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EFFECT OF INITIAL PERTURBATION OF LAND SURFACE PROCESSES ON TROPICAL CYCLONE FORECAST

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Abstract: Many studies have explored the importance and influence of planetary boundary layer processes on tropical cyclones (TCs). However, few studies have focused on the influence of land surface processes on the activity of TCs. To test the effect of initial perturbations of land surface processes on TCs, a land surface process perturbation module is built in a global ensemble prediction system. Ensemble experiments for the TCs that occurred from 12 UTC 22 August to 18 UTC 24 November, 2006 show that consideration of the uncertainties within the land surface process could increase the predictability of the global ensemble prediction system. Detailed analysis on TC Xangsane (2006) indicates that the perturbation of land surface processes may increase the variation of sensible heat flux and latent heat flux. Meanwhile, the effect from land surface perturbation can be transferred to the upper atmosphere, which leads to better TC forecasts.

Key words: tropical cyclone; land surface process; initial perturbation; ensemble prediction

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1 INTRODUCTION

A lot of literatures have demonstrated the effect of planetary boundary layer processes on tropical cyclones (TCs)[1-5], as well as on atmospheric circulations driven by regional differences in the land surface state[6-9]. As it is well known, the atmosphere and the upper layers of soil or sea form a united system. The first few meters above ground have a thermal capacity comparable with 1/10 that of the entire atmospheric column standing upon it and the soil temperature can change considerably. Similar considerations have been applied to the ocean and the capacity of the soil water[10]. Much improved understanding of land-atmosphere interaction and far better measurements of land-surface properties, especially soil moisture, would constitute major intellectual advancement and may hold the key to dramatic improvements in a number of forecasting problems, including the location and timing of deep convection over land, quantitative precipitation forecasting in general, and seasonal climate prediction. Results of the sensitivity experiments indicate that the planetary boundary layer is most sensitive to the amount of soil water content and the proximity of the soil water content to critical soil texture value. However, the studies on the effect of land surface processes on TC is rare[11, 12], especially using an ensemble prediction system. We speculated that an error in the land surface state may change some of the details of the forecasts of planetary boundary layer processes and convection and precipitation, and ensemble forecasts may gain appropriate spread by considering the uncertainties with land surface processes, thereby increasing the predictability of TC.

Ensemble forecasts start from a set of different states that are sampled from a probability density function which is approximated using a finite sample of initial perturbations. However, how to better generate these initial perturbations for an ensemble forecasting system is still a research issue. The initial perturbation techniques already put into operation at different forecaster centers are: singular vectors used at the European Center for Medium-Range Weather Forecasts (ECMWF)[13], bred vectors used in the National Centers for Environmental Prediction (NCEP)[14] and National Meteorological Center (NMC)/China Meteorological Administration

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(CMA)[15], the perturbed observation (PO) approach at the Meteorological Service of Canada (MSC)[16] and methods of ETKF/ET that are more consistent with the data assimilation systems[17]. Although the first generation of ensemble forecasting system was put into operation 20 years ago, the perturbations created are almost all in the atmosphere part. The effect of perturbations on land surface processes has not been investigated in previous works. To test the influence of land surface processes on TCs, we add a module of perturbation on land surface processes to the global ensemble prediction system[17, 18]. It is expected that the perturbed land surface process would modulate the planetary boundary layer process through the exchanges of shortwave radiation, evapotranspiration (latent heat flux), ground surface temperature (surface sensible heat flux and upward longwave radiation), etc.

This article is organized as follows: Section 2 provides a brief description of the methods to generate initial perturbations for the global prediction system. Section 3 presents a preliminary evaluation of predictability of global ensemble prediction system due to land surface perturbation. In Section 4, a severe TC Xangsane (2006) is selected to further examine the effect of land surface process perturbations on TC track, intensity and structure forecasting. Discussion and summary is given in the final section.

2 METHODS AND EXPERIMENT DESIGN

Global Forecast System (GFS) at NCEP is T382. The horizontal resolution is approximately 35 km in both the analysis and forecast model for the four GFS cycles at 0000, 0600, 1200, and 1800 Coordinated Universal Time (UTC). The vertical resolution is 64 layers. The model is run for 16 days. The GFS land-surface model component was Noah Land Surface Model (Noah LSM)[19-21], which has 4 sub-surface layers (10, 40, 100, 200 cm). It also contains improved treatment of frozen soil, ground heat flux, and energy/water balance at the surface, along with reformulated infiltration and runoff functions and an upgraded vegetation fraction. To obtain initial values of soil moisture and soil temperature, the Noah LSM cycles are performed in the Global Data Assimilation System (GDAS). Values are updated every model time step in response to forecasted land surface forcing (e.g., precipitation, surface solar radiation, near-surface temperature, humidity, and wind speed).

