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An Ensemble Forecasting Alternative Based on Stochastic Parameter Perturbation (SPP) on Potential Vorticity Anomalies through the Identification of Weather Features as Coherent Objects †

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Abstract: The Pacific Ocean witnesses frequent cyclonic activity. The destructive impact of these storms, including strong winds, heavy rain, and storm surge, causes flooding, landslides, and extensive damage. Understanding cyclone genesis and evolution is crucial for accurate forecasts and minimizing harm. Towards this direction, an alternative ensemble forecasting approach based on a stochastic parameter perturbation (SPP) scheme, applied in potential vorticity (PV) anomalies, was developed. Testing it on Typhoon Usagi demonstrated its effectiveness in introducing uncertainties to storm tracks and cyclone development. These findings highlight the potential of stochastic methods in regional forecasting systems.

Keywords: typhoon; ensembles; stochastic perturbations

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1. Introduction

Super Typhoon Usagi was a very intense cyclone (equivalent to a category 4 hurricane on the Saffir–Simpson hurricane wind scale) developed in the Western Pacific Ocean on 16 September 2013. Its development was influenced by a combination of favorable atmospheric conditions, including warm sea surface temperatures and low vertical wind shear [1]. The cyclone exhibited a well-defined eye at its center, surrounded by concentric bands of intense thunderstorms. Analysis of satellite imagery and meteorological data revealed that Cyclone Usagi underwent rapid intensification, with the minimum sea level pressure reaching 910 hPa [2]. This powerful tropical cyclone exhibited characteristics of a mature system, featuring sustained wind speeds of up 205 km/h (according to the Japan Meteorological Agency—JMA).

Cyclone Usagi had significant impacts on several countries in its path, primarily affecting the coastal regions of the Philippines, Taiwan, and southern China. It triggered extensive flooding, landslides, and infrastructure damage, leading to 39 deaths and significant economic losses estimated at approximately USD 4.32 billion [3,4]. These impacts underscore the importance of preparedness measures, early warning systems, and resilient infrastructure in vulnerable coastal regions to mitigate the devastating effects of tropical cyclones.

In this way, ensemble forecasts are employed in order to quantify the uncertainties in cyclone paths, dynamics and impacts. The present study is an effort to propose an alternative way of producing model ensembles based on stochastic parameter perturbations (SPP) on potential vorticity anomalies through the identification of weather features as coherent objects.

2. Model Set-Up

The numerical simulations presented in this study are performed using the Advanced Weather Research and Forecasting Model (WRF-ARW, version 4.2.2, [5]). The domain is set up with horizontal grid resolution of 4 km and a hybrid 61 terrain-following η levels up to 50 hPa. Initial and boundary conditions were obtained from hourly ERA5 reanalysis [6] at 0.25° grid spacing.

The specific physical parameterization schemes common to all the simulations performed in this study are summarized in the following table (Table 1):

Table 1. WRF parameterizations used for the study.

Microphysics	the single-moment Thompson microphysics scheme [7,8]
Cumulus Parameterization	Kain–Fritsch [9]
Short- and long-wave radiation physics	RRTMG scheme [10]
Planet boundary layer	non-local K Yonsei University scheme [11,12]

3. A Feature-Based Stochastic Scheme (FBS)

The future-based stochastic system (FBS) aims to perturb stochastically the grid points that dynamically describe a cyclone system. This is carried out via a four-step procedure:

Step one—PV budget calculation: A module has been developed that calculates the non-conserved PV components of the total atmospheric PV at the beginning of every model time step. This module is described in detail in [13] where it has been used to analyse the processes that contribute to the intensification of Mediterranean cyclones.

Step two—Identifying and tracking objects: A new module has been developed and implemented into WRF to identify coherent 3D objects. Each object is composed of neighboring grid points of PV_{diab} or PV_{mo} that exceed the absolute value of 0.75 PVUs. However, we retrain only objects that include at least one grid point of more than 2 PVUs. From the perspective of PV invertibility, these two absolute value thresholds are deemed adequate for retaining objects which describe meso-scale systems in terms of size, and have a significant impact on the atmospheric state. Since this study focuses on cyclones, we included an additional criterion that demands from objects to be composed of grid points with negative pressure perturbation (P′, expressed in pressure anomalies from model level averages) (Figure 1).

