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# An algorithm for generating location-specific NWP total cloud cover forecast with potential application to sea breeze forecast at the Hong Kong International Airport

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# An algorithm for generating location-specific NWP total cloud cover forecast with potential application to sea breeze forecast at the Hong Kong International Airport

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## Abstract

This paper describes a post-processing algorithm based on objective consensus of global and regional NWP model outputs to produce the location-specific total cloud cover forecast. The algorithm employs down-scaling, ensemble, and model output statistics (MOS) weighting techniques with reference to the available cloud cover observations on-site or nearby. The post-processed forecast of cloud cover was verified against human observations and found to be satisfactory and outperformed the forecasts from individual model. The improved cloud cover forecast over the grid of the Hong Kong International Airport is also ingested into an empirical sea breeze forecast model used at the Airport Meteorological Office of HKO for assessing its contribution in the prediction of sea breeze occurrence during the day. Test results for 2013 and 2014 showed that it improves the accuracy of sea breeze forecast with a higher POD and lower FAR, resulting in a raise of CSI from 0.51 to 0.56.

## 1. Introduction

The Hong Kong Observatory (HKO) has developed a site-specific multi-model consensus forecast system called the objective consensus forecast (OCF) in 2011. In 2014, the OCF is extended to include cloud cover forecast to assist forecaster's assessment on the state of sky. A potential use of OCF cloud cover forecasts is its ingestion into the sea breeze prediction model that the HKO has been using for predicting sea breeze occurrence at the Hong Kong International Airport (HKIA). With test run on past data, it has been found that with the use of OCF cloud cover forecasts, the accuracy of sea breeze predictions could be improved. In this paper, a detailed description of the OCF technique is given in Section 2. Section 3 of this paper firstly gives a brief introduction on the sea breeze prediction model and subsequently explains how OCF cloud cover forecasts are ingested into the model for testing. The results of the test runs are showed in Section 4. The last section, Section 5, of this paper is reserved for a summary of and some discussions on this paper.

## 2. Forecasting cloud cover using the objective consensus approach

In the past decades, there have been significant improvement in numerical weather prediction (NWP) model due to improvements in model physics, model resolution and data assimilation process. However, it is generally known that forecasts from a single model would have their own model bias, and by using a multi-model ensemble approach, the individual model bias could be reduced. The idea of objective consensus forecast (OCF) is to apply post-processing technique and combine multi-model output determined objectively by weightings on past performance. The HKO has developed a site-specific, Kalman-filtered and past-performance weighted multi-model consensus forecast [1]. Five weather elements including temperature, dew point, relative humidity, wind speed and wind direction are available in OCF system.

To assist forecaster's assessment on the state of sky, the OCF system is extended to include cloud cover. However, as cloud cover forecast is a bounded variable, expressed in percentages (0 to 100), and cloud cover observations are discrete variables, expressed in oktas (0 to 8), the use of Kalman filter to remove bias and the past performance determined by mean absolute error is not appropriate. Therefore, another algorithm on post-processing and weighted performance consensus forecast tailored for cloud cover forecast is introduced in this paper.

## 2.1 Data

The following four models are used to construct OCF, namely ECMWF, JMA, Meso-NHM and ECMWF EPS. Meso-NHM is the operational regional limited model in HKO [2]. For ECMWF EPS, the average and median of the forecasts from all 51 ensemble members are taken to become "EPS Mean" and "EPS Median". Table 1 shows the model data used in constructing OCF cloud cover forecasts.

To determine the past performance of the various models, cloud cover observations reported in units of oktas are used. However, since cloud cover observations currently still relies on human observations, therefore it is only available at two stations, namely HKO and HKIA.

Cloud cover consensus forecasts are implemented in 15 stations (shown in Figure 1) for potential application onto the public Automatic Regional Weather Forecast in Hong Kong website (http://maps.weather.gov.hk/ocf/index_e.html).

## 2.2 Methodology

### 2.2.1 Post-processing of model cloud cover forecast

The model cloud cover forecast is interpolated spatially from individual model grid onto station location using bilinear interpolation. The time resolution for the consensus forecast developed is at hourly interval. However, as shown in Table 1, only Meso-NHM has hourly forecast data, the other models have forecasts in time steps of 3 or 6 hours. These 3-hourly or 6-hourly data would be linearly interpolated in time to produce hourly forecasts.

