REALISTIC SIMULATIONS OF EARTHCARE OBSERVATIONS

Bernhard Mayer*
Meteorological Institute, Ludwig-Maximilians-Universität München, Germany

Françoise Faure, Luca Bugliaro, Tobias Zinner, and Robert Buras
Deutsches Zentrum für Luft- und Raumfahrt (DLR), Oberpfaffenhofen, Germany

ABSTRACT

The EarthCARE mission is expected to provide new insights into aerosol-cloud-radiation interactions thanks to simultaneous active and passive observations of the Earth. To prepare for this mission we have been developing a simulation environment for currently three of the four instruments (MSI, BBR, and ATLID), with special emphasis on the realism of the 3D cloud and aerosol data and on the accuracy of the radiative transfer simulations. As input we use data from the operational numerical weather prediction model COSMO-DE of the German Weather Service which provides consistent 3D fields of temperature, pressure, water vapour, as well as of water and ice clouds. To obtain a spatial resolution suitable for 3D radiative transfer, a downscaling technique has been developed that yields a pixel size of 560 m. Spectral characteristics of the surface as well as scattering and absorption properties of ice clouds, water clouds and aerosols are taken into account in a consistent way. Such data sets, where both radiation as well as physical properties are known, are extremely useful to develop, test and tune retrieval algorithms for the EarthCARE payload.

1. INTRODUCTION

Solar radiation drives atmospheric circulation and hence weather and climate. Tropospheric and stratospheric chemistry are controlled by photochemical reactions and thus by shortwave radiation. Accurate knowledge about solar and terrestrial radiation and their interaction with clouds, aerosol particles, and trace gases is therefore required for all fields of atmospheric science, in particular for the determination of the Earth's radiation budget that controls our climate.

ESA's Earth Clouds, Aerosol and Radiation Explorer (EarthCARE) mission, with its unprecedented collection of instruments on one single satellite platform, is expected to yield an outstanding contribution to the understanding of the cloud-aerosol-radiation interaction. EarthCARE will provide accurate global observations of top of atmosphere (TOA) fluxes with coincident cloud and aerosol properties with the aim to improve the understanding and modelling of climate, to characterise the impact of aerosol and clouds on radiation, and to investigate feedback processes in the Earth-Atmosphere system. Possible products from the four EarthCARE instruments (either individually or in synergy) comprise optical, micro- and macrophysical properties of clouds (e.g., effective cloud particle radius and cloud top temperature), vertical velocities (convection and/or sedimentation processes), rain rates (rainfall, drizzle), aerosol properties, as well as narrow band and broad band TOA fluxes.

Validation of retrieved cloud properties is essential but complicated. The difficulty stems from the large difference in scale between the satellite footprint and the independent ground based or aircraft observation. Cloud observations from the surface are one possible source of validation data for cloud cover and optical thickness (or liquid water path). While EarthCARE will provide averages over at least the footprints of the individual instruments and usually only over several lidar or radar shots, a ground station typically measures vertical profiles which are representative for the point location but not necessarily for a larger area. Differences between satellite and ground or aircraft observations may therefore be due to retrieval or instrumental problems on the one hand; on the other hand, however, they may simply be caused by the different scales of the data compared and thus give no indication of the uncertainty of the retrieval. For cloud microphysical properties like phase and droplet or particle size, the situation is even worse: Only few in-situ data, measured by aircraft, are available. To get reliable estimates of cloud microphysical properties from the ground, a complex combination of instruments is required to obtain quantitative results (e.g. microwave radiometry, radar, lidar). In addition, as has been shown e.g. by Zinner and Mayer (2006) cloud inhomogeneity and 3D effects introduce bias and considerable noise into the retrieved optical thickness and effective radius. Although one could live with a small bias, noise hampers the validation by in-situ observations, as many data are needed to ob-

* *Corresponding author address:* Bernhard Mayer, Meteorological Institute, Ludwig-Maximilians-Universität München, Germany. E-mail: bernhard.mayer@lmu.de

tain a statistically significant result which is often prevented e.g. by the rarity of satellite overpasses over validation sites.

