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Case Study of Typhoon Kalmaegi (1415)

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Case Study of Typhoon Kalmaegi (1415)

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Abstract

Typhoon Kalmaegi (1415) required the issuance of Gale or Storm Wind Signal No. 8 in Hong Kong in 2014, even though it passed by at a distance of 370 km from Hong Kong during its closest approach. Storm surges triggered by Kalmaegi caused backflow of sea water in some low lying areas in both Hong Kong and Macao. This paper reviews the use of observational data in monitoring the cyclone characteristics and studies the synoptic factors leading to the fast movement and extensive circulation of Kalmaegi. The combined analysis of multi-platform satellite wind retrieval, in-situ surface observations and aircraft reconnaissance data over the northern part of the South China Sea is found to be useful in depicting the cyclone structure. Synoptic analysis suggests that the relatively large size of Kalmaegi is mainly attributed to monsoon shear pattern during its formation stage and the subsequent strengthening of southwesterlies over the northern part of the South China Sea. A strong subtropical ridge north of Kalmaegi not only provides strong steering and thus its high translational speed, but also leads to extensive gale force wind distribution over the northern semi-circle of the typhoon. The performance of various numerical prediction models in forecasting the movement, intensity change and wind structure of Kalmaegi, as well as the storm surge triggered, is assessed and presented.
1. Introduction

Typhoon Kalmaegi (1415) required the issuance of Gale or Storm Wind Signal No. 8 in Hong Kong in 2014, even though it passed by a distance of 370 km from Hong Kong during its closest approach. Moreover, storm surge triggered by Kalmaegi caused backflow of sea water in some low lying areas in both Hong Kong and Macao.

In this paper, an overview of some interesting aspects of Kalmaegi is described in Section 2. Section 3 reviews the use of observational data in monitoring the cyclone characteristics and analyzing the synoptic factors leading to its fast movement and extensive circulation. The effectiveness of meteorological observations for nowcasting local wind changes and the performance of NWP and other numerical products available during the passage of Kalmaegi are evaluated in Section 4. Finally, concluding remarks are given in Section 5.

2. Overview of Typhoon Kalmaegi

The track of Kalmaegi is shown in Figure 1. Due to its fast-moving speed and extensive circulation, it was the first time the Standby Signal No. 1 was issued for a tropical cyclone centred outside the 800-km range of Hong Kong since Typhoon Gordon in 1989. Furthermore, with a closest approach to Hong Kong at a distance of 370 km, Kalmaegi was the farthest tropical cyclone necessitating the issuance of Gale or Storm Wind Signal No. 8 since 1960.

During its closest approach, Kalmaegi generated significant storm surges and brought sea flooding in some low-lying areas in Hong Kong due to its extensive gale coverage. Kalmaegi was also the farthest tropical cyclone causing a storm surge exceeding 0.9 m and storm tide exceeding 3.0 m (above chart datum) since records began at the tide gauge station at Quarry Bay. A maximum storm surge of 0.92 m and a maximum storm tide of 3.03 m (above chart datum) were recorded at 0211 HKT at Quarry Bay around the time of high astronomical tide on the early morning of 16 September (Figure 2). Storm surges and storm tides were even larger at some other tide gauge stations in Hong Kong that morning (Table 1).
3. **Cyclone Characteristics**

3.1 **Fast Movement**

According to the provisional best track of the Observatory, Kalmaegi moved west-northwestwards steadily at a speed of about 30 km hr\(^{-1}\) over the northern part of the South China Sea, much higher than the climatological normal of about 20 km hr\(^{-1}\) at a latitude between 15\(^o\) to 20\(^o\) N [1]. The dominant factor leading to the high translational speed of Kalmaegi was attributed to the strong subtropical ridge to the north of Kalmaegi that provided the steering flow (Figure 3). With Kalmaegi’s high speed of movement, it is one of the reasons for higher winds over its northern semi-circle than the southern semi-circle.

