We thank the reviewer for his/her analytical comments that helped us to improve the manuscript. Replies to the reviewer's comments are provided below. Line numbers refer to the version with track changes.

GENERAL COMMENTS

The manuscript by Fountoulakis et al. presents the results of a modelling system for estimating the UV Index at the surface (UVIOS2) during an international comparison campaign of broadband UV radiometers in Davos. The system is described, and the results are illustrated for both (i) clear-sky days and (ii) all-sky conditions. The factors influencing the comparison are discussed.

In my opinion, the research topic is important and within the scope of the journal, and the results are in good agreement with the reference instrument. However, the description of the methodology and the presentation of the results could be improved. Hence, I recommend publication after the authors address the issues outlined below.

SPECIFIC COMMENTS

- **The study evaluates the performance of the UVIOS2 system during a summer campaign (June–August). The authors should be cautious not to extrapolate these results to seasons when snow is present near the measurement area, as surface albedo determination and the estimation of cloud properties from satellite data could be problematic. Additionally, at higher altitudes and latitudes, snow or ice may persist even in summer. A discussion on this topic would be beneficial.**

Reply

Discussion about the role of surface albedo has been also provided in the introduction. The following lines have been added (103-107):

"In general, the change in the levels of the solar UV irradiance with altitude depends on atmospheric composition and has a strong wavelength dependence which is introducing difficulties in the modelling of the UVI at mountainous sites (e.g, (Dvorkin and Steinberger, 1999; Krotkov et al., 1998)). At very high altitude (or/and latitude) sites ice and/or snow may persist even in late spring and summer resulting in extremely high UV exposure for skiers or other visitors (e.g., (Schmalwieser et al., 2017b; Siani et al., 2008; Utrillas et al., 2016))."

In lines 143-144 at the introduction, we also added the following:

"It must be clarified that the study refers to a snow-free period at Davos, and thus the uncertainties related to the parameterization of surface albedo, which may be significant for higher altitude sites even in the summer, are not quantified or discussed here."

To further clarify what we mean with "Further investigation is needed to assess the uncertainties due to the cloud effect parameterization over higher albedo terrains, although we expect that the assumption of homogeneity in the satellite pixel would still be the main uncertainty factor"

A brief reference is given in lines 423–424 ("we expect that the assumption of homogeneity in the satellite pixel would still be the main uncertainty factor"), but the basis for this expectation is unclear.

Reply

We added at the end of the sentence (line 537):

"(e.g., large gradients in cloudiness, aerosol properties, surface albedo, surface altitude)."

Could the authors provide a bibliographic reference? Moreover, depending on the SEVIRI channel used for retrieving the COT, is there sufficient contrast between snow and clouds?

Reply

Since we do not refer to snow/ice-covered terrain, we did not add any discussion in the manuscript relative to the COT retrieval from SEVIRI, and the contrast between snow and clouds. We provide the required information here

The retrieval of COT (by the CMIC algorithm) is performed only for satellite pixels that have been caracterized as cloudy by the Cloud Mask (CMA) product, which distinguishes between snow/ice covered areas and clouds (Météo-France, 2016). Cloud free areas covered by snow or ice are identified during the daytime by their very low reflectivity at 1.6 or 3.8 μm and high reflectivity at 0.6 μm. Moreover, thin cirrus clouds can be detected and distinguished from snow and ice due to their different emissivities at 10.8 micron and 12.0 μm. Thus, there are sufficient thresholds to differentiate between snow and clouds. The validation of the CMA product shows that the accuracy of cloud detection reaches up to 97.1% over European areas using SYNOP observations (Meteo France, 2016).

- **Role of broadband radiometers in the manuscript: The authors state in the abstract that "Radiometers that were not properly maintained and/or calibrated were found to provide UVI measurements with uncertainty that was comparable to the uncertainty of the UVIOS2 estimates, which highlights the significance of systematic maintenance and calibration of the UV**

radiometers." They further state (lines 434–436) that "The uncertainty in the UVIOS2 forecasts was found to be comparable to the measurements of filter radiometers when they were not properly calibrated, but ~3 times larger compared to the measurements of accurately calibrated radiometers, which shows the significance of systematic and accurate calibration of such instruments." However, is a model really needed to affirm the importance of systematic and accurate calibration of UV instruments? The comparison of the model accuracy with that of the least reliable broadband radiometers is not particularly insightful. For example, should the conclusion be that UVIOS2 estimates are only as accurate as an uncalibrated or poorly maintained radiometer? In summary, are considerations regarding broadband radiometers necessary in this paper?

Reply

The reviewer is right. We have removed the considerations regarding broadband radiometers from the paper.

- **Model inputs require a more detailed description:**

1. **Extraterrestrial spectrum: A more recent extraterrestrial spectrum (QASUMEFTS) exists compared to "Atlas plus MODTRAN." Given that QASUMEFTS was obtained using the same instrument employed here as a reference, why was it not used for the calculations? What is the expected deviation resulting from this choice?**

Reply

The pre-calculated LUTs (i.e., the "core" of UVIOS2) were based on the Atlas Plus MODTRAN ETS. Using a different ETS would require either recalculation of the LUTs or to run libRadtran directly. Nevertheless, we added the following lines in the document (lines 214 - 216):

"Using a different ETS might result to differences in the simulated erythemal irradiances, as for example was shown in the study of (Gröbner et al., 2017). Based on the results of the latter study we estimate that the simulated irradiances might differ by up to 5% if a different ETS was used, making the used ETS spectrum a major uncertainty factor in UVIOS II simulations. "

2. **Cross-sections: These should be presented in a separate table. Are the ozone cross-sections used in the model consistent with Brewer retrievals?**

Reply

We do not believe that a separate table is necessary since the appropriate reference is provided. Nevertheless, we have added the following lines (lines 218 - 223):

"TOC is among the main regulators for the UVI levels at the surface and thus using TOC values that have been retrieved using different ozone absorption cross sections relative to those that have been used to create the LUT (Molina and Molina, 1986) would result in differences between the measured and the simulated UVI. Differences of 1 - 3% have been reported in the retrieved TOC depending on the used absorption cross sections (Fragkos et al., 2015; Redondas et al., 2014), which may result in differences of up to ~5% in the calculated UVI, depending mainly on the used cross sections, the SZA, aerosols load, and cloudiness (Blumthaler et al., 1995; Kim et al., 2013).

3. **Total Ozone Column (TOC): How was the TOC from the Brewer instrument obtained? Additionally, why was TEMIS ozone used instead of CAMS, given that other parameters are derived from CAMS?**

Reply

The retrieval of total ozone from the Brewer is discussed analytically in the provided references (line 172). We do not believe that a detailed description is necessary in this paper

4. **Cloud properties: What is the spatial resolution of the COT and CMFUV products? This information is crucial for understanding the influence of shadows/3D effects and parallax errors in cloud property determination over complex terrain. Furthermore, which SEVIRI channels were used for retrieving cloud optical properties? Do they enable reliable discrimination between clouds and surface snow?**

Reply

Appropriate references have been provided (lines 242-243).

"A detailed description of the cloud products by MSG can be found in the relevant bibliography (Deneke et al., 2021; Météo-France, 2016)."

5. **Altitude correction for the station (line 270): How was it determined? Is it just the 5% factor per km mentioned a few lines above?**

Reply

Yes, it is the 5%/km correction that has been discussed earlier. We tried to make it clearer in the manuscript.

- **Results for all-sky simulations: It would be beneficial to compare CMFs in addition to UV Indices to exclude the trivial correlation arising from the diurnal SZA cycle.**

Reply

An extended discussion for the effect of CMF has been already performed Papachristopoulou et al., (2024). The effect of clouds is already visible in Figure 9 (Fig. 8 in the previous version), and thus we believe that adding another graph for the CMF would be beneficial. An additional discussion has been, however, added in this section to point out that the large differences shown in Fig. 9 are in all cases due to the model inability to predict accurately if the fraction of the solar disc that is occluded by clouds, especially under broken cloud conditions.

- **Classification of clear/cloudy skies: The classification, based on measured direct irradiance (lines 275–279), appears simplistic. For instance, the situation shown in the upper-right image of Fig. 5 does not seem to represent clear-sky conditions (as defined by the model). The authors could refine their classification to better account for scattered clouds and their effects on surface UV radiation.**

Reply

The situation that was shown in the upper right image of Figure 6 (Fig. 5 in the previous version) was not, and was not supposed to, represent clear-sky conditions. Moments before or after the time of that image there may be clear-sky conditions according to the criteria that we have set, and this is what we try to show. Figure 6 has been updated to in the context of the overall major revision of the manuscript.

We do not believe that using a more refined algorithm to distinguish occluded/unoccluded solar disc conditions would result in large differences. As discussed in the manuscript, the largest deviations seem to be due to enhancement of the UVI because of the presence of clouds (see Fig. 5) that are near the solar disc in the sky. To our knowledge there is no way to capture and consider such situations.

- **Figures: Three different types of plots are used: (i) ratios (e.g., Figs. 2–3), (ii) absolute UVI values (e.g., Figs. 6–7), and (iii) absolute differences (Figs. 8–9). Can these be more homogenised for consistency?**

Reply

The three different types of figures are there on purpose, since showing all three, relative differences, absolute differences, and absolute UVI values, is necessary to understand the reliability of the model, the impact of different factors that affect the UVI, and the impact of these factors when UVI is large (i.e., when it is more significant to have accurate simulations).

Nevertheless, we tried to improve the quality of the figures.

- **Other services, such as TEMIS and CAMS, already provide UV Index estimates, at least on a European scale. The authors should clarify the advantages offered by UVIOS2, such as improvements in spatial and temporal resolution.**

Reply

Table 2 which summarizes the main differences/similarities between the UVI from UVIOS2 and TEMIS/CAMS, and some relevant discussion have been added in Section 2.3.

- **Spectral validation: Have the authors attempted to compare the spectral output of UVIOS2 with spectra measured by QASUME-II? This could provide additional insights into the influence of various factors.**

Reply

We agree with the reviewer. That will be indeed very interesting and more informative regarding the impact of different factors, not only on the modeled UVI, but also on other quantities (e.g., the effective dose for the production of vitamin D). That is out of the scope of the present study, but we will do it in the future considering wider spatial and temporal scale.

TECHNICAL REMARKS

- Lines 20–21: "The UVIOS2... depending on the inputs" is too general and can be removed.

Reply

Done

- Lines 76–84: The distinction between nowcasting and forecasting is unclear. If all inputs are forecasted (as suggested in lines 76–77), what differentiates nowcasting from forecasting?

Reply

The reviewer is right. The word nowcasting has been deleted.

- Line 118: "system that its basic features" → Incorrect grammar; rephrase.

Reply

The manuscript has been rephrased.

- Line 134: Remove the typo "as Heading 2."

Reply

Done

- Lines 136–139: The stated considerations apply to all radiative transfer models, not specifically to UVIOS2. The description of UVIOS2 should begin with details that are unique to this system.

Reply

We believe that few introductive lines are necessary to set the discussion context for the reader before discussing the unique characteristics of UVIOS2. Thus, we did not change the manuscript at this point.

- Figure 1: What does "% altitude" represent on the colour scale?

Reply

It was a typo. It has been corrected.

- Section 2.2 (QASUME-II vs QASUME): The uncertainty of QASUME is discussed in Sect. 2.2, but QASUME-II is used in the study. Why was QASUME not used, and why is the uncertainty of QASUME-II not discussed?

Reply

What was written in the manuscript was inaccurate. We were referring to QASUME II uncertainties as it is clearly stated in revised version.

- Table 2: A similar table for all-sky UV determination might be useful, with different headings.

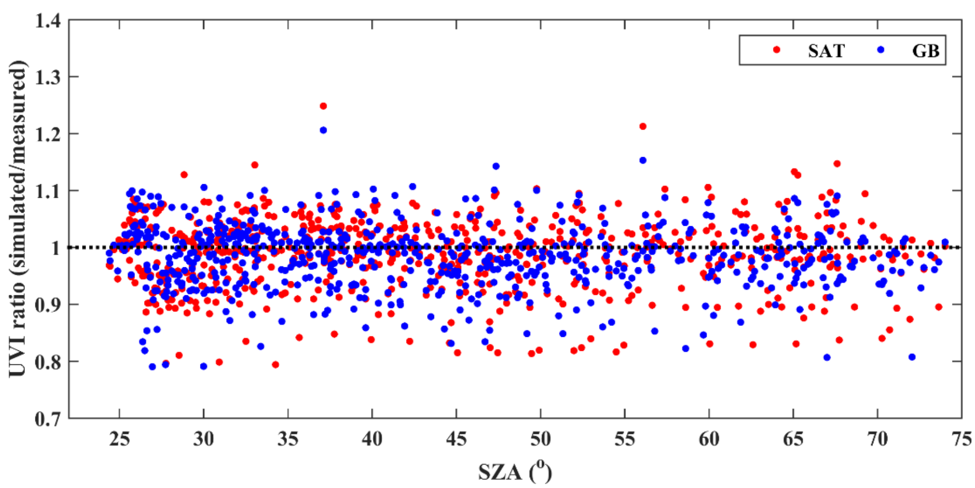
Reply

The only difference between the clear-sky and the all-sky simulations is the use of the UV-CMF. Thus, we do not believe that another Table for all-sky conditions would be useful. (now Table 3)

- Figure 2: The y-axis label should clarify that the ratio represents simulated vs measured values. In addition, would plotting the ratio against solar zenith angle provide useful insights?

