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Ultraviolet Forecasting in Thailand

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ABSTRACT: Total ozone and erythemal UV models have been created for UV Index forecasting in Thailand. Versions of an ozone model for Chiangmai, Ubon Ratchathani, Bangkok and Songkhla and a UV model for Bangkok and Songkhla are available for operation on a daily basis. The procedure is to forecast ozone from upper air data, and then calculate the forecast erythemal UV irradiance from the ozone forecast. In the ozone models, a linear regression technique was used with fifteen coefficients for temperature and dynamic height at the 100 hPa and 50 hPa levels where the ozone exists and daily balloon observations are made. Simple ozone models were also developed for use in the areas without upper air observations. The data are in the form of time series over three consecutive days. The UV models were obtained from Brewer UV data from Bangkok and Songkhla fitted to a non-linear three dimensional equation which is a function of ozone and its air mass to obtain five coefficients for the empirical formula. The models are used to estimate cloud-free values of the UV Index over the different areas of the country. The output of the erythemal UV for a clear sky is converted to the UV Index. The UV Index is then used to select one of five categories for issuing to the public every noon. Reductions of the UV Index for cloudy skies are also given. The average accuracy of the models is acceptable as the squares of the correlation coefficients (R^2) are 0.88 and 0.99 for the ozone and UV models respectively, while the mean absolute percentage errors are 1.5 % and 7.5 % for the ozone and UV forecasting respectively.

KEYWORDS: ozone, ultraviolet, UV Index, erythemal UV, cloud modification factor, aerosol optical depth.

INTRODUCTION

An appropriate forecast method has been developed to provide daily information on ultraviolet radiation at ground level in four areas of Thailand.[1,2,3] The purpose of this paper is to give full details of the method used, and of the current measurement on which the forecasts are based. The procedure is to forecast ozone from upper air data by a modification of the method developed in the University of Thessaloniki, and then calculate the forecast erythemal UV irradiance from the ozone forecast by the Canadian method with new coefficients based on observations in Thailand.

Ultraviolet Index

The Ultraviolet Index (UVI)[4] is a simple measure of the ultraviolet (UV) radiation level at the Earth's surface and an indicator of the potential for skin damage. It serves as an important vehicle to raise public awareness and to alert people to the need to adopt protective measures when exposed to UV radiation. The UVI was developed through an international effort by the World Health Organization (WHO) in collaboration with the United Nations Environment Programme (UNEP), the World Meteorological Organization (WMO), the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the German Federal Office for Radiation Protection.

The calculation of the UVI based on modeling of erythemal irradiance, which depends on solar zenith angle, altitude, ozone, surface albedo, aerosols and clouds. The erythemally weighted irradiance,[5] E_{CIE}, is defined by the integral

$$E_{CIE} = \int_{250nm}^{400nm} E_G(\lambda)C(\lambda)d\lambda , \qquad (1)$$

where $E_{G(\lambda)}$ is the global spectral irradiance and $C(\lambda)$ is the CIE erythemal effectiveness function proposed by Mckinlay and Diffey[6] in 1987. A UVI value is the result of multiplying the erythemally weighted irradiance (W/m^2) by 40. The typical UVI levels in Thailand usually range from 0 to 14. The UVI for different amounts of cloud and different altitudes is calculated using the following equation[7]

$$UVI = UVI_0 \times CMF(1 + 0.08\Delta H) , \qquad (2)$$

where UVI_0 is the UVI for a clear sky at a reference altitude, CMF is a Cloud Modification Factor, and ΔH is the altitude (km) above the reference altitude.

Factors Affecting the Solar UV Radiation Flux[8]

Zenith Angle of the Sun. The rays from the sun are attenuated by scattering and absorption from gases and particles in the atmosphere. The nearer the sun is to the zenith, the higher is the intensity of UV radiation at the surface.

Atmospheric Ozone molecules absorb some of the UV radiation that would otherwise reach the Earth's surface. Therefore, the more depleted the ozone is, the stronger is the UV intensity.

Aerosols generally decrease the amount of UV radiation at the surface by atmospheric scattering and absorption.

