

P1.21 AN EMPIRICAL MODEL FOR AERODROME WIND FORECASTING DURING THE PASSAGE OF TROPICAL CYCLONES

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1. INTRODUCTION

Study of past cases of significant flight delay and/or flight cancellation at the Hong Kong International Airport (HKIA) indicated that high crosswind brought by tropical cyclones (TCs) stands out as the top weather factor causing airport disruptions. The Hong Kong Observatory (HKO) provides regular briefings to the airport community in TC situations to facilitate their planning and decision-making in flight operations and emergency arrangements. The crosswind forecasts, amongst other weather information, are also included in the Weather Summary for HKIA on the Aviation Meteorological Information Dissemination System (AMIDS) to supplement the terminal aerodrome forecast (TAF) in support of decision making by the aviation users.

To support preparation of the Weather Summary in TC situations, hourly wind forecast is required to assess the wind strength and crosswind condition at HKIA for the next 36 hours. Fig. 1 shows the location of HKIA in Hong Kong. An empirical model based on the TC parameters including the TC wind radii, forecast positions and intensities was developed to provide objective guidance on hourly wind forecast at HKIA during the passage of TCs. Adjustments to the forecast are made to account for the surface property (land/sea/coastal area) that the TC moves across and the local terrain effect.



Figure 1. The Hong Kong International Airport (HKIA) and its neighbouring areas.

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A web-based interactive tool was implemented for displaying the empirical model wind forecasts at hourly intervals up to 72 hours ahead. Model outputs are generated automatically based on the TC parameters in the HKO's TC warning bulletins and are updated every three hours. Manual adjustment to the TC parameters can be applied on-the-fly to enable generation of model output to facilitate forecaster's formulation of alternative scenario of wind forecast taking into account the forecast uncertainty of individual TC parameters.

This paper presents the formulation of the empirical model and the evaluation of performance of the model wind forecasts for HKIA using TC cases in 2008.

2. THE EMPIRICAL MODEL

2.1 Construction of wind profile within TC circulation

The analysed intensity and wind radii of the TC at time T and the forecast positions and intensities at T + 24h, T + 48h and T + 72h are obtained from the TC warning bulletin issued by the HKO every 3 hours. A sample of the bulletin is given in Table 1.

ZCZC MESSAGE NO. 059 TROPICAL CYCLONE WARNING AT 210300 UTC, TYPHOON NURI (0812) WITH CENTRAL PRESSURE 960 HECTOPASCALS WAS CENTRED WITHIN 30 NAUTICAL MILES OF TWO ZERO POINT TWO DEGREES NORTH (20.2 N) ONE ONE SEVEN POINT EIGHT DEGREES EAST (117.8 E) AND IS FORECAST TO MOVE NORTHWEST OR WEST-NORTHWEST AT ABOUT 8 KNOTS FOR THE NEXT 24 HOURS. MAXIMUM WINDS NEAR THE CENTRE ARE ESTIMATED TO BE 75 KNOTS. RADIUS OF OVER 33 KNOT WINDS 100 NAUTICAL MILES. RADIUS OF OVER 47 KNOT WINDS 60 NAUTICAL MILES. RADIUS OF OVER 63 KNOT WINDS 30 NAUTICAL MILES. RADIUS OF OVER 2 METRE WAVES 210 NAUTICAL MILES. FORECAST POSITION AND INTENSITY AT 220300 UTC TWO TWO POINT TWO DEGREES NORTH (22.2 N) ONE ONE FIVE POINT ZERO DEGREES EAST (115.0 E) MAXIMUM WINDS 70 KNOTS. FORECAST POSITION AND INTENSITY AT 230300 UTC TWO FOUR POINT FIVE DEGREES NORTH (24.5 N) ONE ONE TWO POINT NINE DEGREES EAST (112.9 E) MAXIMUM WINDS 30 KNOTS. FORECAST POSITION AND INTENSITY AT 240300 UTC DISSIPATED OVER LAND. DISPATCHED BY HONG KONG OBSERVATORY AT 13:09 HKT ON 21.08.2008 NNNN
Table 1 – Sample of TC Warning Bulletin issued by the Hong Kong Observatory