### 2.2.2 Determining past performance of individual models

Currently for elements like temperature, dew point, the past performance of individual model is determined by calculating the mean absolute error in the last 30 days. However, as cloud cover observations are discrete categories from 0 to 8 expressed as oktas and have a seasonal skewed distribution, the past performance based on the absolute value of the model output is not desirable [3] and only have limited meaning in terms of its categorical performance.

To determine the performance of cloud cover forecasts, we introduced a skill score metric to represent the forecast skill. Forecast that comes within ± 1 okta of the observed cloud cover is considered as correct (i.e. a hit).  To account for the seasonal dependency of cloud cover, the past performance is determined by using observation data in the last year. The detailed calculation is as follows:

1. The model forecast data in units of percentages (%) is first converted to cloud cover in units of oktas using the lookup table (Table 2) to prepare for comparison with observations.
2. For each category in oktas (from 0 to 8), count the Hit/Miss/False Alarm/Correct Negatives of forecast. Figure 2 shows an example for formulating the counts for category 7. Then, the Hit/Miss/False Alarm/Correct Negatives for all categories are combined to show the performance of forecasts across different categories.
3. A score called Symmetric Extreme Dependency Score (SEDS) was introduced to determine the skill of model forecasts. SEDS measures the association between forecast and observed events; it is equitable for large samples, transpose symmetry, less susceptible to hedging and can be used

for un-calibrated forecasts [4]. The equation of SEDS is shown below and the a, b, c, d variable is defined in Figure 2.

$$SEDS = \frac{\ln q + \ln p}{\ln(\frac{a}{n})} - 1$$

where $q = \frac{a+b}{n}$ , $p = \frac{a+c}{n}$ , $n = a + b + c + d$

### 2.2.3 Weighting forecast data

The OCF cloud cover is constructed by using the forecast output between various models and weighted according to their SEDSs. The SEDS is calculated separately for 00UTC and 12UTC. For each model run, the skill score is calculated according to past one year's performance and the score is updated in every run. To account for the difference in the performance of models at various lead times, the SEDS is grouped by forecast day. That is, model forecast hour from 0 to 24 uses day 1 score, model forecast hour from 24 to 48 uses day 2 score, etc.

### 2.2.4 Producing station-specific forecast

Since observed cloud amounts are only available in HKO and HKIA, SEDSs at other stations are computed using either HKO or HKIA's observation as actual depending on which of the two is closer to the site under consideration. A station-specific forecast is then generated following the same weighting method as described above.

## 2.3 Verification results

Figure 3 shows the root mean squared error (RMSE) of the forecast cloud cover for OCF and different individual models verified from November 2013 to 2014 in HKIA. It is observed that the OCF forecast generally exhibits the lowest

RMSE among the models, only ECMWF EPS Mean sometimes have comparable skill.

To understand the categorical performance of cloud cover forecasts, a separate verification using the oktas system (0 to 8) as the categories was set up (reverse conversion using Table 2). The accuracy was determined as the proportion of correctly forecast within ± 2 oktas. Table 3 shows the accuracy score for different individual models and OCF. From Table 3, OCF shows the highest accuracy of over 80% for the first three days and thus it also outperformed the individual models under categorical verification schemes.

## 3. Ingesting forecast cloud cover into sea breeze forecasting model

### 3.1 Introduction on SBI

Since 2005, the Airport Meteorological Office (AMO) of HKO has been using Sea Breeze Index (SBI) to assess the likelihood of sea breeze occurrence at the HKIA. Originally, the assessment was made once daily at 0530 HKT (Hong Kong Local Time) for the likelihood of sea breeze occurrence on the day [5]. In the last couple of years, a number of enhancements have been made. SBI-based assessments updated half-hourly during 0500-0630 HKT are referenced by the aviation forecaster for the issuance of the terminal aerodrome forecast (TAF) at 07 HKT. Basically, SBI is given by the following simple formula [6]:-

$$\text{SBI} = \frac{\pm U^2}{\Delta T} \qquad (1)$$

where U is the speed of offshore wind; ΔT is the temperature differential between air over land and sea surface. With equation (1), one can find out the threshold value of SBI (termed "critical SBI", SBIc) that best describes the critical situation of sea breeze occurrence/non-occurrence from historical data.

