Multivariate Ensemble Sensitivity for Typhoon Haiyan

Sijing Ren and Lili Lei

School of Atmospheric Sciences, Nanjing University, Nanjing, China

Background

- Univariate ensemble sensitivity ignores correlations cross variables and often results in overestimations for sensitivities.
- Multivariate ensemble sensitivity proves to be an effective alternative, but lack of evidences from real cases.

Data

- The Typhoon Haiyan (2013) is selected because of great challenges in its intensity forecast.
- Ensemble forecasts of 80 members are produced using WRFV3.4 from 0000 UTC 4 November to 0600 UTC 9 November. Each member has two vortex following domains of 9km (D02) and 3km (D03), and one fixed parent domain at 27 km (D01).
- Simulations show significant underestimation of intensity and huge ensemble spread (Figure 1) .Seeing that, ensemble sensitivity analysis on this problem can be a great challenge.

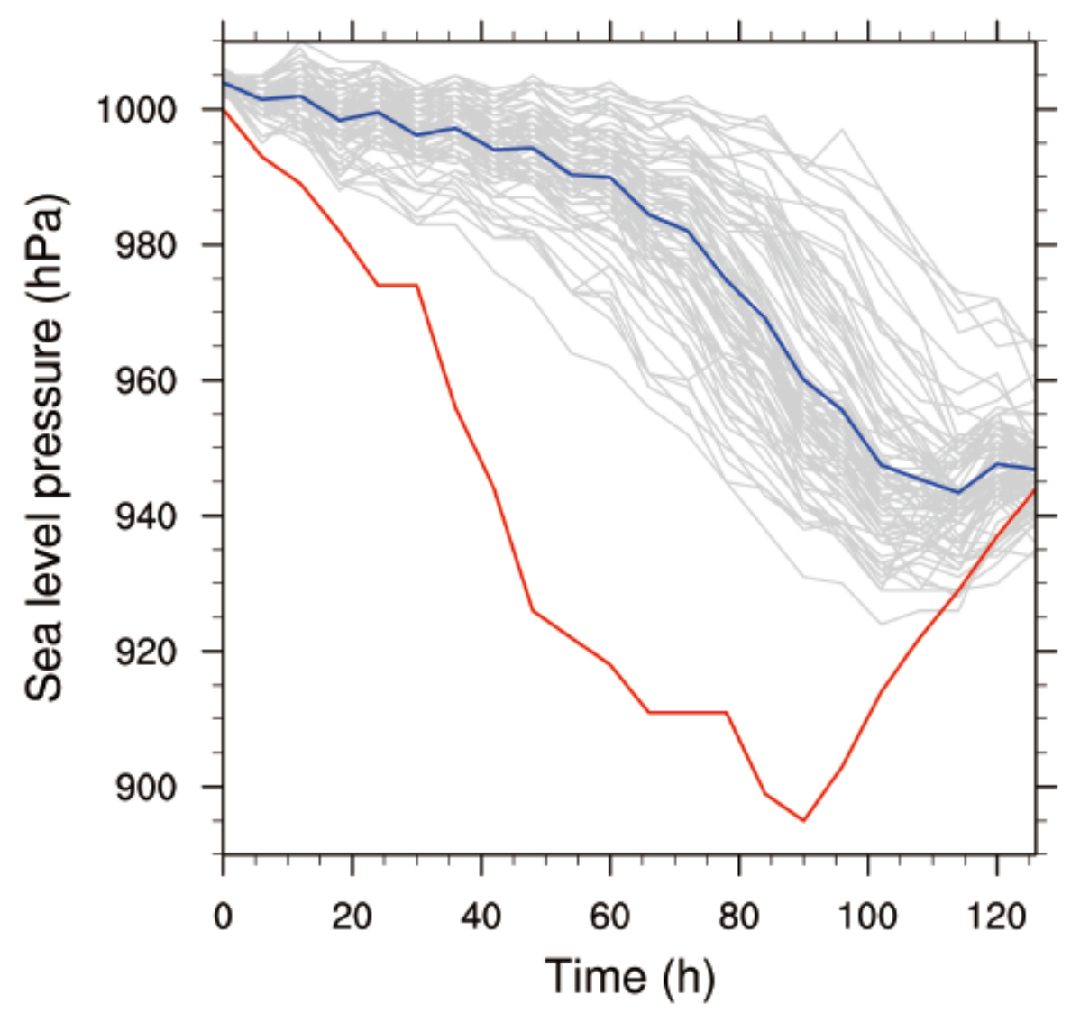

Figure 1. Time variation of sea level pressure(SLP) in observations (red line), ensemble forecasts of each member (grey line) and ensemble mean (blue line).

