Variability of the UV-Index in Paramaribo, Surinam.

Dirk Malda

Graduation Research Project

Performed at

Royal Netherlands Meteorological Institute (KNMI)

Climate Research and Seismology Department

Atmospheric Composition Division

De Bilt, The Netherlands

December, 2004

Wageningen University,
Section of Meteorology and Air Quality
Duivendaal 2
6701 AP Wageningen
The Netherlands

Contents

Abstract

The ultimate intention for this research is to better understand the variability of the UV-index (UVI) in the Tropics and also to be able to improve the prediction of the UVI at Paramaribo (5.81°N, 55.21°W), Surinam.
This is the research question: What is the variability of the UV-index and what is its cause in Paramaribo under cloudless circumstances and corrected for the total ozone column, SZA and Earth-Sun distance? The *ozone profile* and *aerosols* are known to have an effect on UVI, but have not been investigated for Paramaribo. Cloud effects on UVI also have not yet been studied in Paramaribo, but for this research it is too complex to look at the combined effects of clouds, ozone profile and aerosols. Therefore, we restrict ourselves to cloudless situations.
The sub-research question is: To what extent is the empirical algorithm, used to predict the UVI in Paramaribo, valid for cloudless moments? If not, what is a typical deviation of the measurements from the algorithm? What is the cause of this deviation?

In **Chapter 1** a short description is given of the effects of UV radiation for human health. Further, an explanation of UVI, our objectives and research questions.
In **Chapter 2** information is given about Paramaribo station and afterwards a more technical description of the UVI and its affecting parameters. These parameters are: surface altitude, surface albedo, solar zenith angle (SZA), Earth-Sun distance, clouds, total ozone column, ozone profile, stratospheric temperature, aerosols and trace gases.
In **Chapter 3** the selection of cloudless situations is described. This is done in three steps. The first selection is based on known effects of clouds on UVA. An upper and lower limit is chosen for the irradiation ($W/m^2/nm$) at two wavelengths in the UVA. The second selection is based on comparison of the UV-spectrum with a reference spectrum. The third selection is a check of the remaining situations with pictures of a total Sky Imager (TSI) and the solar Radiation Station. Only few selected (totally cloudless) situations remained after selection 3. For 9 months with pictures of TSI and 11 SZA ranges of 1º, only 58 cloudless situations were found. Data of tropospheric ozone and aerosols were also very scarce. That is why we decided to use also the remaining situations after selection 2 ('cloudy' but 'sunny' situations) for this research.
In **Chapter 4** results are given of the variability of the UVI and its affecting parameters.
First, the variability of the *absolute* (measured) UVI is considered. The measured UVI variability at Paramaribo is defined within SZA ranges of 1º. The variability of the UVI is much higher for the situations after selection 2 than after selection 3. The maximum variability for a SZA range after selection 2 is 4 points of UV-index. For selection 3, it is about 1 point of UV-index. This difference is due to effects of clouds after selection 2, which are eliminated in selection 3. Clouds can cause an increase as well as a decrease of the UVI.

Second, the variability of the *relative* UVI is considered. In this report this is defined as the measured UVI divided by the calculated UVI. The UVI is calculated using the empirical algorithm with the Earth-Sun distance, the total ozone column and SZA as input parameters. After selection 2 the relative UVI varies typically between 0.8 and 1.1; after selection 3 typically between 0.85 and 1.05. The smaller range after selection 3 is again due to eliminating the cloud effects in this selection. The expectation was that total ozone column and SZA are not related with the relative UVI. However, our results suggest that for cloudless situations the relative UVI increases with SZA.
For the situations after selection 2 as well as selection 3 the average relative UVI is 0.96. This suggests a calibration error of the Brewer (the instrument measuring UV-radiation).

For quantifying the effects of the ozone profile on the UVI, the tropospheric ozone column is used as parameter. The tropospheric ozone column (0-5 km) at Paramaribo varies between 7 and 16 DU. There is no significant variability of the UVI caused by this variability of the tropospheric ozone column.
An increase of the aerosol optical depth (AOD) with 0.4 can cause a significant variability in the UVI of typically 10%. The AOD at Paramaribo varies between 0 and 0.5. The AOD was typically higher in the dry season than in the wet season of 2003.
Diffuse radiation at cloudless circumstances is a possible indicator for the AOD.
In **Chapter 5** a summary is given of the conclusions from this study. Also some recommendations are given for further research and improvement of the algorithm predicting the UVI.

1 Introduction

1.1 UV radiation

UV radiation (200-400 nm) is divided into three ranges: UVC (200-280 nm), UVB (280-320 nm) and UVA (320-400 nm). UVC is absorbed in the upper atmosphere entirely by ozone (O_3) and oxygen (O_2; only short wavelengths in UVC); UVB is partly absorbed. UVA is not absorbed by ozone. Above 320 nm a very small, decreasing part of the radiation is absorbed by ozone.

UV radiation can have harmful effects on human skin and eyes. The main effects are erythema (sunburn), skin cancers, cornea affections and cataract for which UVB radiation is responsible. Further, skin aging, loose of elasticity of the skin and crystalline affections for which UVA is responsible.

1.2 UV-index

In order to warn people, predictions of the UV-index (UVI) are made for many places in the world. The UVI is a quantity that indicates the strength of the danger on human skin of UV radiation at a specific moment. The total ozone column in Dobson Units (DU) and the solar zenith angle (SZA) are the most important parameters affecting the UVI. With a satellite, ozone is measured all over the world when the satellite passes. With a transport model, the total ozone column is calculated for moments that the satellite does not pass. Predictions of the UVI are made with the total ozone column calculations and some other parameters.

1.3 Objectives for this research

The ultimate intention is to better understand the UVI variability in the Tropics and also to be able to improve the prediction of UVI for Paramaribo, Surinam.

In the Tropics the UVI is higher than at higher latitudes. The main cause is the smaller SZA at noontime in the Tropics with respect to higher latitudes. Nevertheless, in the Tropics are only few stations where UV radiation is measured. Because of the lack of data, the effects of different parameters on UVI are not studied and quantified very well for the Tropics. However, in Paramaribo is a station where UV radiation is measured together with a lot of parameters affecting the UVI.

In this research we want to learn more about the parameters, which are known to have an effect on UVI, but have not been investigated for Paramaribo. These are the *ozone profile* and the amount of *aerosols*. Until now only the effects of SZA and the total ozone column are quantified for Paramaribo. Allaart et al. (2004) found an algorithm for these parameters. More about the algorithm and the effects of different parameters on the UVI is to be found in **Chapter 2**.

1.4 The research question

This is the research question: What is the variability of the UV-index and what is its cause in Paramaribo under cloudless circumstances and corrected for the total ozone column, SZA and Earth-Sun distance?

The sub-research question is: To what extent is the empirical algorithm, used to predict the UVI for Paramaribo, valid for cloudless moments? If not, what is a typical deviation of the measurements with respect to the algorithm? What is the cause of this deviation?

We expect significant deviations of the actual cloud-free UVI from the predicted cloud-free UVI with the model. This is because the model only takes into account the SZA, the total ozone column and the day of the year. We hypothesize that the cause of the deviations is mainly the effect of the ozone profile and aerosols.

1.5 Approach

To study the separate effects of the ozone profile and aerosols on the UVI, other parameters that affect the UVI have to be constant or a correction is needed.

Four other parameters are not (assumed to be) constant or negligible: the Earth-Sun distance, the total ozone column, the SZA and clouds. For the first three parameters an empirical algorithm is made by Allaart et al.(2004). Cloud effects on UVI also have not yet been studied in Paramaribo, but for this research it is too complex to look at the combined effects of clouds, the ozone profile and aerosols. Therefore, we restrict ourselves to cloudless situations.

Within the cloudless situations it is possible to investigate the variability of the UVI. However, to study only the effects of the ozone profile and aerosols a correction for the Earth-Sun distance, the total ozone column and the SZA is needed. Therefore, the measured UVI is divided by the calculated UVI from the algorithm. Next the variability of this ratio can be investigated and in relation to the ozone profile and aerosols.

1.6 Outline

The method used for this research exists of four steps. The first step (**Chapter 2**) is a description of the measurements location, the climate at the location and the instruments. Further, a detailed explanation is given of the definition of UVI and also of the parameters affecting the UVI.

The second step is to give a list of the available and used data and the selection of cloudless moments from that data. The cloudless moments are selected within three steps. This is all described in **Chapter 3**.

The third step (**Chapter 4**) is a description and discussion of the results. The results are divided into two parts.

Part one is focused on the variability of the UVI in Paramaribo. This is divided in the variability of the *absolute* UVI measurements and the variability of the *relative* UVI, i.e., the measured UVI divided by the expected UVI of the algorithm. The function of quantifying the relative UVI variability is to study ozone profile and aerosols as the only parameters that are not (assumed to be) constant or corrected for. Part two focuses on the relation between the ozone profile and aerosols respectively and the relative variability of the UVI.

The fourth step (**Chapter 5**) summarizes the conclusions of the results and gives recommendations for further studies.

2 Background

2.1 The station Paramaribo

Surinam is a country, located at the northern coast of South-America. Paramaribo (5.81°N, 55.21°W) is the capital of Surinam. With 300,000 inhabitants, 75% of the inhabitants of Surinam (400,000) live in Paramaribo. The local time at Paramaribo is UTC – 3 hours.
The station is located southwest of Paramaribo, between the city and the rural environment. The traffic is the only continuous source of air pollution in the neighbourhood of the station. A second possible intermittent source of pollution is forest fire. The area is flat; no mountains or hills are visible from the site.

2.2 Climate

The inter-tropical convergence zone (ITCZ) migrates over the site of the station twice per year. The migration of this zone causes the wet seasons. The short wet season is in December and January; the long wet season from April to July. The other parts of the year are called the short and the long *dry* season.

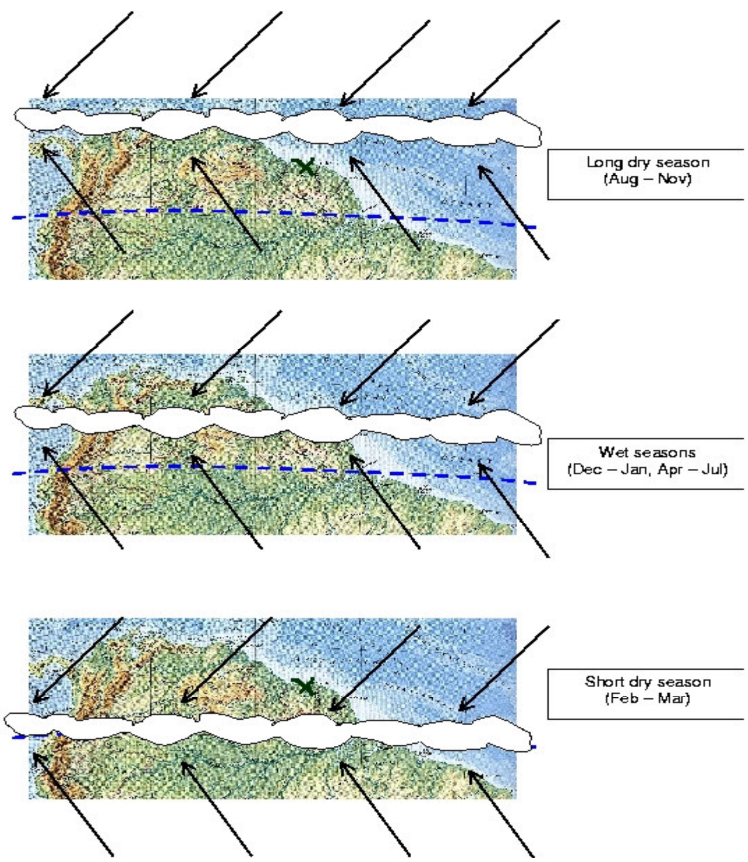


Figure 2.1.
An overview of the wet and dry seasons in Paramaribo and the migration of the ITCZ.
Source: http://www.knmi.nl/~verver/fortuin/radchis.html

In the short dry season and partly in the wet seasons, the wind direction is North-East most of the time, i.e., the air is transported to the station from the Atlantic Ocean and over the city of

Paramaribo. In the long dry season, the wind blows from the South-East, i.e., the air is transported to the station over the tropical rain forest.
Even in the dry seasons, almost every day at least a few clouds arise in the sky. However, in the dry seasons, the probability of cloudless moments is higher than in the wet seasons.

