# Can ensemble simulations featuring clustering properly estimate probability distributions? A 1000-member ensemble study


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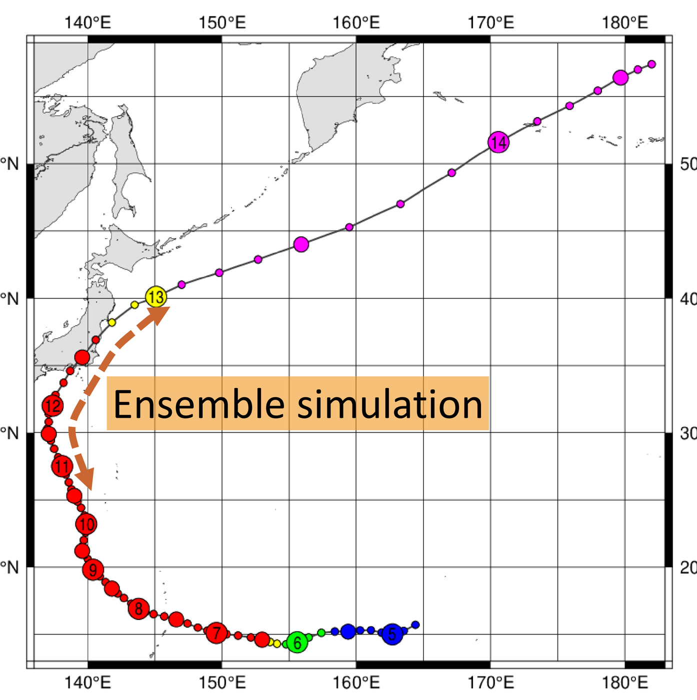
## Introduction

In ensemble simulations, to get a fair variety of probable states, it is preferable to introduce perturbations to factors to which prediction results are sensitive. Multi-physics, or multi-models, are approaches commonly used to consider model errors in an ensemble. However, clustering also usually occurs when the number of independent perturbations is smaller than the ensemble size, i.e., the perturbation rank is insufficient. Compared to the popular use of ensembles that likely include clustering, it remains unclear how clustering impacts ensemble-derived estimates. In this study, we addressed this question by comparing the results from two 1000-member ensembles. One is featured by clustering due to the lack of lateral boundary condition perturbations (BCPs), and the other is the one that improved by providing the same size of BCPs as the ensemble size.

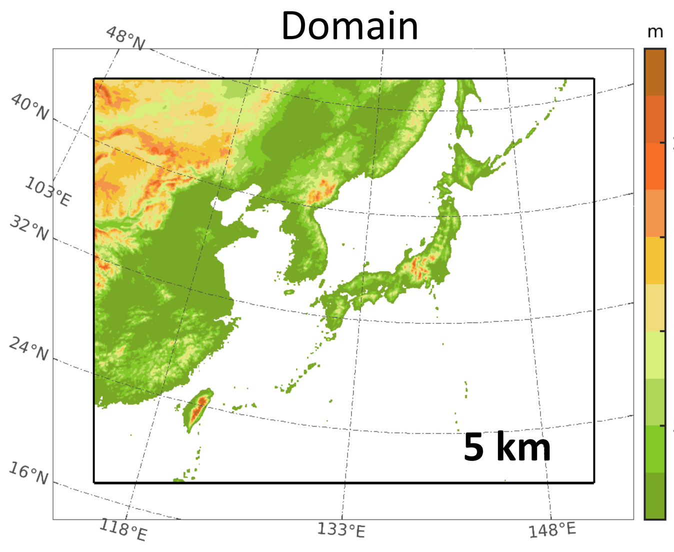
## Experimental settings

Typhoon Hagibis (2019)




7 Oct. 0000 UTC → DA cycles → 10 Oct. 1800 UTC → Ens. forecast → 13 Oct. 0000 UTC

Domain




Poor **PrBCP**

Only fifty (25*2) BCPs are repeatedly used on 1000 members.

| SV1+ | SV1- | SV2+ | SV2- | …, | SV25+ | SV25- |
|---|---|---|---|---|---|---|
| BC1, | BC2, | BC3, | BC4, | …, | BC49, | BC50 |
| 001, | 002, | 003, | 004, | …, | 049, | 050 |
| 051, | 052, | 053, | 054, | …, | 099, | 100 |
| 101, | 102, | 103, | 104, | …, | 149, | 150 |
| … | | | | | | |
| … | | | | | | |
| 951, | 952, | 953, | 954, | …, | 999, | 1000 |