Reply

The y-axis label has been changed. We did not find any dependence on SZA (see the following figure)



- Figure 3: "ratio BG" should be replaced with "UVIOS2 / QASUME" or a similar term to clearly define the ratio. Also, why are the plots not ordered by increasing SSA?

Reply

We use "BG" for the UVIOS2/QASUME ratios, with ground-based measurements as UVIOS2 inputs, as stated earlier in the manuscript. This is necessary since we have used many different input combinations. We show the graph for SSA=0.9 first, because that is the used value (i.e., this is the reference graph).

- Lines 330–331: If the aerosol is primarily secondary, could hygroscopicity have influenced the correlation between AOD and SSA?

Reply

Hygroscopicity would have probably affected the correlation between AOD and SSA in the opposite way (i.e., resulting in higher SSA values) during the transfer of the particles from Germany to Davos.

- Line 342: Cloud-induced irradiance enhancements near the solar disk typically last for a short time. What do short-term variations in the ratio indicate about this effect?

Reply

As shown in Figure 5 (added in the new version) confirms, we noticed that the increased albedo during broken cloud conditions can be very significant at Davos.

- Lines 355–356: The treatment of limited horizon effects in the model is crucial due to the site complex orography. This information should be presented earlier. Additionally, provide an approximate (cosine-weighted) fraction of the sky obstructed by mountains.

Reply

We specified in the manuscript that ~ 5% of the diffuse irradiance is blocked by the mountains. For the SZAs for which we made the comparison the direct solar beam is not blocked.

- Figure 10: If retained, specify the UVIOS2 configuration used (in the caption).

Reply

Done

- Lines 408–409: The past tense may be more appropriate in the conclusions.

Reply

Done

- Table 3: It is unusual to introduce new results in the conclusions. Would it be better placed in the results section?

Reply

Table 3 (now Table 4) and the relative discussion has been moved to Section 3.2.

- Line 434: The term "UVIOS2 forecasts" is ambiguous here, as—if I understand correctly—clouds are not forecasted.

Reply

The sentence has been deleted

Assessment of the accuracy in UV index modelling using the UVIOS2 system during the UVC-III campaign

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Abstract. The third campaign for the calibration and intercomparison of solar UV radiometers (UVC III) took place at Davos, Switzerland in June - August 2022. More than 70 radiometers participated in the campaign and measured side-by-side with the portable reference spectroradiometer QASUME. ~~By using inputs from various sources, the UVIOS2 system was used to estimate the UV index (UVI) for the site of the campaign.~~ The UVIOS2 system is a flexible UVI modelling tool that can be exploited for different applications depending on the inputs. Thus, different combinations of satellite, reanalysis, and/or ground-based inputs were used to test the UVIOS2 performance when it is used as a tool for UVI nowcasting or for climatological studies. While UVIOS2 provided quite accurate estimates of the average (for the period of the campaign) UVI levels, larger deviations were found for individual estimates. The average agreement between the UVI from the UVIOS2 and QASUME was better than 1% for all the different sets of inputs that were used for the study. The range of the variability was of the order of 40% for instantaneous measurements (15 min), mainly due to the model's inability to capture the instantaneous effects of cloudiness, especially under broken cloud conditions. Under clear-sky conditions the model was found to perform much better, with the differences between the model estimates and the QASUME measurements being smaller than 12% for 95% of the studied cases. Even at the pristine environment of Davos, single scattering albedo (SSA) was found to contribute significantly to the modelling uncertainties under cloudless conditions. For relatively small Aerosol Optical Depth (AOD), of the order of 0.2 – 0.4 at 550 nm, the role of the SSA was found to be comparable to the role of AOD in the modelling of the UVI. ~~Radiometers that were not properly maintained and/or calibrated were found to provide UVI measurements with uncertainty that was comparable to the uncertainty of the UVIOS2 estimates, which highlights the significance of systematic maintenance and calibration of the UV radiometers.~~

1 Introduction

Exposure to solar ultraviolet (UV) radiation is vital for many living organisms including humans (e.g., Caldwell et al., 1998; Erickson III et al., 2015; Häder, 1991; Häder et al., 1998; Juzeniene et al., 2011; Lucas et al., 2019) but can be harmful when it exceeds certain limits (Diffey, 1991). Exposure of the human skin to UV radiation is the main mechanism that drives the formation of vitamin D, which, in turn, contributes to the strengthening of the immune system (e.g., Lucas et al., 2019; Webb et al., 2022). Moderate exposure to UV radiation has many more benefits for human health that are not related to the formation of vitamin D, such as the contribution to the maintenance of a good mental health and the curation of various skin diseases (Juzeniene and Moan, 2012). Nevertheless, overexposure to UV radiation is the main environmental risk factor for non-melanoma skin cancer, and among the main environmental risk factors for melanoma skin cancer and cataract (WHO, 1994). Determination of optimal sun exposure behaviors is not a simple task and, additionally to the surface solar UV radiation availability, it also depends on the physiology of each individual person (e.g., Armstrong and Cust, 2017; Hoffmann and Meffert, 2005; Lucas et al., 2019; McKenzie and Lucas, 2018; Webb et al., 2018; Webb and Engelsen, 2006).

A commonly used quantity for human health purposes is the UV index (UVI) (Schmalwieser et al., 2017a; Vanicek et al., 2000), which is a metric of the efficiency of UV radiation to cause erythema to the human skin. Generally, smaller exposure times and more precaution measures are recommended with increasing UVI. UVIs smaller than 2 are considered low, UVIs of 8 – 10 are considered very high, and UVIs exceeding 10 are considered extreme. In the 1980s and the 1990s, public awareness was caused due to the severe ozone depletion over high and mid latitudes which, if continued, would result in extreme UVI levels over densely populated regions of our planet (van Dijk et al., 2013; Newman and McKenzie, 2011). Although the adoption and the successful implementation of the Montreal Protocol prevented further depletion of stratospheric ozone and the consequent dangerous UV levels (McKenzie et al., 2019; Morgenstern et al., 2008), the future evolution of the levels of surface solar UV radiation is still uncertain, mainly due to the uncertainties in the impact of ~~future climatic~~climate changes on surface solar UV radiation (Bernhard et al., 2023; Zerefos et al., 2023).

Since the 1980s, national and international networks for the monitoring of the UVI have been established to ensure accurate and timely information of the public (Blumthaler, 2018; Schmalwieser et al., 2017). Maintenance of a station that provides reliable UV measurements demands properly trained personnel to run the station and application of strict calibration and maintenance protocols. Furthermore, there are prerequisites for the installation of such stations (e.g., power supply, safety). Thus, it is impossible to achieve UVI monitoring with global coverage from the ground. Progress in satellite monitoring during the last decades allowed the retrieval of the UVI on a global scale. Currently, the UVI has been estimated with high spatial and temporal coverage using various techniques and various satellite products (e.g., see Table 1 in Zerefos et al., 2023). One of the most widely used climatological UVI datasets is provided by the Tropospheric Emission Monitoring Internet Service (TEMIS). TEMIS provides clear-sky UV doses since 1960 and all-sky UV doses since 2004, that have been calculated using measurements from various satellite sensors (https://www.temis.nl/uvradiation/UVarchive.php; Zempila et al., 2017). Widely used climatological datasets of the UVI with global coverage have been also retrieved using measurements from the Total

Ozone Mapping Spectrometer (TOMS) (Herman et al., 1999), the Ozone Monitoring Instrument (OMI) (Tanskanen et al., 2006), and the TROPOspheric Monitoring Instrument (TROPOMI) (Lindfors et al., 2018). As a result of the rapid progress in Earth observation monitoring, the aforementioned climatological satellite-based UV products have been proven to be reliable over wide regions of the planet (e.g., Lakkala et al., 2020; Zempila et al., 2016, 2017), although biases of the order of 10 – 20% have been reported over complex and polluted environments, while uncertainties can be even larger over highly reflective terrains at high latitudes (e.g., Lakkala et al., 2020). The accuracy of satellite-based estimates is mainly limited by due to the (Bais et al., 2019bfinite width of the satellite pixel (Kazadzis et al., 2009) and the weakness of satellite sensors to accurately probe the lower troposphere (Bais et al., 2019). In particular, assumptions are made in the satellite algorithms to describe the complex interactions between radiation, aerosols and clouds, which increase the uncertainty in the retrievals. Uncertainties in the assumed aerosol properties (Arola et al., 2021; Parisi et al., 2021), inaccurate distinction of the effect of highly reflecting terrains and cloudiness (Bernhard et al., 2015; Lakkala et al., 2020b), and uncertainties in the description of cloud cover, especially over high-altitude sites (Brogniez et al., 2016; Schenzinger et al., 2023a) are among the main uncertainty sources. t bed (Bais et al., 2019b)

Meteorological services provide UVI nowcasting and forecasting that is usually based on meteorological forecasting in conjunction with radiative transfer models (e.g., Feister et al., 2011; Long et al., 1996; Roshan et al., 2020). The Copernicus Atmospheric Monitoring Service (CAMS) - Atmosphere for example, provides five days clear-sky and all-sky UVI forecasts on a global scale based on the synergistic analyses of Earth-observation data, weather prediction and chemistry model forecasts, and radiative transfer modelling (Peuch et al., 2022; Schulz et al., 2022). UVI forecasts are commonly governed by the uncertainties in the forecasted meteorological parameters, mainly cloudiness (e.g., Schenzinger et al., 2023). Geostationary satellites provide continuous, nearly instant information for cloudiness over wide regions of the planet (Derrien and Le Gléau, 2005), which can be used to provide more accurate UVI estimates in nearly real time (Kosmopoulos et al., 2020) or UVI climatological products (e.g., Arola et al., 2002; Fragkos et al., 2024; Verdebout, 2000; Zempila et al., 2017).

Monitoring and/or forecasting of the UVI at mountainous sites is exceptionally challenging. Complex atmospheric conditions and complex terrains increase the uncertainties in the modelling of the UVI, while calibration and maintenance of sensors is not easy due to difficulties in access, power supply, and harsh weather conditions. Nevertheless, UVI increases with altitude and can reach extreme levels, which makes this information valuable for the inhabitants and the visitors of such locations. For example, extreme UVI of ~20 has been recorded in the Bolivian Andes (Pfeifer et al., 2006; Zaratti et al., 2003). Elevated UVI levels have been also recorded at high-altitude deserts in Argentina (Piacentini et al., 2003), while UVI frequently exceeding 15 has been measured at Tibet (Dahlback et al., 2007). UVIs frequently exceeding 11 have been also measured at European alpine stations (Casale et al., 2015) as well as at high altitude locations in Northwestern Argentina (Utrillas et al., 2016). Depending on atmospheric and terrain conditions, increases of the surface solar UV radiation levels with altitude can range from a few percent per km (Chubarova and Zhdanova, 2013; Pfeifer et al., 2006; Rieder et al., 2010; Schmucki and Philipona, 2002; Zaratti et al., 2003) to 10-20% (e.g., Chubarova et al., 2016; Sola et al., 2008), or even to more than 30%/km when surface albedo also increases with altitude (Bernhard et al., 2008; Pfeifer et al., 2006). During summer (if absence of snow is absent), UVI increases with altitude mainly due to decreased Rayleigh scattering (Allaart et al., 2004; Blumthaler et al., 1994; Sola et al., 2008). -In general, the change in the levels of the solar UV irradiance with altitude depends on atmospheric composition and has a strong wavelength dependence which is introducing difficulties in the modelling of the UVI at mountainous sites (e.g. (Dvorkin and Steinberger, 1999; Krotkov et al., 1998)). At very high-altitude (or/and latitude) sites, ice and/or snow may persist even in late spring and summer resulting in extremely high UV exposure (e.g., (Schmalwieser et al., 2017b; Siani et al., 2008; Utrillas et al., 2016).

The continuous operation of ground-based networks that provide highly accurate information is necessary, not only for the information of to the public, but also for the validation and the improvement of satellite based UVI climatological and forecast/nowcast products (e.g., Fountoulakis et al., 2020b). In addition to the strict maintenance, operation, and calibration protocols that must be applied by the monitoring stations operators (e.g., Fountoulakis et al., 2020a; Garane et al., 2006; Gröbner et al., 2006; Lakkala et al., 2008), participation of the instruments to field campaigns further ensures the high quality and the homogeneity of the measured UVIs at different stations (Bais et al., 2001; Hülsen et al., 2020). The uncertainty in the UVI measured by the most accurate spectroradiometers that serve as world references can reach 2% (Gröbner and Sperfeld, 2005; Hülsen et al., 2016). Broadband filter radiometers that are commonly used in regional, national, or international networks for UVI monitoring are affected by larger uncertainties. In the context of the solar ultraviolet filter radiometer comparison campaigns (UVC, UVC-II, and most recently UVC-III) that were organized by the Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center (PMOD/WRC) in 2006, 2017, and 2022 many broadband radiometers measured side-by-side with the world reference QASUME (e.g., Hülsen et al., 2020; Hülsen and Gröbner, 2007). Analyses of the measurements by the 75 instruments that participated in UVC-II resulted in the estimation of a calibration uncertainty of 6%. The overall uncertainty in the measurements was larger, due to other factors, mainly the imperfect angular response of the radiometers (Hülsen et al., 2020).

