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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 Ultraviolet Index (UVI) is a measure of the intensity of UV radiation relevant to the effect on human body (World Health Organization, 2002). To raise the public awareness of the potential harm of UV radiation, the Hong Kong Observatory (HKO) started a UVI advisory service in 1999 to provide information on measured UV radiation to the public (Leung, 2003). In 2006, the HKO launched a UVI forecasting service which enabled members of the public to plan protective measures against possible harm from UV radiation (Lee, 2007; Wong, 2008). The UVI observation and forecast information was disseminated to the public through various channels. This article documents the method and statistical analysis of the UVI measurement, the development of the UVI forecast technique and its performance, and the various UV-related services provided to the public by the HKO.

2. Measurement of UV Index

The HKO uses a broadband UV-B ultraviolet pyranometer to measure the UVI (Yankee Environmental System, 1997). The pyranometer is sited at the King's Park meteorological station (latitude 22°19'N, longitude 114°10'E), an urban site of altitude 65 m above mean sea level. It measures the global solar UV-B irradiance or power per unit area of UV-B radiation received by a horizontal surface from the entire hemisphere of the sky. This includes both the UV radiation transmitted directly through the atmosphere and that scattered by atmospheric gases and aerosols. The pyranometer has a spectral response similar to the erythemal response spectrum defining the UVI. It outputs the total erythemally weighted UV irradiance which can be converted to the UVI by multiplying a constant. Although UV-A radiation is not measured by the pyranometer, the erythemally weighted irradiance of UV-A is much smaller than that of UV-B and can reasonably be neglected in the calculation of UVI.

Operationally, UVI values are extracted from the pyranometer every 5 minutes. They are used to compute the 15-minute mean, the hourly mean, the daily mean and the daily maximum values of the UVI, which are disseminated to the public through the HKO's website and the broadcasting media.

3. Statistical analysis of the measured UV Index

The HKO has been measuring and recording the UVI since August 1999. Statistical analysis of the daily mean and daily maximum was carried out on the UVI data collected between August 1999 and July 2008. Daily mean for a given day is defined as the averages of all the 15-minute mean UVI values between 7 a.m. and 6 p.m. in the day while daily maximum refers to the maximum of all the 15-minute mean UVI values recorded during the period. The frequency distributions of daily mean and daily maximum in different exposure categories are shown in Tables 1 and 2.

Category	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Percentage
Low (UVI 0-2)	231	157	152	130	71	80	53	72	68	72	140	236	1462	44.59%
Moderate (UVI 3-5)	47	97	127	132	174	136	131	151	186	207	130	43	1561	47.61%
High (UVI 6-7)	0	0	0	8	34	54	95	53	12	0	0	0	256	7.81%
Very high (UVI 8-10)	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00%
Extreme (UVI >=11)	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00%

Table 1 Frequency distribution of daily *mean* UVI in different exposure categories and months (1 August 1999 - 31 July 2008)

Category	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Percentage
Low (UVI 0-2)	39	36	44	25	13	18	6	16	5	6	15	16	239	7.29%
Moderate (UVI 3-5)	169	84	71	74	33	40	26	31	41	39	96	198	902	27.51%
High (UVI 6-7)	68	91	83	46	38	34	30	32	44	126	146	65	803	24.49%
Very high (UVI 8-10)	2	43	79	88	109	70	58	79	145	107	13	0	793	24.18%
Extreme (UVI >=11)	0	0	2	37	86	108	159	118	31	1	0	0	542	16.53%

Table 2 Frequency distribution of daily *maximum* UVI in different exposure categories and months (1 August 1999 - 31 July 2008)

It can be seen that the daily mean was “Low” and “Moderate” in over 90% of the time and was never “Very High” or “Extreme”. For daily maximum, more than 40% was “Very High” or “Extreme”. The “High” cases in daily mean and the “Extreme” cases in daily maximum were mostly found in May to August and never occurred from November to February. The highest daily maximum on record is 15.4, measured shortly after noon time on 23 July 2003.

4. Development of the UVI forecast technique

Using the UV data recorded since 1999, the Observatory carried out a study on the forecast of UVI. In developing the technique, focus was placed on forecasting the daily maximum UVI for the next day, as this parameter is more meaningful than the daily mean UVI when it comes to taking protective measures against UV. Drawing on the experience of the Environment Canada (Burrows, 1994), the Observatory developed an empirical formula relating surface UV radiation in clear sky conditions to elevation of the sun, ozone concentration and the time of year. As the next step, the attenuation of UV in the presence of clouds and weather was calculated using a set of modification factors. Further details are as follows.

