Original Article

Ground-based Observations of Ultraviolet and Total Solar Radiation in Shenyang, Northeast China*

GAO Qian[1], HU LiWen[1], GONG HuiZhi[1], GAO Na[1], YU JiaMing[2], WANG Yang[1], CHU Chun[1], YANG Hui[1], and LIU Yang[1,#]

1. Department of Environmental Health, School of Public Health, China Medical University, Shenyang 110001, Liaoning, China; 2. The 4th Affiliated Hospital of China Medical University, Shenyang 110032, Liaoning, China

Abstract

Objective This work explores the diurnal variation of Solar ultraviolet radiation (UVR) and total solar radiation (TSR) in northeast China, using daily observations of UVR and TSR in Shenyang.

Methods UVR and TSR measurements were carried out from March 1st, 2006 to December 31st, 2009 in Shenyang, Liaoning province, China (41°51′ N, 123°27′ E).

Results Both TSR and UVR showed seasonal variation, reaching the highest levels in summer and the lowest in winter. They showed the greatest fluctuation in summer and autumn. The irradiance of TSR and UVR on clear days around the equinoxes and solstices increased substantially compared with the mean seasonal irradiance, especially in autumn. The whole day accumulated dose of UVR in winter was far less than that during the middle part of a summer day (i.e. between 10:00 and 14:00). It was also less than the accumulated summer dose of morning and afternoon (i.e. between 8:00 and 10:00 and 14:00 and 16:00).

Conclusion The instant irradiance and daily accumulated amount of UVR are low in Shenyang, especially in autumn and winter. Thus concern about the health effects arising because shortage of UVR in northeast China is warranted.

Key words: Ultraviolet radiation; Total sun radiation; Broadband radiometer

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INTRODUCTION

Solar ultraviolet radiation (UVR) is an important environmental factor that affects human health. On the one hand excessive solar UVR exposure may lead to skin cancer, eye damage, immune suppression, skin photo aging and other ailments[1-3]. On the other hand, adequate ultraviolet B (UVB) initiates the production of pre-vitamin D and prevents skeletal diseases such as rickets[4-5].

China is a country with a vast territory, complex topography, and diverse climates. Ground-level UVR varies greatly from place to place. The health problems due to UVR in different areas are also different. For example, in the southern part of China, an area of low latitude, the prevalence of cataracts is much higher than that in northern high latitude areas[6]. But the morbidity of rickets in high latitude northern China is higher compared with that in low latitude southern China[7-8].

We can get Total Ozone Mapping Spectrometer (TOMS) Erythemal UVR irradiance data for almost

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#Correspondence should be addressed to Professor LIU Yang, No.92 North Second Road, Heping District, Shenyang, 110001, China. Tel: 86-24-23256666-5407. Fax: 86-24-23264417. E-mail: cmuliuyang@yahoo.com

Biographical note of the first author: GAO Qian, female, born in 1980, lecturer at School of Public Health, China Medical University, majoring in occupational and environmental health.

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anywhere on Earth. These data are derived from measured UVR irradiance entering the atmosphere, TOMS total ozone and surface reflectivity information available from the website of the National Aeronautics and Space Administration (NASA). But because most locations on the earth are viewed by the TOMS instrument only once per day, the model cloud optical thickness is presumed to be valid throughout the day. This can lead to some discrepancies between TOMS-estimated exposures and ground-based measurements[9]. So from a health perspective, to prevent the risk of excess sun exposure and to improve vitamin D deficiency caused by insufficient sun exposure, it is necessary to monitor ground solar UVR and analyze the distribution and trends of UVR in different areas in China.

In this work, we present the results of UVR and total solar radiation (TSR) measurements at Shenyang from 2006 to 2009. These results and their analysis should contribute to improving the knowledge about actual UVR and TSR levels in northeast China. These data can also serve as a valuable reference for comparison with values measured in other regions.

MATERIALS AND METHODS

The measurements were carried out between March 1st, 2006 and December 31st, 2009 in the north of the city of Shenyang, Liaoning province, China (41°51' N, 123°27' E), at a mean altitude of 50 m. Shenyang is located in the southern part of northeast China, and is the biggest city in this region with 7.4 million inhabitants. It has a temperate continental monsoon climate featuring abundant sunshine and four distinct seasons.

