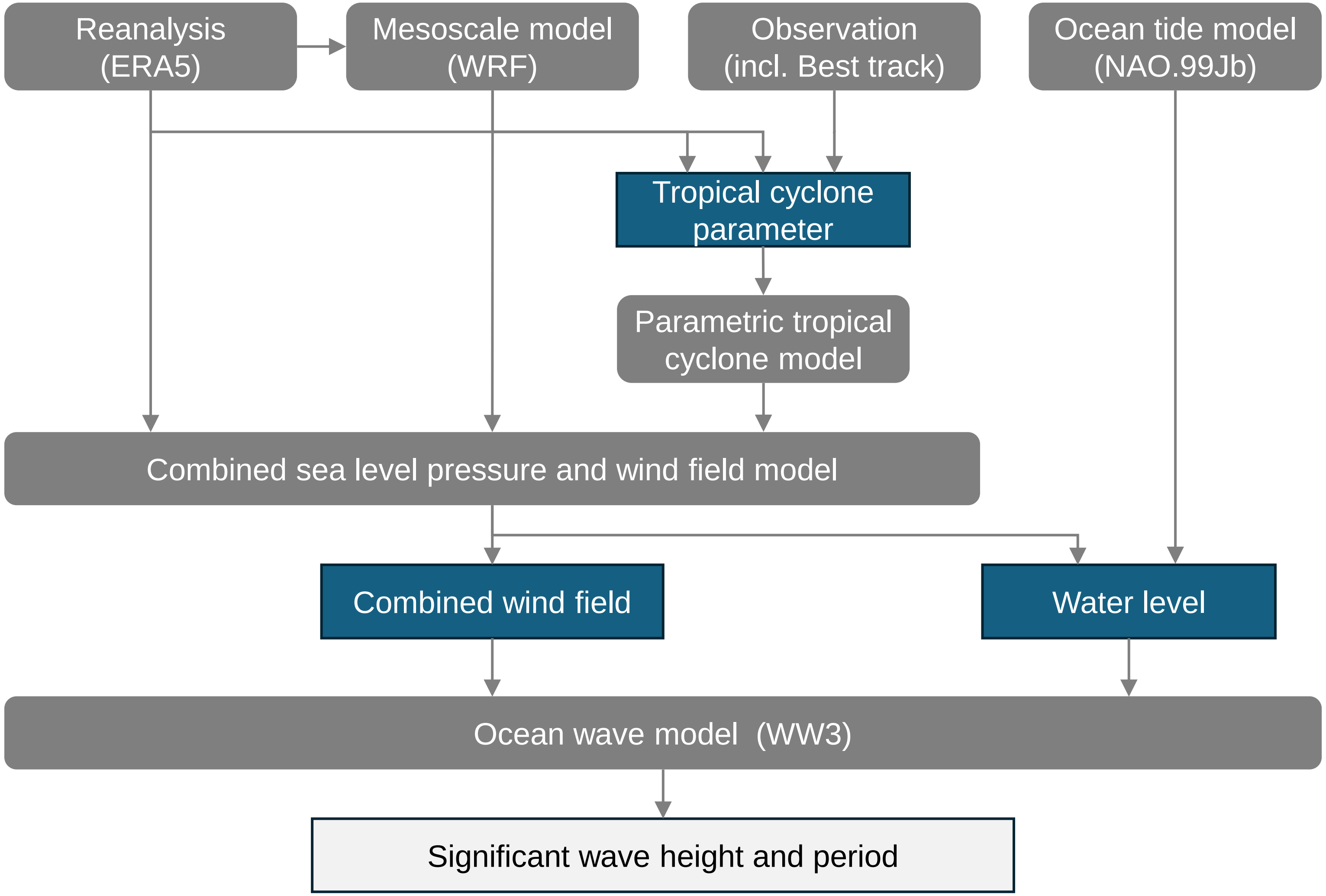
The proposed models need to be validated by long-term observations.

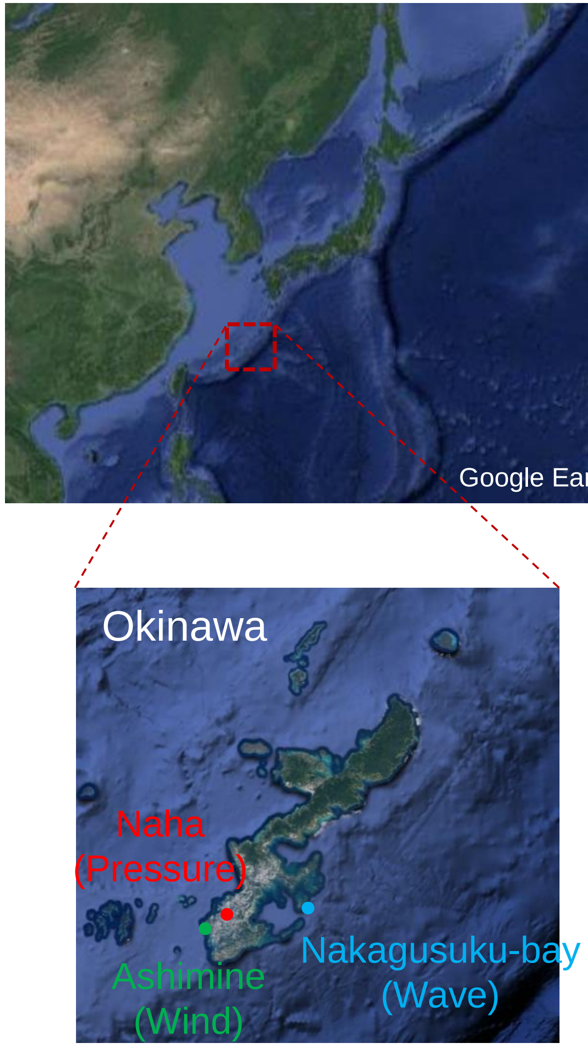
Objectives

1. Propose a new identification method for tropical cyclone parameters used in the Holland model.
2. Propose a new combined model for typhoon-induced wind fields using mesoscale model and typhoon model.
3. Validate the proposed model by long-term observations for sea level pressure, wind speed and significant wave height.