The equation developed by the Environment Canada was taken as a reference to represent the maximum clear sky UVI:

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

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 the varying distance from the sun;

θ 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;

μ is defined as $1/\cos\theta$; and

Ω is the column ozone concentration in Dobson Units / 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 data selected from clear and near-clear sky days (0 to 1 okta cloud) during April 2000 to April 2006. Days of 1 okta cloud were also included in view of insufficient data for performing a valid regression analysis if only days of 0 okta cloud were used. Ozone data measured by the satellite-borne Total Ozone Mapping Spectrometer (TOMS) was extracted to represent the daily column ozone concentration over Hong Kong. Parameters a to e of the clear sky UV equation for Hong Kong were found to be 10.9, -16.6, -3.2, 21.6 and 1.0 respectively.

After obtaining an empirical equation for the clear sky condition, the next step was to analyze how the UVI was attenuated when there were clouds and weather. In respect of clouds, it would be operationally easier and less time-consuming for the weather forecaster to predict the total cloud amount than to predict the cloud amounts at different altitudes. Therefore only the effect of total cloud amount on UVI was examined. Using the data from 2000 to 2006, it was found that for days with cloud amount up to 6 oktas, the daily maximum UVI calculated using the clear-sky regression equation did not deviate much from the actual value. This was possibly because the attenuation of surface UV intensity through scattering and absorption by clouds was more or less counterbalanced by the increase of surface UV intensity through reflection of UV radiation from the sides of clouds when the sky was not entirely overcast. Based on this finding, the modification factor for 0 to 6 oktas of clouds was set to 1.

When the cloud amount was 7 or 8 oktas, the UVI value calculated using the regression equation was found to deviate from the actual maximum. Further investigation of the cloud types revealed that the attenuation of UV was small at about only 5% when it was dominated by cumulus clouds. On the contrary, the attenuation of UV was found to be significant, sometimes reaching 50%, when the clouds were not of the cumulus type. Based on this finding, the modification factor was set to 0.95 for situations when the cloud amount was 7 and the cloud type was cumulus. It was set to 0.5 for situations when the cloud amount was 7 oktas and the cloud type was non-cumulus, or when the cloud amount was 8 oktas.

In respect of weather affecting the UVI, haze, mist and 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 project COST[1] Action 713 undertaken by the European Commission in 2000 recommended modification factors of 0.4 and 0.2 for fog and rain respectively (Vanicek, 2000). Since there were no recommended factors for mist and haze, these values were identified in the present study by carrying out a sensitivity analysis which involved varying the factors from 0.5 (starting with the value just above 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 was adopted for all the rain cases, 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.

With respect to the methodology of UVI calculation discussed above, 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 HKO's day-to-day weather forecast. As cloud type is not given in the routine forecast, persistence method is used as the first guess. If the cloud type is cumulus in three consecutive hours from 11 a.m. to 1 p.m., the cloud type near noon time of the next day is assumed to be cumulus too. In respect of ozone, extrapolation is used to forecast ozone concentration, as the day-to-day ozone variation near latitudes such as that of Hong Kong is usually only a few percents (Hudson, 2003). The total column ozone concentration over Hong Kong of the next day is approximated by the following equation:

$$\Omega_{\text{the next day}} = a + b\,\Omega_{\text{yesterday}} + c\,\Omega_{\text{the day before yesterday}}$$

where Ω is the total column ozone concentration.

Ozone concentrations measured by the satellite-borne TOMS were used to perform a regression analysis and 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 and is extracted for input into the equation.

5. Verification of the performance of UV forecast

As an independent set of data, the data from April 2006 to April 2007 was used to verify the performance of the methodology discussed in Section 4. Daily maximum UVI values for this period were computed and the accuracy of the forecast UVI was assessed against actual observations. The histogram in Figure 1 presents the results, showing the distribution of forecast errors. It was found that over 65% of the UVI forecasts were within ±2 units of the actual UVI.

[1] The acronym COST stands for "European Cooperation in the Field of Scientific and Technical Research".

