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Towards analysis and predicting maps of ultraviolet index from experimental astronomical parameters (solar elevation, total ozone level, aerosol index, reflectivity). Artificial neural networks global scale approach

Jolanta Natalia Latosińska *, Magdalena Latosińska, Jarosław Bielak

Faculty of Physics, Adam Mickiewicz University, Umultowska 85, 61-614 Poznań, Poland

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ABSTRACT

UV radiation is an important problem in climatology, ecology but also has direct effect on human health. A novel method for analysis and prediction of global erythemal UV for clear-sky at noon at any localisation, expressed as the UV index, has been proposed. The supervised artificial neural networks (ANN) were trained using purely experimental astronomical parameters (input: solar elevation, total ozone level, aerosol index, reflectivity and required output: erythemal local noon UV irradiance expressed as the UV index) for all dates from a 3-year representative period (2001–2003) collected by Total Ozone Mapping Spectrometer (TOMS). The input data from the 3-year period provide three sets of 1095 grids, each consisting of 288 × 180 i.e. 56,764,800 training vectors for total ozone level, aerosol index, reflectivity, while the output data provide only one set of data of the same resolution. The trained network delivers a good long-term representation of the physical problem as it is able to predict clear-sky global UV index maps (UVI for any location and date) with an excellent accuracy close to the detection error (3%, 0.5 unit of UVI). The omission of data on aerosol index (slightly) and reflectivity (highly) deteriorates the quality of UVI prediction (MSPE error 6.4%, 1 unit of UVI) but also confirms the importance of total ozone level for the UVI prediction. The neglect of data on aerosol index and reflectivity evidently removes the inhomogeneities and results in smoother and less reliable UVI maps. Reflectivity plays a very important role in variation of UV radiation level. The results are presented in the form of 2D rectangular maps (WGS-84 projection) of UV index. The neural network approach to UVI forecasting and analysis yields reasonable results and can be considered as an alternative to traditional approaches mainly based on radiative-transfer or regression models.

1. Introduction

A stable level of UV radiation is vital for climatology [25,32,58,62,64], and ecology [60]. Disturbances in different radiative processes [43] are key factors forcing variations in the Earth's climate [25,26,31,32,64] and affecting the dynamics of the atmosphere [25,31,32]. The unstable level of UV radiation affects the equilibrium in the main components of the Earth's biosphere ecosystems (aquatic – marine and freshwater [16,30,33] – as well as terrestrial [8,9]). On the one hand, UV is indispensable for photosynthesis, for activity of DNA-related repair mechanisms (UV-A band), it is a natural method of disinfection of surface waters (lakes, rivers, reservoirs) or air, it regulates the circadian rhythm, enables hyperspectral vision responsible for food discrimination, mating rituals and permits navigation at dawn or even at night [45]. On the other hand, UV irradiation has negative effect on plant morphology, growth-rate, reproduction capabilities, species diversity, life-span, habitats, ecosystem stability, trophic interactions and ultimately global biogeochemical cycles increasing the mutation rate from major biomass producers (phytoplankton) to organisms higher in the food chain (zooplankton, fish) [16,30,33,41,62,81]. UV radiation is essential not only for vegetation and animals, but also for human life [18,53]. Its deregulation belongs to the factors highly influencing human health on global scale [28,45]. Positive effects associated with UV include the cutaneous synthesis of vitamin D and prevention of rickets, osteomalacia and osteoporosis [65], conversion of bilirubin to biliverdin which protects against jaundice, reduction of the risk of affective disorder, schizophrenia or multiple sclerosis [67], reduction of the risk of some diseases such as

* Corresponding author. Tel.: +48 61 8295277.
E-mail address: Jolanta.Latosinska@amu.edu.pl (J.N. Latosińska).

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tuberculosis or seasonal diseases spread by air like e.g. influenza, possible benefit for psoriasis, hypertension, ischaemic heart disease, diabetes (insulin dependent) and decreased risk for breast and prostate cancer [66]. The negative effects of UV radiation are the acute and chronic lesions in human skin (sunburn, chronic sun damage, photodermatoses, photoageing), eyes (acute photokeratitis and photoconjunctivitis, climatic droplet keratopathy, Pterygium, cancer of the cornea and conjunctiva, cataract, uveal melanoma, acute solar retinopathy and macular degeneration), and immune system (suppression of cell mediated immunity, increased susceptibility to infection, impairment of prophylactic immunisation and activation of latent virus infections) but also some kinds of skin cancer (malignant melanoma, basal cell carcinoma, squamous cell carcinoma) [20,23,28,42,66]. Excessive UV radiation is associated with a considerable number of premature deaths worldwide [22,46,59,79]. Development of civilisation, which strongly disturbs the thickness of ozone layer and the amount of UV reaching the Earth's surface [73,74] can have serious consequences, as just one percentage of ozone reduction in stratospheric atmosphere is estimated to result in 8000 cases of skin cancer in a year [22]. Exposure to excessive UV radiation (sun-bathing, sun-tanning) has been recently classified by WHO/International Agency for Research on Cancer as a possible carcinogen, on the basis of the evidence collected for 25 years [12,17,68,69] (Group 2B). The incidence-sun exposure relationship for cancers is well described by the power law [57]. This evidence and classification have resulted in a growing interest in health care products that reduce the risk of overexposure to the solar radiation [6,18,21,46], in the systems for the prediction of UV radiation level and in identification of factors that can lead to variations or systematic increase in the UV radiation level in some regions of the world.

