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CloudS
**A new parameterization of
radiative transfer through clouds
(summary of development and first validations)**

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Preface

The work presented in this report is part of the deliverable D8.2 for the European research project Heliosat-3. It belongs to workpackage 3020 (Cloudy sky scheme). The Heliosat-3 project is supported by the fifth frame-work program of the European Commission under contract number NNK5-CT-2000-00322.

CloudS

A new parameterization of radiative transfer through clouds
(summary of development and first validations)

Rolf Kuhlemann and Jethro Betcke, 28.5.2005

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Introduction

To derive a new “all sky” scheme for radiative transfer through the atmosphere within the Heliosat-3 project, the problem has been separated in “clear sky”, “cloudy sky”, and “broken cloud” cases. For “clear sky” situations the **SOLIS** scheme has been developed [1], which takes advantage of the radiative transfer library of according solvers, *libRadtran* [2]. It is used within **SOLIS** for generating an approximation with two sampling points at solar zenith angles 0° and 60° , and provides data with the spectral k-band resolution of Kato et al. [3]. It considers - like *libRadtran* - information about ozone, water vapour, and aerosols, either derived from satellite measured data or taken from climatological data bases. Consequently, **SOLIS** provides accurate information about global irradiance and its components as well as illuminance for all atmospheric states, but calculates much faster than *libRadtran*.

The new “cloudy sky” scheme **CloudS**, described here, works closely related to **SOLIS**. It modifies the “clear sky” irradiance calculated by **SOLIS** and uses the k-band resolution of Kato et. al.. The radiative transfer code SBDART [4] is used to study radiative transfer through clouds and its sensitivity to cloud properties like optical thickness τ_c , cloud height and thickness, and effective droplet radii r_{eff} for different geometries.

The parameterization of the whole target space calculated with SBDART is the next step of development. Several functions and functional compositions are tested for an accurate approximation.

A comparison between results calculated with **CloudS** and original SBDART data gives an idea of the best quality achievable. A similar comparison with more accurate *libRadtran* results will allow for an improved evaluation. For this purposes, cloud properties are derived from Meteosat-8 data. They are generated by DLR with the APOLLO software [5].

Finally, first validation results for Vaulx-en-Verlin (nearer Lyon) show its overall quality and possible further improvements by comparison with ground measured data.

Sensitivity studies with SBDART

SBDART allows the simulation of radiative transfer through homogeneous cloud layers, while isotropic ground reflection models for ground types vegetation, water, and sand are used.

The atmospheric state is described in SBDART by standard profiles, e.g. *Midlatitude Winter*. Here, the profile for *Midlatitude Winter* has been chosen due to its low water vapour content, combined with a disregard of any type of aerosol. This choice should conserve the general applicability of the results.

Prior further investigations the wavelength resolved effect of different ground and cloud configurations has been tested to identify sensitive wavelength ranges. Furthermore, the match of such ranges with Kato bands for the whole wavelength

range between 240 nm and 4600 nm has been checked.

