JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, D01203, doi:10.1029/2005JD006444, 2006

Effects of altitude and aerosol on UV radiation

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Received 30 June 2005; revised 6 September 2005; accepted 13 October 2005; published 10 January 2006.

[1] Measurements of erythemally weighted UV radiation during about 600 days at different sites in Bolivia and Germany ranging from 550 to 5240 m above sea level have been used to derive the altitude effect AE under cloud-free conditions. In Germany, AE values between 7 and 16%/km have been obtained. In Bolivia, the altitude effect between the lowlands and the Bolivian plateau reached values of 5–10%/km. An altitude effect of 8–23%/km has been measured between the plateau and a high-mountain station. In accordance with previous studies these results indicate that the altitude effect of UV irradiance cannot be described by a single number in %/km, because it strongly depends on the atmospheric and surface parameters. In order to understand the high variability of the AE, the effects due to variations in solar elevation, albedo, and aerosol properties on UV radiation and the AE have been analyzed. To eliminate the influence of clouds, an algorithm for the selection of cloud-free time intervals has been developed and applied. Furthermore, the measured data have been normalized to a fixed ozone content to avoid masking of the AE by different ozone amount. In addition, the background altitude effect, i.e., the AE resulting only from the reduced barometric pressure and reduced ozone content with increasing altitude, has been modeled. Depending on solar elevation and albedo, it ranges between 3 and 7%/km. Measured higher values of the AE, as well as negative values of the AE, are explained by the specific regional aerosol conditions, with important sources at high altitudes. The aerosol influence on UV is shown in detail for extreme conditions after strong bonfires in connection with a local holiday.

Citation: Pfeifer, M. T., P. Koepke, and J. Reuder (2006), Effects of altitude and aerosol on UV radiation, *J. Geophys. Res.*, *111*, D01203, doi:10.1029/2005JD006444.

1. Introduction

[2] Generally, UV irradiance increases with altitude because of the decreasing amount in absorbing and scattering material above the observer. In addition, enhanced radiation from below due to increased albedo can elevate downward irradiance by multiple scattering effects. This albedo effect further enhances UV irradiance with altitude since albedo increases with altitude because of increased probability of snow and the change from vegetation to rocks. The resulting increase in UV radiation is described as altitude effect (AE) [*Schmucki and Philipona*, 2002]. This AE is defined as increase of the irradiance E in a high position z_h relative to that in a low position z_l and is given in percent per kilometer altitude difference:

$$\mathrm{AE}[\%/\mathrm{km}] = \left(\frac{E_{z_h} - E_{z_l}}{E_{z_l}}\right) \cdot \frac{1}{z_h - z_l} \cdot 100 \qquad (1)$$

The AE depends on differences in the extinction properties of clouds, aerosols, ozone and air molecules and of surface albedo between the compared sites. Because of spectral dependencies of these parameters the AE is wavelength dependent. In general, the extinction efficiency of all atmospheric components increases toward shorter wavelength [e.g., *Koepke et al.*, 2002], resulting in a corresponding increase of the AE [*Piazena*, 1996; *Blumthaler et al.*, 1994, 1997].

[3] The AE is analyzed here for erythemal weighted irradiance, respectively the UVI [*World Meteorological Organization* (*WMO*), 1994], because this quantity is of particular importance with respect to human UV exposure and behavior. Therefore the UVI has been recommended as measure for solar UV irradiance by the World Meteorological Organization (WMO) and other international organizations [*World Health Organization*, 2002]. Moreover, our investigation of the AE is focused on cloud-free conditions, since different cloud conditions between two stations have such a strong influence on UVI that it should be treated separately.

[4] In the literature, values of the AE between 11 and 40%/km have been reported for the Alps for erythemally weighted UV radiation, however with cloud effects included [*Blumthaler et al.*, 1997; *Seckmeyer et al.*, 1997; *Schmucki and Philipona*, 2002]. For cloud-free conditions the AE is

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0148-0227/06/2005JD006444$09.00

Table 1. Overview of the Stations Used in This Study[a]

Station	Latitude	Longitude	Altitude, m	*n*	Aerosol	AOD	σ AOD	Albedo
Chakaltaya	16.25°S	68.07°W	5240	78	background	0.01	0.02	rock, little snow
El Alto	16.54°S	68.07°W	4000	57	urban polluted			concrete, clay
Lake Titicaca	16.12°S	68.40°W	3820	39	rural			vegetation, water
La Paz	16.54°S	68.07°W	3420	159	moderate urban	0.18	0.09	concrete, clay, vegetation
Zugspitze (summit)	47.42°N	10.99°E	2964	92	background	0.03	0.02	snow, rock
Valencia	16.70°S	67.60°W	2800	47	rural	0.05	0.02	clay, vegetation
Zugspitze (UFS)	47.42°N	10.98°E	2650	41	background	0.03	0.02	rock, snow
Caranavi	15.75°S	67.50°W	605	28	rural	0.08	0.02	vegetation
Munich	48.15°N	11.57°E	527	55	urban	0.20	0.12	concrete

[a] The aerosol optical depth (AOD) at 550 nm is given as the daily average of Sun photometer measurements together with its standard deviation; *n* denotes the number of UV measurement days.

given with values between 5 and 25%/km. Remarkable regional differences in the AE have been reported, with higher values for Europe [*Reiter and Munzert*, 1982; *Blumthaler et al.*, 1992; *Schmucki and Philipona*, 2002] than for Hawaii [*McKenzie et al.*, 2001], and the South American Andes [*Cabrera et al.*, 1995; *Piazena*, 1996; *Zaratti et al.*, 2003]. Such large variability of the AE also has been found in the measurements presented here for different sites in Bolivia and Germany. The large amount of measured data, for a wide spectrum of different site properties, enables the separation of various influence parameters on the AE, shown in the following.

2. Methods

[5] The AE is analyzed on the basis of measurements at stations in Germany and Bolivia. The measurements have been performed for all kinds of atmospheric conditions and for different solar elevation, but in general not simultaneously at different altitudes. Therefore cloud effects have to be eliminated. Moreover, the measurements have to be normalized with respect to total ozone content.

2.1. UV Measurements

[6] The data presented in this study have been obtained during three measurement campaigns. Table 1 shows the geographical location, duration of measurement, and environmental properties for all sites. UV irradiances have been measured using a broadband radiometer (Scintec, UV-S-E-T) designed to coincide in its spectral response with the erythema action spectra [*McKinlay and Diffey*, 1987] (see Figure 1). The obvious deviation between both curves due to the specific characteristics of the optical components of the instrument is taken into account by elaborate calibration and data processing [*Oppenrieder et al.*, 2003]. The measured intensity of the UV radiation is described by the UVI [*WMO*, 1994]; however, deviating from the recommendations of *WMO* [1997], the UVI is utilized in this study as a physical unit, and therefore decimal places are given.

