CLIMATOLOGY OF ULTRA VIOLET (UV) IRRADIANCE AT THE SURFACE OF THE EARTH AS MEASURED BY THE BELGIAN UV RADIATION MONITORING NETWORK

Praveen Pandey [(1)], Didier Gillotay [(1)], Cedric Depiesse [(1)]

[(1)] *Royal Belgian Institue for Space Aeronomy (BIRA-IASB),Ringlaan 3, Uccle -1180, Belgium,*
praveen.pandey@aeronomy.be, didier.gillotay@aeronomy.be, cedric.depiesse@aeronomy.be

ABSTRACT

In this paper we describe the network of ground-based ultraviolet (UV) radiation monitoring stations in Belgium. The evolution of the entire network, together with the details of measuring instruments is given. The observed cumulative irradiations -UVB, UVA and total solar irradiation (TSI)- over the course of measurement for three stations -a northern (Ostende), central (Uccle) and a southern (Redu)- are shown. The longest series of measurement shown in this study is at Uccle, Brussels, from 1995 till 2014. Thus, the variation of the UV index, together with the variation of irradiations during summer and winter months at Uccle are shown as a part of this climatological study. The trend of UVB irradiance over the above mentioned three stations is shown. This UVB trend is studied in conjunction with the long-term satellite-based total column ozone value over Belgium, which shows two distinct trends marked by a change point. The total column ozone trend following the change point is positive. It is also seen that the UVB trend is positive for the urban/sub-urban sites: Uccle and Redu. Whereas the UVB trend at Ostende, which is a coastal site, is not positive. A possible explanation of this relation between total column ozone and UVB trend could be associated with aerosols, which is shown in this paper by means of a radiative transfer model based study -as a part of a preliminary investigation. It is seen that the UVI is influenced by the type of aerosols

1. INTRODUCTION

The solar irradiance reaching the surface of the Earth, ranging from the ultraviolet (UV) to the infrared (IR) wavelength of the electromagnetic spectrum, has various effects on the Earth's atmosphere and ecosystem. At the same time, there are several applications of solar irradiance on the surface of the Earth, namely, climatic, environmental, hydrological, agricultural, biological, solar energy and engineering applications, among others [1].
Together with the advantage of solar irradiance in the visible spectrum (400-700nm), the UV wavelength of the solar irradiance (280-400nm) reaching the surface of the Earth affects human health and the environment in many ways ([2], [3], [4]) The UV irradiance plays an important role in building and maintaining human bones [5]. In spite of its advantages on humans, an excess of UV irradiance has harmful and acute effects on humans, namely, damage to DNA [6], effects on human skin and eye damage [7], among others.
UV irradiance plays an additional significant role in Earth's atmospheric chemistry, via actinic flux ([8], [9], [10], [11]), which becomes complex under varying condition of cloudiness [12].
It is not only that UV irradiance is affecting the atmosphere and environment, but, UV irradiance is also affected by various factors, namely, solar zenith angle (SZA), total column ozone-including stratospheric and tropospheric ozone, clouds, aerosols, albedo, among others. One of these factors, ozone, is a crucial one, having a seasonal variation in its total column value. An anticorrelation between stratospheric ozone and UV irradiance has been [13]. Ozone gains attention also due to various anthropogenic impacts on it, which resulted in ozone hole, which in turn affects the UV irradiance [14], [15], [16].
Therefore, the measurement of UV irradiance is very important. Thus, already since a long time there have been several studies dedicated to the UV irradiance measurements, e.g., [17], [18], [19], [20], among many others. Together with the ground-based measurements, there have been several reports on studying the UV irradiance using model-based approach ([21], [22]). At the same time, remote sensing satellite-based techniques have also been used to study UV irradiance (23], [24]).
Identifying the importance of UV irradiance, several long-term measurements are carried out for climatological studies that have also been used for cross validation with other approaches ([25], [26]). Driven by the Antartic ozone depletion in 1980s, one of the ground-based UV irradiance measurement site was established in Uccle, Brussels, Belgium, which is now providing a long-term climatological characteristic of local UV irradiance and associated measurements. Brussels being the capital of Belgium that hosts several national and international institutions, thus, it accommodates a large population that are exposed to an urban atmosphere. This UV irradiance measurement site commenced the foundation of UV ground-based measurement network of Belgium. The data from this network has already been used in several studies ([27], [28], [29]).
In this study, we present the ground-based UV network

of Belgium that features in the European UV measurement network. The long-term database of Brussels is used to analyse the climatology of UV irradiance and associated parameters by studying the seasonal and yearly variations. Attention is also given to two more stations in Belgium -a northern and a southern station- in analysing the trend of UV irradiance over the course of measurements. Subsequently, the effect of varying aerosol is also expressed by conducting a simple radiative transfer modelling approach.