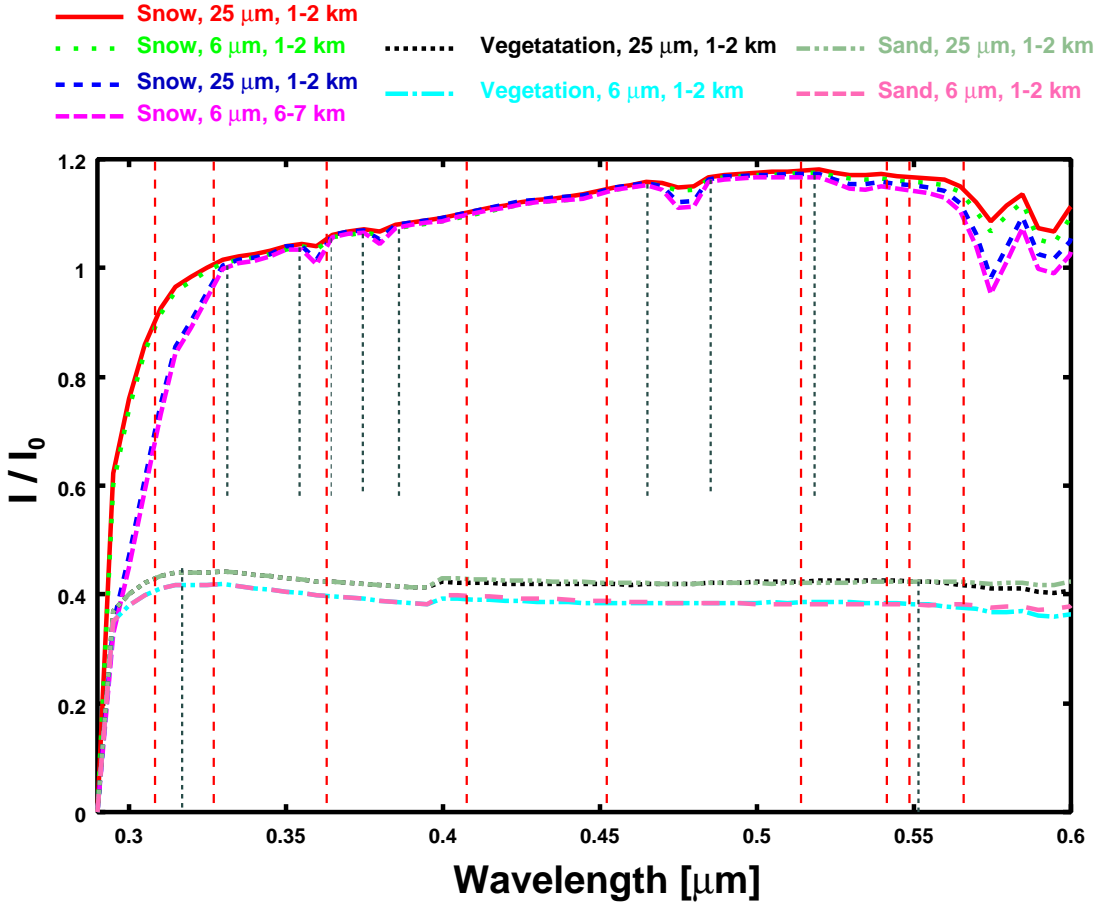


Figure 1: Example of wavelength dependent effects of ground model, effective droplet radii r_{eff} , and cloud height on the relation between “cloudy sky” and “clear sky” irradiance. For simulations $\tau_c = 24$ and $\theta = 0^\circ$. Black vertical lines separate sensitive and insensitive ranges, red vertical lines denote Kato band separations.

Figure 1 gives an example of such wavelength dependent effects for a sensitive configuration at solar zenith angle $\theta = 0^\circ$ and optical depth $\tau_c = 24$ (see also Figure 3). It shows, that the mentioned match between sensitive regions and Kato bands does not exist. Furthermore, the meaning of the ground model is obvious. The stronger ground reflection is, the more complex the radiative situation under clouds gets. Surprisingly, the irradiance under clouds can even exceed the “clear sky” irradiance over snow for the short wave part of the visible spectrum. The model for vegetation does not differ much from sand. The sensitivity to effective cloud droplet radii seems to be nearly constant over the wavelength range. The sensitivity of the mentioned intensity relation to cloud height and thickness has been studied next. These simulations are done with a mean effective droplet

radius of $8 \mu m$, at a wavelength sensitive to water at 720 nm , and with a ground model for snow, representing an extreme situation (Figure 2).

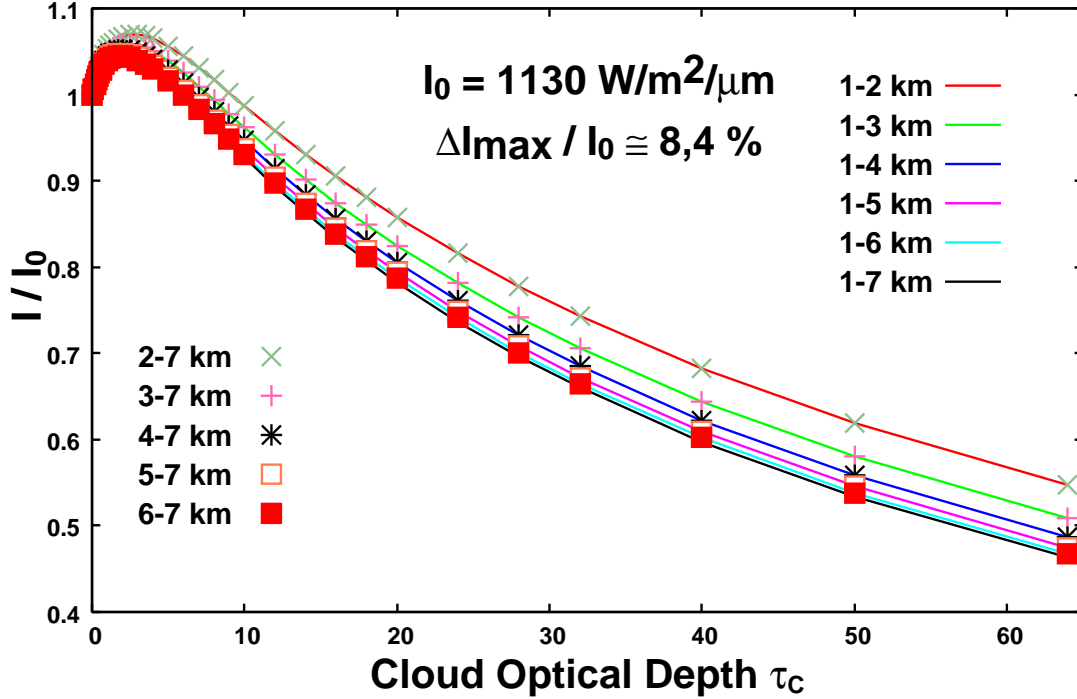


Figure 2: Influence of height and thickness of clouds on the relation between “cloudy sky” and “clear sky” irradiance with varying optical depth. Most sensitive situations (Snow, $\theta = 0^\circ$, $r_{eff} = 8 \mu m$, $\lambda = 720 \text{ nm}$) are given altogether with maximum deviation in intensity ΔI_{max} .

