Outline of the Typhoon Ensemble Prediction System at the Japan Meteorological Agency

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Abstract

The Japan Meteorological Agency (JMA) began operation of a new Ensemble Prediction System (EPS) known as the Typhoon EPS (TEPS) in February 2008. TEPS has been designed to improve track forecast targeting for tropical cyclones (TCs) in the Regional Specialized Meteorological Center (RSMC) Tokyo - Typhoon Center's area of responsibility within the framework of WMO. It runs up to four times a day with a forecast range of 132 hours. The ensemble size is chosen as 11, and a singular vector method is employed to make initial perturbations.

The results of TEPS verification during a quasi-operational period from May to December of 2007 showed that ensemble mean track forecasts have a statistically better performance than deterministic forecasts under non-perturbed runs; the error reduction is 40 km in five-day forecasts. Moreover, there is a strong spread-skill relationship between the position errors of the ensemble mean and the ensemble spreads of tracks, indicating that TEPS would be useful in representing the confidence level of TC track forecasts.

1. Introduction

In 1997, the Japan Meteorological Agency (JMA) began providing three-day track forecasts of tropical cyclones (TCs) in the western North Pacific, including the South China Sea, based on numerical weather prediction (NWP) (JMA, 1997). Since then, we have seen a significant improvement in track forecasting due to the remarkable progress of the NWP system. According to verification of the global NWP system at JMA, the three-year running mean of position errors in five-day forecasts in 2007 (451 km – the average of 2005, 2006 and 2007) is smaller than that of three-day forecasts in 1997 (472 km – the average of 1995, 1996 and 1997). This indicates that we have succeeded in gaining a two-day lead time in deterministic TC track forecasts over the past decade.

While the accuracy of TC track forecasts has drastically improved, it is also true that forecast uncertainty is inevitable due to the chaotic behavior of the atmosphere and imperfections in the NWP system. Accordingly, a certain amount of forecast error should be added to each track forecast. (Puri et al., 2001; WMO, 2008a). JMA uses probability circles to express uncertainties in positional forecasting; a TC is expected to move into the circle with a probability of 70 % at a certain forecast time. The radius is determined statistically as a function of the forecast time, the direction of movement and the velocity of movement in consideration of recent years' results of verification for TC track forecasts at JMA.

Under these conditions of deterministic and probabilistic forecasting at JMA, TEPS is expected to further improve the accuracy of track forecasts using the ensemble mean and to enable proper estimation of the uncertainty of each forecast event using the ensemble spread, making it possible to optimize the radius of the probability circle flow-dependently. In order to assess the performance of TEPS, we conducted quasi-operational runs from May to December of 2007.

This report describes the results of verification during this period as well as the specifications of the system. Section 2 describes the specifications of TEPS, the NWP system and the method of making initial perturbations. Section 3 describes the performance of TEPS, the position errors of the ensemble mean and the spread-skill relationship between the position errors of the ensemble mean and the ensemble spreads of tracks. A summary and conclusions are given in Section 4.

2. Specifications

2.1 General specifications

TEPS is operated for TCs analyzed by the Regional Specialized Meteorological Center (RSMC) Tokyo - Typhoon Center. It runs up to four times a day starting at 0000, 0600, 1200 and 1800 UTC with a forecast range of 132 hours when one of the following conditions is satisfied:

1. a TC of tropical storm (TS) intensity (the maximum sustained wind speed of 34 knots to 47 knots near the centre) or higher exists in the RSMC Tokyo - Typhoon Center's area of responsibility (0 – 60N, 100 – 180E);
2. a TC is expected to reach TS intensity or higher in the area within 24 hours;
3. a TC of TS intensity or higher is expected to move into the area within 24 hours.

The NWP model for TEPS is a global model with a resolution of TL319L60, which is a lower-resolution version of the JMA Global Spectral Model (JMA/GSM) at TL959L60 (Iwamura and Kitagawa, 2008; Nakagawa, 2009). Global analysis for JMA/GSM at TL959L60, which is based on a four-dimensional variational data assimilation system (4DVAR) (Kadowaki, 2005; JMA, 2007), is interpolated to TL319L60 and used as the initial condition of TEPS. The ensemble size is set at 11 with one non-perturbed run and ten perturbed runs, where the perturbations are generated using the singular vector (SV) method (Buizza, 1994; Molteni et al., 1996; Puri et al., 2001) (see Section 2-2 for details).

