NOTES AND CORRESPONDENCE

Time Modeling of Daily UVB Values in Madrid, Spain

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ABSTRACT

This paper presents the daily solar ultraviolet-B (UVB) values measured in Madrid, Spain, during the period 1994–97 with a Brewer MKIV spectrophotometer. The range of the measured values was 0.042–6.41 kJ m^{-2}. A description of the values is shown. Periodicities of 7 and 3 days, associated with synoptic patterns, are significant. Ozone (with 5- and 3-day periodicities) and cloudiness also are studied for the same period; their association with UVB is investigated. The radiative amplification factor value between UVB and ozone is 0.62. The correlation coefficient between UVB and a cloudiness index [equal to one minus the (number of sun hours divided by the number of theoretical sun hours)] is −0.57. A time series model describing the UVB series is shown. It is useful in estimating the UVB values, even on days when radiation values are not available. It provides accurate performance, can be used any day of the year, and has no main restrictions for its application. Thus, this kind of model can be a useful tool when modeling UVB behavior, complementing the information provided by other models.

1. Introduction

The interest in ultraviolet-B (UVB, consisting of wavelengths from 290 to 320 nm) radiation has risen steadily since ozone (O_3) depletion was first detected more than 10 years ago (Chubachi 1985). Since then, great effort has been invested in detecting trends in its behavior as well as possible effects on the climatic system (Kryszin 1996; Kerr and McElroy 1993; Weatherhead et al. 1997). The main concern with UVB radiation is its association with different health problems, mainly skin cancers (Amstrong 1994) and non-Hodgkin's lymphoma (Bentham 1996). This health aspect has lead to a growing public awareness about UVB.

The behavior of UVB shows high variability with time (because of seasonalities and the possible existence of trends) and space (from latitude and altitude effects). However, UVB measurements are not as available as might be desired because of their cost and difficulty. Therefore, a great part of the information currently available is based on models.

UVB modeling has been used for two main purposes: getting information about the UVB behavior in areas where no measurements are available (Frederick and Lubin 1988; Madronich and de Gruijl 1994), and in-

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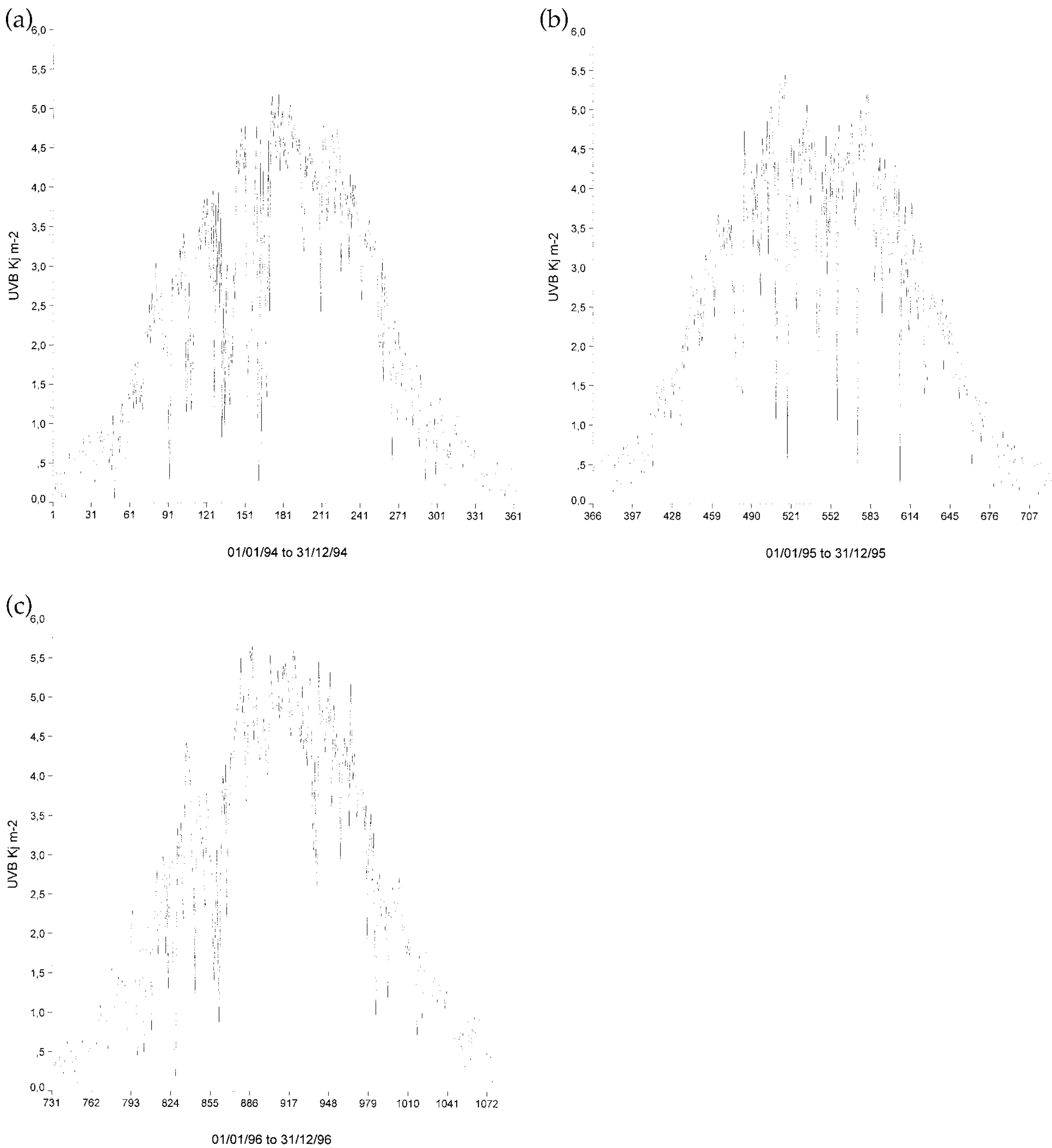