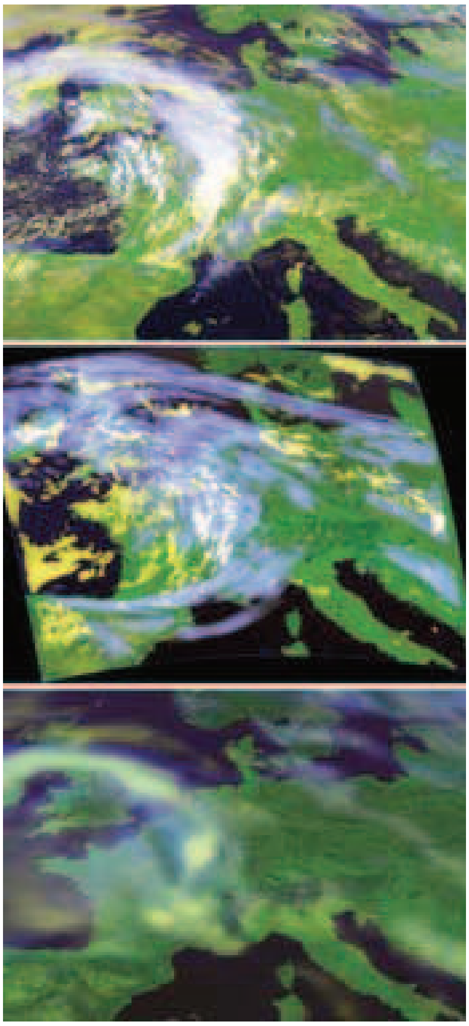

FIG. 1. False color composites of (top) a real MSG observation over central Europe, August 12, 2004, noon; (middle) a simulated MSG observation based on the output of a forecast by the German Weather Service (DWD) COSMO model at 7 km resolution; (bottom) a simulated MSG observation based on ECMWF reanalysis data. All data were processed by the same false color algorithm which uses the channels at 0.6 μm, 1.6 μm, and 10.8 μm.

Thus, we propose an alternative approach for validation and retrieval testing to complement the "traditional" methods: Starting from known cloud and aerosol distributions the satellite observation is simulated to produce datasets where radiation as well as cloud properties are fully known (in contrast to using satellite observations alone where only the radiances are available and the accuracy of the derived cloud information cannot be assessed because the real cloud properties are not known). On this basis, retrieval algorithms can be tested and tuned, by comparing the retrieved properties with the initial cloud properties. For such studies it is mandatory to use as-realistic-as-possible input data sets because otherwise the performance of the retrieval under real-world conditions is not properly assessed. Here we show consistent, accurate and bias-free 3D simulations of three of the four EarthCARE instruments MSI, BBR and ATLID. These simulations are based on the output of the numerical weather prediction model COSMO for the area of Germany and take into account all known characteristics of the EarthCARE payload. This work is based on many years experience with 3D radiative transfer and with the generation of realistic cloud and aerosol data.

An application of this method is presented in Figure 1 which compares a real MSG/SEVIRI (Meteosat Second Generation, Spinning Enhanced Visible and InfraRed Imager) observation (top), a simulated MSG observation based on the output of the COSMO model of the German Weather Service (middle), and a simulated observation based on ECMWF data (bottom) for the same date and time. The false color algorithm combines solar and thermal channels in a way to enhance differences between different cloud types: low clouds appear yellowish, middle level clouds white, and high, cold clouds blueish. That way the human eye can easily discern between cloud types. In this example, the general structures agree well between the weather forecast models and the observation. However, the representation of clouds and its interaction with radiation could be improved: Concerning the COSMO simulation, the low clouds are in reasonable agreement, while the model produces much more (or thicker) cirrus clouds and the mid-level clouds are basically missing completely. The reason for the missing mid-level clouds is that the model liquid and ice water content is mainly contained in precipitation (rain and snow) which has consequences for the interaction with radiation: For a given liquid water content, many small droplets scatter solar radition much more efficiently than few large droplets for which reason the rain droplets are not visible in the image. Concerning the ECMWF model, low-level clouds are comparable to the satellite observation and also for cirrus clouds a better agreement between model and observation is found. This example illustrates that simulated satellite data can be used to validate satellite retrievals on the one hand, but also to validate model results on the other hand. With the latter we follow the same philosophy as in data assimilation: Rather than comparing derived products where all kinds of a-priori assumptions went into the retrieval we can directly compare radiances and thus make the best possible use of the satellite data.

Similar comparisons have been done previously, using the thermal infrared channels of Meteosat or MSG only. For instance, the thermal radiances are calculated operationally in the COSMO model using the fast RTTOV radiative transfer code. As the example above illustrates, one can gain much more information if the visible and near-infrared channels are also taken into account. While already moderately thick cirrus clouds are opaque to thermal infrared radiation, solar radiation penetrates much deeper and gives a better insight into lower cloud levels and their interaction with radiation.

