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Application of Multi-platform Satellite Surface Wind Analysis in Aerodrome Wind Forecasting during the Passage of Tropical Cyclones

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APPLICATION OF "MULTI-PLATFORM SATELLITE SURFACE WIND ANALYSIS" IN AERODROME WIND FORECASTING DURING THE PASSAGE OF TROPICAL CYCLONES

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1. INTRODUCTION

Multi-platform Satellite Surface Wind Analysis (MSWA) provided by the National Oceanic and Atmospheric Administration (NOAA) utilizes data from multiple satellites (Knaff et al [1]). Its merit is that geostationary and polar satellite data are assimilated and data from different channels, such as infra-red, scatterometer and microwave probes, are integrated. The analyzed wind field updated at 6-hourly intervals (a sample in Figure 1) has referential and practical value in estimating the evolution and asymmetry of tropical cyclone (TC) wind structure and high wind radii. The product is particularly useful for TCs as conventional observations are sparse over the seas.

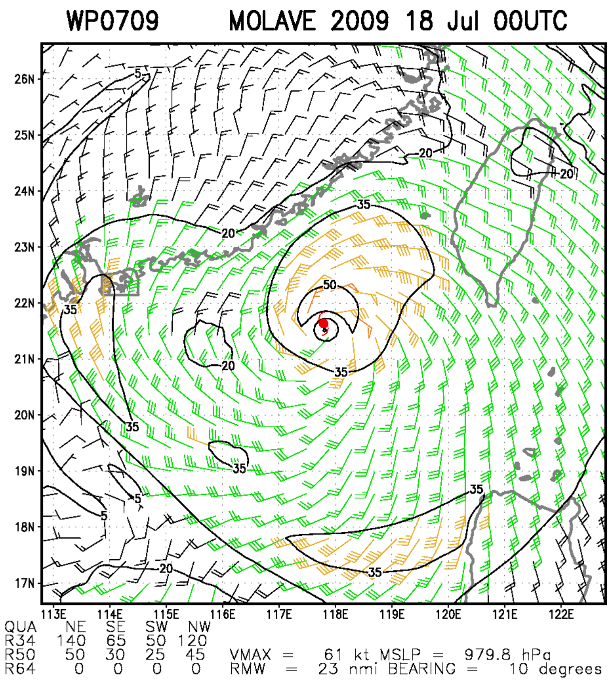

Figure 1 A sample wind field of MSWA.

In the first part of this paper, the reliability of the MSWA wind field and its practical value in local application were evaluated. Its performance was gauged against wind radii data during 2006-2008 contained in the best-track database of Regional Specialized Meteorological Center (RSMC) and Joint Typhoon Warning Center (JTWC). Fine tuning of the MSWA field towards local wind characteristics is also introduced.

In the second part, a multiple linear regression model based on MSWA data was established for estimating TC wind structure. With TC intensity, latitude, speed of movement and the radius of maximum sustained wind as inputs, the model estimates radii of strong, gale, and storm force wind in four quadrants.

A system for forecasting winds at the Hong Kong International Airport (HKIA) was developed using the regression model. Forecast of local wind is achieved by applying the model to estimate wind field using TC parameters available in the Observatory's TC warning bulletin for the shipping community. The performance of the forecasting system was assessed with TC cases in 2009.

2. SOURCE OF DATA

MSWA dataset used were 700 hPa wind fields of all TCs over the western North Pacific and the South China Sea during 2006-2009. The spatial resolutions were 20 km and 10 degrees respectively in the radial and azimuthal direction and the time resolution is 6 hours. There were totally 1,409 wind fields for 79 TC cases.

In the verification, the parameters in the single column method described in [1] were applied to reduce upper-air winds at the 700 hPa level to surface before the verification was conducted. Best tracks of JTWC and RSMC for TCs in 2006-2008 were acquired from their websites. In regard of local observations, 10-minute mean wind direction and speed as well as gust recorded at the anemometer R2C located at the central part of the northern runway of HKIA and the anemometer TMT located at Tai Mo To, an island about 4 km to the east of the Northern runway, were chosen. Station locations are shown in Figure 2.