The initial perturbations of the NCEP global ensemble forecast system are generated by an Ensemble Transform (ET) method, which was formulated in Bishop and Toth[22] and Wei et al.[17] primarily for target observation studies. In this paper, we adopt this technique for ensemble forecasting. Let

$$\mathbf{Z}^f = \frac{1}{\sqrt{k-1}}[\mathbf{z}_1{}^f, \mathbf{z}_2{}^f, ..., \mathbf{z}_k{}^f] \quad \text{and} \quad \mathbf{Z}^a = \frac{1}{\sqrt{k-1}}[\mathbf{z}_1{}^a, \mathbf{z}_2{}^a, ..., \mathbf{z}_k{}^a] \tag{1}$$

where the n dimensional state vectors $\mathbf{z}_i{}^f = \mathbf{x}_i{}^f - \mathbf{x}^f$ and $\mathbf{z}_i{}^a = \mathbf{x}_i{}^a - \mathbf{x}^a$ $(i = 1, 2, ...k)$ are k ensemble forecast and analysis perturbations, respectively. In our experiments, $\mathbf{x}^f$ is the mean of k ensemble forecasts and $\mathbf{x}^a$ is the analysis from the independent NCEP operational data assimilation system. Unless stated otherwise, the lower case letters indicate vectors, and upper case bold letters indicate matrices. The $n \times n$ forecast and analysis covariance matrices are formed, respectively, as in

$$\mathbf{P}^f = \mathbf{Z}^f \mathbf{Z}^{fT} \quad \text{and} \quad \mathbf{P}^a = \mathbf{Z}^a \mathbf{Z}^{aT} \tag{2}$$

where T indicates the matrix transpose. For a given set of forecast perturbations $\mathbf{Z}^f$ at time *t*, the analysis perturbations Z^a are obtained through an ensemble transformation $\mathbf{T}$, namely, $\mathbf{Z}^a = \mathbf{Z}^f\mathbf{T}$. Suppose we have obtained the analysis covariance matrix from the operational data assimilation system, then $\mathbf{P}^a = (\mathbf{Z}^f\mathbf{T})(\mathbf{Z}^f\mathbf{T})^T$. The ET solution is $\mathbf{Z}^a = \mathbf{Z}^f\mathbf{T}$, where $\mathbf{T} = \mathbf{C}\mathbf{\Gamma}^{-1/2}$, $\mathbf{C}$ contains column orthonormal eigenvectors ($\mathbf{c}_i$) of $\mathbf{Z}^{fT}\mathbf{P}^{a-1}\mathbf{Z}^f$ and $\mathbf{\Gamma}$ is a diagonal matrix containing the associated eigenvalues (λ_i), that is, $\mathbf{C} = [\mathbf{c}_1, \mathbf{c}_2, ..., \mathbf{c}_k]$ and $\mathbf{\Gamma} = \mathrm{diag}(\lambda_1, \lambda_2, \ ....., \ \lambda_k)$. Although the forecast perturbations are, by definition, centered about the ensemble mean, i.e., $\sum_{i=1}^{k} \mathbf{z}_i{}^f = 0.0$, the analysis perturbations produced by the ET are not centered around the analysis ($\sum_{i=1}^{k} \mathbf{z}_i{}^a \neq 0.0$). A simple transformation that will preserve $\mathbf{P}^a$ and center the analysis perturbations about the analysis is the simplex. Similar to the ETKF experiments, $\mathbf{C}^T$ is one of the solutions of this transformation. Hence, $\mathbf{Z}^a = \mathbf{Z}^f\mathbf{T}\mathbf{C}^T$ will be used in this study as initial analysis perturbations for the next cycle forecasts (Figure 1a).

To test the effect of land surface processes on TCs, we devise a parallel test. In the control experiment, only atmospheric variables are perturbed by using the ET, which includes initial perturbation (IC) on the atmospheric part with one control and four perturbations and vortex relocation technique. On the other hand, we make perturbations on both the atmospheric side and land surface processes, called the perturbation run (Figure 1a). Besides all the contents in the control run, we also emphasize surface perturbations, and a simplified breeding method[14] (Figure 1b) is applied to surface variable perturbation: (a) obtaining different forecasting surface variables, such as soil moisture and soil temperature, with different ensemble members; (b) subtracting one forecast from another; (c) scaling down the difference field so that it has the same norm as the analysis error; and (d) adding this perturbation to the control forecast. The steps (a) through (d) are repeated forward in forecast cycles. Control surface analysis is used at cold start for a cycle (6 h), then forecasted soil temperature and soil moisture are used as model initial surface conditions at the next cycle, repeating likewise all the way till the end of experiment (Figure 1). To keep the values of perturbations within a reasonable range, the maximum amplitude of the perturbations is scaled to the climate reference values. Factors that are perturbed include soil temperature (4 layers) and soil moisture (4 layers), including soil volumetric water content in fraction and liquid soil moisture (Table 1). The testing period is from 12 UTC 22 August to 18 UTC 24 November, 2006. During this period, several TCs formed in western North Pacific area. Considering the characteristics and resolution of the global prediction system, a strong TC Xangsane (2006) is selected for further analysis.