The wind profile at the analysis time is constructed using the maximum wind and the wind radii given in the warning bulletin as follows. From the JTWC western North Pacific TC best track dataset from 2001 to 2007, the radius of maximum wind could be as small as 10 km or as large as around 110 km. Based on the past surface wind observations of direct-hit TCs in Hong Kong, the radius of maximum wind is about 30-50 km and the wind near the TC centre is about 5 kt. In the present TC empirical model, the maximum wind is assumed to occur near the eyewall with a radius of $R_{mw} = 30$ km and the wind is set to 5 kt right at the TC centre. The wind speed within the strong wind radius is estimated by linear interpolation between R_{mw} and the given wind radii. An illustration of the constructed TC wind profile is given in Fig.2. Although there exists another type of analytical model of the TC wind profile (e.g. Holland, 1980), the prescribed wind radii in the warning bulletin cannot be fitted into this type of model. Considering that forecasters should have assimilated all available meteorological information including surface and remote-sensing observations such as Doppler weather radar and QuikSCAT satellite data in the analysis of the strong/gale/hurricane wind radii of the TC, the construction of the TC wind profile is solely based on the information in the warning bulletin.

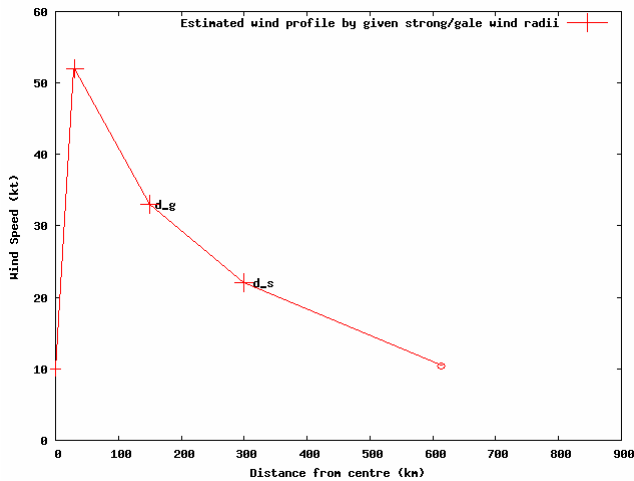


Figure 2. Construction of a TC wind profile based on information on the maximum wind, gale wind radius (d_g) and strong wind radius (d_s).

For the area outside the strong wind radius, the decay rate of wind speed over distance is taken to be a factor of the decay rate between the gale wind radius and the strong wind radius. Currently, such factor is taken to be 0.5, and the wind speed at the TC outermost circulation is set at 10 kt, so that the deduced TC size is consistent with the subjectively analysed radius of the outermost closed isobar of the TC circulation based on the study of past cases.

Since the TC warning bulletin does not contain information on wind radii forecast in association with the change in TC intensity, the wind profile will be adjusted based on the forecast change of maximum wind. The forecast wind w_t at time t for a point P at a distance $R > R_{mw}$ from the centre is given by the empirical formula in Eqn.(1), where w_0 is the wind strength at P at $T = 0$. m_0 and m_t are the maximum wind speeds at $T = 0$ and $T = t$ respectively.

$$w_t = \varepsilon w_0$$

$$\varepsilon = \frac{m_t - f}{m_0 - f} \quad (1)$$

$$f = \beta(1 - e^{-\frac{m_0}{w_0}}), \beta = 10$$

The formulation in Eqn.(1) is to model a change such that the size of the TC circulation will decrease as the TC weakens.

2.2 Adjustment to wind speed

There will be increased frictional effect due to interaction of the TC circulation with the landmass when the TC comes close to the coastal region. Taking into account the surface conditions that the airstream of the TC traverses, rectangles with length of 100 km and width of 6 km are drawn on a map with land/sea mask, with one end at the HKIA, pointing towards the upwind direction. The selection of 6-km width is based on the size of Chek Lap Kok Island where HKIA is located at and the grid size of the terrain data.