2. Cloud Model

For the generation of realistic cloud fields over regions as large as to encompass a considerable variability of cloud as well as surface properties the output of the COSMO-DE model of the German Weather Service has been used. It is a high-resolution non-hydrostatic Model (Steppeler et al. 1997) with a horizontal mesh size of 2.8 km on a 421 x 461 horizontal grid. The model domain encompasses the area of Germany plus some surroundings. COSMO uses generalised terrain following vertical coordinates which divide the atmosphere into 50 layers from the surface up to 21 km. The prognostic model variables are the wind vector, temperature, pressure perturbation, specific humidity, cloud liquid and ice water, rain and snow water. The model physics includes a level-2 turbulence parameterisation, a delta-twostream radiation scheme, and a multi-layer soil model. The model contains a grid-scale cloud and precipitation scheme as well as a parameterisation of moist convection (Tiedtke 1989).

For our radiative transfer simulations we use vertical profiles of pressure, temperature, specific humidity, cloud liquid water and cloud ice together with surface skin temperature, orography, and the land-sea mask. As an example for the EarthCARE simulation we selected July 3, 2008, 12:00 UTC, where an extended cirrus cloud on top of water clouds or cloud-free regions is present over Germany, in order to address some of the most delicate retrieval situations (thin cirrus, multi-layer clouds).

As the COSMO model, like all weather models, does not provide information on scales below a few kilometres, statistical downscaling is applied as a possibility to merge the potential of weather models to provide realistic large scale cloud structures in three dimensions and the potential of statistical models to generate realistic small scale variability at the ($\sim$ 10-100 m) scale. Starting from the original horizontal resolution of 2.8 km, the resolution of the main output quantities of the COSMO is increased by a factor of 5 to 560 m under the constraint that water content (liquid and ice) must not change on the original horizontal resolution (2.8 km). The core idea is that the Fourier spectrum of the water fields shall behave according to a -5/3 power law, as shown by various in-situ observations, e.g. (Davis et al. 1999). Thus, layer by layer the 5/3 Fourier power spectrum is forced on the sub COSMO resolution cloud fields while the total water content at the original COSMO resolution is conserved. The Fourier spectrum of the original COSMO fields is thus conserved on larger scales while it is forced towards a -5/3 power law at smaller scales (see Figure 2).

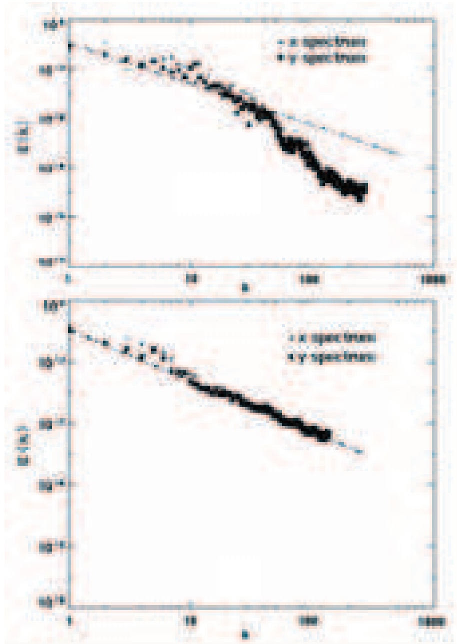

FIG. 2. Example of Fourier spectrum before (top) and after (bottom) resolution enhancement.

Once resolution has been enhanced, cloud microphysics needs to be associated to the cloud liquid and ice water fields because numerical weather prediction models as well as most other cloud models do not provide information about water droplet or ice particle size or numbers. For water clouds we use a parameterization of the effective radius r_{eff} [μm] as function of the liquid water content LWC [kg/m^3] provided by the model:

$$r_{eff} = \left(0.75 * \left(\frac{\mathrm{LWC}}{\pi * \mathrm{k} * \mathrm{N} * \rho}\right)\right)^{1/3} * 10^{-6} \quad (1)$$

The droplet number density N [1/m^3] is determined by the number of cloud condensation nuclei; here we assumed a constant number density of 150 cm^{-3}. k is the ratio between the volumetric radius of droplets and their effective radius which is determined by the size distribution of the droplets

(Schüller et al. 2003): $k = r_v^3/r_{eff}^3$ varies between 0.67 ± 0.07 for continental clouds and 0.8 ± 0.07 for marine clouds according to Martin et al. (1994). Here we used a typical value of $k = 0.75$. ρ is the density of liquid water at 4°C in kg/m^3.

For ice clouds the parameterisation of randomly oriented hexagonal columns by Wyser and Ström (1998) and McFarquhar et al. (2003) is used which relates ice particle effective radius to ice water content and temperature. More complex relationships are easily introduced into the scheme.