Clouds can increase and decrease UV radiation by reflection and absorption processes respectively. The levels are highest under cloudless skies and lower under cloudy, rainy and hazy skies.

Altitude. At higher altitudes the thinner atmosphere absorbs less UV radiation. With every 1000 meters increase in altitude, UV radiation levels increase by 10-12%.[8]

Latitude. The UV radiation is highest in low latitudes because of higher sun elevations.

Ground Reflection. UV radiation is reflected or scattered by different surfaces to varying extents. For example, fresh snow, dry beach sand, and sea foam can reflect as much as 80%, 15% and 25%, respectively[8].

Materials and Methods

The ozone and UV data used are measured regularly by the Thai Meteorological Department (TMD) in the framework of the WMO Global Atmosphere Watch programme. The measurements are made using a ground-based Dobson spectrophotometer for the total column ozone and a Brewer spectrophotometer (Fig.1) for UVA (315-400 nm) and UVB (285-315 nm).

Total Column Ozone

The Brewer spectrophotometer is designed to measure the light intensity for determining the total ozone, sulphur dioxide, nitrogen dioxide and UV spectra. The first instrument was designed by Alan Brewer who worked at the Sub-department of Atmospheric, Oceanic and Planetary Physics, University of Oxford during 1948-1962. In modern instruments, sun tracking, appropriate filter selection, wavelength calibration and data logging are managed through internal electronics and a compatible PC host computer. Control software for the host computer provides twenty-four hour scheduling.

Total ozone and sulphur dioxide measurements are made at five wavelengths, namely 306.3, 310.1, 313.5, 316.8 and 320.1 nm. These measurements are expressed in Dobson Units (100 D.U. = 0.1 atm-cm).

The measured intensity of direct sunlight at each of the five wavelengths is given by

$$\log I_\lambda = \log I_{0\lambda} - \beta_\lambda m - \delta_\lambda \sec\theta - \alpha_\lambda O_3 \mu - \alpha'_\lambda SO_2 \mu',$$

where

I_λ is measured light intensity at wavelength λ,

$I_{0\lambda}$ is extra terrestrial light intensity at wavelength λ,

β_λ is Rayleigh scattering coefficient at wavelength λ,

δ_λ is particulate scattering coefficient at wavelength λ,

α_λ is ozone absorption coefficient at wavelength λ,

O_3 is amount of total column ozone,

α'_λ is sulphur dioxide absorption coefficient at λ,

SO_2 is total sulphur dioxide amount,

$m, \sec\theta, \mu, \mu'$ are relative air masses for the Rayleigh, aerosol, ozone and sulphur dioxide terms, respectively.

Ultraviolet

The Brewer spectrophotometer measures the global solar UV irradiance between 286.5-363.0 nm at 0.5 nm wavelength steps and resolution. Non-weighted spectral values of UV radiation from a hemispherical field of view are determined for each wavelength increment as W/m^2. Erythemally weighted irradiance integrated over the wavelength range (mW/m^2) and over time (J/m^2 per day) is also available.

Fig 1. Brewer spectrophotometer MKIV used at TMD

Aerosol Optical Depth

Aerosol optical depth (AOD) is a consequence of scattering and absorption of solar radiation by aerosols; although ozone absorption and molecular scattering are much more important, aerosols also have an influence on UV radiation.

AOD can be measured by the Brewer spectrophotometer at UV wavelengths. A small change of AOD can give a big change in the UV flux. The calculation of AOD[9] in the UV wavelength range is:

$$\tau_{aer} = \tau_{tot} - \tau_{ray} - \tau_{O3} - \tau_{SO2},$$

where

τ_{aer} is the aerosol optical depth,

τ_{tot} is atmospheric total optical depth,

τ_{ray} is optical depth due to Rayleigh scattering,

τ_{O3} is optical depth due to ozone absorption,

τ_{SO2} is optical depth due to sulphur dioxide absorption,

The total optical depth for a vertical path is defined[10] by

$$\tau_{tot} = \frac{1}{m}\ln\left(\frac{I_0}{I}\right),$$

where I is intensity of radiation at the point of observation, I_0 is intensity of radiation at the top of the atmosphere and m is relative air mass taking into account the direct beam slant path through the atmosphere. The molecular optical depth τ_{ray} depends[11] only upon surface pressure and wavelength:

$$\tau_{ray} = \frac{0.008569\lambda^{-4}(1+0.0113\lambda^{-2}+0.00013\lambda^{-4})p}{1013.25}$$

where λ is the wavelength (μm), and p is the atmospheric pressure in hPa at the site.