The proportion of land and sea in the rectangular area is then counted. The wind speed will be multiplied by a reduction factor τ as defined in Eqn.(2) below.

$$\tau = \tau_1 p_{land} + \tau_2 p_{sea} \quad (2)$$

where p_{land} is the fraction of land and p_{sea} is the fraction of sea inside the rectangle.

The initial values of τ_1 and τ_2 are taken to be 0.4 and 0.8 respectively by making reference to Thompson (1998). By fitting the forecast wind speed to the actual observations at HKIA based on 1995-2007 dataset, location-specific values for τ_1 and τ_2 can be obtained and they are found to be 0.5 and 1 respectively.

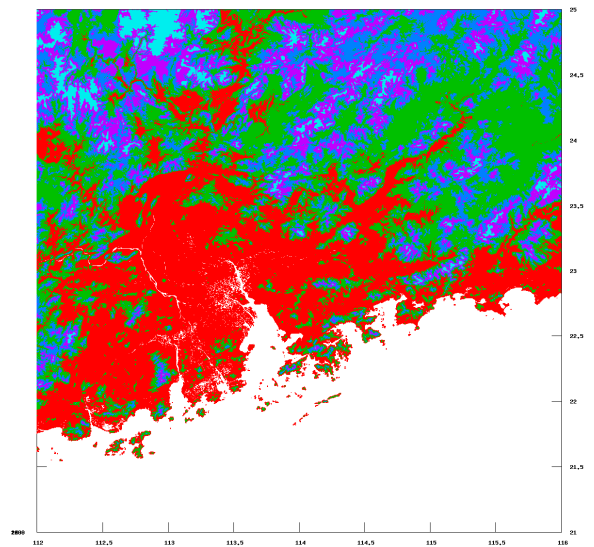


Figure 3. Topographical map around HKIA with colors indicating the height of the topography (RED: <100 m above sea level; GREEN: 100-300 m; BLUE: 300-500 m; PURPLE: 500-800 m; CYAN: above 800 m).

Fig. 3 shows the topographical map around HKIA. At present, information on the topographical height and the type of land use is not utilized in the empirical model. It is expected that fine tuning based on topographical information for further adjustment of the local wind speed may better reflect the actual situation. The adjustment of the local wind speed could be an enhancement if there is channelling effect or a reduction if there is blocking of the airstream.

2.3 Forecasting the prevailing wind direction

Ideally, the gradient wind equation applies to cyclones. However, due to surface friction, the wind will actually spiral anti-clockwise inward towards the low pressure centre in the northern hemisphere.

We denote the wind direction at HKIA by $\phi - 90^\circ - \delta$, where ϕ is the bearing of the TC measured from HKIA and δ is the ageostrophic component of the wind direction. The values of δ are modelled with reference to the climatological data of the prevailing wind direction at HKIA (Fig. 4(a)) and Waglan Island, an outlying island southeast of Hong Kong whose location is indicated in Fig. 1.