2.2 Initial perturbations

TEPS adopts an SV method to generate initial perturbations. If a perturbation grows linearly, an SV with a large singular value represents a fast-growing perturbation (Lorenz, 1965). In addition, using an SV method enables the computation of perturbations that have a large influence on an arbitrarily chosen domain, which can be associated with the development or movement of TCs when the domain is targeted to the TC's surroundings.

The tangent-linear and adjoint models used for SV computation come from 4DVAR, which has been in operation since February 2005. While their resolutions were T159L60 for 4DVAR as of September 2008, TEPS uses the lower-resolution version T63L40. The models consist of full dynamical core and physical processes including vertical diffusion, gravity wave drag, large-scale condensation, long-wave radiation and deep cumulus convection. SVs based on the tangent-linear and adjoint models including the full physical processes (the simplified physical processes without moist processes) are called moist (dry) SVs. TEPS calculates dry SV targeting for the mid-latitude area in the RSMC Tokyo - Typhoon Center's area of responsibility, aiming to identify the dynamically most unstable modes of the atmosphere, such as the baroclinic mode (Buizza and Palmer, 1995). It also calculates moist SV targeting for TC surroundings where moist processes are critical (Barkmeijer et al., 2001).

JMA's computing system allows TEPS to target up to three TCs at a time. If more than three TCs are present, three of them are selected in the order of concern of the RSMC Tokyo - Typhoon Center. The targeted area of dry SV calculations is fixed as 20 – 60N, 100 – 180E, and that of moist SV calculations covers a rectangle of 10 degrees in latitude and 20 degrees in longitude with its center at the forecasted TC's central position at a forecast time of 24 hours. The optimization time interval for SV calculations is 24 hours for both dry and moist SVs. As shown in the following equation (1), the norm to evaluate the growth rate of dry and moist SVs is based on a total energy norm that includes a specific humidity term (Barkmeijer et al., 2001):

$$
\begin{aligned}
(x, \mathbf{E}x) \;=\; & \frac{1}{2}\int_0^1 \int_S (\nabla\Delta^{-1}\zeta_x \cdot \nabla\Delta^{-1}\zeta_x + \nabla\Delta^{-1}D_x \cdot \nabla\Delta^{-1}D_x \\
& + g(\Gamma_d - \Gamma)^{-1}\frac{T_x T_x}{T_r} \\
& + w_q \frac{L_c^2}{c_p T_r} q_x q_x) dS \left(\frac{\partial p}{\partial \eta}\right) d\eta \\
& + \frac{1}{2}\int_S \frac{R_d T_r}{P_r} P_x P_x dS
\end{aligned}
\qquad (1)
$$

where ζ_x, D_x, T_x, q_x and P_x are the vorticity, divergence, temperature, specific humidity and surface pressure components of vector x, and **E** represents a norm operator. Note that the temperature lapse rate Γ is taken into consideration as an available potential energy term (Lorenz, 1955). c_p is the specific heat of dry air at a constant pressure, L_C is the latent heat of condensation, and R_d is the gas constant for dry air. T_r = 300 K is a reference temperature, Pr = 800 hPa is a reference pressure, and

w_q is a constant (w_q = 1 in TEPS). The representative value of $2/3\Gamma_d$ is used for Γ. In Eq. (1), the vertical integration of the kinetic energy term and the available potential energy term is limited to 100 hPa (the 26th model level), and the specific humidity term can be up to 500 hPa (the 15th model level). Otherwise, as is the case with the study by Barkmeijer et al. (2001), SVs have a shallow vertical structure in the upper troposphere or have a large specific humidity contribution in the upper troposphere where the amount of specific humidity is relatively small. Since such SVs have little influence on TC track forecasts, we set a limit on the vertical integration in Eq. (1).