In principle, as soon as $SBI_c$ is known, one can compute SBI, with $U$ and $\Delta T$, case by case to see whether SBI would exceed $SBI_c$ or not in order to assess the likelihood of sea breeze. In case that SBI exceeds $SBI_c$, sea breeze would be unlikely to occur. For the HKIA, the value of $SBI_c$ has been found to be 7 (in unit of $m^2s^{-2}K^{-1}$). This implies that sea breeze would be unlikely to occur at the HKIA if SBI exceeds 7.

However, SBI itself bears no inherent predictive capability at all as both $U$ and $\Delta T$ are past observations. To confer SBI with predictive capability for predicting sea breeze at the HKIA, we base our SBI computation on the following parameters:-

$U$: the latest east-component of wind speed at the HKIA

$T_{land}$: the maximum air temperature at the HKIA (forecast or observed, whichever is higher)

$T_{sea}$: 24-hour running average air temperature over sea surface, which is determined by the mean value of air temperatures recorded by three weather buoys to the west of the HKIA

such that $T_{land} - T_{sea} = \Delta T$. The parameters have been carefully chosen in consideration of various practical factors such as availability of information in the operational environment and stability of the outputs, etc. The predictive capability is mostly due to the adoption of forecast maximum air temperature at the HKIA for $T_{land}$. Since forecasts of air temperature over sea surface are not available, 24-hour running average air temperature over sea surface is used as a proxy for $T_{sea}$. (In the past, we used sea surface temperature measured at North Point at 1900 HKT in the previous evening as the proxy which is even more remote in both distance and time). For $U$, we assume persistence and keep on adopting the latest east-component of wind speed at the HKIA.

### 3.2 Potential use of forecast cloud cover in sea breeze prediction

On top of the "SBI-criterion" (i.e. whether SBI>7 or not) described above, two supplementary criteria, namely "cloud-criterion" and "RH-criterion", have been applied for assessing the likelihood of sea breeze at the HKIA. The overall rule of assessment is that sea breeze would be unlikely to occur if:-

(a) SBI>7; or

(b) cloud cover≥6 oktas and mean relative humidity (RH) between 925 and 850 hPa≥85%.

It has been found that the introduction of the cloud-criterion and the RH-criterion, i.e. (b) above, helps to increase the accuracy of predictions solely made with the SBI-criterion, i.e. (a) above. Practically, the cloud cover is determined by human observation (sourced from the latest SYNOP report) while the mean RH between 925 and 850 hPa is sourced from information obtained by the latest upper air sounding (at 2000 HKT in the previous evening or 0800 HKT on the morning of the day). The rationale of the cloud-criterion and the RH-criterion is the assumption that large extent of cloud cover would likely to persist when the lower part of the atmosphere (925-850 hPa) was moist.

Solar radiation is a crucial factor to the temperature differential between air over land and sea surface. And, the amount of solar radiation reaching the surface is directly influenced by the cloud cover. So, cloud cover should be a factor to be considered for forecasting the temperature differential between air over land and sea surface.

However, if forecasts of temperature differential were perfectly accurate, theoretically the cloud-criterion and the RH-criterion should be mostly redundant as the effect of cloud cover, a primary factor, should have been readily reflected in the temperature differential. But in practice, the cloud-criterion together with the RH-criterion really helps to make sea breeze predictions more accurate. This is because not only forecasts of maximum air temperature at the HKIA ($T_{land}$) can hardly be perfectly accurate, but also a proxy, which is based on running average of past observations (with slow response), is used for $T_{sea}$.

A known shortcoming of the cloud-criterion is that cloud cover in the early morning might not persist long until noon. Clouds would thin out or even dissipate in the wake of solar heating during the day. It is expected that in lieu of observed cloud cover, forecast cloud cover, if available and accurate enough, would further help to boost the accuracy of sea breeze predictions.

