TECHNICAL MEMORANDUM

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Optimized surface radiation fields derived from METEOSAT imagery and a regional atmospheric model

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Abstract

High quality fields of surface radiation fluxes are required for the development of Land Data Assimilation Systems. A fast offline integration scheme was developed to modify NWP model cloud fields based on Meteosat visible and infrared observations. From the updated cloud fields downward shortwave and longwave radiation at the surface are computed using the NWP's radiative transfer model.

A dataset of 15 months covering Europe was produced and validated against measurements of ground stations on a daily basis. In situ measurements are available for 30 stations in the Netherlands, and two BSRN stations in Germany and France. The accuracy of shortwave surface radiation is increased when the integration system is applied. The rms error in the model forecast is found to be 32 and 42 $\mathrm{W\,m^{-2}}$ for the period from October 1999 to December 2000 for the two BSRN stations. These values are reduced to 21 and 25 $\mathrm{W\,m^{-2}}$ through the application of the integration scheme. During the summer months the errors are generally larger than in winter. Due to an integrated monitoring of surface albedo, the performance of the scheme is not affected by snow cover. The errors in the longwave radiation field of the original NWP model are already small. However, they are slightly reduced by applying the integration scheme.

1 Introduction

The land surface component of the hydrological cycle is of fundamental importance for applications in climate and atmospheric science. Processes at the land-atmosphere interface are governed by rainfall and incoming shortwave radiation at the surface, defining the total amount of energy and water available for the physical, chemical and bio-chemical processes. Some of these processes are parameterized by the land surface scheme in numerical weather prediction (NWP) models. The atmospheric component of the NWP model provides the rainfall and radiation forcing for the land surface model. Errors in these forcing data accumulate in the hydrological components with the longest memory, thus leading to strong drifts in the soil moisture variable of the land surface scheme. These drifts, in turn, generate erroneous atmospheric feedbacks (Viterbo 1996). Land Data Assimilation Systems (LDAS) are being developed to reduce the errors in the land surfaces' water and energy balance and consequently to improve reanalysis and forecasts by NWP models.

Within the framework of the European Land Data Assimilation System (http://www.knmi.nl/samenw/eldas, ELDAS) surface forcing data for radiation and precipitation are derived from observations instead of using direct model output only. The description of the generation of the surface radiation fields based on satellite observations and NWP output for ELDAS is the subject of this paper. Modeling the radiation at the surface strongly depends on an accurate description of clouds. Although cloud microphysical properties characterize the interaction between clouds and radiation, cloud cover has probably the most significant impact on the radiation balance at the surface. Comparisons between modeled clouds and observations indicate that the spatial distribution of clouds is not well represented by NWP models (Crewell et al. 2002). Satellite measurements in the visible and infrared spectral range have been extensively used to detect clouds (e.g. Feijt et al. 2000, Rossow and Garder 1993a,b). Since the wavelengths measured by these satellites are only sensitive to cloud top properties, it is difficult to uniquely project this information into the vertical structure of a NWP model. Yucel et al. (2002) used GOES-derived cloud images to change liquid and ice water content in a nonhydrostatic mesoscale model. In a later study, Yucel et al. (2003) combined GOES visible and infrared images along with mesoscale model-derived fields to generate three-dimensional cloud fields. A complex nudging scheme was used to introduce these cloud fields into the model. The primary goal of both studies was improvement of cloud and precipitation forecasts. Although this technique results in more realistic surface radiation fluxes as well, it is too complex to be used for the generation of radiation fields for ELDAS. We present a computationally cheap integration system, which uses Meteosat radiances and NWP output in an optimized physically consistent way.

2 The data integration procedure

2.1 Overview and rationale

The radiation forcing data for the ELDAS soil moisture assimilation system are subject to a number of requirements: (i) Radiation data need to resolve the diurnal cycle of shortwave radiation at the surface, as the evaporation process affecting the soil water reservoir depends on this diurnal cycle. (ii) Clouds must be incorporated as they have a major effect on the surface radiation. (iii) The system generating the radiation data must be efficient to keep computational cost within reasonable limits. (iv) The data availability must allow a quasi operational production system.