[7] Measurements have been taken continuously at time intervals of 10 seconds. Further analysis and interpretation has been performed on the basis of one minute averages. The radiometer has been calibrated, including detailed laboratory characterization of the spectral response and the cosine dependency of the instruments, providing a calibration matrix depending on total ozone content and solar elevation [*Oppenrieder et al.*, 2003].

[8] In Bolivia the UVI has been measured during a first campaign (June 2000 to June 2001) at 6 stations located between 605 m and 5240 m altitude. These sites represent the variable conditions in Bolivia. Caranavi (605 m) stands for the Bolivian lowlands with rural surrounding and low pollution. On the Altiplano, a region with high population density, measurements have been performed at Valencia (2800 m), La Paz (3420 m), Lake Titicaca (3820 m) and El Alto (4000 m). La Paz and El Alto represent urban conditions, with moderate to high aerosol load, while Valencia and Lake Titicaca are located in rural areas. The high-mountain station Chakaltaya (5240 m) has been selected as especially high site with low aerosol content. During this first campaign the UVI has been measured twice at every station in order to consider seasonal variations. Each measurement period lasted at least two weeks to get a statistical significant number of data. In 2002 additional measurements have been carried out in Caranavi, La Paz and Chakaltaya from June to August. Thus measurements up to a solar elevation of 70° are available. In Germany measurements have been performed in urban conditions at the roof of the Meteorological Institute in the center of Munich (527 m) and at the Alpine site of Zugspitze (2964 m) [*Oppenrieder et al.*, 2004]. At Zugspitze the UVI has been measured both on the top of the mountain (summit) and at the Environmental Research Station Schneefernerhaus (UFS) located about 300 m below the summit. Both sites are characterized by similar low

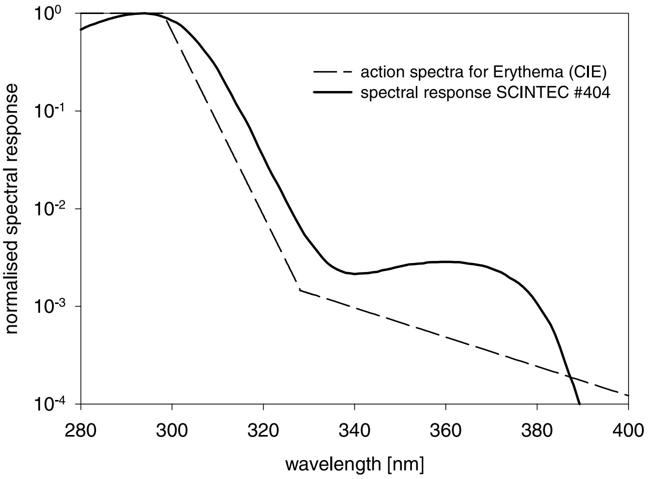

Figure 1. Spectral response of the instrument (type SCINTEC UV-S-E-T) used within the study and spectral course of the standardized erythema action spectrum defined by CIE [*McKinlay and Diffey*, 1987].

aerosol optical depth but different albedo due to a small glacier and the surrounding mountains.

2.2. Cloud Detection

[9] Clouds can attenuate and enhance solar UV radiation at the surface depending on their amount, their optical depth, and their position in relation to the Sun [*Koepke et al.*, 2002]. In general, clouds between a low and a high station will reduce the UVI at the low station because of attenuation and enhance it at the high one because of increased albedo. For the elimination of this strong and variable effect on AE, an algorithm has been created to detect cloud affected periods on the basis of the measured UVI. In order to detect the signatures of different cloud types, several empirically derived criteria have been applied on the data.

2.2.1. Criterion 1

[10] Cumulus clouds generate high spatial and temporal variations and can enhance and attenuate the UV radiation at the surface. Typical features are prominent spikes in the course of the UVI due to the rapid changes between cloud shadow and additional illumination of the receiver by radiation reflected by the clouds. In order to detect these effects a criterion proving the steadiness of the graph has been applied. A data point at the time t has been defined as cloud-free if its deviation from the value before ($t - \Delta t$) is below a threshold of 3%. The time step Δt corresponds to one minute. In the strict sense the threshold has to be adjusted to solar elevation because of its diurnal course, as the slope of the graph decreases approaching noon. However, this criterion is supposed to detect only the prominent peaks and therefore the higher effort in adapting the critical limit is not justified.

2.2.2. Criterion 2

[11] Typical stratiform clouds have high optical depths and a mostly homogeneous structure within the cloud. Therefore the reduction of UVI against cloud-free conditions is high but often nearly constant over comparatively long periods. To identify the influence of stratiform clouds, absolute UVIs have been modeled for cloud-free conditions and compared to the measured values. The used model STAR [*Ruggaber et al.*, 1994; *Schwander et al.*, 2001] takes into account date, time and geographical coordinates and altitude of the station. The albedo has been used with regional values, adapted to the surroundings of the station. Total ozone content, and aerosol optical depth have been used with one value per day. The ozone values have been derived from ground based measurements at La Paz and Hohenpeissenberg. All UVI data have been modeled with the aerosol type “continental average” [*Hess et al.*, 1998]. The aerosol optical depth has been adapted to fit measured and modeled UVI during a period which has been declared cloud-free from visible inspection. Finally a measured UVI value has been defined to be cloud-free if the difference between model result and measurement is less than 20%.

2.2.3. Criterion 3

[12] Cirrus clouds have relatively small optical depths and therefore only a weak impact on the UV radiation at the surface. However, their optical depth is highly variable which can be recognized by small short time variations in the measured UVI. To detect these minor disturbances against the variation due to changed solar zenith angle, the slopes of the modeled and measured course of the UVI have been compared. The slope a has been defined as the absolute difference of the UVI for a selected time step of 60 s.

$$a = \frac{\mathrm{UVI}_{t_2} - \mathrm{UVI}_{t_1}}{t_2 - t_1} \tag{2}$$

An UVI value has been considered to be influenced by a cloud, if

$$\left(\frac{a(\mathrm{modeled}) - a(\mathrm{measured})}{a(\mathrm{modeled})}\right)^2 > 3 \tag{3}$$

The threshold of 3 has been determined by empirical testing of the data.

2.2.4. Criterion 4

[13] Especially in the case of cumulus clouds it is possible that the modeled and the measured UVI coincide although the values before and after are clearly detected by Criterion 1 to be influenced by clouds. To minimize the probability of such events, a period of measurements is defined as unaffected by clouds only if a series of 12 consecutive values, respectively a time interval of 12 minutes, has been recognized as cloud-free. Nevertheless it is possible that Cirrus clouds with very small optical depths are not detected and can still be included in the data. Their effects, however, will not mask the altitude effect for cloud-free conditions.