TSR was measured by pyranometer MS-402 (300-2 800 nm, Eko Instruments Co. Ltd., Tokyo, Japan). Broadband UV radiometers, type MS-210A (315-400 nm, Eko Instruments Co. Ltd., Tokyo, Japan) and type MS-210W (280-315 nm, Eko Instruments Co. Ltd., Tokyo, Japan), were used for ultraviolet A (UVA) and UVB measurement, respectively. These radiometers were the same types as used by Hiromasa et al.[10]. All instruments had wild fields-of-view (-180°). Therefore, sun-trackers were not needed and both direct and scattered light components could be detected. The spectral sensitivity of UVR radiometers is plotted in Figure 1. All sensors were mounted horizontally on a metal shelf on the roof of a one-story building, so as to avoid the shade from surrounding objects. The TSR, UVA, and UVB irradiances were recorded every 10 min by data logger. Hence 432 original records were collected every day. The data were downloaded every three months. Time integration of the measurements allowed the calculation of a total daily UVR and TSR dose.

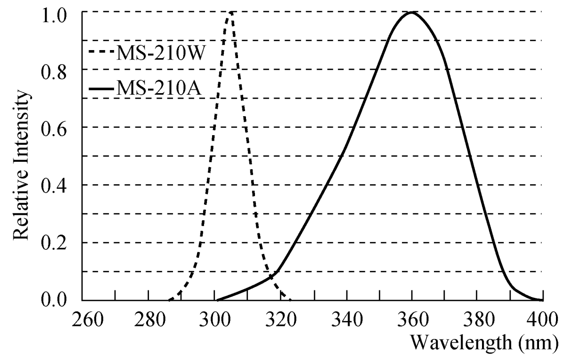


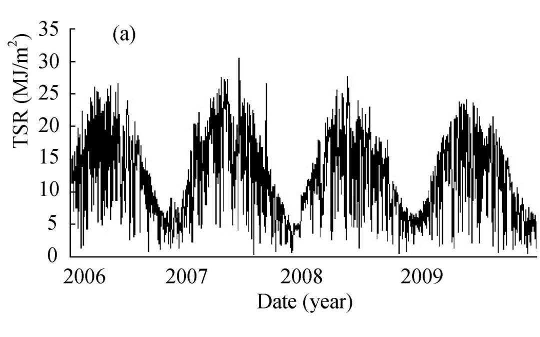
Figure 1. Spectral sensitivity of UV radiometers (MS-210W and MS-210A).

In Shenyang, March, April, and May are regarded as spring, June, July, and August as summer, September, October, and November as autumn, and December, January, and February as winter. To exclude the influence of weather conditions, four clear days near the equinoxes and solstices were selected to represent the characteristics of each season. They were Mar 19th, 2008, Jun 20th, 2009, Sept 22nd, 2009, and Dec 20th, 2008, respectively.

RESULT

Evolution of Daily TSR and UVR

Daily accumulated radiation estimates throughout the period of study are shown in Figure 2. Both TSR and UVR showed seasonal variation. The upper envelope curve followed a sinusoidal shape with minima and maxima near the solstices. The seasonal variation between each year was minimal. The maximum daily accumulated value of UVA was 1 496.82 kJ/m^2 (Jul 19th, 2007), for UVB it was 30.98 kJ/m^2 (Jul 19th, 2007), and for TSR it was 30.40 MJ/m^2 (Jul 19th, 2007).



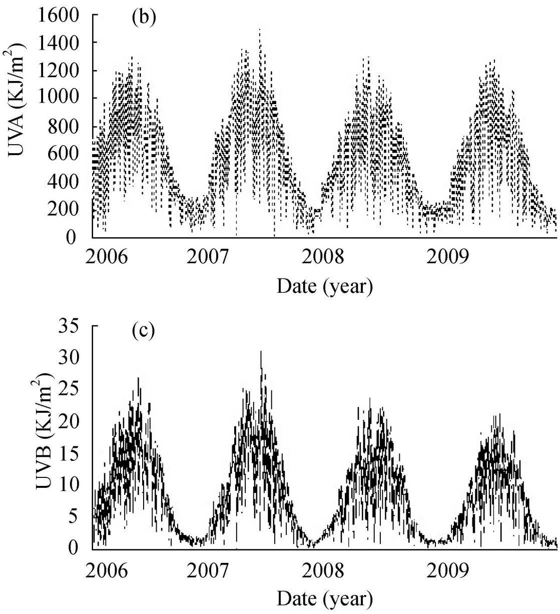


Figure 2. Evolution of daily TSR and UVR from Mar 1st, 2006 to Dec 31st, 2009 in Shenyang.