2. DESCRIPTION OF THE UV NETWORK

2.1. The UV network

The Royal Belgian Institute for Space Aeronomy (BIRA-IASB) has developed and deployed a fully automatic network for the measurements of solar irradiance (UV and visible: 280-600 nm) and ancillary parameters as meteorological data, clouds, sunshine duration, among others. The initial measurements started in 1993.

The Belgian UV network comprises of six stations. There is an additional station in Luxemburg as a result of collaboration between Belgium and Luxemburg. Fig. 1 shows the locations of all these stations. However, the focus in this study is on the Belgian network.

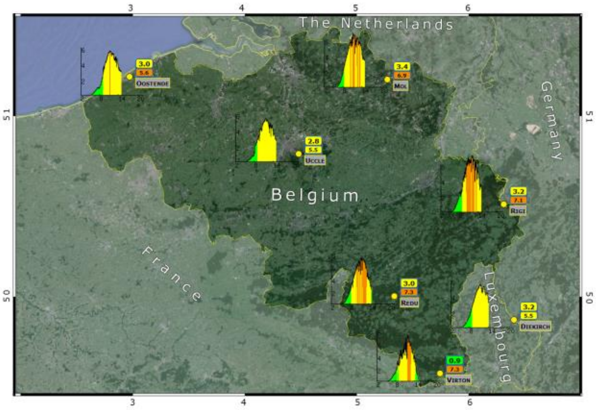

Figure. 1. Location of the ground based UV measurement sites in Belgium and Luxemburg

The first station was deployed in 1993 on the rooftop (100 m amsl-above mean sea level) of the Belgian Institute for Space Aeronomy in Uccle, south of Brussels-a green suburban area. The second station, Redu, was established almost a decade after the first one, that is in 2004, in the Belgian Ardennes. The Redu measurement station is at an altitude of 450 m amsl in the proximity of heavy traffic. The third station was established in 2006 in Ostend (in Dutch it is written as Oostende and in French as Ostende), which is a coastal city. The measurement site is located 200 m away from the sea at an altitude of 10 m amsl. The fourth station is at Virton, a small town, since 2007, at an altitude of ~250 m amsl. The fifth station was deployed in 2008 in the northern part of Belgium, Mol, which has a drier and warmer climate. The station is located at an altitude of ~75 m amsl. The most recent station was deployed in 2011 in Mont-Rigi at an altitude of ~700 m amsl, which is almost the highest peak in Belgium. All the sites were chosen in a way to take into account the aspect of varying background climatology together with a better coverage of the field of view.

2.2. Data and instruments

The first ground-based UV observations made at Uccle were the spectral measurements. They were made by means of a modified Jobin-Yvon HD10 double spectro-radiometer. The home-made modification pertaining to the spectro-radiometer concerned especially the improvement of its scanning mechanism in order to increase the scanning stability in atmospheric conditions. The modification also pertained to the design of new slit and grating supports, which allowed more accurate alignment of the double monochromator. An additional modification was the entrance optics, which offered a nearly perfect cosine response. Following which, the instrument is fitted inside a thermostatic container flushed with dry nitrogen. The modification is completed by fitting a quartz dome that highlights the entrance optics.

The scanning frequency of Jobin-Yvon HD10 double spectro-radiometer is fixed to 15 minutes. The spectral measurements is completed by the addition of broadband UVB meter, UVA meter, pyranometer and narrow band filter radiometers. The measurement frequency of these instruments is fixed to 1 mean value every minute.

Presently, Uccle is equipped with two double monochromators, (Modified Jobin-Yvon HD10 and BenthamTM300, since 2004), broadband instruments (UVB, UVA and total solar pyranometer), filter radiometers (GUV 2511, UVMFR-7, MFR-7 and SPUV-10) and ancillary instruments to measure the meteorological parameters (EOLE-200), the cloud fraction and ceiling (CIR-4 and CIR-13) and the sunshine duration (SDM MS-093).