Finally, initial perturbations are generated by linearly combining SVs. Each SV calculation can produce up to ten SVs depending on the operationally allocated calculation time period, which means that up to 40 SVs can be obtained (i.e., 10 dry SVs and 30 moist SVs) for one forecast event. Before determining the binding coefficients, SVs with structures similar those of others are eliminated. When the value of the inner product of any two SVs is 0.5 or more, one of them is eliminated from the group of SV candidates used to make initial perturbations. After this process, the binding coefficients are determined based on a variance minimum rotation, which makes the spatial distributions of the perturbations widely spread. If no SV is eliminated, we have the same number of independent initial perturbations as the number of SVs computed. For the ten perturbed runs, we select five perturbations randomly from the initial perturbations, and positively and negatively add them to the analysis field. The amplitude of the perturbations is adjusted so that the maximum zonal or meridional wind speed equals 6.0 m/s.

Table 1 gives a summary of the specifications. It should be noted that JMA also operates the One-Week Ensemble Prediction System (WMO 2008b), which has specifications similar to those of TEPS but is designed to improve medium-range forecasts. For reference, we add the specifications of the EPS shown in Table 1.

Table 1 Specifications of the Ensemble Prediction Systems at JMA

<table>
<tr><th colspan="2"></th><th colspan="2">Typhoon Ensemble Prediction System (TEPS)</th><th colspan="2">One-Week Ensemble Prediction System (WEPS)</th></tr>
<tr><td colspan="2">Forecast domain</td><td colspan="4">Global</td></tr>
<tr><td colspan="2">Truncation wave number</td><td colspan="4">Spectral triangular truncation at 319 wave numbers with linear Gaussian grid (TL319)</td></tr>
<tr><td colspan="2">Horizontal grid,
grid spacing</td><td colspan="4">640 x 320,
0.5625 deg. (– 60 km)</td></tr>
<tr><td colspan="2">Vertical resolution</td><td colspan="4">60 unevenly spaced hybrid levels (from surface to 0.1 hPa)</td></tr>
<tr><td colspan="2">Forecast range</td><td colspan="2">132 hours</td><td colspan="2">216 hours</td></tr>
<tr><td colspan="2">Initial time</td><td colspan="2">00, 06, 12, 18 UTC</td><td colspan="2">12 UTC</td></tr>
<tr><td colspan="2">Ensemble size</td><td colspan="2">11 members (10 perturbed forecasts and 1 control forecast)</td><td colspan="2">51 members (50 perturbed forecasts and 1 control forecast)</td></tr>
<tr><td rowspan="7">Perturbation</td><td>Perturbation generator</td><td colspan="4">Singular Vector (SV) method</td></tr>
<tr><td>Inner model resolution</td><td colspan="4">Spectral triangular truncation at 63 wave numbers (T63),
40 unevenly spaced hybrid levels (from surface to 0.4 hPa)</td></tr>
<tr><td>Norm</td><td colspan="4">Moist total energy</td></tr>
<tr><td>Perturbed area</td><td>Western North Pacific (20 – 60N, 100 – 180E)</td><td>3 Typhoons (20 deg. x 10 deg. in the vicinity of each typhoon)</td><td>Northern Hemisphere (30 – 90N)</td><td>Tropics (20S – 30N)</td></tr>
<tr><td>Physical process</td><td>*Simplified physics</td><td>**Full physics</td><td>*Simplified physics</td><td>**Full physics</td></tr>
<tr><td>Optimization time interval</td><td colspan="2">24 hours</td><td>48 hours</td><td>24 hours</td></tr>
<tr><td>Evolved SV</td><td colspan="2">Not used</td><td colspan="2">Used</td></tr>
</table>

*Simplified physics: initialization, horizontal diffusion, surface turbulent diffusion and vertical turbulent diffusion

**Full physics: the elements of simplified physics plus gravity wave drag, long wave radiation, large-scale condensation and cumulus convection

