Application of Kalman Filter for Adjusting Tropical Cyclone Track Forecasts

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Abstract:

Recently, Kalman Filter (KF) technique has been used widely for applications in many disciplines. In meteorology, particularly in postprocessing sections, Kalman filter has been used mainly for adjusting forecasted temperature and the surface wind magnitude, which are essentially scalar quantities. However, in this work, we attempt to assess the effectiveness of a simple Kalman filter to adjust the track forecasts (which is a two-dimensional quantity) from numerical models and guidance from Regional meteorological centers. The physical basis of this approach is that the error patterns of models and/or the interpretation of forecasters in representing the effects of environment on storm motion as well as the tropical cyclone itself are likely to evolve gradually from one base time to another for the same cyclone.

The main content of this article includes a brief description of our method for applying KF for tropical cyclones tracks and some preliminary results with two tropical cyclones DAMREY (0518) and KAITAK (0521) that directly affected Vietnam coast in 2005. The analysis on these first results showed some encouraging signs that KF maybe used to improve the predictions of tropical cyclone tracks.

1. Introduction

The application of Kalman filter (Kalman, 1960) for postprocessing NWP outputs have been put in practice for relatively long period of time since the years 1980s. As pointed out by several authors (e.g. Persson (1991), Homleid (1995, 2004) and Kalnay (2003)), this tool is proved to have a good capability of removing the systematic errors from model output with an inexpensive cost of computing and archiving model runs. In practice, Kalman filter has been found effective in correcting the predicted scalar variables such as surface and 850-hPa temperatures, dewpoint temperature and wind magnitude according to the newly observed values of the corresponding variables. As a result, this technique has been utilized widely in several meteorological centers such as ECMWF for bias removal (Persson, 1991) and Hongkong Observatory for adjusting ensemble forecast products (Lam et al., 2005).

In relation to tropical cyclone track forecasts, however, the statistical interpretation of NWP outputs has been focused mainly on the use of multi-model or the consensus forecasts rather than correcting the forecasts from each source independently (Elsberry and Carr (2000), Aberson (2001), Weber (2003) and Lee and Wong (2002)). In those works, even though the information of the errors characteristics has been utilized and displayed its effectiveness in improving the overall performance of ensemble (e.g. in Weber (2003) and Lee and Wong (2002)), the common agreement is still that a combination of averagely weighted members seems to be good enough to outperform any individual model on average.

The utilization of Kalman filter for correcting track forecasts from model outputs proposed in this work is motivated by our observation that the errors in interpretation of the atmospheric conditions affecting the TC movement and the tropical cyclone itself are likely not to change greatly during the lifetime of an individual storm. In other words, if a model has the systematic error in representing a particular weather system that affects tropical cyclone motion, that situation, and thus, the model's error in predicting TC movement, is likely to persist from one base time to another until the tropical cyclone moves to another area which is affected by a different system. A similar argument is also valid for the representation of the characteristics of the tropical cyclone in question. Therefore, with the use of Kalman

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filter, it is expected that this kind of ‘fresh’ systematic errors, once being detected, would be removed or lessen in the subsequent forecast base times.

2. Method of implementation

The Kalman filter used in this work is adapted from Persson (1991) scheme for correcting the temperature forecasts from ECMWF’s model. A detailed description of this KF scheme can be found in Persson (1991). The two options of this scheme used here are the 1-parameter scheme (K1) and the 2-parameter scheme (K2). The main difference between these two options lies in their observation equations that have the forms as follows:

For K1: \[ Y(\tau) = X_1(\tau) + \nu(\tau), \]  
and

For K2: \[ Y(\tau) = X_1(\tau) + X_2(\tau) \times FC(\tau) + \nu(\tau), \]

where \( \tau \) is the time index; \( Y \) is the observed forecast error; \( \nu \) is the non-systematic noise; \( FC \) is the quantity to be forecasted; and \( X_1 \) and \( X_2 \) are the changing with time coefficients that are to be determined by the KF scheme. Thus, in K1 scheme, the systematic correction to the predicted value is based on the forecast errors from previous runs, whereas it is modeled to be dependent on the magnitude of the forecast quantity in the K2 case. Furthermore, it was pointed out by Persson (1991) that K2 option is proved to be very effective when the forecast errors can be linearly fitted against the forecast variable itself.

