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using Regional Spectral Model

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W.K. Wong, C.C. Lam and Hilda Lam

Hong Kong Observatory
134A, Nathan Road, Kowloon, Hong Kong, China

1. Introduction

In 1998, the typhoon season started exceptionally late due to the influence of El Nino effect. The first tropical cyclone (TC) signal in Hong Kong was hoisted on 9 August, the latest date for hoisting TC signal in post-war years. During the year, only five TCs necessitated the hoisting of warning signals. Typhoon Babs (9811) was the closest tropical cyclone (TC) that affected Hong Kong.

Typhoon Babs developed over the western North Pacific in mid-October. It posed a potential threat to Hong Kong after entering the South China Sea. Imageries from geostationary satellite observations provide visual perceptions of the position, movement and flow structure of TC for operational forecasters. Forecasters can use these imageries to determine the center of TC and its intensity. Moreover, quantitative products like the wind data derived from satellite observed cloud motion are also invaluable for numerical models to assimilate the outer wind flow of the tropical cyclone.

This paper discusses the numerical simulation of Typhoon Babs using the Regional Spectral Model (RSM) to study the impact of typhoon bogussing techniques and SATOB satellite cloud motion wind on TC track forecasting. RSM was originally developed by the Japan Meteorological Agency (JMA) and was adapted for use in the Hong Kong Observatory (HKO) in 1997.

Section 2 outlines a summary for the track of Typhoon Babs and its effects. The model configuration, the data and method for initializing the TC are given in Section 3. Simulation results are discussed in Section 4 and the conclusion is given in Section 5.

2. Track of Babs

The track of Typhoon Babs is shown in Figure 1. Typhoon Babs developed about 320 km northwest of Yap on 15 October 1998. It intensified into a tropical storm on 18 October and became a typhoon two days later. It swept across the Philippines and brought about severe rain, flooding and landslides. When it entered the South China Sea on 23 October, it first took on a northwesterly track and posed a potential threat of direct hit to Hong Kong. HKO hoisted the Standby Signal No. 1 to alert the public of the TC on the morning of 23 October. As Babs approached Hong Kong, the Strong Wind Signal No. 3 was hoisted on 24 October. In the late evening of 25 October, Babs turned north and then northeast towards the Taiwan Strait and started to weaken on encountering the northeast monsoon. Eventually, it dissipated over the Taiwan Strait on 27 October.

Under the influence of the combined effect of Babs and the northeast monsoon, the northerlies
strengthened and the offshore winds occasionally reached gale force locally in Hong Kong. The maximum hourly wind, gust and sea level above chart datum recorded at Waglan Island were 81 km/hr, 113 km/hr and 3.0 m respectively. The minimum hourly sea-level pressure of 1001.4 hPa was recorded at the HKO at 3 a.m. and 4 a.m. HKT on 26 October. Babs was closest to Hong Kong at around 8 a.m. HKT on 26 October at a distance of 240 km to the east-southeast of Hong Kong.

The distribution of rainfall over Hong Kong during the passage of Babs on 24-26 October is shown in Figure 2. A total of around 30 mm was recorded at the HKO Headquarters while more than 40 mm of rainfall fell in other parts of Hong Kong during the period. Several fallen trees and collapsed scaffoldings were reported with a total of 14 people injured.

3. Regional Spectral Model

The Regional Spectral Model (RSM) has been put into semi-operation at the HKO since mid-1998 to provide 48-hour prediction to forecasters twice a day (00 and 12 UTC). Various data like SYNOP, SHIP, BUOY, TEMP, PILOT, AIREP, SATEM, SATOB and satellite observed cloud amount are included in the data assimilation. These data are quality controlled to ensure spatial and temporal consistency. Using the first guess field from the previous model forecast or from the JMA Global Spectral Model (GSM) output, the observational data are assimilated using three-dimensional multi-variate optimal interpolation method to produce the initial field for the forecast model (NPD/JMA, 1997). In the analysis system, physical variables including surface pressure, geopotential height, wind, temperature and relative humidity are analyzed.

The forecast model is formulated in hydrostatic, primitive equations for mass, momentum, specific humidity and virtual temperature using the advection form. The horizontal resolution is 60 km and there are 20 vertical levels in hybrid $\sigma$-P terrain following coordinates. Currently, the forecast model generates 48-hour forecasts using the latest 6-hourly boundary conditions from JMA GSM. Graphical products of 3-hourly forecasts on the surface and standard pressure levels, and time series of some selected meteorological elements at the model grid point over Hong Kong are generated from the model outputs.

