INFLUENCE OF CLOUDS ON THE DETECTABILITY OF TRENDS IN THE UV–B IRRADIANCE CAUSED BY REDUCTION OF THE TOTAL OZONE CONTENT

A.V. Belyavskii, V.M. Zakharov, and G.M. Kruchenitskii

Central Aerological Observatory (CAO), Dolgoprudnyi
Ukrainian Regional Scientific –Research Hydrometeorological Institute (USRHI), Kiev

Received May 5, 1991

Detectability of trends in the UV–B irradiance and their significance for biological systems are estimated from the series of synchronous measurements of the total ozone content and the UV–B irradiance.

During the last decade both the scientific and broad public communities have become more and more concerned about the problem of the depletion of the global ozone layer. That concern is mainly based on the statements similar to the following: "The destruction of ozone will lead to higher levels of the UV radiation, which, in its turn, will result in the growth of infectious diseases and of skin cancer".[1] The same source speaks about the danger of lowered crop productivity, of the reduction of forested areas, of disturbance of the marine feeding chains, and of other unfavourable effects of the increased UV–irradiance on biological systems, all triggered off by the negative trend in the total ozone content (TOC).

We will not discuss the problem of reliable identification of such a trend (when analizing a random process from only a limited realization available there always exists a probability of detecting a false trend, produced by the low–frequency harmonics in the energy spectrum of this spectrum of this process). Instead we will focus out attention on the problem of the relative contribution of the reduction of the TOC to the increase of the UV–irradiance. From the very beginning we should note that the level of the UV–irradiance depends not only on the TOC, but on the vertical profile of ozone (VPO).

Indeed, molecular scattering increases at lower atmospheric heights, so that the contribution of ozone found at these altitudes to the extinction of the UV–radiation also increases, since the path length being travelled by the scattered radiation is extended within the lower atmospheric layers. This effect becomes more important at higher radiation frequencies, since both the molecular scattering cross section (proportional to $\sim\lambda^{-4}$, where λ is the wavelength) and the absorption cross section of ozone sharply increase at these frequencies. However, for lack of statistically reliable information on the trends of the VPO, we presently has to ignore its possible changes and to restrict ourselves to the account of trends in the TOC only.[2]

As applied to the problem of the trends in the UV–irradiance, the situation is described in the WMO Report[2] according to the authors, reflects the viewpoint of the international scientific community, and is summarized in the following.

1. Trends in the spectral density of the UV–irradiance are predicted for clear sky conditions and are calculated employing the model of radiative transfer[3] on the basis of the data on the ozone trends, published in the Ozone Trends Panel[4] (OTP).

2. Results are available of the trend analysis[5] of the data on the UV–irradiance obtained in 1979–1985 (annual integrals) in the wavelengths 295–340 nm, at eight US actinometric stations located between 30.4° N and 46.8° N latitude belt. These results definitely point to lack of any positive trend, while the data from five of these stations indicate a negative trend (statistical dependence on a level of 2σ).

3. Integrating the trends (item 1) over the instrumental band (item 2), the authors of Ref. 6 showed, that the positive trends in the UV–irradiance measured in the 40–52° N latitude belt had to vary within the limits from 1.5–1.6% (July) to 4.7–4.8% (March), which corresponded to negative ozone trends of 2.2 and 5.6% derived from the OTP.

4. Disagreement between the predicted trends in the UV–irradiance and the results of the analysis of data from the US UV–metric network was related to a lack of long–term stability of the Robertson–Berger instruments employed at that network.

In the present paper we approach the problem of relationship between the trends in the TOC and in the UV–irradiance from another angle, namely, try to estimate detectability and significance of variations in the UV–irradiance, produced by reduction of the TOC, against the background of their spontaneous variability associated with cloudiness. The importance of that factor has been emphasized by all researchers, however, the radiative transfer equation is analytically and systematically difficult to take into account, so that at present in such studies[2] the authors are usually restrict themselves to the approximation of linear increase of a cloud–cover index.[7,8]

For the initial data in our analysis we employed the results of routine synchronous measurements of the TOC, the UV–irradiance, and the cloud–cover index which have been performed at the Ukrainian Scientific–Research Hydrometeorological Institute (USRHI), Kiev, since July 1990. These measurements follow the scheme of a routine ozonometric network station. An M–124 instrument is used as an ozonometer, the same type of instrument, though modified at the Main Geophysical Observatory (MGO), serves as an UV–meter. The instrument is capable of integral measurements in the UV–A (315–400 nm) and the UV–B (up to 315 nm) wavelength regions, while the cloud cover index is visually determined.