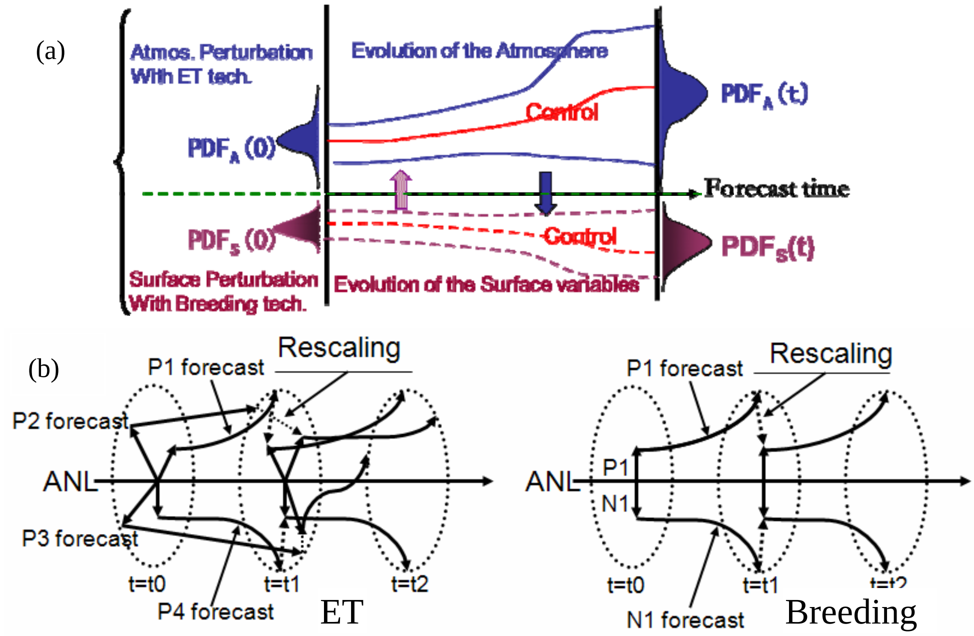

Figure 1. (a): Configuration of atmosphere perturbation (control run) and atmosphere/surface perturbation (perturbation run); (b): schematic diagrams of the ensemble transform (ET, left) and breeding (right) methods.

Table 1. Summary of experiment design.

Experiment	Forecast Model	TC Relocation	Land Surface Process	Ensemble Size	Atmosphere Perturbation	Surface Perturbation
Control	GFS T382	Yes	Noah Land Surface Model	4	ET (perturb U,V,T,Q,GH)	No
Perturbation	GFS T382	Yes	Noah Land Surface Model	4	ET (perturb U,V,T,Q,GH)	Breeding (Perturb soil moisture and temperature at 10, 40, 100, 200 cm)

3 EVALUATION OF PREDICTABILITY OF GLOBAL ENSEMBLE PREDICTION SYSTEM DUE TO LAND SURFACE PERTURBATION

To understand the effects of perturbation of land surface processes on the global ensemble prediction system, various of scores to evaluate the performance of probability forecasts are calculated for the control run and perturbation run in different forecast areas, such as Asia, Europe, North America, South America, etc, during the three-month experiment. In addition, a strong West Pacific TC Xangsane is selected to analyze the effect of land surface processes on the predictability of TCs. The verification area of the TC prediction is selected as the Asian region.

For probabilistic forecasts, there are lots of verification methods to evaluate the performance of the system. Some measures assess resolution or reliability while others provide a combined measure of both[23, 24]. No single approach for verification provides complete information about the quality of a product[25]. To assess the effect of land surface processes on the global ensemble prediction system, various scores evaluating the performance of probability forecasts are calculated for the control run and perturbation run. The verification area is in the Asian area and the period from 23 August to 25 November, 2006.

3.1 *Continuous Ranked Probability Skill Score (CRPSS)*

Continuous Ranked Probability Score (CRPS) measures the difference between the forecast and observed cumulative density functions (CDFs) of scalar variables[26].

$$\mathrm{CRPS}=\int_{-\infty}^{\infty}[P_{fcst}(x)-P_{obs}(x)]^2\,dx \tag{3}$$

where $P_{obs}(x)$ and $P_{fcst}(x)$ are the observed and predicted CDFs, respectively. The CRPS is the generalization of the Brier score over all the possible thresholds of the variable under consideration. Negatively oriented, the CRPS reaches its minimum value of zero for a perfect deterministic system. The CRP skill score is:

$$\mathrm{CRPSS}=\frac{\mathrm{CRPS_c}\text{-}\mathrm{CRPS_f}}{\mathrm{CRPS_c}} \tag{4}$$

where $\mathrm{CRPS_c}$ is the Continuous Ranked Probability Score of climatology. The CRPSS has the advantages of being sensitive to the whole range of values of the parameter of interest and does not depend on predefined classes at the same time. Figure 2 shows the continuous ranked probability skill score of 10-m *u* component and 850 hPa temperature in the Asian region from 23 August to 25 November in 2006. The score of the perturbation run is slightly better than that of the control run from the forecast lead time of day 3 to day 10, indicating that consideration of the uncertainties of land surface processes could increase the forecast skill of the ensemble prediction system in the characteristics of reliability or resolution, or both. Further verifications (figure omitted) show that the increasing skill mainly resulted from resolution. It is worth noting that the resolution of ensemble forecast cannot be improved by simply correcting model output bias.