FIG. 1. (a)–(c) Evolution of the daily UVB irradiance values (kJ m^{-2}) for the period 1 Jan 1994 to 31 Dec 1996.

vestigating the effects of meteorological factors such as ozone or pollution on UV radiation (Tsay and Stammes 1992), through different approaches. Recent models usually use radiative transfer methods to compute UVB from ozone, aerosol, cloudiness, and albedo data taken from satellites (Krotkov et al. 1998; Hudson et al. 1995; Hudson and Thompson 1998).

Usually both types of models evaluate the relationship between measured UVB and different parameters, from a radiation transfer approach (e.g., Lubin et al. 1998).

The aim of this paper is to present for the first time some daily UVB measured values from Madrid, Spain, and to show a stochastic model that describes the time changes of daily UVB measured in Madrid. The model includes O_3 and cloudiness information and is valid without restrictions in Madrid.

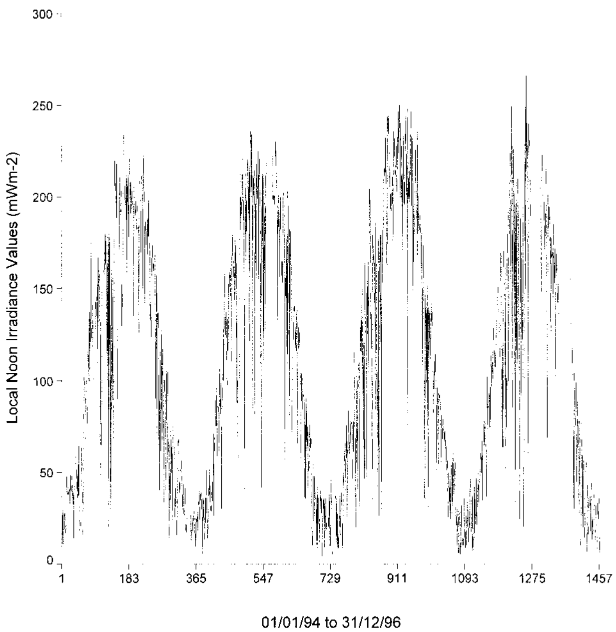

FIG. 2. Local noon irradiance values (mW m^{-2}).