Methodology

- To analysis sensitivity of a forecast response function J to perturbations in the ith analysis state variable x_i^a, frequently-used univariate ensemble sensitivity is calculated through the following form:

  $$\frac{\partial J}{\partial x_i^a} \approx \frac{cov(\boldsymbol{J}, \boldsymbol{x_i^a})}{Var(\boldsymbol{x_i^a})} \qquad (1)$$

  $$(i = 1,2, \dots, N, N\ is\ dimension\ of\ model\ state)$$

  Here, $\boldsymbol{J}$ and $\boldsymbol{x_i^a}$ are vectors of perturbation from ensemble mean of J and x_i^a respectively.

  Actually, Eq.(1) is a diagonal approximation of multivariate ensemble sensitivity:

  $$\frac{\partial J}{\partial \boldsymbol{x^a}} = \boldsymbol{X_a}([\boldsymbol{X_a}]^T \boldsymbol{X_a})^{-\boldsymbol{1}} \boldsymbol{J} \qquad (2)$$

  where $\boldsymbol{x^a}$ is analysis state vector and $\boldsymbol{X_a}$ is a matrix containing the ensemble of state vector perturbations.

- When the ith analysis state variable has an improvement that equal to its ensemble spread $\sigma(\boldsymbol{x_i^a})$, the predicted change of J by univariate ensemble sensitivity is

  $$\delta J_u = \sigma(\boldsymbol{x_i^a}) \times \frac{\partial J}{\partial x_i^a} \qquad (3)$$

  As for multivariate ensemble sensitivity with localization:

  $$\delta J_m = \boldsymbol{\rho} \circ \left(\sigma(\boldsymbol{x^a}) \frac{\partial J}{\partial \boldsymbol{x^a}} \right) \qquad (4)$$

  Where

  $$\sigma(\boldsymbol{x_j^a}) = \sigma(\boldsymbol{x_i^a}) \times \frac{cov(\boldsymbol{x_j^a}, \boldsymbol{x_i^a})}{Var(\boldsymbol{x_i^a})}$$

  $$(j = 1, \dots, i-1, i+1, \dots, N)$$

  and $\boldsymbol{\rho}$ is localization function.

- choose forecast error of sea level pressure ($SLP_{forecast} - SLP_{observation}$) at 0000 UTC 8 November as J.

  choose water vapor mixing ratio (QVAPOR), perturbation potential temperature (T), radial wind (RW) and tangential wind (TW) in D03 at 0000 UTC 7 November as $\boldsymbol{x^a}$.
- Comparisons between the actual change of J in model with the predicted change δJ_u and δJ_m responding to the same perturbed $\boldsymbol{x^a}$ can reveal how these two methods behave in real case.

Results

- Consistent results are obtained from univariate (Figure 2) and multivariate (Figure 3) ensemble sensitivities that reducing of SLP forecast error and increasing intensity is associated with a moistier deep convection region in mid-lower troposphere, a stronger warm core, an increased primary circulation particularly at maximum wind radius and an increased secondary circulation.

  However, amplitudes of response are always smaller in multivariate sensitivity estimation than univariate, especially for upper levels.