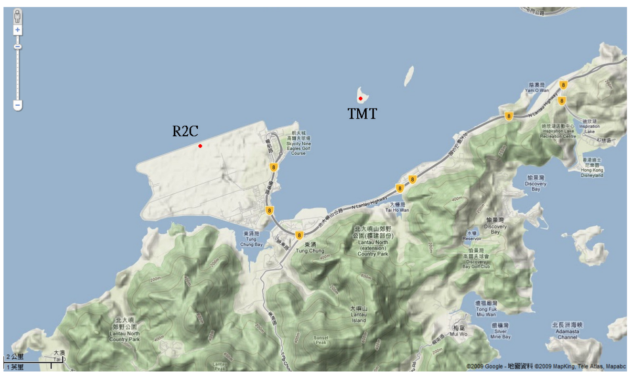

Figure 2. The location map of the anemometers R2C and TMT in the vicinity of HKIA.

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3. VERIFICATION OF MSWA DATA

3.1 Comparison of high wind radii

First of all, MSWA wind fields were divided into four quadrants, namely northeast, southeast, southwest and northwest, and the mean wind speed along the arc of radius r in each of the quadrants was computed to find the high wind radii in the quadrant. For example, gale radius (R34) is taken as the distance from the cyclone centre at which wind speed falls below 34 knots for the first time. Accordingly, the high wind radii in each quadrant were computed. It was noted that R64, R50 and R33 were accompanied with the best-track data provided by JTWC whereas R50 and R30 were accompanied with the best-track data provided by RSMC.

The high wind radii of MSWA were compared with those of JTWC and those of RSMC, and the results were tabulated in Table 1 and Table 2, respectively. From the tables, it can be seen that the deviation was around 10% of the mean value of JTWC and around 30% of the mean value of RSMC. High wind radii of MSWA were generally larger in the northeast (NE) quadrant and smaller in the southwest (SW) quadrant than those of JTWC and RSMC. These deviations might indicate over-estimation and under-estimation of the high wind radii of MSWA over the NE and SW quadrants respectively. This is believed to be associated with the way MSWA processes the speed of TC movement. In general, tropical cyclones track north-westward over the South China Sea. Accordingly, the effective high wind radii in the NE quadrant were stretched and that in the SW quadrant were compressed.

It can be seen from Table 1 and Table 2 that the deviations of high wind radii near the centre, such as R64 and R50, were less significant while those for gale wind or below were more significant. The MSWA data were generally closer to the JTWC analysis.

R64

Quadrant:	Northeast	Southeast	Southwest	Northwest
Number of data	468	446	421	451
Deviation	15	8	0	6
Root mean square error	28	24	19	22
JTWC mean value	72	69	67	70

R50

Quadrant:	Northeast	Southeast	Southwest	Northwest
Number of data	675	658	609	634
Deviation	16	6	-4	6
Root mean square error	42	38	25	31
JTWC mean value	105	101	96	100

R34

Quadrant:	Northeast	Southeast	Southwest	Northwest
Number of data	929	928	872	878
Deviation	16	-6	-26	-4
Root mean square error	79	77	56	58
JTWC mean value	195	184	175	182

Table 1: Comparison of wind radii between MSWA and JTWC, units in km

R50

Quadrant:	Northeast	Southeast	Southwest	Northwest
Number of data	643	635	608	627
Deviation	12	-3	-11	2
Root mean square error	45	46	43	41
RSMC mean value	119	120	115	114

R30

Quadrant:	Northeast	Southeast	Southwest	Northwest
Number of data	607	644	537	620
Deviation	-71	-97	-114	-79
Root mean square error	127	153	145	117
RSMC mean value	291	309	268	265

Table 2: Comparison of wind radii between MSWA and RSMC, units in km

The comparison result might suggest that the wind field of MSWA possesses reference value and the high wind radii obtained from the analysis could be used for studying TC structure.

3.2 Comparison with wind speed at the Hong Kong International Airport (HKIA)

The general performance of MSWA over a large spatial scale could possibly be inferred by comparing the high-wind radii in section 3.1. To assess its practical usefulness in the local territory, wind speeds recorded at the anemometer R2C located at the middle of the northern runway of the HKIA were compared with the MSWA winds.

Although R2C is a fixed station, as and when the TC moves, R2C station record at different times can be regarded as the wind at different locations within the TC circulation. To ensure the representativeness of the result, the verification dataset is limited to those with TCs centred within 400 km or less from R2C. Under this condition, around 50 MSWA wind fields during 2006-2008 were available for verification. Hourly wind data were generated from time interpolation of MSWA wind fields at 6-hourly intervals in accordance with the best-track data of the Hong Kong Observatory. The winds from MSWA were reduced to surface following the single column method as mentioned in section 4.1 before comparison. As a result, 334 pairs of data were obtained for the verification. The verification results show a mean bias of 1.9 knots and a root mean square error of 7 knots in wind speed and a right bias of 13 degrees in wind direction.

