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Characteristics and Prediction of Total Ozone and UV-B Irradiance in East Asia Including the Korean Peninsula

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The average ratio of the daily UV-B to total solar (TS) irradiance at Busan (35.23°N, 129.07°E) in Korea is found as 0.11%. There is also a high exponential relationship between hourly UV-B and total solar irradiance: UV-B=exp (a×(TS-b))(R^2=0.93). The daily variation of total ozone is compared with the UV-B irradiance at Pohang (36.03°N, 129.40°E) in Korea using the Total Ozone Mapping Spectrometer (TOMS) data during the period of May to July in 2005. The total ozone (TO) has been maintained to a decreasing trend since 1979, which leading to a negative correlation with the ground-level UV-B irradiance during the given period of cloudless day: UV-B=239.23-0.056 TO (R^2=0.52). The statistical predictions of daily total ozone are analyzed by using the data of the Brewer spectrophotometer and TOMS in East Asia including the Korean peninsula. The long-term monthly averages of total ozone using the multiplicative seasonal AutoRegressive Integrated Moving Average (ARIMA) model are used to predict the hourly mean UV-B irradiance by interpolating the daily mean total ozone for the predicting period. We also can predict the next day's total ozone by using regression models based on the present day's total ozone by TOMS and the next day's predicted maximum air temperature by the Meteorological Mesoscale Model 5 (MM5). These predicted and observed total ozone amounts are used to input data of the parameterization model (PM) of hourly UV-B irradiance. The PM of UV-B irradiance is based on the main parameters such as cloudiness, solar zenith angle, total ozone, opacity of aerosols, altitude, and surface albedo. The input data for the model requires daily total ozone, hourly amount and type of cloud, visibility and air pressure. To simplify cloud effects in the model, the constant cloud transmittance are used. For example, the correlation coefficient of the PM using these cloud transmissivities is shown high in more than 0.91 for cloudy days in Busan, and the relative mean bias error (RMBE) and the relative root mean square error (RRMSE) are less than 21% and 27%, respectively. In this study, the daily variations of calculated and predicted UV-B irradiance are presented in high correlation coefficients of more than 0.86 at each monitoring site of the Korean peninsula as well as East Asia. The RMBE is within 10% of the mean measured hourly irradiance, and the RRMSE is within 15% for hourly irradiance, respectively. Although errors are present in cloud amounts and total ozone, the results are still acceptable.

Key Words : Total ozone, UV-B irradiance, Statistical predictions, UV-B MED, Parameterization model, Cloud transmittance

1. Introduction

Ozone is one of the most significant atmospheric constituents controlling the intensity of solar UV-B irradiance (280 to 320 nm). The decrease of total ozone results in the increase of UV-B irradiance on the Earth's surface. High levels of UV-B irradiance are harmful to all humans, plants, and animals. Biologically harmful UV irradiance has been measured by satellite. These measures of ozone and reflectivity include TOMS, SBUV (Solar Backscatter Ultraviolet) and TOVS (TIROS Operational Vertical Sounder) [1~3]. Despite the help of measures, the long-term monitoring of ground-based total ozone and UV-B irradiance is necessary for evaluating and predicting these im-

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pacts on human health and the Earth's ecosystems.

Since the measuring networks of total ozone and UV-B irradiance have not been established adequately in Korea and other countries, numerical models can be used instead of to calculate present and future amounts. Three-dimensional chemical transport models and radiative transfer models can be used. Most UV-B radiative transfer models such as MODTRAN, however, have been validated at one dimension with irregular measurement or simulation data of vertical profiles of ozone. Such models are not intended for practical computation of surface estimates of UV-B irradiance. It is not easy to predict the total amount and vertical profiles of ozone using 3-D chemical transport models because of input data and the feedback effects associated with atmospheric dynamics, radiation and chemistry. Therefore, it is important to provide prediction models of total ozone and UV-B irradiance that can calculate the amounts from readily available meteorological parameters such as air temperature, air pressure, cloud condition and visibility.

Total ozone on timescales of hours to several days has been correlated with lower stratospheric temperatures, geopotential heights, winds, tropopause pressure (or height), and isentropic potential vorticity near the tropopause. A number of recent studies have presented methods for predicting total ozone based on statistical correlations between total ozone and these meteorological variables[4~7,1)]. The daily total ozone data have been taken by TOMS, SBUV, TOVS and other satellite instuments, and the meteorological variables have been provided by NCEP (National Centers for Environmental Prediction), ECMWF (European Centre for Medium-Range Weather Forecasts), NWS (National Weather Service), NMSs (National Meteorological Services) and any other regional NWP (Numerical Weather Prediction) models. Korea Meteorological Agency (KMA) has been conducting a regular measurement of total ozone using the Brewer spectrometer since 1994 at Pohang (36.03°N, 129.40°E) and 1997 at Seoul (35.57°N, 126.95°E), and LIDAR since 2002 at Anmyun (36.31°N, 126.20°E) in Korea. The daily data analyses show a strong correlation between total ozone and maximum air temperature at the earth's surface. Like this, it's important to predict total ozone using readily available meteorological factors. Above all, it's necessary for us to develop the regional prediction model of total ozone that can consider dense population and complicated mountains as in East Asia as well as South Korea. The predicted total ozone is usually used to input data for the forecast model of UV-B irradiance.

Theoretical studies of UV-B increase due to ozone depletion have been made extensively since the 1970's, but the long-term observational studies have not yet been enough[8)]. The main concern has been to demonstrate model sensitivity for cloudless skies[9-13)]. Most UV-B irradiance has been predicted by using radiative transfer models. In general, two important factors that influence surface UV-B irradiance are total ozone and clouds. Clouds have been incorporated as constitutes of particular atmospheric layers with specified optical depths and scattering properties[14~19)]. Daily forecasts of UV-B irradiance derived from predicted total ozone may be determined by the cover degree, optical thickness, height, opacity, and type of cloud[10)]. Therefore, UV-B irradiance can be calculated using cloud attenuation factors based on an empirical exponential, linear, and constant relationship[20,15,3)]. Because these empirical values may be due to different climatic conditions and different transparencies of clouds, the transmittance with types of clouds needs to be confirmed using long-term observation data.

Total ozone and biological UV-B MED (Minimum Erythema Dose: 1 MED = 210 J/m^2) have been measured at Pohang (36.03°N, 129.40°E) in Korea since 1994. Additionally, UV-B, UV-A and total solar irradiance had been observed at Busan (35.23°N, 129.07°E) in Korea during the 2 yr period of 1997 - 1998. The purpose of this study is to identify interrelationship among UV-B, UV-A and total global irradiance measured at Busan, to analyze time series of total ozone and UV-B irradiance using the TOMS and Brewer spectrophotometer data at Pohang, and to predict of total ozone and UV-B irradiance using the MM5 output data in East Asia (20°N–60°N, 120°E–150°E) including the Korean peninsula. For the daily prediction of total ozone, we compose a multiple regression model that uses simple variables such as the daily total ozone retrieved by TOMS and the meteorological factors observed at each meteorological monitoring site of the Korean peninsula as well as the MM5 output forecasted in East Asia. In order to predict long-term variations of total ozone, we introduce

ARIMA (Auto-Regressive Integrated Moving Average) model, which is one of the most general classes of models for forecasting a time series using a single variable. In particular, these statistical models are useful when the remote sounding data such as TOMS and other satellites have not been provided. In addition, we introduce and verify the parameterization model of UV-B irradiance that can consider the influences of solar zenith angle, total ozone, albedo, turbidity (or visibility), altitude, and cloud transmittance under cloudiness skies.

2. Characteristics of total ozone and UV-B irradiance

2.1. Data

To account for average ratios of UV-B irradiance reaching the ground with UV-A and total solar irradiance, we used the data of biological UV-B MED (Minimum Erythema Dose: 1 MED = 210 J/m^2, 1 MED/HR =$5.83*10^{-2}$ W/m^2). The data was taken by UV-Biometer from 1996. UV-B (280-315nm), UV-A (315-400nm) and total solar (300-2800nm) irradiance (kJ/m^2) were taken by EKO radiometers from 1997. All measures were carried out at Busan (35.23°N, 129.07°E) in Korea. The UV-Biometer, which was employed in the worldwide network for UV-B monitoring, was made sensitive to the wavelength range of the UV-B through a combination of special filters and a spectral sensitivity adapted to the action spectrum of a biological reaction in the human skin Erythema[21). The characteristics of the UV-Biometer are introduced by http://www.solarlight.com/faqs/documents/501.pdf. The measurement was taken every day by integrating UV-B MED every 5 minutes from sunrise to sunset. The EKO radiometers also are instruments specially designed for measurement of UV-B, UV-A and total solar irradiance. They are extremely useful in evaluating the increase of the ultraviolet radiation, and that has well-known harmful effects on organisms caused by the depletion of the ozone layer. These radiometers are specially designed to minimize the spectral mismatch error that occurs due to changes in the sun's spectrum. The spectral responses of these radiometers are shown at http: // www.eko.co.jp/eko/english/03/a.html.