[14] All thresholds have been developed and optimized empirically. A typical example for the functionality of the algorithm for cloud detection is given in Figure 2. It shows the measured and modeled daily course of the UVI at Chakaltaya on 25 August 2002. The data within the shaded boxes have been identified as influenced by clouds. For the further study only cloud-free data have been taken into account.

2.3. Ozone Normalization

[15] Under cloudless conditions the total ozone content TOC is the major factor affecting the UVI at the surface. Since ozone varies with time and location, the effect of different TOC has to be eliminated for investigations of the AE that do not base on simultaneous measurements. Thus all measured cloud-free UVI data used in this study have been normalized to fixed ozone with values depending on altitude. Since the normalization procedure is performed for every individual measurement day, it accounts implicitly for the variation of solar radiation due to the annual changes in Sun-Earth distance.

[16] The ozone value for the normalization (TOC_{norm}) has been set to 300 DU for both low-altitude stations Munich and Caranavi. For the normalization of the UVI data measured at the other stations TOC_{norm} has been adapted to the site altitude. The procedure considers the average reduction of the TOC with increasing altitude due to missing tropospheric ozone by truncation of the low atmospheric parts. An ozone decay of 3.5 DU per km has been used. This average tropospheric ozone gradient of 3.5 DU/km has been determined from monthly averaged ozone soundings for two different sites in Europe (for details, see *Reuder and Koepke* [2005]). From this work also an

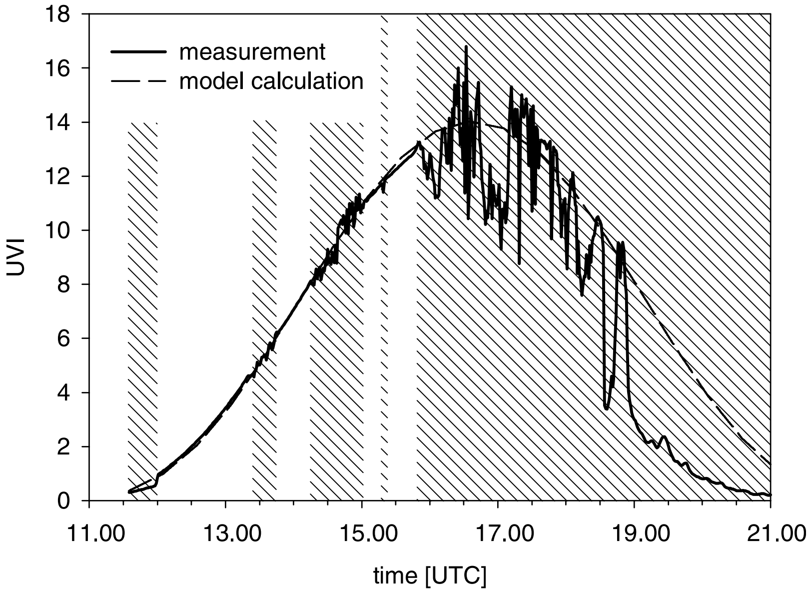

Figure 2. Measurements and model calculations of the UVI for 25 August 2002 at Chakaltaya. Shaded areas indicate time intervals when the automatic detection algorithm defines cloud influence.

annual variability of ±0.5 DU/km can be determined. For the Bolivian region no adequate ozone soundings are available. Total ozone measurements performed with a MICROTOPS instrument [*Holdren et al.*, 2001] by one of the authors (J. Reuder, August 2003) during a 5 hour trip from Tambo Quemado (4800 m) at the border between Chile and Bolivia close to Arica (500 m) resulted in a comparable total ozone gradient of 4 DU/km. Starting with the basic value of 300 DU for Munich and Caranavi the total ozone content for normalization TOC_{norm} at the other sites has been determined and is shown in Table 2.

[17] Daily averages of TOC are available from ground based Brewer measurements in La Paz, Bolivia, and Hoher Peissenberg, Germany. Thus these data have been converted to actual, altitude-dependent TOCs for every site, again by substraction of the tropospheric ozone with its climatological value of 3.5 DU/km. To normalize the measured UVI, its daily course has been modeled both with TOC and TOC_{norm} for all stations with the site-dependent values. The resulting ratio N defines a normalization factor.

$$N = \frac{\mathrm{UVI}(\mathrm{TOC}_{norm})}{\mathrm{UVI}(\mathrm{TOC})} \qquad (4)$$

The factor N depends on solar elevation with marginal decrease for increasing solar elevation, since the ozone effect is less pronounced for high Sun. The average value of N for each site is given together with its standard deviation in Table 2. Considering actual albedo and aerosol conditions, the measured data (UVI_m) have been multiplied by the particular factor N (equation (4)), to determine the normalized UVI values (UVI_{norm}).

$$\mathrm{UVI}_{norm} = N \cdot \mathrm{UVI}_m \qquad (5)$$

Since the influence of aerosol and albedo is only slightly dependent on ozone content, their effects in the measured UVI are preserved in UVI_{norm}. Since both TOC and TOC_{norm} are adapted to altitude by the same climatological value, the effect of ozone reduction with altitude is also conserved in UVI_{norm}.

[18] The combined effect of cloud screening and ozone normalization is shown as an example for Chakaltaya in Figure 3. Figure 3a depicts all measured UVI data in 2002. The full variability of all atmospheric parameters, i.e., mainly cloudiness, but also total ozone content, aerosol properties and albedo, cause the wide scatter of the data. Figure 3b presents the UVI values for cloud-free conditions and normalized with respect to ozone. At a given station,

Table 2. Total Ozone Content Used for Normalization, Resulting Average Normalization Factor N and Its Standard Deviation, and the Overall Number n of Available 1-min UV Measurements Selected as Unaffected by Clouds for the Different Stations

Station	Altitude, m	Total Ozone Content, DU	Normalization Factor N	SD N	n
Munich	527	300.0	1.08	0.10	25,170
Caranavi	605	300.0	1.14	0.08	8191
Zugspitze (UFS)	2650	292.1	1.06	0.11	17,340
Valencia	2800	292.0	1.16	0.07	13,830
Zugspitze (summit)	2964	291.0	1.04	0.10	21,615
La Paz	3420	289.8	1.16	0.08	29,265
Lake Titicaca	3825	288.4	1.15	0.08	12,210
El Alto	4000	287.8	1.17	0.06	15,930
Chakaltaya	5240	283.5	1.16	0.09	24,810