4. CORRECTION TO MSWA WIND FIELD

4.1 Single column method

In accordance with [1], winds at 700 hPa were reduced to surface using a "single column method". The reduction algorithm is as follows: wind direction backs 20 or 40 degrees towards the TC centre depending on whether the underlying surface is the sea or the ground; wind speed multiplied by an attenuating factor depending on whether the underlying surface is the sea or the ground as well the distance from the TC centre. Verification using local winds shows that MSWA has systematic bias in both wind direction and speed, which hinted that the parameters in the single column method described in [1] were not optimized for the complex local environment. To address this issue, local wind observations were used to fine tune the parameters in the single column method.

In addition, the process of reduction of 700 hPa wind speed to the surface was further decomposed into two steps:

firstly, 700 hPa wind speeds were converted to wind speeds as measured at a standard anemometer on the surface according to the WMO specifications [2]; secondly, the values were further adjusted to the local anemometer based on the actual roughness at the wind station.

4.2 Wind speed correction based on station exposure

When the exposure of the anemometer (represented by surface roughness Z0) differs from the standard requirement of Z0=0.03m [2], Wieringa [3] put forth that "standard" observational data could be reconstructed, according to a logarithmic vertical distribution of wind speed:

$$v_{measured} * f_{corr} = v_{std}$$
$$f_{corr} = 0.76 \frac{4.1 - \ln Z_0}{\ln h - \ln Z_0} \quad (1)$$

, where v_{std} represents the wind speed measured at a height of 10 m above a flat lawn (Z0=0.03 m) in an exposed environment, h is the elevation of the anemometer, f_{corr} the correction factor.

Values of the surface roughness Z0 at R2C for different wind directions as obtained from gust analysis [3] were tabulated in Table 3 below.

Wind direction (degree)	<G> Gust factor	Z_0(metre) Degree of roughness	f_corr Correction factor
0-45	1.35	0.04	1.0
45-90	1.36	0.05	1.0
90-135	1.35	0.04	1.0
135-180	1.49	0.20	1.1
180-225	1.49	0.20	1.1
225-270	1.35	0.04	1.0
270-315	1.33	0.04	1.0
315-360	1.25	0.004	0.9

Table 3: Roughness lengths and the corresponding adjustment factor in different wind directions at R2C as obtained from gust analysis

The Z0 values for northeasterlies, northerlies and southeasterlies are very close to 0.03 m. R2C data of these wind directions were extracted and regarded as wind speed on a standard surface. Such data were matched with MSWA 700 hPa wind strength to adapt the single column formula adopted by Knaff[1]. In view of the uncertainties in TC positions and the possible shearing off of its centre from the vertical axis, all data associated with R2C lying within the maximum wind radius $R_{700\max}$ of MSWA 700 hPa wind field were not used in the tuning. Subject to the above selection criteria, among the 334 data points, 225 remained usable. Subsequent to the adaptation, the optimized parameters are as follows:

$$v_{surface} = \begin{cases} 0.55 * v_{700} & r > 230km \\ (0.55 + 0.2 * \frac{r-50}{230-50}) * v_{700} & 230km \geq r \geq 50km \\ 0.75 * v_{700} & r < 50km \end{cases} \quad (2)$$

Figure 3 compares the parameters before and after the tuning. It can be seen that the new parameters render weaker attenuation of wind speed near the TC centre but stronger and quicker attenuation of wind speed at the periphery of the TC.

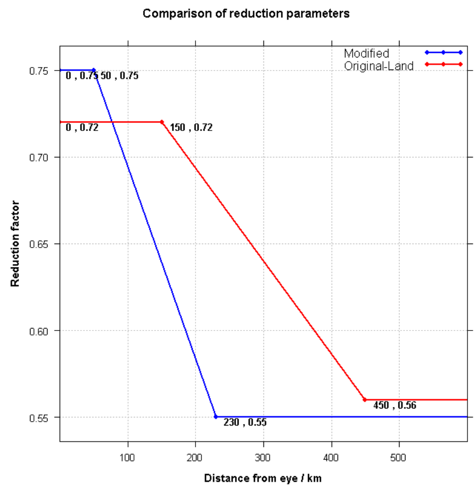


Figure 3. Comparison of the single column parameters before and after tuning.