2. UVB values

In this paper, UVB measurements taken near Madrid (40°27′N, 3°43′W) between January 1994 and December 1996 are reported. An MKIV Brewer spectrophotometer has been used. It operates routinely in the Instituto Nacional de Meteorología (INM) and it is 624 m above mean sea level in a semiurban area of Madrid. UVB measurements were taken approximately every 50 min throughout the day. The spectra were weighted with an erythemal action spectrum and integrated to give an erythemal flux (McKinlay and Diffey 1987). Time integration of the measurements allowed for a total daily UVB dose. Standard operating procedures such as those found in Kerr et al. (1981) were followed.

The daily values are shown in Figs. 1a–c (values are kJ m^{-2} erythemally weighted). The annual cycle is the dominant feature, with maximum values for the summer months. Figure 2 shows the evolution of the local noon irradiance for the same period. Measurements were performed routinely for the period of 1994–96. During 1997 the Brewer was moved to different locations for comparison purposes so the series is not complete for that year. The absolute maximum daily value was 5.68 kJ m^{-2} (6 June 1996). The absolute minimum was 0.04 kJ m^{-2} (1 November 1994). Table 1 shows the monthly averages for the whole period. Power spectrum analysis shows periodicities of 7 and 3 days as significant. Those could be associated with the circulation patterns over the area (Hernández and Soler 1977) and are related to the average life of low pressure centers over the Iberian Peninsula.

It is well known that UVB radiation in a certain location depends mainly on time of year, cloudiness, total ozone amount, albedo, and aerosol concentrations (Kerr and McElroy 1993; Lorente et al. 1994; Madronich and de Gruijl 1994; Marenco et al. 1997). Therefore, the relationship between UVB and these variables in Madrid was investigated.

First, we assumed that the albedo remains constant through the year, because snow or ice days rarely occur at Madrid. Additionally, a small conifer forest surrounds the measurement point, so significant changes in albedo are unlikely. Unfortunately, no information is available routinely on the aerosol content in Madrid, and turbidity is not measured so the impact of aerosols cannot be estimated.

To evaluate the influence of cloudiness, a daily cloudiness index was computed: $c = 1 -$ (number of sun hours/number of theoretical sun hours). The number of sun hours is determined from the heliographs operating at the INM. It is well known that UVB depends not only on the amount of cloud cover but also on the the type of clouds (Estupiñán et al. 1996). However, this index provides a good picture of the overall effect.

The values of c show an average value for the whole period of $c = 0.35$ with summer minima and winter maxima. The power spectrum reveals the annual cycle to be the most significant periodicity, with some minor peaks on the scale of days. The correlation coefficient r between UV radiation and c has been computed and is equal to -0.57 (significant at $\alpha = 0.05$).

Next, the values of the daily total ozone amount over Madrid were studied. Ozone was measured with the same Brewer spectrophotometer that made the UV measurements. Figure 3 shows the evolution of the whole period [values are in Dobson Units (DU)]. Again the annual cycle is the predominant feature; however, now maximum values are recorded in spring and minimum values in late autumn as is usual in these latitudes. The cycle is less evident than in the rest of the series and minor periodicities of 5 and 3 days also are detected.

The correlation between UVB and O_3 for the whole period is $r = 0.13$, significant at $\alpha = 0.05$. The positive sign is unexpected, but it can be attributed to spurious

TABLE 1. Average values of UVB irradiance for the 1994–97 period (values are in kJ m^{-2}).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1994	0.50	0.73	1.99	2.76	3.11	4.34	4.26	3.90	2.47	1.23	0.66	0.33	2.21
1995	0.45	0.94	2.09	3.10	4.29	3.93	4.19	3.85	2.64	1.62	0.68	0.37	2.24
1996	0.43	1.02	1.85	3.09	3.58	4.77	4.65	2.22	2.51	1.57	0.79	0.35	2.46
1997*	0.43	1.13	2.21	2.89	3.62	4.25	4.21	3.59	3.06	1.48	0.64	0.39	2.20

* In this year, the spectrophotometer did not operate during the periods: 25 Jun–18 Jul and 10 Sep–9 Oct.