2.3 Relevant instruments at Paramaribo station

This is only a list of instruments. More about the instruments and their measurements is described in **Appendix A**.
A Brewer MKIII spectrometer measures short-wave light: UV-radiation. The global UV-irradiance is measured, so direct and diffuse UV-radiation are not measured separately.
Measurements are done between 286 and 363 nm with steps of 0.5 nm. Each day about twenty measurements are performed, and only when the SZA is between 0° and 60° (after November 2002 between 0° and 70°).
The Brewer measures another important parameter, the total ozone column. This is done either by direct sun or zenith sky measurements.
The Total Sky Imager (TSI) gives every minute between sunrise and sunset a picture of the sky. The pictures are made by a camera, positioned above a mirror, which is shaped as a hemisphere.
A Pyrheliometer measures the direct solar radiation, integrated over 300 to 3000 nm.
A Pyranometer, shadowed, measures the diffuse solar radiation. Another Pyranometer, not shadowed, measures the global solar radiation. Both instruments measure the integrated solar radiation over 300 to 3000 nm.
A Sunphotometer measures the direct radiation at 5 different wavelengths. After some calculations it gives the aerosol optical depth (AOD) for every wavelength. For a well-calibrated Sunphotometer, the error in the aerosol optical depth is *at least* 0.01.
Finally, balloon soundings are done every week in order to measure, among other things, the ozone profile.

2.4 The UV-index

UV radiation is dangerous for the human skin, it can cause sunburn. The UV-radiation relevant for erythema (sunburn) is weighted by the CIE (Commission Internationale de l'Eclairage) action function (McKinley & Diffey, 1987).
The definition of the UVI is as follows:

$$UVI = \frac{1}{25mW/m^2} \int S_\lambda E_\lambda d_\lambda \qquad (2.1)$$

Where

S_λ	= Solar irradiation at the surface (mW/m^2/nm).	
E_λ	= Erythemal action spectrum (McKinlay and Diffey 1987)	
E_λ	$= 1$	for $\lambda \leq 298$ nm
E_λ	$= 10^{0.094(298-\lambda/nm)}$	for 298 nm $< \lambda \leq 328$ nm
E_λ	$= 10^{0.015(139-\lambda/nm)}$	for 328 nm $< \lambda \leq 400$ nm
E_λ	$= 0$	for 400 nm $< \lambda$

S_λ is also measured by the Brewer, so the UVI can be calculated from S_λ and the spectral UV measurements, made by the Brewer.

2.5 Parameters affecting the UVI

A lot of research has been performed into the parameters that affect the UVI. Below is a list of the different parameters and for each parameter a short explanation.

2.5.1 Surface Altitude

The UVI depends on the surface altitude and increases for high plateaus with 5% per kilometer, with the condition that snow is absent. This effect is due to a decrease of air density, causing a reduction of scattering of solar radiation.
If the orography is more detailed, the surface altitude dependence of UVI is much stronger (Gröbner et al. 2000). The albedo (for example snow cover) and air pollution affect also the altitude dependence of UVI. Because the station in Surinam is in a flat area at sea level with never snow cover, the altitude dependence of UVI is not important for this research.

2.5.2 Albedo

Snow cover (Feister & Grewe 1995) and some types of sand affect the albedo significantly. The changed albedo affects the UVI. A higher albedo gives a higher UVI.
At Paramaribo station snow cover is not a realistic situation. The land is covered with trees and grass, so sand is no important parameter in this research.

2.5.3 Solar Zenith Angle

An increase of SZA with 1º decreases the UVI with 0.04% (SZA = 0º-1º) to 7.3% (SZA = 59º-60º). This is calculated using the same algorithm as in **paragraph *2.5.6***. The decrease of UVI is mainly due to the longer path length of the radiation through the ozone layer at higher SZA.

2.5.4 Earth-Sun Distance

The distance between the Earth and the Sun varies through the year. That can give a variability of more than 6% in UVI under the same atmospheric and geographical conditions (Liou, 1980). In the algorithm for the UVI we correct for the Earth-Sun distance. This is the algorithm for the correction factor of the Sun-Earth distance:

$$\theta_0 = 2\pi * \frac{DN}{365} \qquad (2.2)$$

Where
DN = Julian day number (1-365 (366))

$$\left(\frac{D_0}{D}\right)^2 = V + W * \cos(\theta_0) + X * \sin(\theta_0) + Y * \cos(2\theta_0) + Z * \sin(2\theta_0) \qquad (2.3)$$

Where
$\left(\frac{D_0}{D}\right)^2$ = Correction factor for Earth-Sun distance
D_0 = Average Earth-Sun distance (m)
D = Actual Earth-Sun distance (m)
V = 1.00011
W = $3.4221 * 10^{-2}$

X = $1.28 * 10^{-3}$
Y = $7.19 * 10^{-4}$
Z = $7.7 * 10^{-5}$

2.5.5 Clouds

The influence of clouds on UVI is very complex. Clouds can increase or decrease the UVI. Overcast skies can reduce the UVI in a very wide range, typically 8% for thin clouds, and 70% for thick clouds (Renaud et al. 2000).
In the UV-A, Tunc (1999) observed an increase of 16% for broken clouds. In this research we do not consider cloud effects, so we need to look at cloudless moments. Nevertheless, these percentages are useful for selecting cloudless moments.

2.5.6 Total Ozone Column

Allaart et al. (2004) describe an algorithm to predict the UVI with the total ozone column in Dobson Units (DU) and the SZA. 1 DU = $2.69*10^{20}$ molecules per m^2.
The algorithm has been based on data from De Bilt (The Netherlands) and Paramaribo (Surinam). Using the algorithm, the UVI decreases typically with 5% when the total ozone column increases with 10 DU. Ozone only affects the irradiation at small wavelengths. In the UVC (200-280 nm), ozone absorbs the total incoming radiation. In the UVB (280-320 nm) the radiation is partly absorbed by ozone. UVA (320-400 nm) is a very small, decreasing part of the radiation absorbed by ozone.
The algorithm is built up as follows (Allaart et al. 2004). In the algorithm, UVA is calculated with 'a parabolic weighting function, peaking at 350 nm and nonzero between 340 and 360 nm'. Therefore, it is called here UVa instead of UVA.
The first step is the calculation of UVa as a function of the SZA and a few other parameters.

$$UVa = \left(\frac{D_0}{D}\right)^2 * S_0 * \mu_0 * \exp\left(-\frac{\tau_a}{\mu_0}\right) \qquad (2.4)$$

Where
S_0 = Extra-terrestrial value for UVa at $D = D_0$
μ_0 = cos(SZA)
τ_a = Atmospheric extinction (molecular scattering and aerosol scattering and absorption for SZA=0)

After a correction for scattered light:
$\mu_x = \mu_0(1-\varepsilon)+\varepsilon$
Where $\varepsilon = 0.17$

And defining
S = 1.24 $Wm^{-2}nm^{-1}$
τ = 0.58

The equation for UVa becomes:

$$UVa = \left(\frac{D_0}{D}\right)^2 * S * \mu_x * \exp\left(-\frac{\tau}{\mu_x}\right) \qquad (2.5)$$

Now the UVI is expressed as a function of UVa and the total ozone column:

$$UVI = UVa\left(F * X^{G} + \frac{H}{TO} + J\right) \tag{2.6}$$

Where

$$X = 1000 * \frac{\mu_0}{TO} \tag{2.7}$$

TO = Total ozone column (DU)
F = 2.0
G = 1.62
H = 280.0
J = 1.4

2.5.7 Ozone Profile

Not only the total ozone column is important for the UVI on the ground. The *vertical distribution* of ozone is also very important. Per molecule ozone, the effect on UVI is higher in the troposphere than in the stratosphere. The cause is the longer average path length of (scattered) photons in the troposphere. For example the same total ozone column placed in the Tropics can give 8% higher UVI compared to the mid-latitudes (Van Weele et al. 2001), due to the different vertical distribution of the ozone.
Van Weele et al. (2001) found also that 50% increase of the tropospheric ozone column (DU) below 16 km can cause a UVI decrease of 8% at maximum. A condition for a significant effect on UVI of differences in tropospheric ozone is that the measurement has to be done with an accuracy of 10 DU or 3%.
The amount of ozone in the troposphere varies from day to day. It depends on the local rate of air pollution at the surface and transport from elsewhere at higher altitudes.

2.5.8 Stratospheric Temperature

The absorption coefficient of ozone is temperature dependent in the stratosphere. In the Tropics, the monthly-average temperature of the stratosphere varies typically 5 K. Because of this small range, the stratospheric temperature plays no important role for the day-to-day variability of the surface UVI in Paramaribo.

2.5.9 Aerosols

Aerosols are very small, generally invisible particles in the atmosphere. They cause a decrease in UV, with the exception of a snow-covered area.
The decrease of UV radiation by aerosols depends on two properties of the aerosols: absorption and scattering, together called the extinction.
The extinction is described by the Beer-Lambert Law:

$$I = I_0 e^{-\tau/\mu_0} \tag{2.8}$$

Where
I_0 = Extra-terrestrial solar radiation (W/m^2)
I = Transmitted direct component (W/m^2)
τ = Aerosol optical depth (-)

The optical properties of aerosols are described by three parameters: the aerosol optical depth (**equation 2.8**), the SSA (single scattering albedo) and the phase function (P).

The SSA is a definition of the relative importance of absorption and scattering.

$$SSA = \frac{\sigma_s}{\sigma_s + \sigma_a} = \frac{\tau_s}{\tau_s + \tau_a} \qquad (2.9)$$

Where

σ_s = cross section for scattering (cm^2/molec)

σ_a = cross section for absorption (cm^2/molec)

τ_s = Aerosol optical depth for scattering (-)

τ_a = Aerosol optical depth for absorption (-)

The phase function (P) is the angular distribution of a scattering event. G is an efficient parameter, called the asymmetry factor.

$$G = \frac{1}{2}\int_{-1}^{1} P(\Theta)\cos(\Theta)d\cos(\Theta) \qquad (2.10)$$

When G is –1, the aerosols have a perfect backscattering and when G is 1, the aerosols have a perfect forward scattering. Madronich (1993) found that typical values for G are between 0.6 and 0.8 for aerosol particles in the atmosphere.

Badosa & van Weele (2002) found a maximum absolute effect of AOD_{368} on the UVI of 6. The SZA dependence of that effect is less than 6% and 4% (from 0º to 60º) for AOD_{368} and SSA, respectively. SSA has a maximum absolute effect of 2.8 on the UVI.
In this research G is assumed to be constant. That will give an uncertainty in UVI of *at most* ±0.4 (Badosa & van Weele 2002).

2.5.10 Trace gases

As ozone, sulphur dioxide (SO_2) and some other trace gases can absorb UV-radiation. In Paramaribo the concentrations of SO_2 and other trace gases are assumed very low, so the influence on surface UVI is not considered significant.

3 Data selection

The selection of data exists of two parts. The first part is the selection of time period. The second part is the selection of cloudless situations in the selected time period.

3.1 Time period

First it is needed to give an overview of the available data. The used time period is where all relevant data are available.
From the *Brewer MKIII*, UV spectra are used from October 2002 to August 2004. For a few days data were not available because of technical problems. Data derived from the Brewer are the UVI and the SZA at which the spectrum is measured. The error in the measured UVI is typically ±5%.
Also from the *Brewer* are the data of the total ozone column. These data are separated from the spectral data in other data files. The error in the measured total ozone column is typically ±2%.
Weekly data from *balloon soundings* (ozone profiles) are used from January 2002 to August 2004. The error in the calculated total ozone column from the soundings is typically ±10%.
The *Sunphotometer* data, from which the AOD can be derived, are available from November 2002 to January 2004. Only data of 69 different days are good to calculate the AOD out of it. The error in the calculated AOD is *at least*, when the instrument is well-calibrated, typically ±0.01.
Data from the *TSI* are available for the months October, November and December of 2002 and January, July, August, September, October and November of 2003, except a few days of some months. TSI pictures of most other months are still at Paramaribo station.
From the *solar radiation station* (two Pyranometers and one Pyrheliometer) data are available from October 2002 to September 2004, except a lot of days without valid data. The error in this data is not very important, only pictures are used to see if the radiation varies smoothly or not.
The time period used for this research is **October 2002 to August 2004**.

3.2 Selection of cloudless moments

A selection of cloudless moments is needed. The way to find cloudless moments is done in three selection steps. The first step is not to check all situations with the total Sky Imager. This is because of three reasons. The first is that we did not know at the start of the research that TSI data were available. The second reason is that it costs too much time to check all situations with the TSI. The third reason is that TSI data are not available for all months within the selected research period. Therefore, first two other selection steps need to be made.