Furthermore, Davos is one of the few mountainous sites in the world where both, highly accurate UVI measurements, and measurements of the main factors that determine the levels of the UVI at the surface (and can be used as inputs for its modelling) are available, which allows us to assess the efficacy of a state-of-the-art UVI model to produce estimates and reconstructed UVI series under such conditions.

The first version of the UVIOS (UV-Index Operating System) nowcasting system that its basic features havehas been already described in Kosmopoulos et al., (2021). The system has been upgraded recently in order to achieve faster and more accurate simulations. The new, improved UVIOS2 radiative transfer scheme can be used either as a tool for UVI nowcasting and forecasting or for climatological studies, depending on the inputs. In this paper, the UVI that has been simulated using the new UVIOS2 system with different inputs is described and validated against very accurate ground-based UVI measurements that were performed during the UVCIII campaign. The world reference QASUME that operated during the campaign provides measurements that are ideal for the validation of UVIOS2 due to their high accuracy, which allows the identification of the uncertainties in the modelling of UVI by UVIOS2. Highly accurate ancillary measurements that were available at the same period also allow the identification of the uncertainty sources in the UVI modelling. The main targets of the study can be summarized as follows~~.~~ :

- Describe the upgrades in UVIOS2 relative to the previous (UVIOS) system.
- Quantify the uncertainties, and the main uncertainty factors, in UVIOS2 simulations during the UVCIII campaign, when it is used as a tool for UVI nowcasting and climatological analysis.
- Evaluate and discuss in depth the uncertainty factors in the modelling of UVI at complex topography sites such as Davos.
- Discuss the uncertainty in forecasted UVI with respect to the uncertainty in the measurements of filter radiometers and discuss what are the prerequisites for improved UVI modelling.

It must be clarified that the study refers to a snow-free period at Davos, and thus the uncertainties related to the parameterization of surface albedo, which may be significant for higher altitude sites even in the summer, are not quantified or discussed here. The paper is organized as follows. A description of the used data and methods is provided in Section 2. The results of the analysis are discussed in Section 3, and the main conclusions are summarized in Section 4~~.1.1 Subsection (as Heading 2)~~.

2 Methodology

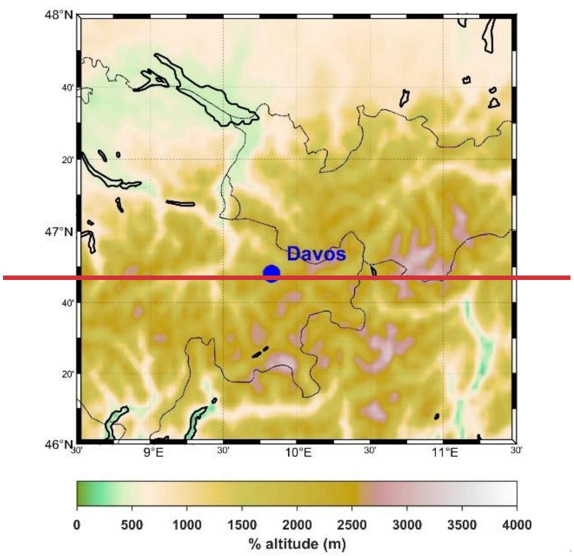
The UVIOS2 system is a flexible tool that can be exploited for different applications depending on the inputs. It can be used either as a nowcasting/forecasting tool, or to perform climatological studies. The accuracy of the simulated UVI depends on the compromise between the achievement of realistic computational times (i.e., the spatial and temporal extent of the simulations) and the use of the most accurate model inputs. In the context of this work, we assessed the accuracy of UVIOS2 when it operates for real time applications (i.e., default setup that is used to simulate the real-time UVI over Europe) and when it is used for climatological studies (i.e., using ground-based measurements or reanalysis data as inputs) at the mountainous environment of Davos, Switzerland during the UVC III campaign (Hülsen and Gröbner, 2023). Assessment of the accuracy in UVIOS2 forecasts is out of the scope of the present study.

2.1 The UVC-III campaign

The third International Solar UV Radiometer Calibration Campaign (UVC-III) took place at Davos, Switzerland (Figure 1; 46.8°N, 9.83°E, 1610 m a.s.l.) from 13 June to 26 August 2022, and was organized by the PMOD/WRC as part of the WMO/GAW program (Hülsen and Gröbner, 2023). The QASUMEII data (see Sect. 2.2) ~~was~~ were used as reference for the calibration of the broadband radiometers during the campaign. QASUME and QASUMEII were frequently calibrated during the campaign using a portable calibration system with 250 W lamps. The two spectroradiometers remained stable within ±1% for the campaign period and their measurements differed by less than 3%. Seventy-five solar UV broadband filter radiometers were shipped to Davos and participated in the campaign. The UVI ~~measured by the participating instruments~~ was derived from the measurements of the participating instruments using the calibration factors provided by the operators and the calibration factors that were calculated at Davos, and then the ~~measurements~~ UVI from the radiometers ~~were~~ was compared to the UVI measured by QASUMEII. All participating instruments were also characterized for their angular and spectral response.

Ancillary measurements of many parameters that are valuable for the determination of the factors that result in discrepancies between the simulations of UVIOS2 and the measurements were performed during the whole period of the campaign. In particular:

- Aerosol optical properties were measured by a CIMEL radiometer (and many other radiometers that operate at the site) that is part of the AERONET network (Holben et al., 1998).
- Total Ozone Column (TOC) was measured by a Brewer spectroradiometer (Kerr, 2010; Kerr et al., 1985).
- Global and direct total solar irradiance by pyranometers and a pyrheliometer.
- Hemispherical sky images from sky cameras.
- Cloud cover in octas by a pyrgeometer (Dürr and Philopona, 2004)



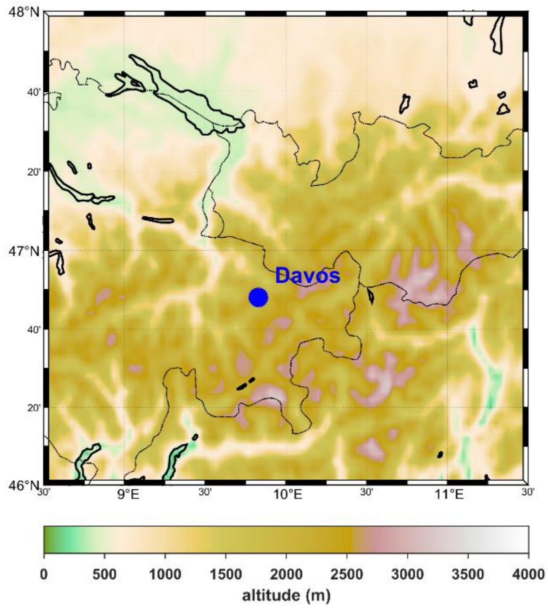


Figure 1. Topographical map of Davos, Switzerland.

2.2 QASUME

QASUME is a transportable spectroradiometer that is traceable to the scale of spectral irradiance established by the Physikalisch-Technische Bundesanstalt (PTB) and serves as a reference for spectral solar UV irradiance. The system is maintained by the PMOD/WRC and its measurement accuracy has been improved significantly in the last two decades. Since 2014, a second reference spectroradiometer (QASUMEII) is also operating and is used as an additional reference standard (Hülsen et al., 2016). Upgrades of technical characteristics and improved characterization methodologies have reduced the expanded uncertainties in QASUMEII measurements at wavelengths above 310 nm from 4.8 % in 2005 (for QASUME) to 2.0 % in 2016 (Hülsen et al., 2016). More information about QASUME and QASUME II can be found in several relevant studies (Gröbner et al., 2005, 2006; Gröbner and Sperfeld, 2005; Hülsen et al., 2016). Since 2014, a second reference spectroradiometer (QASUMEII) is also operating and is used as an additional reference standard (Hülsen et al., 2016). Both, QASUME and QASUMEII were measuring in the range 290 – 420 nm with a 15 min temporal resolution during the UVC-III campaign. These spectra were weighted with the erythema action spectrum (Webb et al., 2011) and were then integrated to calculate the erythemal doses, and subsequently the UVI (by dividing the doses in mW/m^2 with 25). For this work we have used only the UVI measured by QASUMEII, since the agreement between QASUMEII and QASUME is better than 3%. QASUMEII is ~~referred~~referred to as QASUME throughout the manuscript

2.3 The UVIOS2 system

UVIOS2 is built upon the UVIOS system (Kosmopoulos et al., 2021). The main change in the system configuration relative to the previous version is that the UVI is calculated in two steps:

(i) the UVI is calculated under cloudless ~~(clear)~~ skies and

(ii) the effect of clouds is quantified as a second step for the calculation of the all-skies UVI.

This change in the system's configuration was accompanied by two major modifications/upgrades: (1) the use of a more detailed UV look up table (LUT) for ~~clear~~cloudless-sky calculations that increases the accuracy relative to the original version, and (2) the use of the UV cloud modification factor (CMFUV) concept used for the all skies UVI estimates. The variables that correspond to each of the five different dimensions of the LUT are listed in Table 1, along with their range and resolution. When SZA exceeds 89°, then UVI is considered equal to 0. When values of the other input parameters are above/below the limits shown in Table 1, then inputs are set to the upper/lower values of the used range. Such occasions are, however, very rare for mid-latitude sites.

Table 1. Inputs of the LUT

Parameter	**Range**	**Resolution**
SZA (°)	1 - 89	2
TOC (DU)	200 – 600	10
AOD at 550 nm	0 - 2	0.1
SSA	0.6 - 1	0.1
AE	0 – 2	0.4

The radiative transfer simulations for the creation of the LUT were performed using the UVSPEC model of the libRadtran package (Emde et al., 2016; Mayer and Kylling, 2005). Simulations were performed using the National Infrastructures for Research and Technology (GRNET) High Performance Computing Services and the computational resources of the ARIS GRNET infrastructure. Spectral simulations per 0.5 nm were performed for the spectral region 290 nm – 400 nm, using the atlas plus modtan extraterrestrial spectrum (ETS) and the sdisort solver (Dahlback and Stamnes, 1991) which assumes pseudospherical atmosphere. Using a different ETS might result to differences in the simulated erythemal irradiances, as for example was shown in the study of ~~(~~Gröbner et al., (2017). Based on the results of the latter study we estimate that the simulated irradiances might differ by up to 5% if a different ETS was used, making the used ETS spectrum a major uncertainty factor in UVIOS2 simulations. The default libRadtran absorption cross-sections of species that absorb radiation in this spectral region (mainly O_3, SO_2, and NO_2) were also included. TOC is among the main regulators for the UVI levels at the surface and thus using TOC values that have been retrieved using different ozone absorption cross sections relative to those that have been used to create the LUT (Molina and Molina, 1986) would result in differences between the measured and the simulated UVI. Differences of 1 - 3% have been reported in the retrieved TOC depending on the used absorption cross sections (Fragkos et al., 2015; Redondas et al., 2014), which may result in differences of up to ~5% in the calculated UVI, depending mainly on the used cross sections, the SZA, aerosols load, and cloudiness (Blumthaler et al., 1995; Kim et al., 2013). In the domain for which the system is commonly used (i.e., Europe, North Africa, Middle East), variability in SO_2 and NO_2 has a minor impact on the UVI, and thus default values of their total concentration have been used. The US standard atmosphere (Anderson et al., 1986) was used to describe the profiles of atmospheric state and composition, and the surface albedo was set to 0.05. Adjustment of the surface albedo to the local conditions when UVIOS is used over more reflective terrains (e.g., deserts, snow-covered surfaces) is within the model improvements that are planned for the future since under such conditions assuming a standard value of 0.05 could result in large uncertainties (e.g., Weihs et al., (2001)).

The profiles of libRadtran default aerosol model (Shettle, 1990) were scaled to the values of AOD (spectrally using the corresponding Ångström Exponent, AE) and SSA provided in Table 1. We did not consider the spectral dependence of the absorbing aerosol optical depth (as e.g., in the OMI and TROPOMI algorithms (Arola et al., 2021)), which may induce increased uncertainties over polluted regions (e.g., Roshan et al., (2020)). However, considering such information would increase significantly the size of the LUT and thus the computational time needed for the simulations, making the provision of the UVI in near-real time for wide areas impossible.

The UV spectra were weighted with the action spectrum for the induction of erythema in the human skin (Webb et al., 2011) to calculate the UVI. A correction for the effect of altitude, assuming an increase of 5% per km (e.g., Zempila et al., 2017) has been applied on the calculated UVI.

The cloud optical thickness (COT) from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument aboard the Meteosat Second Generation (MSG) satellites has been used to calculate the CMF. The COT product is extracted operationally using the EUMETSAT Satellite Application Facilities of Nowcasting and Very Short-Range Forecasting, NWC SAF software package (Derrien and Le Gléau, 2005; Météo-France, 2016) and the broadcasted MSG data. A detailed description of the cloud products by MSG can be found in the relevant bibliography (Deneke et al., 2021; Météo-France, 2016). Using the MSG COT values and the SZA as inputs to the multiparametric equations described in Papachristopoulou et al. (2024) the shortwave CMF is calculated. Then, it is converted to CMFUV as described in Staiger et al. (2008). Finally, the UVI is calculated by multiplying the ~~clear~~cloudless-sky values with the CMFUV. Using cloud optical thickness to simulate UV instead of using the CMFUV might be more accurate (Krotkov et al., 2001), but would increase computational time, and still the dominant uncertainty factor related with cloudiness would be the visibility of the solar disc.