(a) Typhoon Bogussing

It is well known that the accuracy of track forecasts for TCs is sensitive to the resolution of cyclone structures in the initial field. Therefore, bogussing techniques to introduce TC structures into the model analysis field were developed and incorporated into many numerical models. In RSM, symmetric and asymmetric typhoon bogussing techniques may be used.

Information like vortex position, estimated minimum central surface pressure and 30-knot wind radius are required in producing the symmetric bogus profiles. Firstly, these parameters are used to define the domain of TC for bogussing according to an empirical formula. The surface profile is constructed by using the Fujita's formula (1952), in which the gradient wind balance is used to calculate the surface pressure profile at a particular radius. Geopotential profile at upper levels is determined by another empirical formula (Ueno 1989) that is based on studies of TC structures by Frank (1977). It is assumed that the deviation in temperature has its maximum at 250 hPa. Wind fields on the upper levels are derived from geopotential height profiles by gradient wind balance. Surface wind field is deduced by using the same balance with surface pressure, taking surface friction into account.
For asymmetric TC bogussing, the asymmetric components are extracted from the first guess (FG) field (Ueno 1995) that is obtained from previous model forecast or GSM output. The axi-symmetric component for geopotential height is obtained by taking an azimuthal average of the geopotential height in FG around the TC center. This geopotential height field is then used to compute the axi-symmetric component of wind in FG under the gradient wind balance. The required asymmetric bogus for either geopotential height or wind is the difference between the calculated axi-symmetric component and the corresponding field in FG. Symbolically, the asymmetric part and the resulting bogus profile are calculated using the following formulae:

\[
\text{Asymmetric bogus} = \text{FG} - \text{Axi-symmetric component in FG}
\]

\[
\text{Total bogus} = \text{Symmetric bogus} + \text{Asymmetric bogus}
\]

The total bogus profile will be added to the data set for assimilation to generate the analysis field for model forecast. According to Ueno (1995), the asymmetric bogus technique can improve the track forecasts in GSM in reducing the systematic northward drift of TC.

(b) Satellite Derived Wind

To better depict the cyclone structure, wind data retrieved from satellite cloud motion tracking are used to provide additional information of flow structure around TCs. HKO receives the SATOB wind data around TCs that are derived from JMA GMS observations when TCs are found over the region 0 N - 60 N, 100 E - 180 E. It was discussed in Wong et al. (1998) that the inclusion of SATOB data into operational RSM analysis helped improve the initial condition for model forecast, resulting in better predictions of intensity change of Babs in some of the forecast runs.

Typically, the SATOB message contains satellite derived wind speed, wind direction and temperatures at 850 hPa. Figure 3 shows an example of the distribution of SATOBs and other data around Babs. It can be seen from this figure that though most data were found in the northwest quadrant of Babs at the time, the density of data was quite high to provide a detailed flow structure in this region.

4. Case Studies

A set of experiments was designed to investigate the impact of bogussing technique and the SATOB satellite cloud motion wind on the RSM performance of track forecast. This is to illustrate the following points:

(a) The inclusion of bogus data can reduce the position errors for TC track forecast.

(b) With asymmetric bogussing profile, the position errors of TC center are further reduced in the early forecast hours.

(c) Analysis incorporating SATOB data includes more information on the upper level (850 hPa) and leads to positive impact on the track forecast for Babs, especially when the maximum vorticity centers on 850-hPa level are used to locate the positions of TC in model forecasts.

Two analysis times were chosen to study the model performance, namely the 00 UTC analyses on 23 and 25 October. In both cases, FG fields were taken from JMA GSM forecasts. In the discussion and figures below, the following notations are used to designate the analysis field and the corresponding forecast output based on different combinations of the use of bogussing method and
SATOB data in model simulation:

Set A: No bogus and no SATOB data

Set B: Symmetric bogus profile with no SATOB data.

Set C: Symmetric bogus profile with SATOB data.

Set D: Asymmetric bogus profile with no SATOB data.

Set E: Asymmetric bogus profile with SATOB data.

Forecast track errors based on model outputs in these five sets of experiment were calculated using mean-sea-level pressure (MSLP) field and 850-hPa relative vorticity field (850VT).

4.1 Analysis at 00 UTC 23 October 1998

At 00 UTC 23 October, the best-track analyzed position of Babs was 16.0 N, 120.3 E with a central minimum surface pressure of 965 hPa. The 30-knot wind radius was estimated to be around 330 km. The radius of domain defining the area for bogus calculation was about 600 km. The analyzed MSLP fields for the five sets of experiment are shown in Figures 4(a)-(e).