The measurement at Uccle invoked the idea of developing a ground-based network in Belgium. Over the ten years of the measurement at Uccle and its maintenance, an adequate choice of various instruments were made and were deployed at other sites sequentially. All the other ground-based stations of the current UV network of Belgium are equipped with following instruments: (a) Filter radiometer, (b) broadband UV-B meter, (c) broadband UV-A meter, (d) broadband pyranometer, (e) cloud infrared radiometer (CIR-4), (f) sunshine duration meter and (g) meteo station Eole 200 that can measure temperature, dew point temperature, pressure, relative humidity, wind speed & direction and rainfall.

2.3. Data management and data processing

The data recorded by the different instruments are stored on their respective computers, and thereafter sent to the main data base in Uccle, Brussels, every five minutes, by automatic ftp procedure. These ‘level 0’ data are used to generate ‘real time’ information to the public, displayed on our website: http://uvindex.aeronomie.be .

Once the data is transferred to the main data base, it is reprocessed. The spectral data from the spectroradiometers is verified by a quality control procedure developed under the EU SUVDAMA programme in order to remove potential wavelength shifts. Correction of the response curve of the broadband instrument is applied to take into account the temperature dependence. At the same time, no correction is applied on the angular response of the instruments. Their optical characterization shows nearly perfect cosine response curve up to SZA = 80°.

3. RESULTS AND DISCUSSION

3.1. Daily values of cumulative UVB, UVA and total solar irradiance

In this section we show the irradiance values as measured by the Belgian ground-based stations. Since Uccle, in Brussels -a representative of the centre of Belgium, is the station that has the longest ground-based UV irradiance measurement, the prime focus of this study remains over Uccle. The observation at Uccle comprises the measurements done by spectral, narrow band and broadband instruments.

Fig. 2 shows the time-series of the daily cumulative UVB, cumulative UVA and cumulative total solar irradiation (TSI) values as observed at Uccle from 1995 till 2014. It is to be noted that the observations are continuously ongoing and it is for the sake of representation here that the time-series has the limit till 2014. It can be seen that the cumulative values of the irradiations are lower in the beginning and end of each and every calendar year, which is marking the winter months, as less irradiation is measured at the surface. Whereas, during the middle of the calendar year the irradiation values are higher, this corresponds to the summer months. Later in this study (section 3.2) we have focused on the summer and winter months. It can be seen from Fig. 2(a) that there are some years that exhibit higher cumulative UVB than others, namely, 1995, 2000, 2008 and 2009-which exhibits the maximum cumulative UVB till date. In future, a closer attention could be given to these years in order to study any relation, if at all, with the EU heat wave. Fig. 2 (b) shows the cumulative UVA variation. It can be seen that the amount of UVA is much higher than UVB. The year-to-year variation can be seen in cumulative UVA irradiation too. Fig. 2(c) shows how the cumulative total solar irradiation at Uccle varied in the last 20 years. Moreover, the fluctuations in the amplitude of the TSI can be seen too. The value of the cumulative TSI is much larger than the UV spectrum, which is obvious, as the TSI comprises the wavelength between 280nm to 3000nm. It can also be seen from Fig. 2 that the variation in the amplitudes of UVA, UVB and TSI do not follow similar trends. It implies that the irradiance in different wavelengths reaching the surface of the Earth is affected in an unequal way by various atmospheric factors. The year-to-year variation in the amplitude of the irradiation values implies that the total solar irradiance reaching the surface varied from one year to other.

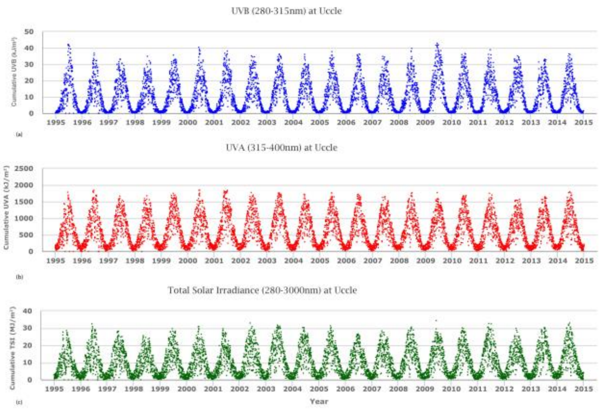

Figure 2. Time-series of daily cumulative (a) UVB irradiance, (b) UVA irradiance and (c) total solar irradiance (TSI) during the period 1995-2014 as measured at Uccle, Brussels.