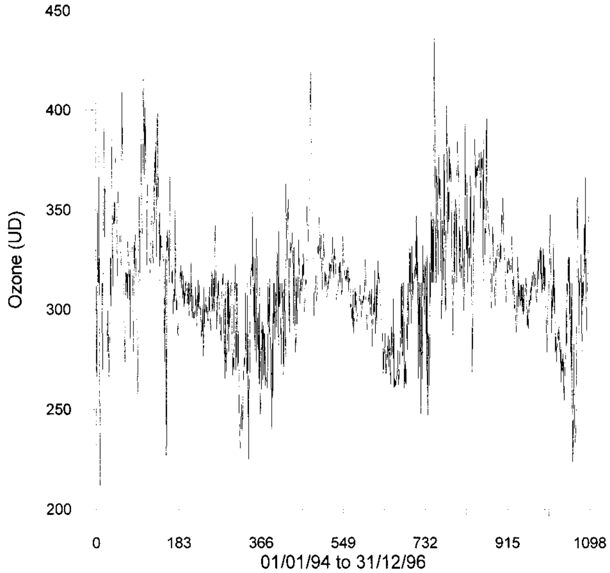

FIG. 3. Same as Fig. 1 but for ozone measured in Dobson Units (UD).

time effects and to the complex interaction among UVB, ozone, and cloudiness associated with fronts. This effect will be discussed in the next section.

3. Modeling

The use of statistical models for descriptive or forecasting purposes can be a useful alternative, especially in locations such as Madrid where the interactions among UVB, ozone, and cloudiness are rather complex to describe physically. In fact, in Madrid, most of the ozone variability can be explained in terms of the transport phenomena linked to frontal systems that affect Iberia. Spring maxima are associated with the transport of northern air masses, usually rich in columnar ozone content. Autumn minima are associated with fronts that transport southern air masses, usually with lower ozone concentrations. When the air mass changes, cloudiness also changes. This change, acting jointly with the strong ozone absorption, modifies UVB irradiance reaching the surface in a way that is difficult to forecast.

To illustrate this type of situation, the period starting 19 January 1996 and ending 30 January 1996 has been analyzed. UVB and ozone values are represented in Figs. 4a and 4b, respectively. The period was chosen because it led to one of the ozone maxima of the period (438 DU) and it is characteristic of the interrelations that affect the incidence of fronts over Madrid.

The analysis of isobaric surfaces lower than 500 hPa shows that at 1200 UTC a deep trough extended from Iceland to northwestern Iberia. The sky was mostly or completely cloud-covered over all Iberia. UVB values recorded in Madrid were very low (0.24 kJ m^{-2}). The ozone value was 332 DU. Then a number of fronts passed over Madrid (Fig. 5 shows the sequence) for a period between 20 and 25 January. The ozone reached its maximum on 24 January (438 DU); the values of 26 January were similar to those of 19 January. As fronts passed, cloudiness experienced large variability. Those changes mask the effect of ozone on UVB irradiance up to a point that, if the period 19–26 January is considered, a positive correlation between ozone and UVB is apparent. Thus, when changes of air mass are produced by very active thermal fronts, UVB forecasting