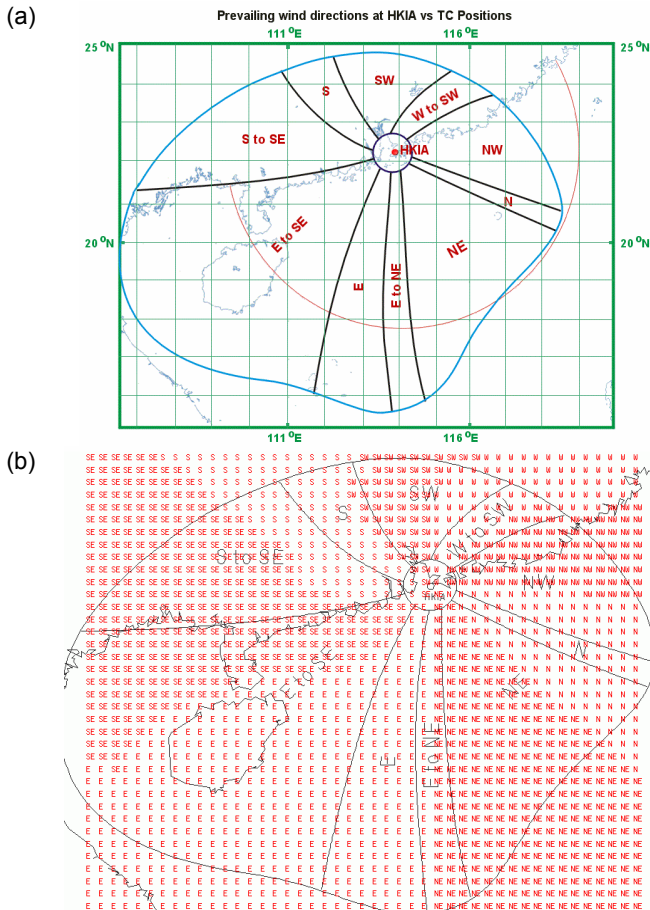


Figure 4. (a) Climatology of prevailing wind direction for HKIA during TC situations. The wind direction labelled in each sector indicates the prevailing wind at HKIA when a TC is located within that sector; (b) Wind direction estimated by using the empirical model as compared with the climatology method.

An algorithm was devised to “digitize” the climatological data (Fig. 4(a)) for use in forecasting the prevailing wind direction at HKIA in the TC empirical model.

The main contribution factor to δ , say δ_1 , should be the inflow angle of TC wind depending on the site-specific surface characteristics, viz. land or sea surface. Due to frictional effect, the surface wind should be backed in direction from the gradient wind. The magnitude of δ_1 depends on the stability of air and the roughness of the surface. Rough surfaces increase the frictional effect and greater stability reduces the turbulent exchange of energy between the flow aloft and that at the surface. In conditional instability situations, the angle of deviation may range between 5° and 15° over the sea; and between 20° and 30° over land (The Met. Office, 1993). In the present TC empirical model, a value of 15° is taken for sea surface, while 30° is taken for land surface. The method used to determine the percentage of land that the airstream of the TC traverses is similar to that in section 2.2 except that the length of the rectangle is taken as 60 km instead of 100 km. For future enhancement to the model, the type of land use and topographic features could be taken into account and used to fine tune the value of δ_1 .

From Fig. 4(a), it was noticed that the boundaries of regions of different groups of wind direction are generally curled instead of radiating outward in a straight line. It implies that the wind direction depends on the distance from the TC centre. The pressure gradient of the TC circulation is a function of distance from the centre. The radius of maximum pressure gradient is smaller than the radius of maximum wind because of the dependence of gradient or cyclostrophic winds on the radius as well as the pressure gradient (Holland, 1980). Different wind speeds may result in different inflow angles. Another contribution or adjustment factor, say δ_2 , is thus introduced in Eqn. (3) and shown in Fig. 5, to account for the distance-dependent characteristics of the inflow angle.

$$\delta_2 = \begin{cases} 0 & , \quad d < 30 \\ 15 \left(\frac{d-30}{135} \right)^2 e^{\left(-\frac{(d-30)^2}{135^2} \right)} & , \quad 30 \leq d < 300 \\ 3 + 12 \left(\frac{1000-d}{350} \right)^2 e^{\left(-\frac{(1000-d)^2}{350^2} \right)} & , \quad 300 \leq d < 1000 \\ 3 & , \quad 1000 \leq d \end{cases} \quad (3)$$

where d is the distance from the TC centre.

The residual factor for “fitting” the climatological data to the automatic algorithm is taken as δ_3 . It is assumed to be related to the location of the TC centre. If the TC is over the open sea, the wind should be tangential to the centre near the TC eyewall. When the TC is on land, surface friction would probably force the wind to spiral inward slightly even at the eyewall. δ_3 is set to 5° and 0° for the TC over land or sea respectively. Considering the physical size of the eyewall and ensuring a smoother change across the

boundary, a continuous transition when the TC traverses between land and sea is achieved by using a buffer of 50 km on both sides of the coastline, where δ_3 changes from 5° at 50 km landward of the coastline to 0° at 50 km seaward of the coastline linearly.