3. Radiative Transfer Simulations

The libRadtran radiative transfer package has been jointly developed since beginning of the 1990s by Mayer and Kylling (2005) and more recently by Ulrich Hamann, Claudia Emde, and Robert Buras. libRadtran is freely available at http://www.libradtran.org and has been used for many different purposes as documented by more than 150 peer-reviewed publications listed at the web page. Some of the most advanced options are not included in the free version but might be available on request, because we prefer to use those in collaboration with the users.

LibRadtran is a flexible and user-friendly package to address all kinds of radiation-related questions: to compute irradiances (fluxes), radiances (intensities), actinic fluxes, and heating rates over the complete solar and thermal spectral ranges (120 nm – 100 μm). Different methods to solve the radiative transfer equation are implemented, ranging from simple two-stream approximations over the "standard" discrete coordinate code DISORT by Stamnes et al. (1988), to a complex 3D radiative transfer solver MYSTIC (Mayer 2009; Emde and Mayer 2007) including inhomogeneous clouds, topography, polarization, and spherical geometry. Radiation quantities may be calculated at very high spectral resolution (line-by-line), at intermediate resolution (suited e.g., to simulate satellite instruments), and with some accurate k-distributions for integrated shortwave and longwave values. libRadtran has been validated in several model intercomparison campaigns, e.g. (Cahalan et al. 2005), and by direct comparison with observations, e.g. (Mayer et al. 1997; Bais et al. 2003). Particular attention has been laid on the detailed and most realistic representation of water and ice clouds in the model. Optical properties of water droplets are computed using Mie theory. Several parameterisations are available for ice clouds, including (Key et al. 2002; Yang et al. 2000), (Baum et al. 2005a,b, 2007), (Fu 1996; Fu et al. 1998). For the simulation of satellite radiances the parameterization by Baum is the method of choice because it includes the detailed scattering phase function in contrast to the other parameterizations which usually use a Henyey-Greenstein or double Henyey-Greenstein approximation. The optical properties by Baum are also used for the latest version (collection 5) of the MODIS ice cloud products MOD06 and MYD06.

Considerable effort has been spent to allow accurate representation of aerosol. Aerosols may be defined in different levels of complexity, starting from simply using a default set of profiles according to Shettle (1989), up to providing detailed description of optical properties, with many options to adjust e.g. the extinction profile, the optical thickness, the asymmetry parameter, etc. Also, the OPAC database (Hess et al. 1998) has recently been included which allows to define composition as well as size distribution of the aerosol particles. For the simulations in this paper we used the rural aerosol model by Shettle (1989) in the boundary layer, spring-summer conditions, a horizontal visibility of 50 km, and a background aerosol above 2 km. More complex aerosol including horizontal variability can be easily introduced into the simulation.

The most advanced solver of libRadtran is the 3D MYSTIC (Monte Carlo code for the physically correct tracing of photons in cloudy atmospheres) code by Mayer (2009); Emde and Mayer (2007). MYSTIC (which is not part of the free package) does not need any simplifying assumptions and serves as a benchmark for radiation in complex environments. It has been specifically developed to address inhomogeneous clouds which are one of our main research topics but also includes inhomogeneous surface albedo, BRDF, and topography. MYSTIC was one of the few codes solving all seven cases of the Intercomparison of 3D Radiation Codes, I3RC (Cahalan et al. 2005), and generally agreed within better than 1% with a small group of advanced codes. Figure 3 shows as an example for the numerical accuracy a comparison between MYSTIC and the 1D discrete ordinate solver DISORT by Stamnes et al. (1988) (switching between both requires only one statement in the libRadtran input file and thus it is guaranteed that both solvers use exactly the same optical properties as input). For cloudless as well as for 1D cloud cases both models agree within 0.1% or better. The noise is specific for the Monte Carlo method and could be further reduced by tracing more photons which, however, becomes quickly computationally very expensive since the uncertainty decreases only with the square root of the number of photons. The excellent agreement between the conceptionally very different methods suggests that both are very accurate. While this is of course only a test for a 1D, horizontally homogeneous atmosphere, a comparison with observations during a solar eclipse has demonstrated that