After incorporating the bogus profile into the analysis, the central minimum surface pressure for Babs in the analysis field was reduced from 995 hPa (no bogussing) to 992 hPa. The distance error of the model analyzed position was 46 km when no bogus profile was applied, while the errors dropped to 11 km when using symmetric or asymmetric bogussing. The bogussing techniques helped initialize better TC position and intensity in the model initial field.

The surface wind distributions near the center of Babs with no bogus, symmetric and asymmetric profiles are given in Figures 5(a)-(c) respectively. It can be seen that the surface wind speed around the center of Babs was the smallest when no bogus data were used. In Figure 5(c), the asymmetric feature of the wind distribution around Babs is given.

On the upper levels, the bogus profile was found to enhance the structure of TC in the model field. Figures 6(a)-(e) show the 850-hPa wind and relative vorticity fields for the five sets of experiment. It is noticed that the maximum vorticity was higher which indicated a stronger vortex when bogus data were used. On the other hand, SATOB data also adjusted the wind field on the upper levels in the model analysis. It can be seen from Figure 3 that most SATOB data were found in the northwest regime of Babs at that time. The resulting analyzed wind speeds over that area were found to be smaller than those without SATOB data in general. In addition, the cyclonic vorticity value over the area with SATOB data was also smaller than that without in the case of Babs.

Figure 7 shows the forecast tracks from the five sets of experiment (00 UTC 23 October - 00 UTC 25 October). They were plotted using the minimum pressure centres on the MSLP field. The forecast positions were compared with the best-track positions at 6-hourly intervals. Without bogus profile, the forecast track (TC positions denoted by open-red circles in Figure 7) was biased to the left after 12 hours from model analysis time. Symmetric bogus resulted in a northward biased track in the early forecast period. This northward bias was reduced when asymmetric profile (Sets D and E) was used in the analysis. The forecast tracks in both Sets D and E were closer to the best track analyzed by HKO than those in Set B and C in the first 12 hours forecast. However, as Babs
started to take a more northward track on 24 October, the forecast position errors in both Sets D and E became larger than those using symmetric bogus.

The SATOB data were found to have positive impact on the track forecast. Figure 8 shows the time series of forecast track position errors in the five sets of experiment. In forecasts based on both symmetric and asymmetric bogus, position errors were further reduced if SATOB data were used.

Figure 9 shows the forecast tracks in the same forecast period based on 850-hPa vorticity field. The two forecast tracks using symmetric bogus were still found to have northward bias compared with the best track in the early stage. Though asymmetric bogus reduced the bias, the mean position errors were larger than those with symmetric bogus in the whole forecast period (Figure 10). This shows that the forecast results based on asymmetric profile may not be necessarily better than those based on symmetric profile on the average. A good initial guess for constructing the asymmetric component might be essential for the current asymmetric bogus scheme.

The inclusion of SATOB data was again shown to have smaller forecast position errors in the case of using either symmetric or asymmetric bogus profiles. It was noted from Figure 10 that the forecast position errors were no greater than those without SATOB data during the 48-hour forecast period. In the case of using symmetric bogus (Sets B and C), the position errors were reduced by more than 10 km at T+48 hour if SATOB data were ingested.

Table 1 summarizes the forecast position errors (in km) for the five sets of experiment based on MSLP and 850VT fields:

<table>
<thead>
<tr>
<th></th>
<th>Forecast position errors (km) for MSLP field</th>
<th>Forecast position errors (km) for 850-hPa vorticity field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sets</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>T+0 h</td>
<td>46</td>
<td>11</td>
</tr>
<tr>
<td>T+24 h</td>
<td>77</td>
<td>15</td>
</tr>
<tr>
<td>T+48 h</td>
<td>157</td>
<td>126</td>
</tr>
</tbody>
</table>

Table 1

4.2 Analysis at 00 UTC 25 October 1998

Babs intensified after crossing the Philippines on 23 October. The 30-knot wind radius at 00 UTC 25 October was estimated to double that on 23 October by the HKO forecasters. This led to a much larger TC domain for calculating the asymmetric component. Due to the proximity of the model boundary, the asymmetric profile was not generated in this case so as to eliminate the boundary effect. Therefore, only results from sets A to C are discussed here for this model initial time.

Figure 11 shows the forecast tracks based on MSLP field together with the best track. The forecast track of Babs without bogus and SATOB data lied to the west of the one with symmetric bogus data. It also had a slow bias in the latter part of the forecast period. With symmetric bogus data, the model forecast Babs to move north in the early forecast hours and agreed with observations. However, after T+15 hour, the forecast track changed slightly to the northwest, in contrast to the observed northeast track.
The SATOB data did not seem to help improve the forecast positions of Babs based on MSLP field. The forecast positions during first 24 hours were found to be slightly due east of the best-track positions. The mean position errors from T+6 to T+24 hours were larger than those without SATOB data (Figure 12).