Framework of this study

- Okinawa Prefecture is selected as the study area since it is frequently affected by strong typhoons.
- WRF and WW3 are used for the prediction and observations are obtained from JMA and NOWPHAS.

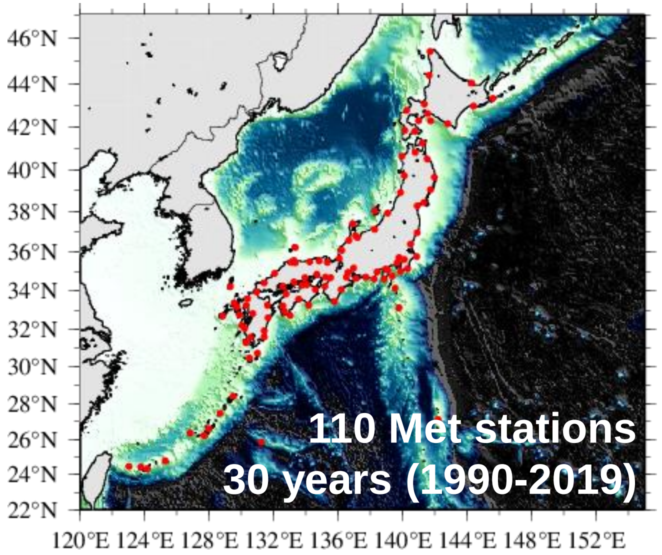


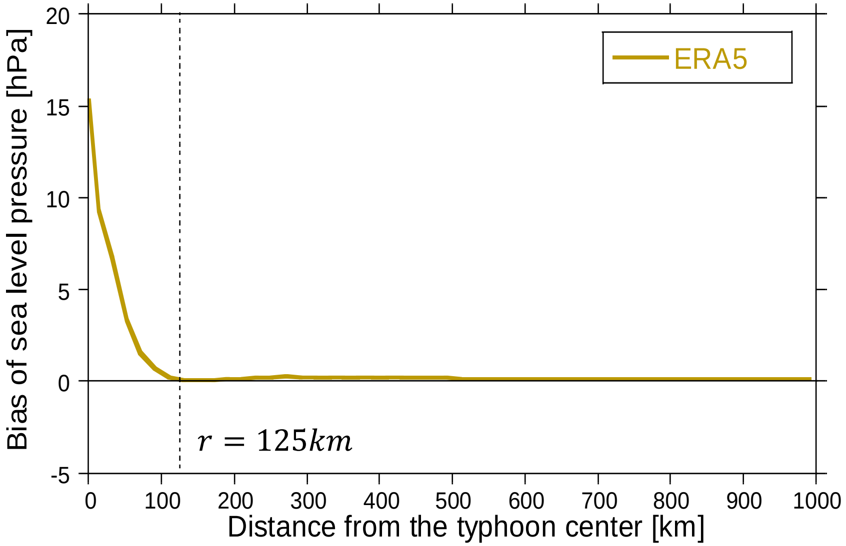


New Identification Method for TC Parameters

- A new identification method for TC parameters is proposed using the best track and ERA5 pressure data instead of onshore observational data.
- To investigate how much range ERA5 is accurate from the center, the ERA5 pressure data are compared with observations from 110 meteorological stations over the past 30 years.

	Conventional methods	Proposed method
Database	Best track Onshore observational data	Best track ERA5 pressure data