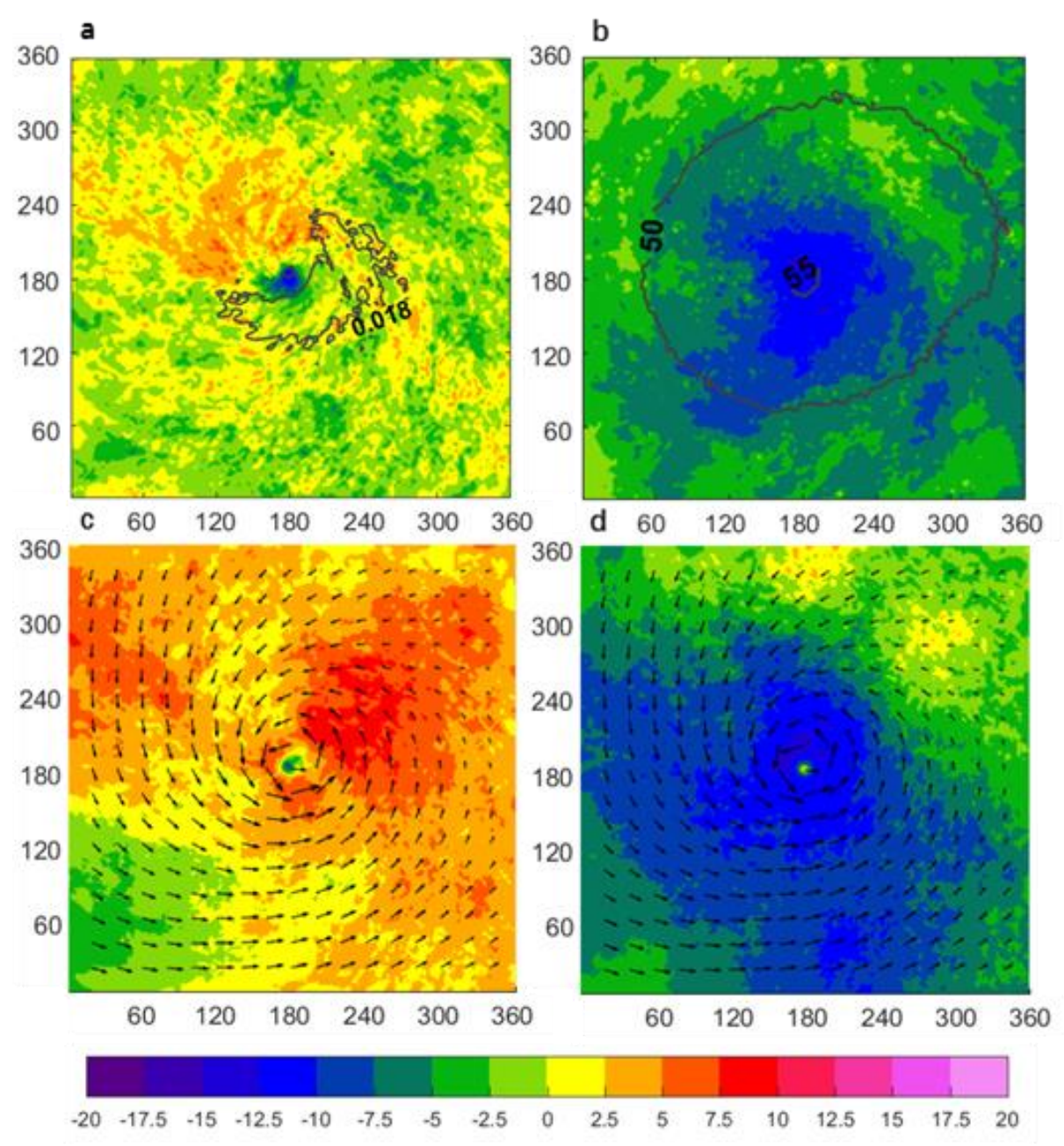

Figure 2. The predict δJ_u (shading, hPa) when adding σ improvement to (a)QVAPOR in model level closest to 950hPa, (b)T in model level closest to 200hPa, (c)RW and (d)TW in model level closest to 950hPa at corresponding point of D03 and ensemble mean (contours,(a) kg/kg, (b) K and wind vector)