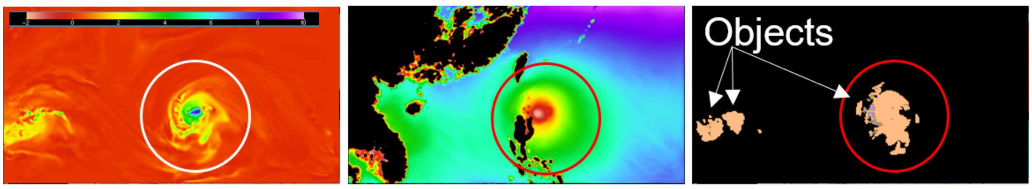

Figure 1. An example for Identifying and tracking objects—Cyclone Usagi.

Step three—tracking objects in time: Once identified each object is separately labeled according to the time step it was identified. If there are overlapping objects, then the oldest time label is assigned to the object.

Step four—assigning a perturbation coefficient: Finally, every object is assigned to a coefficient c_t that changes in time according to the following equation:

$$c_t = \left(1 - \frac{dt}{\tau}\right)c_{t-1} + 0.5\chi\sqrt{1 - \left(1 - \frac{dt}{\tau}\right)^2} \quad (1)$$

If $c_t < -1$, then $c_t = -2 - c_t$, if $c_t \geq 1$, then $c_t = 2 - c_t$. χ is a random number that ranges from -1 to 1, t is the time step, dt is the model time step and τ is a constant in units of time. The choice of τ is arbitrary but nevertheless it is crucial for the frequency of changes of the perturbation coefficient. As an example, Figure 2 shows examples of the time evolution of the perturbation coefficient c_t at every model time step for τ = 12 h.

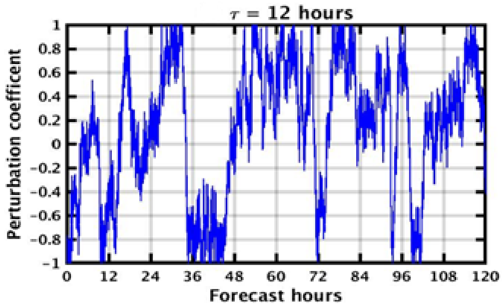

Figure 2. Five-day time evolution of the perturbation coefficient for characteristic length (τ in Equation (1)) equal to 12 h.

4. Results

In terms of the trajectory of Usagi, we can observe that the control simulation shows a similar track compared with the ones obtained from the JMA, specially during the initiation and mature stage of Usagi (Figure 3). Although the control trajectory starts to diverge in the dissipation phase of Usagi, we can certainly conclude that the control simulation performs with accuracy enough the typhoon trajectory.