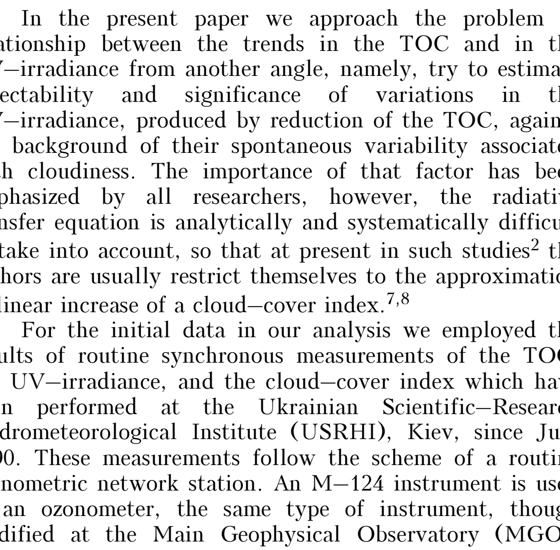

FIG. 1. The correction factor F for modified Bouguer's law vs. the sun elevation angle above the horizon.

0235-6880/91/09 692-05 $02.00

At the first stage of our study we tested the reliability of our initial data. The analysis of the six–month observational series (July, 1990–January, 1991) was based on the Schuster approximation of the radiation transfer equation,[9] so that the spectral density of the net solar radiation could be presented in the form

$$Q_\lambda = F(V)\, I_{0\lambda} \exp\left(-\alpha_\lambda \frac{X}{\sin V} \right), \tag{1}$$

where $I_{0\lambda}$ is the spectral density of the solar constant, X is the total ozone content, α_λ is the spectral absorption coefficient, V is the elevation angle of the sun, and

$$F(V) = (1 + S)^{-1} \sin V \times$$
$$\times \left\{ \exp\left(\frac{-(\beta+\delta)}{\sin V} \right) + \left[\frac{\beta\eta + \delta\xi}{\beta+\delta} + \left(1 + \frac{\beta\overline{\eta} - \delta\overline{\xi}}{\beta+\delta} \right) \sin V \right] \times \right.$$
$$\left. \times \left(1 - \exp\left(\frac{-(\beta+\delta)}{\sin V} \right) \right) \right\};$$

$S = \left[\beta(1 - \overline{\eta}) + \delta(1 - \xi) \right](1 - R)$, R is the albedo, β is the molecular scattering coefficient, δ is the aerosol scattering coefficient, η is the relative fraction of radiation scattered by the molecules of air when the direct ray propagates to the earth's surface, is the relative fraction of radiation scattered by the olecules of air downward from the upper hemisphere, ξ and $\overline{\xi}$ are the same factors for aerosol scattering. Neglecting the anizotropy of air molecules, we assume $\eta = \overline{\eta} = 0.5$ and employ the approximation for ξ proposed in Ref. 10 $\overline{\xi} = 0.742$. The function $F(V)$ at $\lambda = 307$ nm is shown in Fig. 1. The spectral dependence of F may also be neglected, for the UV radiation reaching the surface varies within the limits of only a few per cent. Based on the integral mean value theorem, we may write for the net radiation in the UV

$$Q = F(V)\, I_{0\lambda'} \exp\left(-\alpha_{\lambda'} \frac{X}{\sin V} \right)(\lambda_2 - \lambda_1), \tag{2}$$

where $\lambda_2 = 315$ nm, λ_1 is the minimum wavelength of radiation reaching the ground, $\lambda' \in [\lambda_1, \lambda_2]$, or