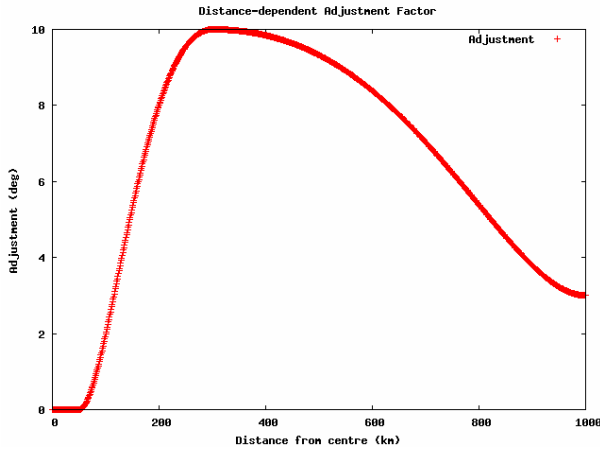


Figure 5. The distance-dependent adjustment factor, δ_2 against distance from the TC centre.

The wind direction estimated by applying the sum of the above three factors, viz. $\delta_1 + \delta_2 + \delta_3$, is shown in Fig. 4(b). It can be seen that the delineation of wind directions matches rather well with that from the climatology data.

3. INTERACTIVE WEB-BASED TOOL

An integrated web-based tool was developed to generate a forecast time series of wind forecast based on the empirical model as described in section 2. The layout of the outputs of the tool is shown in Fig. 6.

3.1 Time series forecast

The T + 24h, T + 48h and T + 72h forecast positions and intensities are interpolated hourly up to 72 hours ahead. On each hour, the wind at HKIA is calculated using the algorithms in sections 2.1 to 2.3.

The tool aims at assisting forecasters in the formulation of TAF and forecast strategy taking into account the alternative scenarios when the TC is in the vicinity of Hong Kong. As crosswind may have significant impact to flight operation, the magnitude of crosswind is also computed based on hourly forecast of wind speed and direction. Since the strength of crosswind is sensitive to the wind direction and there will be forecast uncertainty, the values of crosswind with wind direction deviated by 22.5° to both sides of the forecast wind direction are also displayed for forecasters' reference.

Gust forecast is not produced from the TC empirical model. Gust factors for different wind directions calculated by using climatology method are used to produce gust forecast which is also displayed on the tool. The past data used in the derivation of the gust factor include those cases in which a TC is present within 500 km from HKIA, and the maximum sustained wind speed reaches strong force. This is to ensure that only cases under the direct effect of TCs would be counted, and those cases with combined effects of the winter monsoon

are not considered. It was found that the gust factor ranges between 1.4 and 1.6 depending on the prevailing wind direction which is in turn related to the location of the TC with respect to HKIA.

Key forecast parameters, such as the distance and bearing of the TC with respect to HKIA and the timing that the TC is closest to HKIA, as well as the onset and cessation times of strong/gale/storm/hurricane force winds at HKIA, are displayed in the summary box of the tool (upper frame in blue in Fig.7).

The tool can be viewed using all common web browsers and can be run efficiently on ordinary PC web servers. The loading time is within 10 seconds. The short response time enables the tool to provide quick reference to the forecasters in support of their time-critical operations.

Forecast for NURI (0812) (Beta Version)

Based on Shipping Warning issued at 20080822 0300C

20080822 03 T 21.40 114.90 30.00 970.00 65.00 69.00 311.00 11.00 2.50 1002.00 3.00 180.00 1002.00 120.00 996.00 90.00 307.00 6.50 985.00 50.00 NaN NaN 24.10 111.20 NaN NaN 24.20 110.20 285.00 6.00 998.00 25.00 NaN NaN NaN NaN

Switch to T2 hours view

Speed of movement adjusted by 5 kts. Direction of movement adjusted by 25 degrees. [Change](#) [Default Adjustment](#)

Select Model: [Original](#) | [Back](#) | [Print](#) | [Left](#) | [Right](#)
[Move Faster](#) | [Move Slower](#) | [Lead to move to the Left](#) | [Lead to move to the Right](#) | [All](#)