3.2.1 The first selection

This first selection is based on two facts. The first is that clouds can reduce the UVI from 8% (thin clouds) to 70 % (thick clouds) (Renaud et al. 2000). The second fact is that aerosol optical depths measured in Paramaribo (0.04 - 0.5) are expected to have an effect on the UVI of 10% at maximum (Badosa & van Weele 2002). We need to select data for which the UV intensity is reduced at most 10% with respect to a cloudless reference. To be sure to keep all cloudless moments and not to throw away situations with polluted conditions, it is better to use a percentage of 20% instead of 10%.
The first problem is that ozone can also give a reduction of UV-intensity of more than 30%. A 33% decrease of the total ozone column gives typically 50% increase of UVB (KNMI &

RIVM, 1995). To avoid this problem we need to perform the selection for a wavelength in the UVA (>320nm).
The second problem this selection gives is that we do not know at this moment what the clear moments are, so we do not have a reference to reduce 20% percent.
Clouds can also give an increase in UV-radiation with respect to cloudless situations, foremost when it is partial cloudy and the sun is not behind the clouds (Tunc, 1999). Through scattering a big part of the (UV) radiation downward, the intensity of the radiation increases; this is called an enhancement.
The solution we have chosen is quite simple. The estimated maximum enhancement is 10%. We first searched for the maximum intensity and multiplied this value not with the expected 0.80 (to keep the highest 20%), but with 0.68, to keep 12% more, to be sure that all cloudless situations are included in the selection.
When the UV intensity is more than 0.95 times the maximum intensity, the situation will most likely be partial cloudy. This we have discovered through plotting a wider range (65% of the maximum as lower limit and the maximum intensity as upper limit) and checking with the Total Sky Imager data if the situation was partial cloudy or cloudless. Therefore, the maximum intensity multiplied with 0.95 forms the upper limit for the selected moments. Using the same strategy, we found that 0.68 times the maximum intensity is a good lower limit.

The third problem is the question how much wavelengths we have to check for the selection; is one wavelength enough? There is a possibility that a ‘partial cloudy spectrum’ is selected. The time a measurement of a UV-spectrum takes, is around 4 minutes. In those 4 minutes a cloud can ‘pass’ the sun (see figure 3.1b).

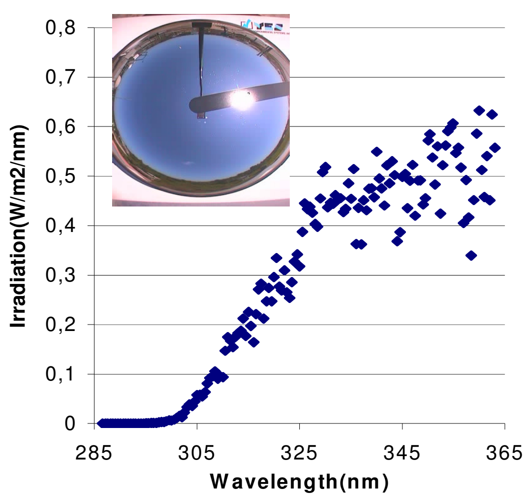


Figure 3.1a.
UV-spectrum (measured by the Brewer) of a cloudless situation (Paramaribo, August 22 2003, 13:19 UTC; SZA is 35.7°), together with a picture from the Total Sky Imager of the same time. This spectrum is used as reference spectrum in selection 2, for the SZA range35-36°.

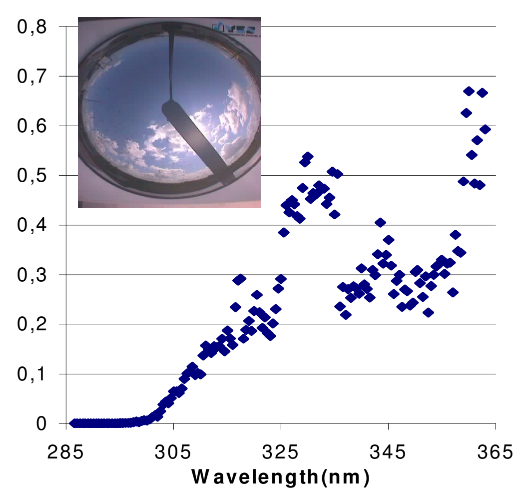


Figure 3.1b.
UV-spectrum of a partial cloudy situation (Paramaribo, January 13 2003, 14:16 UTC; SZA is 35.3°), together with a picture from the Total Sky Imager of the same time. Between 320 nm and 360 nm some clouds ‘pass’ the sun.

The consequence can be that the intensity of the irradiation at one wavelength falls within the selected range and another one does not. Therefore, it is better to check at two wavelengths and only select a situation if the intensity at both wavelengths falls within the selected range of intensities. We have chosen the wavelengths 335 nm and 360 nm.
Note that the spectrum of the cloudless situation (figure 3.1a) is not a smooth line. The cause is that the spectrum of the sun is not a smooth line.
There is still another problem. That is the SZA dependence of the UV-intensity. That is why we chose to compare only moments with a difference in SZA of 1° at maximum. For example, moments with a SZA range of 9-10°, 24-25° etcetera.

3.2.2 The second selection

When we checked a few situations from the first selection with the Total Sky Imager, we found a lot of moments that were not cloudless. A second selection was needed.
This further selection is based on the comparison of every selected spectrum with one reference spectrum, through dividing the selected spectrum by the reference spectrum. The reference spectrum is a spectrum, which is for sure a cloudless situation, and is found by searching in the Total Sky Imager data. At 11 SZA ranges of 1° is searched and found a reference spectrum. The reference spectrum in the SZA range between 35° and 36° is the situation of *August 22 2003, 13:19 UTC* (figure 3.2a).
For every wavelength in the spectrum with a value of irradiation (W/m^2/nm) is that value divided by the value of the irradiation at the same wavelength in the reference spectrum.

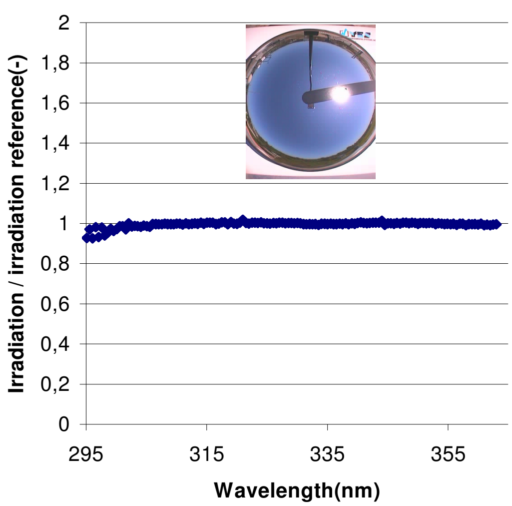


Figure 3.2a.
UV-spectrum divided by the UV-spectrum of the reference (22 August 2003, 13:19 UTC; SZA is 35.7º) for a cloudless situation (Paramaribo, August 25 2003, 13:19 UTC; SZA is 35.4°). The line is almost smooth.

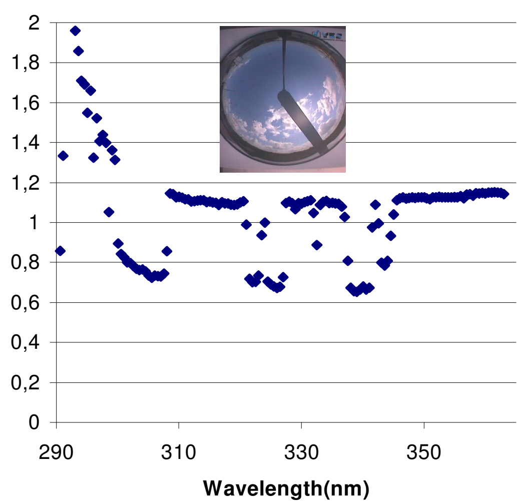


Figure 3.2b.
UV-spectrum divided by the UV-spectrum of the reference (22 August 2003, 13:19 UTC; SZA is 35.3º) for the partial cloudy situation (Paramaribo, January 13 2003, 14:16 UTC; SZA is). The line is only smooth at sunny moments.

The figures 3.2a and 3.2b show respectively a divided spectrum of a cloudless situation and a partial cloudy situation. The picture of the cloudless situation shows an almost smooth line. Only in the small wavelengths we see a different deviation with respect to the reference. This

is due to a very small difference in total ozone column (265.9 on 25 August and 264.2 on 22 August) and possibly a different *ozone profile* gives an extra effect.
The picture of the partial cloudy situation shows the opposite of a smooth line. That is because of the clouds, which 'pass' the sun during the measurement. This situation is not tackled in the first selection, through the coincidence that the irradiation at 335 nm *and* 360 nm fall within the selection criteria. In this selection, it becomes clear by visualizing the divided spectrum that this is not a cloudless situation.
Through this second selection, every situation is tackled where clouds 'pass' the sun and decrease significantly the direct radiation during the measurements.

3.2.3 The third selection

After the first two selections, there is one kind of situation that is not tackled. That is when there are clouds in the sky during the measurement, but they do not pass the sun in those four minutes. Further, they do not amplify the radiation so strong that it would be tackled in the first selection.
The third selection is performed through a check of every remaining situation after selection 1 and 2. The check contains a view of both the data of the Total Sky Imager and the Solar Radiation Station. The most trustable data are those of the Total Sky Imager. The Solar Radiation Station (if data are present) can give an overview of the situation of the whole day. Nevertheless, if the TSI shows a cloudless sky during the *whole* measurement, then is that enough information to call that situation cloudless.

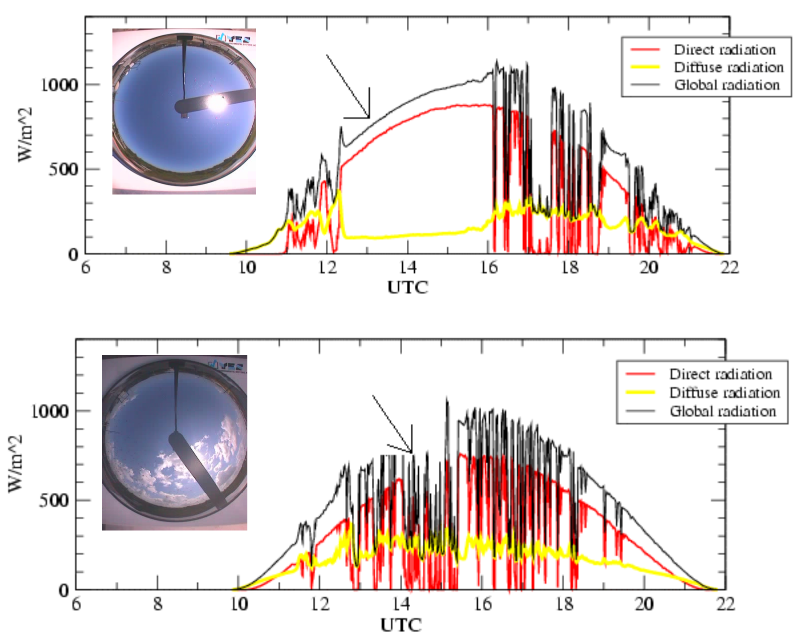


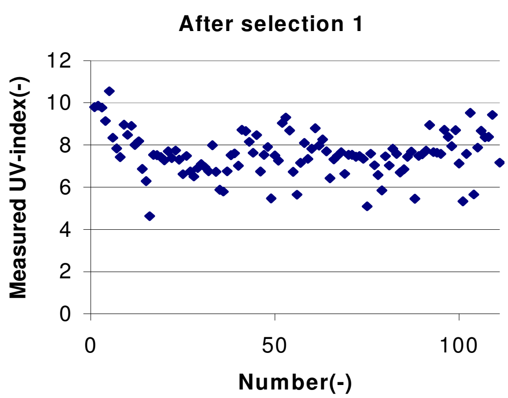
Figure 3.3a and b.
TSI- picture of August 25 2003, 13:19 UTC (cloudless situation), together with a radiation picture of the whole daylight period of that day (figure 3.3a) in Paramaribo. The red (middle) line shows the direct radiation, the yellow (lower) line shows the diffuse radiation and the black (upper) line shows the global radiation, all of them integrated over 300 to 3000 nm. At the cloudless situation al lines are smooth. Figure 3.3b shows a TSI picture of January 13 2003, 14:16 UTC (partial cloudy situation) together with a radiation picture of the whole daylight period of that day. The lines are the opposite of smooth on that moment.