The ground-based UV observation in Belgium with a longer term record following Uccle, is at Redu. It can be considered as a representative of Southern Belgium, which has uneven terrain. The time-series of cumulative UVB, cumulative UVA and cumulative TSI at Redu are shown in Fig. 3. The first year of measurement has partial records of observation. It can also be seen that the year-to-year variation between the cumulative UVA is more evident than the cumulative UVB. The variation of maximum cumulative UVA between 2005-2010 is also noteworthy whilst comparing the Uccle and Redu station. Redu observed more variations during this period than Uccle, with respect to the cumulative UVA. Fig. 3(c) indicates that since 2011 Redu observed less cumulative TSI compared to the previous years.

The other station that has the longer term UV observation in Belgium is Ostend, since 2006. It was established as a representative of the northern Belgium that also captures the coastal climate. Fig. 4(a), 4(b) and 4(c) shows the time-series of the cumulative UVB, cumulative UVA and cumulative TSI, respectively, as observed at Ostend. A comparison of Redu (southern Belgium) and Ostend (northern Belgium) measurements exhibit that the yearly variations are prominent at Redu than at Ostend. This implies that there are differences in the amount of solar irradiance reaching the northern, central and southern part of Belgium.

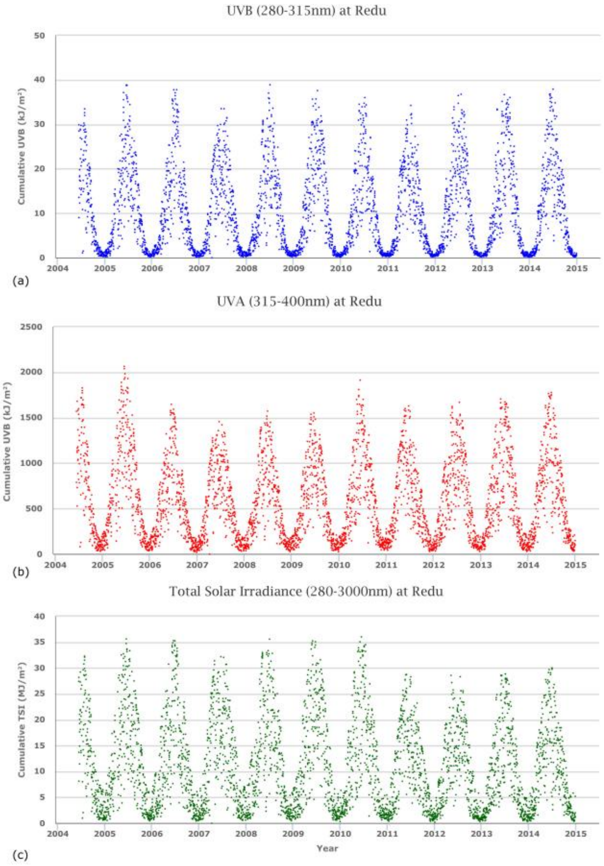

Figure 3. Time-series of daily cumulative (a) UVB irradiance, (b) UVA irradiance and (c) total solar irradiance (TSI) during the period 2004-2014 as measured at Redu

3.2. Seasonal variation of daily irradiances over Uccle

As expectedly evident from the previous section, the cumulative irradiation is higher during the summer months and lowers during the winter months, we focus on these periods -summer and winter months- in this section.

Since the observations are longest at Uccle, it remains our prime focus. The months May-June-July-August represent the summer months, whereas, November-December-January-February represent the winter months. Figure 5 shows the mean irradiations -UVA, UVB and TSI- per day as measured during summer and winter months from 1995 till 2014. It highlights the contribution of the particular month to the yearly irradiance.

In addition to this, it can also be seen, that the quantity of irradiance during June and July is the major contributor to the maximum UVB irradiance observed. Moreover, the month of May also observed more number of times higher mean UVA than August. The maximum mean(UVA)/day is observed in July 2006. The mean TSI per day during the summer months shows that June and July are usually the months of higher 2003 irradiance. The measurement records shows that June and July 2014 received higher irradiance than other months. The month of August is mostly exposed to lower irradiance, as compared to other summer months.