3.2 **Large Size**

Kalmaegi was considered a large tropical cyclone according to Chan et al. (2012) [2], defined as a tropical cyclone with radius of surface winds of 17 m s\(^{-1}\) (R17) larger than 2.61\(^o\) latitude (about 155 nautical miles). The analysis of NOAA multi-platform satellite wind analysis (MTCSWA) at 12 UTC on 15 September (Figure 4) showed that the gale radius over the northern semi-circle of Kalmaegi extended to about 3.5\(^o\) latitude. This was supported by the Observatory’s aircraft reconnaissance data at 03 UTC on 15 September (Figure 5) and surface observations from ships and buoys at 06 UTC on 15 September (Figure 6).

There are three major factors leading to the large size of Kalmaegi.

(a) **Monsoon shear pattern at its formation stage**

Lee et al. (2008) [3] identified six low-level flow patterns associated with large tropical cyclone formation, namely easterly wave (EW), northeasterly flow (NE), co-existence of northeasterly and southwesterly flow (NE-SW), southwesterly flow (SW), monsoon confluence (MC), and monsoon shear (MS).

The MS pattern, the most favourable pattern for the formation of large tropical cyclones, was considered one of the major factors for the large size of Nesat in 2011 [4]. In the case of Kalmaegi, two maxima of zonal winds to the
northeast and southwest of mesoscale convective system about 48 hours before the formation of Kalmaegi (Figure 7) were typical signatures of MS pattern.

(b) Strengthening of southwesterly flow

The strengthening of southwesterly flow over the South China Sea provided additional moisture for convective development of the outer rainbands of tropical cyclones. Latent heat release resulted in diabatic lateral expansion and contributed to the expansion of tangential wind fields, and hence the size of tropical cyclones [5, 6]. Such favourable conditions were evident as Kalmaegi moved across the northern part of the South China Sea. ECMWF 850-hPa analysis depicted enhanced southwesterly flow over the South China Sea from 12 UTC on 14 September to 00 UTC on 16 September (Figure 8). With the strengthening of the southwesterly flow, convective development over the southern semi-circle of Kalmaegi remained extensive as the typhoon moved across the northern part of the South China Sea.

(c) Strengthening of northeasterly flow

A ridge of high pressure over the coast of southeastern China brought a northeast monsoon to the region on 14 September. As shown in Table 2, the values of DPs (difference in mean sea level pressure between Hong Kong and Shanghai) increased from 6.5 hPa at 00 UTC on 14 September to 15.3 hPa at 00 UTC on 16 September. Meanwhile, against a DPs rise of about 9 hPa, local pressure fell only by about 6 hPa in 48 hours during the approach of Kalmaegi, pointing to the part played by the strengthening northeast monsoon over the period. The combined influence of Kalmaegi and the northeast monsoon resulted in an extensive area of gale force winds over the northern semi-circle of Kalmaegi along the coastal waters of southern China.

4. Operational Forecasting Considerations

The large size and fast movement of Kalmaegi posed quite a challenge in the forecasting changes in local weather, such as the strengthening of winds and sea level rise due to storm surges. The effectiveness of meteorological observations for nowcasting local wind changes and the performance of NWP and other numerical products available during the passage of Kalmaegi were evaluated.
4.1 Nowcasting of local wind change

For tropical cyclone steered by the subtropical ridge to its north, Kok et al. (2013) [7] suggested that the descent of gales as measured by the wind profiler at Sham Shui Po (SSP) could give an indication to the onset time of gales at Cheung Chau and Waglan Island. As revealed by the SSP time-series of vertical wind profile from 15 to 16 September (Figure 9), the upper-level gales (depicted by green wind barbs) descended to the surface between 18 to 19 HKT on 15 September. It was observed that winds at Waglan Island (upwind of SSP) and Cheung Chau (downwind of SSP) reached gale force at around 17 HKT and 22 HKT on 15 September respectively. As such, a careful monitoring and extrapolation of the SSP upper-level winds through the depths of the lower troposphere could offer nowcasting guidance for the assessment of changes in local winds in the consideration of warning decisions and signal issuance.

