Forecast of Ultraviolet Index in Hong Kong

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Abstract

The Hong Kong Observatory (HKO) developed a methodology for forecasting the Ultraviolet Index (UVI) in Hong Kong. The methodology consisted of the computation of UVI in clear sky conditions using an empirical equation and the application of a set of factors to adjust the UVI for cloudy days or days with weather. The maximum UVI forecast service was launched in 2006. During a one-year operational experience, about 75% of the UVI forecasts were within 2 units of the actual UVI. This paper aims to document the development of the UVI forecast methodology and the forecast verification results.

1. Introduction

Excessive exposure to ultraviolet (UV) radiation may bring about health effects on human body, including sunburn, wrinkling and increased risk of skin cancers and cataracts. The UVI is a measure of the intensity of UV radiation relevant to the effect on human body (World Health Organization, 2002). The UVI observed in Hong Kong typically ranges from 0 to 15. To raise the public awareness on the potential harm of UV radiation, the HKO started a UVI advisory service in 1999 to provide information on measured UV radiation to the public (Leung, 2003). In 2006, the HKO completed the development of UVI forecasting technique and started the forecasting service in May of the same year, thus enabling members of the public to plan protective measures against possible harm from UV radiation. This paper documents the development of forecast technique and the verification of forecast performance.

It is well known that the variation of surface UV radiation depends on a number of factors including ozone concentration, cloud cover, elevation of the sun, rainfall, particulates and water droplets suspended in the air (World Health Organization, 2002). Ozone and clouds absorb some of the UV radiation that would otherwise reach the earth’s surface. Sun rays are attenuated by absorption and scattering from gases and particles in the atmosphere. Therefore, the lower the sun in the sky, the lower will be the UV radiation level. Rain, suspended particulates and water droplets generally reduce the UV radiation by reflection, scattering and absorption.

To forecast UVI in clear sky conditions, i.e. the clear sky UVI, there are two approaches. The first approach is the development of an empirical formula relating surface UV radiation to elevation of the sun, ozone concentration and the time of year. Canada is among the countries adopting this method (Burrows, 1994). The second approach involves the development of a Radiative Transfer Model (RTM) which calculates the change of solar radiation energy through the emission, absorption and scattering processes as the sun beam traverses the atmosphere and interacts with gases and particles, such as ozone and aerosols. The United States of America is one of the countries using such method (Long, 1996).

Irrespective of whether the empirical formula or the RTM is used, the UV value calculated by these methods is the maximum amount of UV radiation expected under clear sky conditions. In the presence of clouds and weather, i.e. under non-clear sky condition, the attenuation of UV has to be taken into account. One of the recommendations coming from the project undertaken by the European Commission, namely COST Action 713, is the use of modification factors for different
cloud amounts/elevations and weather conditions (Vanicek, 2000).

The present study drew on the experience of the Canadian approach and the COST project. An empirical equation for clear sky UVI was developed based on observed UV radiation. A set of cloud and weather modification factors, broadly based on those used in the COST project but found to be suitable for the circumstances of Hong Kong, was determined.

In developing the forecast technique, focus has been placed on forecasting the daily maximum UVI, as this parameter is more meaningful than the daily mean UVI when it comes to taking protective measures against UV.

2. Data

Past observational data from 1999 to 2003 was studied to find out the correlation between UVI and the relevant astronomical, geophysical and meteorological conditions. The data included:

(i) 5-minute mean UVI data measured by the UV pyranometer at the King's Park meteorological station (about 1 kilometre north of the Observatory Headquarters and 65 metres above mean sea level);
(ii) hourly cloud cover (in oktas) observed by weather observers at the Observatory headquarters;
(iii) hourly total rainfall data (in millimetres) recorded at the Observatory headquarters;
(iv) hourly report of presence of mist, fog or haze at the Observatory headquarters. This roughly represents the amount of particulates and water droplets suspended in the air;
(v) daily ozone concentration (in Dobson Units (DU)) for Hong Kong measured by the satellite-borne Total Ozone Mapping Spectrometer (TOMS); and
(vi) 1-minute solar elevation (in degrees) calculated using astronomical formulas.