The ozone optical depth is given by

$$\tau_{O3} = O_3\kappa_{O3}(\lambda)\,\tau_{O3}$$

where O_3 is the total column amount of ozone (atm-cm) and κ_{O3} is the ozone absorption coefficient (cm^{-1}).

The sulphur dioxide optical depth is given by

$$\tau_{SO2} = SO_2\kappa_{SO2}(\lambda),$$

where SO_2 is the total column amount of sulphur dioxide (atm-cm), and κ_{SO2} is the SO_2 absorption coefficient (cm^{-1}).

UV Forecasting Procedure

The UV forecasting procedure is illustrated in Fig. 2. The sections below give details of the models used in this procedure.

The first step is predicting total ozone from current ozone measurements and other meteorological observations. The predicted total ozone value is then substituted into a clear sky UV model in order to generate the clear sky erythemal and UVI. A cloud modification factor from the current weather forecast can be applied to produce a UVI forecast for the public.

Ozone Modeling

The new methodology in ozone forecasting uses multiple linear regressions of time series in an equation similar to the equation developed at the Laboratory of Atmospheric Physics (LAP), University of Thessaloniki[12]. The total ozone models are based on physical assumptions for ozone formation. When oxygen molecules are broken by UV radiation and release energy to the atmosphere, the consequent effects on air temperature, pressure, and ozone amounts can occur within a couple of days. Upper air data have proved this assumption. The model is obtained by fitting measured data using a linear regression technique. The total ozone on the day of the prediction is forecast from its values on the previous two days together with temperature and dynamic height at the 50 hPa and 100 hPa pressure levels over three consecutive days ending with the current day.

For the work described in this paper the temperatures and dynamic heights were collected from daily balloon observations, and the total ozone values were from ground-based Dobson ozone spectrophotometer measurements made at Bangkok (13.67N, 100.62E), and satellite data retrieved from the NASA Total Ozone Mapping Spectrometer (TOMS) over Chiangmai (18.78N, 98.98E) and Ubon Ratchathani (14.97N, 104.87E) during 1997-2000.

The multiple linear regression model used was:

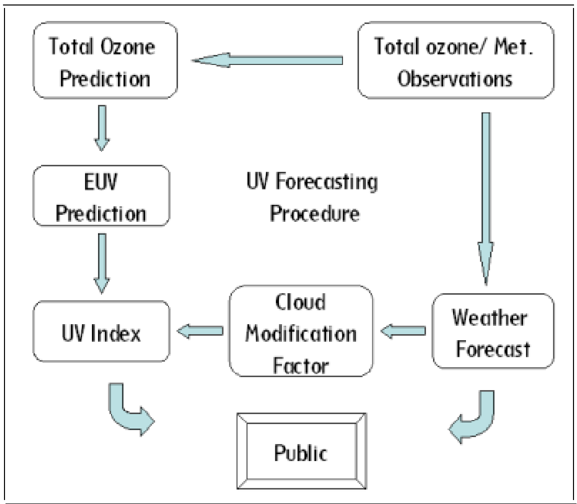

Fig 2. UV forecasting procedure.

$$O_3(i)=\beta_1+\beta_2T_{50}(i)+\beta_3\phi_{50}(i)+\beta_4T_{100}(i)+\beta_5\phi_{100}(i)+\beta_6O_3(i-1)+\beta_7T_{50}(i-1)+\beta_8\phi_{50}(i-1)+\beta_9T_{100}(i-1)+\beta_{10}\phi_{100}(i-1)+\beta_{11}O_3(i-2)+\beta_{12}T_{50}(i-2)+\beta_{13}\phi_{50}(i-2)+\beta_{14}T_{100}(i-2)+\beta_{15}\phi_{100}(i-2) \quad (3)$$

where

is the day for which the forecast is made,

O_3 is the total column ozone in Dobson Units,

T_{50} to T_{100} are temperatures at 50hPa and 100hPa,

ϕ_{50} to ϕ_{100} are dynamic heights at 50hPa and 100hPa, and

β_1 to β_{15} are the coefficients.