Same BCP

Full **FuBCP**

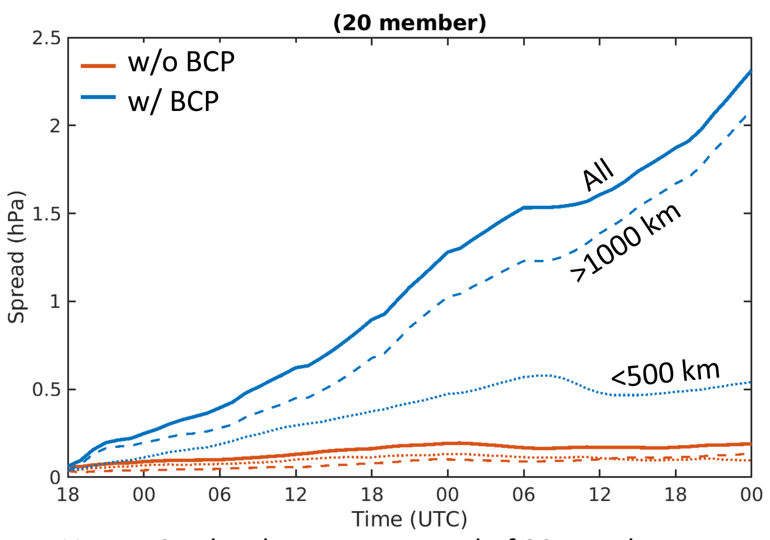
Twenty-five SVs are linearly combined to create 1000 different perturbations.

25 SVs $\quad \varepsilon \sim N(0,1) \quad$ A new BCP

Model state variables (4D)

$$\begin{bmatrix} \delta x_1^1 & \delta x_1^2 & \delta x_1^3 & \dots & \delta x_1^K \\ \delta x_2^1 & \delta x_2^2 & \delta x_2^3 & \dots & \delta x_2^K \\ \delta x_3^1 & \delta x_3^2 & \delta x_3^3 & \dots & \delta x_3^K \\ & & \dots & & \\ \delta x_n^1 & \delta x_n^2 & \delta x_n^3 & \dots & \delta x_n^K \end{bmatrix} \begin{bmatrix} \varepsilon^1 \\ \varepsilon^2 \\ \varepsilon^3 \\ \dots \\ \varepsilon^K \end{bmatrix} = \begin{bmatrix} \delta x_1^{new} \\ \delta x_2^{new} \\ \delta x_3^{new} \\ \dots \\ \delta x_n^{new} \end{bmatrix}$$