3. Methodology

3.1 Clear sky UV

The Canadian approach was adopted to calculate the clear sky UVI. It assumed that the clear sky UV radiation could be represented by this equation:

\[
\text{clear sky UVI} = 0.04 \ C \cos \theta \exp(a + b\mu + c\mu + d(\mu \Omega)^2 + e\mu^2)
\]

where C is the earth-sun distance correction factor defined as (World Meteorological Organization, 1985):

\[
1.00011 + 0.034221\cos(y) + 0.00128\sin(y) + 0.000719\cos(2y) + 0.000077\sin(2y)
\]

in which \(y = 2\pi[(\text{Julian Date} - 1) / 365]\). The factor C reflects the modulation of solar energy arriving at the top of the earth’s atmosphere due to varying distance from the sun;

\(\theta\) is the zenith angle. The term \(\cos \theta\) describes the reduction in solar radiation arriving at a
slant due to absorption and scattering, as compared with that coming vertically downwards;

\( \mu \) is defined as \( 1/\cos \theta \); and

\( \Omega \) is the column ozone concentration in DU / 1000.

Since Canada is at a higher and very different latitude, parameters a to e in the equation above could not be directly adopted in Hong Kong. A new set of parameters applicable to Hong Kong was required. This was achieved by performing regression analysis using a set of training data selected from clear sky days during October 1999 to June 2003.

Regression analysis showed that the correlation between clear sky UVI and individual factors in the above equation was high, with a correlation coefficient R of 0.98. Parameters a to e of the clear sky UV equation were found to be 6.4, -1.5, -0.30, -0.99 and -0.077 respectively. The empirical equation was found to perform well when applied to an independent set of test data from July 2003 to June 2004. Fig. 5-1 shows that the UVI computed by the empirical equation was close to the measured UVI, except for those values close to or above 10 when the computed values tended to be underestimates. The limitation of the empirical equation for cases of UVI above 10 will be discussed further in Section 3.5.

3.2 UV under clouds and/or weather

After obtaining an empirical equation for clear sky situation, the next step was to analyze how the UVI was attenuated when there were clouds and/or weather, i.e. to calculate the non-clear sky UVI. The project COST Action 713 undertaken by the European Commission in 2000 recommended a set of factors (Table 5-1) to modify the clear sky UVI under different weather conditions and cloud amounts/altitudes.

As can be seen from the above table, the cloud factors are stratified according to whether the clouds are low, medium or high. However, starting from April 2000, cloud observations at the Observatory headquarters were reported in total cloud amount regardless of the altitude. As such, it was not
possible to use all the factors recommended by the COST project directly. A new set of factors depending only on total cloud amount had to be developed, so that the performance in respect of the cloud modification factors could be verified using the available observations. Operationally, it would also be easier and less time-consuming for the weather forecaster to predict the total cloud amount than to predict the cloud amounts at different altitudes.

<table>
<thead>
<tr>
<th></th>
<th>0 to 2 oktas</th>
<th>3 to 4 oktas</th>
<th>5 to 6 oktas</th>
<th>7 to 8 oktas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Clouds</td>
<td></td>
<td>0.8</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Medium Clouds</td>
<td>1</td>
<td></td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>High Clouds</td>
<td>1</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weather</th>
<th>Fog</th>
<th>Rain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
<td>0.4</td>
<td>0.2</td>
</tr>
</tbody>
</table>

*Table 5-1  Cloud and weather modification factors recommended by the COST Action 713 project of the European Commission*

The new set of factors, as shown in Table 5-2, was derived by taking the average of factors for low, medium and high clouds as suggested by the COST project. The performance in respect of the new set of cloud factors was verified by applying them to days with clouds but no weather during the period October 1999 to June 2004. Fig. 5-2 shows how the computed UVI correlated with the measured UVI, with a correlation coefficient R of 0.76.

<table>
<thead>
<tr>
<th>Total cloud amount</th>
<th>0 to 2 oktas</th>
<th>3 to 4 oktas</th>
<th>5 to 6 oktas</th>
<th>7 to 8 oktas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
<td>(1+1+1) ÷ 3</td>
<td>(0.8+1+1) ÷ 3</td>
<td>(0.5+0.8+1) ÷ 3</td>
<td>(0.2+0.5+0.9) ÷ 3</td>
</tr>
<tr>
<td></td>
<td>= 1</td>
<td>= 0.93</td>
<td>= 0.77</td>
<td>= 0.53</td>
</tr>
</tbody>
</table>

*Table 5-2  Computation of simplified cloud modification factors depending only on total cloud amount*

Haze and mist/fog are suspension of particulates and water droplets in the air. They lead to attenuation of the UV radiation through reflection, scattering and absorption. The COST project recommended modification factor for fog only. The modification factors for mist and haze were identified in this study by carrying out a sensitivity analysis which involved varying the factors from 0.5 (starting from the value just higher than the factor for fog) to 0.9 for those days with no clouds but with one type of weather, either mist or haze. The optimal factors for both mist and haze were found to be 0.8.