Simple Ozone Modeling

These models were developed from a time series of total ozone to be used at sites where no upper air observations were available. A simple model was run by the stepwise method in linear regression with some statistical applications. The significant parameters are total ozone on the two previous days before the day of forecasting. The time series coefficients are c_1, c_2 and c_3 in the following equation

$$O_3(i)=c_1+c_2O_3(i-1)+c_3O_3(i-2). \quad (4)$$

Ultraviolet Modeling

Forecasts of the UVI are generated from local UV models which are created by a regression technique following the Canadian method[13]. The values of erythemal UV irradiance for a clear sky are calculated using the total ozone forecast O_3.

The data used in modeling were integral erythemal UV irradiances from Brewer measurements made in the complete absence of cloud. The data were fitted to the following non-linear expression for EUV_0 as a function of ozone and its air mass to obtain the five coefficients *a*, *b*, *c*, *d*, and *e* in:

$$EUV_0=C_d\cos\theta\ \exp(a+b\mu O_3+c\mu+d(\mu O_3)^2+e\mu^2) \quad (5)$$

where

EUV_0 is erythemal UV flux at the surface under a clear sky (mW/m^2),

C_d is the Earth-Sun distance correction factor,

O_3 is column ozone amount in atm-cm,

μ is air mass of ozone, and

θ is zenith angle.

The coefficients *a*, *b*, *c*, *d*, and *e* were found by the following steps:

(1) Daily averaged values of the AOD derived from Brewer ozone direct sun measurements in the UV range at 306.3 nm were collected. The values obtained were classified into: completely clear sky with $\tau_{aer}<0.2$, average clear sky with $0.2\le\tau_{aer}\le0.5$, and polluted sky with $\tau_{aer}>0.5$. The maximum value of τ_{aer} observed was 1.50 in Bangkok and 1.78 in Songkhla.

(2) Erythemal UV irradiance was measured regularly by Brewer spectrophotometers at Bangkok and Songkhla. Data for 2000-2004 at Bangkok and 2001-2004 at Songkhla were used for the modeling. Clear sky data were selected by screening out days on which clouds were observed visually and the graphs of *EUV* irradiance versus time were not smooth. The integral of erythemal weighted irradiance was calculated automatically from the raw data by the software of the Brewer spectrophotometer. It was found from the measurements that the maximum EUV_0 is usually in the range of 250-350 mW/m^2 in summer on a clear day. In Fig. 3 plots of EUV_0 are shown for two different aerosol conditions.

(3) Three methods were used to obtain data on total column ozone, namely Brewer spectrophotometer measurements, Dobson ozone spectrophotometer measurements, and TOMS satellite data. The Brewer spectrophotometer measurements were used for ultraviolet modeling in equation (5), and the other measurements were used for ozone prediction in equation (4).

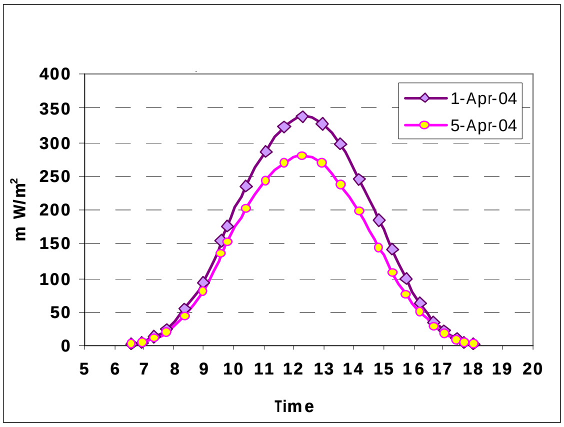

Fig 3. Values of EUV_0 measured as a function of time for two clear days in Songkhla.

