P 333

OBJECTIVE CALIBRATED WIND SPEED AND CROSSWIND PROBABILISTIC FORECASTS FOR THE HONG KONG INTERNATIONAL AIRPORT

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1. INTRODUCTION

Wind is a critical weather element in formulating Terminal Aerodrome Forecast (TAF), especially in tropical cyclone (TC) situations for assessment of crosswind which is known to be one of the top weather factors causing significant flight delay and cancellation at the Hong Kong International Airport (HKIA). In Hong Kong, the wind and crosswind forecasts and their probability, amongst other weather information, are also contained in the Weather Summary for HKIA which serve as a supplement to TAF to facilitate decision making and cost-benefit analysis by the aviation users. If the forecast uncertainty is high, an alternative scenario is also included in the Weather Summary (HKO, 2006).

To assist aviation forecasters in assessing the possibility of different scenarios in the preparation of wind and crosswind forecasts in TC situations, the Observatory developed objective wind speed and crosswind probabilistic forecasts for HKIA based on the European Centre for Medium-Range Weather Forecasts (ECMWF) Ensemble Prediction System (EPS) outputs. As an enhancement to the aviation weather service, the wind speed and crosswind probabilistic forecasts are also made available to the aviation users up to 36 hours ahead as a trial product. The products are updated every 12 hours at around 21 UTC and 09 UTC upon available of the latest ECMWF EPS data. Recently, post-processing using Model Output Statistics (MOS) technique is applied to the ensemble mean wind speed forecast with a view to calibrating the forecast by removing the systematic bias.

This paper describes the methodology for generating the probabilistic forecast and the calibration method. Verification results based on the TC cases in 2009 are also presented.

2. PROBABILISTIC WIND SPEED AND CROSSWIND FORECASTS

TAF is the official weather forecast for an aerodrome. It does not normally contain information on forecast uncertainties or the confidence level of the forecast (ICAO, 2010). To supplement the TAF, the Airport Meteorological Office (AMO) of the Hong Kong Observatory (HKO) also issues a "Weather Summary" which includes a section on "Alternative Scenario" to alert aviation users to possible deviation of forecast track and intensity and the corresponding impact on weather forecast elements when there are high uncertainties in TC situations. To assist forecasters in assessing the possibility of different weather scenarios, probabilistic forecast information were extracted from model Ensemble Prediction System (EPS) outputs.

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Objective wind probabilistic forecasts are generated based on the ECMWF EPS wind forecast at the model grid point closest to HKIA (22.11 °N 114.48 °E). The total number of forecasts is 52 containing 50 ensemble members, the deterministic model forecast and the control model forecast. The U and V components of wind forecasts available at 6-hourly intervals up to 72 hours ahead are interpolated to hourly wind speed and crosswind based on 00 UTC and 12 UTC model run.

2.1 Estimation of probability

Considering a relatively small number of ensemble members, the Kernel Density Estimation (also known as the Parzen-Rosenblatt window method) in Eqn. 1 is employed to estimate the probability density function of wind speed and crosswind for each forecast hour in order to obtain a smoother probability distribution (Wand, 1995):

$$\hat{f}_h(x) = \frac{1}{nh}\sum_{i=1}^{n} K\Big(\frac{x - x_i}{h}\Big) \qquad (1)$$

where $f_h(x)$ is the Probability Density Function (PDF) and K(x) the kernel, Gaussian in this case with n=52. The value of h, the kernel bandwidth, is taken as the standard deviation of the wind speed or the crosswind. The effect of using different values of h in the kernel density estimation is shown in Fig.1.

The PDF for each forecast hour is calculated based on the 52 forecasts available and a 2-D "Probability Table" is constructed. Since the sum of the estimated PDF is usually not equal to unity, a normalization step is required to scale individual value of $f_h(x)$ such that summation yields unity. Due to operation consideration, the PDF for wind speed will be estimated from 0 kt to 60 kt inclusively, whereas for crosswind the estimation is from -60 kt (from south to north) to + 60kt (from south to north), both at 1-kt interval.