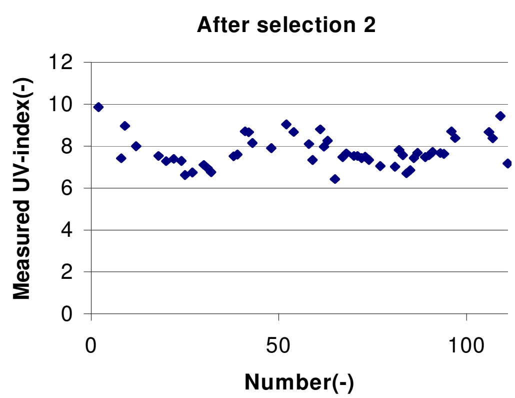
The radiation picture of figure 3.3a shows an almost wrinkleless line around the measurement time of the UV-spectrum. This measurement time is shown with an arrow on the radiation picture. Although the lines of the radiation are wrinkleless on that moment, it can give no absolute confirmation for a cloudless sky. The Total Sky Imager picture is needed to confirm the indication of the radiation picture.
In figure 3.3b the freakish pattern of the radiation picture during the period of measurement confirms the cloudy situation. This situation, if it would not have been tackled in an earlier selection, it would be tackled in this third selection.
A problem for this selection is that it is very intensively searching for every moment. That is why the first two selections had to be done before. Another problem is the lack of TSI data, so probably unknown cloudless moments are unjustifiably thrown away. But we need to be sure that the moments we are to analyze are cloudless.

3.3 The selected data

3.3.1 Selected situations for SZA range 35-36°

We observed that the sky above Paramaribo is most of the time partial cloudy. Often cumulus is observed and sometimes cirrus, but very often both kinds of clouds are observed.
After the first selection 110 situations remained (figure 3.4a), after the second selection 53 (figure 3.4b) and after the third and last selection (figure 3.4c), only 7 situations remained for further analysis at this SZA range (35-36°).





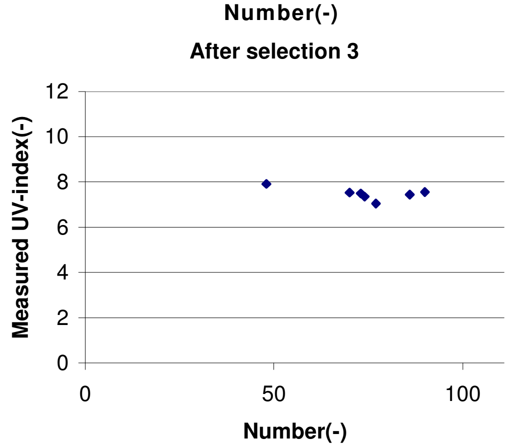


Figure 3.4a, b and c.
The measured UV-Index of the selected situations for the range of measurements with a SZA between 35° and 36°.
3.4a: after the first selection; b: after the second selection and c: after the third selection. The amounts of remaining situations after selection 1, 2 and 3 are respectively 110, 53 and 7.

The figures above show the effect of our selection procedure. The width of the range decreases after every selection. The range develops from 4-11 to 6-10 to 7-8, so the decrease

is on both sides of the range. That gives a very strong indication that the chosen selection procedure is correct, by which every cloudless situation can be found, if the needed data are available.
The remaining situations after the third selection are all from the middle of the range in the first selection. Through the lack of available pictures from the TSI, it is likely that some cloudless situations are not selected.

3.3.2 Selected situations for other Solar Zenith Angles

In the next table, the results of the selections at all SZA ranges are shown.

	Amount of selected situations		
SZA range (°)	After first selection	After second selection	After third selection
9-10	61	30	3
14-15	130	72	3
19-20	128	60	1
24-25	69	63	1
29-30	111	60	3
35-36	110	53	7
39-40	97	53	2
43-44	88	55	7
47-48	92	44	5
51-52	145	79	5
59-60	187	122	21

Table 3.1
An overview of the amounts of selected situations after each selection step for different SZA ranges. A very small percentage of the measurements 'survives' all selections and can be called 'cloudless'.

The amount of cloudless situations after selection three is very low. That is why the remaining situations after selection 2 (691 situations) and 3 (58 situations) are used for further analysis.
The SZA ranges are chosen because a good reference was found. That is why the steps between the ranges are not always 5º. In the ranges below 9º there were only few cloudless situations. In **Appendix C** more details about the 58 cloudless moments are to be found.
Two things can be concluded from this table. The first is the enormous decrease of amounts of situations after every selection and for every SZA range. Totally cloudless situations are very scarce at Paramaribo station. Secondly, the highest amount of selected situations is in the SZA range 59-60°. These situations are foremost from early mornings, when the probability of a cloudless sky is higher than in the end of the morning and in the afternoon. Other variations between the different ranges in amounts of cloudless situations are mainly due to different amounts of measurements for the different SZA ranges.

4 The Results

4.1 The variability of the absolute UV-index

The variability of the UVI is a good indicator of the variability of the parameters affecting the UVI. In order to quantify the effects of tropospheric ozone and aerosols on UVI, the variability of UVI needs to be quantified. In figure 4.1a and b the absolute measured UVI is plotted against the SZA.

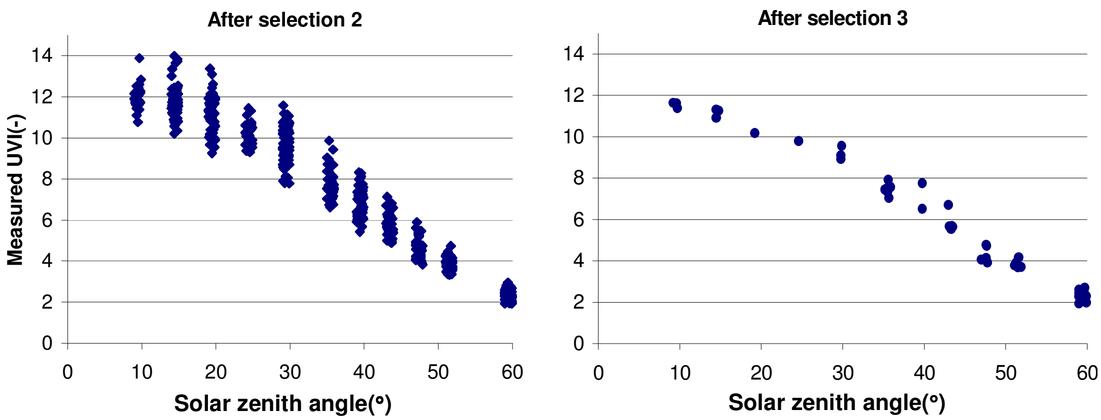


Figure 4.1a and b.
The measured UVI against the solar zenith angle after selection 2 (including partial cloudy situations) and selection 3 (excluding partial cloudy situations). The variability of the UVI within a SZA range is much higher after selection 2 than after selection 3, due to excluding all partial cloudy situations in selection 3.

The measurements of figure 4.1a are from cloudless moments and 'cloudy but sunny' moments. Figure 4.1b only includes cloudless moments. The variability in the first figure is much higher than in the second figure. After selection 2, the variability of the UVI at a SZA range of 1° varies between more than 4 in the range of 19-20° to roughly 1 in the range of 59-60°. After selection 3, the variability of the UVI varies between more than 1 and 0.3.
The causes of the variability are variations in Earth-Sun distance, total ozone column, ozone profile, aerosols and the accuracy of the Brewer. In the first figure clouds are also a possible cause of the variability, through enhancements of UVI (Tunc, 1999).
The main cause of the *differences* in variability after selection 2 and 3 is that clouds do not have an effect anymore after selection 3, in contrast with selection 2. After selection 2, clouds have an increasing or decreasing effect on the UVI. It can be concluded that the variability of the absolute UVI is much higher for partial cloudy situations than for cloudless situations.

4.2 The variability of the relative UV-index

The variability of relative UVI, as defined in **Chapter 1**, is the variability of the measured UVI (by the Brewer) with respect to the calculated UVI (from the total ozone column, SZA and Earth-Sun distance).
The variability of the relative UVI is plotted for the period of this research in figure 4.2a and b.
The value of relative UVI after selection 2 is typically between 0.8 and 1.1. After selection 3 the relative UVI is typically between 0.85 and 1.05. The smaller range after selection 3 is due to eliminating the cloud effects of selection 2.

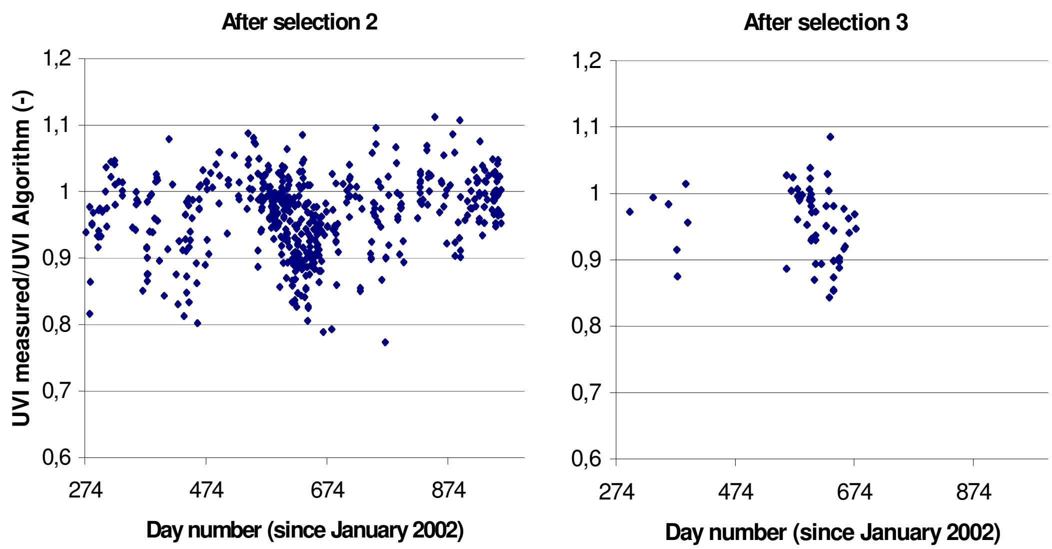


Figure 4.2a and b.
The 'relative UVI', i.e., the UVI measured, divided by the UVI calculated, using the algorithm in the research period (October 2002-August 2004) after selection 2 and 3. The algorithm takes into account the day of the year, the total ozone column and SZA. The two periods in figure 4.2a are the short and the long dry season respectively in 2003. The low values in the dry seasons are probably due to an increased amount of aerosols.

The average relative UVI after both selections is approximately 0.96. That suggests a systematically deviation of the Brewer measurements due to a calibration error.
The accuracy of the Brewer is typically ±5%. We find a variation in the UVI of typically 15% after selection 2 to 10 % after selection 1. The measured variability is significant with respect to the accuracy of the Brewer.
Further, in this measurement period there are two periods with extremely low values of relative UVI. Both periods are in the end of a dry season in 2003. The first period is around March 2003 (the end of short dry season) and the second is around November 2003 (the end of the long dry season). The low values are probably due to an increased amount of aerosols at the end of the dry seasons.
Through the lack of TSI data, the situations after selection 3 are only from two periods (October 2002 to January 2003 and July to November 2003).
To better understand the (seasonal) variability of the UVI at *totally* cloudless moments, more TSI data are needed.

4.3 Causes of relative UV-index variability

The relative UVI, in our expectation, mainly depends on aerosols and variations of the ozone profile for the same total ozone column. Other effects are from possible errors in UV and ozone measurements, made by the Brewer and a possible temperature dependence of the Brewer.

4.3.1 Solar Zenith Angle and Total Ozone column

To be sure if the relative UVI is not depending on the total ozone column and SZA, a check is needed.

After selection 2, no clear SZA dependence of the relative UVI is found (figure 4.3a). Nevertheless, it can be suggested that a trend of higher relative UVI is found with increasing SZA on cloudless moments (figure 4.3b).