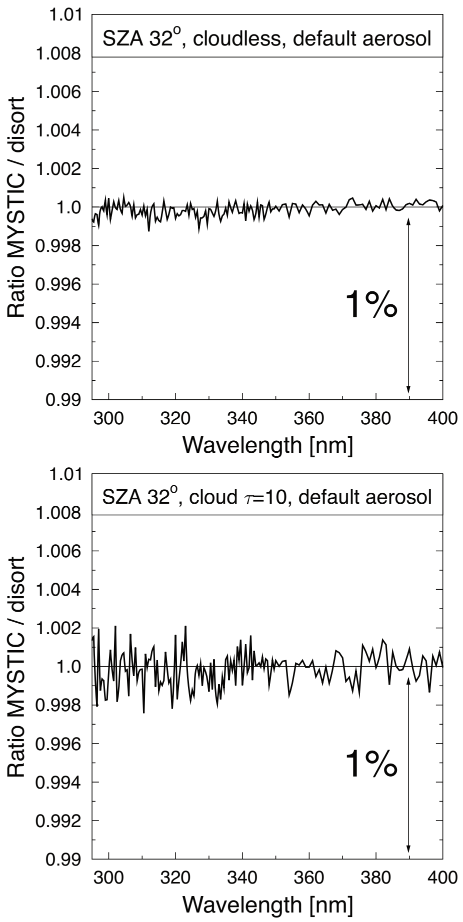

FIG. 3. Comparison between MYSTIC and DISORT for a cloudless case (top) and a homogeneous cloud (bottom). Both plots show the ratio of the spectral surface irradiance calculated by both models.

also the 3D radiative transfer, in particular the horizontal photon transport, is simulated correctly (Emde and Mayer 2007).

Recently, various extensions to MYSTIC have been implemented: backward Monte Carlo (Emde and Mayer 2007), spherical geometry (allowing e.g., simulations for low sun and in limb geometry), polarisation (publication in preparation), and lidar simulations including all orders of multiple scattering. Moreover, various advanced variance reduction techniques have been developed which are of particular importance for the lidar simulations. They are based on methods from Platt (1981); Marchuk et al. (1980); Noormohammadian (1996), but have been improved significantly. The variance reduction techniques have been validated thoroughly with MYSTIC simulations which did not include variance reduction and thus were very time-consuming, as well as with test cases such as the I3RC case 7. The advantage of the MYSTIC variance reduction implementation is that no approximations of the geometry of the photon path were made such as commonly used by other codes in order to solve the problem of the extreme forward peak of cloud scattering phase functions. Any approximation would introduce at least a small bias to the solution. Thus, MYSTIC allows a bias-free yet reasonably fast calculation of satellite radiances and lidar returns including multiple scattering (although it has to be admitted that "reasonably fast" is of course still much slower than 1D solutions).

4. EarthCARE simulations

In this section an example for the EarthCARE simulations is shown and all the necessary details are explained. The general philosopy of libRadtran is to first convert atmospheric and cloud microphysical properties to optical properties which are then passed to the solver in a second step. The spectral transmittances and reflectivities are then post-processed to obtain absolutely calibrated satellite radiances (see Figure 4). That way it is guaranteed that a given input dataset yields consistent optical properties for all solvers and, in the following case, for all EarthCARE instruments. For this purpose we also use the same solver (MYSTIC) for all calculations. Only details regarding the parameterization of atmospheric gas absorption may vary depending on the instrument, in particular the number and width of bands used in the k-distribution.

4.1. *Multi-spectral imager (MSI)*

The MSI instrument aboard EarthCARE is a seven channel imager with a swath of 150 km and a spatial resolution at nadir of 500 m. Its spectral bands reach from the visible to the near infrared to the thermal infrared. As the spectral response functions of the MSI instrument are not yet known, we "borrowed" the 0.6, 0.8, 1.6, and 10.8 μm channels from MSG/SEVIRI. The simulations were done in the backward mode of MYSTIC because it easily allows the consideration of the variable viewing angle across the satellite track. Also, only those satellite pixels are calculated which are actually needed in contrast to a forward simulation where by definition all pixels in a scene are calculated, irrespectively if they are needed or not. Atmospheric gas absorption was parameterized by LOWTRAN (Pierluissi and Peng 1985) which uses an exponential sum fit with a resolution of 20 cm^{-1}. We adopted 15 spectral grid points to simulate each channel.

The underlying surface was described in terms of a Lambertian spectral albedo reconstructed from the MODIS BRDF product MCD43C3 (Schaaf et al. 2002) for the year 2008 and the Julian day 177 for the area corresponding to the COSMO-DE re-