4.3 Local wind adjustment and validation

Equation (2) was applied to reduce 700 hPa wind speed to the standard surface for all the 334 data points. Then, the reduced wind speeds were adjusted to those at the anemometer using equation (1), and the resultant values were subsequently verified against the observational data at R2C. In the actual computation, the wind directions at R2C were simply taken as the wind directions on the 700 hPa level veering 25 degrees towards the cyclone centre. Such adjustment value was obtained from offsetting the deviation in the method adopted by Knaff [1] (veering 40 degrees). The new verification results (Table 4) show that application of equation (1) for exposure adjustment has no effect on R2C. Detailed analysis might hint that the prime reason might be the infrequent southerlies at R2C in TC cases during 2006-2008, so that winds which had blown over a relatively rough surface were infrequent during the period of study. However, since the method of applying equation (1) and equation (2) is more general, it still shows merit over the method of Knaff[1] in respect of the applicability to other anemometer stations. This was verified by using another anemometer at Tai Mo To (TMT), a small island located near the airport.

Gust analysis was carried out for TMT to obtain the factor for exposure correction. Then, equation (2) basing on R2C was applied to reduce MSWA wind speeds on the 700 hPa level to the standard surface, followed by adjustment for the TMT wind speed using equation (1). The resultant values were compared with observational data and are tabulated in Table 4. It shows that the new method could enhance the capability of estimating local wind speed from MSWA wind field at 700 hPa.

R2C

Method	Deviation in wind speed (kt)	Root mean square error in wind speed (kt)
Knaff[1] single column method	1.9	7.1
Adjusted single column method (equation (1))	-0.3	6.4
Adjusted single column method together with exposure correction for anemometer (equation (1)+equation (2))	-0.5	6.4

TMT

Method	Deviation in wind speed (kt)	Root mean square error in wind speed (kt)
Knaff[1] single column method	2.5	8.3
Adjusted single column method (equation (1))	2.0	7.5
Adjusted single column method together with exposure correction for anemometer (equation (1)+equation (2))	-0.5	7.1

Table 4: Verification results of using different methods to reduce the wind speed from 700 hPa to the surface

5. MULTIPLE LINEAR REGRESSION MODEL FOR TC HIGH WIND RADII

The verification results in Section 3 show that the MSWA wind could serve as a good reference for TC wind structure. An attempt was made to use it as the basis for modeling the TC high wind radii using key TC parameters including TC intensity and movement. The aim is to provide objective guidance on TC wind structure forecast.

To model the TC wind structure, a multiple linear regression model was developed for estimating 700 hPa wind field based on the TC forecast track and intensity. We divided the wind field into four quadrants, namely front, rear, left and right, with respect to the TC movement, then by the wind radii of 64, 50 and 34 knots in each of the quadrants. These were chosen as the response variables. The maximum wind speed at 700 hPa (in knots), the latitude of the TC centre, the maximum wind radius at 700 hPa level (in kilometres), and the TC speed of movement in past 6 hours (in knots) were chosen as regressors. MSWA wind fields in 2006-2008 were used in the regression to produce the following 12 regression equations for computing high wind radii at the 700 hPa level for each of the quadrants:

front quadrant:

$$R_{64} = 2.1\lambda + 1.76V_{700\max} + 1.31R_{700\max} - 156$$

$$R_{50} = 3.4\lambda + 2.31V_{700\max} + 1.30R_{700\max} - 169$$

$$R_{34} = 2.2\lambda + 3.03V_{700\max} + 1.31R_{700\max} - 90$$

rear quadrant:

$$R_{64} = 1.2\lambda + 1.37V_{700\max} + 1.14R_{700\max} - 101$$

$$R_{50} = 1.4\lambda + 1.79V_{700\max} + 1.34R_{700\max} - 106$$

$$R_{34} = 2.0\lambda + 3.18V_{700\max} + 1.69R_{700\max} - 145$$

left quadrant:

$$R_{64} = -0.3V_{tc} + 1.1\lambda + 1.43V_{700\max} + 1.21R_{700\max} - 109$$

$$R_{50} = -1.3V_{tc} + 2.2\lambda + 1.95V_{700\max} + 1.25R_{700\max} - 120$$

$$R_{34} = -2.4V_{tc} + 2.6\lambda + 2.28V_{700\max} + 0.99R_{700\max} - 45$$

right quadrant:

$$R_{64} = 1.1V_{tc} + 2.0\lambda + 1.65V_{700\max} + 1.30R_{700\max} - 151$$

$$R_{50} = 1.0V_{tc} + 4.0\lambda + 2.28V_{700\max} + 1.24R_{700\max} - 177$$

$$R_{34} = 1.8V_{tc} + 4.4\lambda + 3.65V_{700\max} + 1.25R_{700\max} - 140 \quad (3)$$