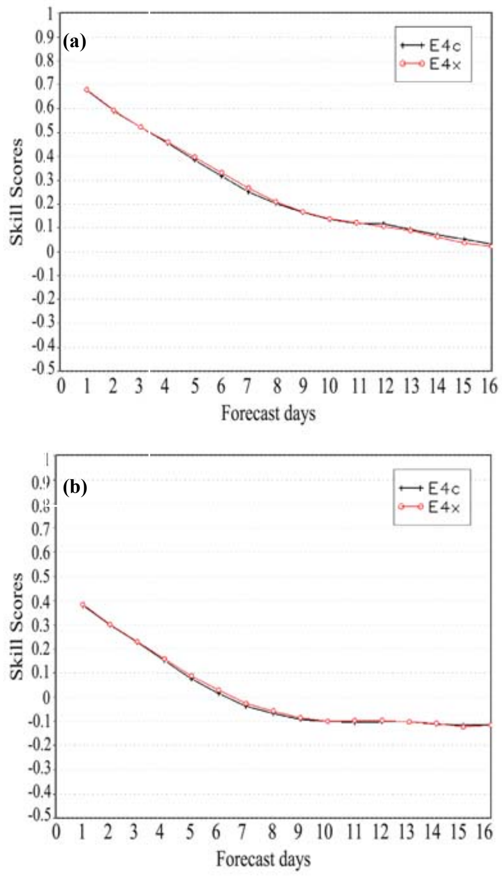

Figure 2. CRPSS for the perturbation (red) and control (black) experiment for 850 hPa temperature (a) and 10-m *u* component (b).

3.2 *Measurements of ensemble mean*

The method selected above to evaluate the effect of land surface processes in the global prediction system is based on probability. Furthermore, this effect can also be assessed from a deterministic point of view, i.e., ensemble mean error and ensemble spread, and the two indices are often combined to verify the performance of a system.

The mean error for an ensemble prediction system is often denoted with Root Mean Square Error (RMSE), which measures the mean distance between forecasts and observations (or analyses).

$$\mathrm{RMSE}=\sqrt{\frac{1}{m}\sum_{i=1}^{m}\frac{1}{n-1}\sum_{j=1}^{n}(f(i)-a(i))^2} \tag{5}$$

where $f(i)$ is the forecast of the member i, while $a(i)$ indicates analysis or observation at corresponding time, m is the sample size (360×181 grid points for the verification domain), and n the ensemble size (4).

Ensemble spread (SPREAD) is calculated by measuring the deviation of ensemble forecasts from their mean. It is denoted by

$$\text{SPREAD} = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\frac{1}{n-1}\sum_{j=1}^{n}(\overline{f} - f(i))^2} \quad (6)$$

where $\overline{f} = \frac{1}{n}\sum_{j=1}^{n} f(j)$ is an ensemble mean, m the sample size, and n the ensemble size. SPREAD has the same unit as RMSE, which measures ensemble's uncertainty. For an ideal ensemble prediction system, the ensemble RMSE should be equal to the ensemble SPREAD.

Figure 3 shows comparisons of ensemble mean and spread for 850 hPa temperature and 2-m temperature, respectively. For the 850 hPa temperature, it seems that the effect of perturbation of land surface processes takes effect at lead time from day 3 to day 16, indicating that the ensemble spread can be increased when land surface uncertainties are considered within the ensemble prediction system. The effect of decreased forecasting error becomes obvious after day 4, one day lagged behind than the spread improvement. However, the RMSE of 850 hPa temperature in the perturbation run is slightly larger than the control after a 14-day forecast. For the 2-m temperature, the overall evaluation result is similar to that in the 850 hPa temperature forecast, i.e., the perturbation experiment increases the spread of the ensemble system but decreases the forecast error, although the improvement is not so obvious as the variables in upper levels.

To check if the effect of perturbation in land surface processes has extended to the whole atmospheric process, the verification scores at low/middle/high latitudes and at different vertical levels are calculated. The results are similar and the above verifications and variables are randomly selected. In general, it indicates that perturbing the land surface process could increase the overall skill of the ensemble prediction system, although the improvement is small due to the limitation of test period and surface perturbation designation. Meanwhile, there is apparently advantage from soil moisture perturbation when the tendency is higher in the upper atmosphere, indicating that the land surface effect could be easily transported to the upper atmosphere through atmospheric turbulence, convection, etc. The results are to trigger and enlarge the uncertainties for free atmosphere.

