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RECONSTRUCTION OF PAST UV RADIATION

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Abstract

Solar ultraviolet (UV) radiation has a broad range of effects concerning life on Earth. Soon after the mid-1980s, it was recognized that the stratospheric ozone content was declining over large areas of the globe. Because the stratospheric ozone layer protects life on Earth from harmful UV radiation, this lead to concern about possible changes in the UV radiation due to anthropogenic activity. Initiated by this concern, many stations for monitoring of the surface UV radiation were founded in the late 1980s and early 1990s. As a consequence, there is an apparent lack of information on UV radiation further in the past: measurements cannot tell us how the UV radiation levels have changed on time scales of, for instance, several decades.

The aim of this thesis was to improve our understanding of past variations in the surface UV radiation by developing techniques for UV reconstruction. Such techniques utilize commonly available meteorological data together with measurements of the total ozone column for reconstructing, or estimating, the amount of UV radiation reaching Earth's surface in the past. Two different techniques for UV reconstruction were developed. Both are based on first calculating the clear-sky UV radiation using a radiative transfer model. The clear-sky value is then corrected for the effect of clouds based on either (i) sunshine duration or (ii) pyranometer measurements. Both techniques account also for the variations in the surface albedo caused by snow, whereas aerosols are included as a typical climatological aerosol load. Using these methods, long time series of reconstructed UV radiation were produced for five European locations, namely Sodankylä and Jokioinen in Finland, Bergen in Norway, Norrköping in Sweden, and Davos in Switzerland.

Both UV reconstruction techniques developed in this thesis account for the greater part of the factors affecting the amount of UV radiation reaching the Earth's surface. Thus, they are considered reliable and trustworthy, as suggested also by the good performance of the methods. The pyranometer-based method shows better performance than the sunshine-based method, especially for daily values. For monthly values, the difference between the performances of the methods is smaller, indicating that the sunshine-based method is roughly as good as the pyranometer-based for assessing long-term changes in the surface UV radiation.

The time series of reconstructed UV radiation produced in this thesis provide new insight into the past UV radiation climate and how the UV radiation has varied throughout the years. Especially the sunshine-based UV time series, extending back to 1926 and 1950 at Davos and Sodankylä, respectively, also put the recent changes driven by the ozone decline observed over the last few decades into perspective. At Davos, the reconstructed UV over the period 1926-2003 shows considerable variation throughout the entire period, with high values in the mid-1940s, early 1960s, and in the 1990s. Moreover, the variations prior to 1980 were found to be caused primarily by variations in the cloudiness, while the increase of 4.5 %/decade over the period 1979-1999 was supported by both the decline in the total ozone column and changes in the cloudiness. Of the other stations included in this work, both Sodankylä and Norrköping show a clear increase in the UV radiation since the early 1980s (3-4 %/decade), driven primarily by changes in the cloudiness, and to a lesser extent by the diminution of the total ozone. At Jokioinen, a weak increase was found, while at Bergen there was no considerable overall change in the UV radiation level.

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Menneen ajan UV-säteilyn rekonstruointi

Tiivistelmä

Auringon ultraviolettisäteily (UV-säteily) vaikuttaa usealla tavalla elämään maan päällä. 1980-luvun puolivälin jälkeen huomattiin, että stratosfäärin otsonimäärä oli vähenemässä etenkin Etelämantereen kevätkaudella mutta myös maapallonlaajuisesti. Stratosfäärin otsonikerros suojelee elämää maan päällä haitalliselta UV-säteilyltä, ja havaitut otsonikerroksen muutokset aiheuttivat huolta ihmiskunnan mahdollisesti aiheuttamista muutoksista UV-säteilymäärissä. Tämän seurauksena useimmat UV-säteilyn mittausasemat ovat perustettuja juuri tähän aikaan 1990-luvun taitteessa. UV-säteilyn mittausaikasarjat ovat siis melko lyhyitä, ja ne pystyvät tyypillisesti kertomaan meille UV-säteilyn vaihteluista vain viimeisten noin 15 vuoden ajalta.

Tämän väitöskirjatyön tavoitteena oli tuottaa uutta tietoa UV-säteilyn vaihteluista menneisyydessä kehittämällä ns. UV-rekonstruointimenetelmiä, joissa hyödynnetään yleisiä meteorologisia mittauksia ja kokonaisotsonitietoa menneen ajan UV-säteilyn arvioimiseen. Tässä työssä kehitettiin kaksi UV-rekonstruointimenetelmää. Molemmissa lasketaan aluksi säteilynkuljetusmallilla pilvettömän sään UV-säteilymäärä. Pilvien vaikutus otetaan tämän jälkeen huomioon joko auringon paistehavaintojen tai pyranometrimittauksien perusteella. Lisäksi kumpikin menetelmä ottaa huomioon lumen aiheuttamat vaihtelut maan pinnan heijastuvuudessa. Ilmakehän pienhiukkaset ovat mukana laskuissa tyypillisenä määränä kullakin paikkakunnalla. Näitä kahta menetelmää käyttäen tuotettiin pitkiä aikasarjoja menneen ajan UV-säteilystä viidelle asemalle Euroopassa. Asemat olivat Sodankylä ja Jokioinen Suomessa, Bergen Norjassa, Norrköping Ruotsissa ja Davos Sveitsissä.

Kumpikin tässä työssä kehitetty menetelmä ottaa huomioon tärkeimmät UV-säteilymäärään vaikuttavat tekijät ja tulokset ovat hyviä verrattaessa riippumattomiin havaintoihin. Tämän vuoksi menetelmiä voidaan pitää luotettavina. Pyranometrimittauksiin perustuva menetelmä on tarkempi kuin paistehavaintoihin perustuva etenkin päiväkohtaisia arvoja verrattaessa. Kuitenkin paistehavaintoihin perustuva menetelmä on kuukausiarvoja tarkasteltaessa lähes yhtä tarkka kuin pyranometrimenetelmä, mikä tarkoittaa että paistemenetelmä on suurin piirtein yhtä hyvä kuin pyranometrimenetelmä arvioitaessa pidemmän aikavälin vaihteluita kuten esimerkiksi vuosi vuodelta tapahtuvaa vaihtelua.

Tässä työssä tuotetut pitkät UV-aikasarjat tuovat uutta tietoa UV-säteilyn ilmastollisesta käyttäytymisestä ja siitä kuinka UV-säteily on vaihdellut menneisyydessä. Esimerkiksi auringon paistehavaintoihin perustuvat aikasarjat ulottuvat vuoteen 1926 Davosissa ja vuoteen 1950 Sodankylässä. Näin ollen ne muodostavat myös uuden vertailukohdan viimeaikaisille muutoksille, joissa otsonikadolla on ollut merkitystä (noin 1980 alkaen). Davosissa UV-säteily on vaihdellut tuntuvasti koko tarkastelujaksolla 1926-2003. Korkeita arvoja oli 1940-luvun keskivaiheilla, 1960-luvun alussa ja 1990-luvulla. Lisäksi huomattiin, että pilvisyyden vaihtelut hallitsivat ennen vuotta 1980 tapahtuneita vaihteluita UV-säteilyssä. Toisaalta sekä pilvisyys että otsonin vähentyminen vaikuttivat jakson 1979-1999 aikana todettuun kasvuun UV-säteilyssä (4,5 %/vuosikymmen). Myös Sodankylässä ja Norrköpingissä UV-säteily on lisääntynyt 1980-luvun alusta (3-4 %/vuosikymmen). Näillä asemilla kasvun aiheutti ensisijaisesti pilvisyyden muutokset ja vähemmässä määrin otsonin vähentyminen. Jokioisissa ja Bergenissä UV-säteilyn muutokset olivat pieniä.

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Lisatietoja

PREFACE

The work presented in this thesis has been conducted during the period 2002–2007 at the Finnish Meteorological Institute (FMI). During this period a lot has happened. FMI's organization has changed and the institute has moved into a new building. I have had a new boss almost every year. In my civil life, I have moved three times, first from Helsinki to Borås in Sweden, where I stayed working at home and studying at Chalmers University of Technology for 1.5 years, then from Borås back to Helsinki, and now finally from Helsinki to Borgå (50 km east of Helsinki) where I live today.