4.2 Short-term to medium range forecasts of track, intensity and wind structure

4.2.1 Track

Given the strong synoptic scale steering by the subtropical ridge, NWP models generally showed good consensus on Kalmaegi’s track throughout the forecast period. The global deterministic models and the ensemble prediction system (EPS) all suggested that Kalmaegi would move in a northwesterly direction into the South China Sea towards western Guangdong. However, most of the model forecasts failed to predict the fast movement, resulting in an average slow bias of about 70 km at T+24 hr and up to 510 km at T+120 hr. Between the mean along-track and cross-track errors, the former contributed a larger part towards the mean direct position errors over all the models across all forecast hours. Of the available NWP models, ECMWF EPS performed the best with an average direct position error of about 55 km for T+48 hr forecasts, while GRAPES-TRAMS also beat the average model performance with an average position error of only 24 km for the T+24 hr forecasts.
4.2.2 Intensity Change and Wind Structure

In terms of cyclone intensity, the available deterministic models and EPS under-forecast the maximum winds and a negative bias of around 20 knots was found in T+48 hr forecasts and beyond. Among them, Meso-NHM [8], NCEP Global Forecast System, as well as the guidance from the RSMC/Tokyo based on the intensity changes from JMA global model forecasts performed relatively better with a negative bias of about 10 knots (Figure 10).

In terms of the trend in intensity change, they also managed to capture its weakening of Kalmaegi as it crossed the Philippines and its re-intensification in the South China Sea (Figure 11), except that the timing of the former and the extent of the latter could have been more accurate.

Model prognoses on wind structure based on 10-m wind forecasts from ECMWF model outputs and from Meso-NHMs using boundary conditions from ECMWF (denoted as NHM-EC hereafter) and JMA global models were studied. It was found that NHM-EC performed the best as the model managed to forecast the expansion of gale force wind radius in terms of the spatial scale as well as the timing.

Kalmaegi underwent a significant expansion when it rapidly intensified into a typhoon later on 13 September. The NOAA multi-platform satellite wind analysis (MTCSWA) from at 18 UTC on 13 September showed the gale radius increasing to 3° latitude compared to only 1° latitude 12 hours before. While the NHM-EC run at 00 UTC on 12 September did not give much indication of the size increase on 13 September (not shown), the subsequent 12 UTC run on 12 September not only showed a growing gale radius, but also forecast it to reach 210 nautical miles by 18 UTC on 13 September, which compared reasonably well with observations (Figure 12).

The potential of cyclone intensification in terms of increases in the strong and gale wind radii was also evident from the ECMWF EPS as early as the 12 UTC run on 10 September (Figure 13). Eight out of 50 ECMWF EPS members suggested intensification over a 6-hour time window centred at 12 UTC on 15 September, with gale force winds becoming more organized within its circulation. In particular, the circles in solid lines in Figure 13 showed members with gales covering, or close to, the adjacent waters of Hong Kong.
There were also members encompassed by dashed circles in Figure 13 that suggested Kalmaegi would continue to intensify in the following hours with a larger coverage of gales over the coastal waters, even though gales were not forecast to affect the coast due to errors in the forecast positions of the cyclone centre.

4.2.3 NWP model guidance on strengthening of the local winds

In general, the NWP models performed fairly well in forecasting changes in the wind structure of Kalmaegi and hence provided useful guidance in assessing the impact arising from the strengthening of winds locally in Hong Kong.

With reference to the ECMWF EPS forecasts from the 12 UTC run on 10 September, the maximum winds taken over all the entire ensemble indicated that the strong and gale force wind radii would cover the Pearl River Estuary by 00 UTC and 12 UTC respectively on 15 September (Figure 14 (a)-(b)). This signal became stronger in later runs, with an increasing number of members forecasting organized gales around the centre of Kalmaegi. By the 00 UTC run on 13 September, over 50% probability of strong force winds was given for Hong Kong for 12 UTC on 15 September and about 40% probability of gale force winds for 15 UTC on the same day (Figure 14 (c)-(d)). Confidence of the NWP models on the intensity of Kalmaegi and its potential impact of gales to Hong Kong grew with each updated model run.

The forecast time series of wind speed at selected reference stations are shown in Figure 15, where red and purple lines depicted the 90th-percentile and median forecasts from ECMWF EPS run at 00 UTC on 13 September. Compared to the actual 10-min mean wind speeds shown in black lines, the EPS forecasts were able to capture the trend on the strengthening of wind over Hong Kong at a lead time of more than two days (and similarly in subsequent EPS runs). Gales were predicted at Waglan (top right), Cheung Chau (centre in bottom row) and Chek Lap Kok (bottom left) with a difference of only a few hours in the timing of gale onset. The stations where the occurrence of gales was not adequately predicted was Lau Fau Shan (top left) and Sai Kung (right in second row).