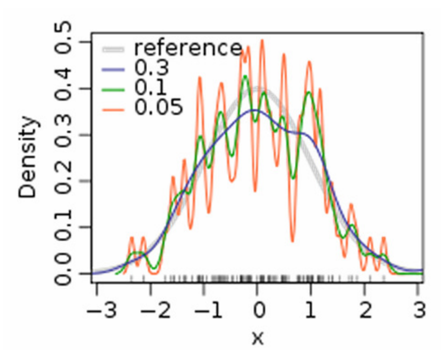
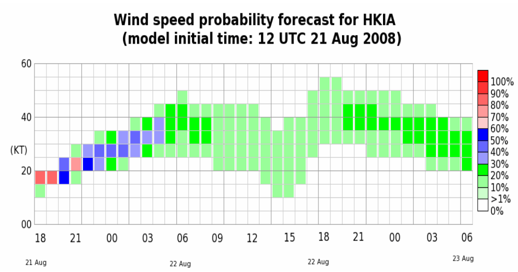


Fig.1 Kernel density estimation using different smoothing bandwidths, h.

2.2 Product layout

There will be a probability value associated with each pair of valid time and wind speed data. The 2-D probability table as mentioned in Section 2.1 is then "visualized" by constructing a colour filled 2-D grid map with x-axis being the valid time and y-axis the associated wind speed, similarly for crosswind. Fig.2 shows a sample layout of the probabilistic forecast products using the case of Typhoon Nuri in 2008. The corresponding probability map of TC forecast positions and the HKO's analysed best track for Nuri are shown in Fig.3 and Fig.4 respectively.

(a)



(b)

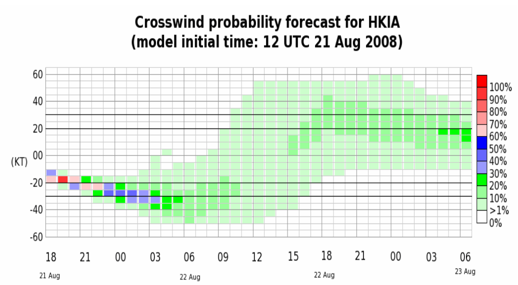


Fig.2 Time series for the probabilistic (a) wind speed forecast, and (b) crosswind forecast based on ECMWF EPS initialised at 12 UTC on 21 August 2008.

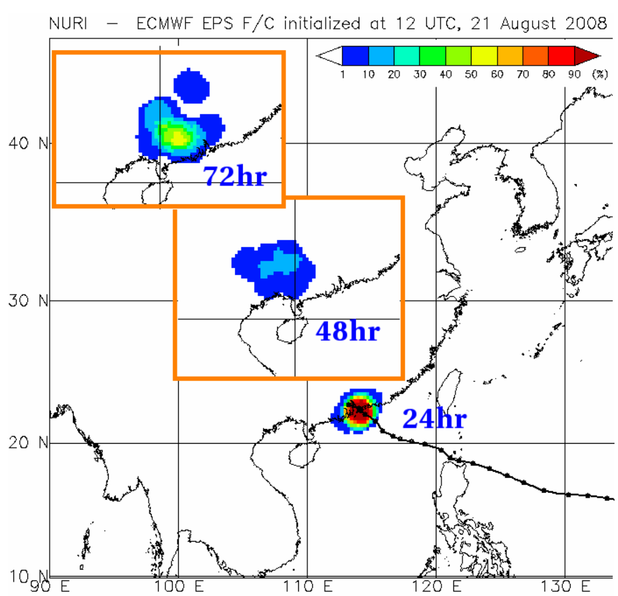


Fig.3 Probability map of 24-, 48- and 72-hour TC forecast positions based on the same model run as in Fig.2.