In spite of all the changes, I have always had people around me to rely on. First of all, I express my immense thanks to my ex-girlfriend, Hanna, who is currently my wife; thanks for being there and for keeping my life alive, and filled with patterns throughout these years. I furthermore thank the people in the UV Radiation Research group at FMI for welcoming me as a member of the group, and for their guidance and support. In particular, I would like to mention Jussi Kaurola, my supervisor, for his encouragement and careful advice, and Tapani Koskela for an unforgettable sailing trip to Sweden in his magnificent 6mR yacht. Special thanks go to Antti Arola, currently at FMI's Kuopio Unit, for always having time to discuss with me; he has been as a second supervisor to me during this work and I hope our fruitful collaboration will continue in the future. Finally, I also want to acknowledge Petteri Taalas, who initiated this work by employing me and by coming up with the idea of reconstructing past UV radiation using sunshine duration measurements.

This work has been financially supported by the MUTUAL project of the Academy of Finland and the SCOUT-O3 EU project. I am indebted also to the COST Action 726 for providing an international forum for developing and discussing ideas. I wish also to thank my co-authors in the original publications included in this thesis. Especially, I express my gratitude to Weine Josefsson, who has always been eager to discuss with me whatever has been on my mind, and Laurent Vuilleumier, who was one of my closest scientific colleagues while working on the Davos paper. At that time, I was profoundly international: I lived in Borås, Sweden, worked with Swiss data from the Davos region, while employed by the Finnish Meteorological Institute.

When asked about when I will finish my thesis, which has been quite a common question during these years, my standard answer since almost three years ago has been *"roughly a year from now"* - and it has always been a completely honest, although somewhat optimistic answer. Now, when I finally dare to give a shorter time frame, *"within some months from now"*, I must admit that life feels good.

Borgå, August 2007
Anders Lindfors

P.S. I wish to thank also the preliminary examiners of this thesis, Berit Kjeldstad at the Norwegian University of Science and Technology, and Juhani Damski at FMI.

Contents

LIST OF ORIGINAL PUBLICATIONS

I Weatherhead, B., A. Tanskanen, A. Stevermer, S. Andersen, A. Arola, J. Austin, G. Bernhard, H. Browman, V. Fioletov, V. Grewe, J. Herman, W. Josefsson, A. Kylling, E. Kyrö, A. Lindfors, D. Shindell, P. Taalas, and D. Tarasick (2005): Ozone and Ultraviolet Radiation, Chap. 5 in *ACIA 2005, Arctic Climate Impact Assessment*, 151-182, Cambridge University Press.

II Lindfors, A. V., A. Arola, J. Kaurola, P. Taalas, and T. Svenøe (2003): Long-term erythemal UV doses at Sodankylä estimated using total ozone, sunshine duration, and snow depth, *J. Geophys. Res.*, **108**(D16), 4518, doi:10.1029/2002JD003325.

III Lindfors, A., and L. Vuilleumier (2005): Erythemal UV at Davos (Switzerland), 1926-2003, estimated using total ozone, sunshine duration, and snow depth, *J. Geophys. Res.*, **110**(D2), D02104, doi:10.1029/2004JD005231.

IV Lindfors, A., J. Kaurola, A. Arola, T. Koskela, K. Lakkala, W. Josefsson, J. A. Olseth, and B. Johnsen (2007): A method for reconstruction of past UV radiation based on radiative transfer modeling: applied to four stations in northern Europe, *J. Geophys. Res.*, accepted.

A. Lindfors is responsible for most of the work in PAPER II–IV. In PAPER I, he contributed by writing text about UV reconstruction methods and by giving comments on the UV part of the manuscript.

1 Introduction

Solar ultraviolet (UV) radiation has a broad range of effects concerning life on Earth. It influences not only human beings, but also plants and animals. It causes degradation of materials and is an important contributor to chemical processes in the atmosphere. A more detailed discussion about the different effects of UV radiation is given in UNEP (1998, 2003, 2007).

After the discovery of severe ozone depletion in Antarctica during the austral spring (Farman et al., 1985), it was soon recognized that the stratospheric ozone content was declining also in the Arctic and at mid-latitudes (WMO, 1989). Consequent concern about possible changes in the UV radiation climate due to anthropogenic activity lead the scientific community to put active efforts into UV radiation research. Many stations for monitoring of the surface UV irradiance were founded around 1990 (e.g., McKenzie et al., 1992; Zerefos et al., 1997; Gurney, 1998; Bartlett and Webb, 2000; Fioletov et al., 2002; Lakkala et al., 2003), thus providing valuable information on the variations in the UV radiation level since then (see WMO, 2007). Although some stations exist with measurements extending further back in time (e.g., Borkowski, 2000; Josefsson, 2006), there is an apparent lack of information on UV radiation in the past; in general, measurements cannot tell us how the UV radiation climate has changed due to the observed decline in total ozone, nor can they tell us about changes in the UV radiation that have occurred further in the past, on timescales of, for instance, several decades. It is, however, possible to estimate, or reconstruct, past UV radiation levels using commonly available, long-term meteorological data on parameters affecting the amount of UV radiation reaching Earth's surface. Moreover, it can be mentioned that also satellite-retrieved estimates of the surface UV irradiance, available from 1978 onward (e.g., Herman et al., 1996), can contribute in this area.

When this work started in 2002, some techniques for reconstructing past UV radiation were already available. Bordewijk et al. (1995), Bodeker and McKenzie (1996) and Kaurola et al. (2000), for instance, all used global radiation and total ozone column for reconstructing the surface UV irradiance, while Fioletov et al. (2001) used, additionally, dew point temperature and snow cover data. UV reconstruction techniques based on observations of sunshine duration were, however, not available at this time, although Eerme et al. (2002) and de La Casiniere et al. (2002) presented their methods soon after.

This thesis aims to improve our understanding of past variations in the surface UV irradiance by developing techniques for UV reconstruction, and by applying these techniques to produce long time series of reconstructed UV radiation at different stations. Two different techniques for UV reconstruction have been developed. Both are based on first calculating the clear-sky UV radiation using a radiative transfer model, given as input the measured total ozone column. The clear-sky value is then corrected for the effect of clouds based on either (i) sunshine duration or (ii) pyranometer measurements.

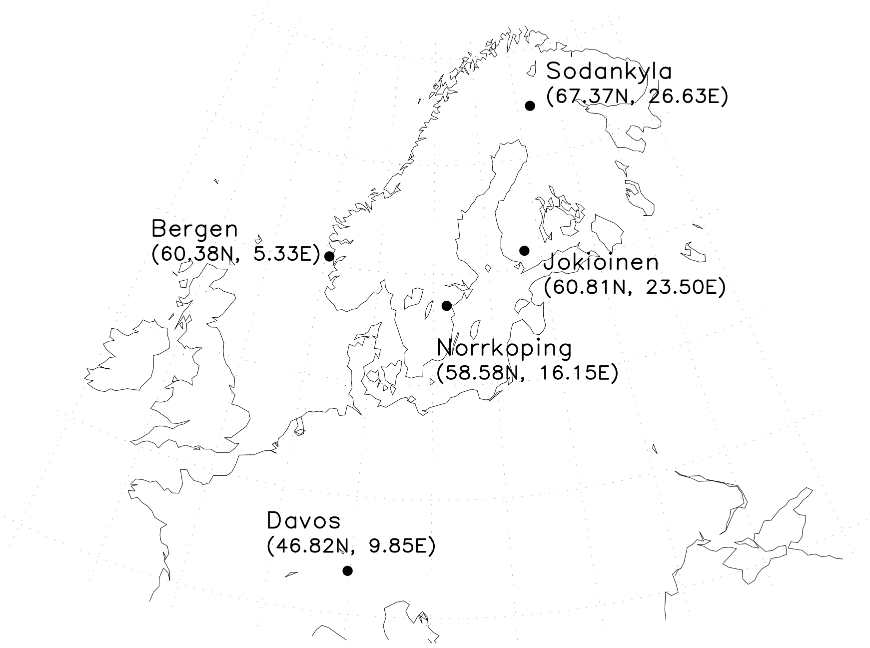

FIGURE 1.1. Map of the stations included in this thesis.

Both techniques account also for the variations in the surface albedo caused by snow, whereas aerosols are included only as a typical climatological aerosol load. Using these methods, long time series of reconstructed UV radiation have been produced for five European locations, namely Sodankylä and Jokioinen in Finland, Bergen in Norway, Norrköping in Sweden, and Davos in Switzerland (Figure 1.1).

This thesis consists of four original papers, that will be referred to by roman numerals (PAPER I–IV). The main contribution of PAPER I to the thesis is a discussion on the different factors affecting the surface UV irradiance. Understanding these factors is essential for all UV reconstruction work. Furthermore, PAPER I gives a general introduction to ozone and UV radiation science, and discusses some techniques for reconstruction of past UV radiation presented in the literature.