3. Performance

3.1 Case studies

Figure 1 shows examples of forecasts using TEPS. The upper figures are for typhoon Maria in 2006, initiated at 12 UTC on Aug. 6th, 2006, and the lower figures are for typhoon Chaba in 2004, initiated at 12 UTC on Aug. 28th, 2004. The panels on the left show track forecasts by JMA/GSM (the solid lines) with a best track (the dashed line), while those on the right show all tracks obtained using TEPS. In the case of Maria, there is a large ensemble spread; some of the ensemble members support the same scenario as JMA/GSM, indicating that Maria is heading for western Japan, while others recurve and head toward eastern Japan. In reality, as the best track shows, Maria recurved and skirted the southern coast of the Kanto region to the east of Japan. It is noteworthy that TEPS captured the possibility of the best track. From the perspective of disaster prevention or mitigation, it is very important to ascertain all possible scenarios in advance and take measures as needed. TEPS is expected to enable the capture of such potential track spreads. In contrast to the case with Maria, Chaba shows quite a small ensemble spread, meaning that the confidence of the forecast is relatively high. In fact, the deterministic forecast by JMA/GSM was almost perfect. As in these two cases, we can expect TEPS to provide track forecast information with high confidence referring to ensemble spreads that could vary by TC and the initial time of forecasting.

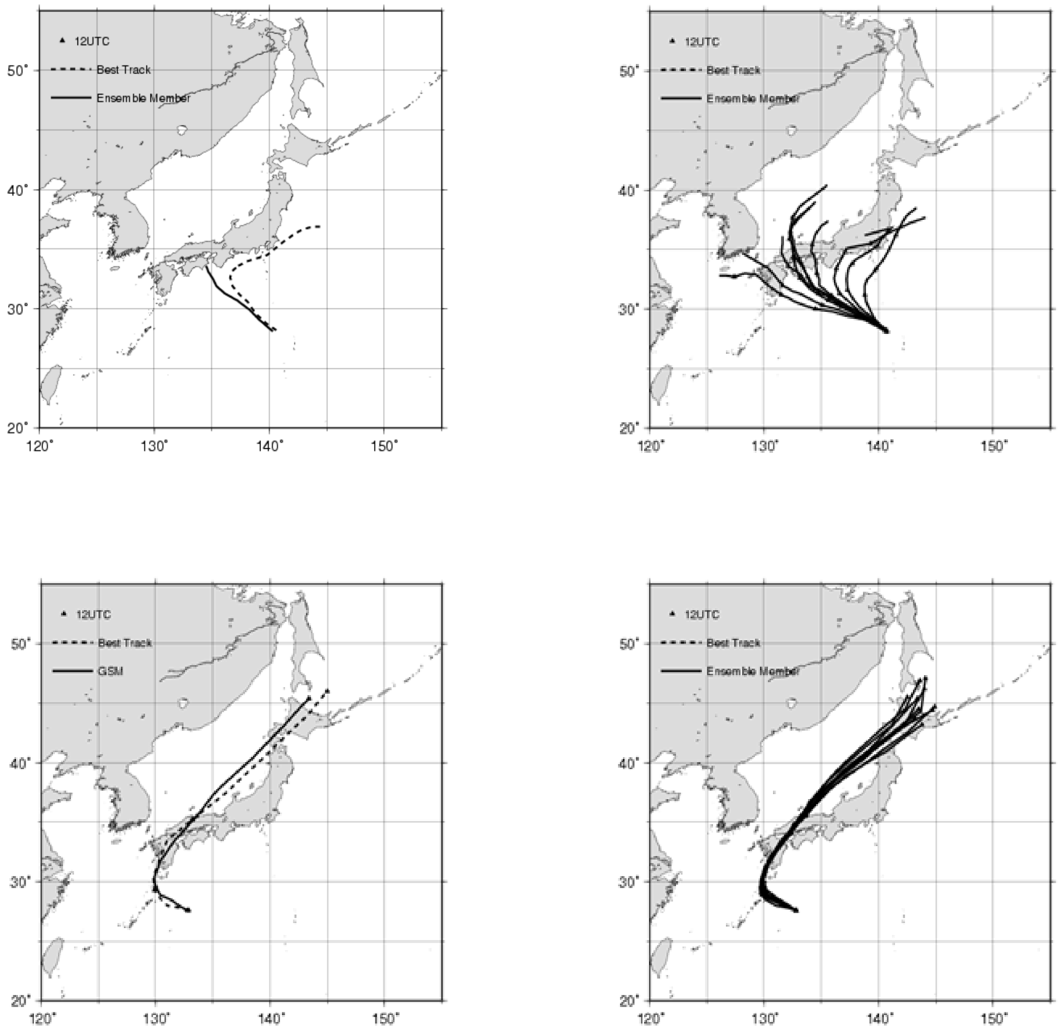

Figure 1. Example forecasts of TEPS. The upper figures are for typhoon Maria in 2006, initiated at 12 UTC on Aug. 6th, 2006. The lower figures are for typhoon Chaba in 2004, initiated at 12 UTC on Aug. 28th, 2004. The figures on the left show the track forecast by JMA/GSM (the solid line) with the best track (the dashed line), and those on the right show all tracks forecast using TEPS.