As Figure 2 shows, the irradiance under a cloud increases when cloud height and thickness are reduced. Furthermore, the differences grow with increasing optical depth. The effect is not very strong, even with a strong reflecting ground model for snow this effect reaches only up to 8% for optical depth $\tau_c \approx 60$. It is much smaller with a ground model for vegetation.

In conclusion, a standard cloud between 1 km and 2 km has been chosen for all following simulations to give an upper limit for calculated irradiances. The same is true for the used ground model for vegetation, which is the closest to the available sites of measurement.

The next step is the investigation of the sensitivity to effective droplet radii. By using the mentioned standard cloud, the change of the irradiance with varying optical depth has been studied. For a water sensitive wavelength of 720 nm the effects of most common droplet radii on radiative transfer have been investigated. Figure 3 shows, that the effect of effective droplet radii on radiative transfer through clouds reaches its maximum for $\tau_c \approx 24$ if a ground model for vegetation, a standard cloud, and a solar zenith angle of $\theta = 0^\circ$ are chosen. For

such an extreme configuration the maximum deviation sums up to about 6 % . For later simulations an effective droplet radius of 8 μm is used, because it is a mean value over all types of clouds and their probability. Nevertheless, the parameterization is generated for variable droplet radii, because in the future this type of information will probably be derived within the APOLLO software.

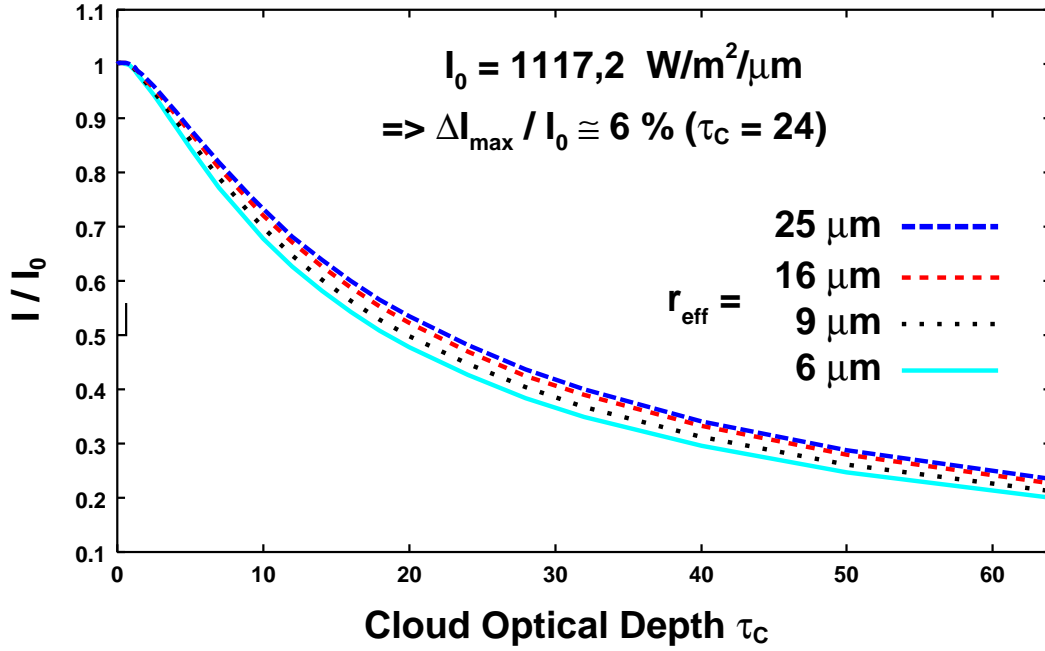


Figure 3: Influence of effective droplet radii on the relation between “cloudy sky” and “clear sky” irradiance with varying optical depth. sensitive situations (Vegetation, $\theta = 0^\circ$, $r_{\text{eff}} = 8 \mu m$, $\lambda = 720 \text{ nm}$) are tested.

Functional composition and properties

With the results of all sensitivity studies it has been decided to derive the new parameterization for the relation $I^{\text{Cloudy}}/I^{\text{Clear}}$ for the Kato bands 3-29 with a ground model for vegetation, an atmospheric profile for *Midlatitude Winter*, no aerosols, and a standard cloud between 1 km and 2 km. An implicit construction of the following type has been used to parameterize radiative transfer through such clouds with properties τ_c, r_{eff} , and dependent of the solar zenith angle Θ :

$$\frac{I_{SBDART}^{\text{Cloudy}}}{I_{SBDART}^{\text{Clearsky}}} = f(\tau_c(\Theta(r_{\text{eff}}))); \quad \tau_c \in [0; 300]; \Theta \in [0 : 80]; r_{\text{eff}} \in [6 : 50] \quad (1)$$

Commonly used radiative transfer relationships have not been successful when applied. A screening of numerous functional relationships finally resulted in the following set of equations:

$$f(\tau_c) = \frac{a_1}{1 + a_2 * \tau_c}; \quad (2)$$

$$a_1 = a_1(\Theta) = a_{11} - a_{12} * \Theta^{a_{13}}; \quad (3)$$

$$a_2 = a_2(\Theta) = a_{21} + a_{22} * \Theta^{a_{23}}; \quad (4)$$

$$a_{j1} = a_{j1}(r_{eff}) = \frac{a_{j11} * r_{eff}}{a_{j12} + r_{eff}} + a_{j13} * r_{eff}; \quad j \in (1, 2); \quad (5)$$

$$a_{j2} = a_{j2}(r_{eff}) = a_{j21} * (1 + r_{eff})^{a_{j22}}; \quad j \in (1, 2); \quad (6)$$

$$a_{j3} = a_{j3}(r_{eff}) = a_{j31} * (1 + r_{eff})^{a_{j32}}; \quad j \in (1, 2) \quad (7)$$

The resulting parameterization gives 14 coefficients a_{jik} , which have to be optimized for each Kato-band (4-29 corresponding to wavelength $\lambda \in [307 \text{ nm}, 3002 \text{ nm}]$).