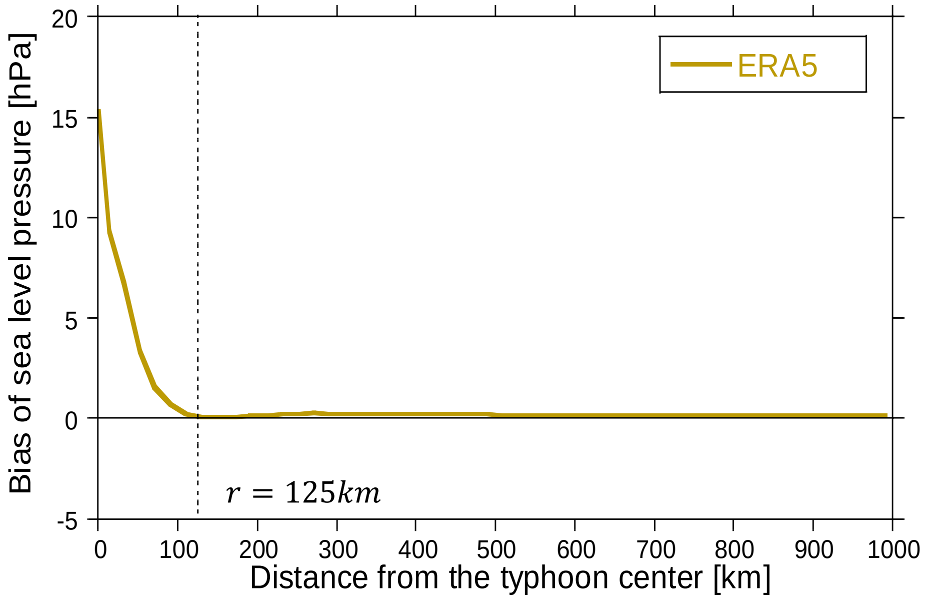


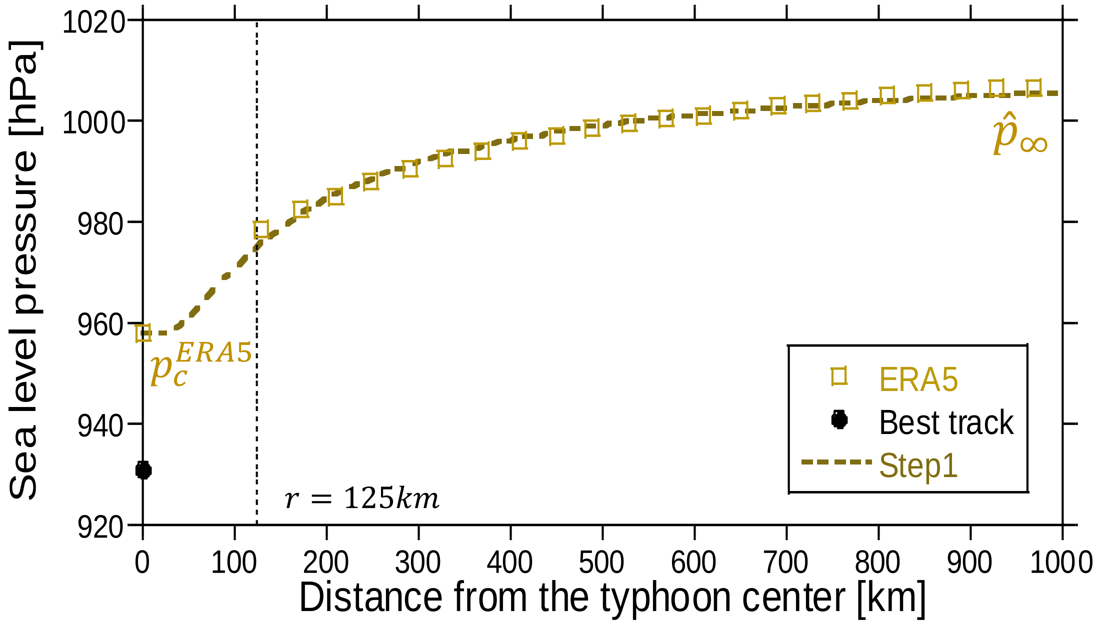
ERA5 pressure data beyond 125km from the center is used for the identification.

New Identification Method for TC Parameters

- The identification is divided into two-step to ensure the stability and accuracy.
- In Step1, p_∞ is identified using only ERA5 pressure data with the assumption B=1.