In PAPER II, a technique for reconstructing past UV radiation using total ozone, sunshine duration, and snow depth as input is presented. The paper includes both method development and validation. Furthermore, the homogeneity of the sunshine duration measurements used as input was assessed. The method was applied to Sodankylä, northern Finland. Using as input the long total ozone record of Tromsø, northern Norway, starting already in 1935 (Svenøe, 2000; Hansen and Svenøe, 2005), enabled UV estimates to be made over the period 1950–1999.

PAPER III continues the work started in PAPER II by adjusting the sunshine duration based UV reconstruction method to the local conditions of Davos. Davos is located in the eastern parts of the Swiss Alps, in a distinctly different environment compared to Sodankylä. The behavior of the method in these two different environments was compared, revealing clear differences between the cloud climate of northern Finland and Switzerland. Also in this study, the homogeneity of the sunshine duration data needed to be examined before a time series of nearly 80 years (1926–2003) of reconstructed UV radiation was produced. The world's longest ozone record, collected at the nearby station of Arosa (Staehelin et al., 1998), was used as input for this. Finally, PAPER III also demonstrates how UV reconstruction techniques can be used for evaluating how changes in other climate parameters, such as ozone, clouds, and surface albedo have contributed to the observed changes in UV radiation.

Paper IV, in turn, presents a method for reconstructing past UV radiation based on pyranometer measurements (global radiation, 300–3000 nm). The method relies strongly on radiative transfer calculations, which were used, for instance, for transferring the information contained in the pyranometer data into a cloud effect in the UV range. Using this method, past UV radiation was reconstructed back to the early 1980s at four stations in northern Europe: Bergen in Norway, Norrköping in Sweden, and Jokioinen and Sodankylä in Finland.

The structure of this thesis is as follows. In the next chapter, the theoretical basis of atmospheric radiation is introduced. Thereafter, Chapter 3 discusses the different factors affecting the surface UV irradiance, while Chapter 4 presents the main results of this thesis, that is, UV reconstruction techniques and reconstructed UV time series, including also a comparison between the performance of the two techniques developed in this thesis. Chapter 5, finally, concludes the thesis.

2 ATMOSPHERIC RADIATION

The electromagnetic radiation emitted by the Sun propagates virtually unaltered through space until it reaches the Earth's atmosphere, where it is attenuated due to a combination of absorption and scattering. For the atmospheric radiation field, also the scattering and absorption properties of the Earth's surface are important. In addition, at longer wavelengths (roughly at wavelengths larger than a few $\mu\mathrm{m}$) also emission of radiation by the atmosphere and surface should be accounted for. Absorption removes the energy of a photon completely from the radiation field, while scattering redirects the photon with essentially no loss of energy. Emission, in turn, can be considered the birth of a new photon as energy is converted into the form of electromagnetic radiation. It is emphasized, that absorption, scattering, and emission all are wavelength-dependent processes.

The radiation field and its propagation in the atmosphere can be described using the radiative transfer equation, which is a fairly complex integro-differential equation. Here, I will introduce the so called two-stream approximation, which serves as a good starting point for a more general understanding of radiative transfer in the atmosphere. Readers interested in a more in-depth understanding of the radiative transfer equation are referred to some of the available text books on atmospheric radiation (e.g., Liou, 2002; Lenoble, 1993; Thomas and Stamnes, 1999; Bohren and Clothiaux, 2006).

The complexity of the general radiative transfer equation arises because it includes all possible directions of propagation. Thus, it can be simplified by reducing the number of directions considered. In the two-stream approximation, the radiation field is simplified to the extent that only two directions (streams) are included, namely upward ($\mathrm{F}_\uparrow$) and downward ($\mathrm{F}_\downarrow$) propagating radiation. Also scattering can occur only in these two directions. Hence, the two-stream approximation takes the form (Bohren and Clothiaux, 2006):

$$\frac{\mathrm{dF}_\downarrow}{\mathrm{dz}} = -(\kappa+\beta)\mathrm{F}_\downarrow + \beta(\mathrm{p}_{\downarrow\downarrow}\mathrm{F}_\downarrow + \mathrm{p}_{\uparrow\downarrow}\mathrm{F}_\uparrow) \tag{2.1}$$

$$\frac{\mathrm{dF}_\uparrow}{\mathrm{dz}} = (\kappa+\beta)\mathrm{F}_\uparrow - \beta(\mathrm{p}_{\uparrow\uparrow}\mathrm{F}_\uparrow + \mathrm{p}_{\downarrow\uparrow}\mathrm{F}_\downarrow) \tag{2.2}$$

Here, z is the vertical coordinate, κ is the absorption and β the scattering coefficient, while p represents the scattering phase function, that is, the probability distribution of scattering into different directions. $\mathrm{p}_{\uparrow\downarrow}$, for instance, gives the probability that a photon propagating upward is scattered downward, given that scattering will occur. In these equations, the first term on the right hand side represents the different ways a photon can be removed from the direction of interest: it can be either absorbed, or scattered out of the beam. The second term represents the ways photons may be added to the direction of interest: both forward scattering of radiation propagating in the direction of interest, and backscattering of radiation propagating in the opposite direction contribute to this term. It is emphasized that thermal emission has been left out of these equations, because it is negligible at UV wavelengths in atmospheric conditions

(Bohren and Clothiaux, 2006). Moreover, the equations (2.1) and (2.2) are valid for monochromatic radiation, that is, radiation of a certain wavelength only. In practice, both the scattering and absorption coefficients as well as the scattering phase function vary with wavelength, which is something that need to be accounted for in order to have a realistic description of the atmospheric radiation field.

As shown in Bohren and Clothiaux (2006), the two-stream approximation can be generalized by increasing the amount of directions considered; the general radiative transfer equation is obtained when all possible directions of propagation are included.

A wide range of numerical solutions exist for solving the general radiative transfer equation. They are very useful tools for a broad range of various applications within UV radiation science. An example of an approximate and efficient solution is the two-stream method presented by Kylling et al. (1995). The Monte Carlo method (see Cahalan et al., 2005), in which one photon at a time is followed along its three-dimensional path, where the scattering and absorption events are defined by suitable probability distributions, is a conceptually straightforward method. The Monte Carlo method is, however, computationally demanding, and, furthermore, its added value is often limited due to inadequate knowledge of the three-dimensional distribution of relevant input parameters, for instance, clouds. The discrete ordinate method presented by Stamnes et al. (1988) is a solution of the radiative transfer equation which has gained great popularity due to its well-balanced accuracy and efficiency. This solution is valid for a vertically inhomogeneous, plane-parallel and one-dimensional atmosphere.

In this thesis, the freely available libRadtran radiative transfer package has been used, applying mostly a solver of the radiative transfer equation (disort2) that is based on the work by Stamnes et al. (1988). The libRadtran package has been described by Mayer and Kylling (2005) and it has been thoroughly validated against both measurements and other models. It has, for instance, been shown to accurately simulate the surface UV irradiance for well-defined clear-sky conditions, with known aerosol optical depth and total ozone column (Mayer et al., 1997). The libRadtran package is flexible, allowing the user to choose between different solvers of the radiative transfer equation, and to define the properties of the atmosphere and the surface in a detailed manner.

3 Factors affecting surface UV radiation

A thorough understanding of the different factors affecting the surface UV irradiance is an essential basis for all UV reconstruction work. This is evident from Paper IV, where the challenge of UV reconstruction was introduced as follows:

> *"The UV irradiance at Earth's surface is largely determined by the solar zenith angle, clouds, total ozone column, surface albedo, aerosols, Earth-Sun distance, and altitude or pressure. If all of these were accurately known, it would be fairly straightforward to simulate the UV irradiance at the surface using a radiative transfer model.*
>
> *Detailed information on the state of the atmosphere and the surface, that could be used as input for a radiative transfer model when simulating past UV radiation, is, however, rarely available. Nevertheless, long-term measurements of parameters that can be utilized do exist. Snow depth measurements, for instance, can be used as a proxy for the surface albedo, and measurements of global radiation can be used for estimating the optical properties of clouds (see, e.g., Barker et al., 1998). The challenge from a UV reconstruction point of view is to find the best way to use the limited information that is available."*

In Paper I (section 5.4), the different factors affecting surface UV radiation are discussed in detail. Although the paper concentrates on the Arctic, the conclusions are valid also more generally. In the following paragraphs, I provide a brief overview of the findings of Paper I regarding the factors affecting the surface UV irradiance, from solar activity to the altitude of the station.

The solar activity exhibits an anticorrelation with the surface UV irradiance. At first glance, this may be somewhat surprising since the extraterrestrial radiation, especially at short wavelengths, increases with solar activity. The increased extraterrestrial radiation, however, enhances the photochemical production of ozone in the stratosphere, which explains the decrease in surface UV irradiance during periods of high solar activity.