To analyze and predict total ozone, one of the most important factors affecting the surface UV-B irradiance of a cloudless day, the daily data were used with UV-B irradiance (McKinley-Diffey action spectrum, $J/cm^2/day$) observed by a Brewer spectrophotometer. The vertical profiles of ozone partial pressure, air temperature, air pressure and humidity were chosen by ozonesondes measured at Pohang in Korea. These measurements had been taken since 1994. A Brewer spectrometer operates at ground level, automatically tracking the sun and reading radiance at wavelengths that are absorbed by ozone, sulfur dioxide and nitrogen dioxide. The total column units used throughout Brewer data are Dobson Units (DU). One DU is equivalent to 1 milliatmosphere centimeter (m- atm-cm) or 1.0E-03cm of pure ozone at STP. Conversions are possible to transform the total column DU to local ozone SI units. UV spectral scans also cover the 290-325nm (optional 286.5-363nm) wavelength range in 0.5nm increments. Non weighted spectral values of UV irradiance from a hemispherical field of view are determined for each wavelength increment as Watts per square meter (http://www. rg-messtechnik.de/ produkte/ solartechnik/ brewer.html). The type of ozonesonde is the model 5A ECC (Electrochemical Concentration Cells). These techniques are introduced at http://katipo.niwa.cri.nz/lauder/nrphome.htm/history. In addition, the data of total ozone for the regression and ARIMA are used in daily and monthly TOMS for a 26yr period (1979-2004) interpolated in Pohang, Busan and other sites in Korea (http://jwocky.gsfc. nasa.gov/news/news.html). In particular, the data of Brewer spectrometers and TOMS were compared for the 4yr period of 1997-2001 as seen in Fig. 1, and correlation

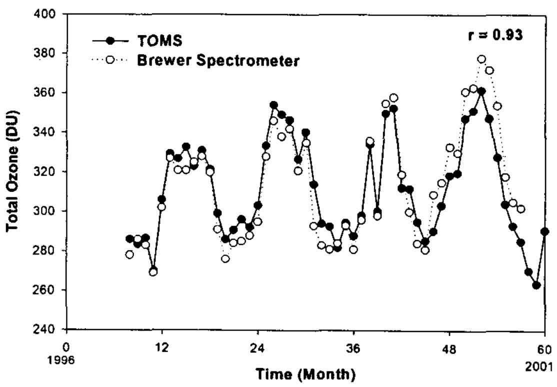


Fig. 1. Intercomparison of total ozone between a Brewer spectrophotometer and TOMS at Pohang for the 4yr period of 1997-2001.

coefficient between both was shown in 0.93.

To predict daily UV-B MED with meteorological data in Korea, the hourly data of UV-Biometers were taken at UV-B monitoring sites such as Anmyun (36.31°N, 126.10°E), and Cheju (33.17°N, 126.19°E) in addition to Pohang and Busan for 1998. Furthermore, the amount and types of clouds for calculating the cloud transmittance were also chosen by the Korea Meteorological Agency (KMA) for the 11 yr period of 1984-1994[22]. In particular, MM5 (Mesoscale Meteorological Model 5) was simulated to predict the maximum air temperature and air pressure, and amount of cloud for the period from May to July 2005.

MM5 was initialized with 2.5 NCEP-NCAR GDAS (National Centers for Environmental rediction-National Center for Atmospheric Research Global Data ssimilation System) datasets for forecasting total ozone in Eastern Asia. We ran two-way nested domains starting at a resolution of 27km over Eastern Asia to 9km for the Korean peninsula. MM5 was integrated for 48 hours, and the time resolution was fixed at 81 sec to domain 1 and 27 sec to domain2, respectively, for 33 vertical layers. The model code was used to a Lambert Conic Conformal projection with a 69 by 60 9-km grid centered at (36.2N, 127.3E) grid. The model domain ranges are in East Asia (20°N-60°N, 120°E-150°E) including the Korean peninsula. We have adopted the following physics for MM5: Mix phase microphysical parameterization; Kain-Fritsch cumulus parameterization; RRTM (Rapid Radiative Transfer Model Rapid Radiative Transfer Model) longwave radiation; cloud-radiation shortwave; MRF (Medium- Range Forecast) planetary boundary layer; 5-lyer thermal diffusion surface layer parameterization model.

2.2. The distribution of total ozone and UV-B irradiance

UV irradiance is usually divided by wavelength in UV-C (less than 280nm), UV-B (280-320nm), and UV-A (320-400nm). These consist of 0.5%, 1.5%, and 6.3% of the solar irradiance at the top of the atmosphere, respectively[22]. Although UV-C is absorbed almost all by the ozone layer because of both ozone and molecular oxygen absorption, there is UV irradiance for wavelengths less than 320nm that is harmful: UV-B, which is strongly absorbed by ozone; and UV-A, which is hardly absorbed by ozone. Fig. 2 shows the daily variation of UV-B, UV-A and total solar (TS) irradiance (kJ/m^2) measured by EKO radiometers at Busan in Korea from September 1997 to February 1999. It clearly shows that UV-B has a non-linear relationship with UV-A and TS because not only the TS irradiance but also the UV irradiance depends on the local tropospheric diffuse sky condition. That is, the seasonal variation in UV-B is due to the larger number of clear days in winter, hence there is less scattering in winter than in other seasons. On the other hand, the reason for uniformity of the ratio to UV-B/TS irradiance may be explained by the compensation of four main factors which affect the scattering: weather, air mass, Rayleigh scattering, and Mie scattering[23]. The daily average ratios of UV-B, UV-A and TS irradiance for the 2yr period of 1997 -1999 are given in Table 1. The average ratios of the daily integrated UV-B/TS, UV-A/TS and UV-B/UV-A were presented as 0.11%, 5.03% and 2.03% on the Earth's surface, respectively. Consequently, the UV-B irradi-

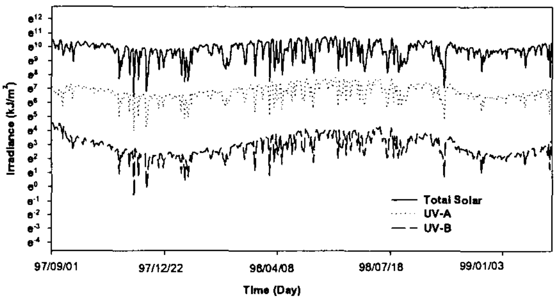


Fig. 2. Variation in daily integrated UV-B, UV-A, and total solar irradiance in Busan, Korea from September 1997 to February 1999.

Table 1. Averages (kJ/m^2) of daily integrated UV-B, UV-A, and TS (Total solar) irradiance with the average ratios (%) of UV-B/TS, UV-A/TS, and UV-B/UV-A from September 1997 to February 1999. σ is the standard deviation of the mean

	UV-B	UV-A	TS	UV-B/TS	UV-A/TS	UV-B/UV-A
Mean	2.12×10^1	9.68×10^2	2.03×10^4	0.11	5.03	2.03
σ	1.51×10^1	5.12×10^2	1.02×10^4	0.05	1.25	0.51

ance at ground level was shown in a small amount as 0.11% of the TS irradiance, which might be due to scattering and absorption by atmospheric constituents from 0.5% at the top of the atmosphere as suggested by Sasaki *et al.* (1993)[23].

To analyze the nonlinear relationship between UV-B MED (Minimum Erythema Dose), UV-B, UV-A and TS irradiance, we took the hourly data at random for 17 days under clear skies at Busan in 1998. The results are compared in Table 2. It is shown that there is a high exponential relationship between hourly UV-B and TS irradiance. We gained a high coefficient of determination (R^2) of more than 0.93 from the exponential relationship: UV-B=exp (a×(TS-b)), where a and b are parameters. As a result, UV-B irradiance can be estimate indirectly by using the hourly TS irradiance observed at each local meteorological monitoring site in Korea.