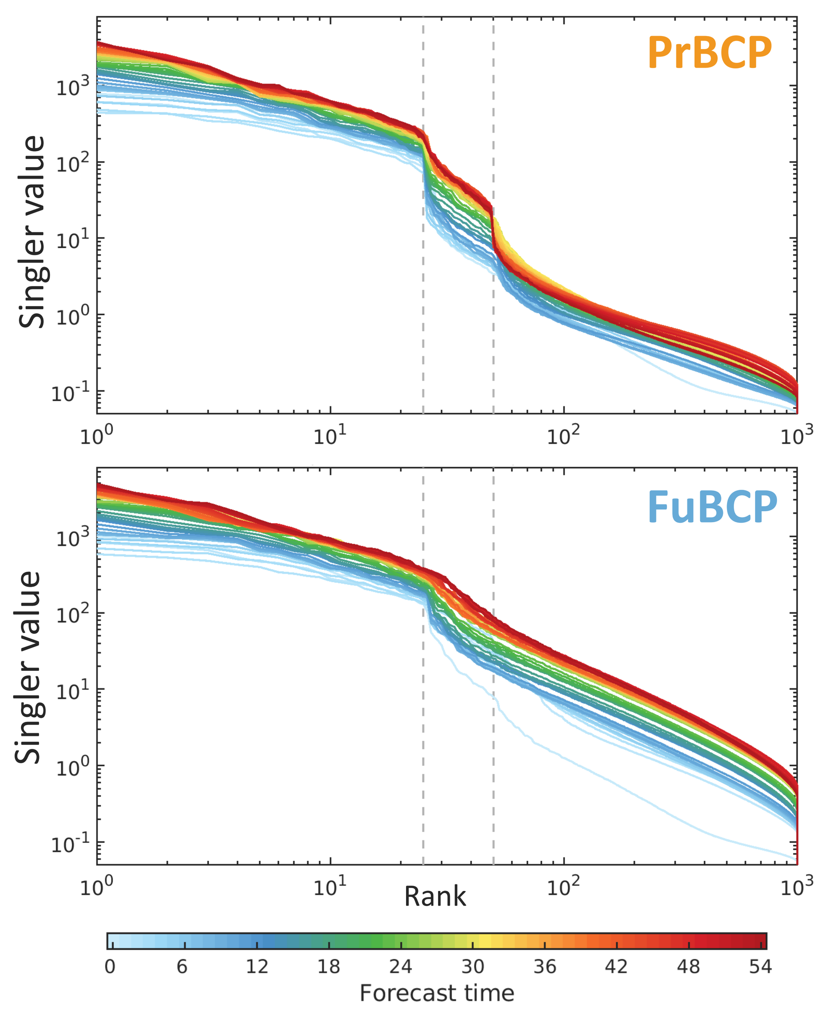
x 1000 times

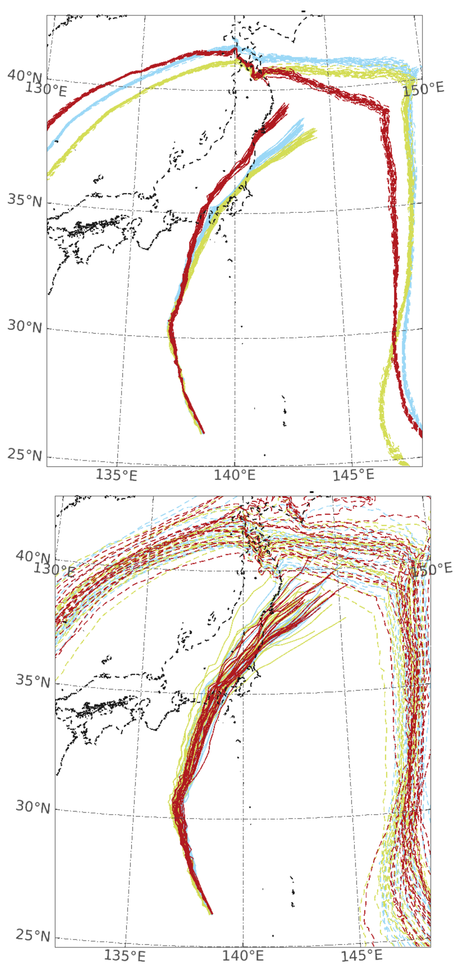



Upper: Sea level pressure spread of 20 member tests with and without BCP.
Right: Singular values of the ensemble perturbations (u, v, qv, and T) over lateral boundary areas.

- Lateral BC greatly affects large-scale simulation results.
- The perturbations from SV pairs further cause the lack of rank.
- The lack of BCP rank resulted in the clustering of typhoon tracks.