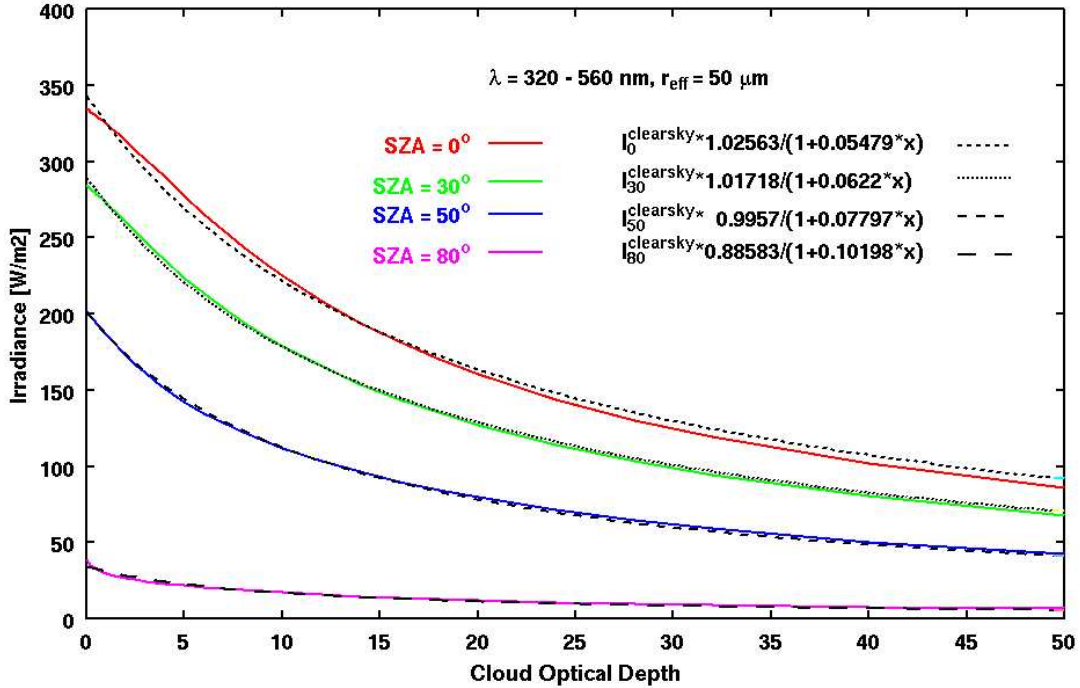


Figure 4: SBDART results (color) and parameterization (black) for irradiance under clouds with varying optical depth for different solar zenith angles in the wavelength range 320-560 nm and an extreme effective droplet radius of 50 μm .

Figure 4 presents examples of the general behaviour of the chosen parameterization (function $f(\tau_c)$) and its quality for sensitive wavelength and droplet radius. It shows, that the match is quite well, unless the solar zenith angle is small. For very small optical depth and small solar zenith angles the intensity

does not decrease instantly and the parameterization does not reproduce this. This problem causes further effects, as the approximation algorithm (Marquard-Levenberg), which defines the coefficients a_{jik} , minimises the overall error. The “clear sky” irradiance is not reproduced for vanishing optical depth, the “cloudy sky” irradiance is too small for an optical depth around 5, and it is too high for a high optical depth.

Accuracy of **CloudS** compared with SBDART

To assess the quality of the method, the whole target space has been calculated with the new parameterization **CloudS** and compared with the original SBDART results (Figure 5).