The solar zenith angle determines the path length of the direct radiation through the atmosphere and is the single most important factor for the surface UV irradiance. Less radiation reaches the surface in conditions of large solar zenith angles (low Sun) and vice versa.

The stratospheric ozone layer protects life on Earth from harmful UV radiation because ozone strongly absorbs UV radiation at wavelengths less than 320 nm. Thus, a decline in the total ozone column yields an increase in the surface UV irradiance.

Clouds affect UV radiation in a very similar way to the familiar attenuation of visible radiation, that is, by reflecting radiation back to space from the cloud top as well as by scattering (and very little absorption) taking place within the cloud. In general, clouds attenuate the surface UV irradiance compared to cloud free conditions. Occasionally, however, clouds can enhance the surface UV radiation: when the Sun is not obscured, broken clouds can act as reflecting surfaces increasing the amount of radiation reaching the surface.

Aerosols usually decrease the level of UV radiation reaching the surface, partly by scattering radiation back to space and partly by absorption. Both total extinction (i.e., aerosol optical depth) and single scattering albedo are important for the effect of aerosols on the surface UV radiation. The single scattering albedo is defined as the ratio between scattering and total extinction. Thus it is a measure of the relative importance of absorption: the lower the single scattering albedo, the more absorption takes place.

The UV surface albedo is generally low, being on the order of 0.05 for most surfaces. Surfaces covered by snow or ice, however, exhibit much higher surface albedos. A high surface albedo may enhance the UV level at the surface significantly due to multiple scattering between the surface and the atmosphere above.

The UV irradiance at the surface usually increases with increasing altitude. This is due to the fact that there is a thinner atmosphere above at high altitudes, and therefore less scattering and absorption taking place. Moreover, the tropospheric ozone is mostly located at low altitudes, which is also the case for other pollutants such as aerosols. At high altitudes there are also typically less clouds, or even clouds beneath acting as a reflecting surface with high albedo, thus increasing the UV irradiance compared to less elevated sites.

4 Main Results

Before going into the main results of this thesis, it is worthwhile to clarify the terminology. In Paper II and Paper III, the UV radiation of the past was *estimated*, whereas in Paper IV it was *reconstructed*. For consistency, I have chosen to use the term reconstruct throughout this thesis. It is worth noting also, that the relative UV radiation, as defined in Paper II and Paper III, is the same as the cloud modification factor of UV radiation used in Paper IV, and that both are used in this thesis. Finally, Paper II–IV all deal with erythemally weighted UV radiation (see Paper I, section 5.1, for details on the erythemal action spectrum).

4.1 Sunshine-based UV reconstruction

In Paper II a method was developed for reconstructing past UV radiation using total ozone, sunshine duration, and snow depth as input. This was done for the station of Sodankylä, northern Finland. Together with the papers by Eerme et al. (2002) and de La Casiniere et al. (2002), this was one of the first methods that utilized sunshine duration data for UV reconstruction purposes. Since sunshine duration measurements are available already from the early 20th century onward, at some locations even since the late 19th century (Hameed and Pittalwala, 1989), these sunshine-based methods enable reconstruction of past UV radiation several decades back in time. In general, the length of the reconstructed UV time series of sunshine-based methods is limited by the availability of historical records of total ozone.

In Paper II, the UV radiation at Sodankylä was reconstructed for the period 1950–1999. Paper III continued this work by applying the method to the local conditions of Davos, Switzerland, where the UV radiation was reconstructed back to 1926.

The idea of the sunshine-based UV reconstruction method arised from some results presented by Josefsson and Landelius (2000). They showed that a systematic relationship exists between hourly values of UV radiation and sunshine duration. As shown in Paper II, a similar relationship exists also for daily values, and this can be utilized for reconstructing past UV doses.

Figure 4.1 shows the general relationship between daily values of relative sunshine duration ($\mathrm{SD_{rel}}$) and relative erythemal UV dose ($\mathrm{UV_{rel}}$) at Sodankylä. This figure was produced using data from Paper II. Here, the relative sunshine duration and relative UV dose, respectively, are defined as:

$$\mathrm{SD_{rel}} = \mathrm{SD_{obs}}/\mathrm{SD_{max}} \quad \mathrm{UV_{rel}} = \mathrm{UV_{obs}}/\mathrm{UV_{clear}} \tag{4.1}$$

where $\mathrm{SD_{obs}}$ and $\mathrm{UV_{obs}}$ are the observed sunshine duration and UV radiation, respectively. The maximum possible sunshine duration, $\mathrm{SD_{max}}$, and the clear-sky UV radiation, $\mathrm{UV_{clear}}$, respectively, are the sunshine duration and UV radiation that would be observed during a perfectly cloud-free day, with otherwise the same conditions. In both

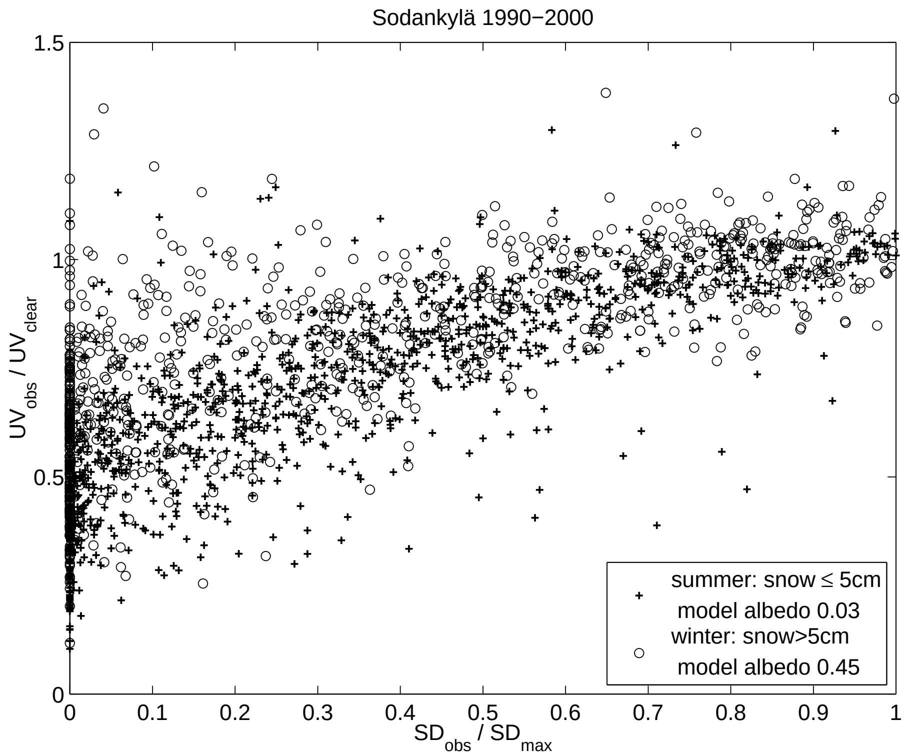

FIGURE 4.1. Daily relative sunshine duration versus relative UV dose at Sodankylä over the period 1990–2000. The data has been divided into winter and summer days as described in the text.

PAPER II and PAPER III, $\mathrm{UV_{clear}}$ was simulated using the libRadtran radiative transfer package, given as input the total ozone column and the surface albedo. Aerosols were also included in the calculations, but because of lack of good data on past variations in the aerosol loading, it was in the calculations held at a constant level representative for each location. In PAPER II, $\mathrm{SD_{max}}$ was defined as the time during which the Sun is above the horizon (solar zenith angle smaller than 90 degrees), whereas in PAPER III, $\mathrm{SD_{max}}$ was determined on an empirical basis, which is more suitable for mountainous regions (see also Figure 4.3).

In order to account for the varying surface albedo, which is highly dependent on the presence of a snow cover (e.g., Blumthaler and Ambach, 1988; Kylling et al., 2000), the data in Figure 4.1 were divided into two groups, namely winter and summer. All days with a snow depth exceeding 5 cm were chosen to belong to the winter group, while days having a snow depth less than or equal to 5 cm belong to the summer group. The clear-sky UV radiation was, as mentioned above, simulated with a radiative transfer model. The model albedo was set to 0.45 for the winter days and to 0.03 for the summer days. It is seen from the figure that there indeed is a systematic relationship between the relative UV dose and the relative sunshine duration. Although there is a considerable amount of scatter, most points are confined to a certain band. As shown in detail in

PAPER II and PAPER III, this systematic relationship can be utilized for reconstructing past UV doses.