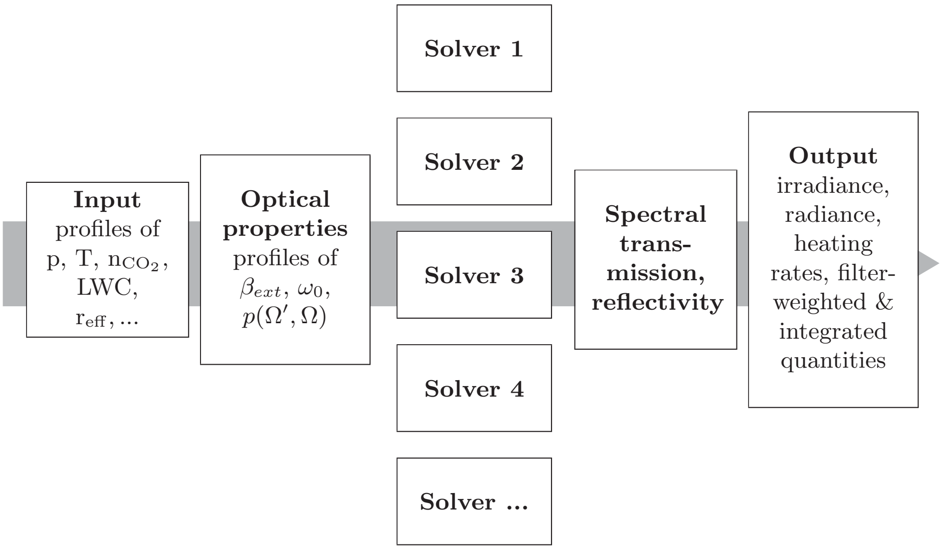

FIG. 4. libRadtran philosophy. First, atmospheric, surface, and cloud microphysical properties are converted to optical properties; these are passed to the radiative transfer solver (MYSTIC, disort, two-stream, ...); post-processing includes multiplication with the extraterrestrial irradiance, weighting with filters, integrating over the spectrum, converting to brightness temperature, etc.

gion and the corresponding three solar MODIS bands (1, 2 and 6). For the 10.8 μm thermal channel emissivity has been taken from collocated pixels of the UW-Madison Baseline Fit Emissivity Database (Seemann et al. 2008) for July.

The solar zenith angle was 29.75° (assumed constant since the variation is small within the selected scene). Satellite zenith angles vary across track from approximately -10° to 10° for the swath width of 150 km.

Figure 5 shows a false colour composite built using the 0.6, 0.8, and the inverted 10.8 μm channels. The simulated image represents the cloud scene on July 3, 2008 at 12:00 UTC as the MSI instrument would see it. In the false color composite thin cirrus clouds appear violet-blueish, while low water clouds are white. Notice the structure of the surface albedo as well as the shadows northwards of the clouds. Furthermore, the cirrocumulus structures produce by the resolution enhancement procedure is also clearly visible.

4.2. *Broadband radiometer (BBR)*

The Broad Band Radiometer measures TOA radiances in two wavebands from three along track views (forward, aft and nadir, i.e., ±55°, 0°). These radiances are filtered by the spectral response of the instrument. Since they are not known yet, an idealised step function has been assumed used to simulate the two spectral bands: the shortwave one from 200 nm to 4 μm, and the total one from 200 nm to 100 μm. Again, the backward MYSTIC radiative transfer solver has been selected because only few pixels in a scene are actually needed due to the limited spatial coverage of the BBR. Atmospheric gas absorption for integrated solar and thermal irradiance has been parameterized according to Fu and Liou (1992). All other conditions were treated identically to the MSI.

4.3. *Lidar (ATLID)*

The High Spectral Resolution Lidar (HSRL) aboard the EarthCARE satellite will be able to distinguish between Rayleigh and Mie backscatter. The MYSTIC Lidar simulator can also simulate in HSRL mode for an ideal HSLR instrument (cross-talk between the Rayleigh and Mie channels has not yet been included). Flight altitude as well as opening angle of ATLID are correctly considered. Atmospheric gas absorption stems again from LOWTRAN. With help of the variance reduction techniques described above the Lidar simulator in MYSTIC can calculate the Lidar signal for the EarthCARE satellite within few minutes to about 1% accuracy, including all orders of multiple scattering and providing also the Jacobian needed for retrieval algorithms. Figure 6 shows a simulation of the Lidar signals measured by EarthCARE passing above the cloud scene defined in Section 2. This simulation with a very high signal-to-noise ratio consists of 2741 Lidar shots with each 209 range bins and took about 10 hours.

Acknowledgments.

libRadtran development is currently supported by ESA project ESASLight, ESTEC contract AO/1-5433/07/NL/HE. Thanks also to Ulrich Hamann for the calculations using ECMWF data.