In order to apply this KF scheme to tropical cyclone tracks forecast, which is essentially a 2-dimensional variable, the track positions are decomposed into two independent components. Specifically, the track positions can be split into different pairs of components such as speed and direction of the TC movement from the previous position; latitude and longitude; and along track (AT) and cross track (CT) errors.

\[ P_{\text{track}} = F(\text{speed}, \text{dir}), \quad (3) \]
\[ P_{\text{track}} = (\text{lat}, \text{lon}), \quad (4) \]
\[ E_{\text{track}} = F(\text{AT}, \text{CT}), \quad (5) \]

where \( P_{\text{track}} \) is the track position, \( E_{\text{track}} \) is equivalent to direct position error (DPE). Although the formulations in (3) and (5) are alike, the use of speed and direction errors are more favoured than AT and CT since the former allows the forecast errors to be updated at an earlier time. After being decomposed, the components are filtered separately by the KF scheme and then are recombined back to latitude and longitude to form the filtered forecast positions.

The forecast track positions are experimentally filtered by the KF scheme in various ways and are referred as follows:

- **KS**: Kalman filter is applied only to the forecasted translating speed
- **KD**: Kalman filter is applied only to the forecasted translating direction
- **KSD**: Kalman filter is applied both to the forecasted translating speed and direction
- **KLL**: Kalman filter is applied to the forecasted latitude and longitude.

3. Results and discussion

Due to the limitation in preparation time and the availability of data at NCHMF only two tropical cyclones in 2005 that directly affected Vietnam coast have been used in this study. The forecasts available to us at the operation times include:
The operational tracks and evolution of translating speed and direction of the two tropical cyclones are shown in Figures 1 and 2. It can be seen from these figures that even though DAMREY’s track exhibits some oscillating pattern of movement, its translating speed and direction vary in a relatively small range. In contrast, KAITAK experiences a much more sudden changes both in speed and direction.

Figure 1. Operational tracks of DAMREY (0518) and KAITAK (0521)
The DPE of the filtered forecasts are displayed together with the non-filtered DPE for all forecast times and are included in the Appendix. As can be seen from those graphs, the

\[
IMP = \frac{DPE_N - DPE_K}{DPE_N} \times 100% ,
\]

where the indices N and K stand for Non-filtered and Kalman-filtered, respectively. With this formulation, negative values of IMP indicate that the Kalman-filtered forecasts are better than the non-filtered ones because of the smaller mean DPE, and vice versa.

Figure 3 shows the IMP indices calculated for each forecast sources. As can be seen from this figure, both options K1 and K2 of the filtered forecasts for DAMREY exhibit clear improvement over the non-filtered for nearly all models and TC guidance centers. In the contrary, filtered forecasts for KAITAK appear to be worse than the non-filtered ones for most forecasts except for the K2 option, which still shows some improvement. In addition, the improvement of K2 option appears to be larger than in K1. On the other hand, it is interesting to note that the application of KF to the subjective forecasts tend to be larger than it is applied to the direct model forecasts. As an example, the improvement of K2 over the subjective TC guidance JP is much larger than that for the JTY and GSM models for tropical cyclone DAMREY (0518). Therefore, as KF is meant to remove the systematic errors, this fact implies that the subjective forecasts tend to have systematic errors for the specific situations and thus could be effectively removed by the means of Kalman filter.
Furthermore, in the search for better understanding of the conditions where the implementation of KF is likely to be beneficial, analysis on the error pattern of the translating speed and direction have been done for all cases. As it could be implied from the KF formulation described in Section 2, the key ingredient of K1 for success is the gradual change of the errors over time. On the other hand, for K2, the gradual change of the linear dependency of the errors on the magnitude of the variable to be forecasted is of importance.