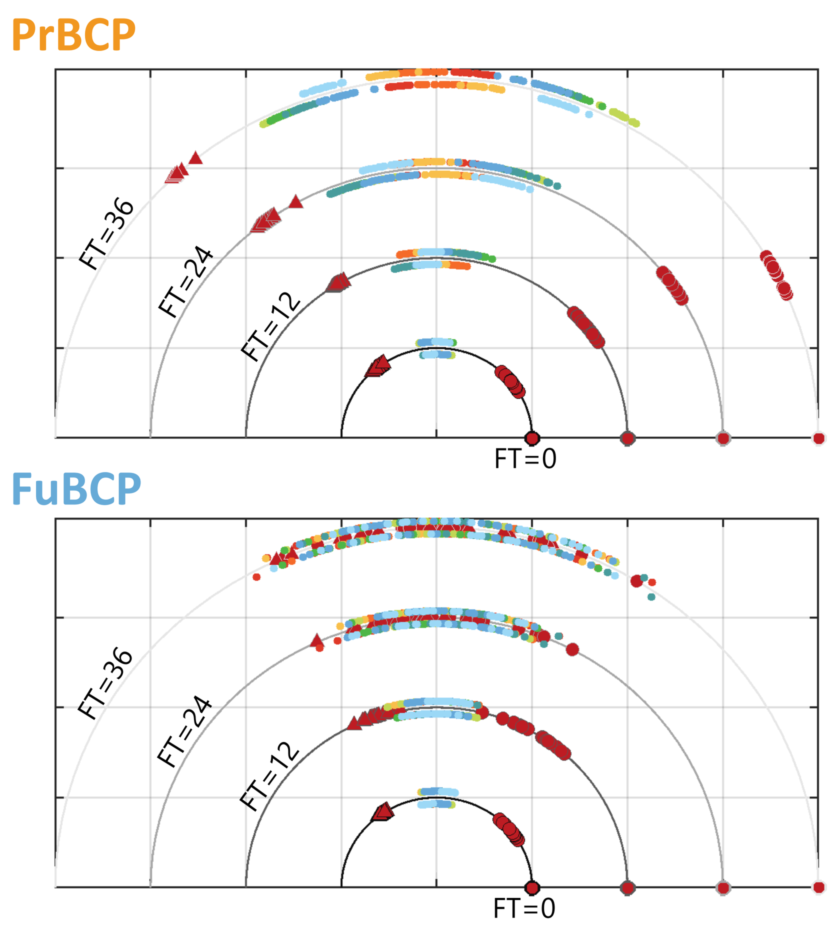
❑ Ensemble rank from BCP



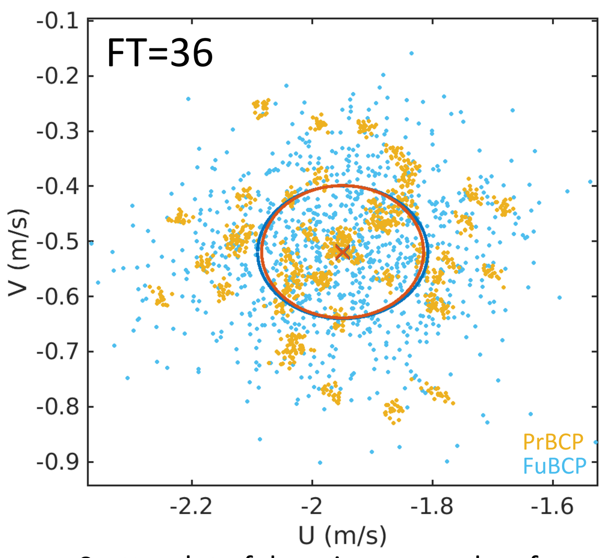
Simulated typhoon tracks and sea level pressures.

❑ Orthogonality between members




Angles between the perturbations of member 1 and other members.