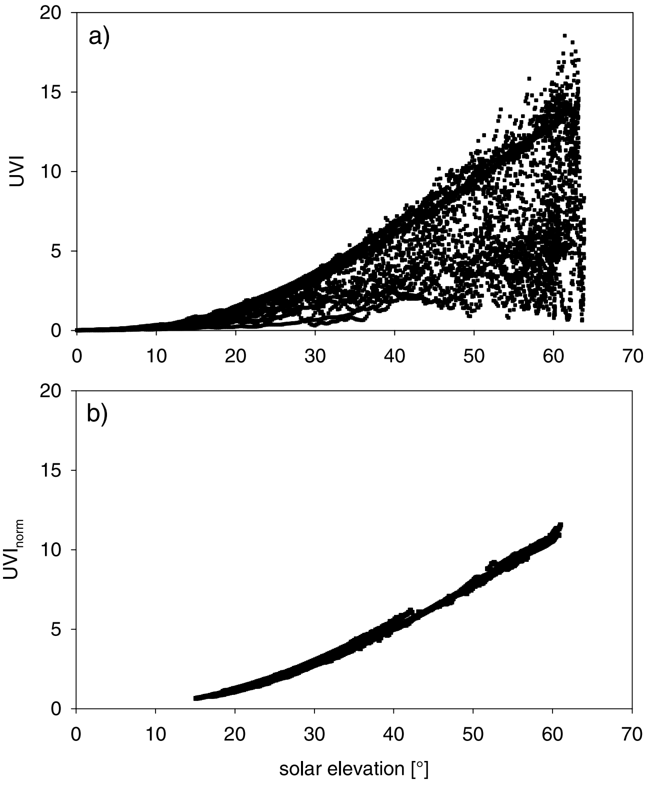

Figure 3. Measurements of the UVI at Chakaltaya. (a) All data of the 78 measurement days during the campaign in 2002. (b) Same data set for cloud-free cases and normalized TOC.

these UVI$_{norm}$ only depend on solar elevation, atmospheric turbidity and changes in the albedo of the terrain.

3. Results

3.1. Normalized UVI

[19] In the following only UVI$_{norm}$ for cloud-free conditions have been considered. Thus the subscript will be omitted from now on. Besides the variations in total column ozone and cloudiness, the solar elevation is the third major factor contributing to changes of the solar UV radiation at the ground. The higher the Sun, the shorter the optical path for extinction processes and therefore the lower the influence of aerosol, tropospheric ozone and Rayleigh scattering on direct and diffuse UV radiation. In the following the normalized cloud-free UVI for all stations is discussed as a function of solar elevation. The mean UVI and its standard deviation have been derived for solar elevations from 20° to 80° for each station, as long as the corresponding elevation has been reached during the campaigns. Averaging has been performed over 10° intervals; that is, the UVI value given for 20° corresponds to all UVI measurements taken at solar elevations between 15° and 25°. The standard deviation can be understood as a measure for the natural variability of UV radiation at a site, considering variable aerosol properties and albedo conditions due to the different times of the campaigns. Thus the data at a given solar elevation for one site do not necessarily represent the same atmospheric conditions at other sites or at other solar elevations.

[20] Figure 4 shows the UVI as example for selected stations. The increase of UVI with solar elevation and also with altitude of the site can be seen clearly. As mentioned the data for the German sites do not exceed a solar elevation of 65°, because of geographical latitude, while for Bolivia values up to 80° are available. The lowland site of Caranavi shows slightly lower UVI values than Munich located at a

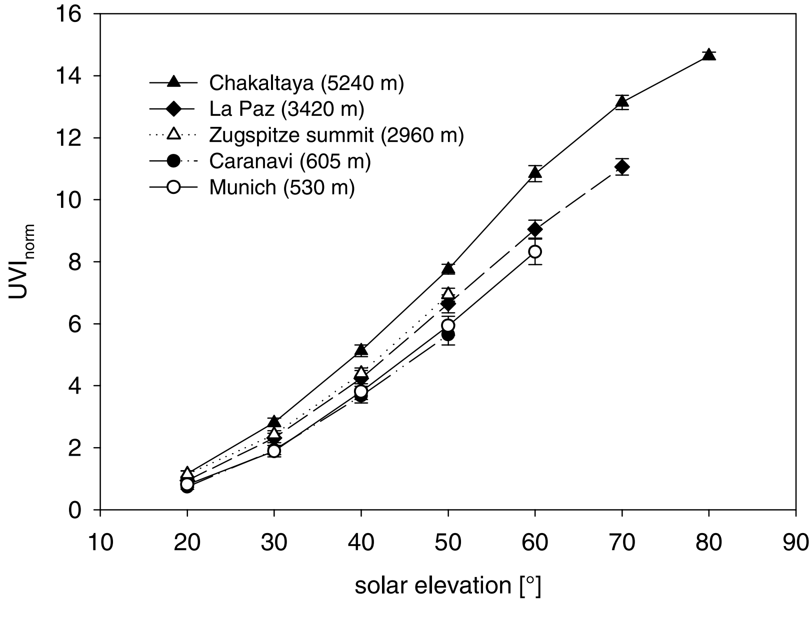

Figure 4. Averaged UVI for cloud-free conditions and normalized with respect to TOC as a function of solar elevation. The standard deviation is given by the error bars. Values at solar zenith angles of 70° and higher are not available in Germany.