Total solar radiation at the top of Earth's atmosphere is composed in about 50% of infrared light (IR), 40% of visible light (VIS), and 10% of ultraviolet light (UV). Although these proportions change in time, but the UV radiation level near the Earth surface does not exceed 3% [27]. The UV radiation below 200 nm (UV-C and UV-D range) is effectively screened out by dioxygen and nitrogen in the upper atmosphere, while that of 200–310 nm (UV-C and UV-B range) by trioxygen (ozone) in stratosphere and troposphere. The remaining part of UV radiation, exclusively form UV-A and UV-B bands, reaching the Earth's surface varies in a small range within the whole 11-year solar cycle [25,76]. Only a tiny (practically negligible) fraction of UV radiation reaching the Earth's surface comes from stars including the brightest Adhara (132 pc from Earth), Vega, β-Car, Spica and Antares (approximately 8.1, 26, 79 and 159 pc from Earth). Within the UV band, the UV-B contributes in about 80% towards biological action, while UV-A contributes the remaining 20%. Although in long-term a continuous increase in total solar UV-B has been observed, it has been effectively masked by seasonal changes and geographic differences [16,31,51].

In general, the total amount of UV radiation reaching the Earth's surface depends on a number of astronomical parameters including the solar elevation (season, latitude, time of day), atmospheric total ozone level, cloud cover, level of aerosols, water vapour (hazes) and dust in the atmosphere as well as reflection from clouds and ground (snow/ice cover, shape and the type of surface, degree of shading) and altitude [50,51,60]. Not all these factors are mutually independent and equally important. Solar radiation intensity changes by approximately 7% at the Northern Hemisphere; 6% at the Southern Hemisphere; 130% in the Antarctic; and 22% in the Arctic, regardless of the wavelength with the change of Earth–Sun distance (January–June) [29]. Higher solar zenith angle (SZA) (the angle between the horizon and the direction to the UV radiation) describing solar elevation according to $1/\cos$ (SZA) rule results in a shorter path of the sunrays through the atmosphere and thus higher probability of absorption or scattering [38]. Therefore, UV radiation strongly changes with latitude, season and time, reaching maxima in the tropics, in summer and at noon. The main absorber of UV-B radiance is ozone, thus the variation in the thickness of ozone layer is highly related to the intensity of UV-B radiation reaching the Earth's surface [52]. Total ozone distribution in extratropical regions reveals characteristic seasonal changes with maximum in spring and minimum in late autumn in the Northern Hemisphere, while in tropical and mid-latitude regions variations are pronounced at the turn of winter and spring. But for a fixed SZA, daily changes in ozone level prevail over the seasonal ones. Civilisation activity (air pollution, deforestation, fires) or to a small degree the anomalies caused geochemical natural activity (e.g. volcanic eruptions) may increase the concentration of absorbing gases (nitrous oxide and hydrocarbon pollutants), which upon UV from sunlight produce ozone in the lower atmosphere or freons, carbon tetrachloride, 1,1,1-trichloroethane, methyl bromide, other chlorofluorocarbon pollutants (CFC-11, CFC-12, CFC-113, CFC-114 and CFC-115, CFC-13, CFC-111, CFC-112, CFC-211, CFC-212, CFC-213, CFC-214, CFC-215, CFC-216, CFC-21) or halons (halon 1211, halon 1301 and halon 2402), which remove ozone from the upper atmosphere [52]. Both effects influence the thickness of ozone column, which acts as a protective layer against UV radiation reaching the Earth's surface [73,74]. Since the beginning of the 20th century, the level of UV radiation has been related to the total ozone layer thickness which has been used as an indirect measure of this level [72,77]. It was dictated by the experimental limitations as the ozone layer thickness measurements were less experimentally demanding. To describe the sensitivity of the UV (especially the harmful UV-B) to the changes in total ozone column, the Radiation Amplification Factor (RAF) concept was introduced [7,49]. But RAF determination requires the measurements at fixed SZA thus its application is limited to a few stations, although UV irradiance and stratospheric ozone are measured simultaneously. The power law describing UV-B radiation level with the total ozone as a base and RAF as an exponent has been proposed. RAF exponent often varies in the range 1.1–1.3 for different solar elevations and total ozone thickness, which means that 1% decrease in the atmospheric ozone induces 1.1–1.3% increase in UV radiation [14]. The other factors like clouds cover, level of aerosols and reflectivity are highly variable and difficult to describe with any empirical formula. Various cloud covers have different effect on UV transmission. The scattered clouds are able to enhance UV radiation, thin cloud cover is a negligible factor, while thick clouds can strongly reduce the UV irradiance at the Earth surface even to about 65–70%. Atmospheric aerosols, solid particles with diameter less than 10 μm, undergoing continuous fluctuations, affect the UV radiation through both scattering and absorption processes [75]. This combined effect is often described by the factor called the aerosol optical depth (AOD) which at high latitudes approaches a few hundreds and at low latitudes varies in the range between 0.05 and 2.0 (in polluted urban areas) [40]. The reflectivity factor, which enhances the UV irradiation, highly depends on the surface properties and reaches for water and land areas only about 5%, while for snow or sand covers as much as 80–90% [34]. The effects of all these factors are nonlinear; clouds, aerosol level and reflectivity reveal random stochastic nature, while the scattering of radiation strongly depends on the wavelength ($\sim 1/\lambda^4$) and is stronger in UV-B than in UV-A range.

As the biological effect of UV radiation also strongly depends on the wavelength [68,17] in 1995 the UV Index (UVI) was introduced as a measure of UV radiation intensity. Its use is recommended by the World Health Organisation (WHO), the United Nations Environment Programme (UNEP), World Meteorological Organisation (WMO), International Commission on Non-Ionising Radiation Protection (ICNIRP) and the German Federal Office for Radiation Protection (Bundesamt fur Strahlenschutz).