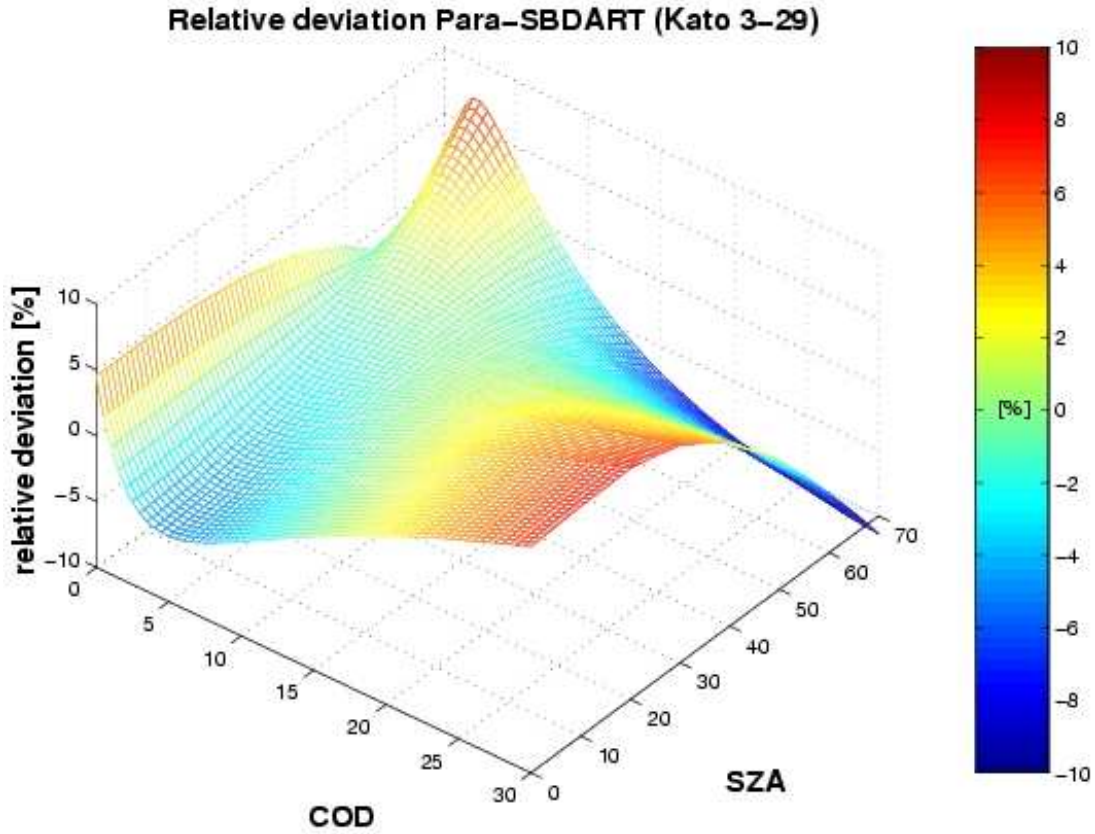


Figure 5: Relative deviation between **CloudS** and SBDART results for all Kato-bands with varying optical depth of a cloud between 1 km and 2km, a varying solar zenith angle, and a droplet radius of $8 \mu m$ (ground model: vegetation).

Two special situations show important deviations. For a very small optical depth and small solar zenith angles the intensity calculated with **CloudS** does not follow the shape of the original SBDART data. The according errors range between -5% and +5% . For large solar zenith angles and the same optical depth even higher

errors occur. With increasing optical depth (> 20) the errors increase steadily, for small solar zenith angles positive, for high solar zenith angles negative. To avoid unphysical results for an optical depth $\tau_c = 0$, the “cloudy sky” irradiance has been set for the following calculations to the “clear sky” value if it is larger.

Validation for Vaulx-en-Velin: Calculations with satellite derived products and input data

To validate the developed parameterization it is necessary to determine a “clear sky” irradiance I_o , a solar zenith angle Θ , an optical depth τ_c , and an effective droplet radius r_{eff} . The “clear sky” irradiance is calculated by **SOLIS** for Vaulx-en-Velin between March and August 2004. It is run with climatological values for aerosols [6] and water vapour [7]. For the evaluation aimed for, this means, that “clear sky” irradiance data is generated with a realistic atmospheric state, while the “cloudy sky” relation I^{Cloudy}/I^{Clear} has been developed with an aerosol-free atmosphere with low water vapour content as described above.

The cloud properties τ_c and r_{eff} , generated with APOLLO and provided by Marion Schroedter-Homscheid (DLR), were calculated taking advantage of the infrared channels of Meteosat-8 and have therefore a spatial resolution of 3 km * 3 km. After geolocation of the according HDF-data a time series of τ_c was available. The according time series have been provided by Jethro Betcke. Similar time series of I_o and Θ for Vaulx-en-Velin allowed the calculation of global radiation under clouds with the new scheme **CloudS**. The effective droplet radius r_{eff} has been set to 8 μm .

The results described below are generated and compared for total overcast situations, as **CloudS** is only developed for homogenous cloud layers. The APOLLO product *cloud fraction* allows to identify such situations.

The library *libRadtran* contains the SBDART solver and this option is used together with the APOLLO products to calculate global irradiance for the mentioned time series. This opens up the opportunity to evaluate the quality of **CloudS** without possible inaccuracies of ground measurements or APOLLO products.

Finally, the well known *Cloud Index* is used together with the **SOLIS** scheme for “clear sky” irradiance for comparison with the known properties of the “old” Heliosat procedure [8]. This has been done with the high resolution data of Meteosat-8 (1 km * 1 km). For this purpose, a proper geolocation [9] was necessary and failures during recording or receiving had to be eliminated.

Validation for Vaulx-en-Velin: Comparison and results

To evaluate the quality and possible effects of **CloudS** plots of the diurnal variation of global irradiance - **CloudS**, libRadtran, SOLIS/Cloudindex, ground measured - have been generated and studied (Figure 6, 7, and Appendix).

Figure 6 shows that the geolocation has been successful. The match between the APOLLO derived values and ground measured data in terms of variations is satisfying. Furthermore, it is easy to recognize, that there is often a positive bias between these values and ground measured data together with an additional positive bias separating the **CloudS** results from the *libRadtran* results. This is not surprising, because the state of the atmosphere used to generate it - a lack of many scatterers - and the “wrong” ground reflection have been expected to increase the irradiance.