(4) The air mass μ for use in equation (5) was calculated from the zenith angle θ of the sun by the equation

$$\mu=\left(\cos(\arcsin\ (\frac{R}{R+h}\sin\theta))\right)^{-1}$$

where *R* is the radius of the Earth (6371 km) and *h* is the height of the ozone layer (22 km).

(5) The Earth-Sun distance correction factor[13], was calculated from

$$C_d=1.000110+0.034221\cos(y)+0.001280\sin(y)+0.000719\cos(2y)+0.000077\sin(2y),$$

Table 1. Cloud Modification Factors.

Cloud Amount	Clear(0-2)	Partly Cloud(3-5)	Cloudy(6-8)	Overcast(9-10)	Fog	Rain
CMF	1.0	0.9	0.7	0.3	0.4	0.2

Table 2. Coefficients of the total column ozone model.

Var.	Coeff.	TO3CHM	TO3UBN	DO3BKK	TO3SKL
constant	β_1	144.149	36.141	-76.179	-13.722
$T_{50}(i)$	β_2	0.065	0.051	-0.047	-0.168
$\phi_{50}(i)$	β_3	-0.003	0.002	0.000	-0.004
$T_{100}(i)$	β_4	0.208	-0.042	-0.042	-0.012
$\phi_{100}(i)$	β_5	-0.013	-0.003	0.008	0.005
$O_3(i-1)$	β_6	0.534	0.562	0.629	0.413
$T_{50}(i-1)$	β_7	0.117	0.141	-0.153	0.223
$\phi_{50}(i-1)$	β_8	0.011	0.001	0.000	0.001
$T_{100}(i-1)$	β_9	0.038	0.047	0.018	-0.036
$\phi_{100}(i-1)$	β_{10}	-0.012	0.000	-0.006	-0.001
$O_3(i-2)$	β_{11}	0.403	0.378	0.274	0.478
$T_{50}(i-2)$	β_{12}	0.076	-0.025	0.267	-0.064
$\phi_{50}(i-2)$	β_{13}	-0.020	-0.002	0.000	0.021
$T_{100}(i-2)$	β_{14}	0.003	0.018	0.182	0.076
$\phi_{100}(i-2)$	β_{15}	0.033	0.002	0.005	-0.024

$$y = 2\pi(Julian\ \ date - 1)/365$$

(6) The cosine of the zenith angle of the sun was calculated from

$$\cos\theta = \cos\delta\cos\omega\cos\phi + \sin\delta\sin\phi$$

where δ is the solar declination, ω is hour angle, and ϕ is latitude.

(7) The quantity $f = \ln\left(\frac{EUV_0}{C_d \cos\theta}\right)$ was then calculated and fitted by the method of least squares to the non-linear regression formula

$$f = a + b\mu O_3 + c\mu + d(\mu O_3)^2 + e\mu^2$$

to find the coefficients a, b, c, d, and e for use in equation (5).

Cloud Modification Factor

The cloud modification factors (*CMF*) for use in equation (2) developed by the European COST-713[8] were applied to the daily data. The *CMF* values used with clear sky EUV_0 are shown in Table 1.

Results

Ozone Models

Ozone models have been created for four areas. The coefficients from the study are given in Tables 2 to 5.

TO3CHM is a model fitted for Chiangmai, TO3UBN is for Ubon Ratchathani, DO3BKK is for Bangkok, and TO3SKL is for Songkhla. The initial 'TO3' is for TOMS

Table 3. Residuals analysis of total column ozone model.

	TO3CHM	TO3UBN	DO3BKK	TO3SKL	Avg.
R^2	0.91	0.93	0.82	0.87	0.88
ME	-0.21	0.09	-0.10	0.09	-0.03
RMSE	5.47	4.85	6.45	4.01	5.19
MAE	4.37	3.79	4.91	3.13	4.05
MAPE	1.66	1.43	1.91	1.17	1.54

Table 4. Coefficients of simple ozone model.

Coefficient.	STO3CHM	STO3UBN	SDO3BKK	STO3SKL
C_1	12.175	6.622	20.704	7.996
C_2	0.552	0.588	0.638	0.499
C_3	0.404	0.389	0.282	0.472

Table 5. Residuals analysis of simple ozone model.