The amount of UV-B irradiance received at any particular location on the Earth's surface, however, depends upon the solar zenith angle, total ozone and aerosols in the atmosphere, local cloudiness and other air pollution. Scientists agree that, in the absence of changes in clouds or pollution, decreases in atmospheric ozone lead to increases in ground-level UV-B radiation, because ozone is an effective absorber of UV-B irradiance. Fig. 3 shows the daily time series of total ozone data interpolated by TOMS at Pohang and Busan for the 22 yr period of 1979~2000, and Fig. 4 presents normalized variation of total ozone from 1979 to 2004 at Seoul, Pohang, and Jeju in Korea. The long-term trend of satellite-based total ozone (TO) in the Korean peninsula has been decreasing since 1979. For example, its trend at Pohang is as follows :TO=316.3675-0.0017*Julian day. As seen in Fig. 4, the sudden decreases of total ozone in the

Table 2. Hourly calculated diagram between UV-B MED and total solar (TS) irradiance, between UV-A and TS irradiance, between UV-B and TS irradiance, and between UV-B MED and UV-B irradiance for cloudless days in 1998

Regression Equation	Coefficient of Determination (R^2)
V-B MED = Exp (0.000955 (TS-2364))	0.93
V-B = Exp (0.000992 (TS-1721)	0.93
V-A = -0.987 + 0.42 TS	0.92
V-B MED = 0.029 + 0.505 UV-B	0.99

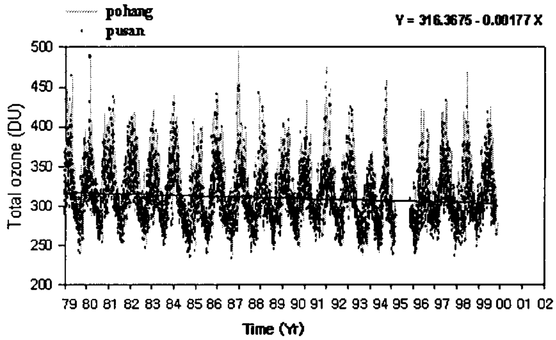


Fig. 3. Daily time series plot of total ozone interpolated by TOMS at Pohang and Busan for the 22 yr period of 1979~2000.

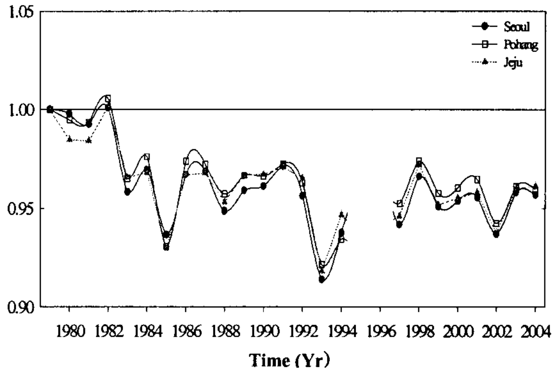
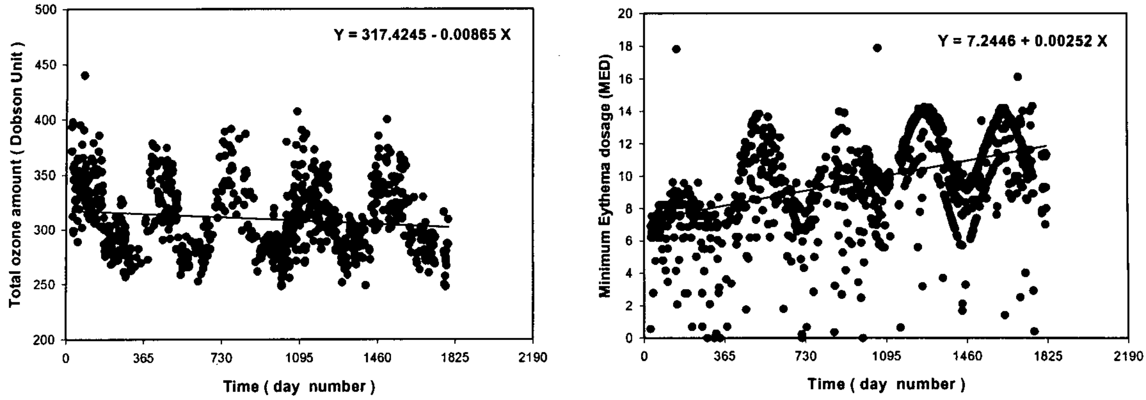


Fig. 4. Normalized variation of total ozone from 1979 to 2002 at Seoul, Pohang, and Jeju in Korea.

Korean peninsula are shown in about 7% and 9% to normalized 1979, respectively, in 1985 and 1993. Such a result could be considered as effect of aerosols by the El Chichon and Pinatubo volcanic eruptions that occurred in 1982 and 1991, respectively[24]. These interrupt reactions for ozone production by decreasing UV-B irradiance.

Fig. 5 shows the daily variation of total ozone and UV-B MED ($J/cm^2/day$) measured by the Brewer spectrometer at Pohang for the 5yr period of 1994-1998. It is expected that the increased total ozone (TO= 317.4245-0.00865*Julian day) leads to decrease in UV-B irradiance (UV-B MED=7.2446 + 0.00252 Julian day) on the Earth's surface. Fig. 6 also shows daily variation and its relationship of TO and UV-B MED retrieved by TOMS during cloudless days from May to July in 2005 at Pohang. It shows a strong negative relationship of UV-B MED to TO: UV-B MED= 223.69-0.056 TO (R^2=0.52).

In particular, however, the UV-B MED of a low



(a) (b)

Fig. 5. Daily variation of UV-B MED (J/cm²/day) and total ozone measured by the Brewer spectrometer at Pohang for the 5 yr period 1994-1998. (a) Total ozone and (b) UV-B MED.

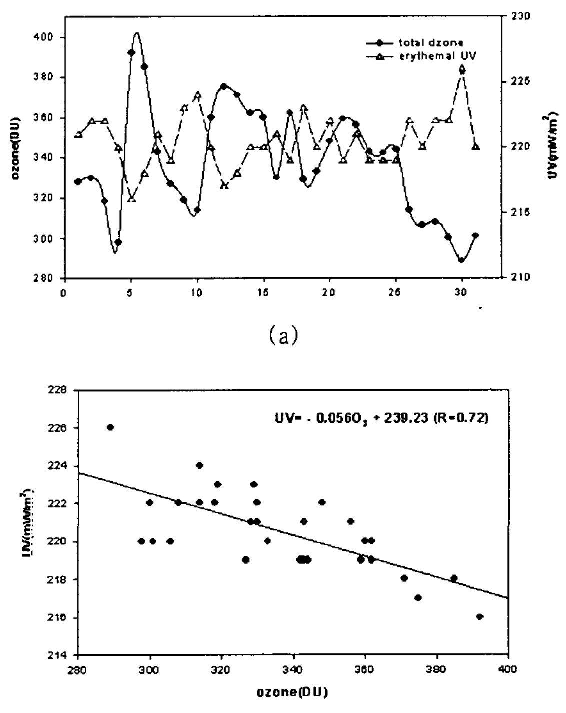


Fig. 6. Daily variation and its intercomparison of UV-B MED and total ozone (O_3) retrieved by TOMS data for cloudless days from May to July in 2005 at Pohong. (a) Daily comparison and (b) the relationship of UV-B MED to total ozone (O_3).

level at Pohang for 1998 seems to be due to the local cloud amounts in Korea. We attempted a linear regression analysis by using the daily data of total ozone (TO) and UV-B MED with cloud amount (C) and other meteorological factors at Pohang in Korea for 1998. As a result, the main valid factors that affects UV-B MED is cloud amount (C) and TO, and its related equation is as follows: UV-B MED= 4.35+0.600C-0.440TO (R^2=0.94). Then, TO and C follow t-value more than two.

Above all, the trends of total ozone and UV-B irradiance require long-term data for the periods longer than ten years together with accuracy of instrumentation. It is difficult to consistently maintain instrumentation over such a long period of time and to compare with other instruments at a site. Many other factors such as local cloud covers and aerosols, altitude and latitude, and the measuring errors of monitoring technique and calibration methods also can affect data trends. It is still difficult to analyze the trends of total ozone using appropriate statistical techniques during a short period. However, it is clear that the total ozone amount is an effective absorber of UV-B irradiance.

3. The prediction models of total ozone and UV-B irradiance at each meteorological monitoring site

3.1. Total ozone

As seen in Fig. 1, there were distinct differences between the ground-based Brewer spectrometer and nadir-viewing TOMS, but the correlation coefficient between both daily total ozone was shown in 0.93. It is shown that the next day's ozone can be predicted by using these daily or monthly mean TOMS data at each meteorological monitoring site without the Brewer spectrometer.

Multiplicative seasonal ARIMA (AutoRegressive Integrated Moving Average) model was examined to predict monthly mean variation of total ozone. This model is useful for predicting time series of a strong seasonal sinusoid with no observation data of TOMS from November 1994 to July 1996 as shown in Fig. 3. When time series of total ozone (Z_t) depends on differential factors of general time series (p, d, q) and that of seasonal time series (P, D, Q) with seasonal period (s=12), the general form of the multiplicative seasonal ARIMA (p, d, q) × (P, D, Q) s model is as follows:

$$\Phi(B^s)\phi(B)(1-B)^d(1-B^s)^D Z_t = \theta(B)\Theta(B^s)\mu_t \qquad (1)$$

where $\Phi(B^s)(=1- \Phi_1 B^s-\Phi_2 B^{2s} \ldots)$ is the seasonal AR (AutoRegressive), $\phi(B)$ $(=1-\phi_1 B-\phi_2 B\ldots)$ is the general AR, $\Theta(B^s)(= 1- \Theta_1 B^s-\Theta_2 B^{2s} \ldots)$ is the seasonal MA (Moving Average), $\theta(B)(1-\theta_1 B -\theta_2 B\ldots)$ is the general MA, B is the backshift operator, and μ_t is the white noise. General and seasonal differential factors, (p, d, q) × (P, D, Q) can be estimated by using the pattern of ACF (AutoCorrelation Fuction) and PACF (Partial AutoCorrelation Function), and the duality of AR and MA.