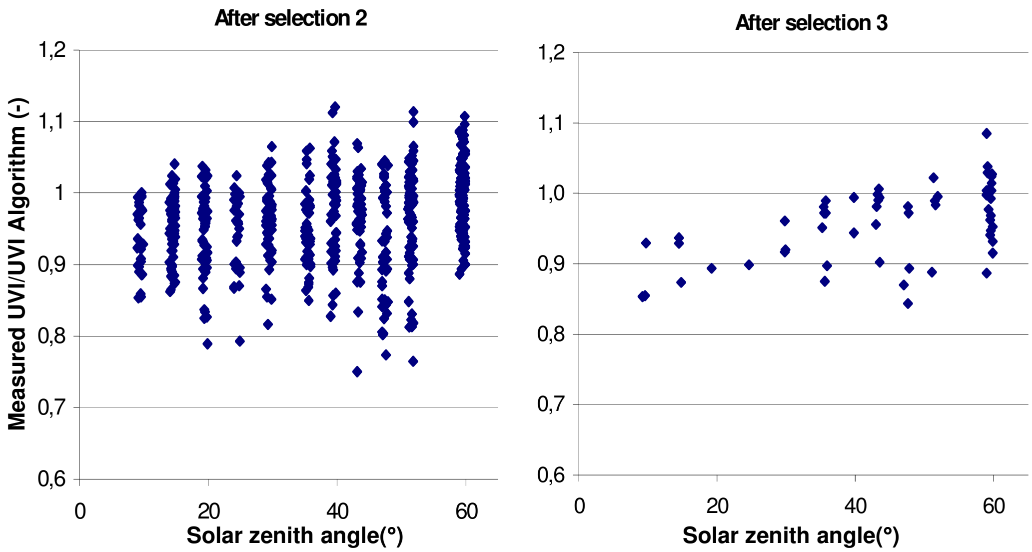


Figure 4.3a and b.
The relative UVI against the solar zenith angle after selection 2 and 3. After selection 3, less variability in relative UVI is found than after selection 2. This is, as in figure 4.2, due to excluding the partial cloudy situations in selection 3. After selection 3, a more clear SZA dependence of the relative UVI is found than after selection 2.

After selection 3, a more clear increase of relative UVI with increasing SZA is found. For larger SZA, the relative UVI is closer to 1 than for smaller SZA. That possibly means that the algorithm is better for larger SZA than for smaller SZA. It is also possible that the effects of ozone profile and aerosols on the relative UVI are SZA dependent.

With this knowledge, a small part of the variability of the relative UVI can be explained by the variation of SZA. This can either be due to SZA dependence of the relative UVI affecting parameters or to a deviation in the fit for the algorithm (day number, SZA, total ozone column).

Figure 4.4a and b show the relative UVI against the total ozone column for one SZA range, because of the (small) SZA dependence of the relative UVI. No significant total ozone column dependence after both selections is found by plotting these figures. As expected, the variability of the relative UVI cannot be explained by the variation of the total ozone column.

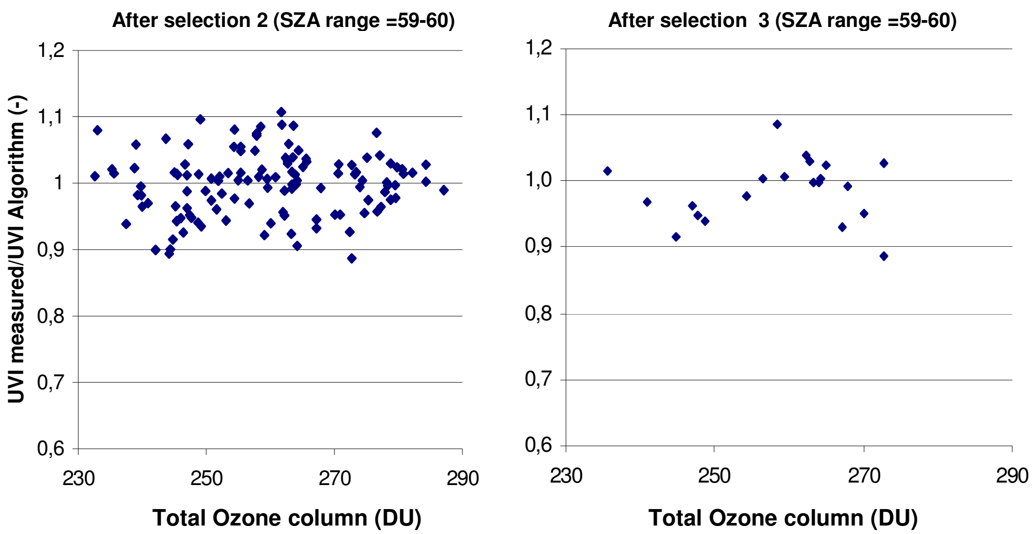


Figure 4.4a and b.
The relative UVI against the total ozone column for the range of solar zenith angles 59-60º, after selection 2 (figure a) and 3 (figure b). No dependence of the relative UVI on the total ozone column is found in these figures.

4.3.2 The Ozone Profile

The expectation was that the main variability of the relative UVI can be explained by the variation of the ozone profile and aerosols. The total ozone column can be divided into the tropospheric ozone column and the stratospheric ozone column.
It is known that variations in the stratospheric ozone profile have less influence on the UVI than displacement of stratospheric ozone into the troposphere. Further, a problem for analyzing the stratospheric ozone column is the lack of data, through burst of the balloon at low altitudes. That is why we try to explain the variability of the relative UVI with variations of only the tropospheric ozone column (DU).
An indication of the temporal variability of the tropospheric ozone column (DU) at Paramaribo is given in figure 4.5.
The nine highest values of tropospheric ozone (all above 20 DU) are eliminated because of a probable calibration error of the instrument (M. Allaart, personal communication).

The measurement points are typically spread between 7 and 16 DU. That means that all values are within a range of 9 DU. According to the results of Van Weele et al (2001), the uncertainty of the column should be 10 DU for significant effects on the UVI. Here, the variability is less than 10 DU. The cause of the small variability in the tropospheric ozone column in Paramaribo is the relatively small amount of sources of air pollution.
In **Appendix B**, graphics of temporal and spatial variability of the tropospheric ozone column are to be found. Those graphics confirm that the variability of the tropospheric ozone column in Paramaribo is relatively low with respect to other places in South-America. That is why we do not expect that the tropospheric ozone column is a very important parameter affecting the relative UVI in Paramaribo.

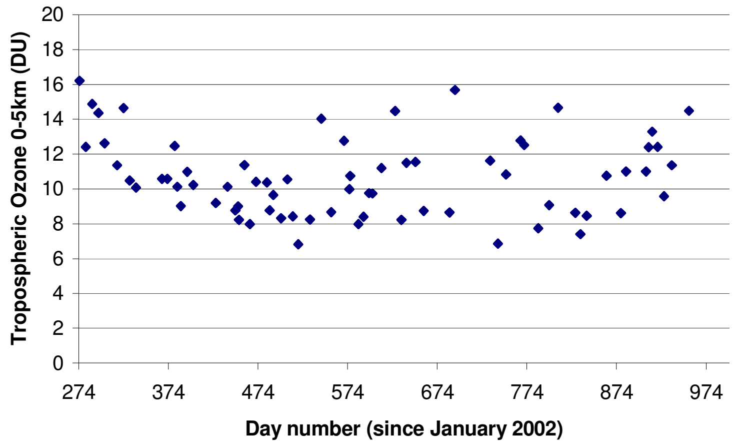


Figure 4.5.
The tropospheric ozone column (DU), integrated over 0 - 5000 m above the Earth surface in the research period (October 2002-August 2004). The ozone measurements are from the balloon soundings in Paramaribo. The value of the tropospheric ozone column varies between 7 and 16 DU.

However, we can check if there is any significant dependence of the relative UVI on the tropospheric ozone column. This is done using the next figure

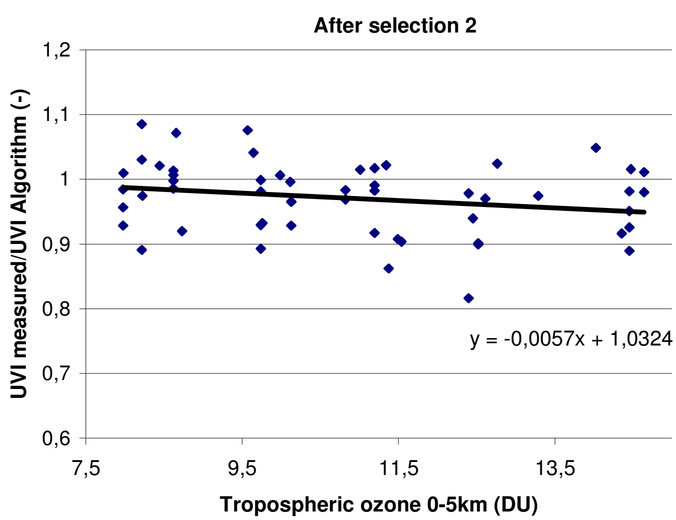


Figure 4.6.
The relative UVI against the tropospheric ozone column (DU) (0-5 km above Earth surface) in Paramaribo, after selection 2. Insufficient situations remained after selection 3 to analyze the relation between the (relative) UVI and the tropospheric ozone column. Within the same tropospheric ozone column the (relative) UVI varies more than 10%. Nevertheless, the line in the figure shows that an increase of the tropospheric ozone column with 10 DU results in a decrease of the (relative) UVI with 6%. However, this dependence of (relative) UVI on tropospheric ozone is not significant.

Only after selection 2 sufficient data of tropospheric ozone were available to analyze. After selection 3, insufficient data were available. This is because of the *weekly* soundings in combinations with the rare cloudless situations.
In figure 4.6 a small dependence of the relative UVI on tropospheric ozone is found. An increase of 10 DU in the tropospheric ozone column means a decrease of almost 6% in the relative UVI. Nevertheless, this needs to be concluded very carefully, because of the high variation of the relative UVI for the same tropospheric ozone column. This can be due to instrument effects, SZA effects, AOD effects, small cloud effects and the uncertainty of the input parameters in the algorithm. Van Weele et al. (2001) found for 50% increase of the tropospheric ozone column (0-16km) 8% decrease of the UVI at maximum. For a tropospheric ozone column of 20-30 DU, 50% means roughly 10-15 DU.
The tropospheric ozone column in Paramaribo ranges between 7 and 16 DU. Taking into account the equation in figure 4.6, the range of 9 DU results in 5% variability in the relative UVI at maximum. This roughly corresponds with the results of Van Weele et al. The standard deviation (σ) of the relative UVI in figure 4.6 is about 0.055 ($2\sigma \approx 0.11$). This 2σ is higher than the variability of the relative UVI (≈ 0.05) caused by the variability of tropospheric ozone. That means that the variability of tropospheric ozone does not affect the relative UVI significantly. We can only conclude that an increase of the tropospheric ozone column results in a decrease of the relative UVI. A small part of the deviations of the measured UVI with respect to the predicted UVI is caused by the variability of the tropospheric ozone column.
Because of the lack of data, it is not possible to check if there is any SZA dependence of the effects of tropospheric ozone on the relative UVI. Another problem, also caused by the lack of data is that the aerosol optical depth, also affecting the relative UVI, is not constant and cloud effects are not eliminated.

More research to the effects of variability of tropospheric ozone on UVI in the Tropics and the SZA dependence of that effects can be done if more data are available, i.e., more AOD data, more TSI data in order to find more *totally* cloudless situations and of course more balloon soundings are needed for tropospheric ozone data. Further, it would be interesting to investigate the effects of tropospheric ozone on the UVI at stations in the Tropics with higher variability of the tropospheric ozone column than in Paramaribo.

4.3.3 Aerosols

For the investigation of the influence of aerosols on the relative UVI, the aerosol optical depth at 366 nm (AOD_{366}) is used. A figure showing the variability of that parameter is to be found in **Appendix A**. The AOD values are all less than 0.5. Only one value of almost 1 is thrown away, because this value was not trusted.
As for the tropospheric ozone column, after selection 3 insufficient AOD data were available to analyse. A problem for AOD data, derived from the Sunphotometer, is that data are only available when the measurement time (around 9 UTC) is cloud free. Further, a lot of technical problems with the instrument have restricted the amount of data.
From figure 4.7 it can be read that an increase of the AOD_{366} with 0.4 typically results in a decrease of roughly 16 % (≈ 0.16) in the relative UVI. The standard deviation (σ) of the relative UVI in figure 4.6 is about 0.07 ($2\sigma \approx 0.14$). This 2σ is lower than the variability of the relative UVI (≈ 0.16) caused by the variability of the AOD. That means that the variability of the AOD does affect the relative UVI significantly. However, there is some variability within an equal AOD, e.g. at AOD=0.13 the relative UVI varies between 0.9 and 1.1. Nevertheless, it can be concluded that the (relative) UVI in Paramaribo significantly depends on the AOD.

The main part of the deviations of the measured UVI with respect to the predicted UVI is caused by the variability of AOD.