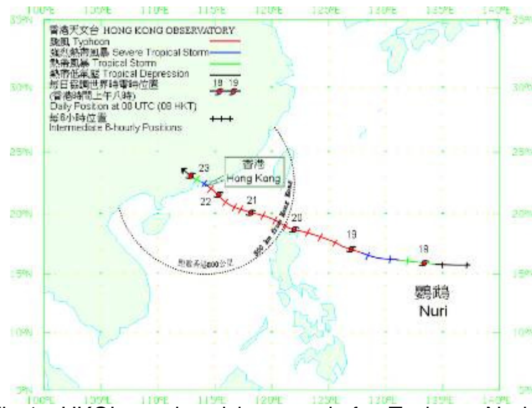


Fig.4 HKO's analysed best track for Typhoon Nuri in 2008.

Using Fig.2(a) as an illustration, the range of wind speed forecast in warm colours indicate higher probability of occurrence. The spread of the probabilistic forecast reflects the forecast uncertainties to a certain extent. As compared with the analysed best track of this TC case in Fig.4, it can be seen that the EPS forecasts gave a good indication of the forecast time of landfall and closest approach to Hong Kong at around 12-15 UTC judging from the "dip" in the wind speed distribution in Fig.2(a), and the change from large northerly crosswind (negative values) to southerly crosswind (positive values) in Fig.2(b). When Hong Kong lies within the inner core and near the TC centre, wind speed will be on the low side. The passage of TC to the east (west) of Hong Kong will bring northerly (southerly) crosswind to Hong Kong. Even though the spread of the forecast track is not large as seen from Fig.3, there could be a large difference in wind speed as Hong Kong lies in the coastal region. Winds may subside quickly shortly after the TC makes landfall near Hong Kong.

2.3 Comparison with EPS Meteogram

Prior to the development of the time series probabilistic products in Fig.2, there is another type of presentation of EPS forecasts made reference by the forecasters. Fig.5(a) shows the EPS Meteogram (Persson, 2001) for the same case as in Fig.2. It is a box and whisker plot (Fig.5(b)) showing the time series of the minimum, 25 percentile, median, 75 percentile and maximum of the 50 EPS members available.

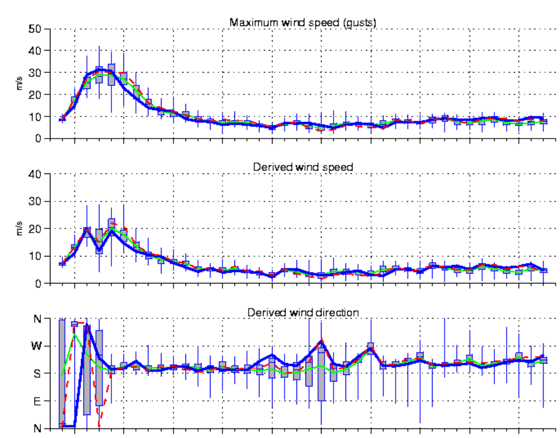


Fig.5(a) Sample of the ECMWF EPS Meteogram for 12 UTC 21 August 2008, using same data as in Fig. 2.

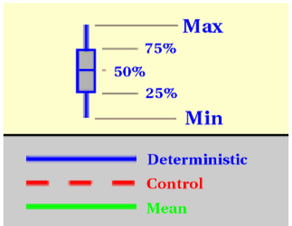


Fig.5(b) Meaning of the box and whisker plot in the EPS Meteogram in (a).

The EPS Meteogram is, in fact, also a form of probabilistic forecast as the span of the box and whisker can be interpreted as the forecast uncertainties. It contains information on the possibility of the occurrence of extreme events. However, detailed information on the PDF is missing. The product layout in Fig.2, however, can preserve information on the full spectrum of the probabilistic forecasts. Imagine a case when the EPS outputs cluster into two groups, one group very close to Hong Kong and the other far away. The EPS Meteogram will then show a time series of tall boxes indicating misleadingly a large divergence of all EPS members. Whereas the presentation of probabilistic forecast in Fig.2 is likely to show a bifurcation of ensemble forecasts in two clusters.