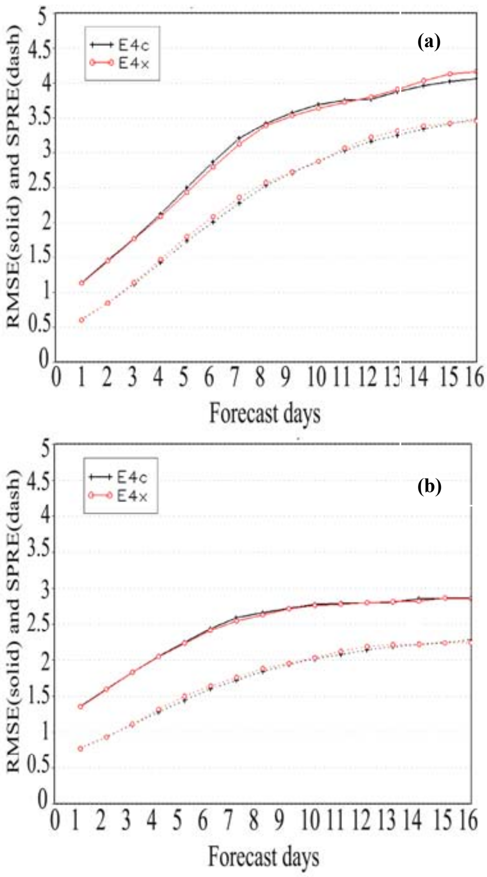

Figure 3. Evolution of spread and RMSE for the perturbation (red) and control (black) experiment for 850 hPa temperature (a) and 2-m temperature (b).

4 EFFECTS OF LAND SURFACE PERTURBATIONS ON PREDICTABILITY OF TC XANGSANE

To show the effect of perturbation of LSP on TCs, cyclones that took place in the experiment period are studied. During this period, TC Xangsane is one of the strongest storms. On September 26, Xangsane became a severe tropical storm to the east of the Philippines, then it passed through the Philippine islands and became the strongest TC that directly impacted Metro Manila in the eleven years right up to 2006. As it entered the South China Sea as a weak TC, Xangsane began to re-intensify, reaching its secondary peak strength shortly before landfall near Hue on 1 October. The TC caused heavy rainfall in the Philippines. It killed over 200 people in the country, produced strong winds and rainfall, broke power lines and caused mudslides. The strong winds caused moderate crop damage worth of up to $7.2 million, and it also killed 71 people in

Vietnam[27]. To understand the influence of perturbing land surface processes on TC Xangsane, the track, intensity, latent and sensible heat flux produced by the control run and perturbation run were compared.

For the case of TC Xangsane, the experiment made forecasts that cover the time from a tropical depression (24 September, 2006) to a strong TC, from the time of landfall to that of dissipation on 2 October, 2006. From 27 September to 30 September, the storm moved into the South China Sea after making landfall and reached its peak intensity. The forecasts in this period are selected and analyzed.

Figure 4 shows the TC tracks forecast for day 4 in the control run (a) and perturbation run (b) from 27 September to 2 October. It is obvious that the storm track (dashed lines) of the perturbation run is closer to that of the observation than that of the control run. Although the verification results show that the spread of the perturbation run during the experiment period is larger than the control run, it does not necessarily mean that the difference between forecast tracks of ensemble members are also greater than that of the control run. Figure 4 indicates that not only the overall forecast track of the ensemble prediction system is improved after considering the uncertainties of land surface processes, but also the four forecast perturbation tracks are closer to each other than in the control experiment. Better TC track forecasts are made possible to achieve.

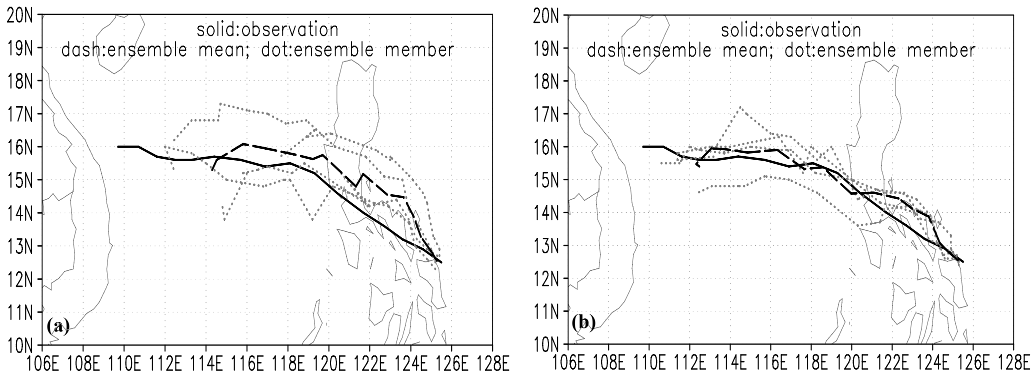

Figure 4. Comparison of 4-day forecasting track for control run (a) and perturbation run (b) from 0000 UTC 27 September.