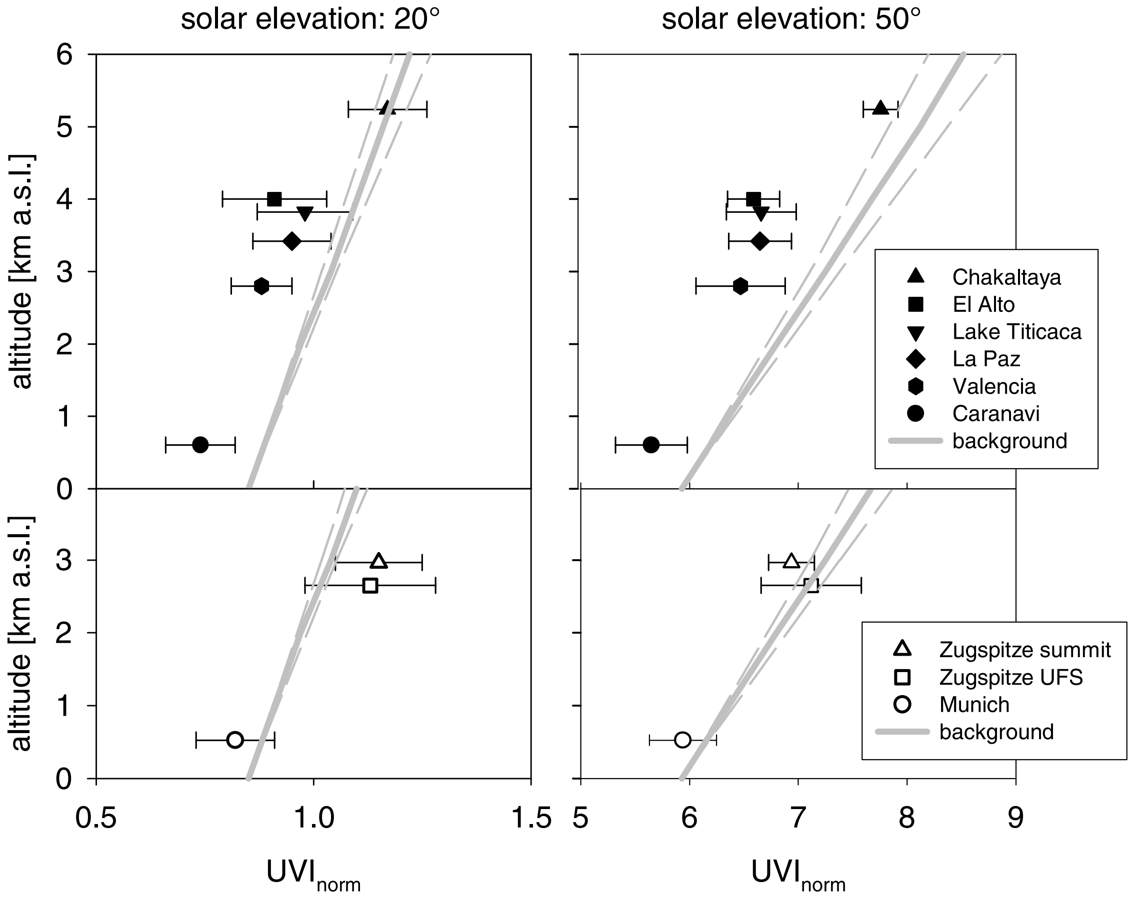

Figure 5. Profiles of averaged UVI for cloud-free conditions and normalized with respect to TOC for solar elevations of 20° and 50°. The standard deviation is given by the error bars. The grey curves represent model calculations of the UVI for an aerosol-free atmosphere and a constant surface albedo of 0.03. The solid grey curves represent results for an average tropospheric ozone gradient of 3.5 DU/km; the dashed grey curves have been calculated under the assumption of 2.0 DU/km and 5.0 DU/km.

similar altitude. This comparable low UV at Caranavi can be explained by the elevation of the skyline. Caranavi is situated in a densely vegetated river valley with an obstruction of the horizon of above 10 degrees to the east and west of the measurement site. This effect seems to overcompensate for the average higher aerosol load expected for Munich. Although located around 500 m higher, the average observed UVI at La Paz is below the values of Zugspitze. One reason for that is the higher aerosol load of La Paz in comparison with Zugspitze. Another effect could be an increase in UVI at the Zugspitze summit due to the influence of light scattered from below in mountainous areas [e.g., *McKenzie et al.*, 2001]. The differences between various stations are discussed in detail in the following.

[21] The UVIs for all stations are presented for solar elevations of 20° and 50° exemplarily in Figure 5 with the results for Bolivia in the upper and for Germany in the lower panels. In addition, as grey curves, a so called background UVI (BUVI) is shown as a function of altitude. These BUVIs have been modeled with STAR in its actual version [*Schwander et al.*, 2002] with altitude-dependent barometric pressure and total ozone amount starting at 300 DU at sea level and being reduced with increasing altitude. The model atmosphere is assumed aerosol-free and a constant surface albedo of 3% has been applied for all altitudes. An average tropospheric ozone gradient of 3.5 DU/km (solid grey curve) has been used [*Reuder and Koepke*, 2005]. In addition this average gradient has been modified to represent potential variability of tropospheric ozone profiles. The dashed grey curves have been calculated under the assumption of tropospheric ozone gradients of 2.0 DU/km and 5.0 DU/km.

[22] The BUVI and all measured UVI show a strong increase with altitude. In general, the measured UVI is below the BUVI. This can be associated with aerosol effects for real atmospheric conditions. The high-mountain sites of Chakaltaya and Zugspitze are located quite close to the calculated BUVI. Especially at the low solar elevation of 20° the measurements at Zugspitze exceed the BUVI from model calculations distinctly. The reason is the potential snow cover in the mountains nearly all over the year, resulting in albedo values clearly above the value of 3% used for the model calculations. This albedo effect also explains the relatively large standard deviation for the station Zugspitze UFS, since this station is situated above a glacier at the southern slope of Zugspitze massif. Snowfall is possible all over the year, leading to highly variable albedo conditions, especially during summertime. The

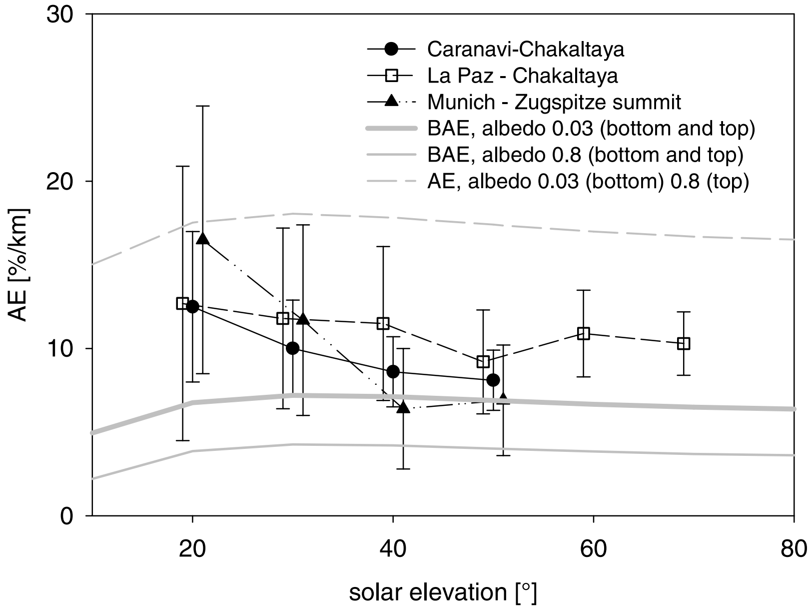

Figure 6. Dependency of the AE on solar elevation for different sites in Bolivia and Germany. The solid grey curves represent model calculations of the background AE for constant surface albedo conditions of 0.03 and 0.8. The dashed grey curve gives the modeled AE under the assumption of an albedo of 0.03 for the lower site and 0.8 for the upper site.

effects of albedo can be seen in addition in the comparison of the sites at Zugspitze summit and UFS. For solar elevation 50°, i.e., during summer with low regional albedo, the UVI at UFS has been higher because of the glacier effect than at the summit. For solar elevation of 20° measurements at winter conditions are included where the regional albedo is high because of snow overall in the area and thus the conditions are similar for Zugspitze summit and UFS.