	p_c	p_∞	R_m	B
Step1 (p_∞)	ERA5	identified $\hat{p}_\infty$	identified	$B = 1$

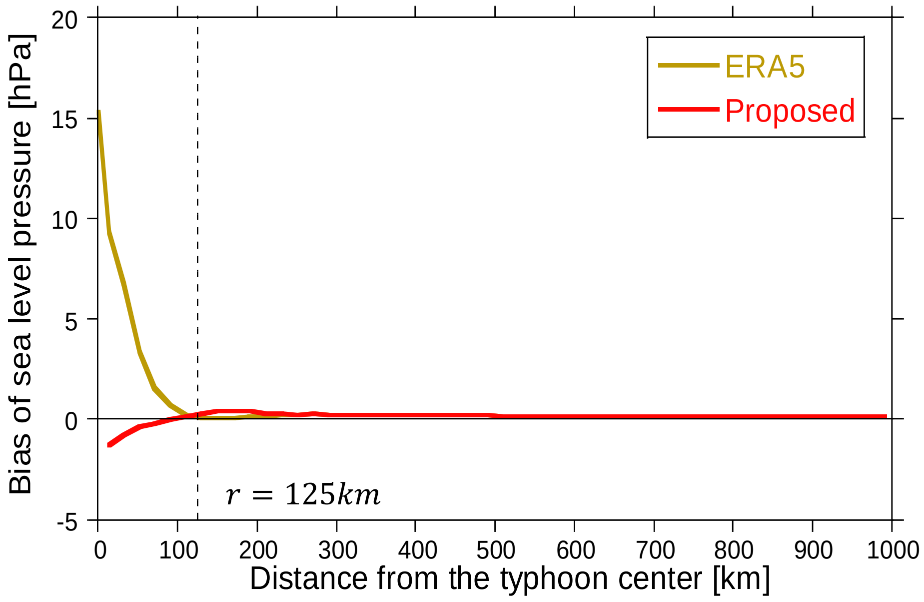


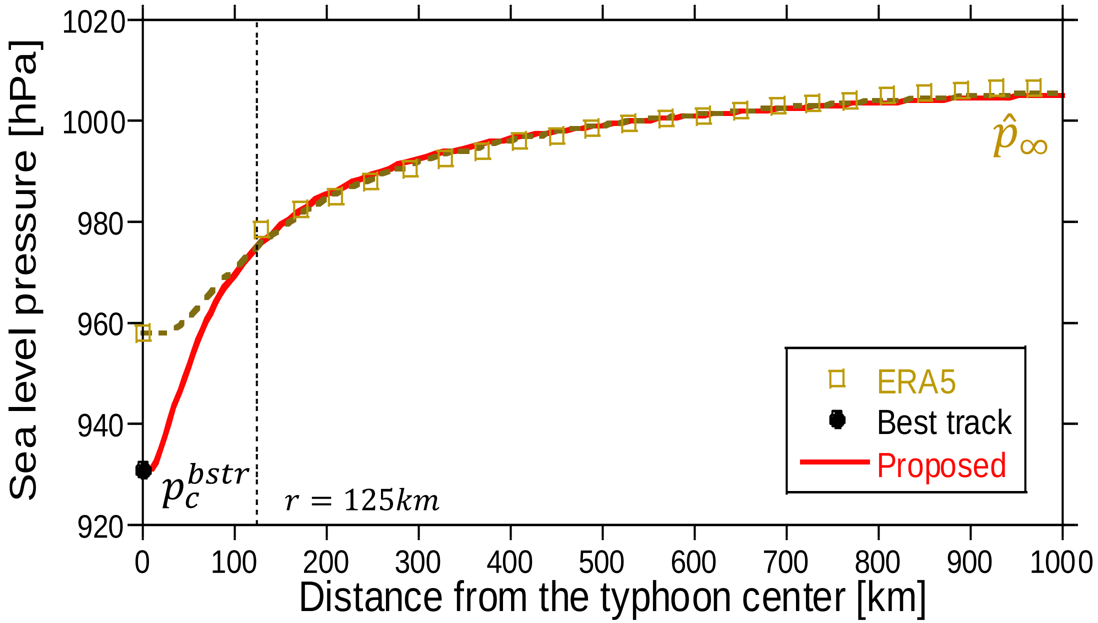


New Identification Method for TC Parameters

- The identification is divided into two-step to ensure the stability and accuracy.
- In Step1, p_∞ is identified using only ERA5 pressure data with the assumption B=1.
- In Step2, R_m and B are identified using both p_c^{bstr} and ERA5 pressure data.

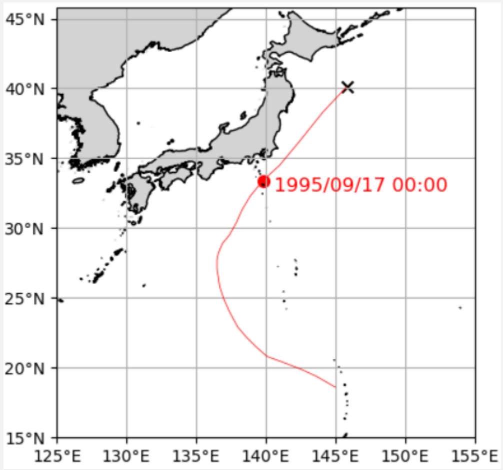
	p_c	p_∞	R_m	B
Step1 (p_∞)	ERA5	identified $\hat{p}_\infty$	identified	$B = 1$
Step2 (R_m, B)	Best track	$\hat{p}_\infty$	re-identified $\hat{R}_m$	identified $\hat{B}$