The multiplicative seasonal ARIMA model using monthly mean TOMS data at Pohang was presented as ARIMA (1, 0, 0) × (0, 1, 1) 12 from the SAS (Statistic Analysis System) package. That is, this model includes the pattern of general AR (p=1) and that of seasonal MA (Q=1) through once seasonal differentiation of D=1 with seasonal period of s=12. The parameters such as Φ, ϕ, θ, and Θ are determined by the maximum likelihood estimation through the SAS package. Equation (2) is rearranged by substituting these differential factors and parameters for equation (1):

$$Z_t = Z_{t-12} + a\ (Z_{t-1} - Z_{t-13}) + \mu_t - b\ \mu_{t-1} \qquad (2)$$

where Z_{t-1}, Z_{t-12} and Z_{t-13} express the amount of total ozone in last month, the 12^{th} last month and the present month last year, respectively, and μ_t and μ_{t-1} represent moving errors between present and last month. The parameters of a and b are obtained by the maximum likelihood estimation, and subscript t denotes the present month.

The simple regression models, which is analyzed by the stepwise method from given data, for predicting the daily total ozone (TO) were examined by using the data of TOMS with the meteorological factors from the Korea Meteorological Administration, and by using the MM5 (Mesoscale Meteorological Model 5) output data such as the maximum air temperature, air pressure and amount of cloud.

As a result, we used the maximum air temperature (T_{max}) next day as the dependent variable:

$$TO_{t+1} = TO_t + c\ T_{max\_t} \qquad (3)$$

where subscript t+1 denotes the next day, t is the present day, and c is a local regression coefficient at a local monitoring site in Korea. The predicted total ozone is used to input data for the parameterization model of UV-B irraiance.

3.2. UV-B irradiance

3.2.1. Parameterization model

The model of UV-B irradiance in a cloudy sky follows the form adopted for broad-band solar radiation[15]. UV-B spectral irradiance $F(\lambda)$ on the earth's surface is given by the following equation:

$$F(\lambda) = F_0(\lambda)\Pi[(1-C_i) + t_i C_i]/(1-\alpha\beta) \qquad (4)$$

where $F_0(\lambda)$ is the cloudless sky UV-B spectral irradiance, C_i and t_i are the observed cloud amount and the cloud transmissivity for cloud type in layer i, α is the surface albedo, and β is atmospheric backscatter for radiation reflected from the surface. The cloud transmission for each cloud layer has a cloudless part ($1 - C_i$) and a cloudy part $t_i C_i$.

UV-B spectral irradiance $F_0(\lambda)$ in a cloudless sky is as follows[25].

$$F_0(\lambda) = S_0(\lambda)\ D_e \cos\theta_z\ \tau_{O3}(\lambda)\ [\tau_R(\lambda)\ \tau_A(\lambda) + \tau_A(\lambda)(1-\tau_R(\lambda))/2 + \tau_R(\lambda)\ (1-\tau_A(\lambda))\ F_w\ \omega_0] \qquad (5)$$

where $S_0(\lambda)$ is the extraterrestrial UV spectral irradiance obtained by Nicolet[26] and MODTRN, D_e is the eccentricity correction factor of the earth's orbit, θ_z is the solar zenith angle, $\tau_{O3}(\lambda)$ is the transmissions after absorption by ozone, $\tau_R(\lambda)$ is the transmissions after absorption by Rayleigh (molecular) scattering, $\tau_A(\lambda)$ is the transmissions after absorption and scattering by aerosol, F_w is the ratio of forward to total scattering by aerosols[27], and ω_0 is the single scattering albedo.

The eccentricity correction factor and various transmission functions are given by the following simplified equation:

$$D_e = 1.00011 + 0.034221\cos\theta_d + 0.00128\sin\theta_d - 0.000719\cos(2\theta_d) + 0.000077\sin(2\theta_d) \quad (6)$$

$$\tau_{O3}(\lambda) = \exp(-k_\lambda O_3 m_r) \quad (7)$$

$$\tau_R(\lambda) = \exp(-0.008735\lambda^{-4.08} m_r) \quad (8)$$

$$\tau_A(\lambda) = \exp(-d_A \lambda^{-e} m_r) \quad (9)$$

$$d_A = 0.55^e\,[(3.912/\text{visibility} - 0.1162)(0.02472(\text{visibility}-5) + 1.132)] \quad (10)$$

$$m_r = [35/(1224\cos\theta_z^2 + 1)]p/p_0 \quad (11)$$

where θ_d is the day angle 2π $(d_n-1)/365$, d is the Julian day, and k_λ *is the attenuation coefficient by* ozone, O_3 is the vertical ozone layer thickness (cm), m_r is the relative optical air mass, d_A is called Angstrom's turbidity coefficient, e is the wavelength exponent, p is the station air pressure (hPa), p_0 is the sea level air pressure (1013 hPa), and the wavelength λ is in micrometers.

Cloud transmissivities are obtained from the following exponential and constant forms:

$$t_i = f_i \exp(-g_i m_r) \quad (12\text{-}1)$$

$$\approx T_i \quad (12\text{-}2)$$

where f_i and g_i are empirically determined parameters for different cloud types[20]. And T_i is the constant cloud transmissivity, which is determined by dividing that observed during a cover cloud type by the solar irradiance calculated for a cloudless day over Korea. Table 4 shows these empirical parameters confirmed by cover clouds for the periods of 11 yrs (1985-1996) in Korea[22].

The albedo of the atmosphere for the reflected radiation can be expressed as follows:

$$\beta = \beta_R(1-C) + \beta_A + \beta_C C \quad (13)$$

$$\beta_A = (1-\tau_A(\lambda))\,\omega_0(1-\beta_A) \quad (14)$$

where β_R is the sum of components due to Rayleigh (molecular) scattering assumed to apply only to the cloudless portion of the sky (0.0685[28]), β_A is scattering by aerosol in the atmosphere below cloud base, β_C is the average cloud albedo (0.6[29]), and C is the total cloud amount.

Table 3. Daily regression models of predicted total ozone (PTO) using TOMS data at each monitoring site (Busan, Pohang, Anmyen and Cheju,) in Korea for *1998*. O_3 is the present day's ozone, T_{max} is the next day's predicted maximum air temperature, and R^2 *is coefficient of determination*

Regression Equation	R^2
PTO = 221 + $0.712O^3$ - 0.452Tmax (Busan)	0.60
PTO = 258.56 + $0.74O_3$ - 0.6Tmax (Pohang)	0.64
PTO = 235.76 + $0.74O_3$ - 0.52Tmax (Anmyen)	0.63
PTO = 162.06 + $0.74O_3$ - 0.29Tmax (Cheju)	0.58

The biological dose of UV at the surface is given by integration of the spectral irradiance $F(\lambda)$ and an Erythemal action spectrum $A(\lambda)$ given by McKinlay and Diffey[30]:

$$\text{UV DOSE} = \iint F(\lambda)\,A(\lambda)\,d\lambda dt \quad (15)$$

$$A(\lambda) = 1.0\ (\lambda \le 298\text{ nm}),\ 10^{0.094\,(298-\lambda)}\ (299\text{nm} \le \lambda \le 328\text{nm}),\ \text{and}\ 10^{0.015\,(139-\lambda)}\ (\lambda \ge 329\text{nm}) \quad (16)$$

3.2.2. Radiative transfer model

To examine the spectral irradiance of the parameterization model in the UV-B band, we compared with radiative transfer model such as MODTRAN3 (Moderate Resolution Transmittance 3) that calculates atmospheric transmittance and radiance for frequencies from 0 to 50,000 cm^{-1}. MODTRAN was driven by a need for higher spectral resolution than LOWTRAN. Except for its molecular band model parameterization, MODTRAN3 adopts all the LOWTRAN7 capabilities, including spherical refractive geometry, solar and lunar source functions, and scattering (Rayleigh, Mie, single and multiple), and default profiles (gases, aerosols, clouds, fogs, and rain). Input data of MODTRAN3 were used in vertical profiles of ozone partial pressure, air pressure, air temperature, and humidity observed by ozonesondes at Pohang in Korea.

3.3. Error assessment

The model will contain errors due to inaccuracies in the model itself and in the input data. The performance of the model in estimating irradiances for periods of a day or longer will be discussed using the mean bias error (MBE) and the root mean square error (RMSE), the relative mean bias error (RMBE), and the relative root mean square error (RRMSE).