The Seasonal Patterns of UVA, UVB, and TSR at Noon

The solar zenith angle (SZA) at 12:00 China Standard Time (CST) is not the smallest in the locality, but the difference between the local time and CST is small. For the convenience of measurement and expression, we took the irradiation at 12:00 CST to represent the maximum value of a day. Figure 3 shows the seasonal patterns of UVA, UVB, and TSR at noon. They followed the seasonal pattern of the SZA. There was a decline during summer days and it reached a secondary peak in late autumn. Both UVR and TSR fluctuated wildly during summer and autumn days.

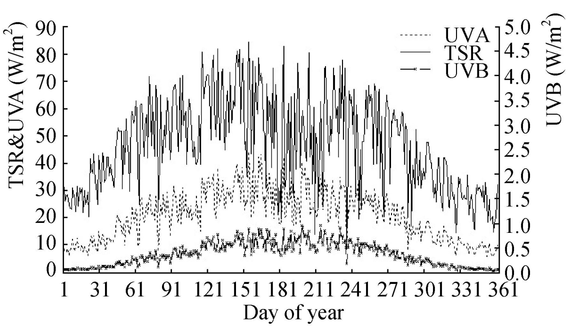


Figure 3. Mean annual variation of midday TSR, UVA (left axis) and UVB (right axis) averaged from Mar 1st, 2006 to Dec 31st, 2009 in Shenyang. **NB** TSR in this figure is actual irradiation divided by 10.

Seasonal Diurnal Variations of TSR, UVA, and UVB

UVA and UVB showed the same diurnal pattern as TSR. The distributions of all of the variables were bell-shaped curves which reached their daily maxima at noon time, about 11:30-12:00, as shown in Figure 4. UVA and UVB both reached their highest levels in summer and lowest in winter. For TSR, the irradiance in spring was similar to that in summer. The mean irradiance of TSR at midday in spring and in summer was 1.87 and 1.72 times as much as that in winter (312.99 W/m^2), respectively. For UVA, the irradiance at midday in winter was 10.88 W/m^2 and it was increased by a factor of 1.70 in autumn, 2.35 in spring, and 2.52 in summer. For UVB, the irradiance at midday in winter was 0.1 W/m^2 and increased by a factor of 3.40 in autumn, 4.40 in spring, and 6.20 in summer.