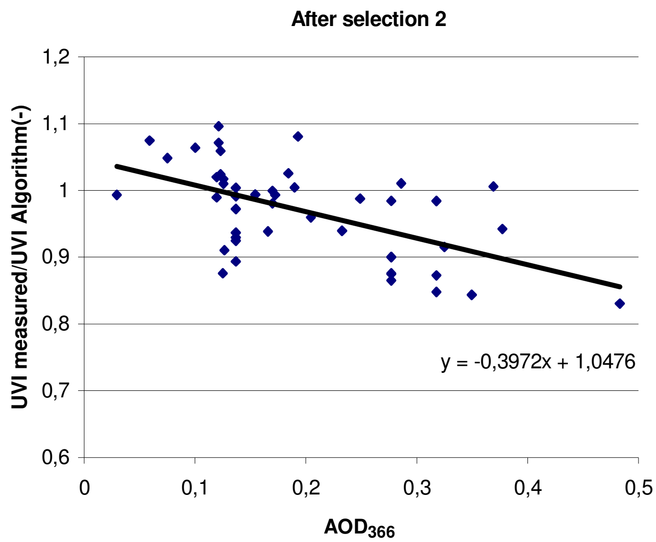


Figure 4.7.
The relative UVI against the aerosol optical depth (366 nm) for the situations selected after selection 2. As for tropospheric ozone, only few data remained after selection 3; insufficient data for a good analysis. Nevertheless, a relation between the aerosol optical depth (366 nm) and the relative UVI is found in this figure. An increase of the AOD_{366} with 0.4 typically results in more than 10% decrease of the relative UVI. That roughly corresponds with the expected 10%.

As for research to the effects of tropospheric ozone on the UVI, more (frequent) AOD data are needed to investigate the effects of AOD on the UVI on *totally* cloudless moments.

We are interested in a possible seasonal variability of the AOD. In dry seasons, higher values of AOD are expected than in wet seasons. The cause is the rainout of aerosols in wet seasons. In the short dry season (February, March), when the air is transported over the city, higher values of AOD are expected than in the long dry season (August-November). In the short dry season, the air is transported from the North-East, over Paramaribo and in the long dry season, the air is transported from the South-East, over the rainforest. The polluted air above the city is a likely source of aerosols. In the rainforest, only fires are a significant (intermittent) source of aerosols.

In figure 4.8 a seasonal overview is given of the AOD data, used after selection 2.
The AOD data, used to find a relation with the relative UVI are plotted in figure 4.8 against the day number since 1 January 2002. A cluster with higher values is found between day 374 (middle of January 2003) and day 474 (middle of April 2003). A cluster with lower values is found between day 490 (end of April 2003) and day 610 (end of August 2003). These periods roughly correspond with the short dry season and the long wet season respectively. The relatively high values in the short dry season confirm our expectation. The lower values in the long wet season also confirm our expectation of a decrease of AOD due to rainout.
A difference in average AOD between the short wet season and the long dry season is found for 2003 in Paramaribo.

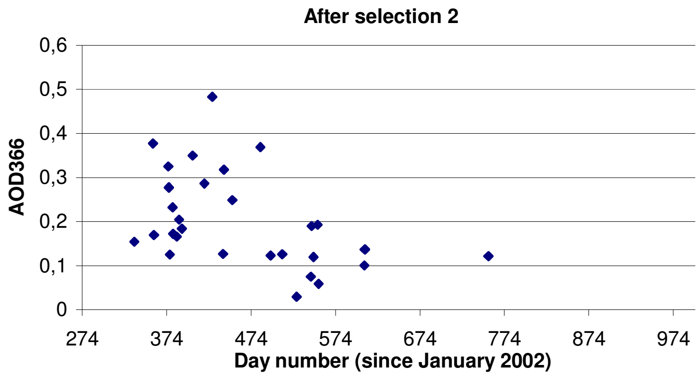


Figure 4.8.
Seasonal overview of the AOD data after selection 2. The highest values are found between the middle of January 2003 and the middle of April 2003 (short dry season). The lowest values are found in the long wet period of 2003 (April to July 2003). Although only few data are available, this result confirms our expectation. In the wet season, the average AOD is smaller than in the dry season, due to rainout of the aerosols in the wet season. The expectation of an average difference in AOD between the dry seasons can not be confirmed, due to the lack of data.

When AOD data are available from other seasons, it would be possible to check this conclusion again and to find more regularity in the seasonal variability of the AOD.

4.3.4 Some clear days

In order to visualize the measured UVI compared with the predicted UVI of the Algorithm, two partly clear days are chosen. Totally clear days are not found in the research period with the available data. The chosen days are 25 August 2003 and 15 July 2004.
Also radiation pictures are shown. From these pictures it can be derived what period of the day was cloudless or (partial) cloudy. Further, these pictures show the diffuse radiation. An increase of diffuse radiation in a cloudless period indicates an increase of the amount of aerosols.

From the first day, 25 August 2003, in **Chapter 3** a cloudless moment is used to illustrate the selection procedure. This cloudless situation is taken from a 4.5 hours lasting cloudless period (12:30-16:00 UTC).

In figure 4.9 all UVI measurements at cloudless moments on 25 August 2003 are plotted. The solid line shows the predicted UVI for the whole day, with an average (of 84 measurements) total ozone column of 274.4 DU. the three measurements between 13:00 and 14:00 UTC are almost equal to the predicted UVI. The last five measurements have a deviation with respect to the prediction. This confirms that the deviations are larger for smaller SZA. Badosa (2002) found that the effect of aerosols on the absolute UVI is larger for smaller SZA.
Badosa also found that the relative effect of aerosols on UVI is higher for *larger* SZA, i.e., the relative UVI is smaller for larger SZA. However, this is *not* confirmed by this figure and figure 4.3b.

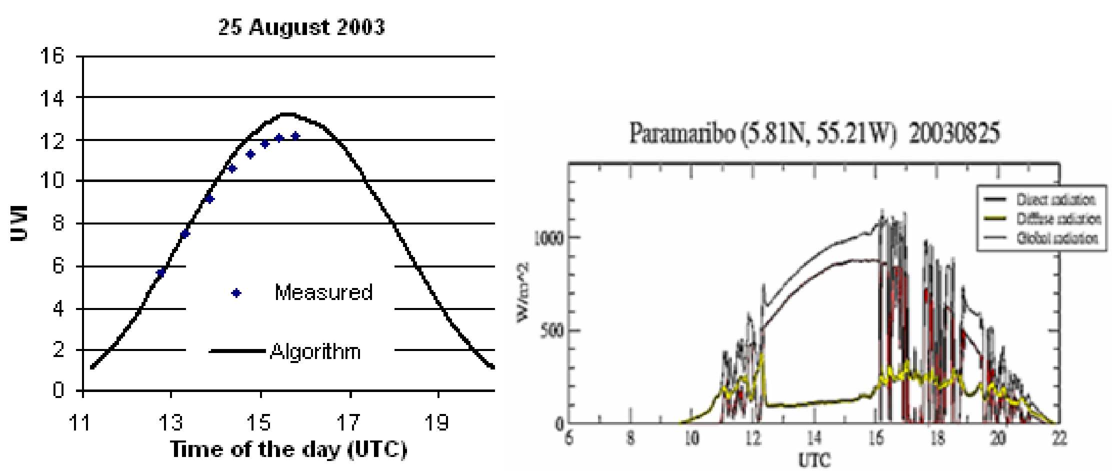
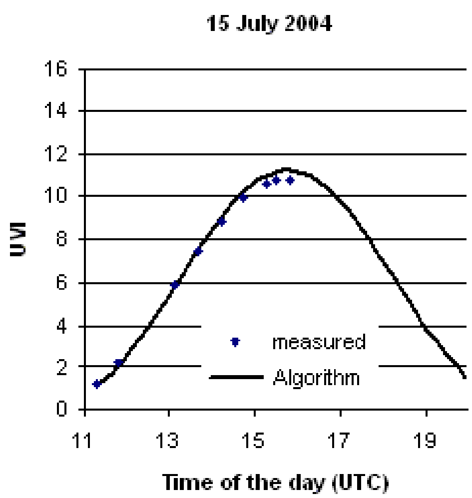


Figure 4.9.
These graphs show the measured UVI on cloudless moments compared with the predicted UVI from the algorithm (total ozone column, SZA, day number) on 25 August 2003, together with a radiation picture of that day in order to show the cloud-conditions. In the left figure, the solid line shows the predicted UVI. In the right figure, the yellow (lower) line shows diffuse radiation, the red (middle) line direct radiation and the black (upper) line global radiation. The sky is cloudless roughly between 12:30-16:00 UTC. At noontime the deviation of the measured UVI with respect to the predicted UVI is about 1.

More research into the SZA dependence of the aerosol effects on UVI can be done for Paramaribo. Therefore, more AOD data are needed, from more days and more frequent each day, because of a possible daily variation of the AOD.

Figure 4.10 is a nice addition to figure 4.9. This figure is the same as 4.9, but for 15 July 2004. More cloudless periods than on 25 August 2003 are found on this day. However, the interesting thing is the smaller deviation of the measured UVI with respect to the predicted UVI. The diffuse radiation decreases between 14:00 and 16:00 UTC, in contrast with the increasing diffuse radiation on 25 August 2003 in the same time period. The decreasing diffuse radiation is a possible indication for a decreasing AOD. That means a higher UVI, closer to the predicted UVI.

More research can be done into the relation between the AOD and the intensity of the diffuse radiation. Then we will be able to better explain the variability of the UVI, even if there is a lack of AOD data.



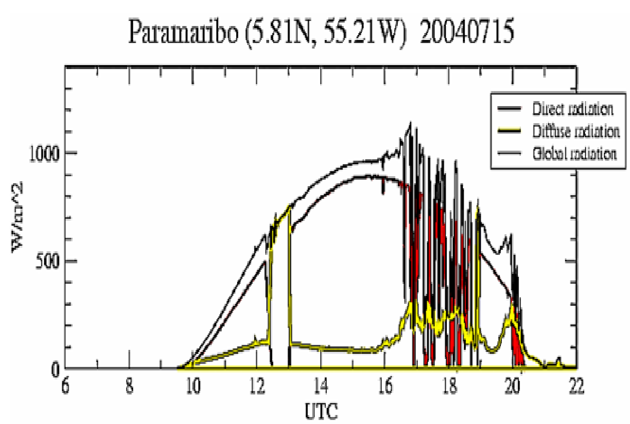


Figure 4.10.
The same graphs as in figure 4.9, but for 15 July 2004. The sky is cloudless roughly between 10:00 - 12:00 UTC and 13:15 - 16:00 UTC and for a short period between 19:00 - 20:00 UTC.
The deviation at noon-time of the measured UVI from the predicted UVI with the algorithm is smaller than 0.5. The diffuse radiation at noon-time is smaller for this situation than at 25 August 2003. This probably indicates a lower AOD than for 25 August 2003. That affects the UVI positively.

5 Conclusions and recommendations

1. Data selection. The following conclusions are drawn:
   - The sky above Paramaribo is most of the time partial cloudy. Often cumulus is observed and sometimes cirrus, but very often both kinds of clouds are observed.
   - The only good criterion for the selection of totally cloudless situations is to look at the pictures of the Total Sky Imager. Radiation pictures (Global, direct and diffuse radiation) are also good tools, but those pictures can never give a confirmation of *totally* cloudless skies.
   - *Totally* cloudless situations are very scarce at Paramaribo station. Within 11 SZA ranges, of 1°, only 58 cloudless situations were found for the periods October 2002 – January 2003 and July – November 2003. The highest amount (21 situations) is found in the SZA range 59-60°. These situations are foremost from early mornings, when the probability of a cloudless sky is higher than in the end of the morning and in the afternoon.

2. Variability of the absolute UV-index (UVI). The following conclusions are drawn:
   - Partial cloudy situations can give either an increase or a decrease in UVI with respect to cloudless situations.
   - The variability of the absolute UVI is much higher for partial cloudy situations than for cloudless situations. The maximum variability for a SZA range after selection 2 is 4 UVI points. For selection 3, it is about 1 UVI point.

3. Variability of the relative UV-index and its affecting parameters. The relative UVI is the measured UVI divided by the calculated UVI, using the Julian day number, the solar zenith angle (SZA) and the total ozone column. The following conclusions are drawn:
   - After selection 2 the relative UVI varies typically between 0.8 and 1.1; after selection 3 typically between 0.85 and 1.05. The smaller range after selection 3 is due to eliminating the cloud effects of selection 2.
   - The average relative UVI is 0.96, in contrast with an expected value close to 1. The most likely explanation for this is a calibration error of the Brewer.
   - The variability of the **tropospheric ozone column** in Paramaribo is relatively low with respect to Natal in South-America (figure B.1 and B.2 in **Appendix B**). In Paramaribo the tropospheric ozone column (0-5 km) varies between 7 and 16 DU.
   - An increase of the **tropospheric ozone column** with 9 DU (the observed range) results in 5% decrease of the relative UVI. This 5% is not significant.
   - The aerosol optical depth ($\mathbf{AOD_{366}}$) at Paramaribo is less than 0.5. However, most of the values are less than 0.4. The average AOD is higher in the short wet season than in the long dry season in 2003 in Paramaribo.
   - An increase of the $\mathbf{AOD_{366}}$ with 0.4 typically results in a decrease of more than 10% in the relative UVI. Note that 10% of the UVI at Paramaribo typically means 1 UVI point. This is a significant dependence. The main part of the deviations of the measured UVI with respect to the calculated UVI is caused by the variability of AOD.
   - For cloudless situations, a small part of the variability of the relative UVI can still be explained by the variation of **SZA**. The relative UVI typically increases

with SZA. This can either be due to SZA dependence of UVI affecting parameters not taken into account for the algorithm or to a deviation in the fit, made for the algorithm (Julian day number, SZA, total zone column).