They are expressed as:

$$MBE = [\Sigma\ (P_i - M_i\ )]/N \quad (17)$$

$$RMSE = \{[\Sigma\ (P_i - M_i)]/N\}^{1/2} \quad (18)$$

$$RMBE = [\Sigma\ (P_i - M_i\ )/M_i]/N \quad (19)$$

$$RRMSE = \{[(\Sigma\ (P_i - M_i)^2/M_i^2)\ /N\ ]^{1/2} \quad (20)$$

where P_i and M_i are the ith predicted and measured UV-B irradiance, and N is total number

4. Results

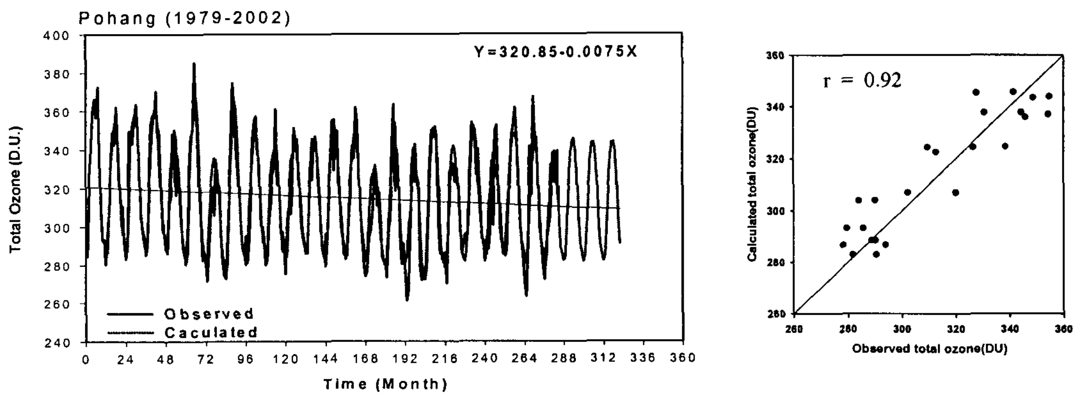
4.1. Prediction of daily total ozone

Fig. 7 presents a monthly time series plot and the correlation of total ozone fitted and predicted by the multiplicative seasonal ARIMA model (1,0,0) x (0, 1, 1) 12 of the equation (2) at Pohang in Korea for the 24 yr period of 1979-2002.
Equation (2) derived from ARIMA (1,0,0) x (0, 1, 1) 12 model is expressed as follows: $Z_t = Z_{t-12} + 0.4595(Z_{t-1} - Z_{t-13}) + \mu_t - 0.8690\ \mu_{t-1}$.

After the model of equation (2) was created by using TOMS data for the 16 yr period of 1979-1994, the monthly mean total ozone was predicted for the next two years (1995-1996). Fig. 7 (b) shows the correlation of monthly mean variations between observed and predicted total ozone from 1995 to 1996. The correlation coefficient was shown in 0.92, and RMBE and RRMSE were seen within 5% and 1.1%, respectively. Monthly averaged total ozone by the multiplicative seasonal ARIMA model is useful for predicting hourly mean UV-B irradiance by interpolating daily mean total ozone for the predicted period. In this way, we can predict the long-term mean variation of total ozone for more than a year at each meteorological monitoring site in Korea or other countries.

Fig. 8 shows the daily time-series plot of the observed and predicted total ozone at Pohang for 1998, and Table 3 shows daily regression models and the errors of total ozone from TOMS data at Cheju, Busan, Pohang and Anmyun for 1998. Time variation in total ozone was seen to be well-captured by regression model. Although coefficients of determination of the regression models were more or less not high, RMBEs and RRMSEs were shown within 5% for 1998. Correlation coefficients of regression models between observed and calculated daily total ozone were seen in 0.80, 0.77, 0.79, and 0.76, respectively, at Pohang, Busan, Cheju and Anmyun for 1998. The predicted models were presented in low errors as results of both RMBEs within 5% and RRMSEs within 3%. The next day's total ozone was founded to be strongly dependant on both the maximum air temperature and the present day's total ozone. In the same way, we can predict the next day's total ozone by using the present day's total ozone retrieved by TOMS and the next day's maximum air temperature predicted by MM5 at each meteorological monitoring site in Korea as well as East Asia.

Fig. 9 shows input parameters of the MM5 output for predicting daily total ozone in East Asia on 27



(a) (b)

Fig. 7. Monthly time series of total ozone fitted by the multiplicative seasonal ARIMA model at Pohang in Korea for the 18 yr period of 1979-2002 (a) and the correlation plot predicted for the 2 yr period of 1995-1996 (b).

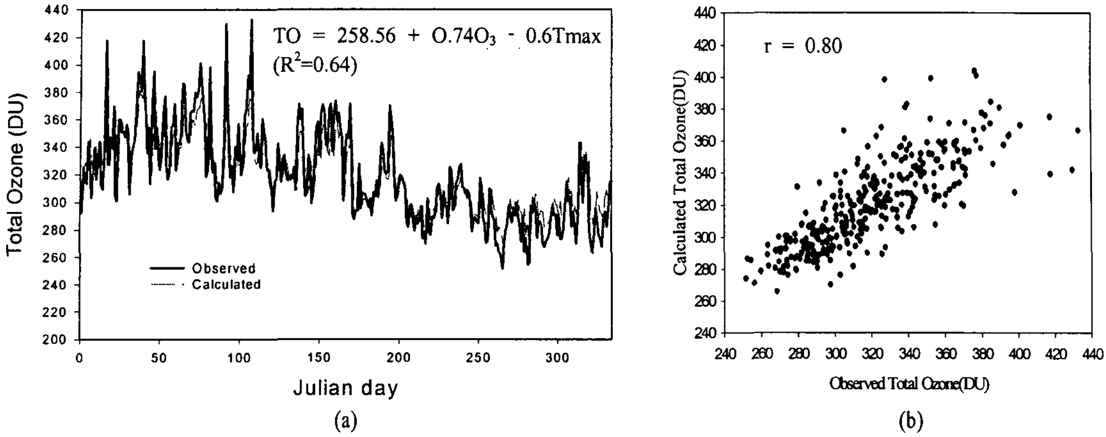


Fig. 8. Daily time series of total ozone fitted using the regression model at Pohang for 1998 (a) and correlation fitted for the same period (b).

Table 4. Cloud parameters confirmed by cover clouds for the period of 11 yr (1985-1996) in Korea. f_i and g_i were examined by Haurwitz (1948)

Cloud type	f_i	g_i	T_i
Altocumulus (Ac)	0.556	0.056	0.730
Altostratus (As)	0.413	0.004	0.560
Cirrocumulus (Cc)	0.923	0.089	0.840
Cirrostratus (Cs)	0.923	0.089	0.820
Cirrus (Ci)	0.871	0.020	0.870
Cumulonimbus (Cb)	0.119	-0.226	0.110
Cumulus (Cu)	0.368	0.045	0.350
Stratus (St)	0.252	0.100	0.225
Nimbostratus (Ns)	0.119	-0.226	0.198
Stratocumulus (Sc)	0.368	0.045	0.518
Fog	0.163	-0.031	-

May 2005 and 17 July 2005. We determined the multiple regression model using input parameters such as present day's total ozone ($TO_{\_present\ day}$), next day's air temperature at 1500 LST on 500hPa level ($T_{\_next\ day\_500hPa\_15z}$), and next day's air temperature at 1500 LST on the Earth's surface level ($T_{\_next\ day\_surface\_15z}$) for the period of May-July in 2005 in East Asia (20°N-60°N, 120°E-150°E) including the Korean peninsula as follows: TO= 704.423 + 0.607 × $TO_{\_present\ day}$ - 1.499 × $T_{\_next\ day\_500hPa\_15z}$ - 0.592 × $T_{\_next\ day\_surface\_15z}$ (R^2 =0.85). As a result, Fig. 10 and Table 5 show intercomparison of correlation coefficient and errors between calculated and observed daily total ozone in East Asia on 28 May 2005 and 18 July 2005. The proposed model can predict, therefore, total ozone within about 5% error rate from RMBE and RRMSE. Especially, the determined coefficient of the regression model was shown in 0.85, and its correlation coefficient was seen in 0.97 for given period. Furthermore, the model is very useful in the region where is no observation of total ozone on the earth's surface. However, the model has disadvantage that there is need to analyze the input data before the data are used every month or every year.