Likewise, NHM-EC forecast from the 12 UTC run on 14 September indicated that gales would affect Hong Kong by 18 UTC on 15 September
(Figure 16). These were again within a few hours of the corresponding wind strengths being recorded at the local stations, thus giving an early indication of the potential impact of high winds due to Kalmaegi.

4.3 Performance of Storm Surge Prediction Model

The Sea, Lake and Overland Surges from Hurricanes (SLOSH) storm surge numerical model developed by the National Weather Services (NWS) of NOAA and operated by the Observatory since 1994 was configured on a polar grid, with grid size ranging from 1 km near Hong Kong to about 7 km over the open sea. To run SLOSH, input parameters including 6-hourly positions (in latitude and longitude) and their corresponding values of central minimum pressure and cyclone size (in terms of radius of maximum winds) from 48 hours before to 24 hours after the time of closest approach to Hong Kong were required. Due to the large gale radius of Kalmaegi, it was found that a radius of maximum winds of 160 km had to be used to adequately represent the wind fields of Kalmaegi (not shown).

As shown in Figure 17, the maximum storm surge and storm tide at Quarry Bay during the passage of Kalmaegi as predicted by SLOSH using a radius of maximum winds of 160 km were 0.76 m and 2.81 m (above Chart Datum) respectively, about 0.16 m and 0.22 m lower than the corresponding observed values. The predicted times for the occurrence of maximum storm surge and storm tide were also in good agreement with observations. Also plotted in Figure 16 for comparison were predictions based on a radius of maximum winds of 56 km\(^1\), typically used for tropical cyclones of normal size. It could be seen that the actual storm tide would then be significantly under-estimated.

5. Conclusions

In summary, Kalmaegi was characterized by its fast movement and extensive circulation. The fast movement was a result of strong easterly steering south of the subtropical ridge. Its relatively large size was due to the presence of monsoon shear pattern at its formation stage, and the strengthening of southwesterly flow and northeast monsoon as it moved across the northern part of the South China Sea. Its high translational speed also led to extensive gale force wind distribution over the northern semi-circle of the typhoon. The

\(^1\) 56 km is the default value for the radius of maximum wind of typical cyclones of normal size in SLOSH
in-situ surface observations over South China Sea and timely aircraft reconnaissance data provided valuable ground truth for confirming the wind structure estimates based on satellite wind analysis.

While NWP models in general could capture the general movement direction of Kalmaegi, a slow bias was also evident. Although intensity forecast remained a challenge for NWP models, NHM-EC and ECMWF EPS nonetheless performed reasonably well in simulating the evolution of wind structure associated with Kalmaegi, hence offering useful guidance for assessing the changes in local winds. By integrating the observational evidence and numerical model guidance on local wind changes, forecasters were able to visualize the possible timing of the occurrence of strong winds and gales in Hong Kong about one day ahead even the traditional climatological forecast tool depicts a low chance of gales in Hong Kong [9]. With appropriate input of wind field in terms of radius of maximum wind, SLOSH could also provide a reliable estimate of the maximum storm surge and highest sea level in Hong Kong during the passage of Kalmaegi.
References


Table 1  The maximum storm surges and storm tides recorded by tide gauge stations at Quarry Bay, Shek Pik and Tai Po Kau during the passage of Kalmaegi

<table>
<thead>
<tr>
<th>Station</th>
<th>Maximum Storm Tide (above chart datum)</th>
<th>Maximum Storm Surge (above astronomical tide)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Height (m) Date/Month Time (HKT)</td>
<td>Height (m) Date/Month Time (HKT)</td>
</tr>
<tr>
<td>Quarry Bay</td>
<td>3.03 16/9 0211</td>
<td>0.92 16/9 0211</td>
</tr>
<tr>
<td>Shek Pik</td>
<td>3.20 16/9 0231</td>
<td>1.03 16/9 0231</td>
</tr>
<tr>
<td>Tai Po Kau</td>
<td>3.28 16/9 0220</td>
<td>1.20 16/9 0220</td>
</tr>
</tbody>
</table>

Table 2  Difference in mean sea level pressure between Hong Kong and Shanghai (DPs) and mean sea level pressure (MSLP) at Hong Kong from 00 UTC 14 September 2014 to 00 UTC 16 September 2014.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UTC)</th>
<th>DPs (hPa)</th>
<th>MSLP at Hong Kong (hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 September</td>
<td>00</td>
<td>6.5</td>
<td>1007.2</td>
</tr>
<tr>
<td>15 September</td>
<td>00</td>
<td>10.8</td>
<td>1004.0</td>
</tr>
<tr>
<td>16 September</td>
<td>00</td>
<td>15.3</td>
<td>1001.1</td>
</tr>
</tbody>
</table>
Figure 1  Track of Kalmaegi from 12 to 17 September 2014.