Measurements from geostationary satellites combining infrared and visible channels have the capability to detect the majority of clouds with good spatial accuracy, resolve the diurnal cycle of reflected radiation, and have excellent operational data availability. However, the use of geostationary data presents challenges under cloudy conditions in which their measurements are only representative of the upper part of cloudy layers, thus complicating determination of surface radiation. While recongnizing this challenge, geostationary data still represents a valuable data source. Descriptions of schemes that meet the above requirements using geostationary data are briefly presented below.

Tarpley (1979) developed a regression technique to estimate hourly insolation from geostationary satellite data. When compared to pyranometer measurements in the Southern Great Plains, an error of 10% for the daily mean was found. Gautier et al. (1980) introduced a simple physical radiative transfer scheme to estimate the incident solar radiation at the surface from GOES measurements. Water vapor absorption and Rayleigh scattering were assumed to be constant while cloud albedo and absorption were derived from the satellite measurement. Comparisons of daily cumulative insolation with pyranometer measurements at Ottawa, Montreal and Toronto showed average errors of 9%. Diak and Gautier (1983) modified the physics of the scheme and introduced ozone absorption as well as a correction for clouds smaller than the GOES sensor field-of-view. Gautier and Landsfeld (1997) compared the incoming surface solar radiation flux calculated using a revised version of the scheme of Gutier et al. (1980) with pyranometer observations taken during a 14-month period at the Atmospheric Radiation Measurement (ARM) program's central testbed site in Oklahoma. For clear sky cases the rms error and bias for daily integrated values were found to be 10 $\mathrm{W\,m^{-2}}$ and 3 $\mathrm{W\,m^{-2}}$. The accuracy decreases to 22 $\mathrm{W\,m^{-2}}$ and the bias increases to 14 $\mathrm{W\,m^{-2}}$ for overcast conditions.

Within the North American LDAS (NLDAS, Mitchell et al. 2003), estimates of shortwave radiative fluxes at the surface and top of the atmosphere (TOA) are derived from GOES (Geostationary Operational Environmental Satellite) visible radiances (Pinker et al. 2003). The corresponding algorithm uses TOA albedos obtained from the visible radiance measured by the GOES-8 imager to determine surface radiation budgets for NLDAS. A clear-sky composite of TOA albedos is collected over a number of days. For each pair of instantaneous and clear-sky TOA albedo a lookup table (generated with a radiative transfer model) provides a shortwave flux transmittance of the atmosphere and thus the surface radiation budget. A validation of the derived radiation and precipitation fields against ground based observations is given in Cosgrove et al. (2003) and Luo et al. (2003).

The procedures described above are designed to generate surface radiation estimates solely from satellite information. In the scheme described in this paper, labeled ELDORADO (ELDAS operational radiation system), we follow the rationale that short-term NWP forecasts contain considerable information describing atmospheric structure. The ELDORADO scheme combines information from both sources – the NWP model and Meteosat measurements – in a physically consistent manner.

To give an overview over the ELDORADO surface radiation scheme it is described briefly in the following. Details are provided in subsection c. The ELDORADO surface radiation scheme consists of four sequential steps.

The first step is a recalibration of the Meteosat radiances. Differences between modelled clear sky radiances and satellite observations are reduced to a minimum. In the second step, the spatial distribution of TOA net shortwave radiation based on the first guess NWP model fields is compared to Meteosat observations. Within each NWP gridbox this quantity is calculated as function of the profile of temperature, moisture content, cloud cover and surface radiative properties. These profiles and associated surface properties are moved horizontally in order to improve the match between modelled and observed TOA net shortwave radiation. In the third step, the vertical profile of cloud cover in the NWP domain is adjusted to match total cloud cover estimates derived from Meteosat. This step uses additional (thermal) information of the available satellite data to detect clouds and may result in an alteration of the TOA net shortwave radiation. Therefore, the fourth and last step is an adjustment of the profile of cloud liquid water content aiming for an optimal agreement between modelled and observed TOA net shortwave radiation.