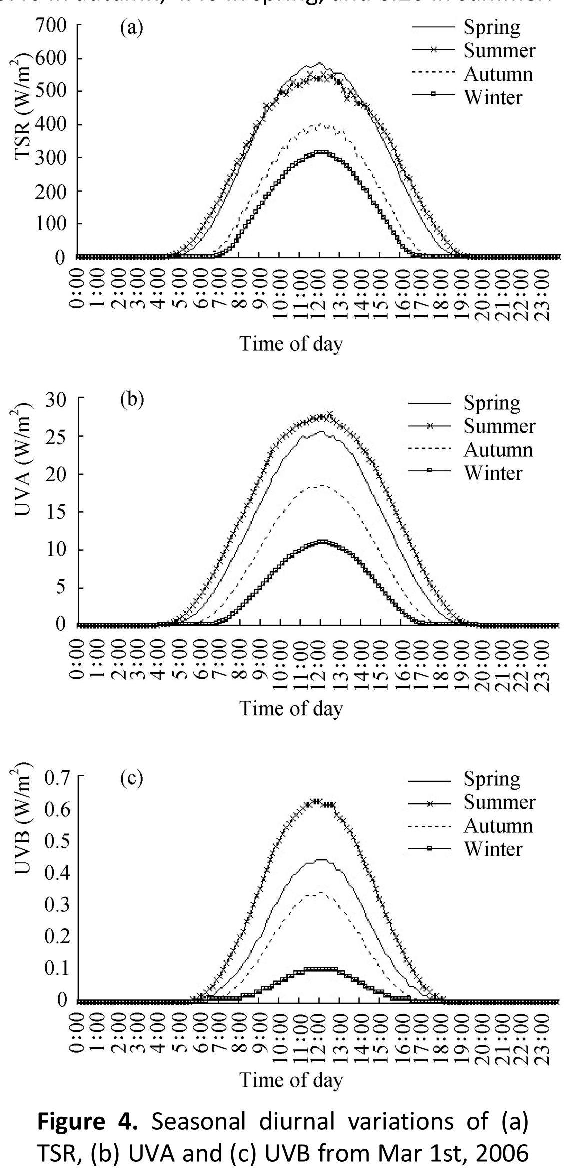
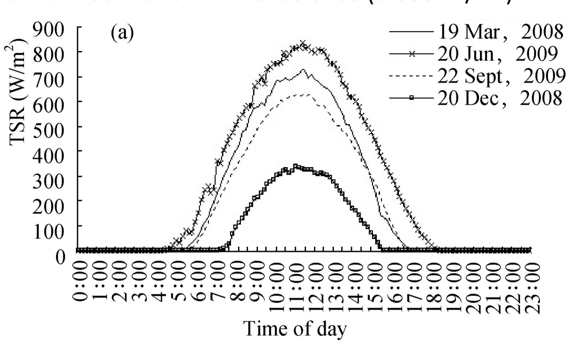
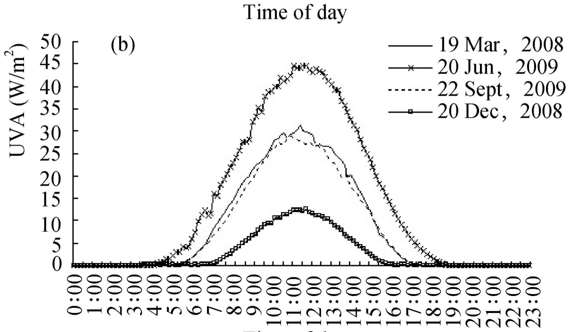


Figure 4. Seasonal diurnal variations of (a) TSR, (b) UVA and (c) UVB from Mar 1st, 2006 to Dec 31st, 2009 in Shenyang.

Diurnal Variation of TSR, UVA, and UVB on Clear Days

Figure 4 shows the general diurnal pattern of TSR and UVR, and includes all meteorological conditions. To exclude the influence of weather, we selected clear days near the equinoxes and solstices to represent the characteristic condition of each season. Accordingly, March 19th 2008, June 20th 2009, September 22nd 2009, and December 20th 2008 were chosen to represent spring equinox, summer solstice, autumn equinox, and winter solstice, respectively. The diurnal variation of TSR and UVR, when only clear days near the equinoxes and solstices were considered, is shown in Figure 5. Both UVR and TSR were maximal at summer solstice and minimal at winter solstice. Except at winter solstice, the irradiance at midday on these clear days for TSR and UVR increased substantially compared with the mean seasonal irradiance. For TSR, the midday irradiance on winter solstice was 330 W/m^2 and it was increased by a factor of 1.91 on autumn equinox, 2.22 on spring equinox, and 2.53 on summer solstice. For UVA, the midday irradiances at spring equinox and autumn equinox were equivalent, at 31.2 W/m^2 and 27.7 W/m^2, respectively. The duration of UVB was similar to that of UVA. But the increase of midday irradiance of UVB between autumn equinox, spring equinox, summer solstice and winter solstice was higher than the increase of TSR and UVA. The midday irradiance of UVB at autumn equinox, spring equinox and summer solstice was 5.29 times, 6.47 times, and 11.29 times respectively as much as that on winter solstice (0.085 W/m^2).