Figure 5 presents maximum observed winds, ensemble average for the perturbation run, and ensemble average for the control run. The perturbation run does not significantly improve the intensity forecasts compared with the control run. It is a challenge for a global ensemble prediction system to forecast the intensity of TCs (The forecast minimum sea-level pressure of TC gets similar results, hereafter omitted). After considering more of the interaction between land surface processes and the atmosphere, the forecast maximum winds are slightly increased during the period of experiment.

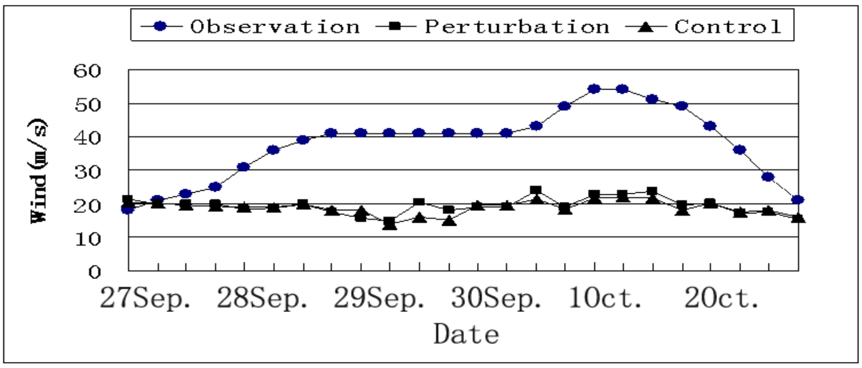

Figure 5. Comparison of 4-day forecasting maximum wind for the control run (triangle) and perturbation run (rectangle) at 2700 UTC.

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5 EFFECTS OF LAND SURFACE PROCESSES ON DEVELOPMENT OF TC XANGSANE

Land surface processes play an important role in numerical weather prediction (NWP) in that as the ground surface heats up during the day, sensible energy is transferred to the atmosphere, moisture evaporates from the soil or transpirates from plants (latent heating), and the soil below is heated. Changes in land-surface properties are shown to influence the heat and moisture fluxes within the planetary boundary layer, convective available potential energy, and other measures of the deep cumulus cloud activity[11, 28]). Therefore, discussing the layout of sensible flux and latent flux is the key to understanding how land surface processes could affect the evolution of TCs.

As is well known, TCs occur where a deep layer of warm water exists by drawing their power from warm and extremely humid air. Figure 6 shows the distribution of latent heat flux for perturbation of land surface processes and the control test at the same period. It shows that the magnitude of latent heat flux increases outward from the TC center to the periphery of the maximum wind radius before decreasing outward slowly. Large-value regions for both experiments are located to the southwest and northwest of the TC center. Detailed analysis of the land surface perturbation experiment demonstrates that the magnitude and area of large latent heat flux in the southwest area is significantly greater than its control counterpart, but for the northwest part, it is slightly smaller. It is notable that the magnitude difference between the control and perturbation results not only from their own value, but from distribution of the wind fields. Xangsane mainly obtained latent heat flux from the southwest of the TC center. When the uncertainties of soil moisture and soil temperature are considered, the interaction between the land surface (external forcing) and the atmosphere is better described, thus resulting in forecast difference between the control and the perturbation experiment. The forecast from the NWP model will be modified due to this interaction. Therefore, Xangsane could have access to more latent heat flux and during the perturbation is likely to acquire more energy and achieve more development. This also could be explained in the control experiment. The TC in one ensemble member weakened and dissipated after a 3-day prediction (Figure 4a). Emanuel[29] used a simple numerical model to demonstrate that the evolution of hurricane intensity depends mainly on three factors: the storm's initial intensity, the thermodynamic state of the atmosphere through which it moves, and the heat exchange with the upper layer of the ocean under the core of the hurricane. The latter two factors relate closely to sensible and latent heat exchanges with surface processes, which further indicates the importance of the planetary boundary layer and land surface processes to the development of TCs.