To evaluate the methodology used for the quantification of the attenuation of the UVI by clouds the all-sky UVI was compared to QASUME measurements. Furthermore, the all-sky UVIs were compared to the corresponding values that were directly simulated by using cloud optical properties as inputs in the UVSPEC model of libRadtran. It was assumed that all low-altitude clouds over Davos extend from 4 km to 5 km (with reference to the a.s.l.), and all high-altitude clouds extend from 7 km to 8 km. High-altitude clouds were in all cases assumed to consist of ice crystals with effective radius equal to 20 μm and ice water content (IWC) of 0.005 g cm^{-3}, while low-altitude clouds were assumed to consist of water droplets with effective radius equal to 10 μm and liquid water content (LWC) value of 1 g cm^{-3}. The COT at 550 nm product from MSG was used as an additional input, which leads to an adjustment of the default LWC and IWC values, using the parameterizations by Hu and Stamnes (1993) for water and by Fu (Fu, 1996; Fu et al., 1998) for ice clouds. The latter simulations were performed for the altitude of the site, while all other model settings were the same as those used to produce the LUT. The simulations that were performed for the altitude of the site were also used to evaluate the assumption that the UVI increases by 5% per km.

Practically there are two ways of using UVIOS2. For past data using the best available information giving priority to ground based/satellite based/modelling based data in this order of preference. For nowcasting or short term forecasting using any existing real time available data.

Table 2. Inputs of the UVIOS2, TEMIS, and CAMS services that provide the UVI.

Parameter	UVIOS2	TEMIS	CAMS
Past/reanalysis data			
Cloud inputs	Based on MSG Cloud Optical thickness	Cloud correction based on satellite data (reflectivity, cloud cover).	Dynamic cloud modeling with real-time weather forecasts.
Spatial	5km x 5km for clouds 13 km x 24 km for Ozone	~80 km x 40 km (GOME-2) to 13 km x 24 km (OMI).	0.4° x 0.4° (~44 km x 44 km).
Temporal	Every 15 minutes	Daily updates (based on satellite overpasses).	Every 1 hour
Aerosol	Ground based measurements or CAMS AOD, based on availability at the location under study	Through cloud reflectivity or historical AOD	advanced atmospheric models and data assimilation from satellite and ground-based observations.
Total ozone	Brewer if available, mainly based on OMI	Based on OMI	Full atmospheric modeling (transport + chemistry).
Nowcast/forecast data			

Cloud inputs	Based on MSG Cloud Optical Thickness and cloud motion vectors (for forecast)	Not available forecasts. Only Cloudless sky UV	Dynamic cloud modeling with real-time weather forecasts.
Spatial	5 km x 5 km for clouds 13 km x 24 km for Ozone	~80 km x 40 km (GOME-2) to 13 km x 24 km (OMI).	0.4° x 0.4° (~44 km x 44 km).
Temporal	Every 15 minutes up to 3 hours	Daily up to 7 days	Every 3 hours up to 5 days
Aerosol	Based on CAMS AOD forecasts	Historical AOD	CAMS forecasting
Total ozone	TEMIS forecast used (previous day)	TEMIS forecast: Based on satellite observations with some basic extrapolation techniques	Uses multiple satellite sources + numerical models.

As shown in Table 2 there are basic differences but also common approaches in the three UVI services. The main advantage of UVIOS2 is that it provides higher spatiotemporal resolution for nowcasted or past data. Nevertheless, it utilizes CAMS and TEMIS forecasts for AOD and ozone nowcasts/forecasts respectively. Overall, all the data used are going through libRadtran towards calculating UVI.

2.4 UVIOS2 inputs

Different combinations of model inputs have been used to assess the UVIOS2 accuracy when it is used for nowcasting and for climatological analyses. In all cases, the modelled ~~clear~~cloudless-sky UVI values were derived by interpolating linearly the elements of the 5-dimensional LUT. An overview of the data that was used to interpolate the UVI is presented in Table ~~2~~3. ~~In all cases, d~~Default values of the aerosol asymmetry parameter (ASY) and the surface albedo were used for the simulations. Analyses of different AERONET datasets show~~s~~ that climatological ~~asymmetry parameter~~ASY at 440 nm usually varies by about ± 0.03 around a typical value that is slightly lower than ~ 0.7 (e.g., Fountoulakis et al., 2019; Kazadzis et al., 2016; Khatri et al., 2016; Raptis et al., 2018). Given that ASY generally de~~in~~creases with wavelength it was assumed to be 0.7 in the UV. The real ASY can however differ occasionally by up to about ± 0.1 (e.g., Fountoulakis et al., 2019). We estimated that a difference of 0.1 in the asymmetry parameter can result in differences of up to ~ 2% in the simulated UVI. Using a default surface albedo (0.05) also introduces uncertainties in the modelling of the UV index. Surface albedo changes spectrally and its impact differs depending on aerosol load and properties (e.g., Corr et al., 2009; Fountoulakis et al., 2019). Nevertheless, during the snow-free period at Davos differences in surface albedo are estimated to be within ± 0.03 (e.g., Feister and Grewe, 1995) resulting in differences that are of the order of a few percent.- Sensitivity analysis revealed that the uncertainty in the UVI simulations for AOD ≤ 0.5 due to the combined effect of using default ASY and surface albedo values (with errors of ± 0.1 and ± 0.03 respectively) is less than 3%.

Table 23. Combinations of input data for the UVIOS2 system for cloudless sky conditions. The three different combinations used to evaluate the system as a tool for climatological analysis are referred to as CAMS, CAMS+OMI, GB.

Variable	Nowcasting I (SAT)	Climatological I (CAMS)	Climatological II (CAMS+OMI)	Nowcasting II and Climatological III (GB)
AOD	CAMS forecasted AOD at 550 nm	CAMS reanalysis AOD at 550 nm	CAMS reanalysis AOD at 550 nm	Measured AOD at 500 nm from CIMEL
TOC	Forecasted from TEMIS	CAMS reanalysis	OMI measured	Measured from Brewer
AE	Climatological (1.5)	Climatological (1.5)	Climatological (1.5)	Measured by CIMEL (440 – 675 nm)
SSA	Climatological (0.9)	Climatological (0.9)	Climatological (0.9)	Climatological (0.9)
ASY	0.7	0.7	0.7	0.7
Surface albedo	0.05	0.05	0.05	0.05

For UVI nowcasting, the aerosol properties and TOC that were used as model inputs were either forecasted forecasts (AOD, TOC) and or climatological datasets were used as inputs for aerosol parametersvalues (AE, SSA, ASY) and TOC. Specifically, 1-day ahead forecasts of the TOC from TEMIS (https://www.temis.nl/uvradiation/nrt/uvindex.php) and of the AOD at 550 nm from CAMS (https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-atmospheric-composition-forecasts?tab=overview), as well as monthly climatological values of the SSA and the AE (typical values of 0.9 and 1.5, respectively, have been estimated for Davos) were used to interpolate the elements of the LUT. Total ozone 5-days ahead forecasts are available from TEMIS on a daily temporal resolution. Detailed description of TEMIS and the available products can be found on the service web-page (https://www.temis.nl/uvradiation/product/index.php). The CAMS forecasted AOD is available for the following 5 days, on a 1-hour resolution, and the forecasts are updated every 12 hours.

For the calculation of the climatological ~~clear~~cloudless-sky UVI, the three combinations of inputs presented in Table ~~2~~ 3 were used:

(1) Reanalysis TOC and AOD from CAMS (Inness et al., 2019) instead of the corresponding forecasted products. All other parameters were kept the same as for nowcasting. The CAMS reanalysis, available from 2003 onwards, is the global reanalysis dataset of atmospheric composition of the European Centre for Medium-RangeWeather Forecasts (ECMWF), consisting of three-dimensional time-consistent atmospheric composition fields, including aerosols and chemical species. It is based on ECMWF's Integrated Forecast System (IFS), with several updates to the aerosol and chemistry modules described by ~~(~~Inness et al., (2019). CAMS reanalysis products are available from the Copernicus Atmosphere Data Store (ADS, https://ads.atmosphere.copernicus.eu/#!/home (last access on 8 August 2024)) on a 3-hourly basis on a regular 0.75° x 0.75° latitude/longitude grid (instead of their native representation).

(2) TOC that has been retrieved from the Ozone Monitoring Instrument (OMI) aboard Aura (Levelt et al., 2006), and reanalysis AOD from CAMS (Inness et al., 2019). All other parameters were again kept the same as for nowcasting.

(3) TOC measurements from the Brewer spectroradiometer with serial number 163 (Brewer#163) (Gröbner et al., 2021), AOD at 500 nm, and AE (440 – 675 nm) from the CIMEL radiometer (Giles et al., 2019), and all other parameters the same as for the default nowcasting setup. The AOD and AE that were used for the study are level 1.5, version 3 AERONET direct sun products. Level 2 AERONET retrievals were not used because they ~~are~~ were not available ~~yet~~at the time of the analysis. Since these inputs are produced in near~~ly~~ real time, we consider that they could be potentially used for UVI nowcasting in addition to climatological studies. Level 2 AERONET retrievals are available with a longer latency and can be used for reanalysis at a later stage.

The ~~clear~~cloudless-sky UVI LUT outputs were in all cases post corrected for the effect of the varying Earth-Sun distance and for the surface elevation (1596 m for Davos). The all-sky UVI values were derived in all cases by multiplying the ~~clear~~cloudless-sky UVI with the Cloud Modification Factor in UV (CMFUV), which was calculated as described in Sect. 2.1 from the MSG-SEVIRI COT.

The UVI was simulated for the period 1 July – 20 August 2022 at the time of the QASUME measurements (15 min temporal resolution). The MSG images, and thus the CMFUV, were available at the exact time of the UV scans. All the other parameters (AOD, TOC, etc) were interpolated linearly to the time of the measurements.

For the analysis, measurements were classified as clear-sky (i.e., sun was not fully or partially covered by clouds) and all-sky (i.e., for all cloudiness conditions). In the following, clear-sky conditions refer to unoccluded solar disc according to measurements (although clouds may be present on the sky). Cloudless-sky conditions refer to cloud-free skies. To classify the measurements, the direct component of the total solar irradiance, as it was measured by the pyrheliometer that was operating at Davos during the campaign, was simulated as described in Papachristopoulou et al.(2024), and was then compared to the measured direct irradiance. When differences between the two components exceeded 10%, we considered that the sun was (fully or partially) covered by clouds.

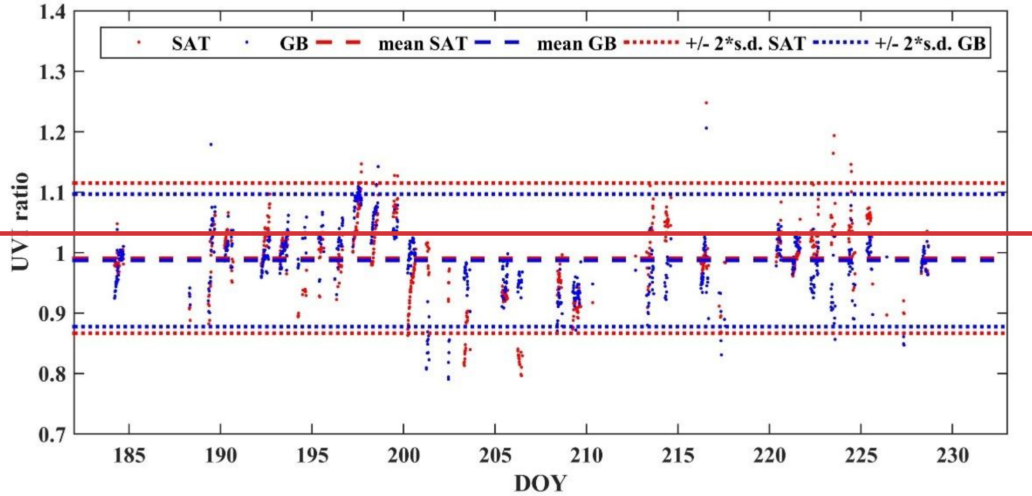
3 Results

3.1 Assessment of UVIOS2 for real time applications

In this section we tried to assess the accuracy of the modelled UVI when UVIOS2 is used for real time applications. Initially we compared the modelled and the measured UVI under clear-sky and all-sky conditions. The UVI was modelled using the default inputs and setup of the UVIOS2 (SAT), as well as using high quality ground-based measurements (GB), that theoretically can be available at near real time for the retrieval of a higher accuracy estimate of the UVI.

3.1.1 Clear-sky UVI

Under clear-skies, the ratio between ~~both,~~ modelled UVI datasets and the corresponding measured UVI from QASUME~~,~~ was then calculated~~,~~ and the results are shown in Fig. 2.