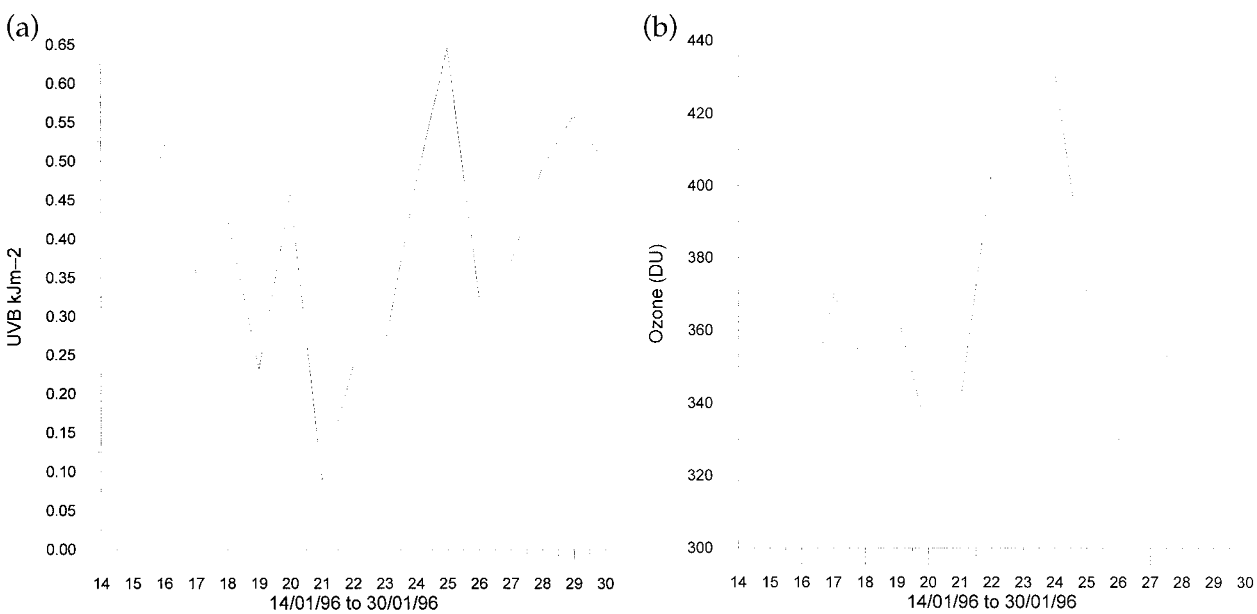

FIG. 4. Evolution of (a) UVB (kJ m^{-2}) and (b) ozone values (Dobson Units) for the period of 14–30 Jan 1996.