4.2. Prediction and estimation of hourly UV-B irradiance

Fig. 11 shows intercomparison of UV-B spectral irradiance calculated by the parameterization model (PM) and the MODTRAN at 1500 LST on 13 March 1996 and on 9 May 1997 for cloudless at Pohong. For the PM, we assumed a fixed value of the surface albedo (0.05), the Angstrom's wavelength exponent (e=1.3), the single scattering albedo (ω_0= 0.9) and visibility (28km) for a cloudless day. At this time, total ozone values were recorded by using the TOMS data. Also, for the MODTRAN, vertical profiles of ozone and meteorological factors such as air temperature, relative humidity and air pressure were taken by ozonesondes. At Pohang, the spectral UV-B irradiance estimated by MODTRAN was shown in high correlation coefficients of 0.91 and RRMSE within 24%. The spectral irradiance of PM was presented in correlation coefficients of 0.88 and RMSE within 25% when was except for the average pattern by Nicolet's solar spectrum at the top of atmosphere. Table 6 and Fig. 12 show sensitivity of solar spectrum adopted by

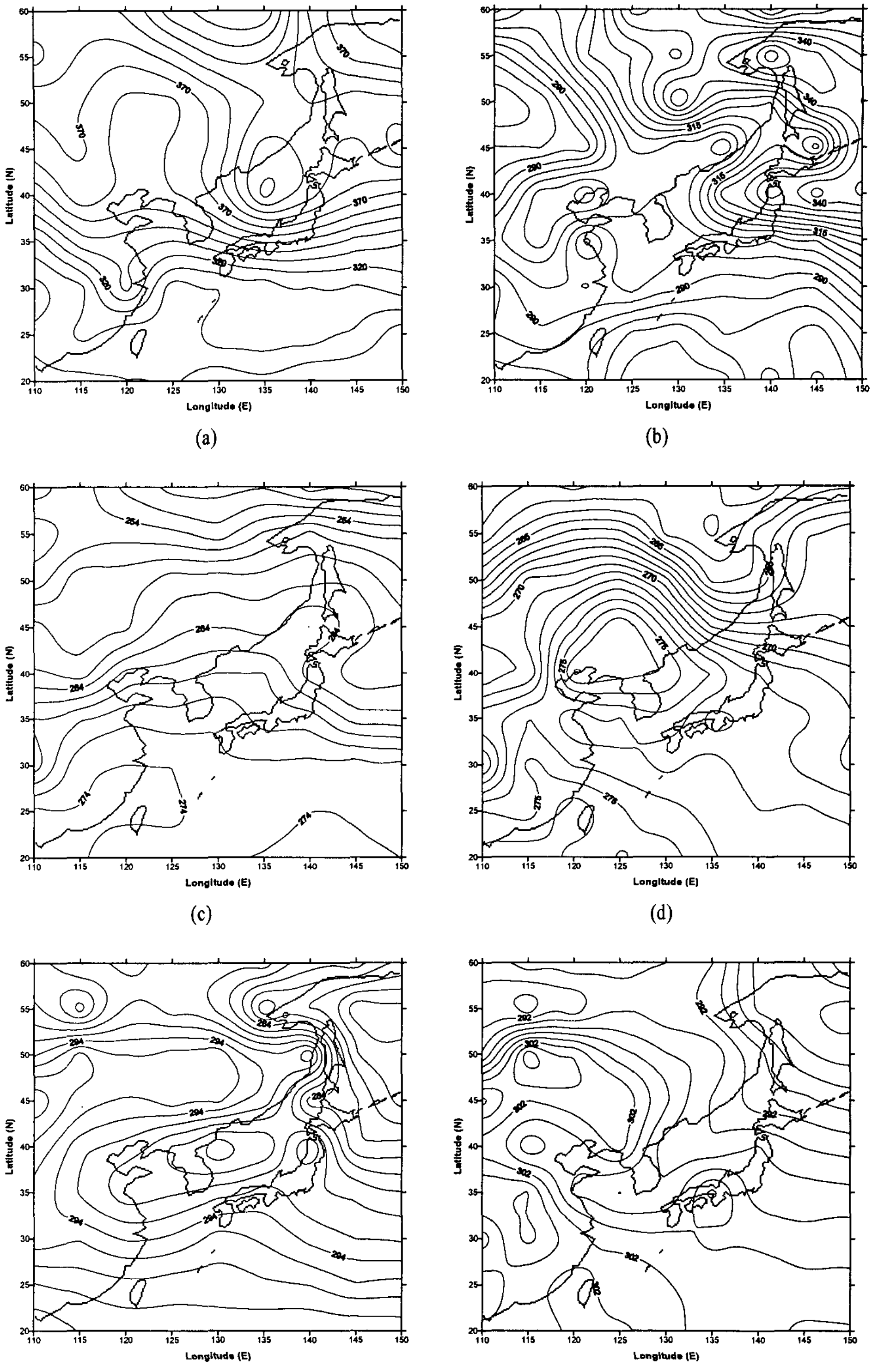


Fig. 9. Input parameters of the MM5 output for predicting daily total ozone in East Asia. (a)-(b) Present day's total ozone, (b)-(d) next day's air temperature at 1500 LST on 500hPa level, and (e)-(f) next day's air temperature at 1500 LST on the Earth's surface level on 27 May 2005 and 17 July 2005.

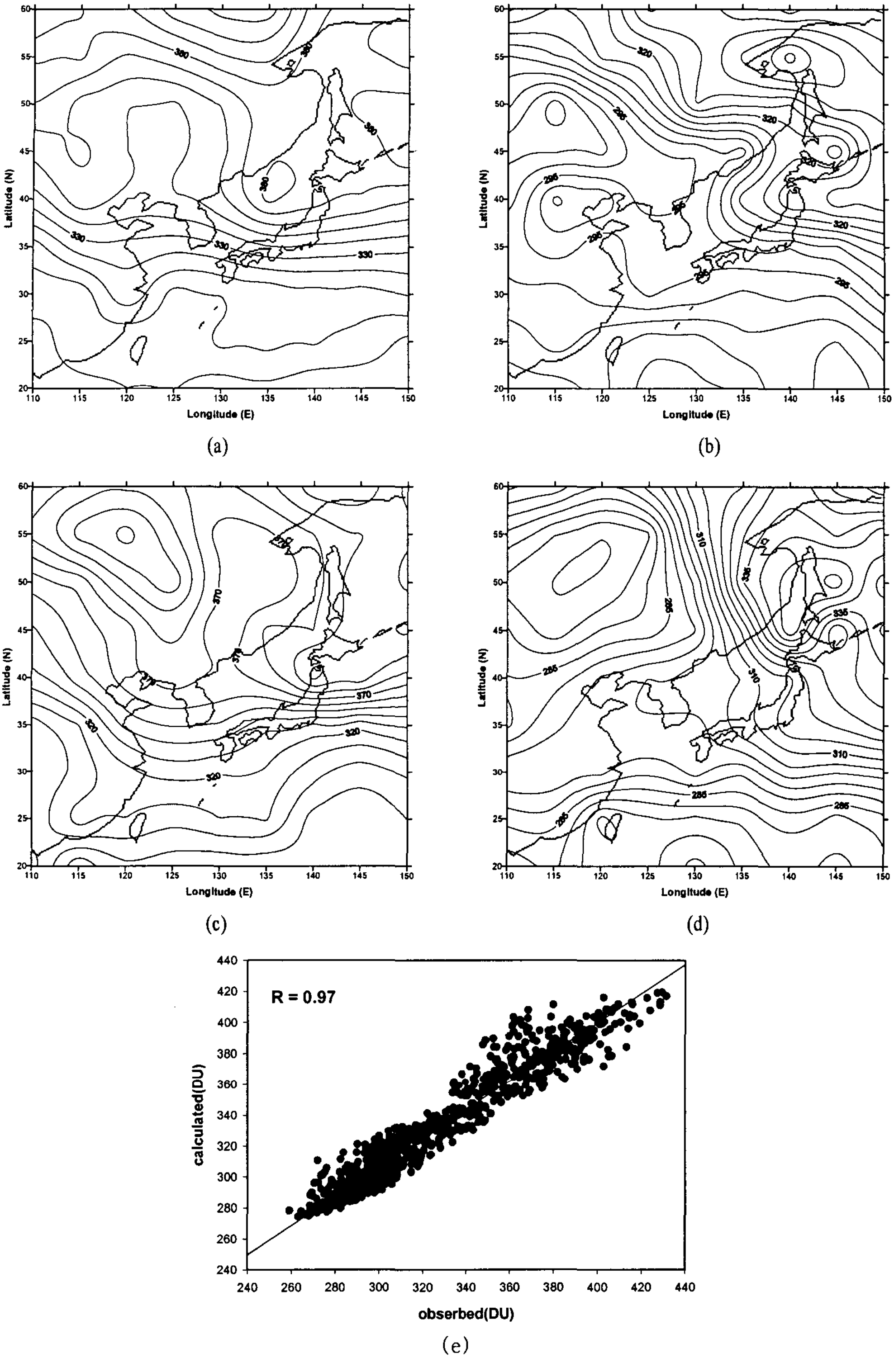
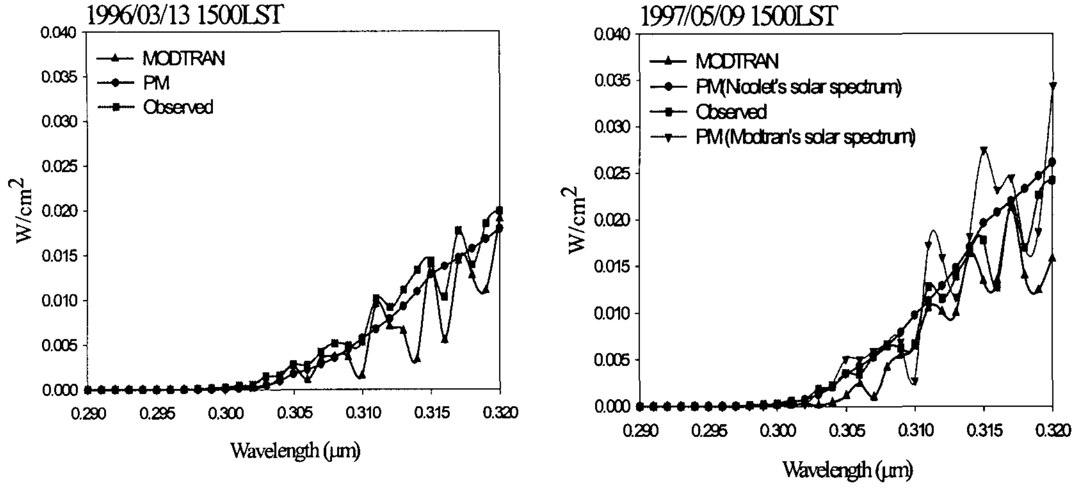