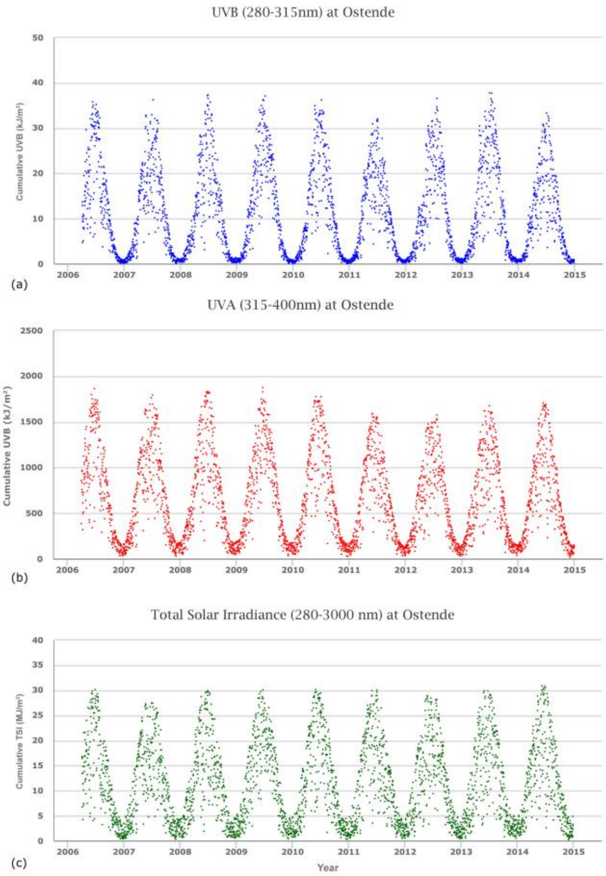

Figure 4. Time-series of daily cumulative (a) UVB irradiance, (b) UVA irradiance and (c) total solar irradiance (TSI) during the period 2006-2014 at Ostende

The winter months clearly shows that the irradiance levels have lowered as compared to the summer months. Approximately winter months observed 15-20% of summer months of UVB. The UVA during the winter months is approximately 25-30% of the summer months. UVA is higher during February, with highest being in February 2008, and lower values during December. The mean(TSI)/day during the winter months exhibits similar pattern as UVB and UVA. A peak is observed in February 2003. Winter months observed approximately 30-35% of summer TSI. This variation in UVB, UVA and TSI during summer and winter is related to the SZA, together with weather conditions and also to columnar ozone. Particularly, UVB irradiance, and to some extent UVA irradiance, is closely related to columnar ozone values.

3.3. Long-term variation of effective UVB and total column ozone

The last two decades of measurements of solar irradiance in Belgium allows us to study the trend with respect to the factors modulating the irradiance.

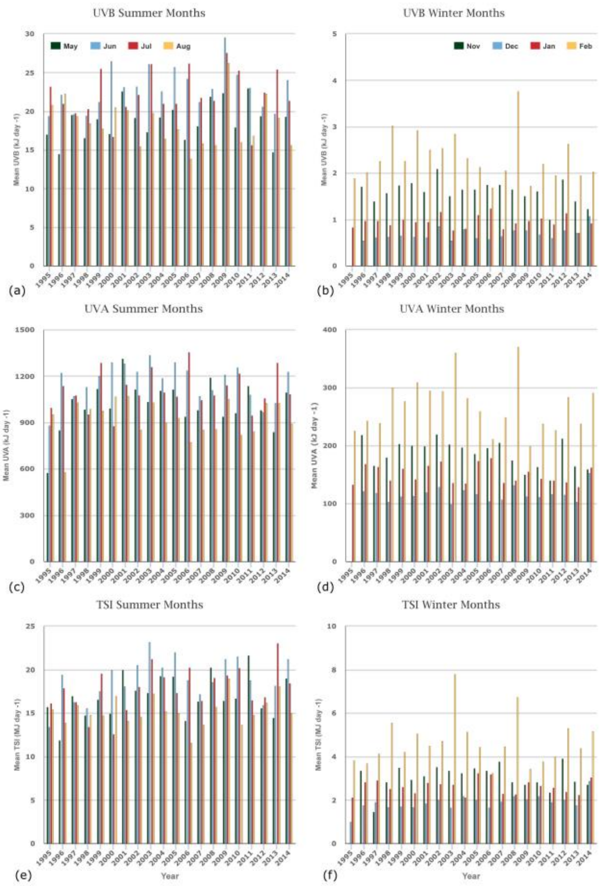

Figure 5. Daily mean UVB irradiance, UVA irradiance and total solar irradiance measured at Uccle during the summer months (a), (c) and (e) and the winter months (b), (d) and (f)

In this section we focus on the long-term variation of effective UVB (UVB_{eff}), as it is directly linked with the UVI, and total column ozone, which is one of the major factors affecting the UVB_{eff}.