Figure 4.1 furthermore shows that there is a difference in the behavior of the sunshine-UV relationship between winter and summer. The winter points in general have a higher relative UV dose than the summer points, especially for $\mathrm{SD_{rel}} < 0.4$. As noted in PAPER II, this difference arises because of variations that occur in the surface albedo and in the typical cloud properties throughout the year. In PAPER III, where the sunshine-UV relationship found for Davos was compared to that found for Sodankylä, this issue was further scrutinized. It was found that both the climatological cloud properties, with a smaller cloud optical depth in winter than in summer, and the albedo, which is high in winter, contribute to the seasonal behavior in the sunshine-UV relationship. Furthermore, it was found that although there is a clear similarity between the sunshine-UV relationship at Davos and Sodankylä, a generalization of the method would probably have to be confined to a region with a fairly homogeneous cloud climate.

In order to account for the seasonal behavior in the sunshine-UV relationship, the data were divided into several groups depending on snow depth and time of year in both PAPER II and PAPER III. At Sodankylä (PAPER II), where the winter months November–February were left out of the analysis because of very low UV radiation levels, the data were divided into four separate groups, namely Winter, May, Summer, and Autumn. Here, May was treated as a separate group because both the surface albedo (snow melts) and the mean cloud properties (first cumulus clouds appear) change during this time of the year. At Davos (PAPER III), the variations in the surface albedo are extensive, with values extending from 0.70 in the winter to 0.05 for a short period during the summer. Furthermore, the whole year was included in the analysis there. Thus, it was necessary to divide the data of Davos into six separate groups (namely Deep Winter, Winter, Early Spring, Late Spring, Summer and Autumn) when setting up the sunshine-based UV reconstruction method.

In both papers, a stepwise linear fit describing the relationship between relative sunshine duration and relative UV was set up for each group. Figure 4.2 shows, as an example, the data points and the fit for the Summer group of Davos. Using such fits, the UV radiation of the past can be reconstructed according to:

$$\mathrm{UV_{reco}} = \mathrm{UV_{clear}} \cdot \mathrm{UV_{rel}}(\mathrm{SD_{rel}}) = \mathrm{UV_{clear}} \cdot \mathrm{CMF_{UV}}(\mathrm{SD_{rel}}) \qquad (4.2)$$

where $\mathrm{UV_{reco}}$ is the reconstructed daily UV dose. As noted above, the relative UV radiation ($\mathrm{UV_{rel}}$) is, in fact, the same as the more well-known term, the cloud modification factor of UV radiation ($\mathrm{CMF_{UV}}$; see also PAPER IV).

Finally, it is worth mentioning that both in PAPER II and PAPER III efforts were made to assess the quality and the homogeneity of the sunshine duration measurements used as input for reconstructing past UV radiation. These measurements have mostly been made using the Campbell-Stokes, glass sphere type of sunshine recorders, which are known to have some problems such as overestimation of the sunshine duration

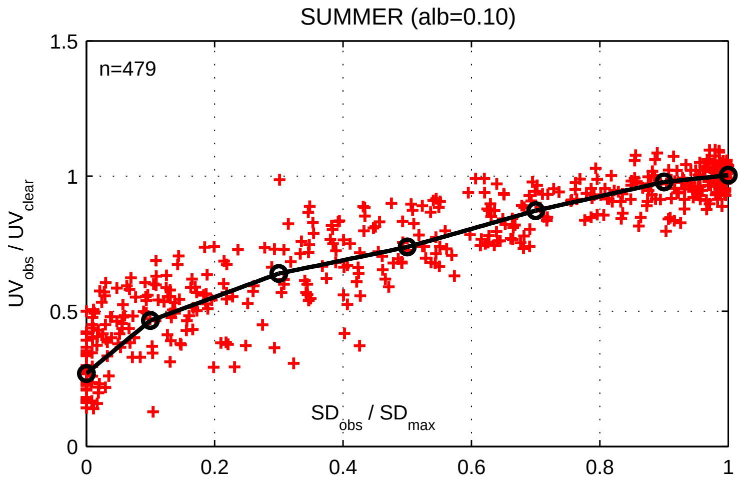

FIGURE 4.2. Daily relative sunshine duration versus relative UV dose and the stepwise linear fit for the summer group at Davos; n gives the number of days included in the group (extracted from Figure 4 in PAPER III).

during intermittent, strong sunshine under broken clouds (e.g., Painter, 1981; WMO, 1996). In PAPER II, however, the Campbell-Stokes sunshine duration data were compared to measurements with a modern, electronic sunshine recorder, with the conclusion that there are no considerable systematic errors introduced by the Campbell-Stokes recorder and that the data is homogeneous enough for the purposes of the study. It was emphasized that the long-term stability of the measurements is good; the instrument is robust and the method for measuring sunshine duration has remained the same throughout the years.

In PAPER III, it was clear from the start that the sunshine duration record as such cannot be considered homogeneous, because of the fact that the measurement site was moved two times in the past. It was found, however, that if the maximum possible sunshine duration is determined empirically, it will reflect systematic changes in the measurement time series, such as changes in instrumentation or location. This means that the relative sunshine duration calculated on the basis of an empirically determined maximum possible sunshine duration will be fairly homogeneous; one can remove systematic differences between different periods by using an empirical maximum sunshine duration that changes with time according to the characteristics seen in the data itself. Thus, also PAPER III concluded that the sunshine duration data can be used for UV reconstruction purposes. Figure 4.3 shows, as an example, the sunshine duration and the corresponding empirical maximum sunshine duration for the three different periods found in the Davos data.

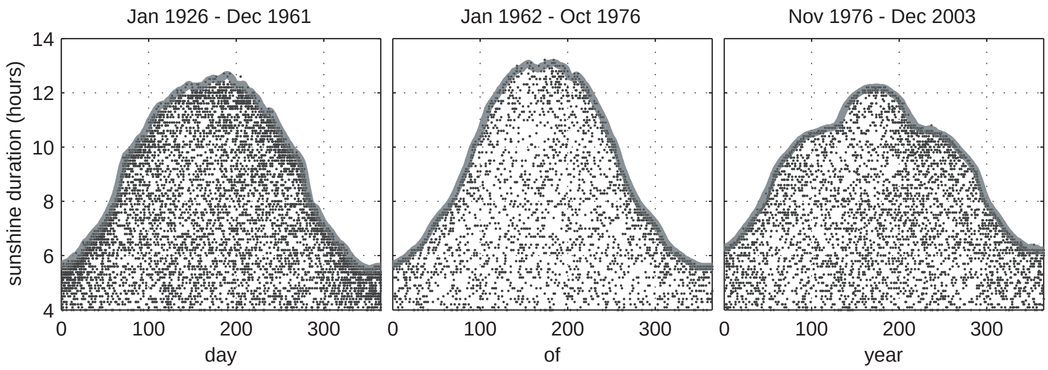

FIGURE 4.3. Measured sunshine duration (points) and empirically determined maximum possible sunshine duration (thick lines) at Davos. The data were divided into three different, internally homogeneous periods (from PAPER III)

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4.2 PYRANOMETER-BASED UV RECONSTRUCTION

Pyranometer measurements of global radiation (300–3000 nm) contain valuable and accurate information about the influence of clouds on the amount of solar radiation reaching the Earth's surface. In PAPER IV, a pyranometer-based UV reconstruction method was developed. This method is similar to the sunshine-based method in that the reconstructed UV radiation ($\mathrm{UV_{reco}}$) is obtained by first simulating the clear-sky UV radiation ($\mathrm{UV_{clear}}$) using the libRadtran radiative transfer package, and then correcting this clear-sky value for the effect of clouds according to:

$$\mathrm{UV_{reco}} = \mathrm{UV_{clear}} \cdot \mathrm{CMF_{UV}}(\mathrm{CMF_G}, \mathrm{SZA}) \tag{4.3}$$

This equation is in principal the same as eq. (4.2). The only difference is that the cloud modification factor of UV radiation ($\mathrm{CMF_{UV}}$) is here determined on the basis of the cloud modification factor of global radiation ($\mathrm{CMF_G}$), and the solar zenith angle (SZA), as described more in detail below.

The idea of PAPER IV was to develop a method that is theoretically sound, and independent in the sense that it should not rely on empirical relationships for determining the cloud effect. Furthermore, the aim was that the method should be general so that it can be applied to a broad range of different locations. In order to achieve these goals, the method was based on the theory of radiative transfer. In practice, the libRadtran package was used as a tool helping to interpret this theory.