Time (UTC)	Lat	Long	Dist	Dir	Dir Fr	Dir To	W	W Dir	W-Wind(kt)	Gust Factor	Land/Sea
2008082203 (T+00)	21.38	114.90	116 km	110°	32kt	N		(-18.6°) 31.6 (3.0°) 28.0 (26.4°) 21.8	1.404 (1.410 / 1.398)	Sea (Coast)	
2008082204 (T+01)	21.38	114.88	109 km	118°	33kt	N		(-20.6°) 32.5 (1.0°) 30.2 (24.4°) 23.2	1.404 (1.410 / 1.398)	Sea (Coast)	
2008082205 (T+02)	22.00	114.78	91 km	116°	34kt	N		(-22.5°) 33.5 (0.0°) 31.5 (22.5°) 24.7	1.404 (1.410 / 1.398)	Sea (Coast)	
2008082206 (T+03)	22.00	114.63	79 km	110°	34kt	N		(-18.6°) 34.0 (3.0°) 31.1 (26.4°) 23.4	1.404 (1.410 / 1.398)	Sea (Coast)	
2008082207 (T+04)	22.18	114.58	67 km	110°	35kt	N		(336.1°) 35.1 (350.2°) 33.2 (381.1°) 26.3	1.404 (1.410 / 1.398)	Sea (Coast)	
2008082208 (T+05)	22.29	114.48	56 km	106°	37kt	N		(328.6°) 36.5 (351.1°) 36.6 (373.6°) 31.1	1.404 (1.410 / 1.398)	Sea (Coast)	
2008082209 (T+06)	22.29	114.38	45 km	98°	48kt	SW		(315.1°) 44.0 (337.6°) 48.4 (360.1°) 45.5	1.396 (1.368 / 1.411)	Land (Coast)	
2008082210 (T+07)	22.28	114.38	35 km	87°	49kt	SW		(315.1°) 44.7 (337.6°) 49.2 (360.1°) 46.3	1.396 (1.368 / 1.411)	Land (Coast)	
2008082211 (T+08)	22.40	114.28	27 km	68°	44kt	SW		(304.3°) 30.8 (316.8°) 40.5 (339.3°) 44.1	1.396 (1.368 / 1.411)	Land (Coast)	
2008082212 (T+09)	22.50	114.18	24 km	40°	32kt	SW		(263.4°) 7.5 (285.0°) 19.0 (308.4°) 27.6	1.396 (1.368 / 1.411)	Land (Coast)	
2008082213 (T+10)	22.60	114.08	27 km	13°	44kt	SW		(234.5°) 11.6 (257.0°) 5.3 (270.5°) 21.4	1.396 (1.368 / 1.411)	Land (Coast)	
2008082214 (T+11)	22.69	113.98	35 km	355°	55kt	SW		(217.1°) 39.8 (239.6°) 9.0 (282.1°) 11.5	1.585 (1.501 / 1.604)	Land (Coast)	
2008082215 (T+12)	22.78	113.88	45 km	344°	57kt	SW		(202.8°) 41.4 (226.3°) 23.1 (268.8°) 1.2	1.585 (1.501 / 1.604)	Land (Coast)	

Figure 6. The interactive web-based tool showing hourly forecast of wind and gust up to 72 hours ahead.

3.2 Alternative scenarios generated by modifications to TC track or structure parameters

A deviation in the TC track and intensity may produce significant difference in the local wind especially crosswind. The provision of alternative scenarios or other possibilities of TC forecast on top of the “deterministic” official TC forecast and its impact to the weather at the airport is very much welcomed by aviation users noting that there exists forecast uncertainty.

Other possible scenarios of the track can be generated from different combinations of modified translation speed and moving direction of a TC. A faster or slower speed (default of the speed change is set to 3 kt), a more westward or eastward track (default of the directional change is set to 25°) can be used to generate other possible tracks, for example, based on the discrepancy of forecast speed from that observed in the past 6 to 12 hours. These two parameters can be modified by the users through the web-based tool and the subsequent changes in the local wind forecast will be generated on-the-fly. The error circles (as colored in Fig. 7) drawn around the TC positions at T + 0h, T + 24h and T + 48h respectively with a radius of 30 km, 150 km and 250 km based on past error statistics may also

be used to generate other possible scenarios of TC track. The function of enabling the generation of other possible tracks facilitates forecasters' assessment of the potential impact to the local wind and crosswind forecasts taking into account the uncertainties in the forecast track.