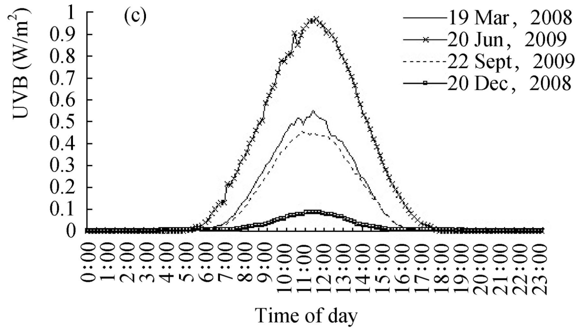


Figure 5. Diurnal variation of (a) TSR, (b) UVA, and (c) UVB on clear days around the equinoxes and solstices.

Annual Variation of Daily Accumulated UVA and UVB Radiation

As shown in Figure 6, daily accumulated UVR dose exhibited an annual maximum in June and July and a minimum in December. When only the middle hours of a day were taken into account (*i.e.* between 10:00 and 14:00 and 8:00 and 16:00, respectively), this pattern remained. The daily accumulated UVR dose received between 8:00 and 16:00 (when most people perform daily activities) in each month was little different to that from the whole day (00:00--24:00) and it almost equaled to the total dose received from a whole day in winter. The daily accumulated UVR doses received between 10:00 and 14:00 accounted for more than 56% of the dose received from the whole day. To exclude the effects of day length throughout the year, daily accumulated UVR dose received between 10:00 and 14:00 was compared with daily accumulated UVR dose received between 8:00 and 16:00. The ratio of the former to the latter for UVB in every month was higher than that of UVA. The ratios were minimal in July (UVB, 70.85%; UVA, 64.91%, respectively) and were maximal in December (UVB, 82.64%; UVA, 78.41%, respectively). Even the accumulated UVA doses received in the morning and afternoon (i.e. the amount received between 8:00 and 10:00 and 14:00 and 16:00) in May, June and July were more than the accumulated doses received from a whole day in January and December. The accumulated UVB doses in morning and afternoon (i.e. the amount received between 8:00 and 10:00 and 14:00 and 16:00) in May, June, July, and August were more than the doses received from a whole day in January, February, November, and December.

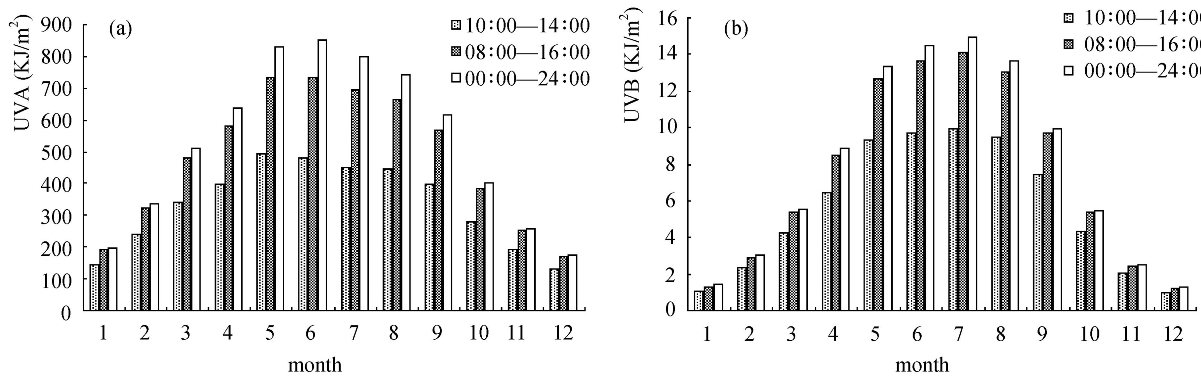


Figure 6. Mean annual variation of the daily accumulated (a) UVA and (b) UVB radiation for all day, 8:00-16:00 and 10:00-14:00.

Diurnal Variation of the Ratio of UVA to TSR and UVB to TSR Irradiance

Figure 7 shows the diurnal variation of the ratio of UVR to TSR from clear days near the equinoxes and solstices. In general, the ratio was maximal at summer solstice and minimal at winter solstice. Figure 7 shows that the diurnal variation pattern of the ratio of UVA to TSR was different to that of the ratio of UVB to TSR. The ratio of UVA to TSR varied slightly during the day ranging from 3.17% to 5.51%, but it changed abruptly at sunrise and sunset. The ratio of UVB to TSR changed significantly during the day, and basically followed a bell-shape curve. The ratio of UVB to TSR reached maximal values at noon on equinoxes and solstices. The ratio of UVB to TSR showed a more conspicuous increase at midday and ranged more widely among seasons than the ratio of UVA to TSR.