❑ Ensemble error space

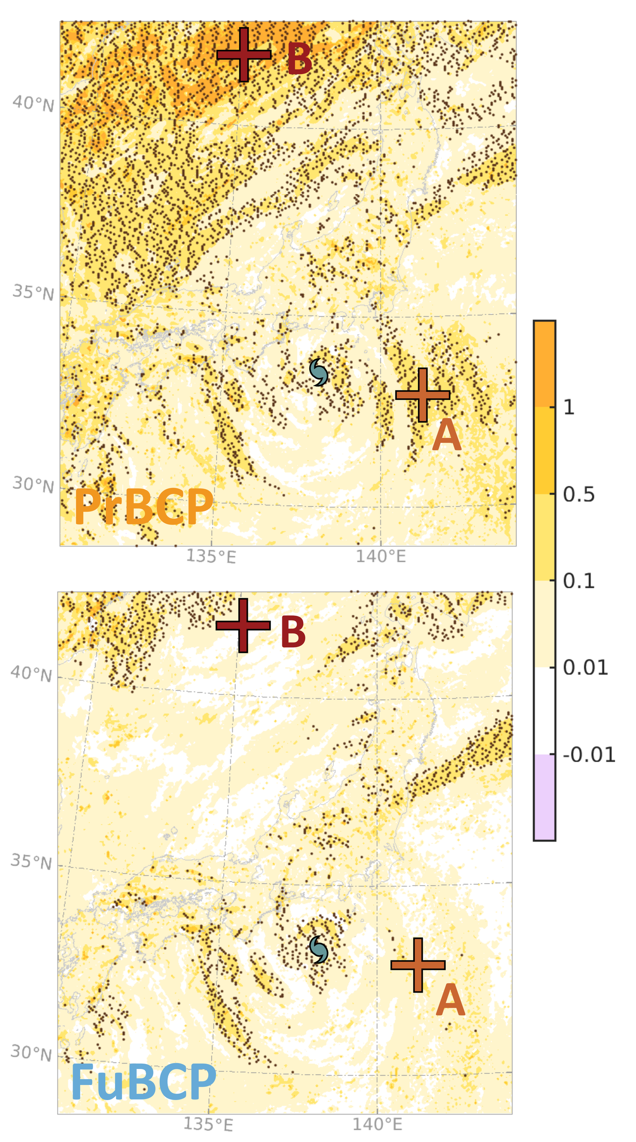



Scatterplot of domain averaged surface winds; crosses and circles are ensemble means and spreads, respectively.

Lack of orthogonality among members and the collapse of the ensemble error space are underlying issues of clustering.