The regressors were chosen in view of the typical positive correlation between high wind radii and the radius of maximum wind (Weatherford et al [4]). The relationship between the size of a TC and its latitude refers to Merrill[5]. The speed of TC movement is also taken as a regressor only for the left and right quadrants in consideration of the asymmetric effect in these two quadrants due to superposition of the speed of movement onto the circulation. With the direct use of MSWA 700 hPa wind field in the regression, not only the extra error in the single column method could be omitted, but the complex asymmetric structure due to underlying sea and land near the coast could also be disregarded.

6. APPLICATION TO WIND FORECASTING

Combining the above, high wind radii in each of the quadrants can be predicted by feeding forecast variables into the regression equations so that the entire 700 hPa wind field is generated. Then the improved single column method is applied to reduce upper-air winds to local anemometer readings in order to forecast surface wind at a given location and time. Based on this methodology, a Multi-platform Satellite Wind Analysis and Forecast System (MSWAFS) was developed. The operation of the system is illustrated in Figure 4. High wind radii are obtained from the regression equations based on the TC forecast position and intensity. Next the entire wind field is constructed with real-time corrections using the latest MSWA wind field. Finally, forecasts of wind direction and speed for each hour during the following 72 hours at the reference location are obtained.

(a)

(b)

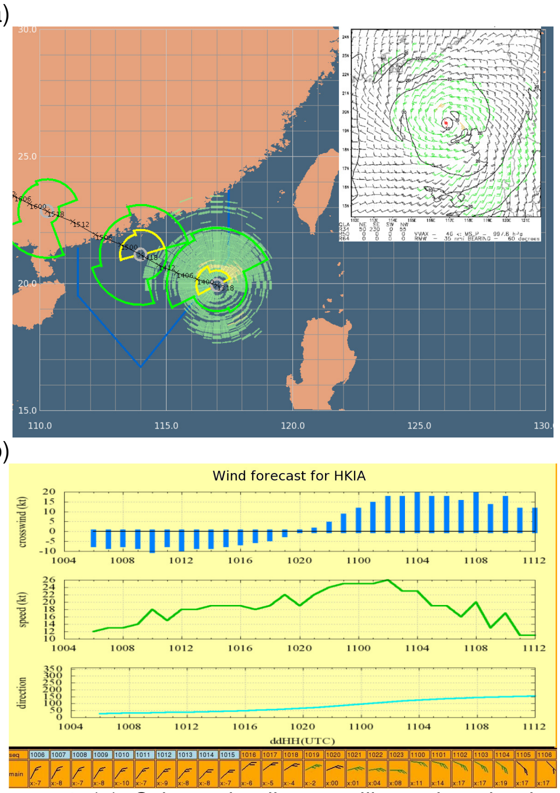


Figure 4 (a) Schematic diagram illustrating the basic operation of MSWAFS. Estimation of high wind radii (yellow for gale; green for strong wind) in different quadrants for the following 72 hours using the regression model based on the TC forecast track (black line). (b) Forecast wind direction and speed for each hour during the following 30 hours at HKIA from the system output.

The system consists of the following modules.

6.1 Obtaining TC forecast parameters for the regression model

The latitude and speed of TC can be obtained directly, or through interpolation, from the HKO's TC forecast. However, to obtain the maximum wind and maximum wind radius on the 700 hPa level, conversion is needed.

The HKO's TC forecast intensity refers to the maximum 10-minute sustained wind speed near the surface (hereafter termed "maximum surface wind speed"). Statistics using HKO's TC best track database show that it correlates linearly with MSWA 700 hPa maximum wind (slope:0.9; coefficient of determination (R^2):0.87). Accordingly, 700 hPa maximum wind strength can be obtained by dividing the maximum surface wind speed with 0.9.