3.2 Quasi-operational application

To statistically evaluate the performance of TEPS, we conducted quasi-operational runs of TEPS from May to December of 2007. We verified the ensemble mean tracks and the spread-skill relationship between the position errors of the ensemble mean and the ensemble spreads of tracks. The specifications of quasi-operational TEPS are different from those of operational TEPS in several respects. For example, the fields analyzed by TEPS before November 21st, 2007 (when high resolution JMA/GSM with TL959L60 became operational) come from those of the lower-resolution JMA/GSM with TL319L40. However, we confirmed through one-month period experimentation that these differences in specifications have little influence on the performance.

3.2.1 Ensemble mean track forecast

Figure 2 shows the position errors of the ensemble mean track, which is made by averaging all forecasted TC tracks. The verifications are based on the best track data produced by the RSMC Tokyo - Typhoon Center. Both Figures 2a and 2b are the results of verifying TCs of tropical storm intensity or higher, but Figure 2b includes the extratropical-transition stages of TC verification. The X-axis represents the forecast time up to five days. The Y-axis on the left gives the position errors (in km) of control runs, or non-perturbed runs (the thin line), and the ensemble mean (the thick line). The dots correspond to the Y-axis on the right, which represents the number of verification samples. As both Figures 2a and 2b show, the position errors of the ensemble mean are smaller than those of the control runs in four- and five-day forecasts, although their performance as control runs up to the three-day forecast point is almost identical. The error reduction in five-day forecasts is 40 km (as shown in Figure 2a), which is equivalent to a gain of about half a day of lead time, given that the position error difference between four-day and five-day forecasts by JMA's global forecasting NWP system was about 100 km in 2007 (see Figure 3).

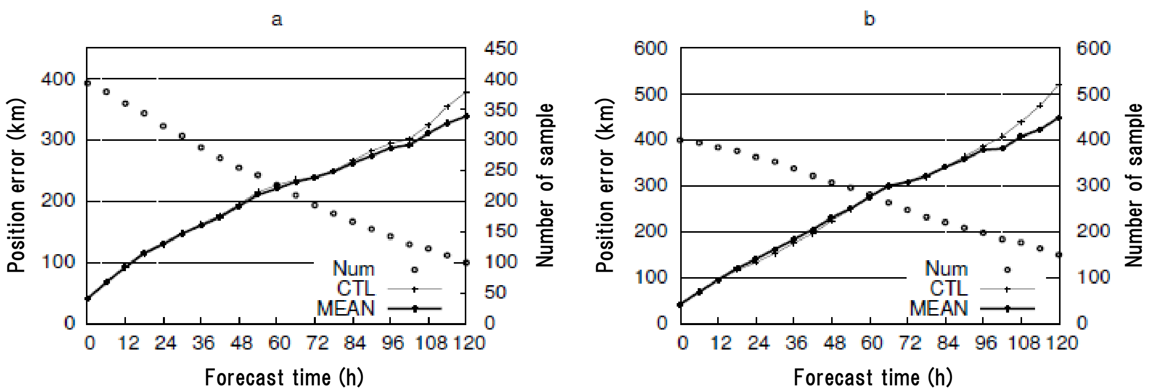

Figure 2. Position errors (in km) of the ensemble mean (the thick lines) as a function of the forecast time up to 120 hours, compared with those of control runs (the thin lines). The dotted lines correspond to the Y-axis on the right, which represents the number of verification samples. Both a and b are the results of verifying TCs of tropical storm intensity or higher, but b includes the extratropical-transition stages of the TCs verified. The verification period was the quasi-operation period of TEPS from May to December, 2007.