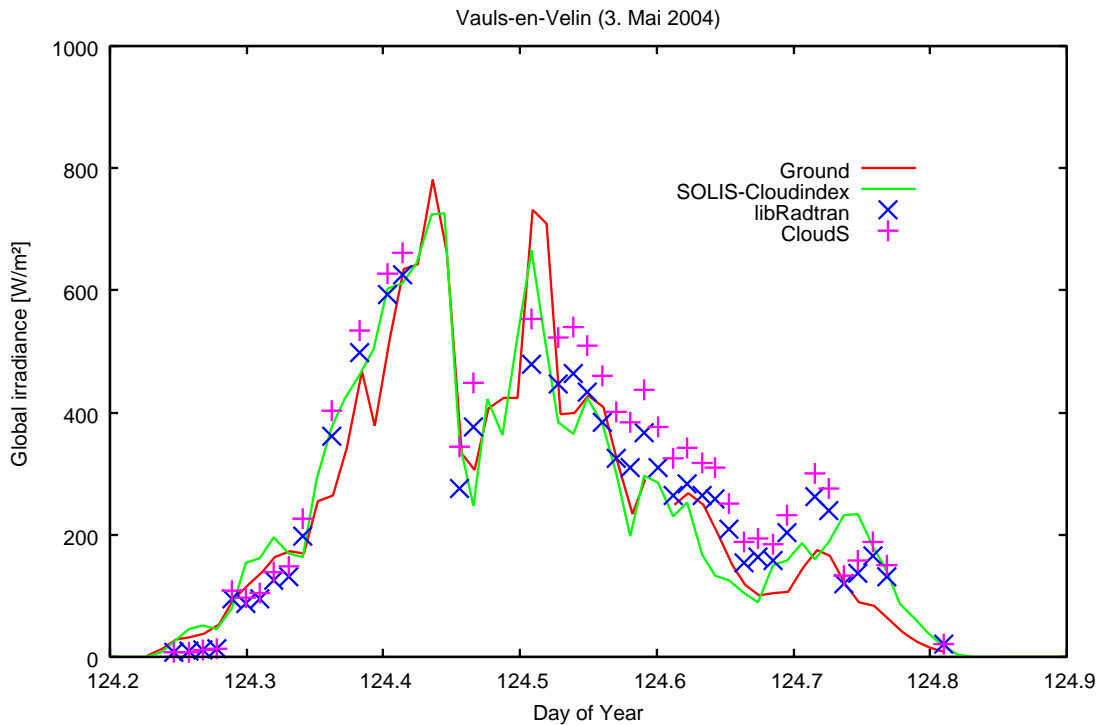


Figure 6: Example (of good quality) for the diurnal variations of the global irradiance in Vaulx-en-Velin. Calculations using APOLLO products (Libradtran, CloudS) and ground measurements for the 3rd of May. Calculations using APOLLO products were done only for total overcast situations. For comparison ground measured data and SOLIS/Cloudindex results are given.

Unfortunately, the situation in Figure 6 represents a very accurate case. Figure 7 shows an example of bad quality. The main reason might be a failure within the APOLLO software, which apparently detected an optically thin cloud, while

there has been a thick one.

A visual quality check of all days between April and August 2004 supports these results. The given examples are more or less extreme cases and all possibilities in between are realized (see Appendix). Therefore it would be interesting to find out, whether this belongs to the boundary conditions used within *libRadtran* or to the quality of the cloud information provided by APOLLO (next chapter).

Beside misdetections of APOLLO there are the two mentioned positive biases of *libRadtran* and **CloudS**. Furthermore, the comparison with the **SOLIS/Cloudindex** procedure shows, that it has a better quality and matches the ground measured data surprisingly well.