Yet another way to present the probabilistic forecast is to make a cross-section to the 2-D probability table. A time series showing the probabilistic forecast of wind speed reaching or exceeding certain thresholds may be useful for supporting decision making as it can be readily transformed into a binary forecast (go or no go) depending on the choice of probability threshold. Fig. 6 shows an example using different wind speed thresholds based on the same case as in Fig.2, but with a different presentation of the full spectrum of the PDF.

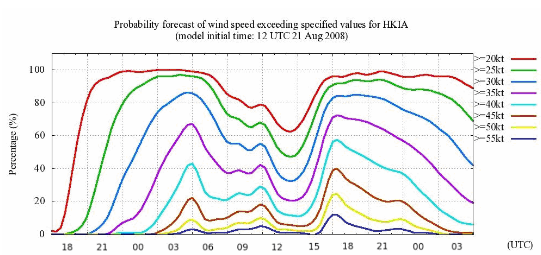


Fig. 6 Probabilistic forecast time series of wind speed reaching or exceeding specified values at HKIA.

2.4 *Calibration of wind speed forecast*

Model bias and errors are inevitable. Post-processing of the direct model output is thus necessary to minimize this problem. A relatively simple table-driven wind speed bias removal algorithm is adopted to calibrate the wind speed forecast.

The model wind speed bias is stratified by different groups of wind direction (E; W; N; S) and wind speed (< 10 kt; 10-20 kt; >20 kt) in different seasons (12 months). Segregation of winds into different directions in the bias calculation is necessary as HKIA is situated in an area of complex terrain which significantly affects the local wind speed for some wind directions. The bias correction will be applied to those forecasts in the corresponding group. The wind speed bias table will be updated annually using EPS data and the 10-minute mean wind observations at HKIA of the previous year.

When estimating the model bias of EPS, it is questionable that model climatology of individual member carries a physical meaning. For simplicity sake, the bias characteristics of the model ensemble mean is assumed to be similar to individual ensemble members and the bias of the model ensemble mean forecast of wind speed is calculated. The bias table so derived is then applied to each member forecast before constructing the 2-D probability table as mentioned in Section 2.1.

Fig. 7 shows samples of calibrated and non-calibrated probabilistic wind speed forecasts. The TC case of Koppu in 2009 (HKO, 2009) and the EPS run for 00 UTC 14 September 2009 were used in this example. The wind speed bias table was constructed based on the EPS data of 2008. The actual wind speed observations in the HKIA METAR report are plotted as black crosses and the span of the wind speeds recorded by the six anemometers on the two runways are indicated by the black segments. The ECMWF deterministic model forecast is also plotted in yellow solid line for reference. It can be seen from Fig.7 that after calibration, the actual 10-minute mean wind observations fell mostly in the range with the highest probabilities and the calibrated probabilities were generally closer to the actual observations than those from the direct EPS output.

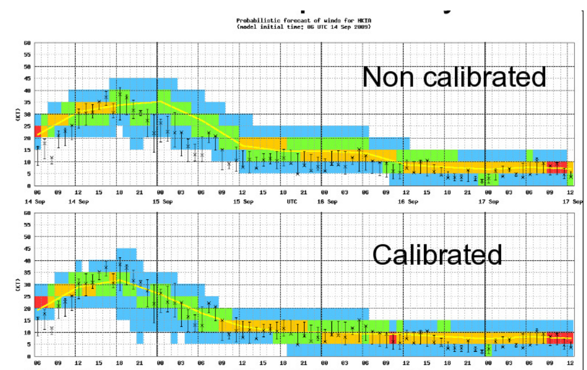


Fig. 7 Non-calibrated probabilistic wind speed forecast (upper) and calibrated one (lower) for Typhoon Koppu based on EPS forecasts initialized at 00 UTC 14 September 2009.