- As expected, the variability of relative UVI can not be explained by the variability of the **total ozone column**.
- Diffuse radiation at cloudless circumstances is a possible indicator for the **AOD**.

Recommendations for further research

If more (frequent) AOD data, TSI data and balloon soundings are available, further research to the following topics is possible:

- The (seasonal) **variability of the UVI** at *totally* cloudless moments. The **effects of** aerosols **on UVI** in Paramaribo with a constant tropospheric ozone column under *totally* cloudless conditions and the SZA dependence of those effects.
- The **variability of the AOD** within and between the seasons.
- The effects of the **tropospheric ozone column** on the UVI can be investigated for stations in the Tropics with higher variability of the tropospheric ozone column than in Paramaribo.
- The relation between the AOD and the intensity of the **diffuse radiation**. Then we will be able to better explain the variability of the UVI, even if there is a lack of AOD data.

Recommendations for improvement of the algorithm

- If possible, the **AOD** should be taken into account in the algorithm for calculating the UV-index. Then the prediction of the UVI will be improved with 10% at maximum.
- The algorithm should be corrected for small s**olar zenith angles**. First the magnitude of the correction needs to be quantified.
- The variability of the UVI caused by the variability of the **tropospheric ozone column** is not significant. That is why no correction is needed for tropospheric ozone at Paramaribo. However, in the future the rate of air pollution could change. Then a correction would be needed.
- The Brewer should be well-calibrated for good validation of the algorithm.

References

Allaart, M., van Weele, M., Fortuin, P., Kelder, H. (2004) "An empirical Model to predict the UVI based on Solar Zenith Angles and Total Ozone", *Meteorol. Appl.*, **11**, 59-64.

Badosa, J., van Weele, M. (2002) "Effects of Aerosols on UV-index", *KNMI* (Scientific Report; WR 2002-07), De Bilt, The Netherlands.

Eggink, G.J., Janssen, L.H.J.M., Van der Woerd, H., kuik, F., Peeck, H.H. (1995)"Ozon en Ultra Violette Straling; verandering gevolgen en effecten", Rapport van KNMI (De Bilt, The Netherlands) & RIVM (Bilthoven, The Netherlands).

Feister, U., Grewe R. (1995) "Spectral Albedo Measurements in the UV and Visible Region over different Types of Surfaces", *Photochem. & Photobiol.,* **62** (4), 736-744.

Gröbner, J., Albold, A., Blumthaler, M., Cabot, T. et al. (2000) "Variability of Spectral Solar Ultraviolet Irradiance in an Alpine Environment", *J. Geophys. Res.*, **105** (D22), 26991-27003.

Liou, K.N.(1980) "An Introduction to Atmospheric Radiation", edited by R. Dmowska, J.R. Holton and H.T. Rossby, Academic Press.

Madronich S. (1993) "The Atmosphere and UV-B Radiation at Ground Level", in *Environmental UV Photobiology*, edited by A.R. Young, Plenum, New York.

McKinlay A.F., Diffey B.L. (1987) "A Reference Action Spectrum for Ultraviolet induced Erythema in Human Skin", In: Human Exposure to Ultraviolet Radiation: Risks and Regulations, *Passchier W. R., Bosnajakovich, B.M.F. (Eds.)* (Amsterdam: Elsevier), 83-87.

Renaud, A., Staehelin, J., Fröhlich, C., Philipona, R., Heimo, A. (2000) "Influence of Snow and Clouds on Erythemal UV Radiation: Analysis of Swiss Measurements and Comparison with Models", *J. Geophys. Res.*, **105** (D4), 4961-4969.

Tunc, S. (1999) "Enhancement of Solar and Ultraviolet Surface Irradiance under Partial Cloudy Conditions", *KNMI* (Scientific Report; WR 99-01), De Bilt, The Netherlands.

Valks, P.J.M., Koelemeijer, R.B.A., Van Weele, M., van Velthoven, P., Fortuin, J.P.F., Kelder, H. (2003) "Variability in Tropical Tropospheric Ozone: Analysis with GOME Observations and a Global Model", *J. Geophys. Res.*, **108** (D11), 4328, 10.1029/2002JD002894.

Van Weele, M., Van der A, R. J., Allaart, M. A. F., Fortuin, J.P.F. (2001) "Satellite and Site Measurements of Ozone and UV at De Bilt (52N) and Paramaribo (6N): II. Relating Ozone Profiles with Surface UV Radiation", In: *Current Problems in Atmospheric Radiation, Proceedings of the International Radiation Symposium 2000,* St Petersburg, Russia, July 24-29.

Relevant Web Pages

Paramaribo measurement site:	http://www.knmi.nl/~verver/fortuin/radchis.html
Total Sky Imager:	http://www.yesinc.com/products/data/tsi880/
Radiation instruments:	http://www.kippzonen.com

Acknowledgements

I would like to give special thanks to Michiel van Weele, my supervisor. He was always ready to help me when I had a question and he gave me a lot of hints. His critical look at my work was very good for me. I have learned very much, which I can use in future research.
Further, I would like to thank Marc Allaart for giving me a lot of data in a well-organized way. He also helped me with analyzing his delivered data. I would like thank Gé Verver also for delivering data and answering my questions about that data.
I would like to thank Leo Kroon for helping me with searching in the data by programming in FORTRAN.
The KNMI and Wageningen University must be thanked for giving me the facilities for doing this research.
For all mental support I would like to thank my girlfriend.

Dirk Malda, 15 december 2004

Appendix A
Instruments

A1. The Brewer MKIII

Plate A.1.
The operators of Paramaribo station around the Brewer MKIII
Source: http://www.knmi.nl/~verver/fortuin/radchis.html

Brewer measurements

1. Irradiation (W/m^2/nm) in the Brewer spectral range

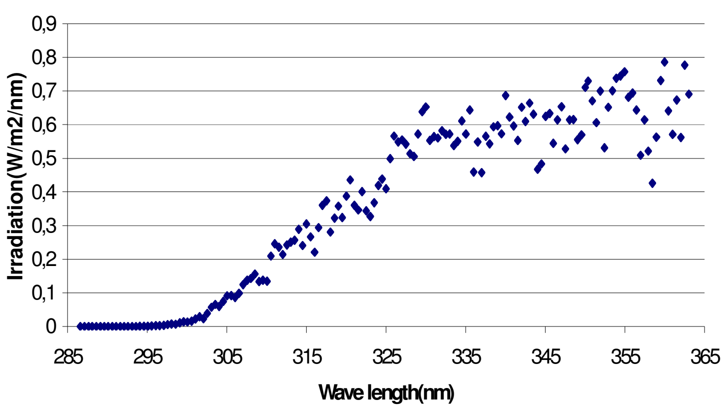


Figure A.1.
UV spectrum of a cloudless situation, measured by the Brewer, for the wavelengths between 286 and 363 nm.

2. Total Ozone column

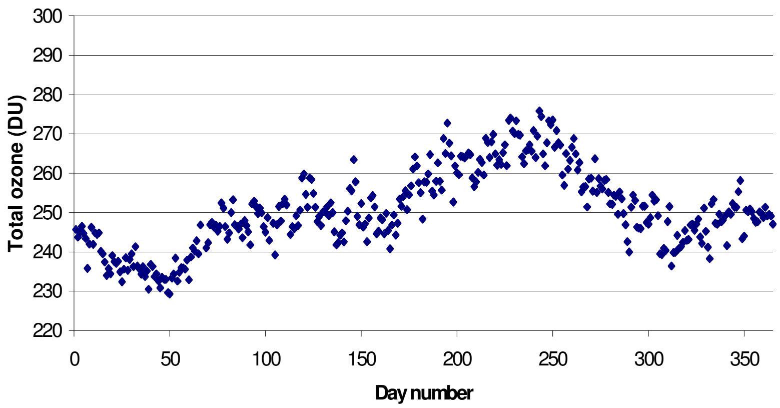


Figure A.2.
Total ozone column in 2003, measured by the Brewer.

A2. The Total Sky Imager

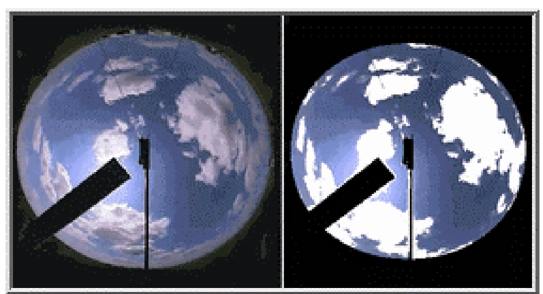


Plate A.2.
Total Sky Imager (left) and pictures from the Total Sky Imager, one real (left) and one processed (right)
Source: http://www.yesinc.com/products/data/tsi880/

A3. The Pyranometer and Pyrheliometer

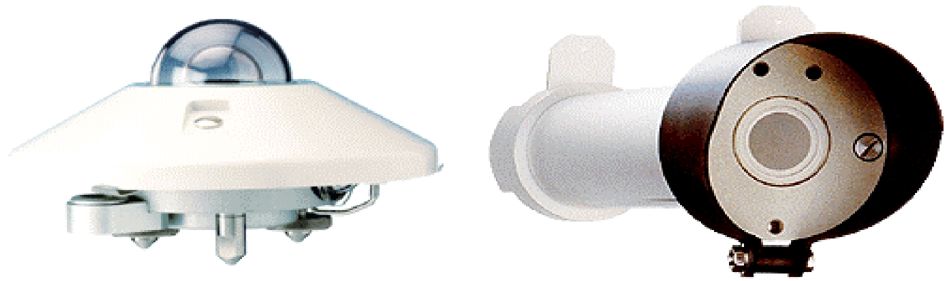


Plate A.3
The Pyranometer (left) measures the global sun radiation (if not shadowed) or only the diffuse radiation (shadowed). The Pyrheliometer (right) measures the direct solar radiation.
Source: http://www.kippzonen.com/pages/141/3 & 693/3

Radiation measurements

1. Direct, Diffuse and Global Radiation

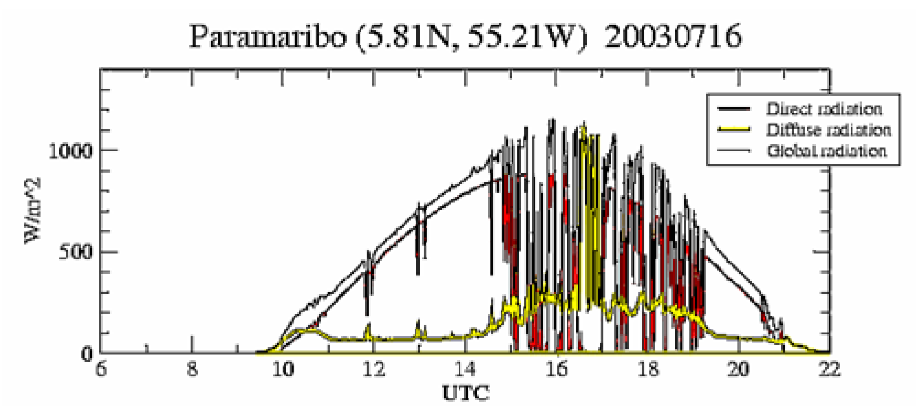


Figure A.3
Graph of the direct (middle line), diffuse (lower line) and global (upper line) radiation, measured by the Pyranometer and the Pyrheliometer on July 16, 2003.