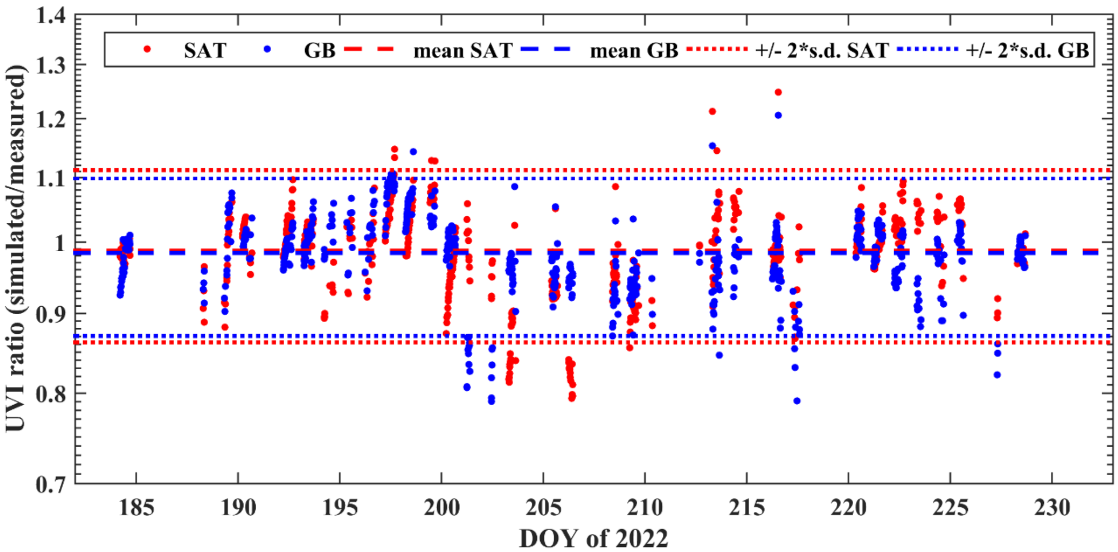


Figure 2. Ratios between simulated and measured clear-sky UVI. Red colour: ratios for simulations performed using forecasted CAMS AOD and TEMIS TOC. Blue colour: ratios for simulations performed using measured AOD, AE (by CIMEL), and TOC (by Brewer). Ratios have been calculated for SZA < 75°. Dashed lines represent the mean, while dotted lines represent the range of 2 standard deviation.

While the average ratio is in both cases ~0.99, the standard deviation is high, 0.062 and 0.055 for SAT and GB respectively, i.e., only slightly lower for GB. This result shows that using highly accurate inputs for TOC, AOD at 500 nm, and AE does not result in a noticeable improvement in the accuracy of the average modelled clear-sky UVI (standard deviation decreases by only a few percent), which denotes that other factors are also important for the formulation of the surface UVI levels at Davos. The role of each of the factors that were found to be the most important is discussed in the following.

AOD and TOC: The AOD forecasted by CAMS is at a different wavelength (550 nm) relative to the AOD measured by the CIMEL (500 nm). To compare the AOD from the two different sources, the AOD from the CIMEL was extrapolated at 550 nm using the measured AE (440 – 675 nm). The differences between the AOD at 550 nm from the CIMEL and CAMS are shown in the Appendix (Figure A1). Differences in AOD are in ~~all~~ most cases within ± 0.1, with an average of ~0, which explains differences of up to about ±10% between the UVIs simulated using the two different datasets. When differences in AOD are larger (e.g., in day of the year (DOY) 201 – 202 CAMS has not captured the large AOD levels over the site and the AOD from CAMS is lower by 0.15 – 0.25 relative to the AOD from CIMEL) they result in correspondingly larger differences between the ratios (of 10 – 20%). Differences in TOC (Figure A2 in the Appendix) are generally within ± 25 DU, with an average of about ~~-~~4 DU (on average, TEMIS slightly ~~underestimates~~ overestimates TOC for the period of the campaign), but occasionally they can reach ± 40 DU. Differences of ± 25 DU in TOC can justify differences of about ± 15% in the UVI modelled using the two different datasets (e.g., Kim et al., 2013). The large differences between the ratios that were calculated for the two different UVI datasets in ~~day of year (~~DOY~~)~~ 194 are mostly explained by differences in TOC (~20 DU during most of the day). Differences in DOYs 200 – 204, 206, and 223 are mostly explained by differences in AOD. The accuracy in the ground-based measurements (~ 0.02 for the AOD (Giles et al., 2019) and better than 2.5% for TOC (e.g., Carlund et al., 2017; Fountoulakis et al., 2019) cannot justify the standard deviation of 0.055 in the ratio between the modelled UVI when GB measurements are used as inputs and the measured UVI.

SSA: While a default SSA value of 0.9 has been used for the simulations, the real SSA at the shorter UV wavelengths, which contribute the most in UVI, can differ significantly, ranging from values smaller than 0.8 (during e.g., events of dust, polluted or biomass burning aerosols that have been transferred over the site) to values exceeding 0.98 (e.g., for mixtures that are dominated by sulfuric aerosols). The sensitivity of the ratios ~~shown in Figure 3~~ to the used SSA increases with increasing AOD as shown in Figure 3. For AOD between 0.3 and 0.4 a change of 0.1 (increase or decrease) in SSA results in a change of ~ 0.1 in the ratio (i.e., ~10% in the simulated UVI) which is of similar magnitude with the change in UVI due to a change of ~ 0.1 in AOD. The effect of changing SSA becomes less significant as the AOD decreases. Nevertheless, even for AOD of ~ 0.1, a change of ~ 0.1 in the SSA results in a change of 0.05 in the ratio (i.e., of ~ 5% in the modelled UVI). Generally, Figure 3 denotes that aerosol mixtures over Davos in the summer are dominated by aerosols that are weak absorbers of the UV radiation.

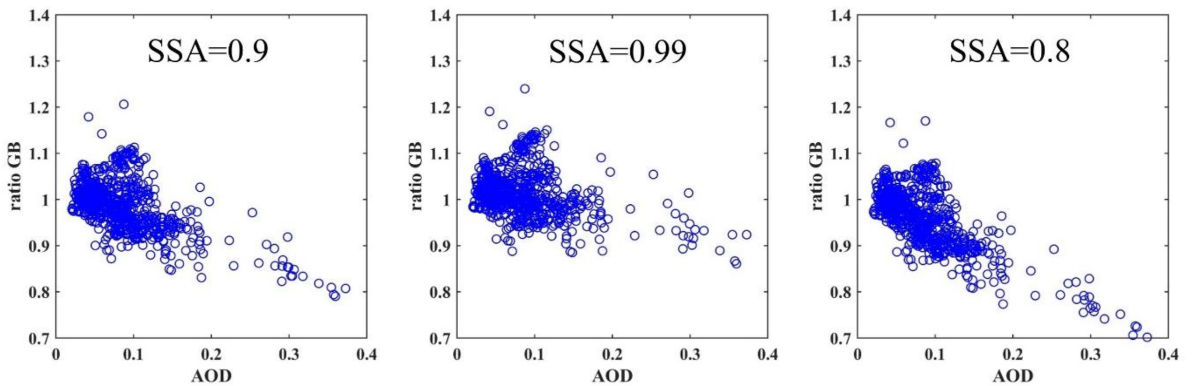


Figure 3. Ratios between simulated (using GB measurements) and measured clear-sky UVI when different SSA values are used for the simulations.

Changing the SSA from 0.8 to 0.99 results in mean ratio values that are similar to each other and close to unity (see Figure A3 in the appendix) ~~an SSA of 0.99 results in the median ratio value (~1.01)~~. Nevertheless, using SSA=0.9 results in a distribution of the ratio that is more symmetrical~~ly distributed~~ around the mean and closer to normal (see Figure A3 in the appendix), which ~~denotes~~ means that the SSA of 0.9 is more representative of the average conditions at Davos, at least during the campaign.

The high values of the ratios between modelled and measured UVIs in DOY~~s~~ 197 – 199 can be possibly justified by real SSA values that are lower than 0.9, and thus assuming SSA=0.9 for the simulations results in an overestimation of the UVI. In these days, the SSA at 440 nm from AERONET was generally lower than 0.9 (values between 0.77 and 0.92). As shown in Figure 4, the low SSA values may be due to air masses that ~~possibly~~ transfer polluted aerosols from lower altitudes at Germany ~~were present over Davos in these days~~. During DOY 200 – 210 when a negative bias is evident in Fig. 2, in addition to the broken cloud conditions that occasionally enhanced significantly the real UVI (see the discussion below), high levels of scattering aerosols were recorded over Davos (AOD at 340 nm from AERONET was ~ 0.6 in DOY 201-202, and SSA at 440 nm was generally above 0.97). We were not able to identify the conditions that favoured the presence of such high loads of reflective aerosols at the region. In DOY 201 and 202 the AOD is underestimated by CAMS by up to 0.25 (Fig. A1). Nevertheless, in these days the agreement between the measured and modelled UVI is much better for SAT (simulated using CAMS AOD) relative to GB. By comparing CIMEL AOD measurements with measurements from other photometers we confirmed that they are accurate. As shown in Fig. 5, broken cloud conditions during these days cannot explain the UVI enhancement (as e.g., in DOY 217). When the CAMS AOD data were used to simulate the UVI, errors in the AOD and the AE possibly counterbalanced the large errors due to the SSA which possibly resulted in better agreement between the modelled and the measured UVI for the particular dataset (see Fig. 2).

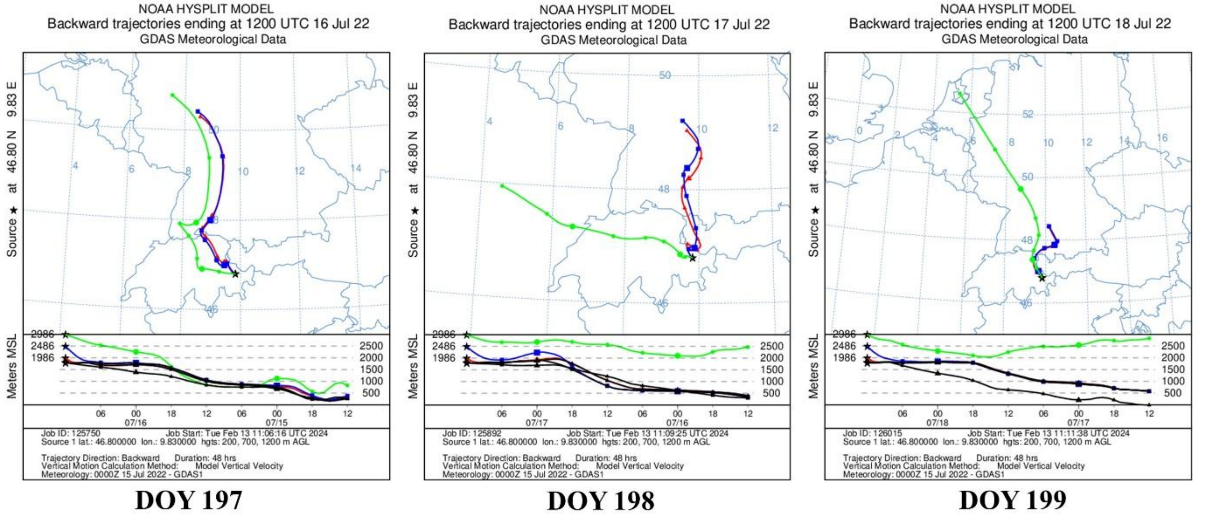


Figure 4. HYSPLIT back-trajectories of the air masses that arrived over Davos (at altitudes 400, 900, and 1400 m over the site).

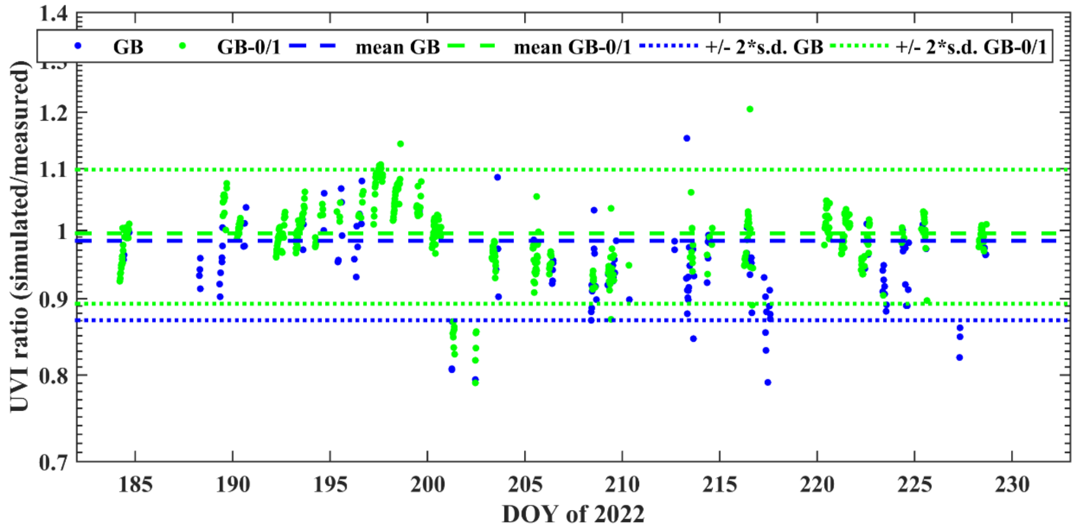
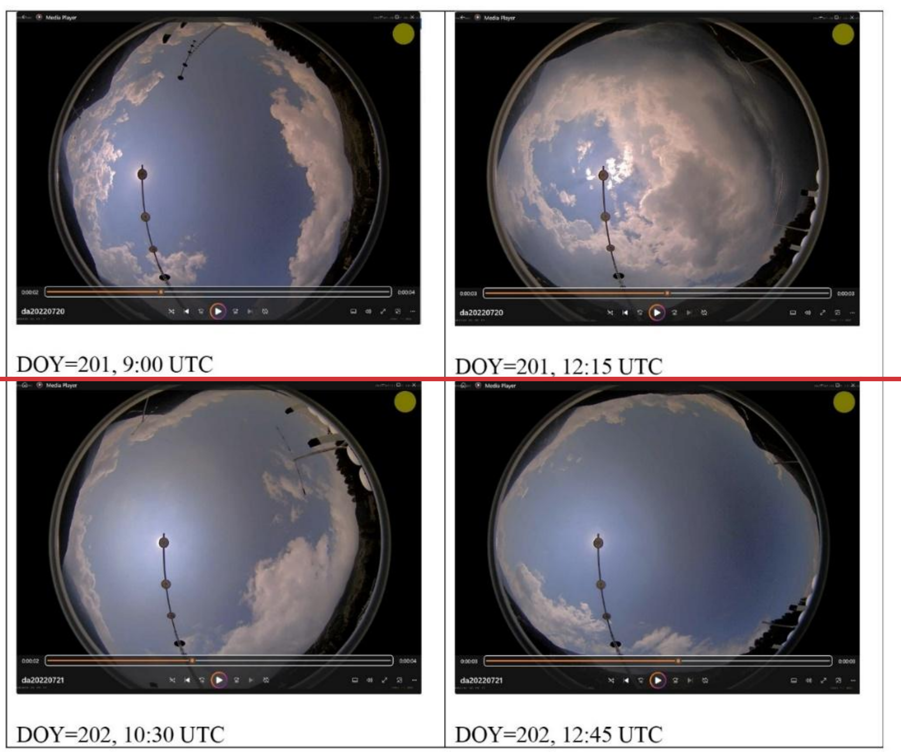


Figure 5. Ratios between simulated and measured clear-sky UVI for simulations performed using measured AOD, AE (by CIMEL), and TOC (by Brewer). Blue color: Unoccluded sun with cloudiness in the sky between 0 and 7 octas. Green color: Unoccluded sun with cloudiness in the sky between 0 and 1 octas.