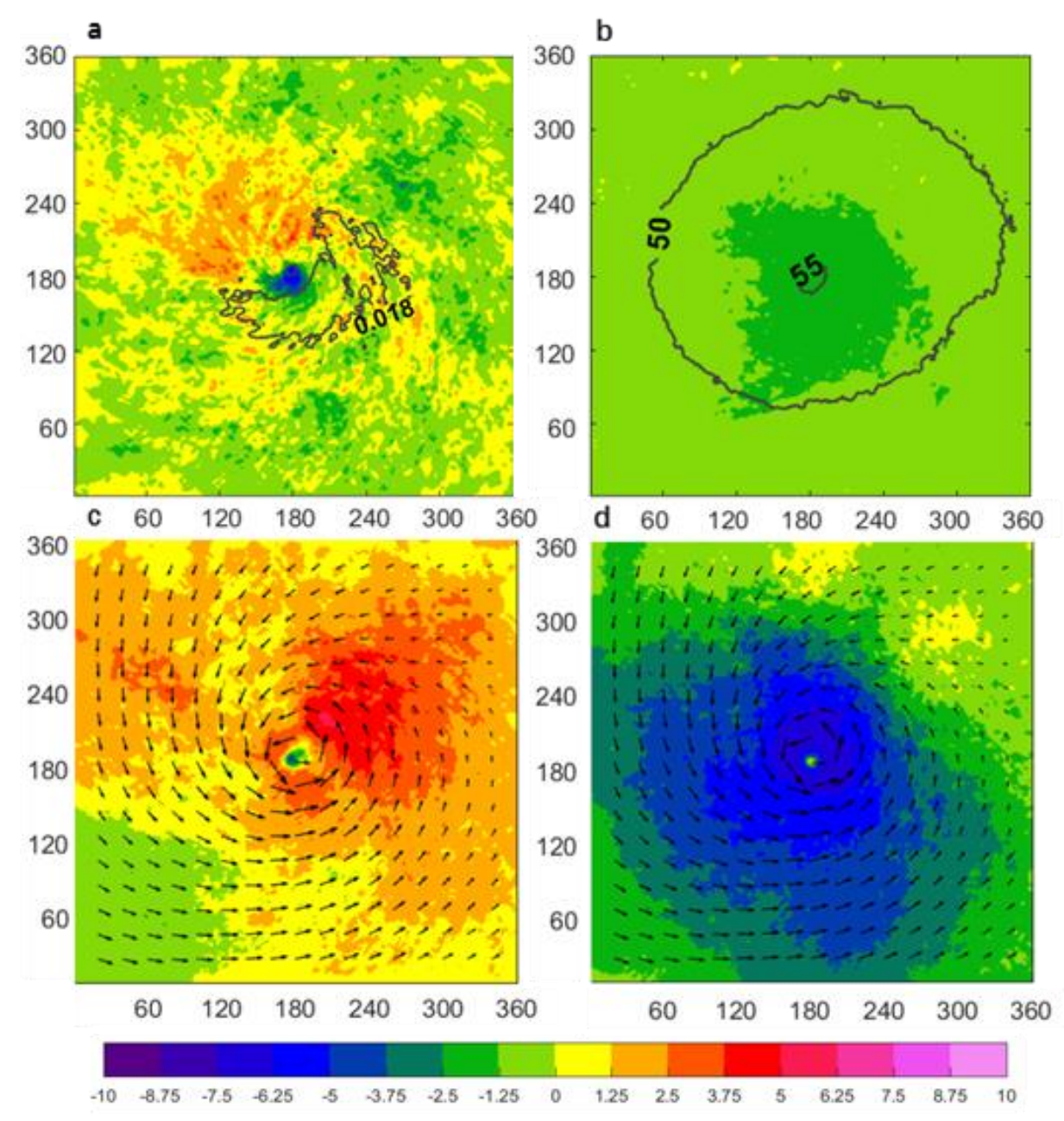

Figure 3. As in Figure 2, but for δJ_m (shading, hPa). Please note that the colorbars in Figures 2 and 3 are not the same.

- Due to computational constraints, only the member closest to the ensemble mean is used for perturbed initial condition experiment. By applying a σ increment of QVAPOR, T, RW or TW to the analysis that leads to the largest improvement of intensity change estimated by univariate ensemble sensitivity at different levels, and integrating the model forward, the actual forecast response can be obtained. The comparison between the univariate and multivariate ensemble sensitivity to the actual response is shown in Figure 4.

  Results shows that univariate ensemble sensitivity always overestimates the intensity change in this case. On the contrary, multivariate ensemble sensitivity can reduce the overestimation and has better agreement with the actual response.