[23] The Bolivian sites also show the general increase of UVI with altitude. However, the station El Alto shows a marked deviation from this general behavior. Although located several hundred meters higher than both other Altiplano sites La Paz and Lake Titicaca, it features smaller UVI values. The area of El Alto is characterized by high emissions of particles and precursors of photosmog, e.g., by the airport, industrial plants, traffic and domestic fuel. Together with low environmental standards this results in higher average aerosol optical depths. In comparison to the other sites on the Altiplano, La Paz also is characterized by high aerosol optical depths. However, the aerosol layer in the La Paz valley is typically located below the UVI measurement site at the University of La Paz, at least until noon. Moreover, because of a diurnal circulation pattern driven by solar heating of the Altiplano [*Egger et al.*, 2005], pollution is transported from the city of La Paz toward El Alto during the daytime. During the night a catabatic outflow of air along the valley of the Rio de La Paz additionally removes polluted air from La Paz. No such regular mechanism for removal of polluted air has been found for El Alto.

[24] The high-mountain station Chakaltaya presents pronounced higher UVI values than the other stations because of the reduced molecular scattering, and the small aerosol optical depths due to the location of the station above the polluted atmospheric boundary layer. The relatively low standard deviation results from the small variability in free tropospheric and stratospheric aerosols.

3.2. Altitude Effect

[25] The altitude effect, defined by the relative change in UVI between two stations at different altitudes z_l and z_h, is given in %/km (see equation (1)).

[26] The error of the $AE = f(UVI_{zl}, UVI_{zh})$ is calculated using the error propagation by Gauss:

$$\Delta AE^2 = \left(\frac{\partial AE}{\partial UVI_{z_l}} \cdot \Delta UVI_{z_l}\right)^2 + \left(\frac{\partial AE}{\partial UVI_{z_h}} \cdot \Delta UVI_{z_h}\right)^2 \qquad (6)$$

Insertion and transformation results in

$$\left(\frac{\Delta AE}{AE}\right)^2 = \left(\frac{UVI_{z_h}}{UVI_{z_h} - UVI_{z_l}}\right)^2 \cdot \left(\left(\frac{\Delta UVI_{z_l}}{UVI_{z_l}}\right)^2 + \left(\frac{\Delta UVI_{z_h}}{UVI_{z_h}}\right)^2\right) \qquad (7)$$

[27] The magnitude of ΔAE is determined by the observed variability in the UVI at both stations and their altitude difference. The smaller the UVI values and the smaller their differences with altitude, the higher is the corresponding uncertainty level ΔAE. The AE and its uncertainty level has been determined for combination of the various sites and for different solar elevation intervals. The results are presented in Figure 6 and in Tables 3–6.

[28] Figure 6 shows the dependency of the AE on solar elevation exemplary for three combinations of a low site with a summit site together with the AE resulting from modeled BUVI. This Background altitude effect (BAE) is also given in%/km and has been determined on the basis of BUVI modeled for 1 km and 4 km altitude. This BAE ranges between 5%/km and 7%/km for a constant albedo of

Table 3. Altitude Effect in Bolivia for a Solar Elevation of 50°[a]

	Chakaltaya	El Alto	Lake Titicaca	La Paz	Valencia
Caranavi	8.1 ± 1.8	4.9 ± 2.4	5.6 ± 2.8	6.3 ± 3.2	6.6 ± 4.3
Valencia	8.2 ± 3.3	1.6 ± 5.9	2.9 ± 8.1	4.5 ± 12.5	–
La Paz	9.2 ± 3.1	−1.6 ± 9.9	0.4 ± 17.3	–	–
Lake Titicaca	11.6 ± 4.3	−5.8 ± 32.7	–	–	–
El Alto	14.3 ± 4.0	–	–	–	–

[a] Values are given in %/km.

Table 5. Altitude Effect in Bolivia for a Solar Elevation of 20°[a]

	Chakaltaya	El Alto	Lake Titicaca	La Paz	Valencia
Caranavi	12.5 ± 4.5	6.8 ± 6.2	10.1 ± 6.4	10.1 ± 6.6	8.6 ± 7.3
Valencia	13.5 ± 6.0	2.8 ± 13.2	11.1 ± 15.0	12.8 ± 23.9	–
La Paz	12.7 ± 8.2	−7.3 ± 26.8	7.9 ± 37.9	–	–
Lake Titicaca	13.7 ± 11.3	−39.7 ± 89.3	–	–	–
El Alto	23.0 ± 15.8	–	–	–	–

[a] Values are given in %/km.

0.03 and between 3%/km and 5%/km for a constant albedo of 0.8. The weak maximum around 30° solar elevation is in agreement with the results of *McKenzie et al.* [2001] and *Staiger and Koepke* [2005]. The slight decrease of the AE for erythemally weighted UV radiation toward higher solar elevation is due to the decreasing extinction with increasing solar elevation. For solar elevations below 20°, the contribution of the direct Sun to the UV irradiance is so small that photons coming from regions near the zenith dominate [*Mech and Koepke*, 2004]. Because of this detour effect [*Schwander et al.*, 1997], these photons undergo less extinction and thus the AE decreases if properties of atmosphere and surface do not change. If an altitude-dependent albedo is introduced, e.g., 0.03 (vegetation) for the low-altitude site and 0.8 (fresh snow) for the high-altitude site, the resulting AE reaches values on the order of 15%/km. This altitude effect is no longer the BAE defined above. In this case the albedo is clearly dominating the AE.

[29] The AE from measured UVI is given for the combination of the stations Caranavi-Chacaltaya, La Paz–Chakaltaya, and Munich-Zugspitze summit. A general increase of the AE toward lower solar elevation can also be seen in the measured data. Data below 15° have not been analyzed because of the large standard deviation. Therefore the decrease of the AE derived from model calculations for low solar elevation cannot be deduced from the presented measurements. For Bolivia the measured values of the AE are on the order of 10%/km. The higher values for the sites La Paz–Chakaltaya compared to Caranavi represent the higher average aerosol load of La Paz.

[30] In Germany the AE is about 7%/km for solar elevations of 40° and 50° and therewith close to the corresponding values of BAE for an albedo of 0.03. The sharp increase in AE for lower solar elevation is an effect of a higher average albedo at Zugspitze compared to Munich because of snow during the winter season. Because of the higher average aerosol optical depth in Munich actually an AE remarkably higher than the BAE would be expected for this site combination. One reason for the observed relatively low AE could be an average albedo on the order of 0.15 to 0.2, both for Munich and Zugspitze during summertime. The institute in Munich is a typical urban site where the relevant albedo is a composite of vegetated surfaces, buildings and streets. Part of these surfaces, like concrete, asphalt, sand and granite, have albedo values on the order of 0.2 and above [e.g., *Koepke et al.*, 2002], resulting in an overall albedo distinctly higher than 0.03. It can be seen from Figure 6 that this would reduce the corresponding BAE. Another reason could be an AOD at the days of UV measurements that is lower than the average value given in Table 1, since measurements of UV and AOD have not been carried out simultaneously.