It was also found that if the single factor of 0.2 for rain as suggested by the COST project for all the rain cases was adopted, the UVI would be much underestimated when the rainfall rate was less than 1 mm per hour. To achieve an optimal forecast performance, it was found by testing with past data that the rain factor should be applied only when significant rain was forecast. In other words, the rain factor should not be used if light rain was forecast.
3.3 Forecasting the astronomical, geophysical and meteorological factors affecting the UVI

With respect to the methodology of UVI calculation discussed in Sections 3.1 and 3.2, a prerequisite for forecasting the UVI for the next day is to forecast the relevant geophysical (ozone concentration), astronomical (the sun’s elevation) and meteorological (cloud cover and weather) factors of the next day. Forecast of the sun’s elevation is straightforward through the use of the relevant astronomical formulas. Forecast of cloud amount, fog, mist, haze and rain is available from the day-to-day weather forecast. Since ozone concentration is not forecast routinely by the Observatory, extrapolation was used in this study as the day-to-day ozone variation near latitudes such as that of Hong Kong is usually only a few percents (Hudson, 2003; Long, 1996). The total column ozone concentration over Hong Kong of the next day could thus be approximated by the following equation:

\[ \Omega_{\text{tommorrow}} = a + b \Omega_{\text{yesterday}} + c \Omega_{\text{the day before yesterday}} \]

where \( \Omega \) is the total column ozone concentration.

Ozone concentrations measured by the satellite-borne TOMS from August 1999 to June 2004 were used to perform a regression analysis. The parameters a, b and c in the above equation were found to be 18.52 DU, 0.73 and 0.20 respectively. Operationally, ozone column data for the past couple of days is readily available from the TOMS database on the Internet for input into the empirical equation. Fig. 5-3 shows how the computed ozone concentration correlated with the measured ozone concentration, with a correlation coefficient \( R \) of 0.91.

3.4 Forecasting the maximum UVI for the next day

The forecast 15-minute UVI values between 11 a.m. and 1 p.m. the next day were calculated using the clear sky empirical equation, followed by application of the set of cloud and weather modification factors determined in Section 3.2 above. The maximum of these eight 15-minute UVI values was then regarded as the maximum UVI for the day. This assumed that the UVI usually
attained its maximum between 11 a.m. and 1 p.m., on the basis of past record of occurrences of maximum UVI. Although the maximum may take place outside this period on a non-clear sky day, there is a degree of difficulty in determining the peak hour operationally as this involves the problem of accurately forecasting all the weather elements affecting UVI for every hour, from sunrise to sunset.

3.5 Limitation of forecasting UV in the extreme category

According to international practice (World Health Organization, 2002), different UVI values can be grouped under five UV exposure categories: low (UVI=0-2), moderate (UVI=3-5), high (UVI=6-7), very high (UVI=8-10) and extreme (UVI=11). It was found that the methodology discussed above was handicapped in forecasting the ‘extreme’ category. This is because extreme exposure is a rare event relative to the occurrence of other exposure categories and as such, is not fully represented in the statistical processes involved in the regression analysis. Another reason is that, in the methodology discussed above, any presence of clouds would only attenuate the UVI, not enhance it. This would result in a statistical bias as UV radiation can actually be enhanced by reflection from the sides of broken clouds. In this study, it was found that of all cases of ‘extreme’ UV category during October 1999 to June 2004, only 3.4% were days with 0 or 1 okta of cloud, and the rest were days with 2 to 7 oktas of clouds.

To alleviate the above problem, persistence was used as a supplementary tool. Specifically, if the measured UV for the day is in the ‘extreme’ category and the synoptic weather situation for the following day is forecast to be similar, then the UV for the following day is likely to be also in the ‘extreme’ category in view of the significant role of the prevailing weather in affecting the surface UV intensity. Operationally, if the day’s measured UV is in the ‘extreme’ category and the forecast UV for the next day is in the category of ‘very high’, the forecast UV will be automatically adjusted upward to ‘extreme’.