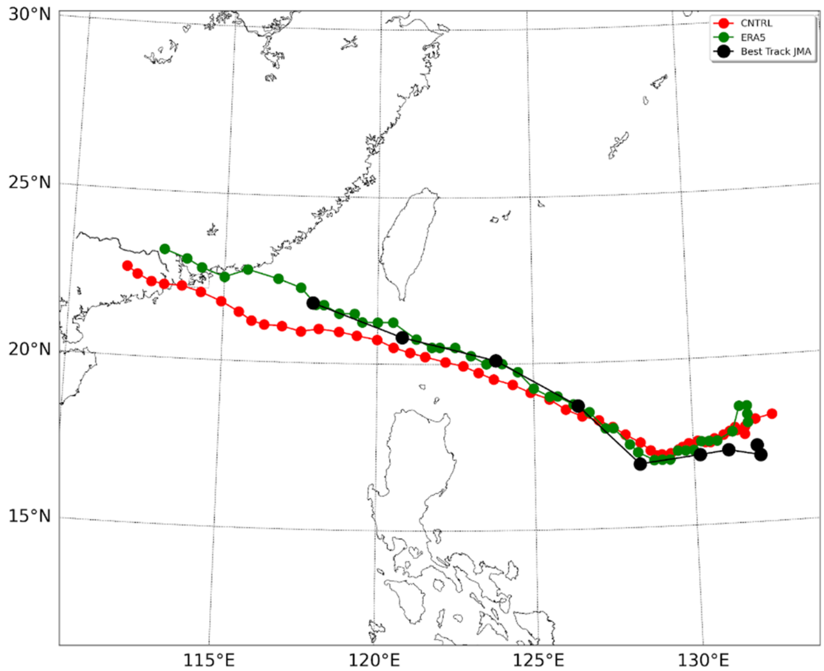

Figure 3. Usagi's trajectories depicted by the CNTRL simulation and the JMA from 16 UTC 9 September to 21 UTC 23 September 2013. CNTRL and JMA data are depicted every 3 h.

To assess the model's sensitivity in cyclone forecasting, six simulations were conducted using the Stochastically Perturbed Parametrization Tendencies (SPPT) scheme within the WRF model, while maintaining the same model configuration. The ensemble cyclone tracks exhibited a close resemblance to the reference track (Figure 4), indicating a comparable spread. Similarly, the development of the cyclonic system, as reflected in the Mean Sea Level Pressure (MSLP) values at its center, varied around those of the control simulation.

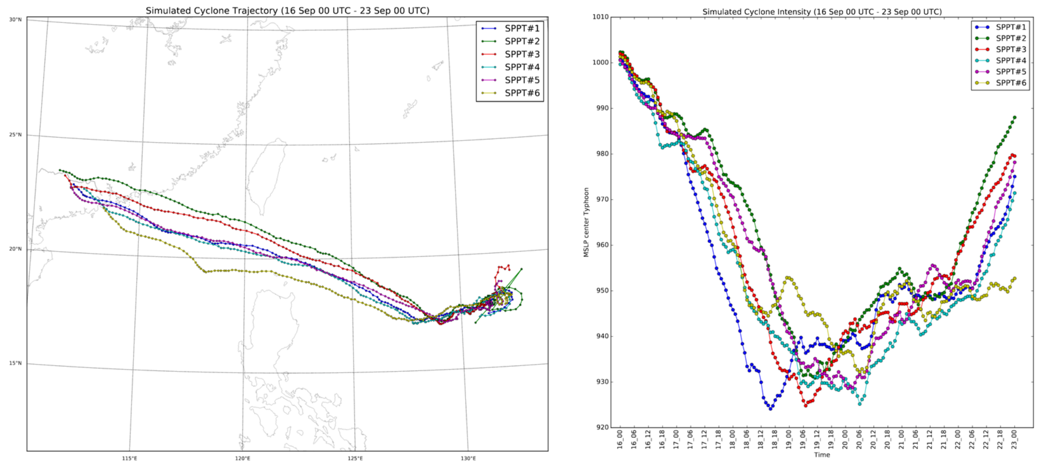

Figure 4. SPPT ensemble member cyclone tracks and minimum MSLP evolution.

Before implementing the perturbation coefficient on the physical tendencies of the objects, a set of experiments was performed by multiplying them with constant values. These values ranged from 0 to 2, with an increment of 0.25. This allowed for a deeper understanding of the impacts this procedure had on the system's evolution. The findings revealed that coefficients smaller than 1 (where 1 represents the control simulation) had a more pronounced effect compared to larger coefficients (Figure 5).