Downward fluxes of shortwave and longwave radiation at ground level are calculated from these modified fields using the radiation modules of the NWP model. During nighttime no corrections to the NWP profiles are performed, since the absence of sunlight makes evaluation of shortwave reflectance properties impossible. The cloud detection algorithm used in the third step does not cover the whole NWP model domain and possibly has a few missing pixels. In these cases only the recalibration (step one) and the resorting of the clouds (step two) are performed. Areas of the ELDAS domain not covered by the NWP model are filled with ECMWF Re-Analysis (ERA-40) data.

2.2 Model description and data sets

ELDORADO relies on Meteosat observations, NWP model runs and the ECMWF operational analysis. The NWP model used in this study is the High Resolution Limited Area Model (HIRLAM), which was updated with the ECMWF physical package of cycle 24r3 (http://www.ecmwf.int/research/ifsdocs). This version is identical to the code used to generate the 40-year ECMWF reanalysis ERA40. The complete system is hereafter referred to as RACMO (Regional Atmospheric Climate Model; see Lenderink et al. 2003). In order to ensure maximum consistency in the ELDORADO integration scheme the radiative transfer modeling uses cycle 24r3 of the radiation code of ECMWFs Integrated Forecast System (Morcrette 1991) as well.

To create a first guess of cloud cover and liquid water profile, short-term forecasts of RACMO are started from spatially interpolated ECMWF operational analysis fields every 6 hours. RACMO uses a rotated latitude-longitude grid with a spatial resolution of 0.2°. The grid rotation ensures that the gridboxes are approximately 20 km apart throughout the entire domain. RACMO has 31 levels in the vertical between surface and 10 hPa. Cloud cover and liquid water profiles are passed between successive forecast cycles as passive (non-analyzed) variables. A monthly climatology for tropospheric aerosols (Tanre et al. 1984), ozone (Fortuin and Langematz 1995) and greenhouse gases (Watson et al. 1990) is prescribed. TOA radiative fluxes and cloud cover generated from short-term RACMO forecasts are archived for later use.

Meteosat geostationary meteorological satellites have been operational since the late 1970s. In ELDORADO, the visible channel (0.35 to 1.1 μm) of Meteosat 7 with 5 km resolution at nadir is used. Fractional cloud cover, which is used in step 3, is also based on Meteosat observations and obtained through the operational Meteosat Cloud Detection and Characterization KNMI (Koninklijk Nederlands Meteorologisch Instituut) (Metclock) scheme (Feijt et al. 2000). Metclock is a cloud detection algorithm based on threshold comparisons between Meteosat infrared and visible measurements and NWP model surface temperature and synoptic observations. The result is a binary cloudy / cloudfree mask at the resolution of Meteosat. Metclock was validated against synoptic observations of cloud cover obtained at 800 stations over Europe for 1997. Metclock detected 89% of the reported cloud cover during daytime over land. 92% of the cloud free scenes over land were analyzed correctly. For more details on the Metclock scheme the reader is referred to Feijt et al. (2000) and Feijt and de Valk (2001). Due to the viewing geometry data are not available north of 67°N and east of the line defined through (35°N, 22°E) and (67°N, 40°E).

2.3 Integration algorithm

The four ELDORADO steps are described in detail below.

2.3.1 Bias adjustment

The narrow-band (0.35–1.1 μm) single-directional irradiances measured by Meteosat must be integrated over polar and azimuthal angles and converted into a broad-band visible range to derive the hemispherical shortwave radiance. This quantity can be compared directly to the NWP model output. For this integration the empirical linear narrow-band to broad-band conversion equation from Arino et al. (1992) is used. The equation is based on a comparison (2700 samples) between Meteosat and NOAA-7/AVHRR (Advanced Very High Resolution Radiometer) visible and near-infrared channels over land.