4. UV forecast performance verified using a set of independent test data

Data from April 2004 to April 2005 was used as an independent set of test data to verify the

Fig. 5-3
Actual ozone concentration versus computed ozone concentration based on extrapolation. The correlation coefficient R is 0.91.
performance of the methodology discussed in Section 3. Daily maximum UVI values for this period were computed and the accuracy was assessed against actual observations. The histogram in Fig. 5-4 presents the results, showing the distribution of forecast errors. It was found that about 71% of the UVI forecasts were within 2 units of the actual UVI.

Category-wise, about 86% of UV forecasts were accurate to within 1 UV category, as shown by the contingency table in Table 5-3.

![Fig. 5-4](image_url) Distribution of errors in computing the daily maximum UVI based on an independent set of test data from April 2004 to April 2005. Statistics for those within 2 units of the actual UVI are shown in grey (71% of total).

<table>
<thead>
<tr>
<th>UVI level</th>
<th>Extreme (&gt;=11)</th>
<th>Very High (8-10)</th>
<th>High (6-7)</th>
<th>Moderate (3-5)</th>
<th>Low (0-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0%</td>
<td>0.3%</td>
<td>0.3%</td>
<td>3.4%</td>
<td>8.3%</td>
</tr>
<tr>
<td></td>
<td>0.3%</td>
<td>2.3%</td>
<td>3.4%</td>
<td>7.0%</td>
<td>3.6%</td>
</tr>
<tr>
<td></td>
<td>1.3%</td>
<td>6.0%</td>
<td>8.8%</td>
<td>8.6%</td>
<td>1.8%</td>
</tr>
<tr>
<td></td>
<td>4.7%</td>
<td>18.2%</td>
<td>7.3%</td>
<td>2.1%</td>
<td>1.0%</td>
</tr>
<tr>
<td></td>
<td>1.6%</td>
<td>4.9%</td>
<td>2.3%</td>
<td>2.3%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Actual UV</th>
<th>Low (0-2)</th>
<th>Moderate (3-5)</th>
<th>High (6-7)</th>
<th>Very High (8-10)</th>
<th>Extreme (&gt;=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (0-2)</td>
<td>1.6%</td>
<td>4.9%</td>
<td>2.3%</td>
<td>2.3%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Moderate (3-5)</td>
<td>4.7%</td>
<td>18.2%</td>
<td>7.3%</td>
<td>2.1%</td>
<td>1.0%</td>
</tr>
<tr>
<td>High (6-7)</td>
<td>1.3%</td>
<td>6.0%</td>
<td>8.8%</td>
<td>8.6%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Very High (8-10)</td>
<td>0.3%</td>
<td>2.3%</td>
<td>3.4%</td>
<td>7.0%</td>
<td>3.6%</td>
</tr>
<tr>
<td>Extreme (&gt;=11)</td>
<td>0.0%</td>
<td>0.3%</td>
<td>0.3%</td>
<td>3.4%</td>
<td>8.3%</td>
</tr>
</tbody>
</table>

Table 5-3 Contingency table of computed versus actual daily maximum UV for the set of independent test data from April 2004 to April 2005. Statistics for those computed values within 1 UV category are shown in grey (86% of total).
5. Start of the UV forecast service and its performance so far

With satisfactory results obtained with the UV forecast methodology, the HKO initiated issuance of UVI forecast on 25 January 2006 internally. The UVI was routinely computed by the methodology, and before its issuance the weather forecaster was allowed to adjust it on the basis of the latest assessment of the weather situation. The information for such assessment included a time series forecast of the meteorological factors (obtained from numerical weather prediction products) affecting the UVI at King’s Park between 11 a.m. and 1 p.m., the time period on which the maximum UVI forecast was based.

The UVI forecast service was launched formally on 11 May 2006 in anticipation of the arrival of summer season. Advisory statements reminding the public to take protective measures against UV are routinely included in the UVI forecast bulletin whenever UV levels in the extreme exposure category are expected.