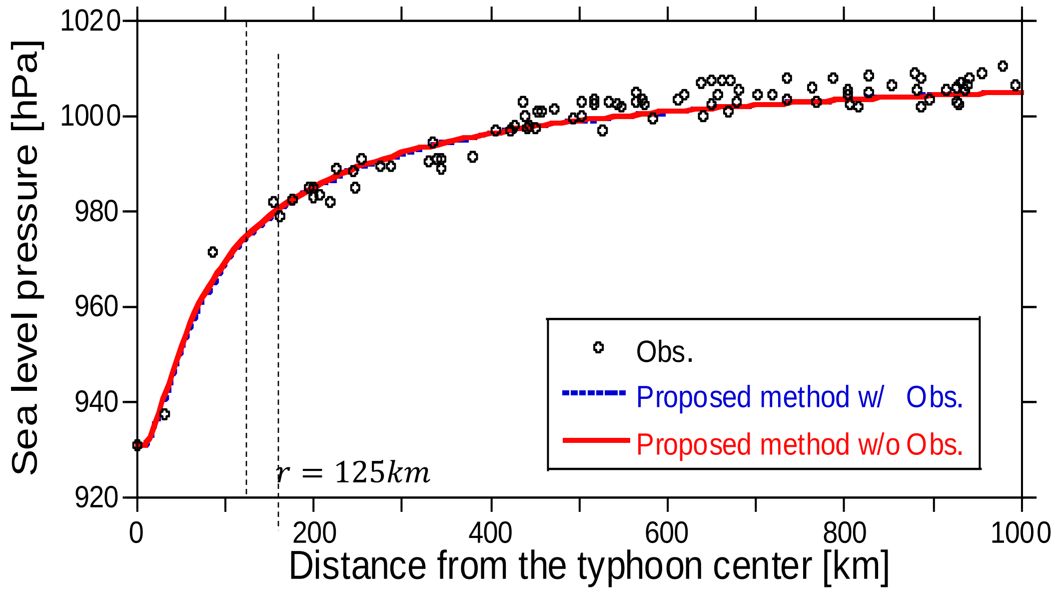


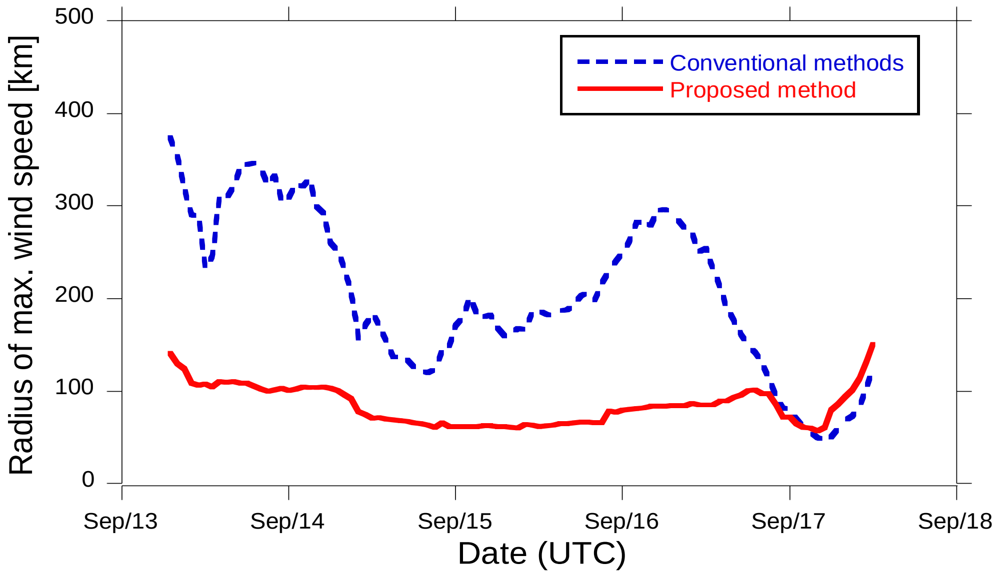


Identification Results for Typhoon OSCAR

- TC parameters for Typhoon OSCAR are identified using the conventional methods and proposed method.
- The proposed method can identify the TC parameters accurately without observations.
- The proposed method provides stable identification results even in offshore regions.



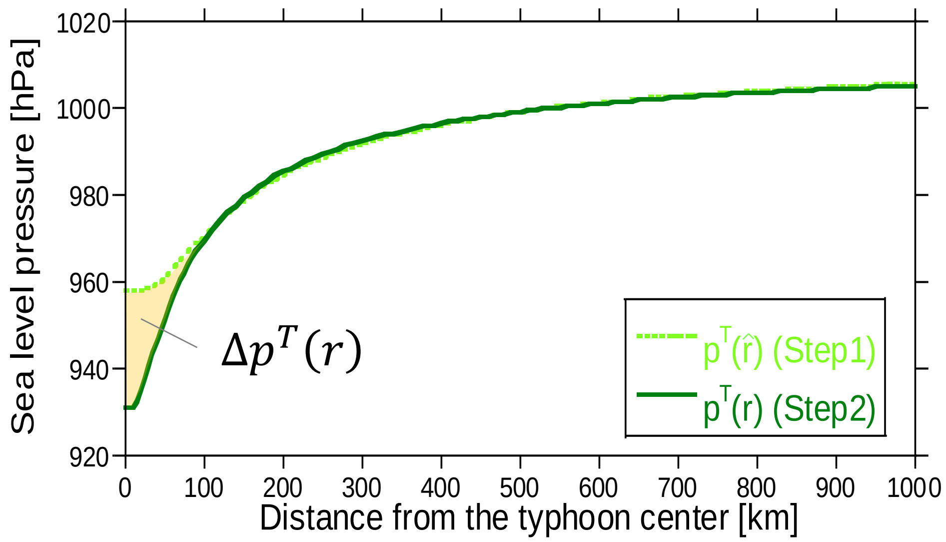
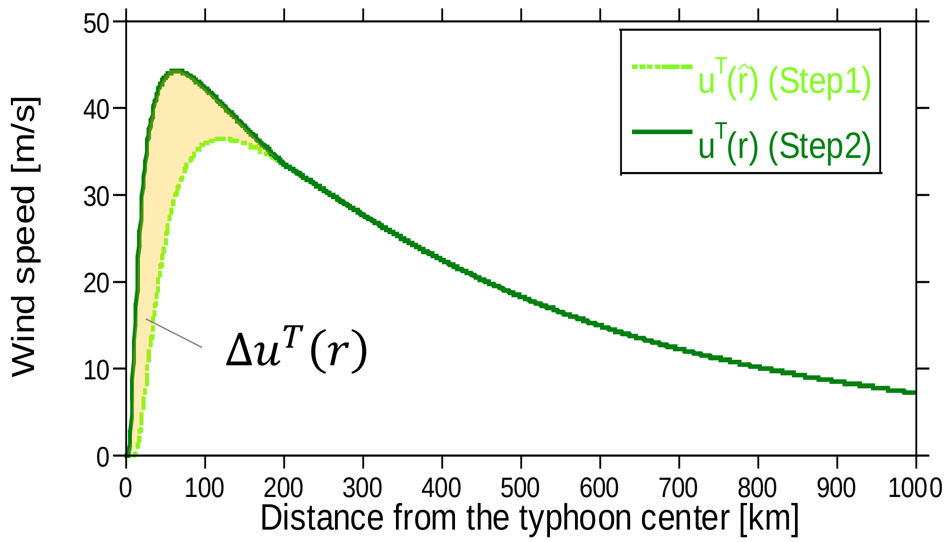




The proposed method is accurate and stable even in offshore regions.