Due to the uncertainties in the spectral response of the underlying land surface, the poor angular sampling of the sensor, its calibration uncertainty and the distortion by the sub-optimal viewing geometry for high latitude areas errors in the observed fluxes must be expected. In addition, systematic differences between Meteosat observations and simulations from the radiative transfer scheme in RACMO can be expected due to the assumptions on areosol content, surface reflectance and spatial aggregation in RACMO.

Meteosat irradiances are bias-adjusted using RACMO calculations for cloud-free conditions. Monthly averaged calibration factors are derived for each diurnal time step and each NWP gridbox separately, and applied to cloudy and cloud-free Meteosat observations prior to feeding these into the ELDORADO system. Since METEOSAT calibration errors are different for cloud-free and cloudy conditions it would be ideal to have different bias corrections for both situations. However, the erros introduced by one correction factor, which is strictly valid for cloud-free scenes only, are considered to be comparably small. For noon the correction factors were typically less than 10% over land and zero over sea. These values correspond with results from Arino et al. (1991) who used a five year time series of TOA reflectance over a Lybian desert target. Likewise, Brest et al. (1997) estimated the absolute calibration uncertainty of the Meteosat visible channel to be about 10% by a comparison with NOAA/AVHRR and an analysis of the overlapping observation areas of the geostationary satellites GOES and GMS (Geostationary Meteorological Satellite).

2.3.2 Resorting of clouds

The second step of the procedure is designed to correct phasing errors in the modeled cloud field by horizontal displacement of model columns, retaining the vertical structure of each column. For every Meteosat pixel the particular model column that best fits a linear combination of the Meteosat observed TOA shortwave radiation, the surface albedo of the target location, and the distance to the target location is identified. A multilinear regression function J – that assigns empirical weights to each of these criteria – is minimized in order to find the closest RACMO column, j, that can replace the NWP profile located at the target location, i. J is defined as

$$J = c_1 \left| r_{NWP} - r_{sat} \right| + c_2 \left| a_i - a_j \right| + c_3 \left| \mathbf{x}_i - \mathbf{x}_j \right|^2 \tag{1}$$

where r_{NWP} and r_{sat} are shortwave TOA reflectivity factors derived from RACMO and Meteosat, respectively, a_i and a_j are surface albedos of the two columns, and $\left|\mathbf{x}_i - \mathbf{x}_j\right|$ is their spatial distance. c_1, c_2, and c_3 are empirical coefficients for normalizing and weighting the three separate difference criteria. In this study, c_1, c_2, and c_3 were set to 3, 50, and $7.5 \times 10^{-6}\,\mathrm{km}^{-2}$, respectively. A relatively small value was assigned for c_1 compared to c_2, since spatial variability of surface albedo is generally small but has a strong impact on the TOA radiation for cloud free conditions. Moreover, differences in surface snow cover are given a high penalty. The c_3 coefficient is set such that the search area is effectively reduced to 12–15 grid points ($\approx$ 240–300 km) in each direction. The search area in the model is limited to a rectangle of 21 by 21 grid boxes. Although the weighting factors are empirical, the corresponding values were optimized through a number of analysis experiments based on data from August and September 2001. All meteorological parameters of the column for which J is minimal, are copied to the target grid box, which is closest to the analyzed Meteosat pixel.

The resorting of clouds distorts the horizontal structure of the atmospheric fields and may produce fields that cannot be created by a real atmosphere. However, the fields are not intended to be the most realistic representation of all atmospheric sate variables, but of the radiative properties of the atmospheric column. Dynamical simulations with the distorted fields are not executed in the context of ELDORADO.