It should be noted that MSWA 700 hPa maximum wind strength refers to the maximum wind speed among wind speeds on the set of concentric circles extending from the cyclone centre, and the radius of that corresponding concentric circle is the 700 hPa maximum wind radius. This is not the same as the way high wind radii in different quadrants are computed. In addition, due to the difference in the number of data points and sampling method, the relationship between such maximum wind speed and maximum surface wind speed is different from equation (2).

In regard of the 700 hPa maximum wind radius, a power law relationship between maximum wind speed and maximum wind radius is used. With the use of the MSWA data during 2006-2008, the following empirical equation is obtained:

$$R_{700\max} = 1046 * V_{700\max}^{\;-0.75} \qquad (4)$$

In the equation above, the wind radius and the wind strength are respectively in units of kilometres and knots.

6.2 Estimation of wind profile using high wind radii

Different high wind radii at the 700 hPa level are used to produce a wind profile along the radial direction from the cyclone centre in each of the four quadrants. For winds within the maximum wind radius, wind speed is assumed to decease linearly to nullity towards the centre. For winds outside the maximum wind radius, the high wind radii are also assumed to decrease linearly. As the coverage of the regression equations limits to R34, at the periphery, the wind speed is assumed to decrease at a rate half of that between R50 and R34 until it reaches 22 knots at R22. In case that the TC is not intense enough so that R50 is not obtainable from the regression equations, then R22 is taken as twice of R34. Beyond R22, the wind speed is set to be 10 knots at a distance of 900 kilometres from the cyclone centre. Reference has been made to a typical Rankine Vortex [6] for the above description of wind profile along the radial direction.

It first appears that wind strength outside R34 is rather arbitrary. However, since the wind profile is representing upper-air wind at the 700 hPa level, winds of 22 knots, when being reduced to surface winds, become 10 knots or so. As such, the impact on forecasting should not be significant in practice. In fact, MSWAFS does not output forecast of wind strength for TCs at a distance of 400 kilometres away or more from the anemometer (R2C).

Based on the four wind profiles, wind speed at any point R from the centre can be interpolated linearly along the arc of radius R. Hence, the entire wind field can be generated. It should be noted that the resultant wind field consists of only tangential winds. As the single column method is applied to reduce the winds to the surface, winds on the ground are veered 25 degrees in a direction towards the centre and those on the sea are veered 20 degrees as per [1].

6.3 Real-time MSWA observational data and real-time offsetting of regression model

The method in Section 6.1 and 6.2 can be used to obtain 700 hPa wind field for each hour from the initial time (T+0) up to 72 hours ahead (T+72). Equation (1) and equation (2) can then be applied to estimate the wind direction and speed at R2C for each hour. As the coefficient of determination (R^2) is only around 0.5 in the regression analysis for high wind radii at the periphery, for a more accurate wind field, the latest MSWA 700 hPa wind field is subtracted from the wind field estimated by 6.1 and 6.2 to obtain a real-time correction field to be applied for offsetting all forecasts of 700 hPa wind for T+1 to T+72.

Figure 5 compares the forecast performance with and without real-time correction. HKO's best-track data for 2006-2008 were used in the verification. It can be seen that real-time correction can effectively increase forecast accuracy for forecasts within 24 hours, with root mean square error falling from around 8 knots to 6 or 7 knots. However, application of the correction field yielded larger error beyond 40 hours. It is understandable because correction at T+0 should not be applicable to long range. In operation environment, the real-time correction field is applied to forecasts within 30 hours.