For K1 option, the changes in direction and speed error over time have been studied in relation to the success and failure cases. However, we could not find a firm relationship between the benefit of K1 implementation and the changing patterns of speed and direction errors. In contrast, the analysis with K2 option shows a very encouraging feature. Specifically, the errors of a characteristic (i.e. speed and direction) are plotted against its magnitude and then are fitted to a linear function. The measure of the linear dependency, \( R^2 \), is found to have a close relationship with the effectiveness of KF implementation. In Table 1, the \( R^2 \) values are shown for all cases, where the cases the good performance of K2 are shaded. It is evident from this table that all studied cases with the sum of \( R^2 \) of

\[
R^2 = 1 - \frac{\text{SSE}}{\text{SST}} = \sum (Y_j - \hat{Y}_j)^2 / \sum (Y_j - \bar{Y})^2 / n.
\]

Thus, the closer \( R^2 \) to 1, the better does the relationship to be fit to that linear function.

"good" cases of Kalman filter implementation are considered to have the negative values of IMP as shown in Figure 3.
speed and direction errors more than 0.3, the implementation of K2 serves to improve the forecasts. Reversely, the sum of $R^2$, which is less than 0.3, corresponds to the bad effect of K2 implementation.

Table 1. $R^2$ value for the linear fitting of the speed and direction errors against its magnitudes.

<table>
<thead>
<tr>
<th>Tropical cyclone</th>
<th>BK</th>
<th>CL</th>
<th>GA</th>
<th>JG</th>
<th>JP</th>
<th>JT</th>
<th>GFS</th>
<th>VN</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMREY 0518 Speed</td>
<td>0.0915</td>
<td>0.003</td>
<td>0.2121</td>
<td>0.1398</td>
<td>0.0774</td>
<td>0.0713</td>
<td>0.8954</td>
<td></td>
</tr>
<tr>
<td>DAMREY 0518 Direction</td>
<td>0.1526</td>
<td>0.4447</td>
<td>0.5035</td>
<td>0.1558</td>
<td>0.5215</td>
<td>0.2385</td>
<td>0.3616</td>
<td></td>
</tr>
<tr>
<td>KAITAK 0521 Speed</td>
<td>0.827</td>
<td>0.7777</td>
<td>0.7381</td>
<td>0.1927</td>
<td>0.0063</td>
<td>0.4124</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KAITAK 0521 Direction</td>
<td>0.792</td>
<td>0.5847</td>
<td>0.5851</td>
<td>0.0043</td>
<td>0.1966</td>
<td>0.2017</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


The application of a simple Kalman filter adapted from the version developed by Persson (1991) has been tested with two tropical cyclones that affected Vietnam in 2005 (DAMREY 0518 and. The preliminary results showed an encouraging indication that it may be used to improve the track forecasts from numerical models as well as the subjective guidance. In particular, the 2-parameter Kalman filter, which assumes the linear relationship between the magnitude of the variable to be forecasted and its forecast errors, showed a better performance over the 1-parameter scheme. In addition, it is an interesting fact that the subjective forecasts in the studied cases tend to be systematically biased and thus could be corrected effectively by the use of Kalman filter.

However, the effectiveness of Kalman filter is by no means a complete tool for improving the track forecasts. Rather, it is likely to be beneficial for certain types of TC movements and/or the forecasting models or centers. In particular, from the two tropical cyclones being tested in this study, the use of Kalman filter appear to be effective with DAMREY (0518), which has a relatively stable movement, whereas it turns show bad effects for the case of KAITAK(0521) which experiences several changes of the motion speed and direction during its lifetime.

Thus, in order to utilize Kalman filter effectively for correcting TC track forecasts, it is desirable that more cases be tested with a broader spectrum of model outputs as well as subjective forecasts. Subsequently, with a good understanding of the conditions that are favourable for the Kalman filter to be helpful, this technique will likely to add values to the quality of tropical cyclone track forecasts.

Acknowledgement.

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APPENDIX

24h Direct Positional Errors of the Kalman filtered and non-filtered forecasts (EFLL) from different models and Regional TC advisory centers for Tropical Cyclone DAMREY 0518
24h Direct Positional Errors of the Kalman filtered and non-filtered forecasts (EFLL) from different models and Regional TC advisory centers for Tropical Cyclone KAITAK 0521
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