This analysis step allows to create (or remove) clouds in grid points that were originally cloud free (or cloudy). After this step shortwave radiation at the TOA agrees much better with the observations from the Meteosat visible channel although cloud amounts might still be wrong.

2.3.3 Adjustment of total cloud cover

The third step adjusts the RACMO total cloud cover to the cloud cover detected by the Metclock scheme, since cloud cover has a major impact on the surface radiation. Observed partial cloud cover is derived by averaging the Metclock binary cloud mask for an area of 3 by 5 Meteosat pixels. In the NWP model, total cloud cover is a diagnostic variable calculated from the cloud fractions of all layers by the radiation scheme. RACMO total cloud cover was modified by changing the cloud cover in every layer by a factor F_c so that the Metclock observed total cloud cover is generated in the cloud overlap scheme in RACMO. F_c is found by the secant approximation method (a sequence of linear iteration steps using secants through the last two approximations respectively; starting values of F_c were chosen to be 0.9 and 1). F_c was chosen to be constant with height, owing to the lack of auxiliary information on the vertical structure of the clouds. If no clouds are detected from Meteosat measurements, all cloud fractions of the according model column are set to zero.

2.3.4 Adjustment of cloud liquid water

The available information does not allow an additional degree of freedom to make a distinction between liquid and ice cloud contents. Liquid water adjustments have a more straightforward effect on radiation profiles than ice clouds due to the large variability in existing particle shapes, sizes and reflectance properties. Therefore only liquid water profiles are modified.

In the fourth and final retrieval step the liquid water content is modified to optimize the agreement with TOA net shortwave radiation derived from Meteosat. Because in the second step TOA shortwave radiation was already used for minimization, changes will be usually relatively small here and are mainly due to cloud cover adjustments in step three. Cloud liquid water adjustment is applied similarly to the adjustment of total cloud cover. Using the secant method a vertically uniform factor is determined, which modifies the modeled cloud liquid water contents to values that result in a better agreement with TOA shortwave radiation as observed by Meteosat.