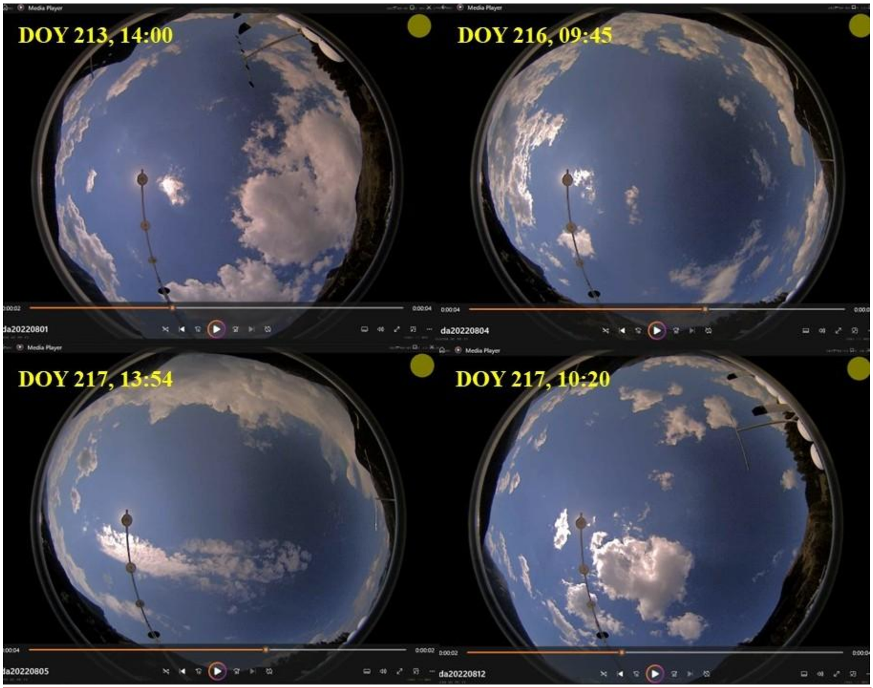


Figure ~~5~~6. Sky camera images for different DOY~~s 201 and 202~~ and times, which show the clouds near the sun that enhance the UVI at the surface.

Clouds near the sun that do not cover the solar ~~disk~~disc: At high altitude stations such as Davos, the presence of orographic clouds is frequent (some examples are shown in Fig. 6). Such clouds can enhance the UVI at the surface if they do not cover the solar disc, by redirecting part of the diffuse irradiance to the surface. Using the GB UVI dataset we tried to assess the impact of the presence of clouds when the sun is unoccluded. By comparing the ratios when there are very few or no clouds in the sky (unoccluded sun, 0 or 1 octas, green points in Fig. 5) with the ratios for all cloudiness conditions (unoccluded sun, 0 - 7 octas, blue points in Fig. 6) we confirm that including conditions with 2-7 octas adds a small negative bias in the ratio, possibly due to the enhancement by clouds. Removing these cases slightly improves the ratio and reduces the variability.

~~In DOYs 201 and 202 the AOD is overestimated by CAMS by up to 0.25. Nevertheless, in these days the agreement between the measured and modelled UVI is much better for SAT relative to GB. By comparing CIMEL AOD measurements with measurements from other photometers we confirmed that they are accurate. As discussed later, the reason for the 10 – 20% underestimation of the UVI by the model is possibly that surface UV irradiance is strongly enhanced by clouds that are near the solar disk during the day (Fig. 5).~~

Other factors of uncertainty in the modelling of the clear-sky UVI: As ~~shown in Table 2~~discussed earlier, fixed values of the ~~asymmetry parameter (~~ASY~~)~~, and the surface albedo have been used to derive the clear-sky UVI. The SSA has been estimated using Kinne, (2019) climatology. Although ASY may deviate from the typical value of 0.7 depending on the type of aerosols, the uncertainties related to ASY are minor relative to the overall simulation uncertainties, as already discussed. The fixed value of 0.05 for surface albedo is also not expected to induce uncertainties larger than 2% in the simulations (e.g., Fountoulakis et al., 2019). The standard correction (of 5%/km, i.e., ~8% for Davos) for the effect of altitude also induces small uncertainties (e.g. Blumthaler et al., 1997; Chubarova et al., 2016). By comparing the UVI simulated with UVSPEC with the results that were derived using the LUT (see Section 3.1.2), and then the correction for the effect of altitude, we found differences that were generally smaller than 1%, which shows that the uncertainties due to the combined effects of using the LUT (i.e., interpolating through the dimensions of the LUT) and the post-correction for the effect of altitude are small. The horizon in Davos is limited by the tall mountains surrounding the site, which at SZAs larger than 75° can block the direct component of the solar irradiance, as well as a large fraction of the diffuse irradiance (Hülsen et al., 2020). Although we have not corrected the modelled UVI for the effect of limited horizon, for SZA<75°, this effect combined with the effect of default altitude correction was estimated to induce uncertainties smaller than 2%. Considering invariant atmospheric properties (i.e., pressure and temperature profiles) based on a standard atmospheric profile (Anderson et al., 1986) which is not necessarily representative for a mountainous site such as Davos, introduces additional uncertainty, which however is expected to be minor relative to the overall uncertainty budget in our estimates. The used ETS and ozone absorption cross sections are more significant uncertainty factors (see Section 2.2).

3.1.2 All-skies UVI

For the default UVIOS2 setup the clear-sky UVI (that is derived using AOD from CAMS and TOC from TEMIS) is multiplied with the CMFUV to calculate the all-sky UVI. This method has been preferred instead of performing directly the simulations using cloud optical properties as libRadtran inputs because it is much faster and has a minor impact on the simulated UVI uncertainty compared to the uncertainty induced by the assumption of cloud homogeneity in the satellite pixel (e.g., Schenzinger et al., 2023). The all-sky UVI that was calculated using the LUT, the all-sky UVI that was calculated directly from libRadtran (for the altitude of the station and using cloud optical properties as inputs), and the UVI measured by QASUME are shown in Fig. ~~6~~ 7 for DOY~~s~~ 188 - 191. During the cloudy DOY~~s~~ 188 and 191 the variability in the modelled UVI (using both approaches) is in quite good agreement with the variability in the measured UVI. As shown in Fig. ~~7~~8, both approaches result in correlation coefficients of ~ 0.95 between the measured and modelled UVIs. The differences between the measured and modelled UVIs (for SZAs below 75°) are presented in Fig. ~~8~~9. For both modelling approaches the average differences in the UVI are nearly identical (~ 0) with a nearly identical standard deviation (~ 1). From figures ~~6, 7 and 8~~7 - 9 it is obvious that the differences between the two modelling approaches are very small, and that the deviations originate mostly from the assumption of homogeneous distribution of clouds within the satellite pixel. The differences between the UVI from QASUME and the model (with both setups) are in some cases very large, reaching even values of ± 8. These large differences are mainly due to the model inability to predict accurately if the fraction of the solar disc that is occluded by clouds, especially under broken cloud conditions.

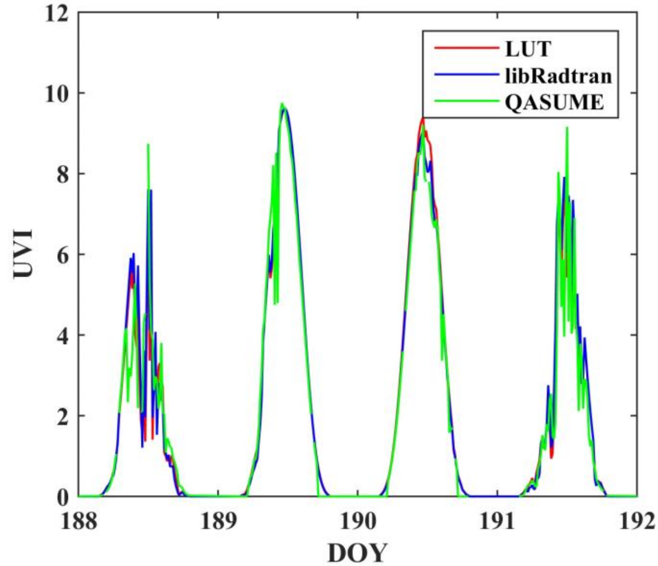


Figure ~~6~~7. Measured UVI, and modelled UVI from the LUT and libRadtran.

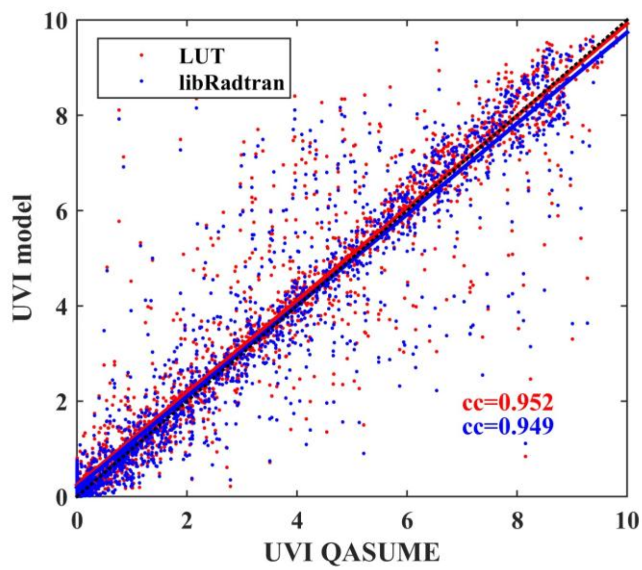
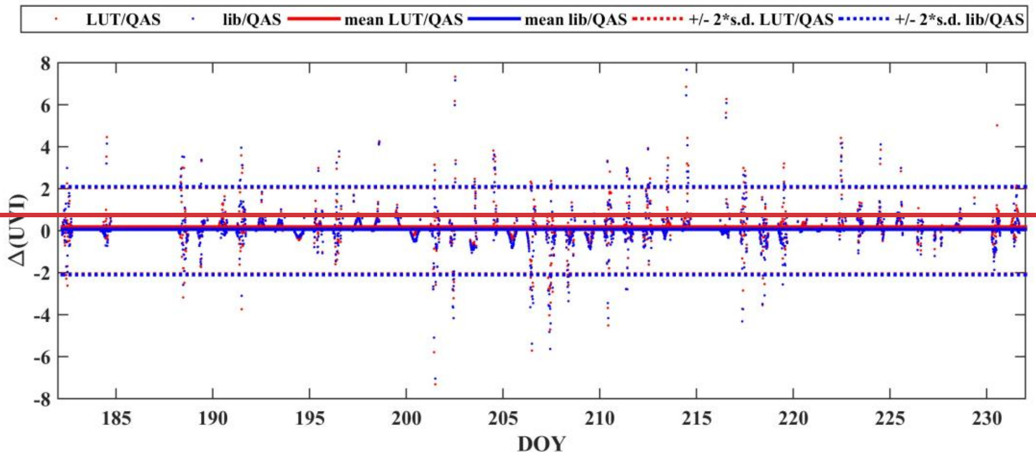


Figure ~~7~~8. Correlation between measured UVI and UVI that was modelled using the two different approaches.