[31] In the following the impact of the albedo and aerosol on the AE will be discussed exemplarily for fixed solar elevations of 50° and 20° (Tables 3–6). Table 3 shows the altitude effect for a solar elevation of 50° for all combinations of Bolivian sites. Using Chakaltaya as high-level site, the AE increases for Caranavi up to El Alto with values between 8.1 and 14.3%/km. This is mainly the effect of the increasing aerosol load in combination with the reduced altitude difference, since albedo effects will be negligible for the stations in Bolivia. Singular short-term snow events influence the UVI only at Chakaltaya and thus they do not contribute to the differences in AE derived by UVI values of different stations in combination with Chakaltaya data. Starting with El Alto as high-level site, again the aerosol effect dominates. Because of the high aerosol optical depth in El Alto, the AE even reaches negative values in comparison to La Paz and Lake Titicaca. Starting from Caranavi as low-level station, an AE in the range of 4.9%/km (for El Alto) to 8.1%/km (for Chakaltaya) has been found. In general, the AE decreases with increase in urbanity of the high-altitude site. If the two stations used to derive an AE are located at similar altitude, the effects of even small differences in aerosol loading or albedo will result in high values of AE. This results in the high uncertainties to be seen in Table 3 for neighboring stations at the Bolivian plateau.

[32] The AE in Bolivia is dominated by the aerosol influence, while in Germany the albedo effect gets more important. Starting with Zugspitze summit as high-level site, an AE of 6.9%/km has been determined in comparison to Munich. This value is close to the values for comparable altitude levels in Bolivia (e.g., Caranavi-Valencia or Caranavi–La Paz). However, the AE between Zugspitze UFS and Zugspitze summit is -8.1%/km. Since these two stations are both located well above the aerosol loaded boundary layer, this effect must be explained by the location of UFS at

Table 4. Altitude Effect in Germany for a Solar Elevation of 50°[a]

	Zugspitze Summit	Zugspitze UFS
Munich	6.9 ± 3.3	9.3 ± 4.7
Zugspitze UFS	−8.1 ± 22.1	–

[a] Values are given in %/km.

Table 6. Altitude Effect in Germany for a Solar Elevation of 20°[a]

	Zugspitze Summit	Zugspitze UFS
Munich	16.5 ± 8.0	17.8 ± 9.4
Zugspitze UFS	5.6 ± 51.4	–

[a] Values are given in %/km.

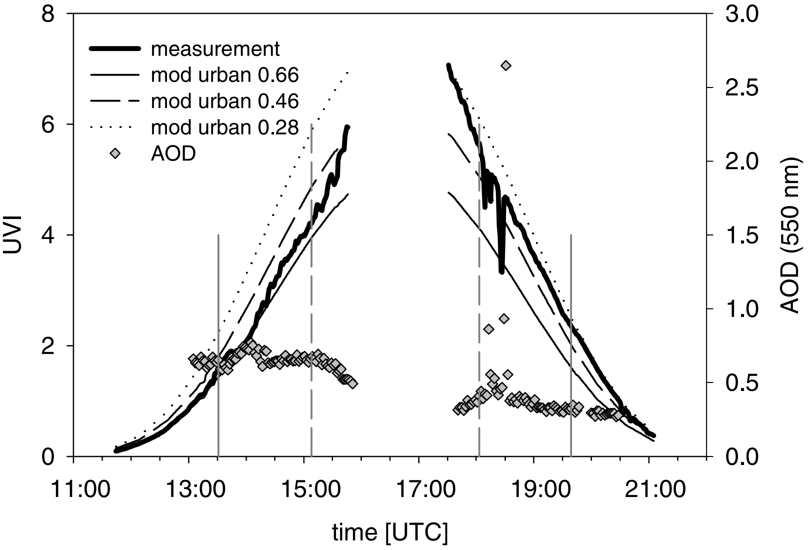

Figure 7. Measured and modeled UVI for 24 June 2002 at La Paz (Bolivia) and corresponding measurements of the aerosol optical depth at 550 nm. The vertical lines mark fixed solar elevations of 30° (solid lines) and 45° (dashed lines).

the slope of a mountain ridge that is snow covered during most time of the year, acting as an effective reflector for UV radiation. Again the small vertical distance between Zugspitze UFS and summit is responsible for the large uncertainty. The enhanced UVI at Zugspitze UFS also explains the increased AE for the combination of Munich-UFS.

[33] Tables 5 and 6 show the altitude effect for a solar elevation of 20° again for all combinations of sites. Compared to 50° the AE is generally increased, both for Bolivia and Germany. This is valid for the AE and its uncertainties. The main features in the AE between various sites in Bolivia remain widely unchanged. Thus the explanation for the AE given above for the solar elevation of 50° is further valid, showing the small temporal variations in atmospheric properties.

[34] The increase in AE and its uncertainty also can be found for the German stations. The only difference against a solar elevation of 50° is the change of the sign to a positive AE between Zugspitze UFS and Zugspitze summit. During wintertime, with a maximum solar elevation of around 20°, both for the summit and the UFS the albedo is enhanced because of snow cover resulting in similar albedo contributions to the UVI and thus in increasing UV radiation with altitude.

3.3. Aerosol Effect: Case Study of 24 June 2002

[35] In general, aerosol conditions are characterized by high spatial and temporal variability, especially in regions with important aerosol sources. A systematic and detailed study of aerosol influence on the UVI can be done by extensive model sensitivity studies [*Reuder and Schwander*, 1999; *Staiger and Koepke*, 2005] or by measurements under highly variable aerosol conditions [*Kylling et al.*, 1998]. In the following, the influence of exceptional high aerosol content on UV irradiance will be discussed exemplarily, using measurements performed during 24 June 2002 at La Paz. In the evening of 23 June the most important local holiday (St. John) in La Paz is celebrated by numerous bonfires spread all over the city [*Andrade et al.*, 1998]. The burning of all kind of combustible rubbish, including plastics, tires and organic waste, results in heavy air pollution and corresponding high values of aerosol optical depth (AOD), which has been measured during the next day, 24 June, by a Schulze Sun photometer [*Wagner et al.*, 2001]. A distinct decrease in aerosol load during the day has been observed, which indicates the cleaning capacity of the atmosphere in the La Paz canyon by a strong thermally induced circulation pattern [*Egger et al.*, 2005]. Simultaneous measurements of erythemally weighted UV radiation enable a detailed case study of potential aerosol effects on UV radiation.