### 3.3 Retrospective test runs using forecast cloud cover

Using data from June 2013 to May 2014 (12 months), contribution of OCF cloud cover forecasts (discussed in section 2) to the accuracy of sea breeze predictions was investigated. OCF cloud cover forecasts, with base time (T) at 12 UTC on the previous day, for 00 UTC to 09 UTC (i.e. T+12 to T+21) every day during the said data period were used. Cloud cover forecasts, expressed in units of percentages, are resolved down to hours of the day from 00 UTC to 09 UTC. Different sets of test data (described in more details below), each corresponds to a representative forecast cloud cover of the day, were generated from averaging the hourly forecasts of cloud cover over different periods.

For each sets of test data, Table 2 was used to convert the representative forecast cloud covers of the day from percentages to the unit of oktas, which ranges from 0 to 8.

In lieu of the observed cloud cover, representative forecast cloud cover of the day were subjected to the same cloud-criterion (i.e. whether ≥6 oktas or not) on top of the SBI-criterion to result in sea breeze predictions retrospectively for the data period. The RH-criterion was skipped (apart from one set of data for comparison purpose) in view of that forecast cloud cover was being used which should logically render the RH-criterion (originally aimed to secure the assumption on the persistence of large extent of observed cloud cover in the near future) redundant.

The predictions were verified against records of sea breeze occurrence/non-occurrence in actual which was judged objectively based on observed wind change at the HKIA, if any, and other meteorological factors. Only predictions made before 0700 HKT, i.e. during 0500-0630 HKT, were verified.

At first, test data over different 4-hour averaging periods during 00-03 UTC, 01-04 UTC, ..., 06-09 UTC were separately generated and tested to obtain preliminary verification results. From the preliminary results, the 4-hour averaging period that gives the best performance was identified. Then, three more sets of test data, with averaging periods of 6, 8 and 10 hours, respectively, centred about the identified best-performing 4-hour averaging period were generated and tested.

## 4. Performance with the inclusion of forecast cloud cover

Table 4 shows the results on the accuracy of the predictions with the use of different representative forecast cloud cover of the day. The 4-hour averaging period for forecast cloud cover that gives the best performance was identified to be 03-06 UTC. Accordingly, the averaging period was respectively extended to 02-07 UTC (6 hours), 01-08 UTC (8 hours) and 00-09 UTC (10 hours) and tested further. In addition, the corresponding figures for the operational setup, one original and the other modified to exclude the RH-criterion, are also stated for comparison purpose.

The result indicated that with the adoption of forecast cloud cover, predictions of sea breeze were generally more accurate. Among all the averaging period of cloud cover that had been tested, greatest improvement was achieved by having forecast cloud cover averaged over the 10-hour period during 00-09 UTC as the representative forecast cloud cover of the day to be used in the cloud-criterion. Compared to the present operational setup (using observed cloud amount in the cloud-criterion with the RH-criterion to supplement the SBI-criterion), the Critical Success Index (CSI) increased from around 0.51 to 0.56, due to increase of Probability of Detection (POD) and decrease of False Alarm Ratio (FAR); whilst the portion of correctness (PCOR) also increased from around 0.70 to 0.74. The performance indicators are defined as follows:-

$$\text{POD} = \frac{a}{a+c};\ \text{FAR} = \frac{b}{a+b};\ \text{CSI} = \frac{a}{a+b+c};\ \text{PCOR} = \frac{a+d}{a+b+c+d}$$

where a, b, c and d are the number of hit, false alarm, miss and correct rejection, respectively.

The more accurate sea breeze prediction achievable with the use of forecast cloud cover is illustrated by the case on 1 October 2013. During 0500-0630 HKT on that day, the cloud cover was reported to be 7 oktas which exceeded the threshold of 6 oktas in the cloud-criterion; the latest available data at that time indicated that RH between 925 and 850 hPa was 95%, which exceeded the threshold of 85%. Pursuant to condition (b) of the rule of assessment (see in Section 3.2), sea breeze was predicted not to occur on that day. However, as the actual cloud cover decreased, possibly due the effect of solar heating, to 2 oktas since 0700 HKT, predictions (updated half-hourly) switched to predict sea breeze occurrence. In actual, sea breeze set in shortly after 1300 HKT. All predictions made before 0700 HKT on that day are incorrect. On the contrary, the representative forecast cloud cover (10-hour average during 00-09 UTC) of that day was 4 oktas, which is a fair reflection of the general situation on that day. If the representative forecast cloud cover was used in lieu of the actual cloud cover, predictions made before 0700 HKT would be correct. This case is typical and representative in the sense that cloud cover often tends to decrease significantly during the few hours after sunrise. However, as the duty Aviation Forecaster at the AMO has to prepare, before 07 HKT, to issue a TAF with a 30-hour validity period commencing at 00 UTC (08 HKT) everyday, there is sure demand for early availability of accurate predictions of sea breeze which in turn calls for the availability of forecast cloud cover. And, the above results showed that the OCF technique is a good candidate to satisfy the need.