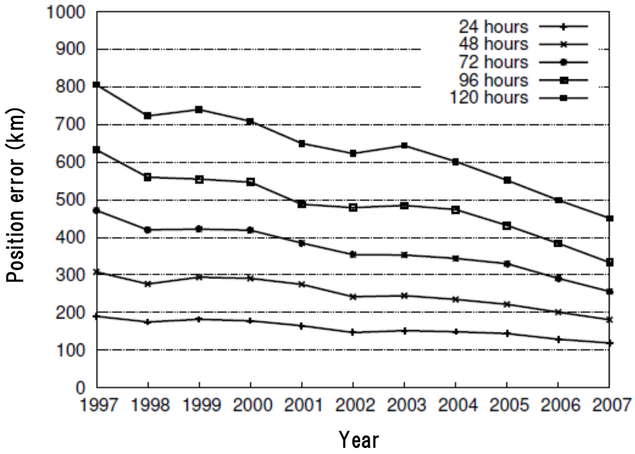

Figure 3. Time series of the three-year running mean of position errors by JMA's global forecasting NWP system from 1997 to 2007 (e.g., the verification value for 2007 is the average of those for 2005, 2006 and 2007). Each line represents the errors of 24-, 48-, 72-, 96- and 120-hour forecasts from the bottom up.

3.2.2 Spread-skill relationship

Figure 4 shows the spread-skill relationship of five-day track forecasts. The TCs verified are exactly the same as those in Figure 2b, and each dot gives the verification result of each forecast event. As Figure 4 shows, there is a strong spread-skill relationship; when ensemble spreads are relatively small, the position errors of the corresponding forecast events are also small. More importantly, there are no cases with large position errors, which occur when ensemble spreads are relatively large. While Figure 4's verification is limited to a forecast time of five days, a strong spread-skill relationship can be seen in verifications for other forecast times.

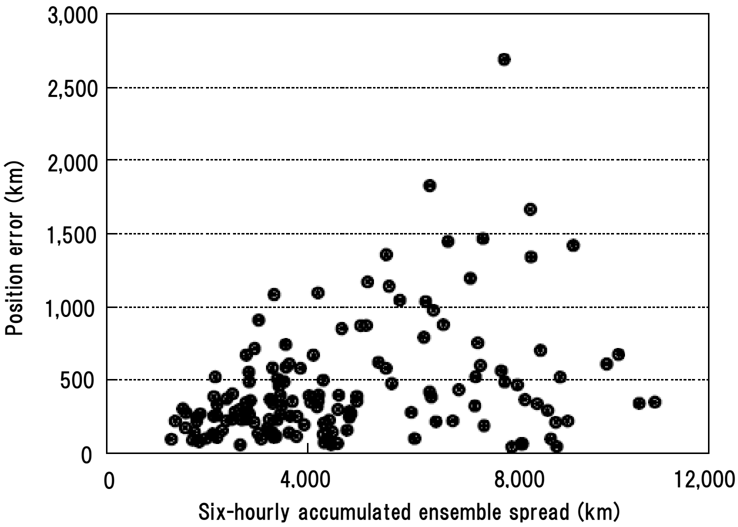

Figure 4. Spread-skill relationship of five-day track forecasts. The X-axis represents ensemble spreads (km) accumulated every six hours from the initial time to the five-day stage. The Y-axis represents the position errors (km) of the ensemble mean for the corresponding forecast events. The total number of cases is 149, which is the same as that of the five-day forecasts in Figure 2b.

Based on this relationship, we classify the confidence level of TC track forecasts (i.e., ensemble mean track forecasts) at each forecast time for each forecast event. A confidence index (A, B or C, representing the categories of the highest, middle-level and lowest confidence, respectively) is allocated, and the frequency of each category is set to 40%, 40% and 20 % respectively. Figure 5 shows that the average position errors in category A are quite small in comparison to those of all track forecasts shown in Figure 2b. As an example, the position errors of three-day forecasts are about 300 km on average, but become less than 200 km if the samples are limited to cases with small ensemble spreads. Conversely, the average position errors in category C are larger than the those of all forecasts.