Figure 2  Storm surge, storm tide and predicted astronomical tide at Quarry Bay from 9 am on 15 September 2014 to 1 am on 17 September 2014.
Figure 3  JMA 500-hPa geopotential height analysis at 00 (left) and 12 UTC (right) on 15 September 2014.

Figure 4  NOAA MTCSWA images at 12 UTC on 15 September 2014.
Figure 5  Winds measured by aircraft reconnaissance (reduced to 10 m) at around 03 UTC on 15 September 2014. Winds reaching strong and gale force are shown in green and red respectively. Centre of Kalmaegi at that time is indicated by blue dot.

Figure 6  Surface observations at 06 UTC on 15 September 2014. Winds reaching strong and gale force are shown in green and red respectively. Centre of Kalmaegi at that time is indicated by blue dot.
Figure 7  Isotachs (in m s$^{-1}$) for the 850-hPa zonal winds of the mesoscale convective system (MCS) associated with Kalmaegi at 18 UTC on 9 September 2014 based on NCEP/NCAR re-analysis data. The centre of MCS was around 9°N 147°E, as indicated by the blue dot. Two maxima, indicated by the red dots, could be identified northeast and southwest of the MCS.
Figure 8  ECMWF 850-hPa analysis from 12 UTC on 14 September 2014 to 00 UTC on 16 September 2014. Enhanced southwesterly flow could be seen over the regions indicated by the blue boxes.
Figure 9  Time-series of vertical wind profile measured at Sham Shui Po from 1219 HKT on 15 September 2014 to 0020 HKT on 16 September 2014. The blue line depicted the descent of gales aloft. Green and black arrows indicate the times of onset of gales at Waglan Island and Cheung Chau respectively.
Figure 10  Mean error (ME), mean absolute error (MAE) and root mean square error (RMSE) of ECMWF, NCEP, RJGM (JMA global model) and Meso-NHM on Kalmaegi’s intensity prediction from T + 0 to T + 72 hours.

Figure 11  12-hour intensity change of Kalmaegi since 12Z on 13 September 2014, according to ECMWF, NCEP, RJGM (JMA global model) and Meso-NHM against the re-analysed data.
Figure 12  (Top): NOAA MTCSWA images at 06 and 18 UTC on 13 September 2014. (Bottom): wind radii forecast (blue for strong and brown for gales) for 12 UTC run on 12 September 2014 by NHM-EC.
Figure 13  Stamp map showing T+120 h wind forecasts of ECMWF EPS from 12 UTC run on 10 September 2014. First four images from left in the first row are respectively the ensemble mean, the 75th-percentile, the 90th-percentile, and the ensemble maximum. EPS control is depicted in the third panel from right in the first row, followed by the forecasts from 50 members. See the text for the explanation of the circles.
Figure 14  (a) and (b): ECMWF EPS maximum wind speed at 00 and 12 UTC on 15 September 2014 (from 12 UTC run on 10 September 2014). (c) and (d): ECMWF EPS probability of strong and gale force winds at 12 UTC and 15 UTC on 15 September 2014 (from 00 UTC run on 13 September 2014).
Figure 15  Forecast time series of post-processed wind speed of ECMWF EPS from 00 UTC run on 13 September 2014 at selected stations. Purple and red lines show the median and the 90th-percentile respectively while actual 10-minute mean speeds are shown in black lines.

Figure 16  The wind structure forecast for 18 UTC on 15 September 2014 from the 12 UTC NHM-EC run on 14 September 2014.
Figure 17  Observed and predicted storm tide at Quarry Bay from 0900 HKT on 15 September 2014 to 0100 HKT on 17 September 2014.