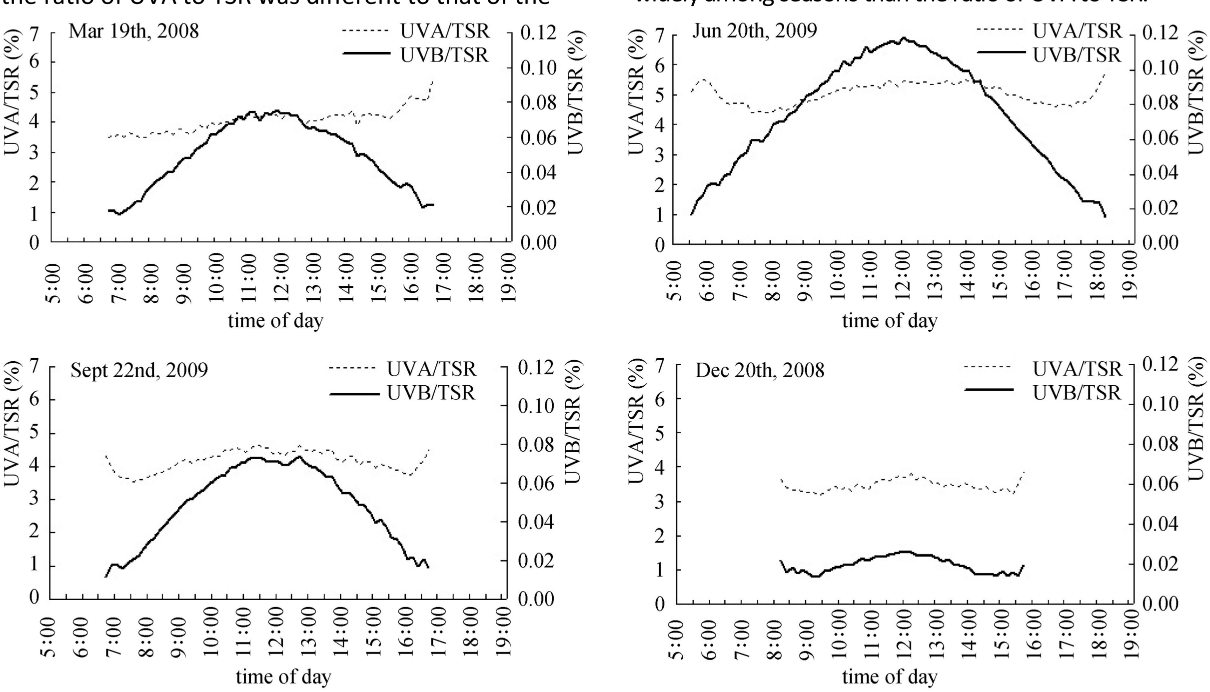


Figure 7. Diurnal variation of the ratio of UVA to TSR (left axis) and UVB to TSR irradiance (right axis) on clear days around the equinoxes and solstices. **NB** UVA/TSR in this figure means the ratio of UVA to TSR. UVB/TSR means the ratio of UVB to TSR.

DISCUSSION

In this study, we have presented a detailed statistical characterization of the distribution of UVR and TSR values at Shenyang, China, using three years and ten months of original measurements. This study should contribute to the understanding of UVR and TSR in northeast China. These values also provide a basis for meaningful comparisons with measurements from other locations.

When only clear days near the equinoxes and solstices were considered, both UVR and TSR reached the highest maximum irradiance on their representative summer day, the secondary maximum on their representative spring and autumn days. There was little difference in UVR and TSR between spring and autumn representative days. The UVR and TSR irradiances were minimal on their representative winter day. However, the UVR and TSR irradiances on clear days were different to the seasonal mean UVR and TSR irradiances. Because of more rain and cloud in autumn, the mean irradiance of autumn was significantly lower than that of spring. Shenyang is located in the north temperate zone with semi-humid continental climate. Monthly sunshine hours over years in Shenyang show that sunshine hours in spring (i.e. Mar., Apr. and May) are greater than those in autumn (i.e. Sept., Oct., and Jan)[11]. The observational data presented here confirms the regularity mentioned above.