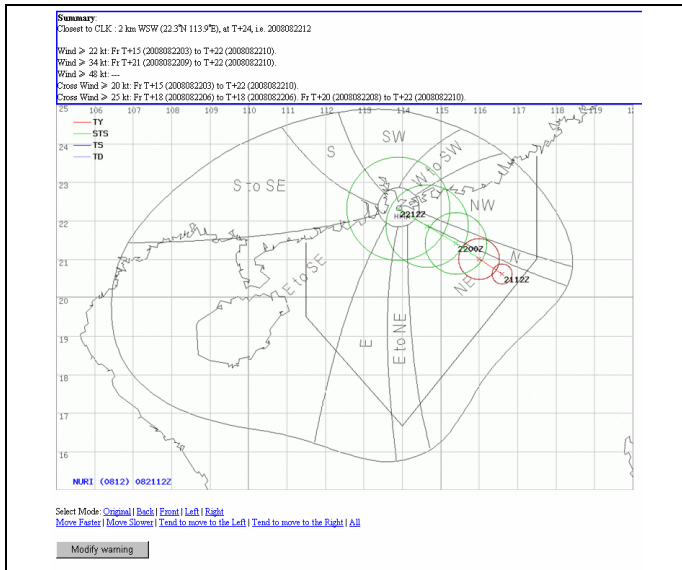


Figure 7. Display of the TC track and the statistically based error circles together with a summary of key forecast parameters on the web-based TC empirical tool. Other possible scenarios of the TC track can be generated on-the-fly by clicking the hyperlinks at the bottom of the display.

Direct modification of the forecast TC parameters used to generate the wind profile is also supported by the tool (Fig.8). This provides the flexibility of adjusting the TC parameters based on the latest observations without restricting to the updating time of the TC warning bulletins. Simple validity checks are imposed to the input parameters to ensure the consistency of the modified parameters.

Adjusting forecast for NURI (0812) in TCFCsys

Modification of forecast only for display in this instance only, it will not affect other users.

Fields highlighted in blue can be modified and they are employed in the forecast by the program.

Fields that are empty or not applicable should be filled with 'NaN'

ID	Name	Value	ID	Name	Value
Data at T+00					
0	YYYYMMDD	20080821	1	HH (UTC)	12
2	Intensity	T	3	Latitude (°N)	20.60
4	Longitude (°E)	116.00	5		
6			7	Maximum Wind (kt)	65.00
14	Radius of Strong winds (nm)	180.00	15		
16	Radius of Gale winds (nm)	90.00	17		
18	Radius of Storm winds (nm)	60.00	19		
Data at T+06, T+12 and T+18					
22	T+12 Forecast Pos (°Lat)	21.40	23	T+12 Forecast Pos (°Long)	115.40
Data at T+24					
26	T+24 Forecast Pos (°Lat)	22.30	27	T+24 Forecast Pos (°Long)	113.90
30			31	T+24 Max Wind (kt)	60.00

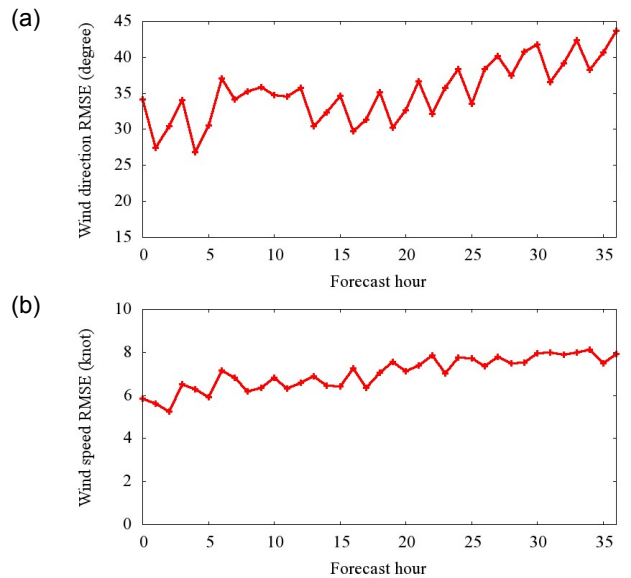
Make Changes Reset

Figure 8. Online form for editing the TC parameters as contained in the TC warning bulletin for use in the TC empirical tool.