## Impacts on probability distribution (FT36)

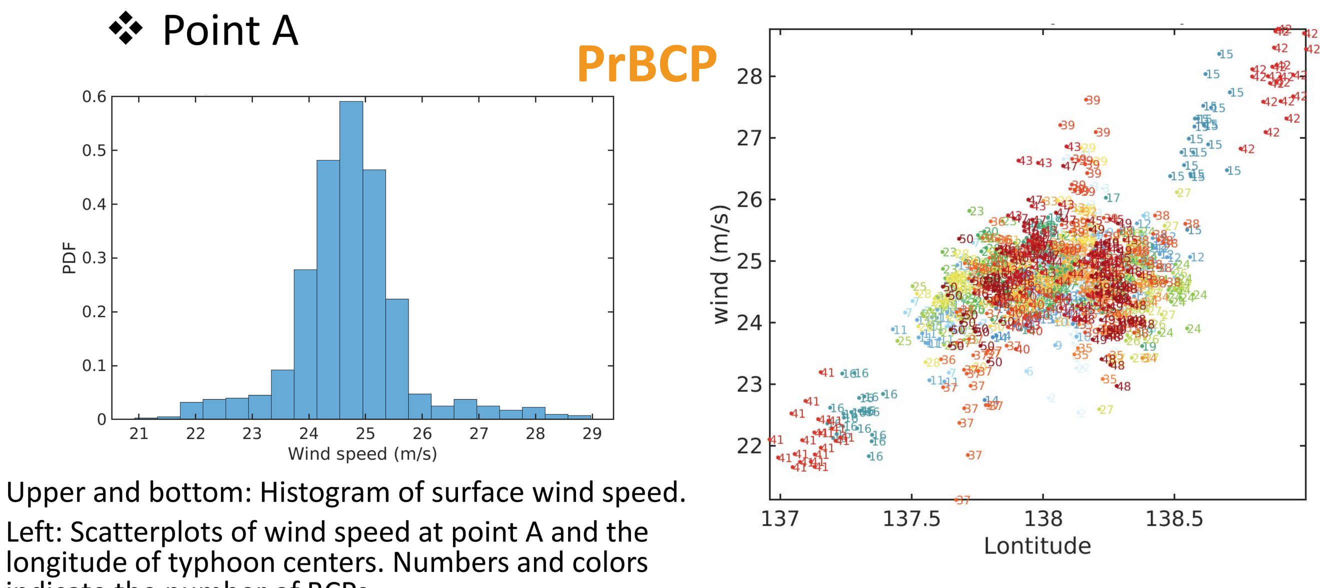
❖ Kullback–Leibler divergence




Color: KLD; Dots: non-Gaussianity

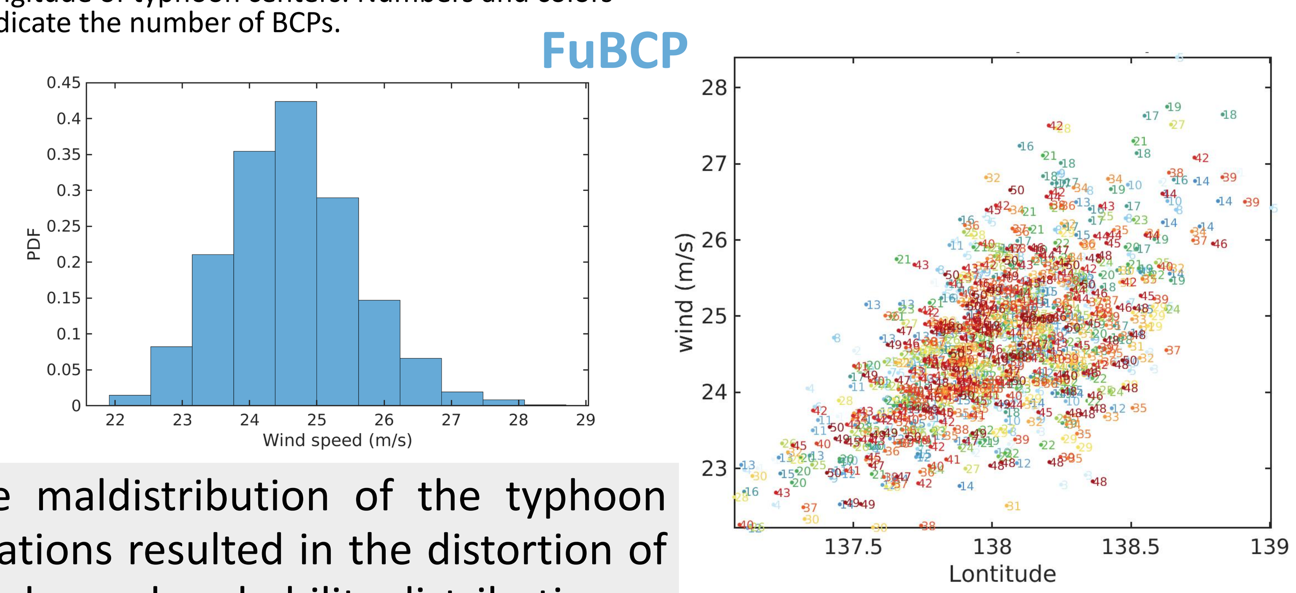
❖ Point A

**PrBCP**



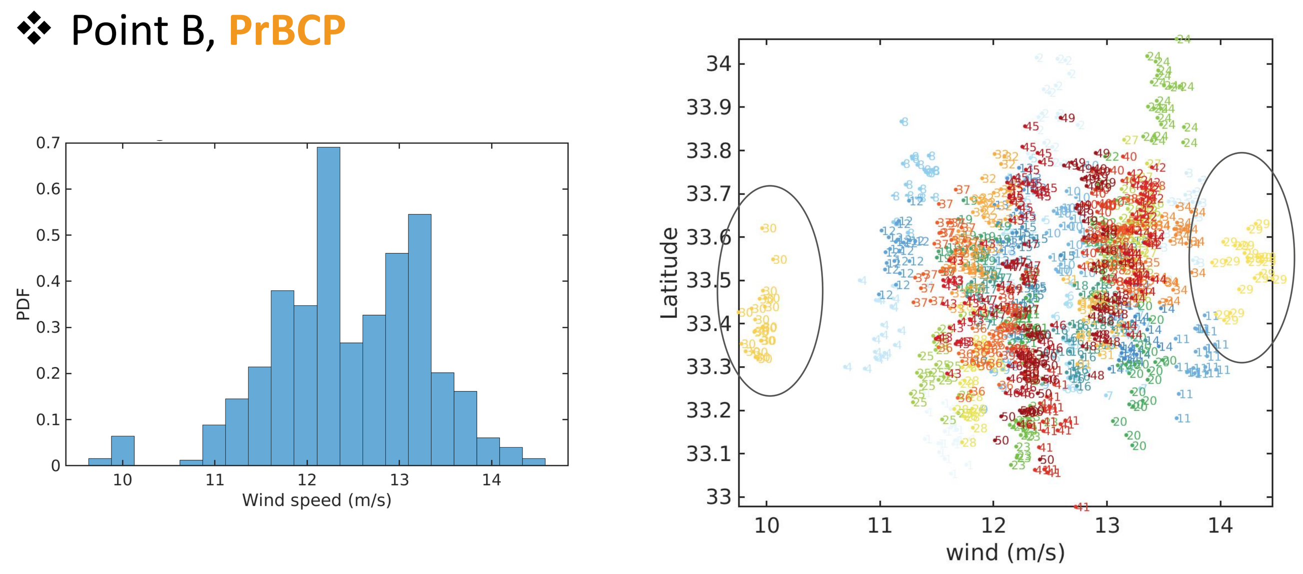

Upper and bottom: Histogram of surface wind speed.
Left: Scatterplots of wind speed at point A and the longitude of typhoon centers. Numbers and colors indicate the number of BCPs.