$$Q = F(V)\, A \exp\left(-\alpha \frac{X}{\sin V} \right). \tag{2a}$$

Relation (2a) indicates a linear dependence of $\ln[Q/F(V)]$ on $X/\sin V$. Figure 2*a* shows the corresponding experimental data for cloudless sky, with the straight line fitting these data by the least–squares technique. To test the reliability of the initial experimental data we may consider the following. It is quite easy to retrieve the value of λ' from $\alpha_{\lambda'}$ (it is the slope of this straight line), and hence – the value of $I_{0\lambda'}$. It is further apparent from considerations of the energy conservation law that the following relation must be satisfied:

$$\int\limits_{\lambda_2 - \frac{A}{I_{0\lambda'}}}^{\lambda_2} I_{0\lambda} d\lambda = A. \tag{3}$$

Check of Eq. (3) for various depths of the ozone layer show that it holds with the rms error 5%. For comparison, Fig. 2*b* illustrates the results of linear interpolation of purely Bouguer's dependence

$$Q = B \exp\left(-\beta \frac{X}{\sin V} \right). \tag{4}$$

The coefficient of correlation for Eqs. (2*a*) and (4) is $R = 0.94$, and the relative spread of experimental points double (amounting to 17.1 and 33.3%, respectively), while the point λ' (for approximation (4) lie to the left of the point λ_1, i.e., Eq. (3) is violated. To test the adequacy of representing the set of experimental points by Eq. (2*a*), relation (4) is employed. If the experimental points are substituted by the points satisfying Eq. (2*a*), and this data array is fitted by Eq. (4), the values of B and β agree with those retrieved before, with rms error of about 1%. Fitting the experimental data on the UV–A radiation for cloudless sky by Eq. (2*a*) we may directly retrieve the value of the solar constant in the wavelength range 315–400 nm. This value is equal to 79.5 W/m^2, which agree quite well with the data of direct measurements (80.5 W/m^2, see Ref. 11). The above results testify that the obtained experimental data may be used to retrieve the average dependences, and that average dependence (2*a*) adequately describes the set of experimental data for cloudless atmosphere.

The rest of experimental data are fitted by Eq. (2*a*) for different cloud–cover indices with the step size of two units. The results of this approximation are outlined in Table I and are illustrated by Figs. 3 *a–e*.

It should be noted that fitting by Eq. (2*a*) the dependence of the net UV–radiation on the ozone depth under cloudy conditions results in an *a priori* overestimation of this dependence (similar to Eq. (4) for the cloudless atmosphere) because the factor $F(V)$ accounts only for molecular and aerosol scattering. Nevertheless, direct numerical experiments, based on Eq. (2*a*), which reproduce the conditions of field measurements for cloud–cover index and for the solar elevation angles and during which the TOC is varied, have demonstrated that the reduction of the TOC by 1% corresponded to an increase of the net UV–B radiation only by 0.84% instead of 1.6–1.9%, yielded by integrating of the data from Ref. 3 over the wavelength $\lambda \leq 315$ nm. (It is interesting to note that an increase of the UV–B radiation by 1.6% have been obtained when applying Eq. (4).) Such a discrepancy is apparently explained by the fact that the authors of Ref. 3 made their calculations at local noon for cloudless sky only. However, another explanation is also possible. Current algorithms used to solve the radiative transfer equation call for much more detailed data on the properties of aerosol than those presently available. The inadequate account for the real conditions of radiative transfer, which is unavoidable, may result in fundamental disagreements between the theoretically calculated values and those really observed in the experiment. In that respect the simple algorithm, constructed by Chandrasekhar and Schuster,[9] is more preferable in the sense of its stability, because it employs the parameters of the scatterers averaged over the hemispheres and over the entire atmospheric column.