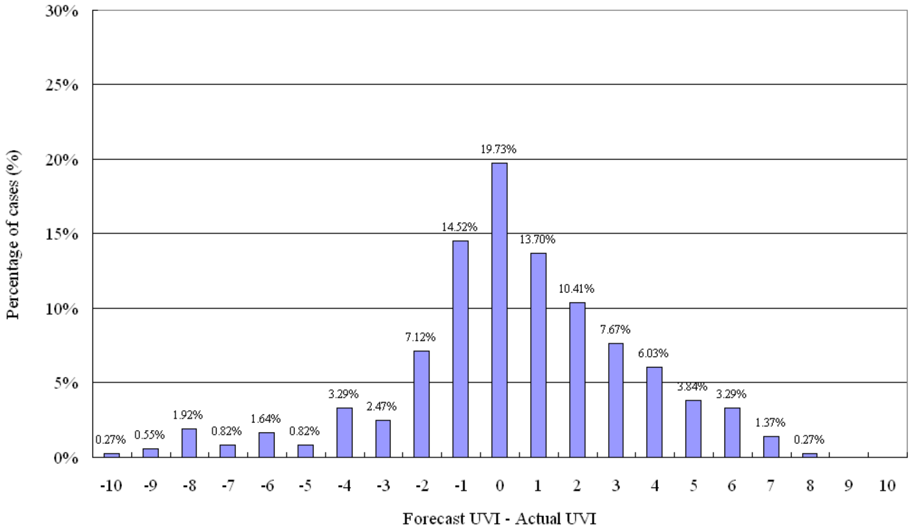

Figure 1 Distribution of errors in computing the daily maximum UVI for data from April 2006 to April 2007.

Category-wise, as shown by the contingency table in Table 3, the probability of detection (POD) for forecasting UV in the 'Extreme' category is 83%, the false alarm rate (FAR) is 46% and the critical success index (CSI) is 0.49.

Forecast UV category		Actual UV category: Low (0-2)	Moderate (3-5)	High (6-7)	Very High (8-10)	Extreme (>=11)
	Extreme (>=11)	0	8	13	20	49
	Very High (8-10)	4	11	15	13	3
	High (6-7)	10	38	30	11	5
	Moderate (3-5)	18	48	19	7	0
	Low (0-2)	10	15	5	11	2

Table 3 Contingency table of forecast versus actual daily maximum UV for data from April 2006 to April 2007.

Operationally, the UVI was routinely computed by the methodology discussed above, and before its issuance the HKO weather forecaster was allowed to adjust it on the basis of the latest assessment of the weather situation. The performance of UVI forecast issued by the HKO weather forecaster from 8 July 2008[2] to 16 September 2008 was verified. About 72% of the UVI forecasts issued by the weather forecaster were within ±2 units of the actual UVI. Category-wise, the CSI for forecasting UV in the 'Extreme' category is 0.65 (POD is 0.75 and FAR is 0.17). The improvement as compared with the forecasts purely based on the methodology demonstrated the value of the weather forecaster in the provision of the service.

[2] Before 8 July 2008, an old set of cloud modification factors adapted from the COST project was used. Since then, it was replaced with the one introduced in this article which was found to perform better.

6. UV-related service provided by the Observatory

The Observatory disseminates the UV measurement and forecast information to the public through radio, television, telephone-based Dial-a-Weather service, the Observatory's website and Personal Digital Assistant (PDA) website. The measured UV level is announced every hour during daytime and the forecast UVI for the next day is provided at 5 p.m. daily. To remind the public of the need to take protective measures against UV, an advisory message will be included in the hourly reading bulletin or the forecast bulletin whenever the actual or forecast UV level is in the "Extreme" exposure category (i.e. UVI >= 11).

In addition to the daily UV measurement and forecast information, the HKO also provides in its website a webpage for searching the past mean and maximum UVI since 1999, a list of suggested precautionary measures against UV and some basic facts and knowledge about UV. In collaboration with the Department of Health, the Observatory distributes a pamphlet to the public highlighting the importance of protection against UV.

7. Conclusion

The HKO started the measurement and dissemination of UV levels in 1999. Past record showed that the daily maximum UVI attained the "Extreme" category mostly from May to August and never occurred from November to February. The highest daily maximum recorded so far is 15. In 2006, the HKO enhanced the UV service by forecasting the maximum UVI for the next day. The forecast methodology involved the calculation of clear sky UVI using an empirical equation which correlated surface UV radiation with the sun's elevation, ozone concentration and the time of year. A set of modification factors was then used to determine the degree of UV attenuation due to the presence of clouds and weather. The performance of this method was found to be satisfactory. The POD for forecasting 'Extreme' UV exceeds 80% while the FAR is below 50%.

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