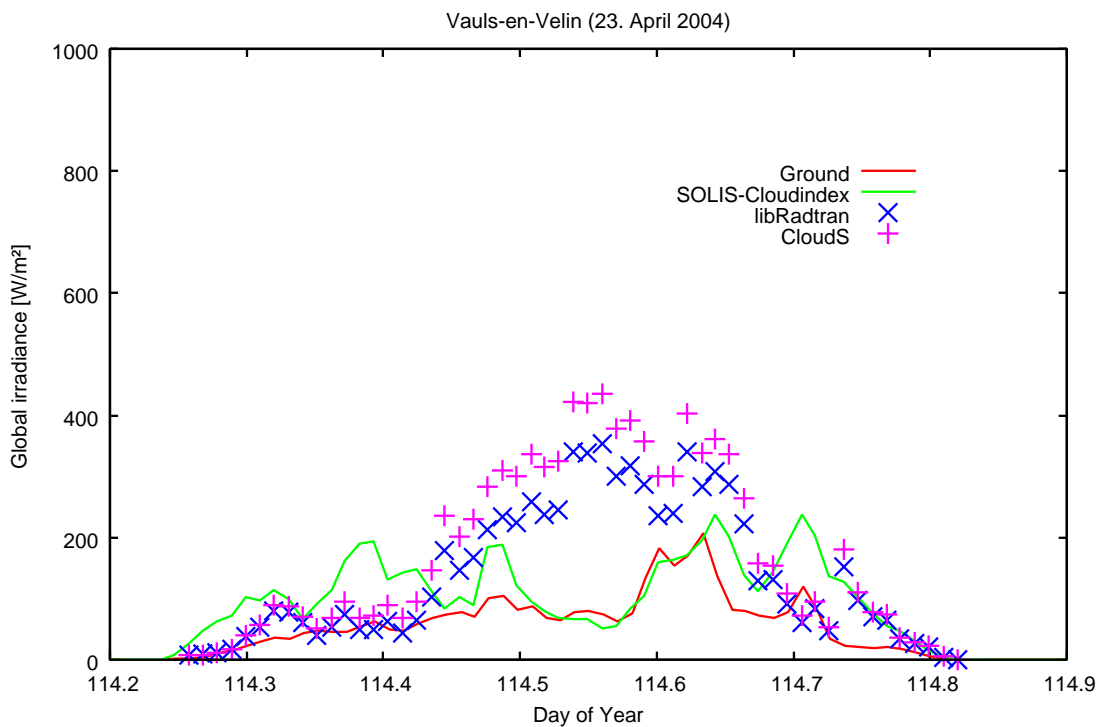


Figure 7: Example (of bad quality) for the diurnal variations of the global irradiance in Vauls-en-Velin. Calculations using APOLLO products (Libradtran, CloudS) and ground measurements for the 23rd of April. Calculations using APOLLO products were done only for total overcast situations.

To quantify these results, statistical analysis have been done. Table 1 summarizes the *rmse* and the *bias* for comparisons between different calculation methods and ground measured data for the months March - August.

For these comparisons it has been necessary to derive averaged 15 minutes values from 5 minutes resolved ground measured data, provided by Dominique Dumortier. No spatial averaging has been performed due to the restriction to total overcast situations.

The results show, that the best quality - given by SOLIS/Cloudindex - is not reached by both, *libRadtran* and **CloudS** calculations. The inaccuracy of *libRadtran* seems to be mainly driven by inaccuracies of APOLLO, while further deviations of **CloudS** can be caused by inaccuracies of the parameterization described above or as consequence of the boundary conditions used to generate it. The latter means the atmospheric description within SBDART.

Comparison	Error	March	April	May	June	July	August
SO/Cl - Ground	<i>rmse</i>	44,44 %	47,72 %	40,75 %	36,64 %	50,16 %	46,24 %
SO/Cl - Ground	<i>bias</i>	0,75 %	12,76 %	10,93 %	1,16 %	-1,65 %	4,25 %
Lib - Ground	<i>rmse</i>	55,70 %	65,15 %	55,55 %	49,58 %	80,57 %	74,83 %
Lib - Ground	<i>bias</i>	24,76 %	23,35 %	11,68 %	6,95 %	13,02 %	14,24 %
CloudS - Ground	<i>rmse</i>	64,05 %	80,32 %	65,48 %	54,66 %	81,23 %	76,02 %
CloudS - Ground	<i>bias</i>	35,57 %	44,03 %	28,44 %	20,18 %	23,20 %	24,74 %
CloudS - Lib	<i>rmse</i>	11,89 %	20,80 %	19,49 %	17,39 %	14,16 %	14,02 %
CloudS - Lib	<i>bias</i>	8,67 %	16,76 %	15,01 %	12,37 %	9,00 %	9,18 %
Total overcast cases		313	595	498	427	267	428

Table 1: Intercomparison between 3 different methods to derive global irradiances for total overcast situations. Calculated results are compared with ground measured data (Ground) for Vaulx-en-Velin and errors are presented in % . Monthly averages of data with 15 minutes time resolution are given. LibRadtran (Lib) and **CloudS** values are calculated with a standard water cloud between 1 km and 2 km height, effective droplet radius of 8 μm , and the optical depth τ_c derived from Meteosat-8 with APOLLO. For comparison the errors of the “old” procedure using SOLIS/Cloudindex (SO/Cl) are given also.

Validation for Vaulx-en-Velin: Reasons for inaccuracy of **CloudS**

The differences between results calculated with libRadtran and ground measured data are not investigated here, as the topic of this paper is the new parameterization **CloudS** and not APOLLO. This work will be done within the ESA project ENVISOLAR and the Virtuel Institute Energy Meteorology (vIEM).

A direct comparison between **CloudS** and libRadtran results has been done by us-

ing scatterplots (Figures in Appendix). They show the overestimation of **CloudS** by as much as 90 W/m^2 . These maximum values are produced for global irradiance between 200 W/m^2 and 500 W/m^2 .

A closer look at the dependencies is presented in Figure 8. For solar zenith angles up to 55° the deviation between both methods grows monotonously with optical depth. Further solar zenith angles up to 70° cause a strong peak for $\tau_c \approx 2$, before the deviation drops down again. Solar zenith angles above 70° cause this peak also, but with growing optical depth it drops down even to negative values. All these features are shown in Figure 5, where the expected differences to SBDART are presented.