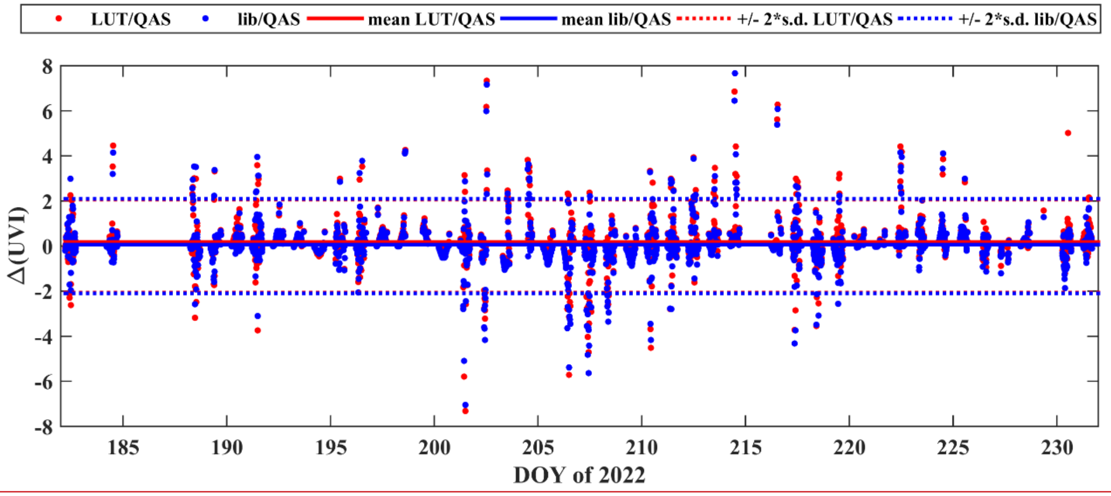
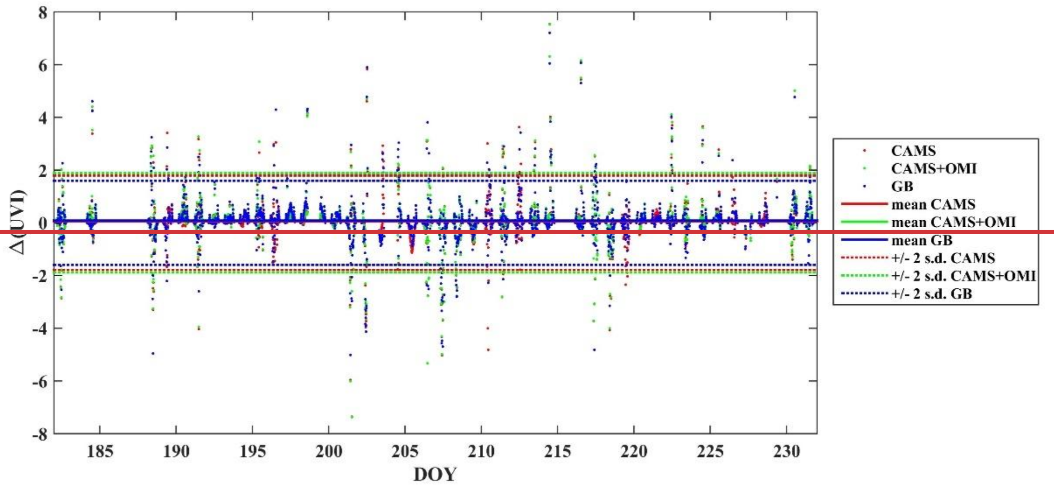


Figure 89. Differences (QASUME-model) between measured and modelled UVI

3.2 Assessment of UVIOS2 for climatological studies

In this section we assessed the accuracy of the modelled UVI when measured or reanalysis timeseries of AOD and TOC are used as inputs for the UVIOS2 system (instead of real time measurements or forecasts), that is the case when the system is used for climatological studies. The results of the comparison between the UVI from the QASUME and the UVI for the three different input datasets that were used as libRadtran inputs (i.e., ground-based TOC and AOD (GB), CAMS reanalysis AOD and TOC (CAMS), CAMS reanalysis AOD and OMI TOC (CAMS+OMI)) are shown in Fig. 910. The comparison has been performed again for SZA<75°. In all cases, the average agreement between the measured and the modelled UVI is nearly perfect (average differences of ~ 0). The standard deviation (2 x standard deviation ~1.9) is very similar to the standard deviation that was calculated for the UVI that was modelled using forecasted CAMS inputs. For the UVI that was modelled using GB data the standard deviation is slightly lower (2 x standard deviation ~1.7).



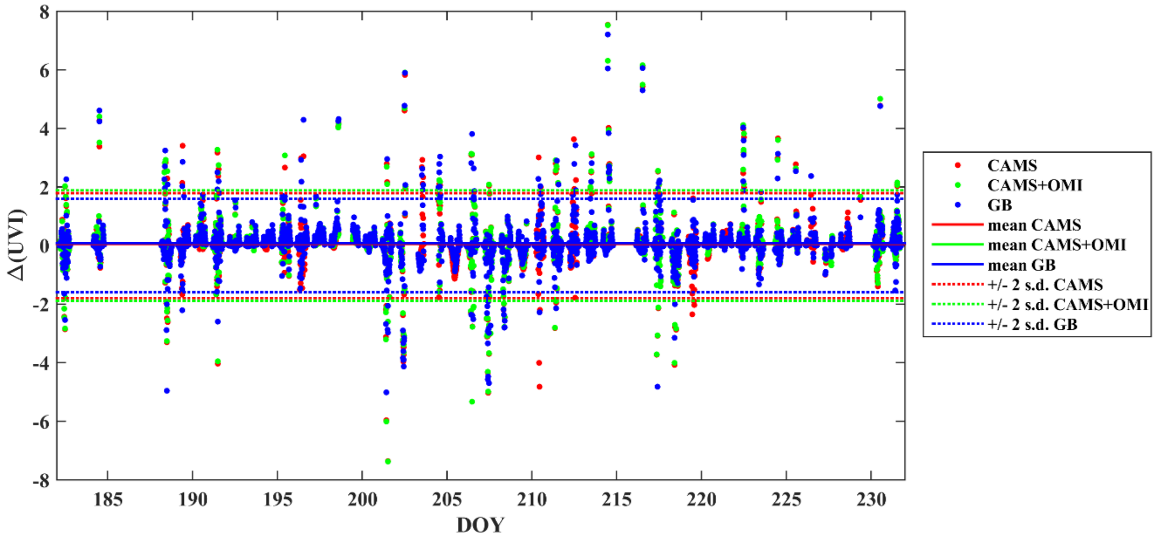


Figure ~~9~~10. Differences between the measured UVI and the modelled UVI for different UVIOS2 inputs.

A summary of the results from the comparison between UVIOS2 and QASUME for the most uncertain (Nowcasting I - SAT) and the most accurate (Climatological III - GB) setup is presented in Table ~~3~~4. The results for the two other setups (Climatological I – CAMS, Climatological II – CAMS+OMI) ~~that were discussed earlier in the manuscript~~ are very similar to those shown in Table ~~3~~4, and thus they are not presented here.

Table 3. Median differences and the corresponding standard deviation between UVIOS2 and QSUME for SZA < 75°.

Setup	All sky Δ(UVI)	St. d.	Clear sky Δ(UVI)	St. d.	All sky (%)	St. d.	Clear sky (%)	St. d.
Nowcasting I (SAT)	-0.03	0.74	0.05	0.35	<1%	66%	1.1%	6.2%
Nowcasting II and Climatological III (GB)	-0.01	0.68	0.05	0.33	<1%	63%	<1%	5.5%

3.3 Comparison with the results of the campaign

In this section we tried to assess the performance of UVIOS2 (with the default setup, i.e., forecasted AOD and TOC from CAMS and TEMIS respectively) with respect to the accuracy of the filter radiometers that participated to the campaign. The relative % differences between the UVI from the radiometers and QASUME (100% x (radiometer-QASUME)/QASUME) are presented for two cases: (1) when the calibration provided by the operator is used (USER) and (2) when the PMOD/WRC calibration is used (PMOD/WRC). In this section there is no extensive discussion relative to the results of the comparison between QASUME and the radiometers, since they have been already discussed thoroughly in Hülsen and Gröbner, (2023). The median of differences between UVIs from QASUME and UVIOS2 is less than 2%, which confirms that UVIOS2 simulated very accurately the average UVI levels over Davos during the period of the campaign, as was also discussed in sections 3.1 and 3.2. Nevertheless, the 2.5th and 97.5th percentiles are at about -20% and 35% respectively. As shown in the previous sections this large spread is mostly due to the inability of the model to predict accurately the presence of clouds under broken cloud conditions.

When the USER calibration is used to derive the UVI from the radiometers, the range between the 2.5th - 97.5th percentile is in some cases of the order of 40%, and thus comparable to the corresponding range for UVIOS2 (~ 55%). When the PMOD/WRC calibration is used, the range between the 2.5th and 97.5th percentiles is in all cases below 20%. These latter findings show the significance of the systematic maintenance and calibration of the sensors.

From Fig. 11 it is clear that, although UVIOS2 achieves to simulate very accurately the average UVI levels, it is still significantly more uncertain than the measurements from usual UV radiometers when they are well calibrated and well maintained, especially under broken cloud conditions.

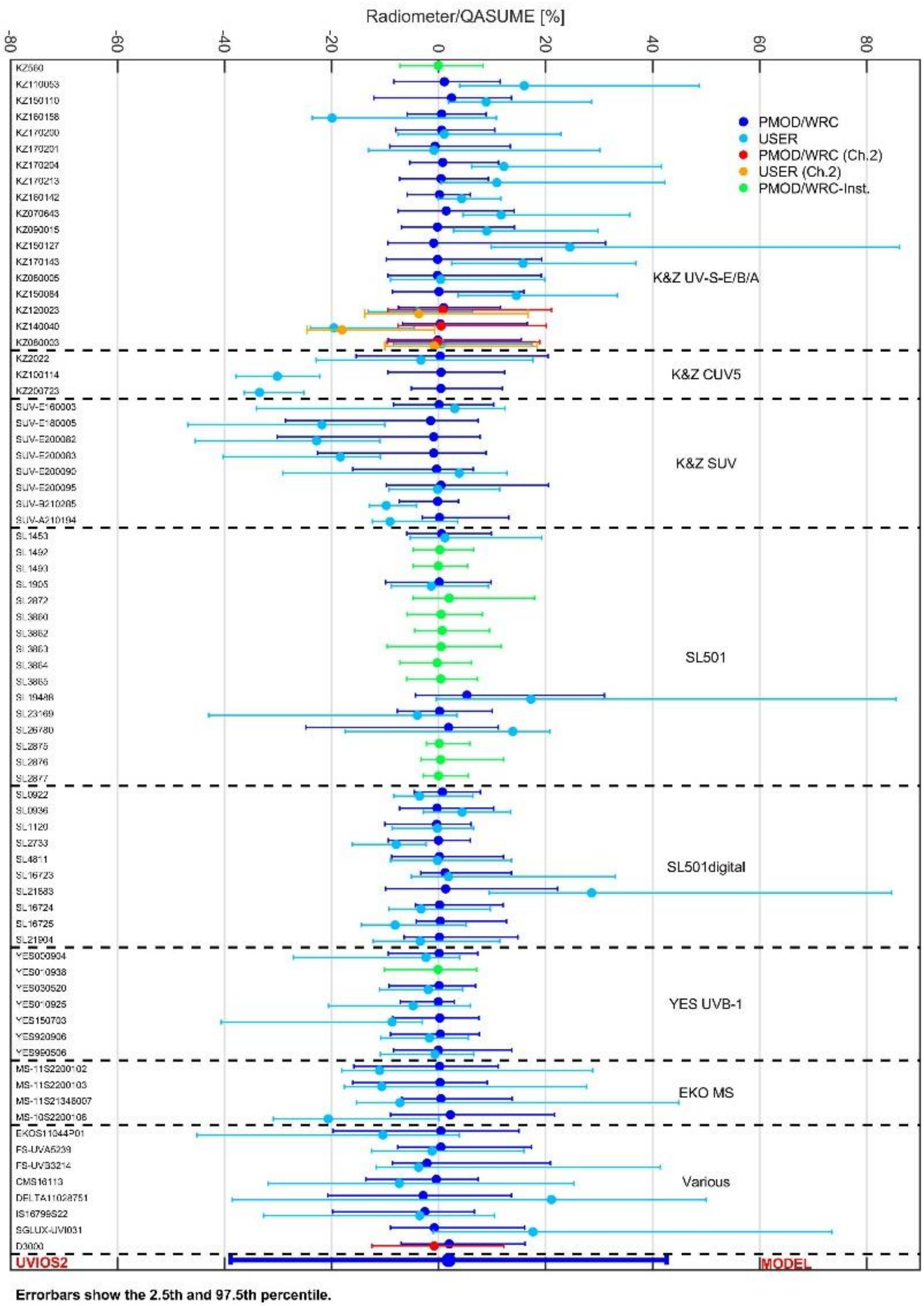


Figure 1011. Relative (in %) difference between the UVI measured by QASUME and by the filter radiometers using the operator (USER) and the new (PMOD/WRC) calibration factors. Comparison has been also performed with the UVI from UVIOS2 (SAT

configuration). Displayed is the median of the ratio for the calibration period as well as the 2.5th and 97.5th percentile for each instrument (95% coverage). Figure has been originally published in (Hülsen and Gröbner, 2023)**.**

4 Summary and conclusions

The UVIOS2 is an upgrade of the UVIOS system described in Kosmopoulos et al. (2021). We described the new features of the system, and evaluated in depth its performance at Davos, Switzerland during the UVCIII campaign. We assessed the accuracy of the UVIOS2 system when it is used for UVI forecasting and when it is used for climatological studies. To achieve that, the system outputs during the UVCIII campaign were compared to the measurements of the world reference QASUME, as well as to the measurements of the filter radiometers that participated to the campaign. The performance of the system was found to be excellent in simulating the average UVI levels, but uncertainties are larger in the simulations of the instantaneous UVI values. ~~A summary of the results from the comparison between UVIOS2 and QASUME for the most uncertain (Nowcasting I - SAT) and the most accurate (Climatological III - GB) setup is presented in Table 3. The results for the two other setups (Climatological I – CAMS, Climatological II – CAMS+OMI) that were discussed earlier in the manuscript are very similar to those shown in Table 3, and thus they are not presented here.~~

~~Table 3. Median differences and the corresponding standard deviation between UVIOS2 and QSUME for SZA < 75°.~~

~~Setup~~	~~All sky A(UVI)~~	~~St. d.~~	~~Clear sky A(UVI)~~	~~St. d.~~	~~All sky (%)~~	~~St. d.~~	~~Clear sky (%)~~	~~St. d.~~
~~**Nowcasting I (SAT)**~~	~~-0.03~~	~~0.74~~	~~0.05~~	~~0.35~~	~~<1%~~	~~66%~~	~~1.1%~~	~~6.2%~~
~~**Nowcasting II and Climatological III (GB)**~~	~~-0.01~~	~~0.68~~	~~0.05~~	~~0.33~~	~~<1%~~	~~63%~~	~~<1%~~	~~5.5%~~

Our analysis ~~shows~~ showed that the parameterization used to derive CMFUV works quite well and has reduced processing time significantly without affecting the accuracy in the system outputs. This is in agreement with the findings of Papachristopoulou et al. (2024) who have shown that the parameterization used to derive the CMF (for total solar irradiance) from COT works well. Further investigation is needed to assess the uncertainties due to the cloud effect parameterization over higher albedo terrains, although we expect that the assumption of homogeneity in the satellite pixel would still be the main uncertainty factor (e.g., large gradients in cloudiness, aerosol properties, surface albedo, surface altitude).