4. VERIFICATION RESULTS FOR 2008 TCs

Fig. 9 shows the verification results of the TC empirical model without forecasters' intervention for the 2008 TC season. The verification dataset includes all model wind forecasts for TCs within 500 km of HKIA. There were a total of eight TCs in the 2008 verification dataset. The data sample size is relatively small with about 80 forecasts for each forecast hour. The average RMS errors of the forecast wind speed and direction were 7 kt and 35 degrees respectively for the 36-hour forecast. For the crosswind forecast, the average RMS error for the 36-hour forecast was around 9 kt. Oscillations are found in the RMSEs in Fig.9 and they are probably related to the relatively small sample size. As observed from Fig.9, the forecast error generally increases steadily with the forecast range. It is believed to be due to inadequate modelling of the evolution of the TC wind profile with time. The empirical formula for estimating the change in wind radii associated with the change in TC intensity obviously does not fit to all cases and the accuracy of the wind radii also depend heavily on the accuracy of the TC intensity forecast. The error in TC intensity forecast has a significant contribution to the error in wind forecast. Further work needs to be done especially on estimating the change of TC intensity and wind structure during and after landfall in the vicinity of Hong Kong.

There is a noticeable error in both wind speed and direction at T + 0h. This is perhaps due to the fact that when the TC circulation is close to the landmass, the asymmetrical structure and characteristics of the TC circulation and hence its wind radii are becoming increasingly different from that over the open sea. The current empirical model does not cater for TC asymmetry. However, it can be enhanced to do so by introducing angle-dependent radii if information on the TC wind structure in real-time for individual storms could be obtained. The use of multi-platform satellite TC wind analysis system in this aspect will be explored in the future.



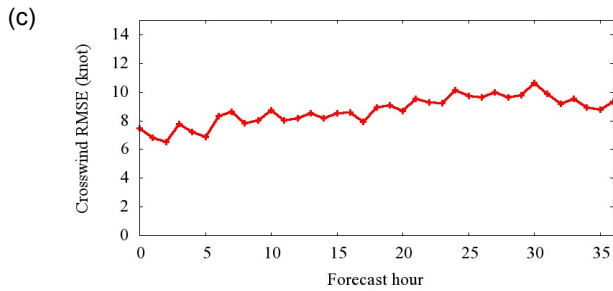


Figure 9. Root-mean-square errors of (a) wind direction; (b) wind speed; and (c) crosswind forecasts from the TC empirical model for the 2008 TC season.

5. CONCLUDING REMARKS

An empirical model based on the TC parameters including the TC wind radii, forecast positions and intensities was developed by the HKO to provide objective guidance on hourly wind forecast at HKIA during the passage of TCs. The TC parameters are extracted from the TC warning bulletin issued by the HKO every three hours. An interactive web-based tool built on the empirical model allows forecasters to adjust the TC track and structural parameters. This facilitates formulation of alternative scenarios on top of the automatically generated wind and crosswind forecasts from the TC empirical model based on HKO's official TC track and intensity forecast up to 72 hours ahead.

Verification of the TC empirical model was performed using 2008 TCs in the vicinity of Hong Kong. The RMS errors of the forecast wind speed and direction were around 7 kt and 35 degrees respectively for the 36-hour forecast. Future enhancements of the TC empirical model will include a better description of the evolution of the TC structure and wind profile by using more real-time remote-sensing data, especially during and after its landfall, the effect of land use, the use of topographical data in adjusting the local wind speed and direction.

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