Figure 13 shows the forecast tracks based on 850-hPa vorticity field. All forecast tracks recurved more to the east and were closer to the observed when compared with those based on MSLP field. In this case, there was quite a large spatial difference in TC positions on the surface and upper level. This was due to the fact that the model predicted the weakening of Babs during the forecast hours.

On the contrary to the MSLP forecasts, the SATOB data reduced the forecast position errors based on 850-hPa vorticity field. The use of SATOB data in the model analysis provides additional wind data at 850-hPa level. The forecast position errors may be reduced if TCs are tracked by the maximum 850-hPa vorticity centres. Figure 14 shows a time series comparing the forecast track position errors in the three sets of experiment.

Table 2 summarizes the forecast position errors (in km) for the three sets of experiment based on MSLP and 850VT fields.

<table>
<thead>
<tr>
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<th>Forecast position errors (km) for 850-hPa vorticity field</th>
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<tr>
<td>Sets</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>T+0 h</td>
<td>42</td>
<td>31</td>
</tr>
<tr>
<td>T+24 h</td>
<td>118</td>
<td>44</td>
</tr>
<tr>
<td>T+48 h</td>
<td>283</td>
<td>216</td>
</tr>
</tbody>
</table>

Table 2

5. Concluding remarks

The bogus data based on the forecaster's analysis significantly reduced forecast position errors in RSM in the case of Babs. The northward bias of forecast tracks was reduced in the early forecast hours when asymmetric bogus profile was used. However, the forecast results based on asymmetric profile may not be necessarily better than those based on symmetric profile on the average. To improve the effect of asymmetric bogussing, a good initial guess for constructing the asymmetric component might be essential for the current asymmetric bogussing scheme in RSM.

The use of SATOB data in the model analysis provided additional wind data at 850-hPa level and reduced the forecast position errors in the case of Babs when TCs were tracked by the maximum 850-hPa vorticity centres.

References:


Figure 1.
Best track of Typhoon Babs (9811) analyzed by the Hong Kong Observatory.

Figure 2.
Rainfall distribution over Hong Kong on 24-26 October 1998. The isoyhets are drawn at 20-mm intervals.

Figure 3.
Decoded upper-air data distribution in RSM analysis at 00 UTC 23 October 1998.
(a) no bogus and no SATOB data

(b) symmetric bogus with no SATOB data

(c) symmetric bogus with SATOB data

(d) asymmetric bogus with no SATOB data

(e) asymmetric bogus with SATOB data

Figure 4. Model analyzed MSLP fields at 00 UTC 23 October 1998 for the five sets of experiment.
Figure 5. Model analyzed surface wind fields with streamlines at 00 UTC 23 October 1998 for the five sets of experiment.

- (a) no bogus

- (b) symmetric bogus

- (c) asymmetric bogus
Figure 6. Model analyzed 850-hPa vorticity fields at 00 UTC 23 October 1998 for the five sets of experiment.

(a) no bogus and no SATOB
(b) symmetric bogus without SATOB
(c) symmetric bogus with SATOB
(d) asymmetric bogus without SATOB
(e) asymmetric bogus with SATOB
Figure 7. Forecast tracks based on MSLP field for the five sets of experiment (Set A: red circle; Set B: green filled triangle; Set C: blue cross; Set D: gray filled rhombus; Set E: black plus) together with the best track (TC symbols marked at 6-hourly intervals with the same initial time at 00 UTC 23 October 1998.

Figure 8. Forecast position errors based on MSLP field for the five sets of experiment. The model initial time was 00 UTC 23 October 1998.
Figure 9: Similar to Figure 7 but based on maxima positions on 850-hPa vorticity field.

Figure 10. Forecast position errors based on 850-hPa vorticity field for the five sets of experiment. The model initial time was 00 UTC 23 October 1998.
Figure 11. Forecast tracks based on MSLP fields for the five sets of experiment (Set A: red circle, Set B: green filled triangle; Set C: blue cross) together with the best track (TC symbol) marked at 6-hourly intervals with the same initial time at 00 UTC 25 October 1998.

Figure 12. Forecast position errors based on MSLP fields for the three sets of experiment. The model initial time was 00 UTC 25 October 1998.
Figure 13. Similar to Figure 11 but based on 850-hPa vorticity field.

Figure 14. Forecast position errors based on 850-hPa vorticity field for the three sets of experiment. The model initial time was 00 UTC 25 October 1998.