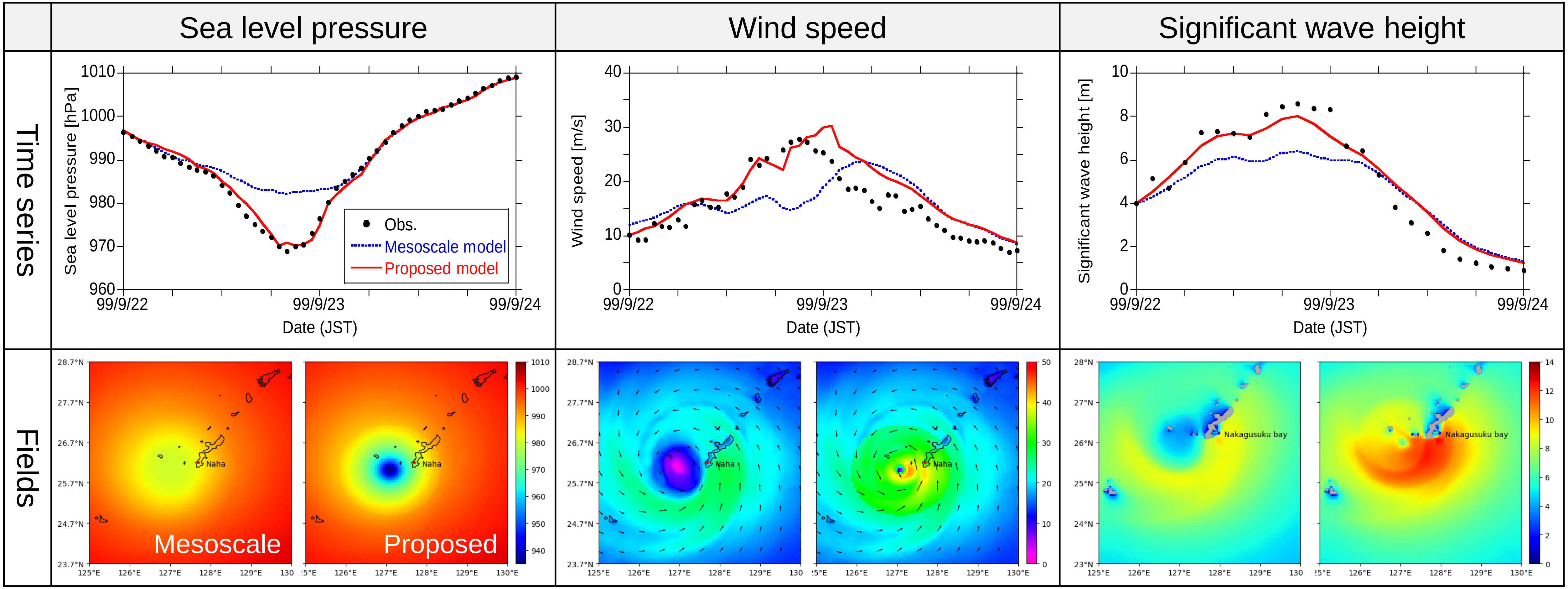
New Combined Model Based on Pressure Difference

- A new combined model is proposed to account for the pressure differences between the mesoscale and typhoon models.
- The proposed model requires no empirical parameters, and the combined pressure and wind fields automatically converge to those of the mesoscale model when the pressure differences decrease to zero.

	Combined pressure field	Combined wind field
Equation	$p^C(r) = p^M(\hat{r}) + \Delta p^T(r) = p^M(\hat{r}) + \left(p^T(r) - p^T(\hat{r})\right)$	$u^C(r) = u^M(\hat{r}) + \Delta u^T(r) = u^M(\hat{r}) + \left(u^T(r) - u^T(\hat{r})\right)$
Distribution		

Results of Predicted Pressure, Wind and Wave (Typhoon BART)

- Since the mesoscale model underestimates sea level pressure depth near the typhoon center, the peak wind speed and wave height are underestimated.



The pressure, wind and wave predicted by the proposed model agree with observations.

Event Extraction Using Long-Term Observations

- To validate the proposed model by long-term observations, annual maximum events of sea level pressure depth, wind speed, and significant wave height over the past 30 years are extracted.