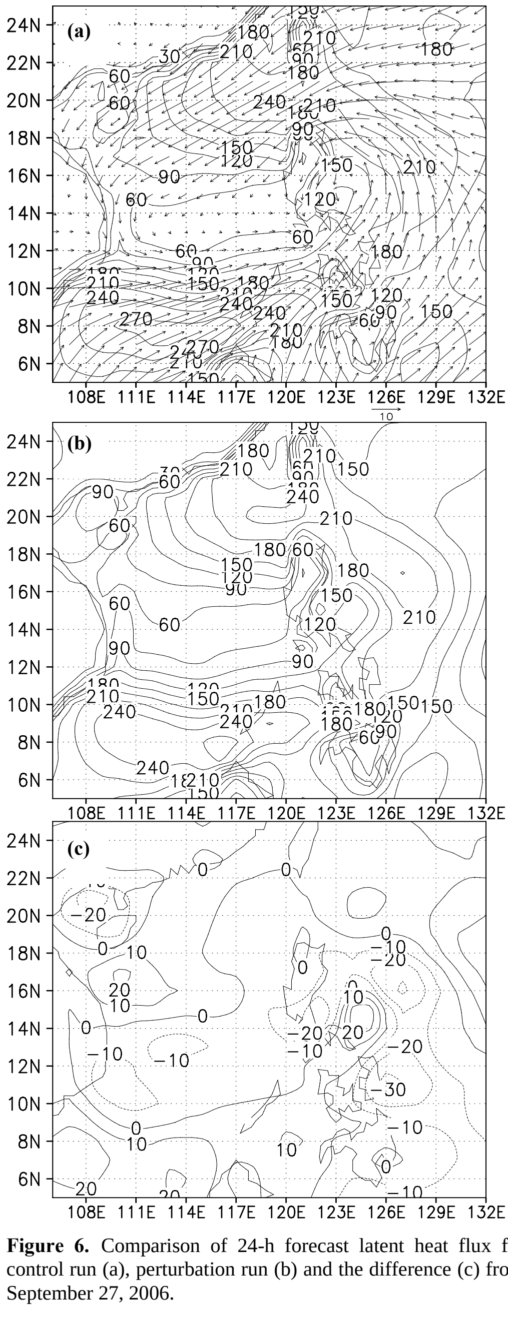

Figure 6. Comparison of 24-h forecast latent heat flux for control run (a), perturbation run (b) and the difference (c) from September 27, 2006.

The distribution of sensible heat flux for the two experiments is very similar to that of the latent heat flux (Figure 7), i.e., the perturbation test could provide more heat than the control. However, the magnitude of sensible heat flux is much less than that of latent heat flux, indicating that the latter plays a more important role in the development of TCs.

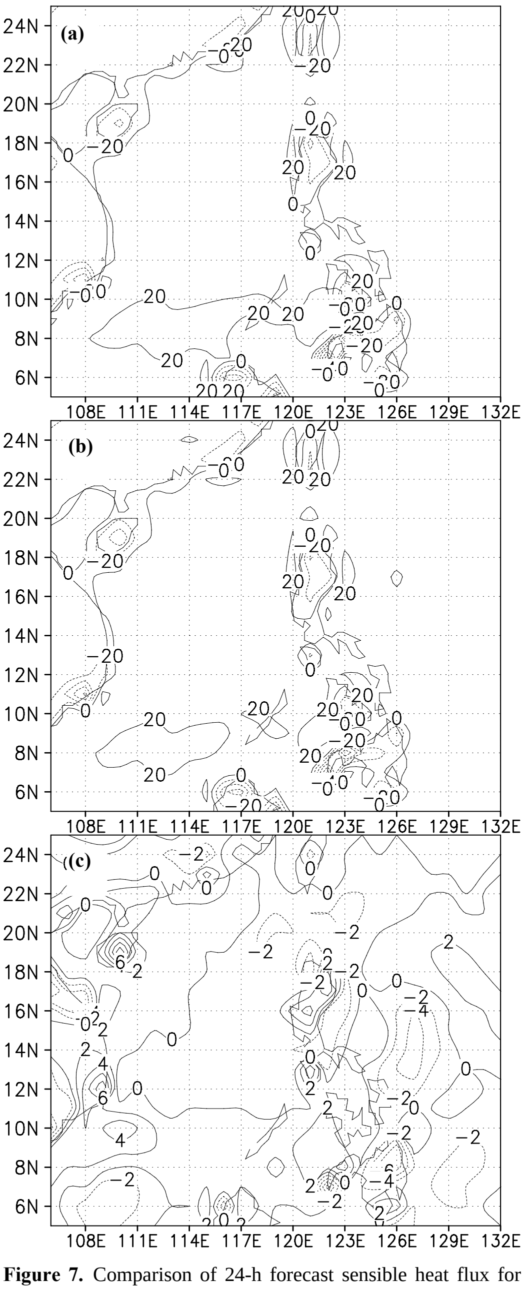

Figure 7. Comparison of 24-h forecast sensible heat flux for control run (a), perturbation run (b) and difference (c) from September 27, 2006.

To further explore the effect of land surface processes on the evolution of TC Xangsane, the thermal structure is analyzed. Figure 8 is the vertical distribution of temperature across the center of average TC Xangsane in the control on 28 September, when its surface minimum pressure was located at around 15.6°N, 123.5°E in the model. Figure 8a shows that the warm core is located at 16°N and decreases slightly at higher levels, which conforms to the typical structure of TCs[30]. Then, by considering the effects of land surface processes, the warm core of TC Xangsane became stronger (Figure 8b). It is notable that there is more (latent and sensible) heat flux exchange between the simulated Xangsane and the planetary boundary layer process in the perturbation run than in the control run (Figures 6 and 7), and the intensity of the perturbation run is slightly stronger than that of the control run (Figures 5 and 8). It is indicated as a warmer TC core (Figure 8b) while the temperature in the outer area becomes colder due to cooling condensation from more precipitation.