In order to transfer the cloud information contained in the global radiation measurements (i.e., pyranometer data) into a cloud effect in the UV range, a so-called cloud modification table was developed. This cloud modification table was based on radiative transfer calculations with the libRadtran package, as described in PAPER IV: *"By simulating the cloudy atmosphere with varying cloud optical depth and solar zenith angle, we produced a look-up-table that describes the dependence between UV and* *global radiation in terms of the cloud modification factor.*" This means that the cloud modification table gives $\mathrm{CMF_{UV}}$ as a function of $\mathrm{CMF_G}$ and SZA, as indicated in equation (4.3).

Figure 4.4 shows the dependence of $\mathrm{CMF_{UV}}$ on $\mathrm{CMF_G}$ according to the cloud modification table for some selected solar zenith angles. It is seen that $\mathrm{CMF_{UV}}$ always is larger than $\mathrm{CMF_G}$ and that the magnitude of the difference depends on the solar zenith angle. These interesting features are not straightforward to understand in detail, although the analysis presented in PAPER IV suggests that the fundamental reason for these features is the strong Rayleigh scattering of photons in the UV range. Simplifying somewhat, $\mathrm{CMF_{UV}}$ is larger than $\mathrm{CMF_G}$ because of more effective trapping of photons in the UV range between the cloud top and the atmosphere above, as discussed by Kylling et al. (1997). To explain the solar zenith angle dependence of the relationship between $\mathrm{CMF_{UV}}$ and $\mathrm{CMF_G}$, however, also the directional distribution of the radiation incident at the cloud top, and its dependence on wavelength, need to be considered (see also Bernhard et al., 2004).

The approach used in PAPER IV, utilizing radiative transfer modeling to describe the relationship between the cloud-induced reduction in global radiation and that in UV radiation, inherits from the work by Kaurola et al. (2004), who developed a method for

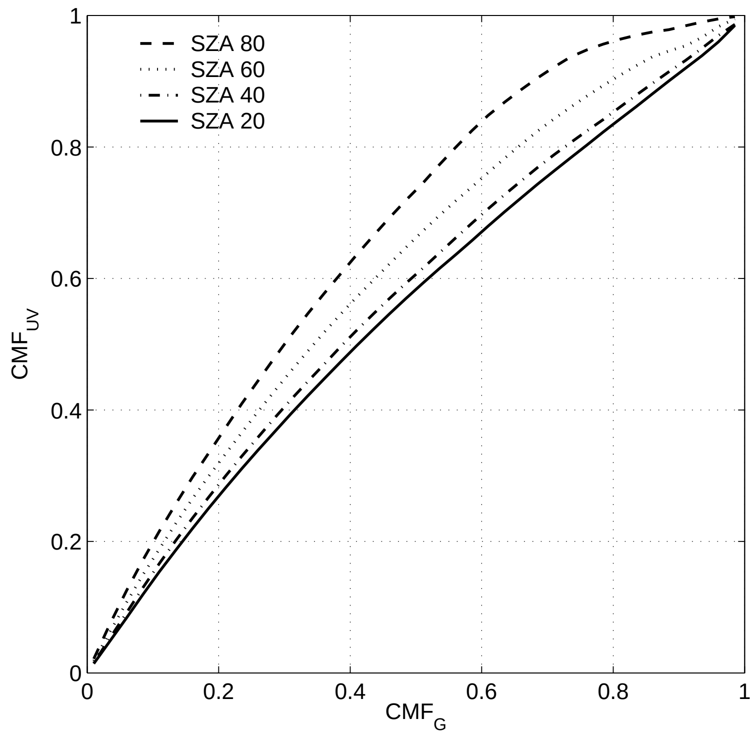

FIGURE 4.4. The dependence of $\mathrm{CMF_{UV}}$ on $\mathrm{CMF_G}$ at selected solar zenith angles according to the cloud modification table of the pyranometer-based UV reconstruction method (from PAPER IV).

deriving UV estimates from coupled chemistry-climate model results. The approach has, however, not been used for reconstructing past UV radiation from actual measurements before. In most pyranometer-based UV reconstruction methods presented in the literature, this transfer of information from global radiation into the UV range has been determined empirically (e.g. Bodeker and McKenzie, 1996; Kaurola et al., 2000; Fioletov et al., 2001; den Outer et al., 2005).

In PAPER IV, efforts were made to set up the radiative transfer model as accurately as possible when simulating the clear-sky irradiances. Both the UV irradiance and the global irradiance were simulated. The clear-sky UV irradiance was needed for calculating the reconstructed UV (eq. 4.3), while the global irradiance was needed for determining $\mathrm{CMF_G}$, which, in turn, was used for retrieving $\mathrm{CMF_{UV}}$ from the cloud modification table.

When simulating the clear-sky irradiances, the model was given as daily input the total ozone column, the total water vapor column (because water vapor absorbs radiation in the near-infrared), and the altitude of the station. In addition, the surface albedo, with one value for the UV albedo and one for the global albedo, was estimated on the basis of snow depth measurements, following an algorithm presented by Arola et al. (2003). Finally, the aerosol loading of the atmosphere was set up to follow a typical climatological annual cycle at the station of interest. Thus, no day to day or year to year variations were included for the aerosols. Since the global radiation data given as input to the method were available on an hourly basis, also the radiation calculations were performed with a time step of one hour.

The method was in PAPER IV applied to four stations in northern Europe: Bergen in Norway, Norrköping in Sweden, and Jokioinen and Sodankylä in Finland. At all these stations, the erythemal UV radiation was reconstructed from the early 1980s up to year 2005.

4.3 PERFORMANCE OF THE METHODS

The performance of the two methods has been thoroughly assessed in PAPER II–IV. The general conclusion was that both methods perform well. The sunshine-based method typically shows a root-mean-square error of 20–25% when comparing daily reconstructed UV doses with measurements. For the monthly doses, the performance is much better, with a root-mean-square error of 4–7%. The pyranometer-based method performs better, especially on the day to day scale, where the root-mean-square error compared to measurements mostly is less than 10%. Both methods showed mostly small systematic errors, typically a few percents, although it should be mentioned that the pyranometer-based method has an underestimation problem under conditions of very low Sun. Most of this underestimation problem was found to be due to the plane-parallel approximation used in the radiative transfer calculations (PAPER IV).

The duration of bright sunshine for a given period is defined as the sum of that sub-period for which the direct solar irradiance exceeds $120\mathrm{W/m}^2$ (WMO, 1982, see also PAPER II). Thus, daily values of sunshine duration, used as input in PAPER II and PAPER III, contain only rough information about the prevailing cloud conditions; the daily sunshine duration only gives the integrated time during which the Sun has not been obscured by clouds (roughly), it does not, for instance, give any information on the cloud optical depth or the type of cloud. Pyranometer measurements, on the other hand, contain quite detailed information on the influence of clouds on radiation. When furthermore considering that PAPER IV used hourly values of global radiation as input, which better capture the cloud variations within a day, the pyranometer-based UV reconstruction method is expected to be more accurate than the sunshine-based method, in line with the results discussed above.

It is still interesting to compare somewhat more in detail the performance of the two methods. Since both methods have been used for reconstructing the UV radiation at Sodankylä, it is convenient to compare their performance there. In order to make the results comparable to each other, I produced a new record of sunshine-based reconstructed UV for Sodankylä, where the method was given as input the local total ozone column instead of the ozone column of Tromsø, that was used in PAPER II. Figure 4.5 shows the distribution of the UV doses reconstructed with each method as compared to measurements. For the daily doses, the pyranometer-based method performs clearly better than the sunshine-based; more than 80% of the pyranometer-based daily UV doses are found within $\pm 10\%$ of the measured ones, whereas the corresponding figure for the sunshine-based method is roughly 60%. For the monthly doses, on the other hand, the difference between the performance of the two methods is not that distinct; although the pyranometer-based method is better at the $\pm 5\%$ accuracy level, both meth-