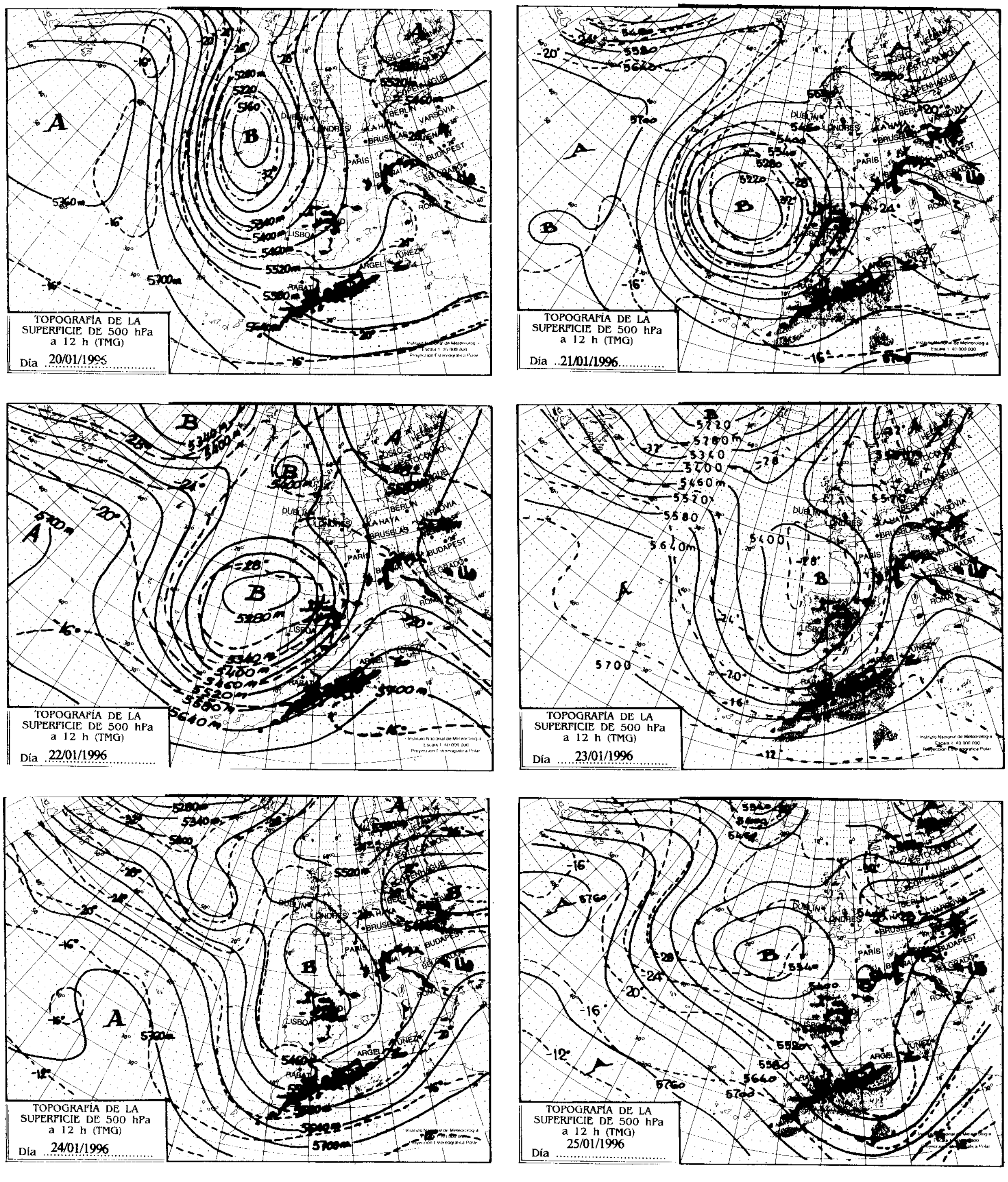

FIG. 5. 500-hPa synoptic charts (1200 UTC) over Spain for the period of 20–25 Jan 1996.

is rather difficult and, of course, must include information about cloudiness.

Thus, clear-sky models are not efficient in this kind of situation. Only models capable of describing any type of meteorological situation can provide good descriptions of the UVB behavior. In this context, statistically based models can provide an interesting and complementary view to those based on radiative transfer functions. In the next paragraph, the results of a time series model fullfilling these requirements will be shown.

Since our main aim is to describe the time variations of UVB in Madrid with a single model, valid for every

TABLE 2. Modeling. In every row, the first set of parentheses shows the nonseasonal component part of the model and the second set shows the seasonal component. The number after the parentheses is the order of the seasonality. Values between parentheses indicate autoregressive order, integrated order, and moving-average order (Box et al. 1994).

Series	Model
ln UVB	(1, 0, 1) (2, 0, 2) 7 + annual cosine
O_3	(2, 0, 2) (1, 0, 1) 3 + annual cosine
c	(2, 0, 1) (2, 0, 2) 5 + annual cosine + semiannual cosine

day and atmospheric condition, a stochastic time series modeling approach was chosen. These models originally were designed by Box et al. (1994) and Makridakis et al. (1983). Briefly they describe the behavior of a series in terms of its own history (univariate or autoregressive moving average models), allowing the introduction of external variables in a second step (multivariate or transfer function models).

The stochastic modeling is based on the well-known fact that the relationship between UVB and ozone is $\mathrm{UVB} \simeq [O_3]^{-\mathrm{RAF}}$ (where [ ] is concentration), thus the correlation of ln(UVB) versus ln(O_3) will be more physically based and the coefficient will be an estimation of the RAF (radiative amplification factor). Thus, the model is not purely stochastic because part of its structure is fixed previously.

4. Results

First, the univariate models for the three series: UVB, O_3, and *c* were computed. (Table 2). It can be seen that all the models show a clear annual pattern through the cosine. In the nonseasonal component, all the series have an autoregressive component of order 2 for O_3 and *c* and order 1 for ln(UVB) and a moving average of order 1 for ln(UVB) and *c* and order 2 for O_3.

The univariate model for UVB performs very well, with a correlation coefficient between predicted and observed values of 0.91; that is, the history of the series explains 83% of the total variance of the series.

In order to build the multivariate model, the cross-correlation functions between the dependent series [ln(UVB)] and the independent ones [ln(O_3) and *c*] have been computed after a prewithening procedure to filter seasonal effects. The cross-correlation functions for ln(O_3) show a significant negative value (−0.2) for lag 0, as is expected, since the decrease in O_3 leads to an increase in UVB; thus, once the time effects have been filtered, a physically meaningful value is evidenced for the correlation between UV and O_3.