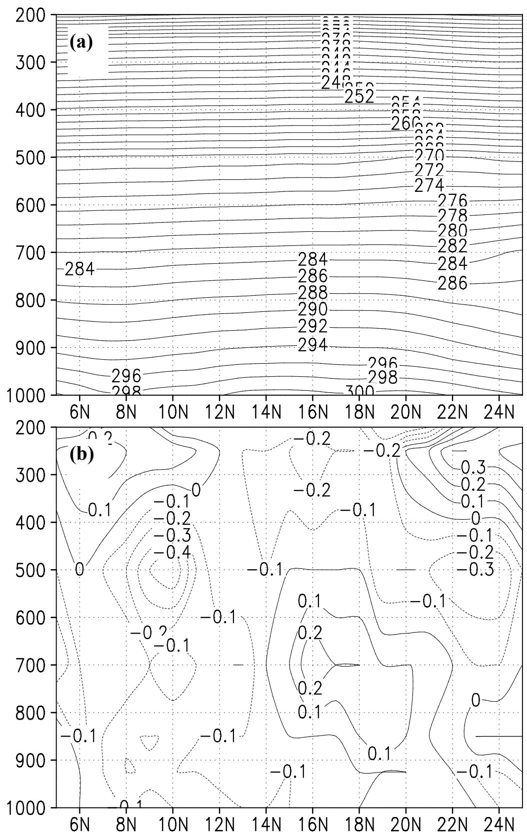

Figure 8. 24-h forecast temperature field along a north-south vertical cross section through typhoon center (15.6°N, 123.5°E) for perturbation experiment from September 27, 2006 (a) and 24-h forecast temperature increments between perturbation and control (b).

Similar to the temperature distribution, the area where Xangsane was located has high humidity (Figure 9), and the lower the latitude, the higher the relative humidity, as the evaporation and convection are more active in the tropical area than in the higher latitude area. In this article, only soil moisture and soil temperature are perturbed through land surface processes, which take place in land initially and then its impact extends to other areas, including tropical domain, due to convection and large-scale circulation, which then affects circulations at global scale (including activities of TCs). It is interesting to see that the average relative humidity field of the perturbation test is slightly drier around the center of TC. Meanwhile, the moisture is higher in the outer rainband in the perturbation test than in the control one, which may be favorable to the development of TC[31].

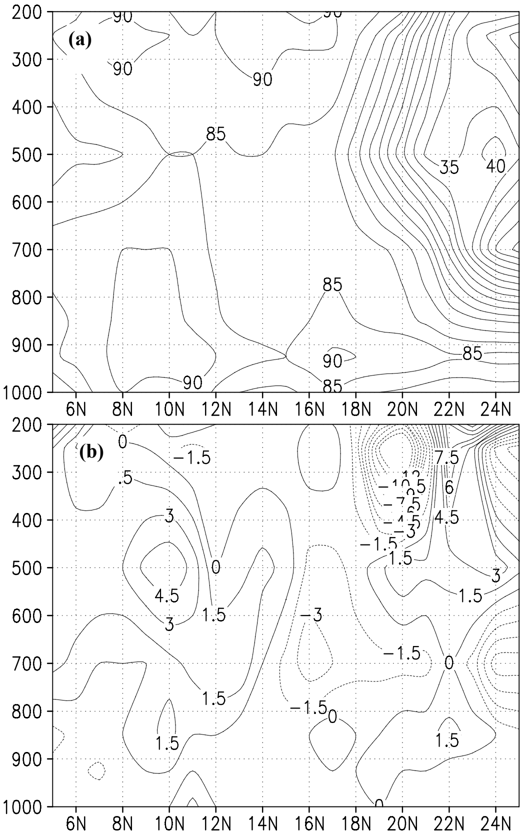

Figure 9. 24-h forecast relative humidity field along a north-south vertical cross section through the typhoon eyewall (around 15.6°N, 123.5°E) for perturbation experiment from September 27, 2006 (a) and 24-h forecast relative humidity increments between perturbation and control (b).

6 DISCUSSION AND SUMMARY

This paper examined the effect of initial perturbation of land surface processes on TCs in the global ensemble prediction system in a three-month parallel experiment. Our results show that perturbation imposed on both atmospheric variables and land surface process variables could increase the spread of the ensemble system and decrease the forecast error.

The performance of Xangsane, a severe TC, during the experiment period was investigated to further examine the effect of land surface processes. The results indicate that when the land surface uncertainties within a numerical forecast system are taken into account, the experiment could achieve better simulated track, intensity as well as a more reasonable structure. It is proposed that the surface process could influence the transfer process between the land and the atmosphere and thereby affect the thermal and aerodynamic characteristics of the planetary boundary layer (e.g., latent heat flux and sensible heat flux). This effect is transferred to upper levels through diffusion and convection.

The interaction between the land and the atmosphere could be summarized as the following three stages: 1) sensible energy is transferred to the atmosphere from the surface; moisture evaporates from the soil then the soil is heated; 2) the changes in land-surface properties influence the heat and moisture fluxes within the planetary boundary layer, convective available potential energy, and other measures of the deep cumulus cloud activity; 3) finally, the effect of land surface processes from a small area is enlarged and extended to other areas which influence the activity and predictability of TCs.

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