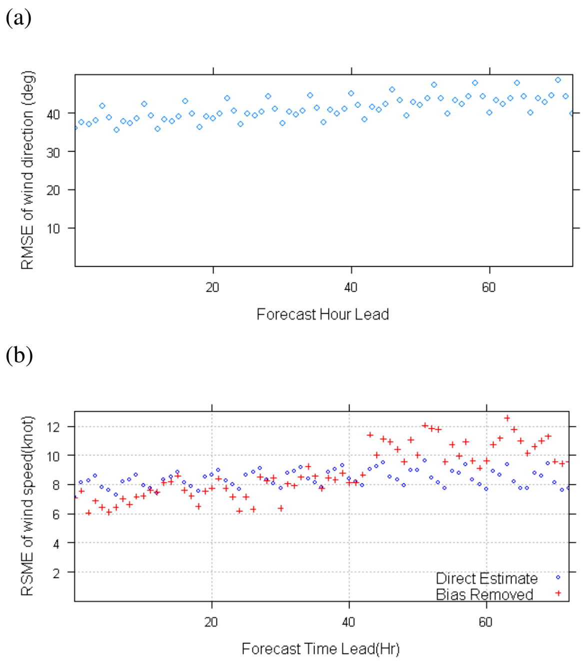


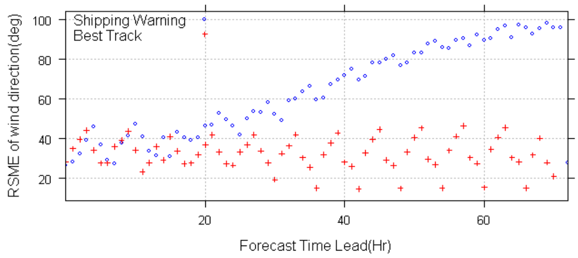
Figure 5 Verification results of MSWAFS during 2006-2008. (a) Wind direction, and (b) wind speed. In (b), blue circles represents forecast from regression model, red cross is the output when the correction field derived from the latest MSWA wind has been applied.

7. VERIFICATION OF MSWAFS IN 2009

In 2009, five TCs entered into the 400-kilometre range of Hong Kong. Taking R2C as the reference anemometer, two separate verifications have been conducted, one using HKO's TC forecasts and the other using HKO's best-track data. The purpose is to study the effect of forecast uncertainties and to assess the performance of the system in an objective way. Figure 6 shows the plot of root mean square errors.

With the use of best-track data, the TC positions and intensities are regarded as perfectly accurate for verification purpose. The root mean square errors in the system forecasts of wind direction were 30 to 40 degrees. Using the forecast tracks, the error significantly soared as the forecast range extended beyond 24 hours. As such, the errors in forecasts for a time period longer than 24 hours ahead should be mostly attributed to the errors in the forecast tracks.

In regard of wind speed forecast, the root mean square errors for T+0 and T+72 hours are 5 knots and 7 knots respectively when using the best-track data. On the other hand, the root mean square error for T+72 hours increased to around 9 knots when forecast track data were used.



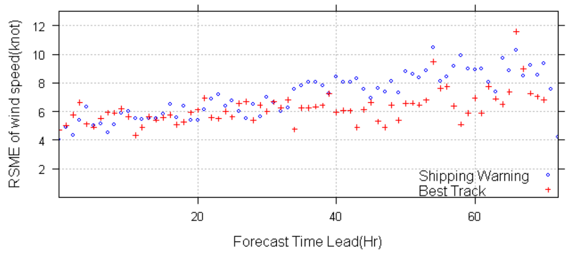


Figure 6 Verification results of MSWAFS in 2009

8. CONCLUSIONS

High wind radii estimated using MSWA wind fields over the western North Pacific and the South China Sea during 2006-2008 were compared with those extracted from the best-track databases of JTWC and RSMC. The comparison study shows that the MSWA wind radii deviated from those of JTWC by around 10% and from those of RSMC by about 30%.

To improve the accuracy of applying MSWA to local wind speed, the parameters of the single column method in MSWA were customized with the data recorded by the anemometer R2C at the HKIA. The correction method for the degree of exposure of the anemometer was also discussed.

Based on MSWA, a regression model was established to estimate the wind radii for 64, 50 and 34 knots at the 700 hPa level in the front, rear, left and right quadrants with respect to the direction of TC movement, using the intensity, latitude, speed of movement and the maximum wind radius of the TC as inputs.

MSWAFS, a forecast system developed based on regression equations and adjustment for local winds, is applied to wind forecasting at HKIA in TC situations. The system makes use of HKO's TC forecast positions, intensities, together with latest MSWA wind field at the time to predict wind direction and speed for each hour in the following 72 hours at R2C as and when a TC is within 400 kilometres of Hong Kong.

Verification results using 2009 TC data show that the root mean square errors of MSWAFS in the 24-hour, 48-hour and 72-hour wind speed forecasts were around 7 knots, 8 knots and 9 knots respectively.

The MSWAFS will be tested in the future to predict wind strengths at the other locations in Hong Kong. However, with the cessation of QuikScat data in November 2009, which is a major component in the MSWA product, the statistics and performance of MSWA is expected to change and more data are needed to be collected to adapt the MSWAFS model accordingly.

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