3. FORECAST VERIFICATION

To objectively assess the performance of the probabilistic forecast products, verification was conducted for all TC cases in 2009. All T+6 to T+72 hour forecasts valid for the times when TC Warning Signals were in force in Hong Kong were included in the verification dataset. Both the calibrated (based on 2008 wind speed bias table) and non-calibrated forecasts were verified.

During the verification, different probability thresholds were used to transform the probabilistic forecasts into deterministic, binary forecasts with respect to a preset wind speed criterion (i.e. the probabilistic product in Fig.6). Comparison with the METAR observations on the hour was then performed to derive the Probability of Detection (POD) and the False Alarm Ratio (FARatio). Part of the verification results is presented in Fig. 8 in the form of a Performance Diagram (Roebber, 2009) using 30 kt wind speed threshold. It appears that the probability forecast in the range of 20-30 % performed the best in terms of Critical Success Index (CSI), which are indicated by dashed grey lines in the figure. The calibrated probabilistic forecasts again outperformed the direct model outputs. The highest CSI was around 0.3 - 0.4.

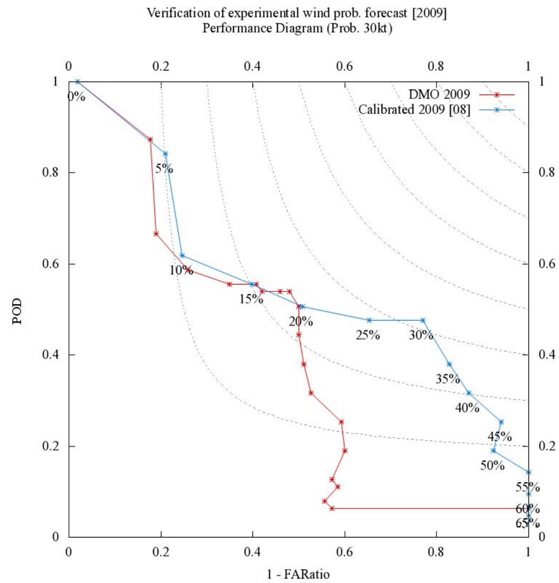


Fig. 8 Performance diagram for the probabilistic wind speed forecast for TC cases in 2009 based on a wind speed threshold of 30 kt.

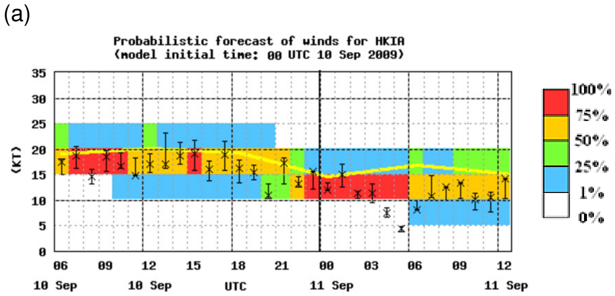
4. RECENT DEVELOPMENT

4.1 Enhancement of product layout

In response to user feedback, the color scheme of the probabilistic forecast products was simplified into four colour levels in Fig.9 as compared with the original in Fig.2. Though the levels contain less details, the new colour scheme seems to be more intuitive for interpretation of high and low probabilities. To enrich the information content in the product, near real-time wind observation data and the ECMWF deterministic model forecast are also included in the probabilistic product.

In the case of Tropical Storm Mujigae in 2009 in Fig.9, the actual 10-minute mean wind observations fell mostly in the range of the highest probabilities, which were also generally closer to the actual observations as compared with the deterministic model forecast (yellow line).

(a)



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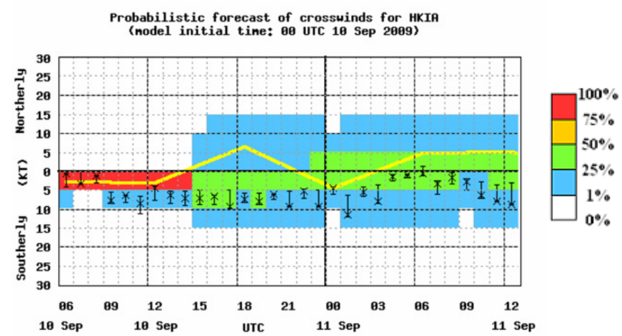

Fig. 9 Probabilistic (a) wind speed and (b) crosswind forecasts based on ECWMF EPS run initialized at 00 UTC on 10 September 2009 during the passage of Tropical Storm Mujigae. The meaning of the symbols can be found in Section 2.4.