<table>
<tr><th>Year</th><th>Pressure</th><th>Wind speed</th><th>Wave height</th><th>Year</th><th>Pressure</th><th>Wind speed</th><th>Wave height</th></tr>
<tr><td>1990</td><td colspan="2">10/5~6 (T9021)</td><td>1/27</td><td>2005</td><td>9/4~5 (T0514)</td><td>8/4 (T0509)</td><td>9/4~5 (T0514)</td></tr>
<tr><td>1991</td><td colspan="3">9/13 (T9117)</td><td>2006</td><td colspan="2">7/9 (T0603)</td><td>7/12 (T0604)</td></tr>
<tr><td>1992</td><td colspan="2">6/29 (T9203)</td><td>8/30 (T9216)</td><td>2007</td><td colspan="3">7/13 (T0704)</td></tr>
<tr><td>1993</td><td>8/9 (T9307)</td><td colspan="2">9/2 (T9313)</td><td>2008</td><td>7/26 (T0808)</td><td>5/11 (T0802)</td><td>11/11</td></tr>
<tr><td>1994</td><td>7/31 (T9411)</td><td>8/20 (T9416)</td><td>11/6 (T9434)</td><td>2009</td><td colspan="3">8/6 (T0908)</td></tr>
<tr><td>1995</td><td colspan="3">7/21~22 (T9503)</td><td>2010</td><td>8/31 (T1007)</td><td colspan="2">10/28 (T1014)</td></tr>
<tr><td>1996</td><td colspan="2">8/12~13 (T9612)</td><td>7/30 (T9609)</td><td>2011</td><td>8/5 (T1109)</td><td>5/28 (T1102)</td><td>8/5 (T1109)</td></tr>
<tr><td>1997</td><td colspan="3">8/17 (T9713)</td><td>2012</td><td colspan="2">9/29 (T1217)</td><td>6/5 (T1203)</td></tr>
<tr><td>1998</td><td colspan="2">10/17 (T9810)</td><td>12/31</td><td>2013</td><td>10/24 (T1327)</td><td colspan="2">10/5 (T1323)</td></tr>
<tr><td>1999</td><td colspan="2">9/22 (T9918)</td><td>5/22</td><td>2014</td><td>10/11~12 (T1419)</td><td>7/8 (T1408)</td><td>10/11~12 (T1419)</td></tr>
<tr><td>2000</td><td colspan="3">9/12 (T0014)</td><td>2015</td><td colspan="3">7/10 (T1509)</td></tr>
<tr><td>2001</td><td colspan="3">9/7~8 (T0116)</td><td>2016</td><td colspan="3">10/3 (T1618)</td></tr>
<tr><td>2002</td><td colspan="2">9/5 (T0216)</td><td>7/14 (T0207)</td><td>2017</td><td colspan="2">10/28 (T1722)</td><td>9/13 (T1718)</td></tr>
<tr><td>2003</td><td colspan="3">8/7 (T0310)</td><td>2018</td><td colspan="3">9/29 (T1824)</td></tr>
<tr><td>2004</td><td colspan="2">9/5 (T0418)</td><td>10/19 (T0423)</td><td>2019</td><td colspan="2">9/21 (T1917)</td><td>Missing data</td></tr>
</table>

51 events (about 57% of the 90 events) are extracted.

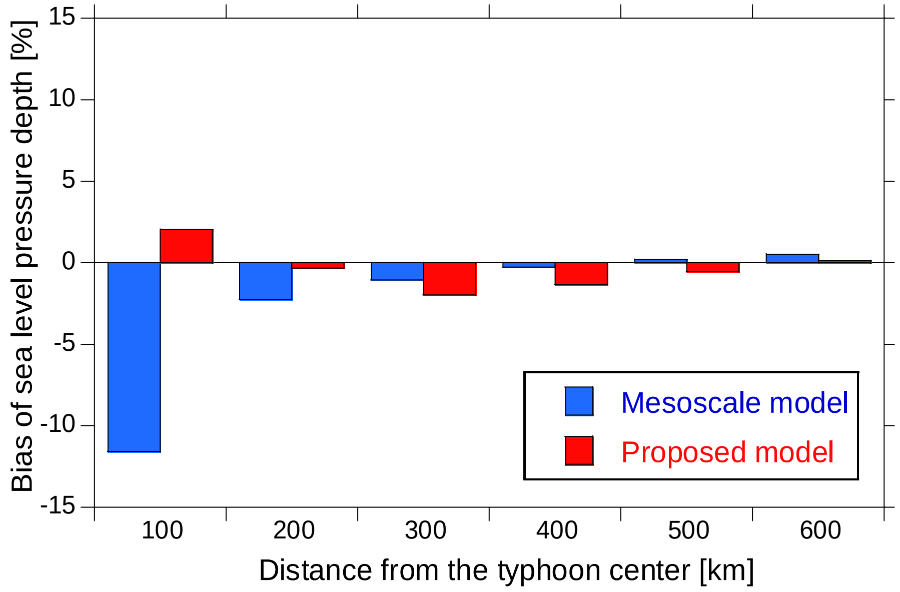
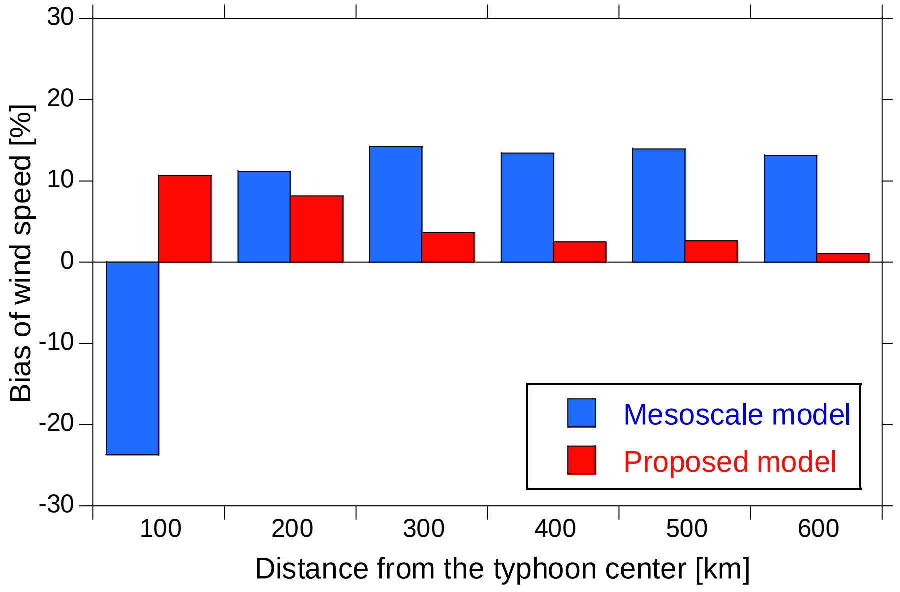
Improvement of Prediction Accuracy