	STO3CHM	STO3UBN	SDO3BKK	STO3SKL	Avg.
R^2	0.90	0.92	0.82	0.86	0.88
ME	0.15	-0.06	-0.01	0.04	0.03
RMSE	5.60	4.98	6.56	4.09	5.31
MAE	4.40	3.93	5.00	3.14	4.12
MAPE	1.67	1.48	1.94	1.17	1.56

Table 6. Coefficients of the UV models.

Model	*a*		*c*		*e*
EUVBKK75	7.1471	-0.6862	-1.7255	0.025	0.2453
EUVSKL75	7.3997	-4.8813	-0.5954	2.56	0.0647

Table 7. Residual Analysis of the UV models.

Model	R^2	ME	RMSE	MAE	MAPE
EUVBKK75	0.99	0.78	7.47	5.15	6.40
EUVSKL75	0.98	1.17	14.58	10.62	8.53
Avg.	0.99	0.98	11.02	7.88	7.47

ozone data, 'DO3' is for Dobson ozone data, and 'S' is for simple model. R^2 is the square of the correlation coefficient, ME is mean error, RMSE is root mean square error, MAE is mean absolute error, and MAPE is mean absolute percentage error.

UV Model

Two versions of a regression model were developed for UVI prediction in Bangkok and Songkhla. The coefficients which come from the study are given in Tables 6 and 7. Figures 4 and 5 compare the measured and calculated Erythemal UV values in Bangkok and Songkhla. At very high values of Erythemal UV, the model underestimates the measured values by about 15%. This suggests that further investigation of the modeling of extreme values is needed.

Daily and seasonal variations in the ratio of the measured to modeled UVI, adjusted by the *CMF*, at noon, during 2004 are illustrated in Fig. 6. There is a tendency for the application of the *CMFs* to underestimate the UV Indices during the wet season (June-October).

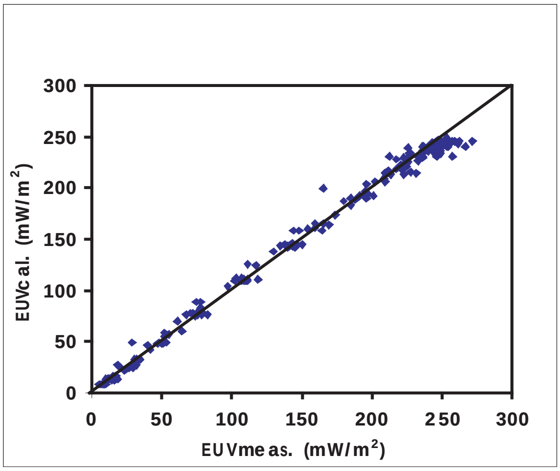

Fig 4. Comparison between measured and calculated Erythemal UV at Bangkok.

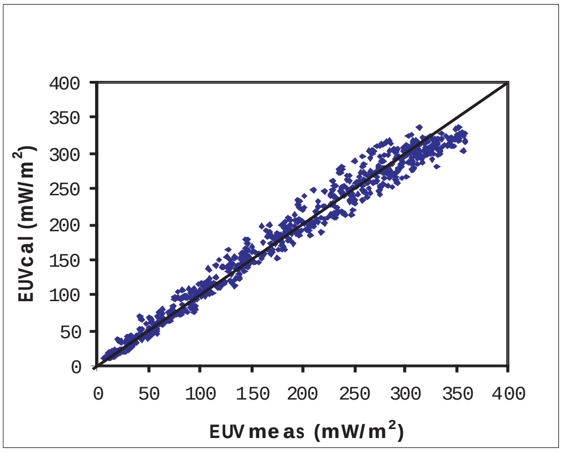

Fig 5. Comparison between measured and calculated Erythemal UV in Songkhla.