Fig. 10. Intercomparison and its correlation between calculated and observed daily total ozone in East Asia on 28 May 2005 and 18 July 2005. (a)-(b) Calculated total ozone, (b)-(d) observed total ozone on 28 May 2005 and 18 July 2005, respectively, and (e) correlation coefficient and its plot between calculated and observed daily total ozone for both days.



(a) (b)

Fig. 11. Intercomparison of UV-B spectral irradiance calculated by the parameterization model (PM) and MODTRAN at 1500 LST on (a) 13 March 1996 and (b) 9 May 1997 for cloudless days at Pohang.

Table 5. Errors between predicted and observed total ozone using the MM5 output data on 28 May 2005 and 18 July 2005 in East Asia

MBE	RMSE	RMBE	RRMSE
-0.098	13.462	0.1%	4%

Nicolet and MODTRAN with the PM of UV-B MED at Busan for cloudless days in 1998. The correlation coefficients between the solar spectrum of MODTRAN and Nicolet were shown in 0.98, and the RMSEs are seen in lower values, 0.08~0.16 MED. We adopted of the solar spectrum of MODTRAN which shows spectral values for constructing the UV-B PM in East Asia including the Korean Peninsular.

Fig. 13 shows hourly variation and its correlation between calculated and predicted UV-B MED for cloudless days at Pohang in 1998. Visibilities and total ozone amounts were also used in measured value.

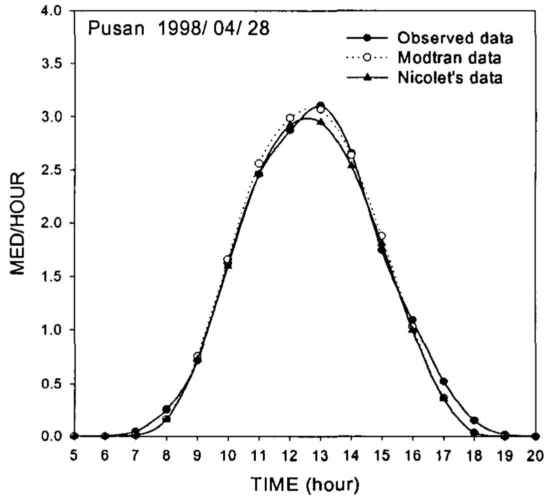
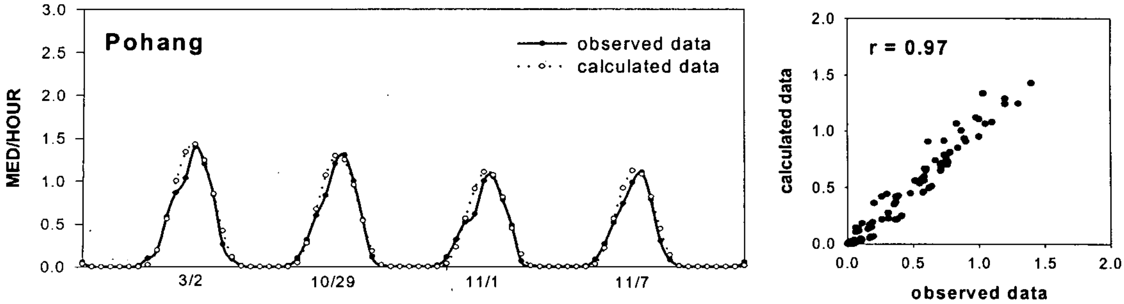


Fig. 12. Sensitivity of solar spectrum adopted by Nicolet and MODTRAN with the parameterization model of UV-B MED for cloudless days at Busan in 1998.

Table 6. Errors between calculated and observed UV-B MED during cloudless days at monitoring sites in Korea

	SITE / YEAR / ERROR	Anmyun 1998	Pusan 1998	Cheju 1998	Pohang 1996	Pohang 1997	Pohang 1998	Pohang 96~98
MODTRAN	r	0.99	0.98	0.99	0.96	0.98	0.93	0.93
	RMSE (MED/hour)	0.08	0.16	0.10	0.32	0.14	0.54	0.35
Nicolet's	r	0.99	0.98	0.98	0.96	0.98	0.93	0.93
	RMSE (MED/hour)	0.09	0.23	0.16	0.25	0.12	0.58	0.33



(a) (b)

Fig. 13. Hourly variations (a) and its correlation (b) between calculated and predicted UV-B MED for cloudless days at Pohang in 1998.

The values between calculated and observed UV-B MED showed a good agreement within about 5% error. This difference may be attributed to errors of parameters such as ozone, aerosols and solar spectrum in the PM itself, as well as instrument errors using UV-Biometer measurements. The correlation coefficients between the measured and calculated hourly UV-B MED were shown in more than 0.97. The RMBE was within 5% (measured irradiance larger than calculated near 1400 LST) of the measured hourly irradiance. The RRMSE was within 10% for hourly irradiance. The results of the model for cloudless days were presented in good agreement with hourly MED.

Fig. 14 shows sensitivity of cloud transmittances adopted by the PM for a cloudy day at Pohang in 1996. Exponential cloud transmissivities were adopted for overcasts of single cloud types without correction for overlying clouds. Also, in the same way, constant cloud transmissivities were determined for overcasts of single cloud types under overlying clouds in Korea from 1986 to 1995 (see Table 5). The correlation coefficients of the PM using these cloud transmissivities were over 0.91, and RMBEs and RRMSEs were less than 22% and 27%, respectively, for cloudy days at Pohang in 1996 as seen in Table 7. Including the effects of clouds in radiation models poses a number of problems such as the scarcity of observed data, the physical and dynamic nature of individual clouds and cloud fields, the variety of geometries and optical properties, and the occurrence of multiple layers, but they have been dealt with quite adequately by estimating the transmissivities for overcasts of single cloud types.

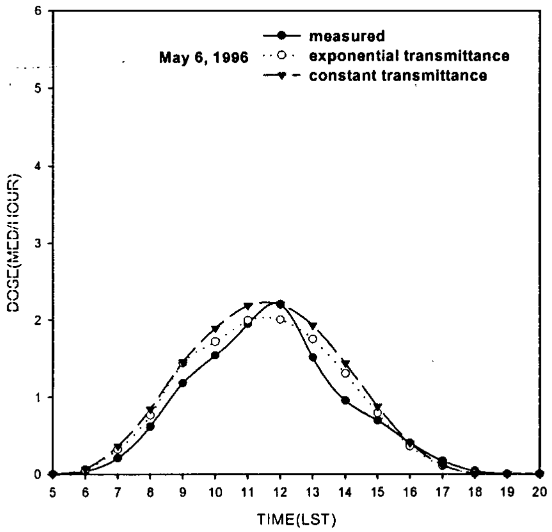


Fig. 14. I Sensitivity of cloud transmittances adopted by the PM for a cloudy day at Pohang in 1996.