The satellite algorithm considers that each pixel is homogeneously covered by clouds, and thus it cannot accurately determine under inhomogeneous cloudiness conditions whether the solar disc is occluded or unoccluded. Furthermore, when solar disc is occluded, ~~we do not know the exact~~ there are uncertainties in the retrieved COT, and even larger uncertainties in the CMFUV that is subsequently calculated. The above can result in very large (especially %) differences between the measurements and the simulations. When the sun is unoccluded, broken clouds ~~near the solar disc~~ in the sky can contribute to the enhancement ~~enhance~~ of the UVI at the surface ~~significantly, by up to ~20% according to our findings~~.

The differences between the measured, forecasted, and reanalysis AOD and TOC that were used as inputs are not critical for the accuracy of the UVIOS2 outputs for Davos, and thus the performance of UVIOS2 does not differ significantly when it is used as a forecasting tool or as a tool for climatological studies. Under cloudless conditions the role of SSA was found to be equally important to the role of AOD, even at a (usually) low aerosol mountainous site such as Davos.

~~The uncertainty in the UVIOS2 forecasts was found to be comparable to the measurements of filter radiometers when they were not properly calibrated, but ~ 3 times larger compared to the measurements of accurately calibrated radiometers, which shows the significance of systematic and accurate calibration of such instruments.~~

The differences between measured and modelled UVI have been also discussed in previous studies (e.g., ~~(~~De Backer et al., 2001; Fioletov et al., 2004; Kylling et al., 1997; Mayer et al., 1997; Reuder and Schwander, 1999; Weihs and Webb, 1997)~~)~~, which have also shown that the assumptions relative to the aerosol optical properties constitute a major uncertainty factor under cloudless sky conditions. Uncertainties of 5–8% at 380 nm and even larger at 305 nm were associated ~~to~~ with the assumptions related to the aerosol optical properties. The significant role of clouds in the UVI forecasting has been also discussed in Malinovic-Milicevic and Mihailovic (2011), who used a numerical model to estimate the UVI at Vojvodina region (Serbia). Vitt et al. (2020) constructed UVI maps for whole Europe based on monthly means and showed that uncertainties in surface albedo can be also significant over mountainous mid-latitude sites in winter. Dahlback and Stamnes (1991) reported that at the Tibetan Plateau (3000-5000 m a.s.l.) the UVI can be enhanced by ~30% under broken cloud conditions compared to cloudless sky conditions. Similar impacts by clouds on the UVI were reported by Allaart et al. (2004).

Our study makes clear that there is a need for more accurate representation of the SSA in UV models in order to achieve more accurate modelling under cloudless conditions, even for low aerosol sites such as Davos. When AOD is 0.3 – 0.4, the effect of changes in the AOD is similar with the effect of changes of the same magnitude in the SSA. SSA measurements at shorter, and more effective regarding their biological impacts, UV wavelengths are not easy to perform, and long-time series are not available ~~(e.g.,~~ (e.g., Bais et al., 2019; Corr et al., 2009; Go et al., 2020; Mok et al., 2016, 2018). Capturing the instantaneous impact of clouds using satellite images is challenging, especially for enhancement events. In this study we showed that enhancement events can not be easily captured even when ground-based information is used. Since using satellite-based cloud information is the only way to forecast the UVI at large spatial scales, the accuracy in the description of the effects of clouds is a common problem for UV models that cannot be easily solved.

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Code and Data availability

Analytical description and instructions on how to access the model are provided in Kosmopoulos et al., (2021). All codes and datasets that are necessary to reproduce the results used in this paper are archived on Zenodo (Fountoulakis, 2024).

Competing interests

The contact author has declared that none of the authors has any competing interests.

Author contribution

Conceptualization: SK, IF. Methodology: SK, IF and KP. Formal analysis: IF, KP, JG, GH, and DK. Software: IF, KP, and I-PR. Validation: IF, KP, SK, GH, and JG. Investigation: IF and KP. Resources: SK and CK. Data curation: IF, KP, NK, JG and GH. Visualization: IF, KP and GH. Writing (original draft preparation): IF, KP, and AM. Supervision: SK. Writing (review and editing): IF, KP, SK, JG, GH, I-PR, DK, AM, CK, and CZ. All authors gave final approval for publication.

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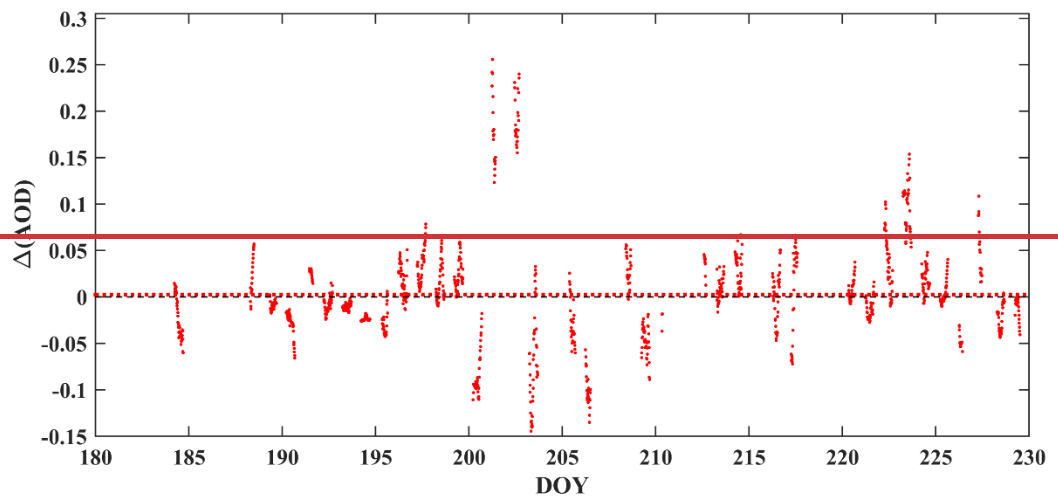
965 **Appendix**



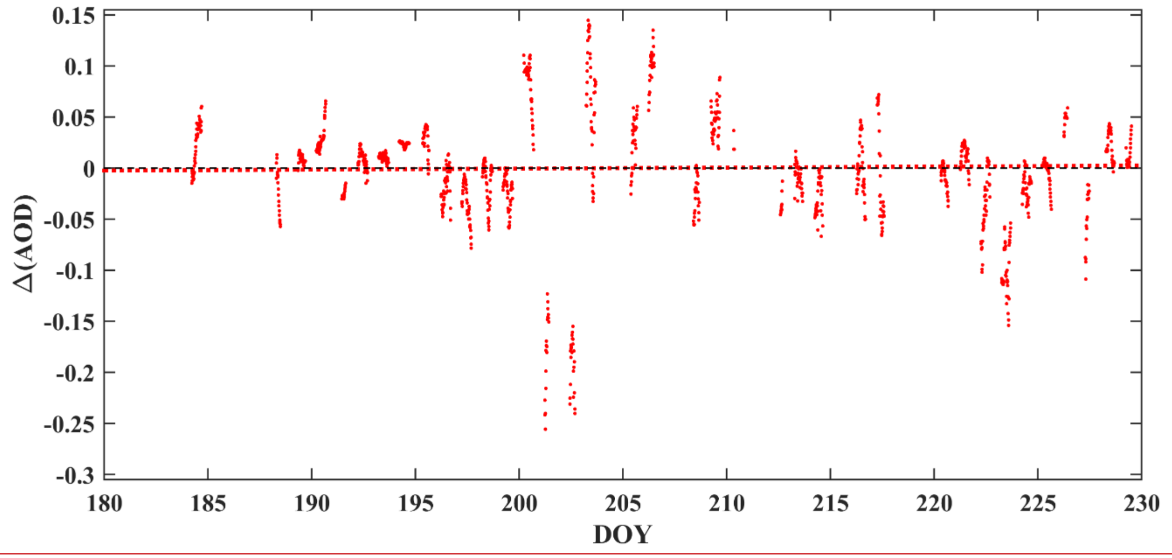


Figure A1: Differences between the 550 nm AOD from CAMS and the CIMEL (CAMS-CIMEL).

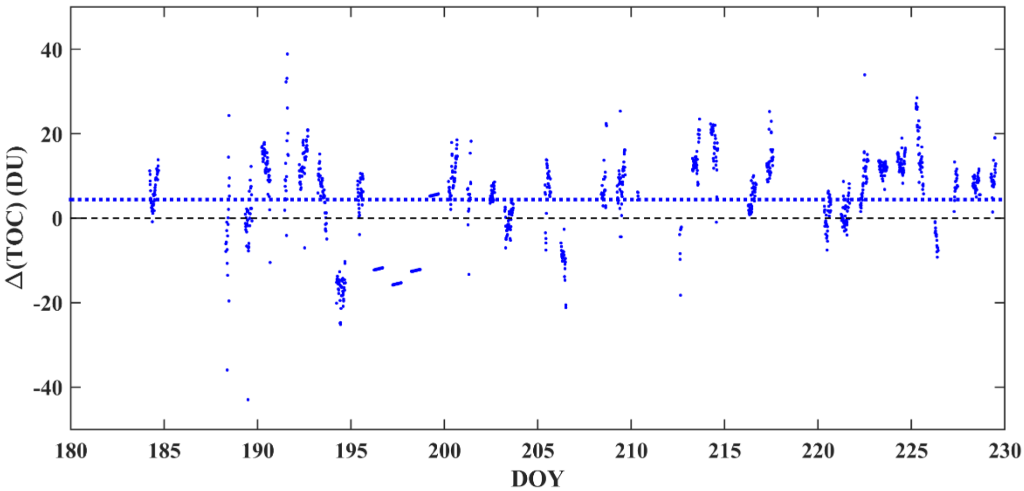


Figure A2: Differences between the TOC from TEMIS and the Brewer (TEMIS-Brewer).

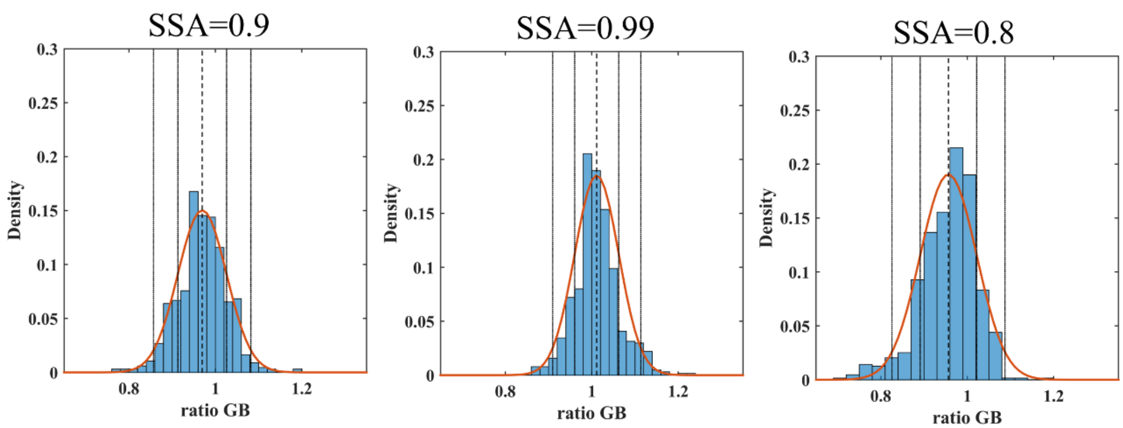


Figure A3: Density plots of the ratio between simulated (using GB measurements) and measured clear-sky UVI when different SSA values are used for the simulations. Vertical lines represent the mean and the 1-sigma and 2-sigma intervals if a normal distribution (red line) is assumed.