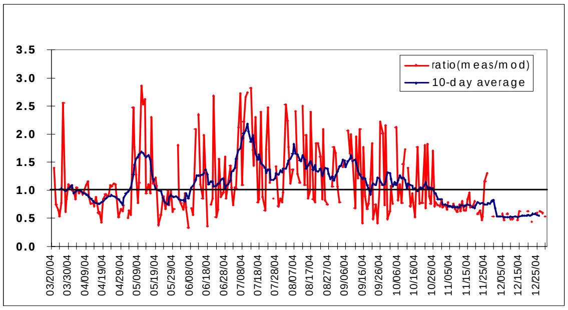

Fig 6. Ratio of measured to modeled UVI at noon, in Bangkok, in 2004, after applying *CMF*. Daily variation is shown by actual data. Seasonal variation is shown by 10-day averages.

STARsci Model

An additional tool for UV forecasting is the STARsci[14] radiative transfer model which is used in parallelwith the statistical model and for other locations where the statistical model is not available. The STARsci model was developed at the Meteorologisches Institut der Universität München in 1999. The STARsci model uses variable data sets for the description of the atmosphere as vertical profiles and totals (where appropriate) of ozone, nitrogen dioxide, sulfur dioxide, pressure, temperature, relative humidity, aerosol extinction, and liquid water content for homogeneous cloud layers, as well as solar zenith angle and ground albedo. The calculations are carried out for irradiance and integrals with respect to wavelength, especially for erythemal dose from 280 nm to 700 nm.

UV Forecasting

The UVI forecast issued daily by the Thai Meteorological Department is in the form of a map showing the UVI values calculated from the predicted clear sky EUV_0 at four locations in Thailand as in Fig.7. The UVI values are arranged in five exposure categories as in Table 8.

When the sky is cloudy the predicted values of the clear sky UVI can be reduced by a *CMF*, as in Table 1, to give predicted UV Indices under various sky cloudiness conditions in addition to the clear sky prediction.

Fig 7. A map of UV Index Forecast for clear sky[15].

Table 8. Exposure Categories.

Exposure category	UVI range
Low	< 2
Moderate	3 to 5
High	6 to 7
Very High	8 to 10
Extreme	11+

Discussion

The models presented in this paper for predicting erythemal UV are valid for zenith angles less than 75 degrees and AOD (τ_{aer}) in the range 0.2 to 0.5 under an average clear sky condition. Models for a completely clear sky with $\tau_{aer} < 0.2$, and for a polluted sky with $\tau_{aer} > 0.5$, are also available, but these models are not in use. Completely clear skies are rare, and although polluted skies often occur in the dry season, the average clear sky model is used with polluted skies to avoid the risk of underestimating the erythemal UV. Research directed towards the development of good AOD predictions would help to improve UVI forecasts.

Predicting the UVI by regression models is a convenient and good quality tool. Under air pollution conditions it may give an overestimation, and under a completely clear sky the result can be an underestimation. The challenge in UV forecasting is not clear sky calculation but applying modification factors. Whatever models are used, the uncertainty is in the unpredictability of aerosols and the dynamics of clouds, which change hour-to-hour or day-to-day. Therefore further study on these factors is necessary.

Conclusion

The total ozone and UVI can be predicted successfully by regression models which were created for the typical climate of Thailand. There are four versions of an ozone model for Chiangmai, Ubon Ratchathani, Bangkok and Songkhla, and two versions of UV model for Bangkok and Songkhla.

The total ozone model in this study uses fifteen coefficients in a linear regression formula, and three coefficients for a simple formula. The total ozone model is to be used on days when the upper air observations are available, and the simple model is to be used on the days without upper air data. The output of ozone forecasts will be the input of the UV models.

Two versions of the empirical UV model are used to predict the level of erythemal UV for clear skies in Bangkok and Songkhla. For the northern part of Thailand, Chiangmai, and north-eastern part, Ubon

Ratchathani, the radiative transfer STARsci model is used to estimate the level of Erythemal UV by choosing appropriate input parameters. The EUV_0 output for a clear sky is converted to a UVI for issuing to the public at noon daily. UV Indices adjusted with the *CMF*s are provided for use in different sky cloudiness conditions.

The average accuracies of all the models are acceptable as the square of the correlation coefficients (R^2) for the ozone and UV models are 0.88 and 0.99, while the mean absolute percentage error of the residuals are 1.5% and 7.5% respectively.

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