In order to study the trend of UVB_{eff} over two decades of measurements, we computed a normalised difference of monthly mean from the long-term mean of the particular month over all the years. Hereafter this quantity is referred as Normalised Difference of monthly Mean - NDM (%), for the sake of simplicity of expression.

The NDM_{UVB} from 1995 till 2014 is shown in the Fig. 6. In general no trend is evident as such, however, a linear regression -shown by the solid red line- exhibits a positive slope

In order to study the total column ozone trend over Belgium, the ozone values that were being obtained since 1978 using satellite observations are put to use. Level 3 total column ozone values from the Ozone Monitoring Instrument (OMI) and the Total Ozone Mapping Spectrometer (TOMS) are extracted over 51N and 4.5E as a representative of the centre of Belgium.

The normalized difference of monthly mean of total column ozone observations from the long-term mean of total column ozone of the particular month over all the years of observations is denoted by NDM_{OZONE} (%).

Figure 7 exhibits the NDM_{OZONE} from 1978 till 2015, where two solid lines show two liner regression curves by following the trend of [30]. They showed that the

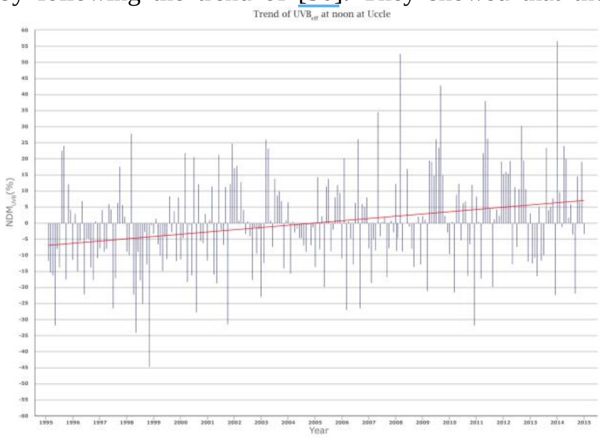

Figure 6. Trend of effective UVB (UVB_{eff}) at Uccle between 1995 and 2014. A linear regression is shown using the solid red curve.

end of 90's experienced a change point in the time-series of the ground-based measured columnar ozone over Uccle. Therefore, we also show two regression curves showing the trend of NDM_{OZONE} over Uccle as monitored by satellites. Until 2000, the regression is negative whereas, beyond the change-point, it is almost constant, which implies that columnar ozone has remained almost constant since end of 90's till date. This could very well correspond to the fact of impact of various protocols put to practice that could have facilitated the ozone recovery.

Figures 7 and 8 in conjunction exhibit a striking feature: columnar ozone trend is stable since around 2000, whereas, the trend in UVB shows a positive increase. This could imply that the contribution of ozone in the UVB irradiance measured at Uccle has disappeared or the UVB irradiance is affected by some other factor. This needs to be studied in detail in future by means of ground-based and satellite-based measurements, together with a radiative transfer modelling approach. However, it is well known that along with columnar ozone, clouds and aerosols play a major role affecting the UVB irradiance. One of the reasons of this continuous increase in UVB trend, despite of a constant total columnar ozone trend, could be related to the aerosol concentration. During the course of measurement of past two decades, the aerosol concentration around the measurement site evolved as a result of changing pattern of traffic emission, emission type, type of vehicular engines, the usage of a different kind of domestic heating fuel (e.g., desulfurised fuel), policies to improve the air quality, among others. These evolutions could be a reason for decrease in aerosol concentration, which thereafter, could explain the positive trend in UVB at Uccle, centre of Belgium, despite of a constant total columnar ozone trend. The impact of pollution on UV irradiance has also been reported in the past ([19]).

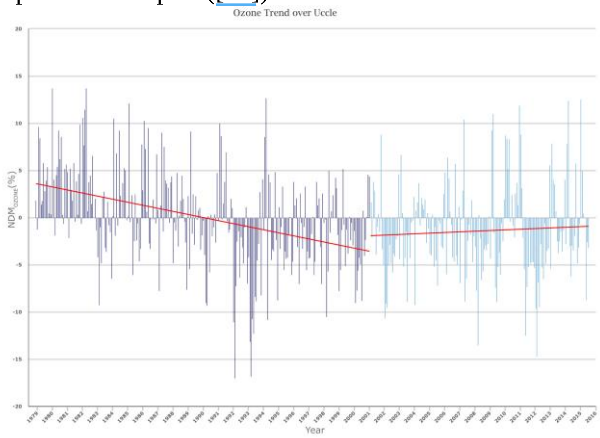

Figure 7. Trend of total column ozone over 51N and 4.5E as computed from the Level 3 data of Ozone Monitoring Instrument (OMI) and Total Ozone Mapping Spectrometer (TOMS) during the period 1979-2015. Two linear regression curves (solid red line) correspond to the change point, representing recovery of ozone, of total column ozone