The performance of UVI forecast issued operationally by the Observatory from January 2006 to January 2007 was verified. The histogram in Fig. 5-5 showing the distribution of forecast errors indicates that 75% of the UVI forecasts issued by weather forecasters were within 2 units of the actual UVI. Without the intervention of the forecasters (i.e. forecasts issued purely based on the methodology), the corresponding figure would have been 69%. The improvement of about 6% demonstrated the value of the weather forecaster in the provision of the service.

![Fig. 5-5 Distribution of errors in forecasting daily maximum UVI from January 2006 to January 2007. Those within ±2 units of the actual UVI are shown in grey (75% of total).](image-url)
Category-wise, 87% of UV forecasts were found to be accurate to within 1 UV category, as shown by the contingency table in Table 5-4.

The verification analysis also revealed that it was technically more difficult to forecast ‘very high’ or ‘extreme’ UV levels than the rest. A histogram showing the distribution of UVI forecast error according to the different actual UV exposure categories is given in Fig. 5-6. It can readily be seen that errors were higher in the ‘very high’ and ‘extreme’ categories. This seems to be a problem inherent in forecasting the maximum value of UV. When cloudy weather is forecast for the next day, a transient break in the clouds, which is very difficult to forecast, could lead to a sudden jump in the UV intensity and thus ruin an UVI forecast. Such error is especially more common in summer time when the noontime UV can reach the ‘very high’ or ‘extreme’ category even for only a short duration when the clouds break. In addition, the performance of the supplementary method in forecasting ‘extreme’ UV category as discussed in Section 3.5 depends on whether the weather is actually persistent.

6. Conclusion

Development of a methodology for forecasting the UVI was described and its performance studied. The development work included the determination of an empirical equation, which correlated surface UV radiation with the sun’s elevation, ozone concentration and the time of year. The application of the empirical equation to forecasting the clear sky UVI was found to give results of high accuracy. A set of cloud and weather modification factors was also determined for application to cloudy days or days with weather, and the results were found to be satisfactory. During the Observatory’s one-year operational experience in issuing the UVI forecast from January 2006 to January 2007, 75% of the UVI forecasts were found to be within 2 units of the actual UVI. Category-wise, 87% of UV forecasts were found to be accurate to within 1 UV exposure category. It was also
found that the overall performance of UVI forecast depended very much on how good the cloud and weather forecasts were.

Fig. 5-6  UVI forecast error (maximum UVI issued by forecaster minus actual maximum UVI) grouped according to different actual UV exposure categories, for the period January 2006 to January 2007. Positive and negative errors stand for over-forecast and under-forecast respectively.

7. Future work

The UVI forecast was a new service introduced by the HKO in 2006. The service will continue to be improved after gaining more operational experience. Some improvement areas worth pursuing in the future were identified:

(i) As an effort to further improve the performance, especially in forecasting UV in the ‘extreme’ category, the method of using an empirical equation to calculate clear sky UVI can be fine-tuned by deriving different sets of equations for different seasons.

(ii) An ensemble of hourly cloud forecasts generated by numerical weather prediction models can be used so that the UVI for each hour throughout daytime can be calculated, with a view to giving a more objective forecast for the forecaster’s reference.

(iii) The effect of aerosols on the intensity of UV radiation through absorption, reflection and scattering can be studied by using the Aerosol Optical Depth (AOD) product from satellite imageries, though the infrequent passes (1 to 2 times) each day over the region covering Hong Kong may limit the full potential of this useful tool.

(iv) The single-number representation of the modification factor for rain suggested by the COST project does not take account of the rainfall rate. Differences in UV attenuation brought
about by light, medium and heavy rain can be studied in the future.

(v) The present method employs extrapolation to forecast the total column ozone concentration for the next day. An empirical equation correlating the variation of ozone concentration with changes in temperature and geopotential height fields at upper atmospheric levels can be developed by performing regression analysis on past observational data. Similar study was carried out by Long (1996) and the result was found to be satisfactory.

Acknowledgement

The authors would like to thank Mr. K.M. Tse, undergraduate student of the Chinese University of Hong Kong in 2004, for his contribution in developing the empirical equation for forecasting clear sky UV. Also thanks to Mr. H.T. Poon for his guidance in the development of UV forecast methodology and Dr. B.Y. Lee, Dr. C.M. Cheng and Mr. W.M. Ma for their comments on this report.

References