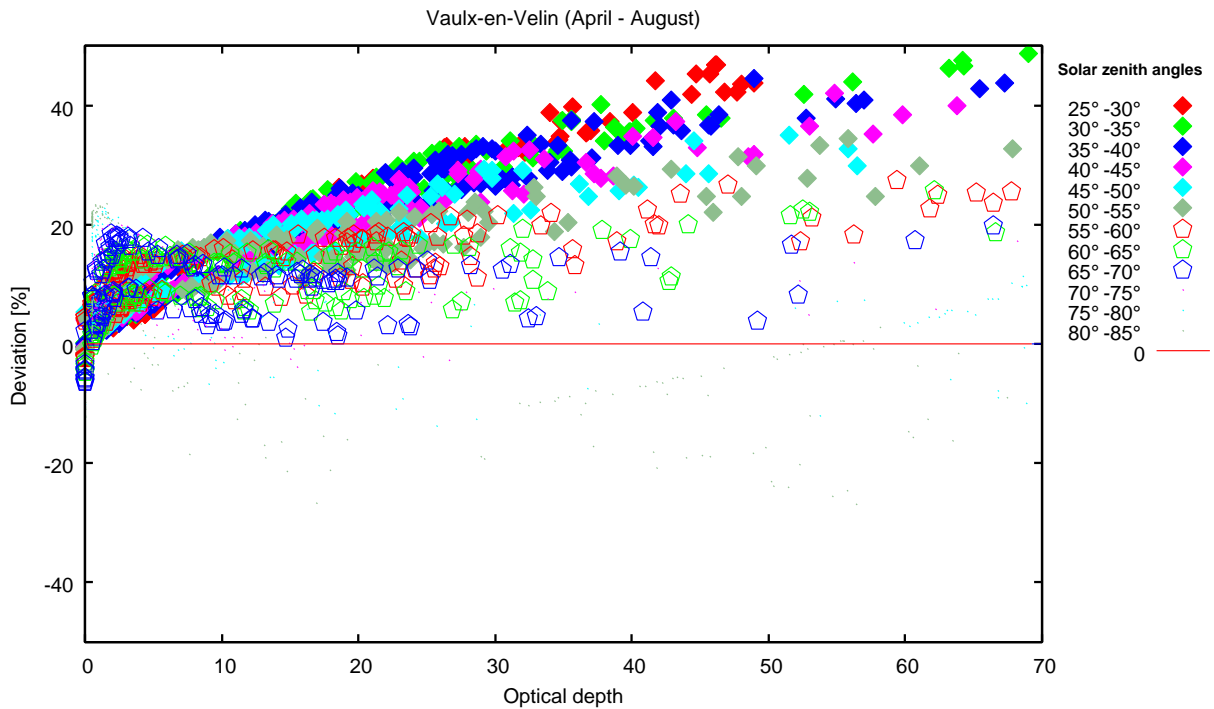


Figure 8: Deviations between **CloudS** and *libRadtran* for April-August 2004 and their dependency on cloud optical depth. Ranges of solar zenith angle with different behaviour are separated by different types of symbols.

While the problem of small solar zenith angles and small optical depths does not occur - the sun never reaches the zenith in Vaulx-en-Velin - a peak arises for small optical depth and high solar zenith angles. For small solar zenith angles, but high optical depth the deviations grow steadily like found here. For both, high optical depth and solar zenith angles (above 70°) the deviation drops down below the SBDART values, just like observed by comparison with *libRadtran*. In conclusion, these features strongly support the result, that most deviations between **CloudS** and *libRadtran* are caused by inaccuracies in the chosen pa-

parameterization for radiative transfer through clouds.

The idealization of neglecting aerosols, small amounts of water vapour, and an isotropic vegetation model seem to have no dominating influence. Note, that the relation of “cloudy sky” to “clear sky” irradiance is developed with such an ideal atmosphere, while “clear sky” values are derived with proper atmospheric data.

Further steps to improve CloudS

Major efforts are still to be done for a new “all sky” scheme for radiative transfer through clouds. The effect of the APOLLO product *cloud fraction* should be studied and parameterized.

Furthermore, *libRadtran* calculations using the APOLLO product *cloud level* as input, which represents three different altitudes of clouds. A comparison of such data with ground measured data will allow for the evaluation of the APOLLO quality and answer the question if corrections to the scheme are necessary.

Before spending more efforts on improving of CloudS, its validation should include other sites of measurement and data of all seasons.

While it is not expected, that better atmospheric descriptions or ground description will improve CloudS very much, unless ground reflection is very strong, a different choice for the parameterization is suggested. The function $f(\tau_c) = (a_1 + a_2 * \tau_c)^{-a_3}$ would improve the quality of CloudS. It has not been used, because of the strong increase in the number of coefficients to optimize. Therefore, it is suggested to neglect the cloud property effective droplet radius, at least as long as this APOLLO product is not available. After this reduction of the problem it might be also possible to test functional compositions $f(\tau_c) = f_1(\tau_c) + f_2(\tau_c)$, which would probably solve the complicated situation for low optical depths (< 5).

A further improvement is possible, if the mesh, used for approximation of SB-DART results and defining the coefficients of CloudS for each Kato band, resamples the frequency distribution of τ_c .

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Appendix

The next four figures show scatter plots to analyse the differences between **CloudS** and *libRadtran*, and to identify according reasons. Further plots give many examples for diurnal variations of irradiance measured and calculated with three different methods between April and August 2004.