Following the UVB trend in central Belgium, the UVB trend in the south of Belgium is shown in Fig. 8 by means of the NDM_{UVB} as observed at Redu. A linear regression -the solid red curve- has a positive slope, implying that there is an increase in the UVB trend. This trend is similar to the observations made in the centre of Belgium-Uccle. Therefore, a reason for this increasing UVB trend could also be similar to those as for the Uccle. However, for Redu the traffic emission could have played a major role. As the measurement site is close to a highway the emission is mostly from traffic. But, since the policies to improve the air quality in-and-around Belgium has been effective in reducing the sulphur dioxide, the UV absorbing aerosols, the concentration of these aerosols could have lowered. Thus, an increase in the UVB trend.

In order to study the UVB trend in the north of Belgium, the NDM_{UVB} at Ostende is shown in Fig. 9. The linear regression -solid red curve- exhibits a decreasing trend of UVB. Although, the decrease in the UVB trend is very low for Ostende, it can even be said as unchanged since the measurements, yet, this is different than the central and southern Belgian stations that experienced an increase in UVB trend. This difference in trend could be associated with the type of climate Ostende experiences. The Ostende measurement station experiences maritime aerosols, unlike urban/sub-urban aerosols. As the station is located very close to the coast -a pristine location, the maritime aerosols from natural origin mostly remain constant, as they are not linked with anthropogenic activities.

It is noteworthy that the hypotheses proposed to explain the varying trend of UVB have to be examined. There could very well be other reason, e.g., associated with the effect of cloud or a combination of cloud and aerosols. Nevertheless, here we propose the hypotheses based on a preliminary approach that are subjected to a detailed future studies.

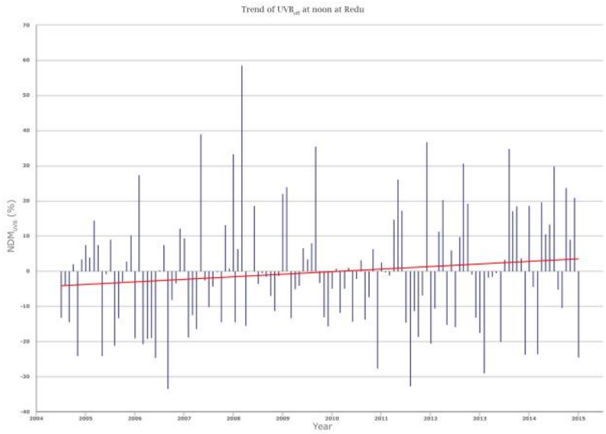

Figure 8. Trend of effective UVB (UVB_{eff}) at Redu between 2004 and 2014. A linear regression is shown using the solid red curve.

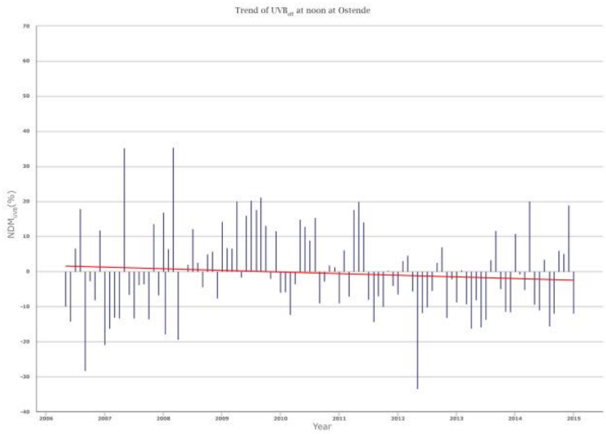

Figure 9. Trend of effective UVB (UVB_{eff}) over Ostend between 2006 and 2014. A linear regression is shown using the solid red curve

3.4. Long-term variation of effective UVB and total column ozone

This section presents a preliminary approach to the above proposed hypothesis of aerosols playing a crucial role in varying UVB, hence UVI, during the course of measurements in Belgium. In order to have an estimate of the effect of aerosols on the UVI, the discrete ordinate radiative transfer (DISORT) model ([22]) is put to use. It is configured for a plane-parallel atmosphere, with one nm wavelength step ranging from 280 to 600 nm. The background albedo is assumed to be 0.1 with 306 DU as the total columnar ozone. It is configured for a clear sky condition, i.e., cloud optical thickness (τ) as zero.