**FuBCP**

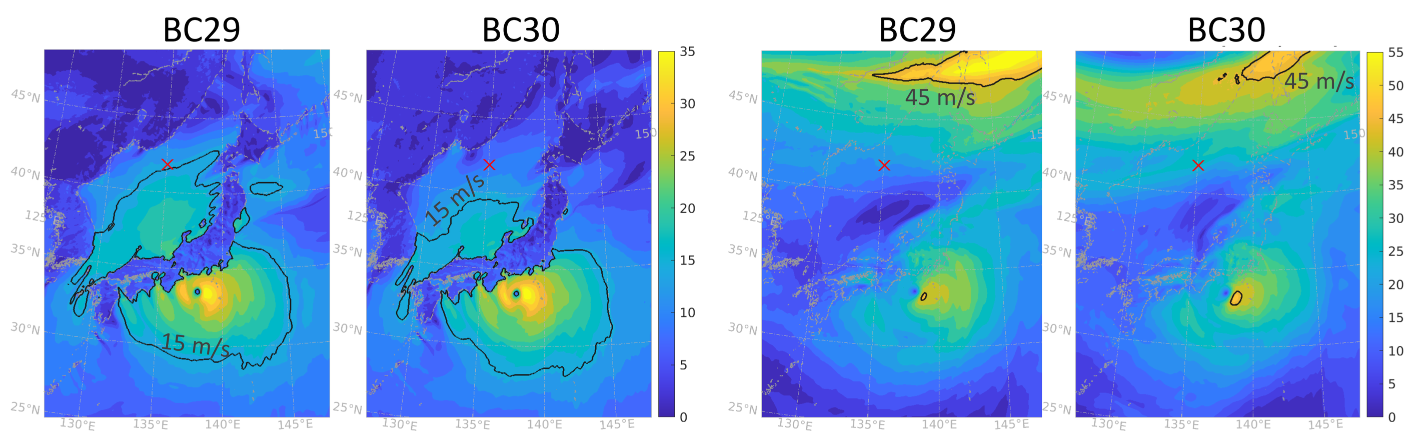



The maldistribution of the typhoon locations resulted in the distortion of wind speed probability distributions.

❖ Point B, **PrBCP**




Synoptic-scale environmental fields, likewise influenced by BCPs, also affect wind speed distributions.

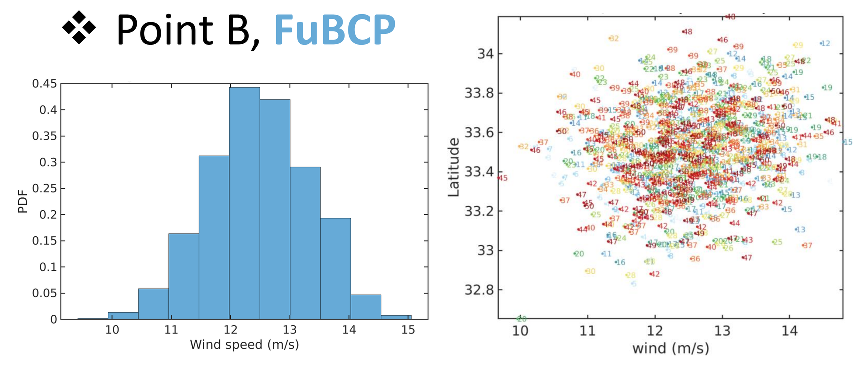



BC29 and 30 sub-ensemble mean of surface wind speed (left) and wind speed over the 500-hpa height (right).

❑ The insufficiency of the BC perturbation rank resulted in clustering, which means that members weren't orthogonal to each other and the ensemble error space shrank. This eventually led to spurious probability distributions.

❖ From the point of view of physical space, the locations of typhoons and synoptic-scale environmental fields have a big impact on surface winds, and the way they were grouped together distorted the probability distributions in the end.

❖ Point B, **FuBCP**



Approaches that might lead to ensemble clustering are problematic for estimating probability distributions. For example, approaches that use multi-model, multi-physic, time-lag initial perturbations, and perturbations with SV pairs must be re-evaluated for their usefulness.