## 5. Summary and discussion

In this paper, we have introduced the OCF technique to generate forecast cloud cover by applying a past performance based weighted average of cloud cover forecast from different NWP models. Verification results showed that OCF cloud cover outperformed forecasts from individual models, especially during the first three days. The cloud cover forecast data generated during June 2013-May 2014 was then retrospectively applied to the sea breeze onset model currently in use in the AMO at the HKIA. Result showed that the forecast cloud amount helped to improve the forecast skill, with the percentage of correct (PCOR) raised from 0.70 to 0.74.

On the other hand, the maximum temperature forecast currently used in the SBI equation is taken from the forecast maximum temperature of the day specified in the TAF. Another possible research direction is to investigate whether OCF maximum temperature forecast could improve on the skill of sea breeze detection, as then cloud and temperature forecast would be both from OCF system automatically and could be more consistent.

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**Table 1** Model data used in constructing OCF cloud cover

| Model | Forecast Range | Temporal Resolution | Spatial Resolution |
|---|---|---|---|
| Meso-NHM | T+72h | 1 hour | $0.1^{o}$ |
| ECMWF deterministic model | T+240h | 3 hours up to T+144h<br>6 hours afterwards | $0.125^{o}$ |
| ECMWF EPS | T+240h | 3 hours up to T+144h<br>6 hours afterwards | $0.25^{o}$ |
| JMA GSM | T+84h for 00Z<br>T+216h for 12Z | 3 hours up to T+84h<br>6 hours afterwards | $0.25^{o}$ |

**Table 2** Lookup table to convert model cloud cover forecasts from percentages to oktas

| Cloud cover category (oktas) | Percentage of model cloud cover (%) |
|---|---|
| 0 | $0 \leq x \leq 6.25$ |
| 1 | $6.25 < x \leq 18.75$ |
| 2 | $18.75 < x \leq 31.25$ |
| 3 | $31.25 < x \leq 43.75$ |
| 4 | $43.75 < x \leq 56.25$ |
| 5 | $56.25 < x \leq 68.75$ |
| 6 | $68.75 < x \leq 81.25$ |
| 7 | $81.25 < x \leq 93.75$ |
| 8 | $93.75 < x \leq 100$ |

**Table 3** Accuracy score for categorical verification of within ± 2 categories for different individual models and OCF

| Model | Forecast day | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Day1** | **Day2** | **Day3** | **Day4** | **Day5** | **Day6** | **Day7** | **Day8** | **Day9** | **Day10** | **Day11** |
| EC | 73.05 | 73.19 | 73.41 | 73.26 | 71.17 | 70.33 | 69.39 | 67.43 | 65.84 | 65.17 | NA |
| JMA | 72.62 | 69.96 | 67.50 | 65.12 | 63.53 | 61.75 | 59.19 | 58.65 | 55.43 | 52.99 | 55.62 |
| NHM | 76.76 | 74.81 | 73.74 | NA | NA | NA | NA | NA | NA | NA | NA |
| ECMWF EPS Mean | 78.47 | 80.16 | 80.46 | 79.63 | 79.11 | 78.51 | 77.57 | 76.43 | 75.71 | 73.60 | 72.90 |
| ECMWF EPS Median | 76.53 | 77.89 | 77.81 | 77.04 | 75.56 | 74.39 | 74.07 | 73.01 | 72.39 | 70.39 | 70.48 |
| OCF | 80.48 | 81.44 | 81.31 | 78.01 | 76.52 | 75.68 | 75.63 | 74.14 | 73.47 | 72.38 | 71.07 |

*NA means forecast data not available

**Table 4** Skill scores of using various representative cloud cover forecast of the day. The skill scores (CSI and PCOR) of sea breeze predictions achieved by the best performer among all tested data vis-à-vis those of the operational setup are highlighted in bold typeface.