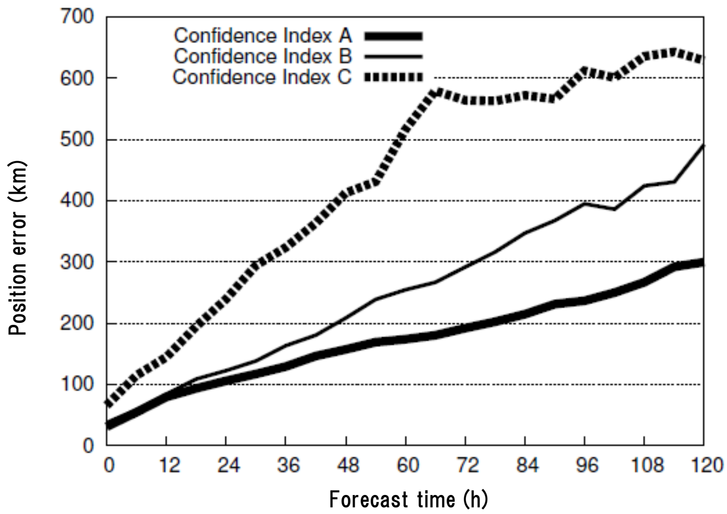

Figure 5. Verification results of confidence indices on TC track forecasts. Referring to the amount of ensemble spread, a confidence index (A, B or C) is given to ensemble mean track forecasts at each forecast time for each forecast event (A represents the highest level of confidence). The thick line shows the position errors of the ensemble mean for all A cases as a function of the forecast time. The thin and dashed lines represent the B and C cases, respectively.

The reason why the categories are set as 40%, 40% and 20% (rather than 33%, 33% and 33%) is to clearly split the position errors into three lines as in Figure 5. Figure 6 shows the position error of each three-day forecast by JMA's global NWP system in 2007 with the errors sorted in ascending order. As the figure shows, the frequency distribution of the errors is not uniform, and the rate of cases with a relatively large position error is about 10 to 20% of the total number of events. We therefore set the rate of category C to be smaller than those of categories A and B.

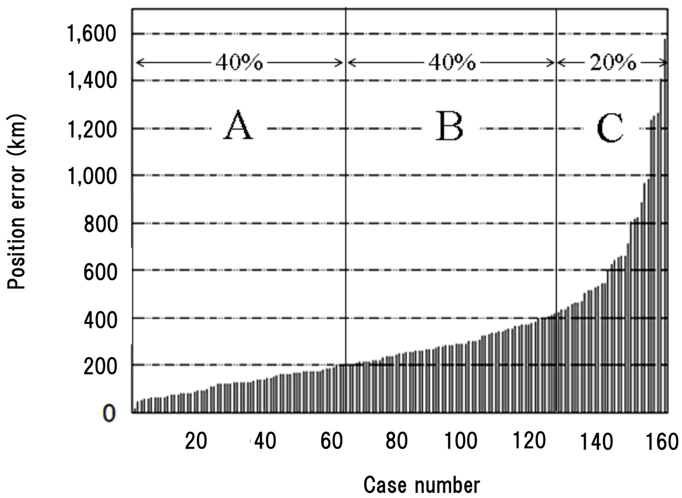

Figure 6. Position error (km) of each three-day track forecast initiated at 00 UTC by JMA's global forecasting NWP system in 2007. The errors are sorted in ascending order, and the total number of cases is 163.

4. Summary

JMA began operation of the new Typhoon EPS in February 2008 with the aim of improving TC track forecasts. TEPS runs up to four times a day with a forecast range of 132 hours targeting TCs in the western North Pacific, including the South China Sea. It is composed of eleven forecast members derived from the TL319L60 global model. The method of making initial perturbations is based on the SV method.

In order to assess the performance of TEPS, we conducted quasi-operational forecasts of the system from May to December of 2007. Verification of these quasi-operational runs showed that two benefits can be expected from TEPS. First, the position errors of deterministic track forecasts will be reduced. Using the ensemble mean obtained a 40-km reduction in five-day track forecasts on average, corresponding to a gain of about half a day of lead time. Second, information on track forecasts' level of confidence can also be obtained. Referring to the ensemble spreads of tracks has enabled the extraction of uncertainty information on track forecasts.

Remaining issues include the question of how to leverage the benefits of TEPS in operational forecasting. In particular, conveying uncertainty information to public users is challenging, and this point must be kept in mind during the development of related applications.

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