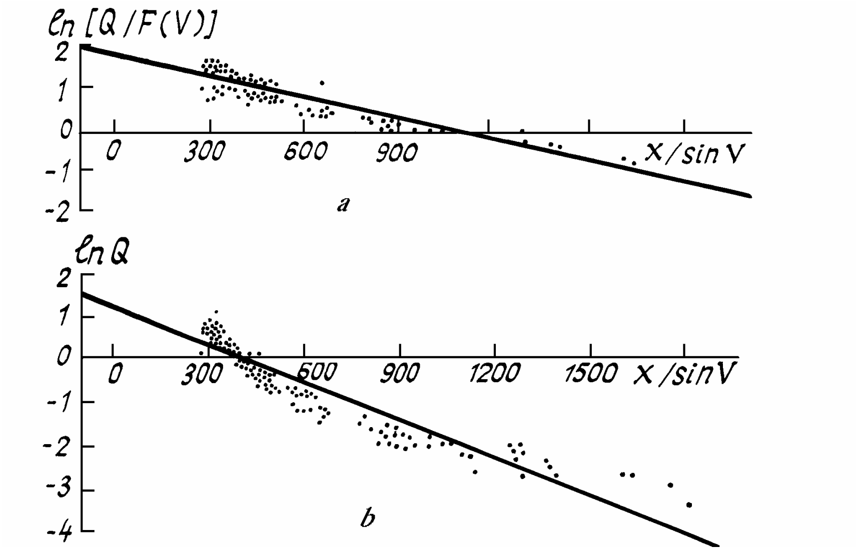

FIG. 2. The UV–B *irradiance for cloudless sky vs. the depth of ozone layer and its fitting by relation (2a) – a, and relation (4) – b.*

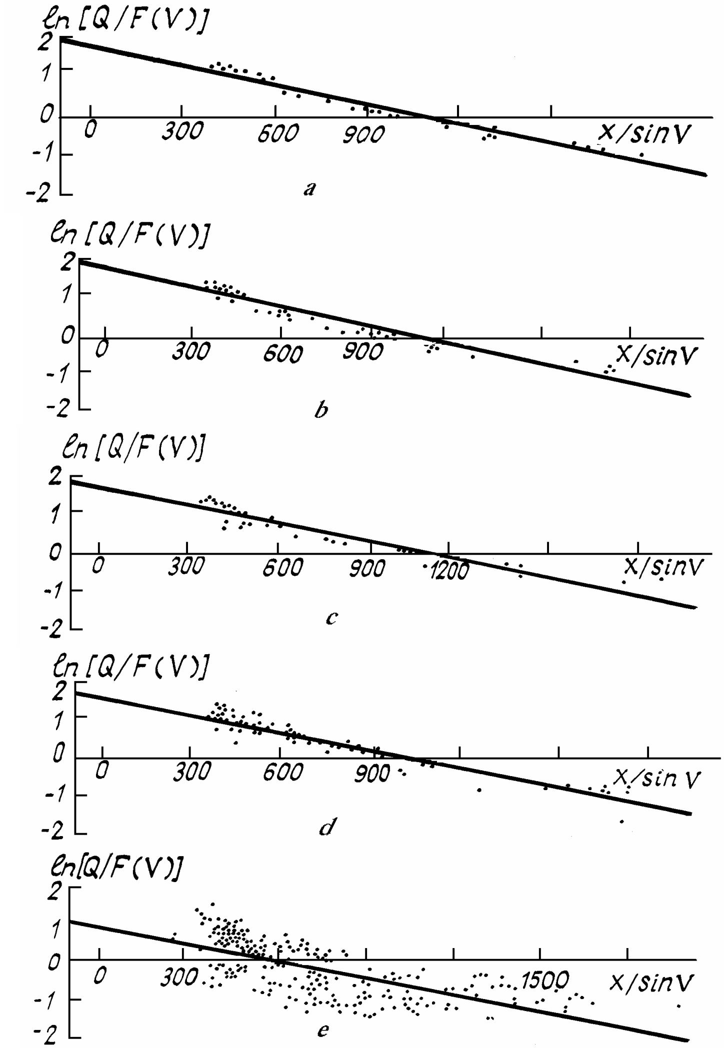

FIG. 3. Approximation of dependence (2a) for different cloud–cover indices: a) 1–2; b) 3–4; c) 5–6; d) 7–8; and e) 9–10.

TABLE I. Parameters of fitting the experimental data by Eq. (2a) at different cloud–cover indices.