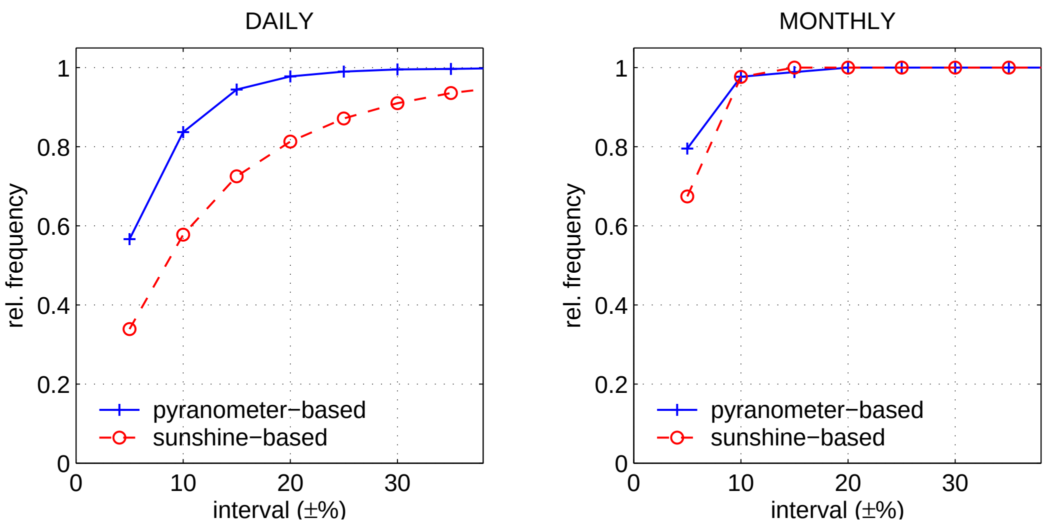

FIGURE 4.5. Distribution of reconstructed UV in comparison to measurements, shown as the number of data points (relative frequency) found within the given interval (e.g., $\pm 10\%$) around the measured values.

ods have 97-98% of the monthly values within $\pm 10\%$ from the measured values. This indicates that the sunshine-based method is roughly as good as the pyranometer-based method for assessing long-term changes in the surface UV radiation, with the caveat of assuming that the typical optical properties of clouds do not change significantly over the period of interest (see PAPER III for more discussion on how changes in the cloud properties may influence the sunshine-based UV reconstruction method).

4.4 TIME SERIES OF RECONSTRUCTED UV

The following time series of reconstructed UV radiation were produced in this thesis: Davos 1926–2003 (sunshine-based), Bergen 1982–2005 (pyranometer-based), Norrköping 1983–2005 (pyranometer-based), Jokioinen 1981–2005 (pyranometer-based), and Sodankylä 1950–1999 (sunshine based) and 1981–2005 (pyranometer-based). These time series have been presented and analyzed in PAPER II–IV.

In general, the reconstructed UV time series show small increasing trends since around 1980. These increases have been driven by decreasing cloudiness, and by the diminution of stratospheric ozone. At Sodankylä over the period 1983–2005 (PAPER IV), for instance, a trend of 1.3%/decade was found for the clear-sky UV radiation, reflecting changes in the total ozone column, while the global radiation, reflecting changes in the cloudiness, showed a trend of 3.8%/decade. For the reconstructed UV radiation, in turn, a statistically significant increasing trend of 4.1%/decade was found. It is emphasized (see also PAPER III), that linear trends such as these should be interpreted with caution since they only reflect the chosen time window, and, in addition, simplify the temporal behavior within this time window into only two figures, namely the trend and its uncertainty estimate.

Figure 4.6 shows as an example the reconstructed UV time series of Davos 1926–2003. Covering almost 80 years, this is the world's longest time series of reconstructed UV including the effect of ozone variations. Junk et al. (2007) managed to go even further, back to 1893, but their calculations did not include total ozone measurements for the period prior to 1964. This figure clearly demonstrates the value of long time series of reconstructed UV; such time series are crucial for our understanding of the past UV radiation climate, and also put the recent changes driven by the ozone decline observed over the last few decades into perspective. The figure shows that the UV radiation at Davos has varied considerably since 1926. High values were present in the mid-1940s, in the early 1960s, and in the 1990s. For the year-round UV doses, a statistically significant (at the 95% level; Student's t-test) increasing trend of 4.5%/decade was found over the period 1979–1999, while the trend over the period 1961–1981 was decreasing by -5.0%/decade, likewise statistically significant (PAPER III).

The lower part of Figure 4.6 shows how the different input parameters have contributed to the changes in the reconstructed UV radiation. The time series of the lower part of the figure were produced letting only one parameter at a time vary as observed,

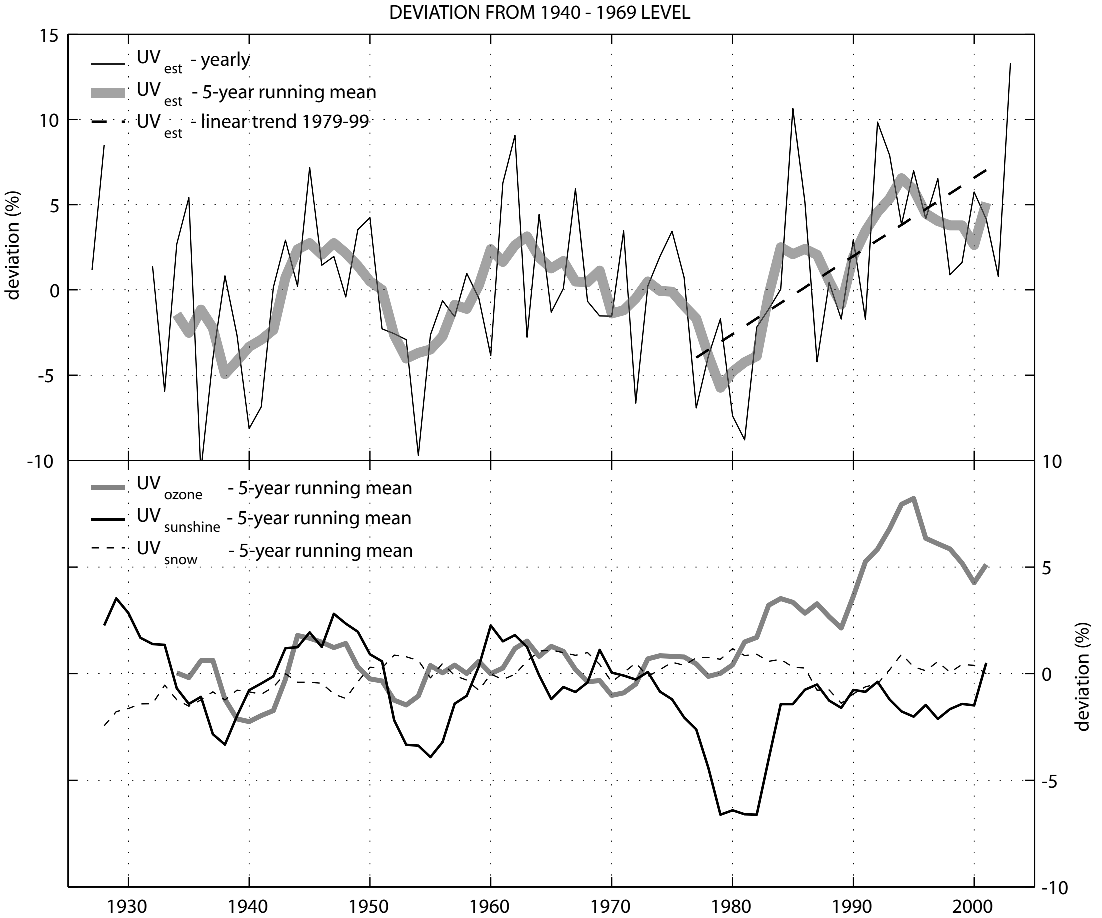

FIGURE 4.6. Time series of reconstructed UV at Davos 1926–2003, shown as deviation from the 1940–1969 mean level: (upper panel) UV reconstructed using all available input data, and (lower panel) the contribution of each input parameter to the UV variations seen in the upper panel (see text for details; from PAPER III).

while keeping the other ones at their climatological values. Thus, UV_{ozone}, for instance, shows how the UV radiation would have varied if the total ozone column were the only input parameter to vary with time. The UV variation prior to 1980 have predominantly been driven by variations in the sunshine duration (i.e., cloudiness), whereas the increase since around 1980 has been supported by changes both in the ozone column and in the sunshine duration.

The sunshine-based reconstructed UV radiation at Sodankylä (PAPER II) requires some additional attention. As pointed out by Engelsen et al. (2004), PAPER II used as input an early version of Tromsø's total ozone record, and the record has to some parts been adjusted since then (see also Hansen and Svenøe, 2005). Therefore, I recalculated the sunshine-based UV radiation at Sodankylä using as input a merged total ozone data set based on the updated version of Tromsø's ozone record, the ozone record of Murmansk, north-western Russia, and local ozone measurements at Sodankylä (details of the merged ozone record are described in Lindfors et al., 2006). Table 4.1 presents the trends of this revised version of the reconstructed UV at Sodankylä (replacing Table 5 in PAPER II). Although some changes appear for the individual months, the general conclusion of PAPER II does not change: the spring months, March–May, still show slightly increasing trends over the period 1950–1999, and, in particular, both March and April still exhibit a more pronounced trend during the latter part of the period (1979–99). Thus, also the revised series of reconstructed UV suggests a connection to the stratospheric ozone depletion which started around the year 1980 and is, at the latitude of Sodankylä, most pronounced during the spring months (Solomon, 1999). Perhaps the most notable change in the revised trends is seen for July, where the trend over the period 1950–1999 has changed from being negative and statistically significant to being slightly positive. In the revised UV series, the months June–September all show negligible trends over the period 1950–1999, although July features a decreasing trend of 5.3%/decade and September an increasing trend of 6.3%/decade over the period 1979–1999 (neither being statistically significant).