Table 1. Effect of Aerosols on UV index (UVI) for different aerosols types at varying aerosol optical thickness (AOT, τ_{aer}) and solar zenith angles (SZA)

Type of aerosol	UVI with TCO = 306 DU													
	SZA = 25°							SZA = 70°						
	AOT (τ_{aer})							AOT (τ_{aer})						
	0	0.1		0.2		0.3		0	0.1		0.2		0.3	
	Ref	Est	Δ	Est	Δ	Est	Δ	*Ref*	Est	Δ	Est	Δ	Est	Δ
Maritime	8.50	8.25	*3*	8.07	*5*	7.91	*7*	0.79	0.70	*11*	0.67	*15*	0.66	*17*
Continental	8.50	8.16	*4*	7.87	*8*	7.62	*10*	0.79	0.69	*13*	0.65	*18*	0.63	*20*
Urban	8.50	7.75	*9*	7.08	*17*	6.47	*24*	0.79	0.64	*19*	0.57	*28*	0.52	*34*

The impact of three different kinds of aerosols - maritime, continental and urban- on the UVI is computed for two solar zenith angles, 25° and 70°, by varying the aerosol optical thickness (AOT, τ_{aer}). It has been observed by the AErosol RObotic NETwork (AERONET, http://aeronet.gsfc.nasa.gov/)that τ_{aer}, on average, ranges between 0 and 0.3 over Uccle, Belgium. Thus, we vary τ_{aer} from 0 to 0.3 in steps of 0.1. The UVI for τ_{aer} = 0, is referred as the reference value (*Ref*), whereas the UVI with other values of τ_{aer} is referred as the estimated value (*Est*). Making use of the *Ref* and *Est*, following is computed: $\Delta\ (\%) = [(Ref - Est) / Ref] \times 100$
This, Δ, indicates the normalised difference of the τ_{aer} with respect to the *Ref* τ_{aer} for the specific solar zenith angle, expressed in percentage. Table 1 shows the effect of varying τ_{aer} on the UVI at Uccle, Belgium, for three different types of aerosols. It can be seen that an increase in τ_{aer} implies a decrease in UVI. This reduction in UVI, for a lower solar zenith angle, is highest for urban types of aerosols than the continental type, with a minimum impact on maritime aerosols. A similar trend is observed for a higher solar zenith angle (70°). In this case, the Δ is higher than the respective Δ of the lower solar zenith angle, implying that the impact of increase in τ_{aer} in decreasing the UVI is bigger for a solar zenith angle of 70° than that of a 25°. However, it can be clearly seen that the urban aerosols play relatively a bigger role than the continental or maritime aerosols in decreasing the UVI. It can be said in another way that the relative effect -reduction or increase- of maritime aerosols on UVI is less pronounced than urban aerosols.
A detailed future study is aimed to investigate the relation between the Belgian ground-based UV observations, aerosol properties and cloud properties.

4. CONCLUSIONS AND OUTLOOK

In this study we presented the Belgian ground-based ultraviolet (UV) irradiance measurement network. Together with the evolution of the entire network, the yearly variation of UVB, UVA and total solar irradiance (TSI) from a northern (Ostende), central (Uccle) and southern (Redu) Belgian station is shown. The trend of UVB, which is directly associated with the UVI, is studied. We found that for the central (Uccle) and southern (Redu) Belgian stations the UVB trend is positive over the course of measurements, whereas, for the northern Belgian station, Ostende, the UVB trend is not positive. As total column ozone is a major modulator of UVB, among other factors, a satellite based long-term trend of total column ozone is considered for a preliminary investigation in conjunction with long-term UVB trend. A change point in the total column ozone is observed, following which, the long-term total column ozone trend is positive: a sign of ozone recovery. It is found that the UVB trend in Uccle and Redu is positive too, even for the duration when the total column ozone trend is positive. We speculate that this behaviour could be explained by the role of aerosols and hence, a preliminary radiative transfer modelling study is conducted to open doors for detail future investigation. The use of a radiative transfer model illustrated that aerosol optical thickness is playing a role on reduction of UVI at the coastal site and an increase of UVI at urban or sub-urban site.

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