4.2 Probabilistic forecast of TC distance from HKIA

To facilitate users' understanding of the nature of spread in the probabilistic wind forecasts, a new product of the probabilistic forecast of TC distance from HKIA (a sample in Fig. 10) is planned for trial in the 2011 TC season. It is a time series showing the probability of a TC at a certain distance to HKIA.

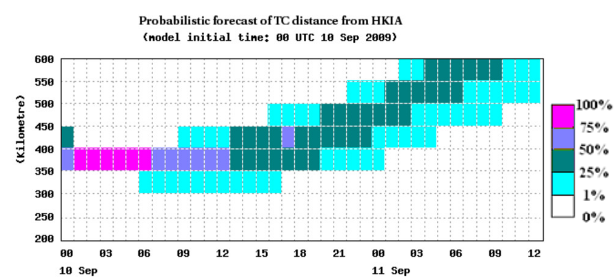

Fig. 10 Probabilistic forecast time series of TC distance from HKIA. The EPS data used are the same as in Fig. 9.

When used in combination, Fig. 9 and 10 can deliver the chances of a TC coming to the proximity of HKIA, and whether the spread in wind forecast is originated from diversified track forecasts or from the forecast timings.

To better understand and utilize these new probabilistic products, users may also make reference to the ECMWF strike probability map and the HKO TC forecast track.

5. FUTURE WORK

Limited by the size of the ensemble, as well as the performance of the model, the spread of probabilistic forecasts may not cover all possible scenarios and the actual situation may fall outside the span of the EPS. One way to tackle this problem is the combined use of different EPS of comparable model resolution and forecast performance to form a super ensemble system after appropriate bias removal. In addition to ECMWF EPS, HKO is also acquiring EPS outputs from the Japan Meteorological Agency (JMA) and the China Meteorological Administration. Their combined used with the ECMWF EPS will be explored in the future.

There is another way of predicting the probability of the occurrence of strong, gale force winds and significant crosswinds in Hong Kong using a combination of statistical and dynamical techniques (Lam 2004, Lau 2005). First, the TC forecast intensity and positions relative to HKIA are determined. Then, using the statistical relationship between the TC intensity, distance of the TC from HKIA and local historical wind data, the probability of occurrence of strong and gale force winds at HKIA can be derived. With the availability of individual forecasts from the EPS, the uncertainties in TC track and intensity forecasts can also be taken into account in the probabilistic forecasts. This method has the advantage of not being limited by the poor representation of local terrain problem in the NWP model. The model will contribute to providing reliable TC track and intensity forecasts. Methods to integrate the EPS forecasts into the above statistical and dynamical formulation will be further explored in the future.

6. CONCLUSION

Objective methods for generation of probabilistic wind speed and crosswind forecasts from ECMWF EPS outputs were developed for the Hong Kong International Airport. The visualization method of using a 2-D colour grid map can present a full spectrum of probabilities to users.

A simple calibration algorithm was employed to calibrate the probabilistic wind speed forecast by removing systematic model bias delineated by wind direction and speed in different seasons. Objective verification of the probabilistic forecasts using TC cases in 2009 showed that the calibrated forecast performed better with the highest CSI of around 0.3-0.4 within 72 hours forecasts.

Testing of calibration of probabilistic wind speed forecasts will continue with more data collected in the future. Additional probabilistic forecast products will be launched to the aviation users after seeking their feedback and communicating with them on the use and interpretation of the products. Tailor-made probabilistic products to facilitate user's risk assessment and decision making may also be explored.

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