As mentioned in section 4.3, Sodankylä is interesting in that both the sunshine-based and the pyranometer-based methods have been used for reconstructing the UV radiation there. Figure 4.7 shows three different UV time series for Sodankylä, extending back to 1990 (measurements), 1981 (pyranometer-based reconstruction) and 1951 (sunshine-based reconstruction; due to part of year 1950 lacking data, it was left out of the figure). Although the pyranometer-based reconstruction is more accurate for daily values, the yearly values are reconstructed with roughly the same accuracy using the sunshine-based method. The discrepancy between the different time series (e.g., in 1998) is partly due to days missing data in the measurements (see also PAPER IV).

Table 4.1 Trends in percent per decade for the monthly mean values of the reconstructed UV doses at Sodankylä, updated from PAPER II as described in the text. The 95% error estimates of the derived trends are shown in the parentheses and the statistically significant (at the 95% confidence level; Student's t-test) trends are indicated by bold font.

month	period		
	1950–99	1950–72	1979–99
March	1.5 (2.6)	1.0 (9.6)	9.6 (9.8)
April	**3.1 (1.6)**	0.4 (4.4)	4.5 (6.8)
May	2.3 (2.4)	4.3 (7.5)	0.8 (9.4)
June	0.9 (2.3)	4.4 (7.2)	1.7 (10.3)
July	-0.2 (2.1)	-0.7 (7.1)	-5.3 (8.6)
August	0.8 (2.4)	-0.5 (8.8)	1.2 (9.6)
September	0.9 (2.3)	3.6 (8.0)	6.3 (9.0)

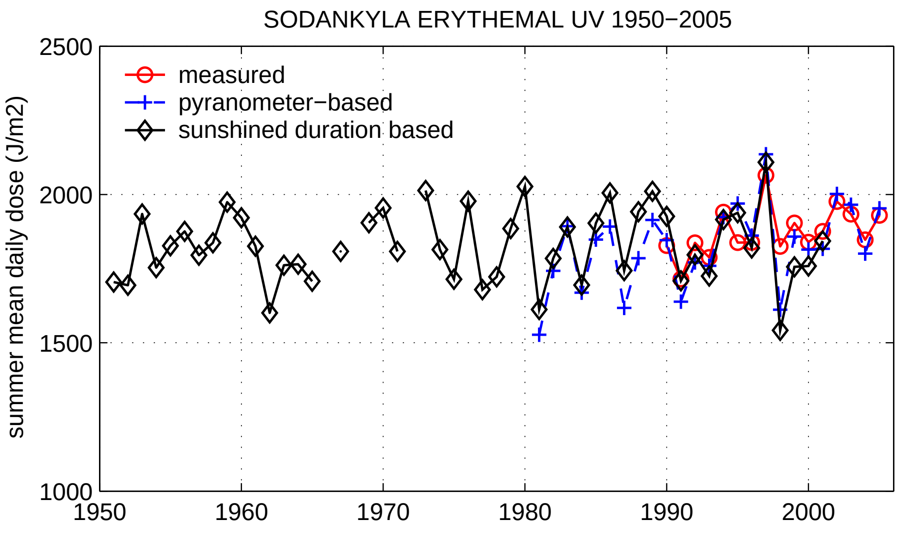

FIGURE 4.7. Sunshine-based, pyranometer-based, and measured UV radiation at Sodankylä shown as mean values of the daily doses during the summer period (June–August).

5 DISCUSSION

In this thesis, two methods for reconstruction of past UV radiation have been developed and discussed. One is based on the use of sunshine duration measurements for accounting for the cloud effect, while the other uses pyranometer measurements. Using these methods, long time series of reconstructed UV radiation have been produced for five European stations. Extending several decades back in time, these time series give new insight into the past UV radiation climate and how the UV radiation has varied throughout the years. Especially the sunshine-based UV time series, extending back to 1950 and 1926 at Sodankylä and Davos, respectively, also put the recent changes driven by the ozone decline observed over the last few decades into perspective. Such time series are also expected to raise interest within the UV impact research community, studying, for instance, the biological effects of UV radiation.

It is emphasized, that both in PAPER II and PAPER III considerable efforts were put into understanding the sunshine duration measurements, and assessing their reliability. Both papers concluded that the old sunshine duration data is fairly homogeneous, and that it can be used for UV reconstruction purposes.

Both UV reconstruction methods presented in this thesis account for the greater part of the factors affecting the amount of UV radiation reaching the Earth's surface. Thus, they are considered reliable and trustworthy, as suggested also by the good performance of the methods. It should be noted, however, that they include aerosols only as a typical climatological aerosol load that does not change from year to year or day to day. This shortcoming, which is due to lack of good data on the aerosol variations in the past (see also PAPER IV), is not that serious at rural locations such as those included in this thesis, where the aerosol load is mostly low. It is emphasized that aerosol information, if only available, could be easily included when simulating clear-sky UV radiation. Without this information, however, it is expected that the methods would show somewhat larger scatter when applied to more polluted sites. In the future, the treatment of aerosols in these methods could perhaps be improved. As discussed in PAPER IV, for instance, the pyranometer measurements do contain information about the aerosol conditions. If this information only could be distinguished from the influence of clouds, it would probably be possible to include a more detailed description for the aerosols in the pyranometer-based method.

The sunshine-based method relies on an empirical relationship between the relative sunshine duration and the relative UV. Both the cloud climate and the surface albedo affect this relationship. In order to account for this, the data was divided into different groups depending on snow depth and time of year when setting up the sunshine-UV relationship. This is also where the method developed in this thesis differs most distinctly from other sunshine-based methods: neither Eerme et al. (2002) nor de La Casiniere et al. (2002) included the influence of a varying surface albedo or varying (typical) cloud optical depth. As shown in PAPER III, the sunshine-based method shows clear similarities between Sodankylä and Davos. Still, it was concluded that a possible generalization of the method would probably need to be confined to a region with fairly homogeneous cloud climate, and preferably without strong variations in the albedo.

The pyranometer-based method, on the other hand, is independent in the sense that it does not rely on empirical relationships for determining the cloud effect. While in most pyranometer-based UV reconstruction methods presented in the literature (e.g., Bodeker and McKenzie, 1996; Kaurola et al., 2000; Fioletov et al., 2001; den Outer et al., 2005) the cloud information contained in the pyranometer data is transferred into a cloud effect in the UV range based on empirical relations found, for instance, by correlating the cloud-induced reduction in global radiation to that in the UV, the method developed in this thesis takes a different approach. Here, this transfer of information between the two wavelength regimes is based on physical relationships determined through radiative transfer calculations. Therefore, the pyranometer-based method is expected to be general, not dependent on the location that it is applied to. Indeed, the method has been successfully tested also at some stations in middle and southern Europe (Koepke et al., 2006).

In this thesis, both methods were used for reconstructing erythemally weighted UV radiation only, although they could both be adjusted to reconstruct UV radiation weighted by other action spectra as well. More importantly, however, the pyranometer-based method can also be extended to reconstruct the whole UV spectrum, as discussed more in detail in PAPER IV. This would allow applying any action spectrum to the reconstructed UV, thus adding the opportunity to study more in detail various effects of UV radiation. This is an interesting possibility that will be investigated more in the future.

Finally, it is emphasized that although accurate and reliable UV reconstruction methods are available, time series of reconstructed UV radiation cannot replace real UV measurements; measurements are always the primary source of information on the surface UV radiation. Thus, it is very important to continue to maintain reliable UV measurements at various locations. Here, UV reconstruction methods can contribute, however, since they constitute useful tools for quality control of measurements, as pointed out in PAPER IV.

To conclude, I would like to provide a brief personal reflection on the less explicit results of this thesis. As pointed out in Chapter 2, the foundation of all UV reconstruction work lies in a good knowledge of the factors affecting surface UV radiation. Indeed, I have while working on this thesis learned a lot, not only about factors affecting UV, but also about radiative transfer in the atmosphere and radiative transfer modeling. I believe this knowledge will be useful in my future work, as long as stay within the atmospheric sciences.

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