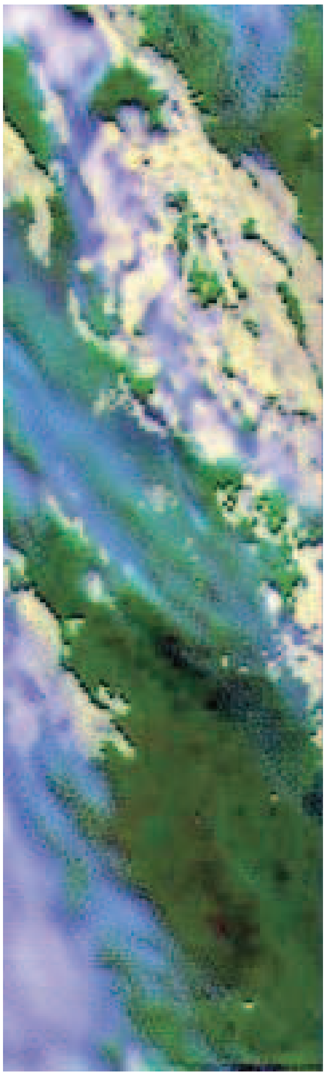

FIG. 5. Simulated MSI false colour composite using the 0.6, 0.8, and the inverted 10.8 μm channels.

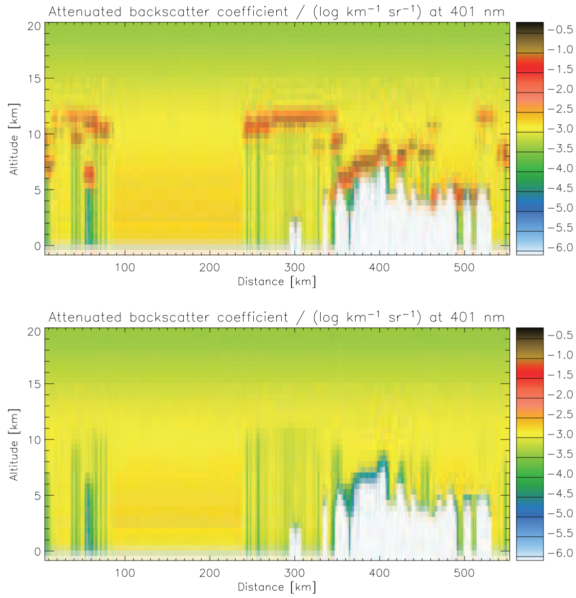

FIG. 6. Simulated ATLID total signal (top) and Rayleigh signal (bottom).

REFERENCES

Bais, A., et al., 2003: International Photolysis Frequency Measurement and Model Intercomparison (IPMMI): Spectral actinic solar flux measurements and modeling. *Journal of Geophysical Research*, **108 (D16)**, doi:10.1029/2002JD002 891.

Baum, B., A. Heymsfield, P. Yang, and S. Bedka, 2005a: Bulk scattering models for the remote sensing of ice clouds. part 1: Microphysical data and models. *J. of Applied Meteorology*, **44**, 1885–1895.

Baum, B., P. Yang, A. Heymsfield, S. Platnick, M. King, Y.-X. Hu, and S. Bedka, 2005b: Bulk scattering models for the remote sensing of ice clouds. part 2: Narrowband models. *J. of Applied Meteorology*, **44**, 1896–1911.

Baum, B., P. Yang, S. Nasiri, A. Heidinger, A. Heymsfield, and J. Li, 2007: Bulk scattering properties for the remote sensing of ice clouds. part 3: High resolution spectral models from 100 to 3250 cm-1. *J. of Applied Meteorology*, **46**, 423–434.

Cahalan, R., et al., 2005: The International Intercomparison of 3D Radiation Codes (I3RC): Bringing together the most advanced radiative transfer tools for cloudy atmospheres. *Bulletin of the American Meteorological Society*, **86 (9)**, 1275–1293.

Davis, A., A. Marshak, H. Gerber, and W. Wiscombe, 1999: Horizontal structure of marine boundary layer clouds from centimeter to kilometer scales. *Journal of Geophysical Research*, **104 (D6)**, 6123–6144.

Emde, C. and B. Mayer, 2007: Simulation of solar radiation during a total solar eclipse: A challenge for radiative transfer. *Atmos. Chem. Phys.*, **7**, 2259–2270.

Fu, Q., 1996: An accurate parameterization of the solar radiative properties of cirrus clouds in climate models. *Journal of Climate*, **9**, 2058–2082.

Fu, Q. and K. Liou, 1992: On the correlated k-distribution method for radiative transfer in nonhomogeneous atmospheres. *Journal of the Atmospheric Sciences*, **49**, 2139–2156.

Fu, Q., P. Yang, and W. Sun, 1998: An accurate parameterization of the infrared radiative properties of cirrus clouds in climate models. *Journal of Climate*, **11**, 2223–2237.