Cloud cover index	Normalized frequency of cloud recurrence	Correlation coefficient	A, (W/m^2)	$10^2\,\alpha$, (km^{-1})
0	0.26	–0.94	6.26	0.151
1–2	0.067	–0.979	5.55	0.137
3–4	0.087	–0.979	6.04	0.143
5–6	0.078	–0.962	5.93	0.144
7–8	0.11	–0.908	4.72	0.131
9–10	0.398	–0.657	2.95	0.137

To determine the actual ratio of the trend of the TOC to the net UV–B irradiance (k), the obtained value of 0.84 should be multiplied by the value of the correlation coefficient $\overline{R} = 0.83$ (the weighted mean over all cloud–cover indices) yielding finally $k = 0.7$. Such an operation becomes necessary because relation (2a), employed in the numerical experiment, inadequately describe the actual dependence of Q on X: there exists a certain spread, associated with other radiation factors, which are not accounted for by that relation.

TABLE II. Empirical probabilities of transition between various cloud–cover indices. The corresponding average increments of the TOC are indicated in parentheses.

0	0	1–2	3–4	5–6	7–8	9–10
0	0.908 (0)	0.036 (2)	0.015 (10)	0.01 (–24)	0.005 (27)	0.026(–31)
1–2	0.077 (–2)	0.481 (0)	0.212 (–12)	0.096 (–26)	0.058 (–29)	0.077 (–33)
3–4	0.029 (10)	0.13 (12)	0.464 (0)	0.188 (–14)	0.166 (–17)	0.072 (–21)
5–6	0 (0)	0.067 (26)	0.2 (14)	0.35 (0)	0.217 (–3)	0.167 (–7)
7–8	0.048 (27)	0.036 (29)	0.072 (17)	0.08 (3)	0.41 (0)	0.325 (–4)
9–10	0.026 (31)	0.013 (33)	0.016 (21)	0.032 (7)	0.078 (4)	0.835 (0)

We analized the significance and detectability of the trends of the net UV–B irradiance (Q) against the background of its spontaneous variability associated with cloudiness. To this end we calculated the normalized frequencies (the empirical probabilities) of transitions from one to another cloud–cover index. The cloud–cover index was determined with a step size of two units. The average increments in the TOC were then determined for each transition (see Table II). After that a randomized numerical experiment was simulated, during which the UV–B irradiance was determined for different scenarios of the development of cloudiness during the observation period. 72 scenarios were simulated, each of them was formed as follows. According to the empirical probabilities of change of the cloud–cover index, it was taken from the random number generator, and assigned to each subsequent measurement, starting from the cloud–cover index of the previous measurement (the first measurement of the actual measurement series was taken as the initial value).

At each subsequent step the values of the TOC were determined by adding the average increment of the TOC, corresponding to the change in the cloud–cover index, to the previous value of the TOC. At each simulated measurement step the UV–B irradiance was calculated from Eq. (2a) with the use of the values A and α corresponding to the determined cloud–cover index (see Table I) and the value of V taken from the actual observation series. The average values of the TOC and of the UV–B irradiances were then calculated for each separate scenario, and the standard deviation of the above–indicated values was then calculated based on the simulated observation series incorporating 72 terms. This numerical experiment demonstrated that the standard deviation of Q amounted to $\sigma_0 = 4.33\%$ under conditions in which the TOC remained practically unchanged (the variance of the TOC constituted $(0.51\pm0.56)\cdot10^{-2}\%$ for the entire experiment, never exceeding 0.016% for the individual realization). Under the above–discussed conditions, the standard deviation of the sample mean over n years from the true value will be $\frac{\sigma_0}{\sqrt{n-1}}$. If the TOC reduces annually by $r\%$ the average increment of Q over the same period will be $\frac{krn}{2}$. The condition for detecting this trend at a confidence level of 0.95 may be written in the form:

$$\frac{2\sigma_0}{\sqrt{n-1}} \le \frac{krn}{2}, \tag{5}$$

or

$$n^3 - n^2 \ge \frac{16\sigma_0^2}{k^2r^2}. \tag{5a}$$

It is clear from inequality (5a) why the attempt of detecting the trend in the net UV–B irradiance undertaken by the authors of Ref. 5 failed. Even at the rate of reduction $r = 0.5\%$ per year (the maximum trend, cited in Ref. 4, corresponding to January in the 53–64°N latitude belt), inequality (5a) yields $n \ge 14$ years, while the authors of Ref. 5 analized only a 12–year series (during 1974–1985). If, on the other hand, we take the mean annual trend for the entire latitude belt in which the Robertson–Berger instruments were located, i.e., assume $r = 0.13\%$ per year, inequality (5a) would yield $n \ge 33$ years. Naturally, the statistics of cloudiness and its scattering properties may differ from the places of the US UV–meter station network, and these may differ from the corresponding characteristics for Kiev, but there are no reasons to assume that the above estimates would be soften. Moreover, for the Robertson–Berger UV–meter with the wavelength band up to 340 nm, the value of k should be significantly lower than 0.7–0.8, as was pointed out in Ref. 2, and this should result in further lengthening of the periods needed to detect the sought–after trends (for the UV–meter based on the M–124 instrument we had $k = 0.7$, its wavelength band was bounded by 315 nm). Note finally that the present estimates are obtained by a numerical experiment based on Eq. (2a), which deliberately overestimates the effect of ozone in forming the net UV–irradiance in the presence of clouds.

As for the importance of trends in the net UV–B irradiance for biological systems, we should like to state the following. When estimating the time period over which the long–term effect of excess UV–irradiance should manifest itself, the coefficient "16" in the right part of inequality (5*a*) should apparently be substituted by "64", since we may expect that such systems will be fluctuationally stable at a level of at least 4σ. Naturally, this relates only to the stability relative to the net UV–B irradiance, and to obtain such estimates for irradiances at the given wavelengths we must use the values of k and σ_0 corresponding to them. To obtain such values we need observational series performed with a spectral UV–meter.

These estimates of the time needed to detect the trends in the UV–B irradiance and their possible effect upon the biological systems are minimum, because they account only for damping effect due to cloudiness variability. To obtain a more adequate estimate accounting for all acting factors, one should add the following terms in the right part of inequality (5*a*): the variance of irradiance due to interannual variations of the TOC σ_0^2; the variance of irradiance due to variations in the solar activity σ_2^2; the variance of irradiance due to the transformations of the aerosol state of the atmosphere σ_3^2, etc. When turning to the problem of significance of these trends for biological systems, one should also add the variance of irradiance over the areal of the given biological system. All the foregoing allows us to conclude that the predicted catastrophic consequences of the depletion of the ozone layer remain at least disputable.

REFERENCES

1. *Conservation of the Ozone Layer.* Joint Project of Swedish Confederation of Trade Unions, Swedish Federation of Industry, Swedish Council on the Design and Coordination of Scientific Investigation, Swedish Council on the Protection of Environment, Swedish State Offices on International Development, and Swedish Academy of Sciences.

2. *Scientific Assessment of Stratospheric Ozone:* 1989, WMO. Global Ozone Research and Monitoring Project **1**. No. 20, 392 p.

3. J.E. Frederick and D. Lubin J. Geophys. Res. **93**, 3825–3832 (1989).

4. *Ozone Trends Panel.* Report (1988).

5. J. Scotto, C. Cotton, F. Urbach, D. Deryer, and T. Feurs, Science **239**, 762–764 (1988).

6. M.N. Caldwell, L.B. Camp, C.W. Warner, and S.D. Flint, in: *Action Spectra and their Key Role in Assessing Biological Consequences of Solar UV–B Radiation Change in Stratospheric Ozone Reduction. Solar Ultraviolet Radiation and Plant Life*, ed. by R.C. Worrest and M.M. Caldwell (Springer-Verlag, Berlin, 1986), pp. 87–111.

7. T. Mo, A.F.C. Green, Photochem. Photobiol. **20**, 483–496 (1974).

8. M. Ilyas, Atmos. Environ. **21**, 1483–1484 (1987).

9. V.A. Belinskii, M.P. Garadzha, L.M. Mezhenlaya, and E.I. Nezval, *Solar and Sky UV Radiation* (Moscow State University, Moscow, 1968), 228 pp.

10. H. Hinzpeter, Zs. Meteorol. **4**, No. 9. (1955); ibid. **1**, No. 11 (1957).

11. *Solar Energy Flux and its Variations.,* ed., O. White (Mir, Moscow, 1980), 558 pp.