| **Data set** | **Performance** | | | | **Remarks** |
|---|---|---|---|---|---|
| | **POD** | **FAR** | **CSI** | **PCOR** | |
| Average forecast cloud cover during 00-03 UTC (4 hours) | 0.676 | 0.294 | 0.53 | 0.72 | |
| Average forecast cloud cover during 01-04 UTC (4 hours) | 0.69 | 0.29 | 0.54 | 0.73 | |
| Average forecast cloud cover during 02-05 UTC (4 hours) | 0.71 | 0.30 | 0.54 | 0.73 | |
| Average forecast cloud cover during 03-06 UTC (4 hours) | 0.73 | 0.30 | 0.56 | 0.73 | Best 4-hour performer in terms of CSI and PCOR |
| Average forecast cloud cover during 04-07 UTC (4 hours) | 0.73 | 0.31 | 0.55 | 0.73 | |
| Average forecast cloud cover during 05-08 UTC (4 hours) | 0.73 | 0.32 | 0.55 | 0.72 | |
| Average forecast cloud cover during 06-09 UTC (4 hours) | 0.72 | 0.32 | 0.54 | 0.72 | |
| Average forecast cloud cover during 02-07 UTC (6 hours) | 0.74 | 0.30 | 0.56 | 0.73 | |
| Average forecast cloud cover during 01-08 UTC (8 hours) | 0.74 (0.7363) | 0.30 (0.2980) | 0.56 (0.5610) | 0.74 (0.7375) | |
| Average forecast cloud cover during 00-09 UTC (10 hours) | 0.74 (0.7363) | 0.30 (0.2966) | **0.56** (0.5618) | **0.74** (0.7384) | Best performer among all tested data in terms of CSI and PCOR |
| SBI and cloud-criterion (using observed cloud amount) | 0.53 | 0.26 | 0.45 | 0.70 | For comparison |
| **Operational**: SBI-criterion, cloud-criterion (using observed cloud amount) and RH-criterion | 0.67 | 0.32 | **0.51** | **0.70** | For comparison |