Hess, M., P. Koepke, and I. Schult, 1998: Optical properties of aerosols and clouds: the software package OPAC. *Bulletin of the American Meteorological Society*, **79 (5)**, 831–844.

Key, J., P. Yang, B. Baum, and S. Nasiri, 2002: Parameterization of shortwave ice cloud optical properties for various particle habits. *Journal of Geophysical Research*, **107 (D13)**, 10.1029/2001JD000 742.

Marchuk, G., G. Mikhailov, M. Nazaraliev, R. Darbinjan, B. Kargin, and B. Elepov, 1980: *The Monte Carlo Methods in Atmospheric Optics*. Springer-Verlag, New York.

Martin, G., D. Johnson, and A. Spice, 1994: The measurement and parameterization of effective radius of droplets in warm stratocumulus clouds. *Journal of the Atmospheric Sciences*, **51**, 1823–1842.

Mayer, B., 2009: Radiative transfer in the cloudy atmosphere. *Eur. Phys. J. Conferences*, **1**, 75–99.

Mayer, B. and A. Kylling, 2005: Technical Note: The libRadtran software package for radiative transfer calculations: Description and examples of use. *Atmos. Chem. Phys.*, **5**, 1855–1877.

Mayer, B., G. Seckmeyer, and A. Kylling, 1997: Systematic long-term comparison of spectral UV measurements and UVSPEC modeling results. *Journal of Geophysical Research*, **102 (D7)**, 8755–8767.

McFarquhar, G., S. Iacobellis, and R. Somerville, 2003: SCM simulations of tropical ice clouds using observationally based parameterizations of microphysics. *Journal of Climate*, **16**, 1643–1664.

Noormohammadian, M., 1996: Varianzreduzierende Monte-Carlo Methoden zur Berechnung mehrfach gestreuter LIDAR Rücksignale. Ph.D. thesis, Ludwig-Maximilians-Universität München, Germany.

Pierluissi, J. and G.-S. Peng, 1985: New molecular transmission band models for LOWTRAN. *Optical Engineering*, **24 (3)**, 541–547.

Platt, C., 1981: Remote sounding of high clouds. III: Monte Carlo calculations of multiple-scattered lidar returns. *Journal of the Atmospheric Sciences*, **38**, 156–167.

Schaaf, C., et al., 2002: First Operational BRDF, Albedo and Nadir Reflectance Products from MODIS. *Remote Sens. Environ.*, **83**, 135–148.

Schüller, L., J.-L. Brenguier, and H. Pawlowska, 2003: Retrieval of microphysical, geometrical, and radiative properties of marine stratocumulus from remote sensing. *Journal of Geophysical Research*, **108 (D15)**, doi:10.1029/2002JD002 680.

Seemann, S., E. Borbas, R. Knuteson, G. Stephenson, and H.-L. Huang, 2008: Development of a global infrared land surface emissivity database for application to clear sky sounding retrievals from multi-spectral satellite radiance measurements. *Journal of the Applied Meteorology and Climatology*, **47**, 108–123.

Shettle, E., 1989: Models of aerosols, clouds and precipitation for atmospheric propagation studies. *Atmospheric propagation in the uv, visible, ir and mm-region and related system aspects*, No. 454 in AGARD Conference Proceedings.

Stamnes, K., S. Tsay, W. Wiscombe, and K. Jayaweera, 1988: A numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media. *Applied Optics*, **27 (12)**, 2502–2509.

Steppeler, J., G. Doms, U. Schättler, H. W. Bitzer, A. Gassmann, U. Damrath, and G. Gregoric, 1997: Meso-gamma scale forecasts using the nonhydrostatic model lm,. *Meteor. Atmos. Phys.*, **82**, 75–96.

Tiedtke, M., 1989: A comprehensive mass flux scheme for cumulus parameterisation in large scale models. *Monthly Weather Review*, **117**, 1779–1800.

Wyser, K. and J. Ström, 1998: A possible change in cloud radiative forcing due to aircraft exhaust. *Geophysical Research Letters*, **25**, 1673–1676.

Yang, P., K. Liou, K. Wyser, and D. Mitchell, 2000: Parameterization of the scattering and absorption properties of individual ice crystals. *Journal of Geophysical Research*, **105 (D4)**, 4699–4718.

Zinner, T. and B. Mayer, 2006: Remote sensing of stratocumulus clouds: Uncertainty and biases due to inhomogeneity. *Journal of Geophysical Research*, **111 (D14209)**, doi:10.1029/2005JD006 955.