In this study, although UVR and TSR showed wide fluctuation, the basic annual variation is due to the underlying astronomical system. The seasonal pattern of ground UVR and TSR follow that of the SZA. The annual SZA variation is greater in high latitudes, thus leading to a large seasonal variation in UVR. The radiation difference between summer and winter for UVR was larger than that for TSR. This indicates that UVR, particularly UVB, has a higher sensitivity than TSR to seasonal change. As SZA changes with each day of the year, it also changes with time of day. For a given latitude, hourly irradiance depends on the SZA. In the morning and evening, SZA is high, and the path of the sun's radiation through the atmosphere is long. Hence, the absorption and scattering of UVR is strong and the absolute level of UVR is small[12]. The diurnal variation of the ratio of UVB to TSR on four clear days near equinoxes and solstices exhibited bell-shape curves, with the maximum around noon. UVB showed a more conspicuous increase at midday than did TSR. Therefore, the dose of shorter wavelength solar radiation reaching the ground, especially UVB, was reduced by atmosphere more significantly than that of longer wavelengths. This also caused the low irradiance of UVB in winter.

Ma JY et al.[13] once observed TSR and UVB on the North China Plain. The UVB radiometer they used was not the same type as that used by us, but it had the same response range, and hence the results may be comparable to those obtained in this study. The UVB irradiances measured at Shenyang were much lower, across all seasons, than the results of Ma JY et al.[13]. On the other hand, the daily UVR dose between 10:00 and 14:00 measured in our study constituted a higher proportion of the dose received from a whole day. The ratio between daily UVR dose received between 10:00 and 14:00, and that received from whole day showed seasonal fluctuation, with winter maxima and summer minima. For UVB the whole day dose in winter was far less than the dose during the middle of a summer day, and even less than the dose in morning and afternoon (i.e. the amount received between 8:00 and 10:00 and 14:00 and 16:00) in summer. Thus, in Shenyang, the instant irradiance and daily accumulated amount of UV in winter are both low.

Vitamin D production in the human body mainly depends on the exposure to solar UVB[14-15]. The human body is perfectly capable of synthesizing 100 percent of the vitamin D it needs by exposure of the skin to sunlight. In this way the UVB level in sunlight plays an important role in skeletal health. In Shenyang, the absolute irradiance of UVB is low in winter and the sunshine hours are short in both autumn and winter. Also, people expose less skin when covering up against the cold of winter, so many people do not get sufficient exposure to UVB in autumn and winter. In addition, the effects of UVB exposure on vitamin D synthesis can be decreased for races with darker skin pigmentation[16-17]. All the above factors will lead to the accumulated dose of vitamin D in human body decreasing to minimal values in winter and a deficiency of vitamin D. The study of Yan L et al., based on population, also indicated that vitamin D status was poor in early spring in Shenyang[18].

Deficiency of vitamin D contributes to not only rickets in children and adolescents, but also osteomalacia and osteoporosis in adults[19-21]. While some researchers focus on the harm of excessive UVR exposure (e.g. cataracts and skin cancer), we cannot neglect the problem of childhood rickets, adult osteomalacia and adult osteoporosis due to a shortage of UVR in northeast China. Because more than 90 percent of human body's requirements for vitamin D derive from cutaneous photosynthesis[22], residents living at high latitudes in winter should protect against vitamin D deficiency.

Everything has two sides and UVR is no exception, it has both positive and negative effects on human health. We should be concerned about different received UVR doses causing different health problems in different regions in China. Thus, it is important to monitor ground UVR in different regions in China.

Although this study provides basic information on UV radiation in northeast China which is now available for use as a benchmark for other areas, comparisons are not always straightforward. Because the instruments utilized for monitoring ambient ultraviolet and solar radiation are different, the spectral sensitivities are often different. This is an important technical problem, and comparisons need to be thoughtful. Notwithstanding, although direct comparisons may sometimes not be possible, the observations are likely to reflect the actual ultraviolet exposure level and are still significant.

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