- The variation in relative bias of sea level pressure depths and wind speeds with distance from the typhoon center is calculated for the 51 events.

$$relative\ bias = \left(\bar{x}_i^{pred} - \bar{x}_i^{obs}\right) / \bar{x}_i^{obs}$$

$\bar{x}_i^{obs}, \bar{x}_i^{pred}$ Averages of observed and predicted values i Distance bin (100km)

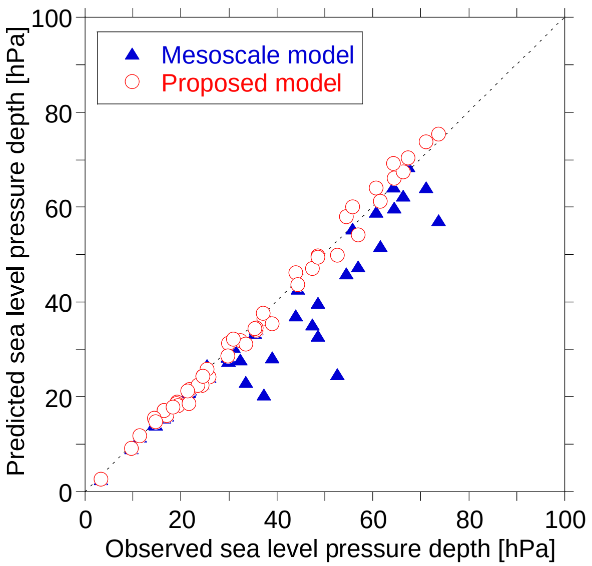
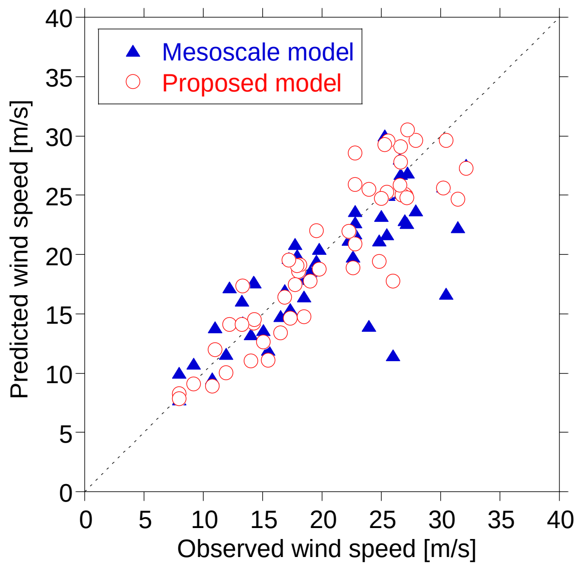
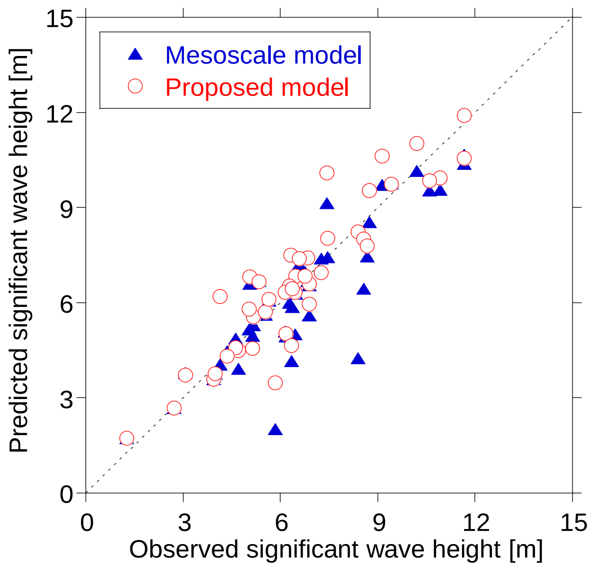
- The mesoscale model exhibits a significant negative bias for sea level pressure depths and wind speeds near the typhoon center.

Sea level pressure	Wind speed
	

Proposed model effectively reduces errors near the typhoon center.

Validation of Proposed Model for Pressure, Wind and Wave

- The peak values of sea level pressure depths, wind speeds and significant wave heights are compared with observations for the 51 events.

<table>
<tr><th></th><th>Sea level pressure</th><th>Wind speed</th><th>Significant wave height</th></tr>
<tr><td>Scatter plot of max. values in each event</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Slope</td><td>0.88 ⇒ 1.01</td><td>0.91 ⇒ 0.97</td><td>0.93 ⇒ 1.01</td></tr>
<tr><td>R^2</td><td>0.98 ⇒ 1.00</td><td>0.97 ⇒ 0.98</td><td>0.97 ⇒ 0.98</td></tr>
</table>

The improvement in predicted significant wave height is attributed to the high prediction of sea level pressure and wind fields by the proposed model.

Conclusions

1. A new identification method for TC parameters is proposed using the best track and ERA5 pressure data. The identification using the proposed method is stable even in the absence of observational data, and the identified pressure distribution shows good agreement with the observations.

2. A new combined model is proposed to account for the pressure differences between mesoscale and typhoon models. The predicted sea level pressure depth, wind speed and wave height by the proposed model show good agreement with observations.

3. The proposed model is validated by the 51 events extracted from 30-year observations and improves the prediction accuracy of typhoon-induced extreme wave height compared to the mesoscale model.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Thank you for your attention!
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