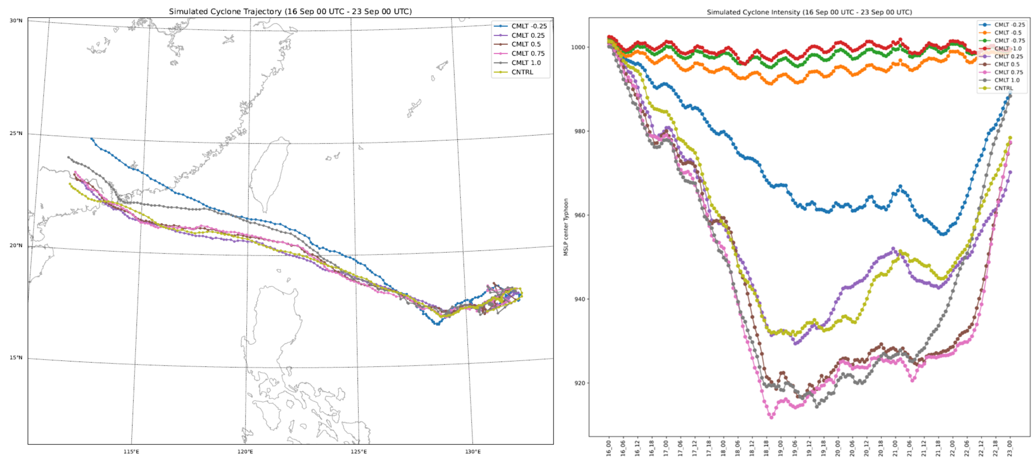

Figure 5. Cyclone tracks and minimum MSLP evolution during the experiments where the identified objects are multiplied with values ranging from 0 to 2 (0% to 200%).

For the purposes of this study, the FSB scheme utilized random coefficients within the range of −0.1 to +0.4. The application of this scheme yielded a satisfactory spread, albeit narrower than that observed with the traditional SPPT methodology. The cyclone exhibited sensitivity throughout all stages, with the minimum mean sea level pressure (MSLP) value consistently higher than the control case in most instances (Figure 6).

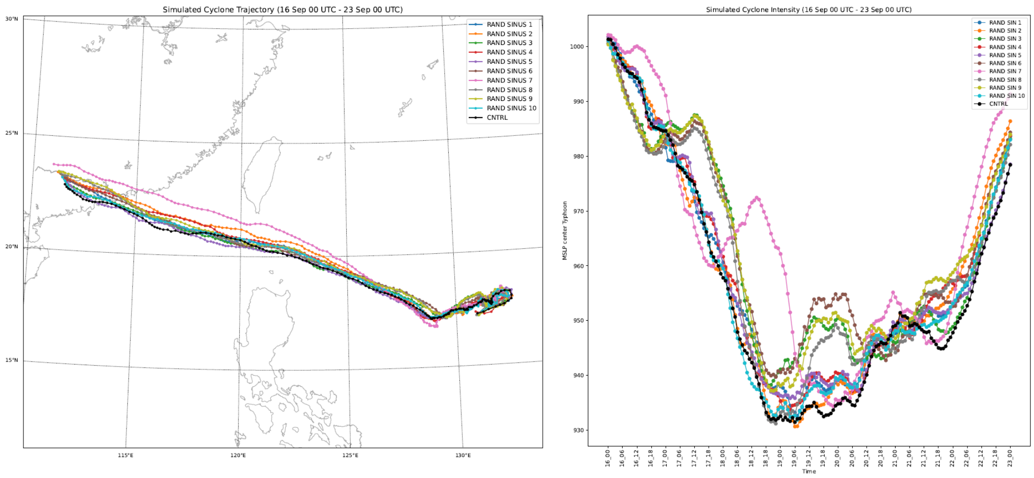

Figure 6. Cyclone tracks and minimum MSLP evolution for all ensemble members produced through the proposed FSB approach.

5. Conclusions

In this study, we present preliminary results on a new SPPT scheme where perturbations are uniquely applied to areas characterized by high PV, produced by diabatic processes. Therefore, we only perturb the grid points which are expected to have a strong impact on the component of the atmospheric state that is sensitive to inherent model uncertainties. Our results show comparable spread on the tracks and MSLP evolution to the one produced by the original SPPT method. In contrast to the original SPPT method, we consider the fact that this approach is based on PV theory and, therefore, that perturbations have a physical basis, to be an advantage

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