[36] Figure 7 shows measured UVI and AOD at 550 nm wavelength during 24 June 2002. The lacking data around noon are caused by a general power cut in La Paz. The time series are plotted in UTC; local noon corresponds to about 1630 UTC. Measurements of AOD start around 1300 UTC, i.e., 0830 in the morning in local time, with values distinctly above 0.6, reaching a maximum of 0.75 between 14 UTC and 15 UTC. From then a slow but steady decrease in AOD can be observed. During the power cut of nearly two hours, a further decrease in AOD has occurred, resulting in AOD below 0.5 afterward. The short time enhancement between 1800 and 1830 UTC, including the two distinct maxima of 0.9 and 2.7, can clearly be associated with cloud effects by an analysis of the spectral course of AOD measurements during this period. An effect of total ozone variation can be neglected. The values derived by Brewer measurements at La Paz remain constant within 3 DU all over the day.

[37] UVI has been measured from sunrise (around 1130 UTC) nearly until sunset (2100 UTC) and is also shown in Figure 7. The afternoon radiation values clearly exceed those in the morning at corresponding solar elevations. For a quantification of the aerosol effect on UVI, situations with stable radiation conditions and comparable solar elevation during morning and afternoon have been selected at 30° and 45°. The corresponding times are

marked in Figure 7 by vertical lines. At a solar elevation of 30° an decrease in AOD at 550 nm by 51% from 0.65 to 0.32 between morning (1331 UTC) and afternoon (1939 UTC) is associated with an increase in UVI of about 44% from 1.6 to 2.3. The increase of UVI for a solar elevation of 45° is less pronounced since the time interval between morning (1508 UTC) and afternoon (1803 UTC) is shorter and thus the purification is less striking and further aerosol effects generally are smaller for higher solar elevation because of the shorter tropospheric path length. An UVI of 4.2 corresponds with an AOD at 550 nm of 0.66 in the morning. In the afternoon the AOD has decreased by about 43% to 0.37, while the UVI has increased by about 29% to a value of 5.4.

[38] With respect to the range of observed AOD during 24 June, radiative transfer calculations of the UVI have been performed to investigate the potential aerosol effect for three different AOD values of 0.28, 0.46, and 0.66 using the aerosol type "urban" [*Hess et al.*, 1998]. The resulting diurnal course of the modeled UVI is also shown in Figure 7. In the morning, until 1415 UTC the measured UVI corresponds to the modeled curve with an AOD of 0.66. Shortly before the power cut, the measured UVI intersects the modeled graph with an optical depth of 0.46 and at the end of the day the measured UVI corresponds to the modeled UVI for an AOD of 0.28.

4. Discussion and Conclusions

[39] The altitude effect for cloud-free conditions has been determined by a large number of UVI measurements in Bolivia and Germany, collected over periods of at least several weeks during different seasons of the year. The AE has been studied at stations in similar altitude but for different climate and different atmospheric conditions. The AE presented in this study includes the effects of molecular scattering, aerosol extinction and surface albedo. The derived values of AE for Bolivia are in good agreement with the results obtained by *Cabrera et al.* [1995] (4–10%/km) and *Piazena* [1996] (8–10%/km) in the Chilean Andes and *Zaratti et al.* [2003] (7%/km) for Bolivia. The results for Germany confirm former studies performed in the Alps [*Blumthaler et al.*, 1997; *Seckmeyer et al.*, 1997].

[40] Additionally, radiative transfer calculations of the BAE, i.e., the increase of UV radiation with altitude only due to reduced molecular scattering and reduced ozone content, have been performed. Even this BAE depends distinctly on surface albedo and ranges between 5%/km and 7%/km for a constant albedo of 0.03 and between 3%/km and 5%/km for an albedo of 0.8. The corresponding model results of the influence of the albedo are an important basic requirement for the interpretation of the aerosol influence on the AE.

[41] If the albedo is unchanged, the deviations between the AE derived from measurements and the BAE are mainly due to the optical depth of the aerosol between the two stations. As the aerosol is mostly concentrated in the boundary layer, the UVI increases strongly with increasing altitude if the high-level station is located outside the aerosol layer, a typical situation for the German Alps. If both stations are within or both above the aerosol layer, the increase in UVI with altitude is relatively small, as, e.g., measured in Chile [*Cabrera et al.*, 1995].

[42] In the data presented here, the consequences for the AE resulting from different aerosol at the two stations can be seen in the measurements in Bolivia, especially starting from El Alto. In the specific situation of the Bolivian plateau even a decrease of UV radiation with increasing altitude has been observed, as a consequence of increased aerosol optical depth at the high-altitude site. The altitude effect with respect to Chakaltaya differs from the results of *Cabrera et al.* [1995], who obtained a distinctly smaller value of 2%/km for the altitudes from 3000 to 5000 m in the clean Chilean Andes. The reason is the high pollution at the Bolivian stations resulting in relatively low UVI values for the lower stations and thus high AE. Furthermore, higher albedo at the upper station enhances the AE. Since snow is the only relevant parameter temporarily changing the albedo in the UV spectral range, a rising probability of snow with altitude, enhances the AE. If both stations have similar aerosol properties, the albedo is the dominant factor to explain variations in AE. For European stations this results in increasing AE during winter, i.e., generally for low solar elevation. Because of the smaller probability of snow the albedo effect on AE is of minor importance in Bolivia.

[43] It has been shown that the choice of the stations to be compared is crucial for the resulting altitude effect as the local aerosol properties and the local albedo conditions can dominate the effects of reduced molecular scattering and decreased tropospheric ozone. This explains the great bandwidth of values for the AE. Comparing similar conditions in Germany and Bolivia, the regional and climatological differences in AE vanish. Starting with an urban low-level site and a clear mountain station as high-level site (Munich/Zugspitze Summit with respect to La Paz/Chakaltaya) the resulting AE is similar.

[44] For a correct description and prediction of the altitude effect besides decreasing pressure, decreasing tropospheric ozone, and clouds, the contributions of albedo and aerosol optical depths have to be considered. In order to take these result into account it is proposed to describe the altitude effect as a combination of the contributions of the altitude, the aerosol, the albedo and the tropospheric ozone profile, even if a clear separation of the influence of the single parameters is not possible because of their interactions.

[45] This however has to be analyzed by a sensitivity study. The case study of 24 June 2002 has shown that the aerosol effect on UV can be measured and modeled for extreme conditions. The good agreement between modeled and measured data shows the possibility to utilize model result for a further sensitivity study on the different parameters that influence the AE.

[46] **Acknowledgments.** The authors are grateful to Umweltforschungsstation Schneefernerhaus (UFS) for providing a grant for 1 year of measurements in Bolivia and at Zugspitze. The three-month internship of Monika Pfeifer has been funded by the German Academic Exchange Service (DAAD) within her diploma thesis for UV measurements in Bolivia. Many thanks are given to Francesco Zaratti, head of the Laboratory of Atmospheric Physics (LFA) of the University of La Paz (UMSA), and all his colleagues for the hospitality and help during the UV measurements in Bolivia.

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