Fig. 15 and Table 8 show daily variations, errors and correlations between calculated and predicted UV-B MED at 1300 LST for 1998 at Pohang and Busan, Cheju and Anmyun in Korea (see Table 3). The cor-

Table 7. Difference between calculated and observed hourly UV-B MED for cloudy days at Pohang, Korea in 1996

Time	MBE	RMSE	RMBE	RRMSE
10:00	0.11	0.23	0.06	0.12
11:00	0.04	0.09	0.01	0.03
12:00	-0.02	0.13	-0.01	0.05
13:00	0.12	0.17	0.07	0.10
14:00	0.25	0.29	0.22	0.27
15:00	0.06	0.13	0.12	0.23
16:00	-0.02	0.09	-0.03	0.17

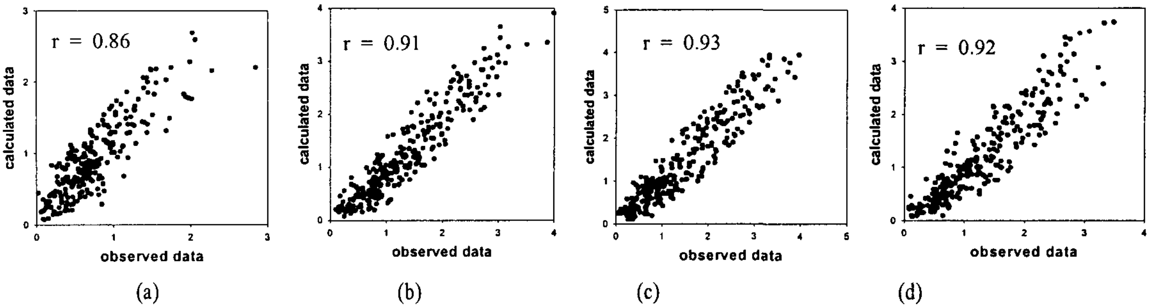


Fig. 15. Correlation coefficients and their plots between calculated and predicted UV-B MED at 1300 LST for 1998 at Pohang (a), Busan (b), Cheju (c), and Anmyen (d) in Korea.

Table 8. Errors and correlation coefficients between hourly predicted and observed UV-B MED at 1300LST for 1998 at monitoring sites in Korea

Sites	Pusan	Pohang	Anmyun	Cheju
Correlation Coefficient (r)	0.91	0.86	0.92	0.93
Root Mean Square Error (MED/hour)	0.23	0.31	0.34	0.35

relation coefficients were shown high in 0.91, 0.86, 0.93, and 0.92 at Busan, Pohang, Cheju, and Anmyun, respectively, for days without rain in 1998 (the correlation for summertime was presented low because of unstable conditions). The RMBEs were within 10% (calculated irradiance larger than measured) of the mean measured hourly irradiance. RRMSEs were within 15% for hourly irradiance.

Fig. 16 shows intercomparison between predicted and observed UV-B MED at 1300LST in East Asia on 28 May 2005 and 18 July 2005 by using the present day's total ozone (on 27 May 2005 and 17 July 2005) and the next day's maximum air temperature as seen in Figs. 13 and 14. At this time, weather conditions of clouds due to Typoon and cyclone play important role in predicting UV-B MED. In particular, we considered 0.8 for these cloud transmissivities. UV-B MEDs were also sensitivity to altitude. They were shown in high values in mountain areas. Table 9 shows errors between predicted and observed UV-B MED at 1300LST for given days in East Asia (20°N–60°N, 120°E–150°E). RMBE and RRMSE were presented low within about 5% and 10%, respectively. Consequently, it is expected that the prediction system of total ozone and UV-B irradiance in East Asia can be used to calculate present and future fluxes where UV-B measurements are not made.

5. Conclusions

The daily variation with increases in UV-B irradiance was due to decreases in total ozone measured by a Brewer spectrometer at Pohang for the period of 5 yrs (1994–1998). Furthermore, the long-term daily trend of total ozone interpolated by TOMS at Pohang and Busan for the 24 yr period of 1979–2002 is decreasing. Using the high exponential relationship between UV-B irradiance and global solar irradiance we can estimate hourly UV-B MED, but can't predict it at each local monitoring site. In particular, we need to predict the variation by using valid models of total ozone and UV-B irradiance with readily available meteorological parameters. Total ozone has been predicted by using statistical methods in order to construct the prediction model of the UV-B irradiance reaching the earth's surface from the top of atmosphere. Monthly averaged total ozone using the multiplicative seasonal ARIMA model is useful for predicting hourly mean UV-B irradiance by interpolating daily mean total ozone for the predicted period. We also can predict the next day's total ozone by using the present day's total ozone from TOMS and the next day's maximum air temperature predicted by MM5 at each meteorological monitoring site in Korea as well as East Asia. The predicted daily total ozone is used to input data of the parameterization model of hourly UV-B irradiance. The model input data needs next day's total ozone, hourly amount and type of cloud, and air pressure. The parameterization model of UV-B irradiance was shown in agreement with MODTRAN3 using vertical profiles of ozone and meteorological

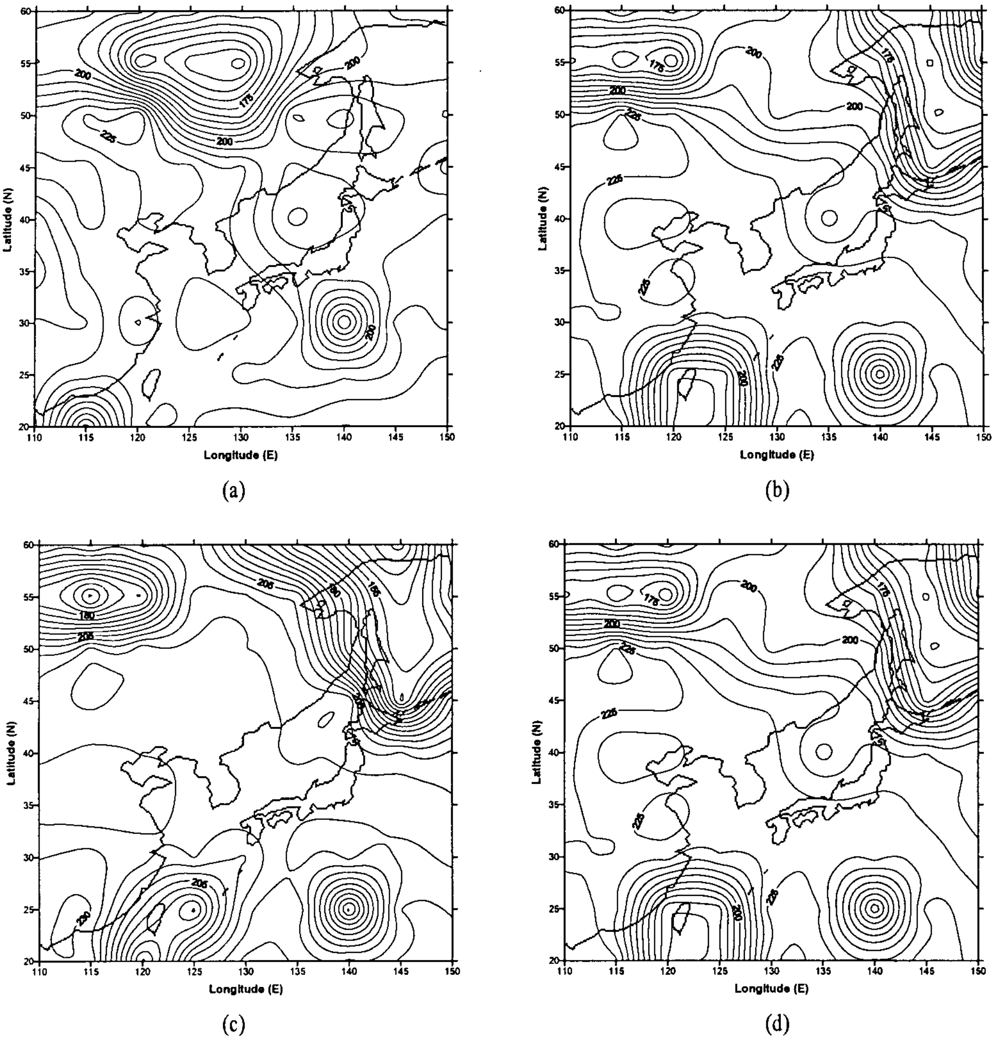


Fig. 16. Intercomparison between calculated and observed UV-B MED(mW/m²) at 1300LST in East Asia. (a)-(b) Calculated next day's UV-B MED on 28 May 2005 and 18 July 2005, and (c)-(d) observed next day's UV-B MED on 28 May 2005 and 18 July 2005.

Table 9. Errors between predicted and observed UV-B MED using the MM5 output data at 1300LST on 28 May 2005 and 18 July 2005 in East Asia

MBE	RMSE	RMBE	RRMSE
9.87	17.53	4.7%	8.34%

factors observed by ozonesondes at Pohang. The hourly predictions of the UV-B MED using the predicted cloud transmittance and total ozone are useful for forecasting UV-B MED or UV index at each monitoring site in Korea as well as East Asia.

Consequently, it is expected that the prediction system of total ozone and UV-B irradiance in East Asia including the Korean peninsula can be used to calculate present and future UV-B index where UV-B measurements are not made. This model is one of the most useful models tested in UV-B irradiance since it yields the best results overall, and can be used at some meteorological stations that make hourly cloud observations. Although exponential and constant cloud transmission parameters have been used successfully in various parts of the world, the model should be validated with data from other locations.

Acknowledgement

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