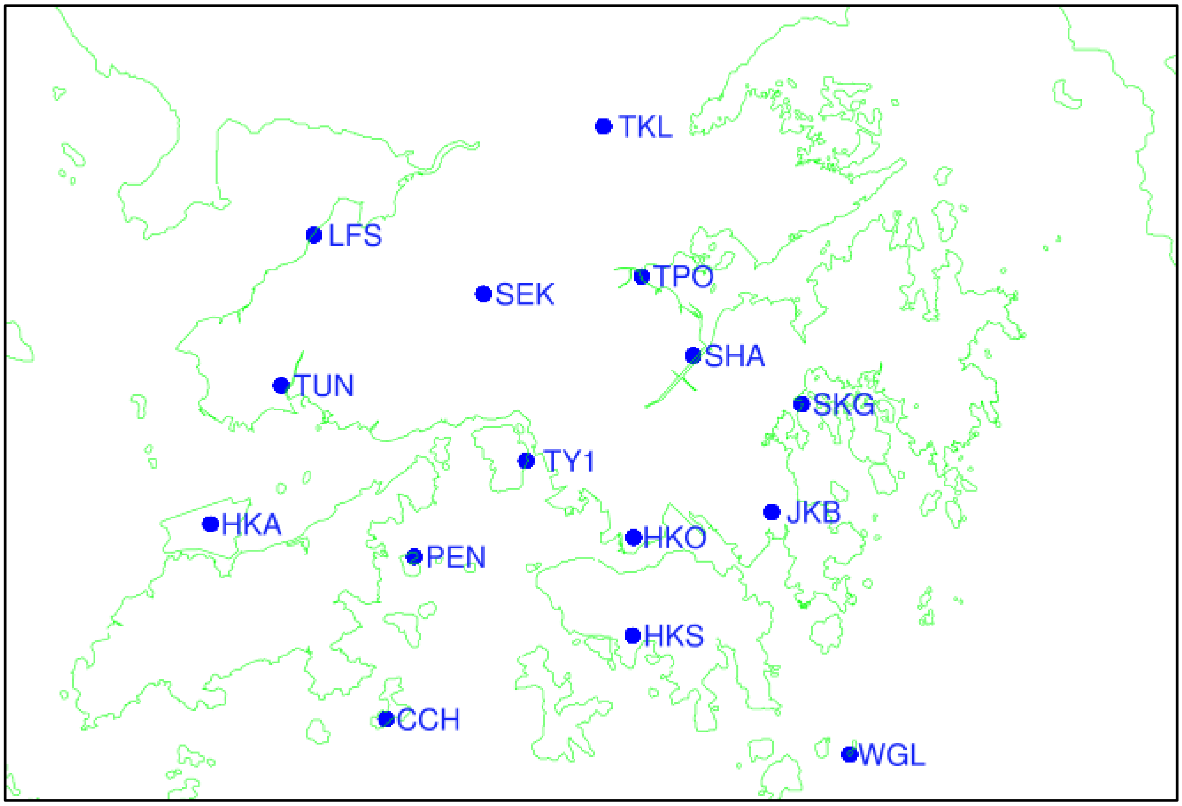
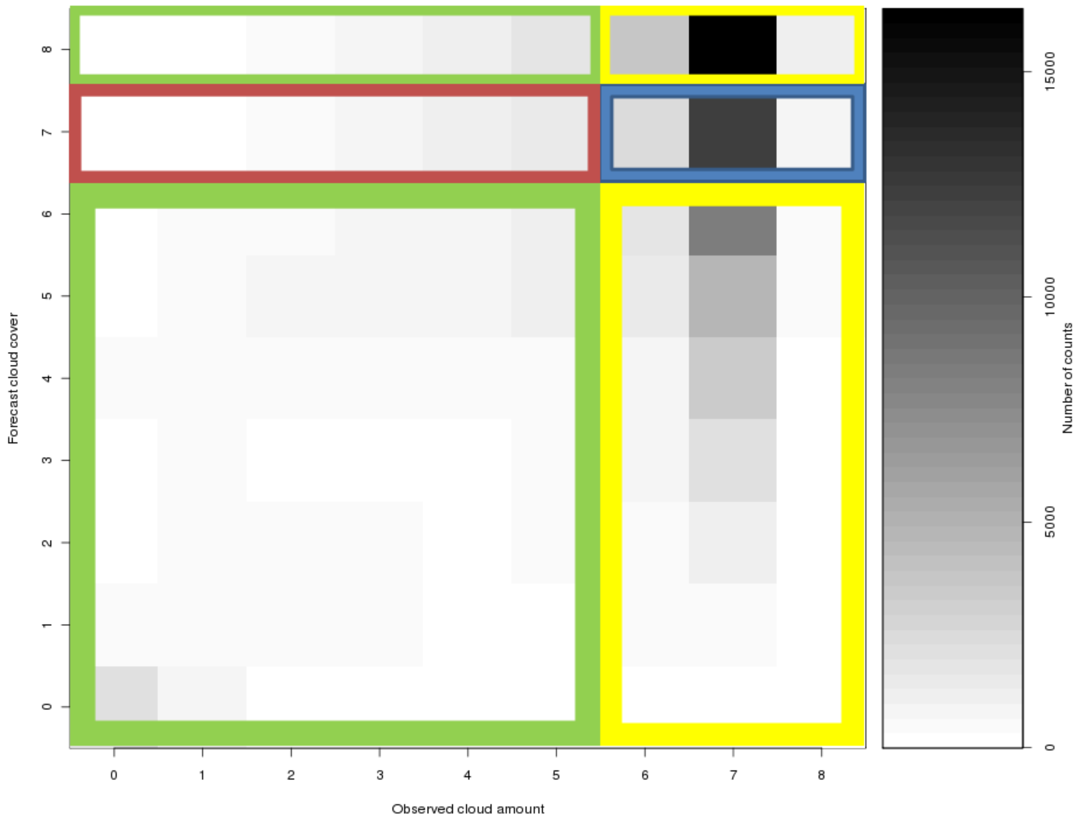



**Figure 1** Locations of stations used for computing OCF




| | Observed Yes | Observed No |
|---|---|---|
| **Forecast Yes** | *(HIT) a* | *(FALSE ALARM) b* |
| **Forecast No** | *(MISSES) c* | *(Correct Negatives) d* |