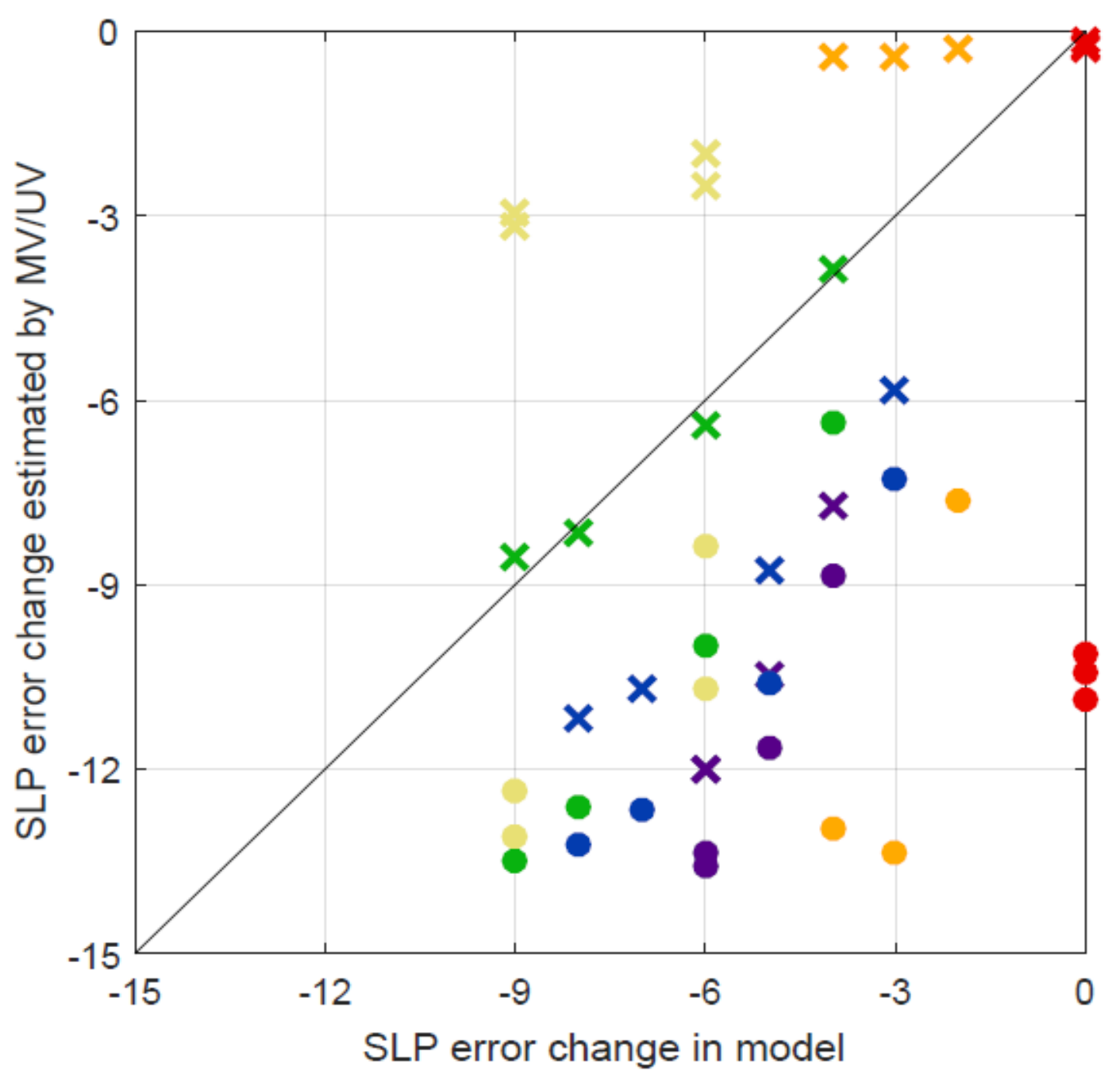

Figure 4. Changes of SLP forecast error in actual model against estimations from univariate (dot) and multivariate ensemble sensitivity (cross) when perturbing variables on model level closest to 950hPa (purple), 850hPa (blue), 700hPa (green), 500hPa (yellow), 200hPa (orange) and 100hPa (red).

Conclusions

- Univariate and multivariate ensemble sensitivities consistently indicates that increasing intensity is associated with a moistier deep convection region in mid-lower troposphere, a stronger warm core, an increased primary circulation particularly at maximum wind radius and an increased secondary circulation.
- However, multivariate ensemble sensitivity behaves better in perturbation response estimation than univariate ensemble sensitivity that invariably overestimates changes.