For *c* a negative correlation in lag 0 ($r_0 = -0.43$) is seen, which is lower than the correlation coefficient. This is caused by the fact that *c* and O_3 have a common annual cycle, thus causing a spurious increase in the meaningful correlation.

With this information, a multivariate model that includes O_3 and *c* was developed. After an identification–estimation process, the equation of the final model chosen is

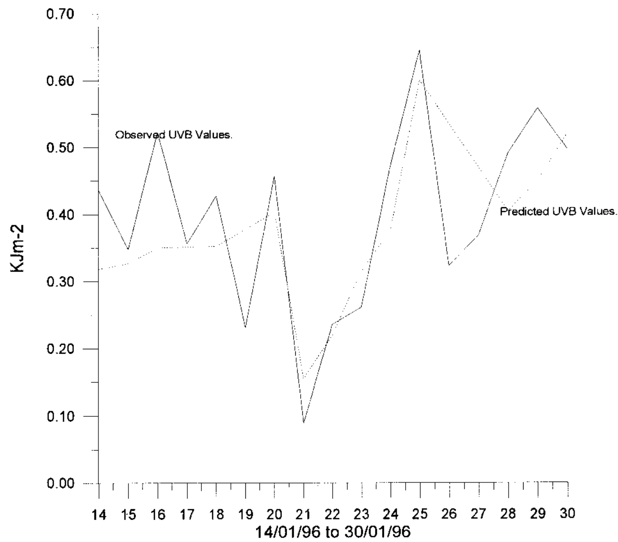

FIG. 6. Evolution of predicted (dashed) and observed (solid) UVB values (kJ m^{-2}) for the period of 14–30 Jan 1996.

$$\ln(\mathrm{UV}_t) = 10.45 + 0.97\ln(\mathrm{UV}_{t-1}) - 1.08\cos(2\pi t/365) - 0.62\mathrm{O}_{3t} - 0.72c_t - 0.82e_{t-1},$$

where $\ln(\mathrm{UV}_t)$ is the natural logarithm of the daily UV value for the day *t*, O_{3t} is the total ozone value for the day *t*, c_t is the cloudiness value for the day *t*, and e_t are the residuals for day *t*.

The model performances have been tested for two different periods: 1994–96 and 1997. For the first one, the correlation coefficient between modeled and observed values is 0.94 (sample size $n = 1096$, confidence level $p < 0.000$), explaining 88.4% of variance. The increase of explained variance is 5% with respect to the univariate model.

The band of the residuals as defined by standard deviation σ becomes narrower: $\sigma_{\mathrm{residual}} = 0.65$ kJ m^{-2} for the univariate model, and $\sigma_{\mathrm{residual}} = 0.22$ kJ m^{-2} for the multivariate model. The number of values outside the $\pm 2\sigma$ band is 50, less than 5% of the total series. When analyzing these large residuals, two main conclusions can be drawn; they occur mostly in spring (70%) and summer (30%) and most of them (63%) are associated with a sudden change in the value of *c* (daily change higher than ± 0.2).

When the model is applied to the 1997 series, which was not used in the estimation procedure, it keeps the high level of accuracy, with $r = 0.97$ ($n = 245$, $p < 0.000$) between observed and modeled data, and $\sigma_{\mathrm{residual}} = 0.18$ kJ m^{-2}.

Figure 6 shows the evolution of observed and predicted UVB values for the period 14–30 January 1996. It can be seen clearly that the model reproduces satisfactorily the UVB values in such a complex situation.

5. Conclusions

UVB irradiance in Madrid is characterized by the expected annual cycle and some minor periodicities of 7 and 3 days, which can have a meteorological origin. It shows a high dependence on cloudiness ($r = -0.54$) and ozone, with an RAF = 0.62. The stochastic model, with a pre-fixed, physically based structure, has provided an accurate description of the UV behavior, accounting for most of the variance of the time series. Moreover, it provides a good answer to the complex association among UVB, O_3, and cloudiness, describing the main episodes adequately. Thus, a single model is valid for any season of the year and has no meteorological restrictions in its applicability. Therefore, this kind of model can be a useful tool for predicting UVB irradiance, alternatively or complementary to radiative transfer models.

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