Where **BLUE for HIT**,
**RED for FALSE ALARM**,
**YELLOW for MISSES**,
**GREEN for CORRECT NEGATIVES**

**Figure 2** Contingency table for calculating Hit/Miss/False Alarm/Correct Negatives and an example of calculating the counts for category 7

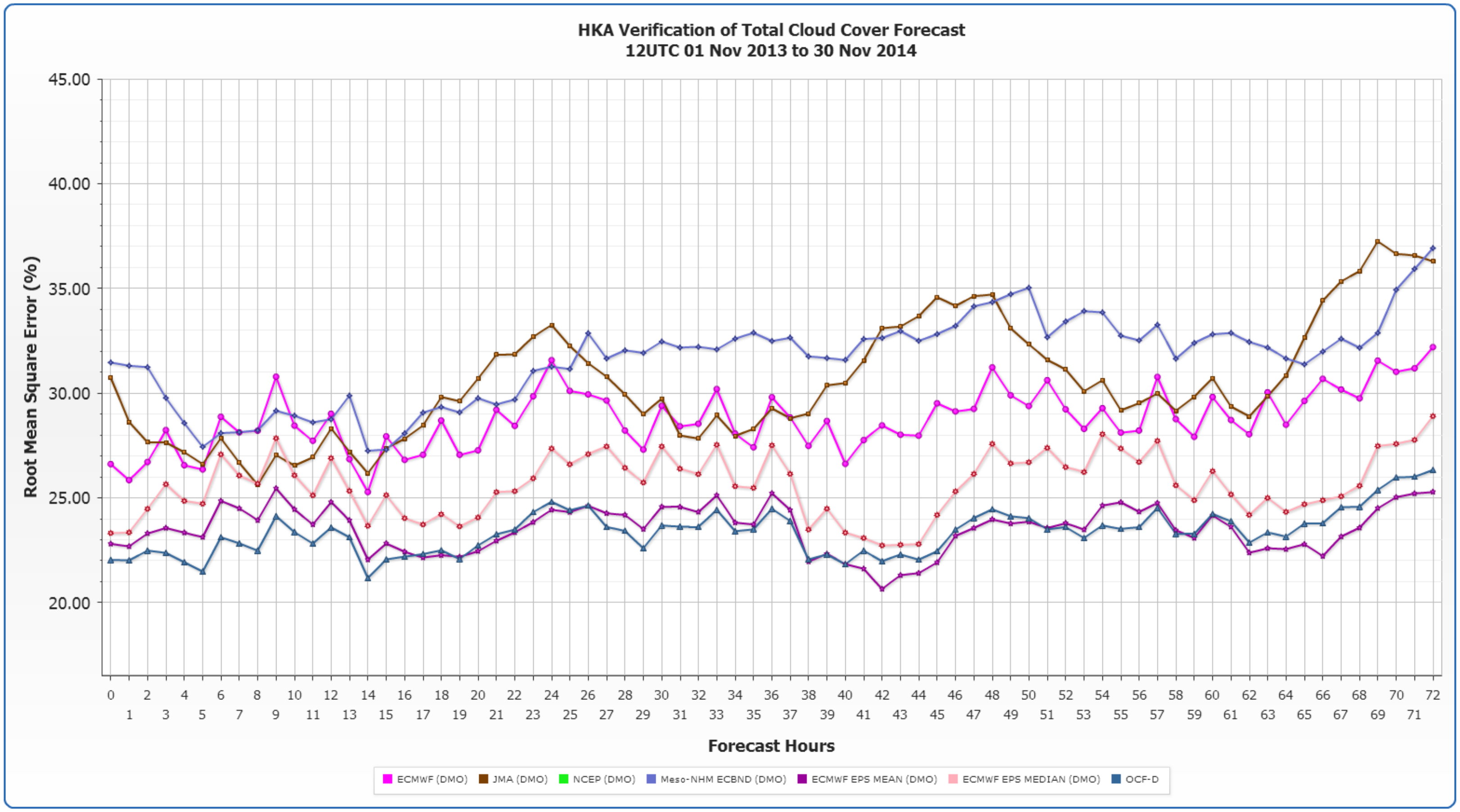



**Figure 3** The root mean squared error of the forecast cloud cover for OCF and different individual models verified from November 2013 to 2014 in HKIA