A4. The Sunphotometer

Plate A.4
Picture of the Sunphotometer, used at Paramaribo station.
Source: http://www.kippzonen.com/pages/682/3

Sunphotometer measurements

1. Aerosol Optical Depth

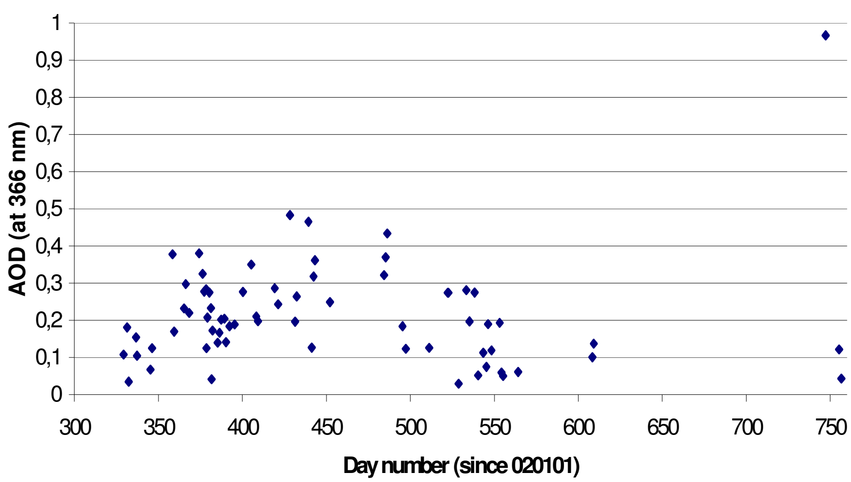


Figure A.4.
Graph of the aerosol optical depth at 366 nm, calculated with the irradiation data, derived from the Sunphotometer in Paramaribo between November 2002 and January 2004.

A5. The Balloon Sounding

Plate A.5
First balloon sounding at Paramaribo station.
Source: http://www.knmi.nl/~verver/fortuin/radchis.html

Measurements of the balloon sounding

1. The Ozone Profile

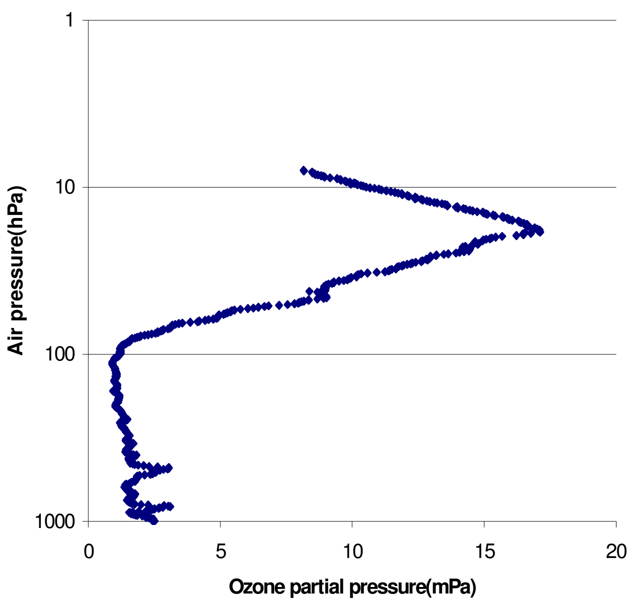


Figure A.6.
Graph of a vertical ozone profile from the sounding.

2. Tropospheric Ozone

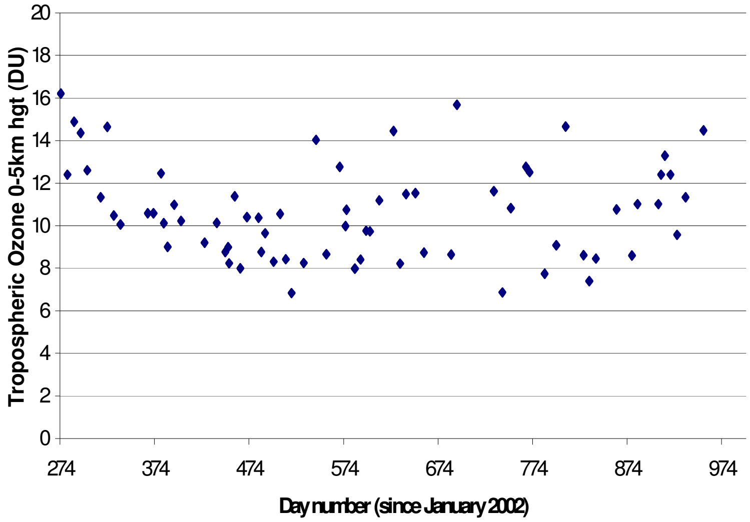


Figure A.7
Graph of the tropospheric ozone column (0-5 km) (DU), derived from the soundings in the research period (October 2002 - August 2004).

Appendix B

Spatial and temporal variability of Tropospheric Ozone in the Tropics.

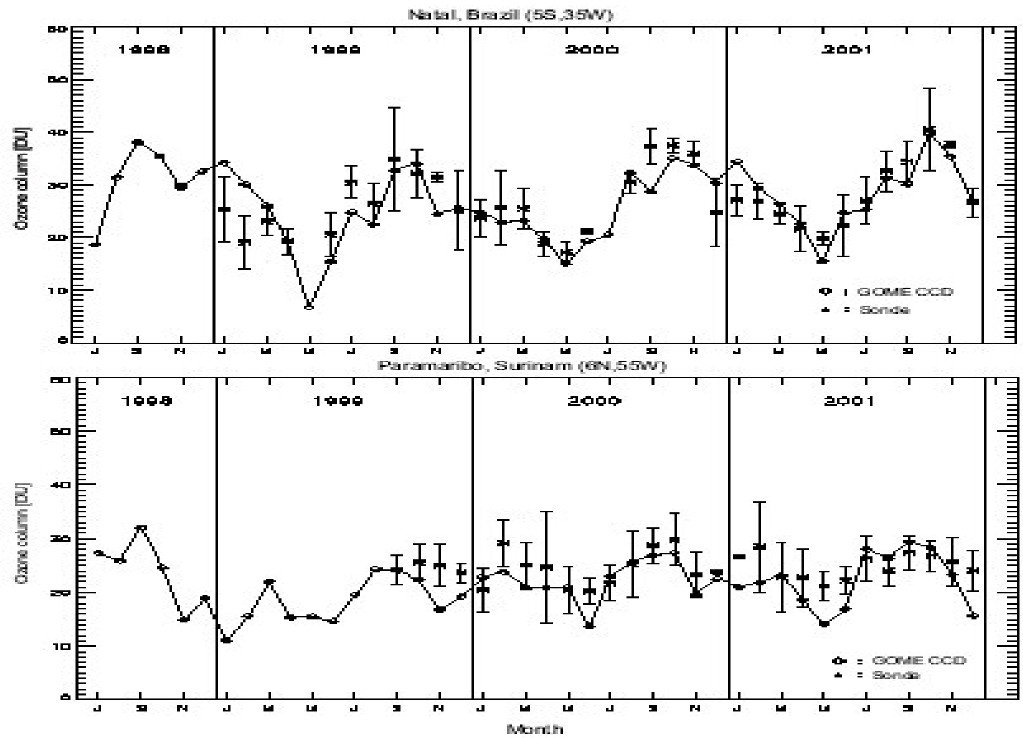


Figure B.1.
Temporal variability of the tropospheric ozone column (DU) below 200 hPa in Natal (Brazil) and Paramaribo, Surinam, respectively. Both stations are within (South-American) tropical region. The time period is July 1998-December 2001. The variability of tropospheric ozone in Natal is much higher than in Paramaribo. The values of the GOME satellite (line) are compared with the soundings (points with errors).
Source: Valks (2003)

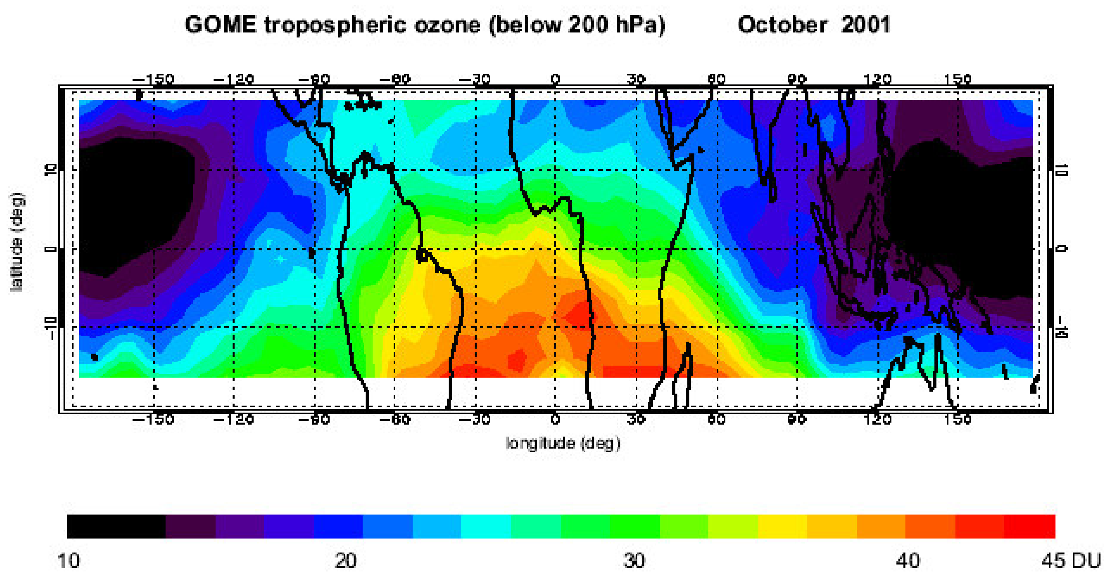


Figure B.2.
Spatial variability of tropospheric ozone (DU) below 200 hPa in the tropical region in October 2001. The average tropospheric ozone column is larger in Natal (5S.35W) than in Paramaribo (6N.55W). The highest values are in the southern Atlantic Ocean and the southern parts of South-America and Africa.
Source: Valks (2003)

Appendix C

58 selected cloudless moments

Year/month/day/time	Solar zenith angle	UVI measured	UVI calculated	UVI measured/ UVI calculated
309011501	9,7	11,38	12,24	0,930
310011521	9,2	11,63	13,63	0,853
310011541	9,6	11,61	13,58	0,855
308251446	14,5	11,30	12,16	0,929
309011441	14,5	10,92	11,66	0,937
310011441	14,8	11,25	12,88	0,874
309111418	19,2	10,18	11,39	0,894
310011357	24,6	9,79	10,89	0,899
308021353	29,8	8,92	9,28	0,961
310191342	29,8	9,10	9,93	0,917
310211343	29,9	9,56	10,39	0,920
301121414	35,6	7,91	9,04	0,875
308221319	35,7	7,53	7,61	0,990
308251318	35,4	7,48	7,63	0,981
308261312	35,5	7,34	7,55	0,972
309011315	35,7	7,05	7,25	0,972
309191312	35,2	7,44	7,82	0,951
310111311	35,9	7,56	8,42	0,897
212021724	39,8	7,75	7,80	0,994
310011253	39,8	6,51	6,90	0,944
301291817	43	6,71	7,02	0,956
308221247	43,4	5,68	5,65	1,006
308231246	43,5	5,64	5,68	0,994
308251247	43,2	5,65	5,65	0,999
308261247	43,3	5,54	5,59	0,991
309191241	43,1	5,67	5,78	0,981
310111239	43,5	5,64	6,25	0,902
210241821	47,7	4,72	4,85	0,972
308301848	47	4,05	4,66	0,870
309011851	47,8	3,91	4,37	0,894
309241839	47,6	4,13	4,90	0,844
310011221	47,6	4,78	4,87	0,981
212281835	51,6	4,16	4,23	0,983
308021218	51,9	3,71	3,72	0,996
308051219	51,5	3,69	3,73	0,989
308231215	51,3	3,91	3,83	1,022
310111207	51,1	3,78	4,25	0,888
301111209	59,9	2,29	2,50	0,915
301261210	59,7	2,70	2,66	1,015
307141145	59,8	2,11	2,05	1,027
307141940	59	1,93	2,18	0,887
307221146	59,7	2,16	2,15	1,004
307251146	59,7	2,20	2,15	1,024
308021146	59,4	2,27	2,26	1,006
308051147	59	2,28	2,28	0,998
308061145	59,6	2,13	2,14	0,993
308101146	59	2,29	2,29	0,998
308181944	59,9	1,98	2,08	0,952
308231143	59,1	2,38	2,30	1,038
308261942	59,9	1,97	2,12	0,932
309211136	59,1	2,40	2,33	1,029
309231136	59	2,43	2,42	1,004
309261135	59	2,60	2,40	1,085
310191134	59,3	2,37	2,43	0,977
310271135	59,5	2,40	2,50	0,962
310281135	59,5	2,33	2,47	0,940
311041137	59,6	2,49	2,57	0,969
311061138	59,6	2,35	2,48	0,947

Table C.1
All selected cloudless moments with solar zenith angle, measured and calculated UV-index and the measured UV-index divided by the calculated UV-index.