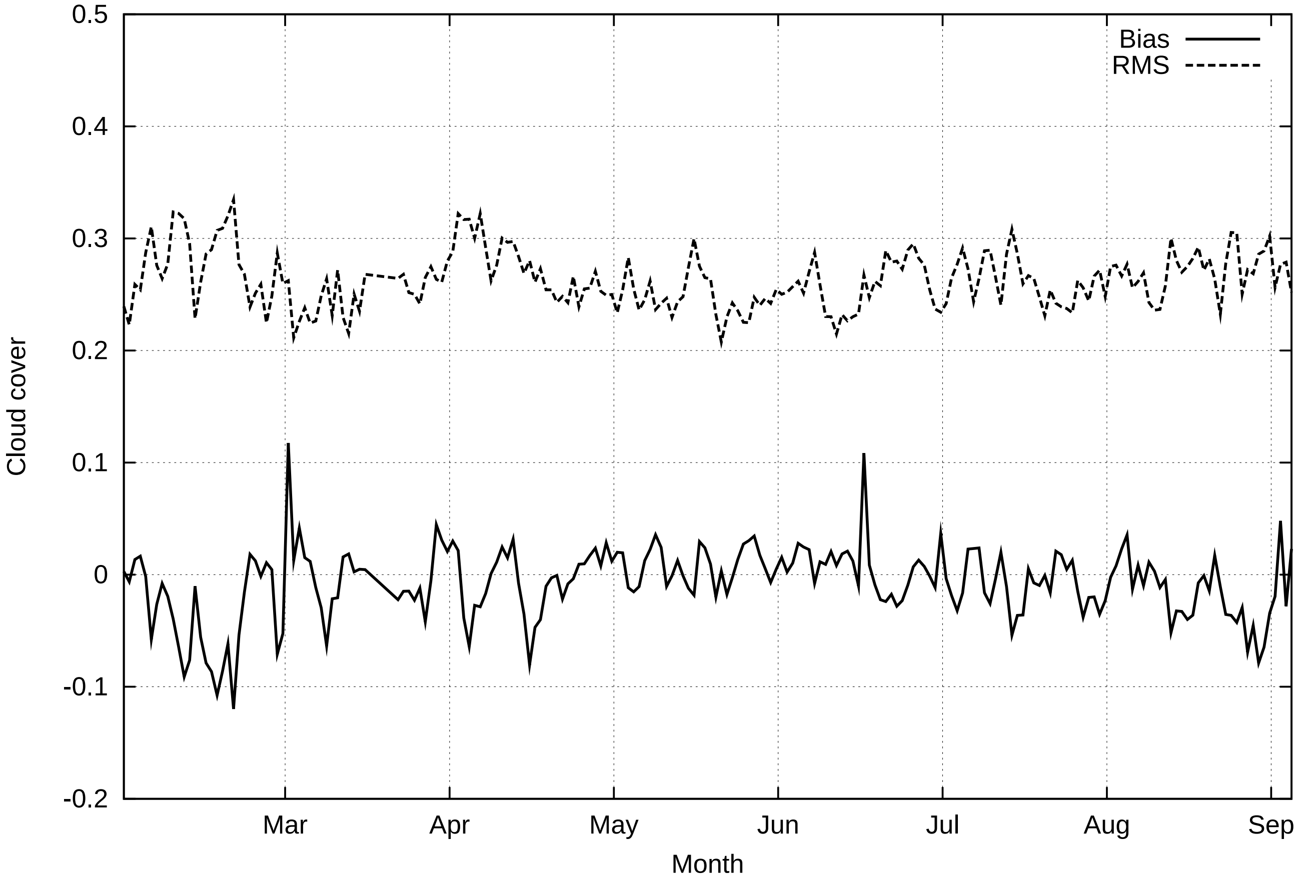

Figure 1: Verification of the Metclock total cloud cover. Shown are the daily averaged bias and rms error averaged over approximately 950 synoptic stations distributed across Europe. Metclock cloud cover was obtained by averaging the cloud mask over 3 by 5 pixels, and interpolating the central pixel value to the location of the synoptic station.

3 Validation

A comparison with ground based observations from pyranometers is the most direct way to validate the ELDORADO derived radiation fields at the surface. However, the number of operational stations reporting downward fluxes is limited. For this study, observations from 30 operational ground stations in the Netherlands (Henzing and Knap 2001) and two stations of the Baseline Surface Radiation Network (BSRN) were available. Following Gautier and Landsfeld (1997) daily mean values were compared because clouds and thus surface shortwave radiation often show strong and fast fluctuations, which may not be captured or averaged out in the coarse satellite observation. Since soil humidity is hardly affected by fluctuations on a shorter time scale daily values will provide a good measure of the quality of this data set with respect to applications in ELDAS.

Since the ELDORADO scheme relies on the Metclock cloud detection product, cloud cover was validated for the study period of 2000. A comparison between Meteosat derived cloud cover and observations at 950 synoptic stations was performed for the European area (Fig. 1). Within the verification period of seven months the daily averaged bias exceeds values of ±0.1 only on four single days. For most of the other days values between -0.05 and 0.05 are found. The average bias for the seven months period is -0.006. The negative bias during March and September might be caused by a higher frequency of low cloud tops in this period, which are more difficult to separate from the cool ground in the infrared channel. In addition, the visible channel of Meteosat provides more information during the summer months due to the smaller zenith angle of the sun and the longer daily insolation period. For most days, the rms error varies between 0.2 and 0.3. Although these values must not be compared directly to the detection probabilities given in Feijt et al. (2000) and section 2.b, we believe that the bias and rms presented in Fig. 1 indicate a similar performance. Given the fact that the ground observations are not perfect measures of the actual cloud cover at the radiometer resolution, the uncertainties obtained for the Metclock product are acceptable for the application in ELDORADO. The impact of the ELDORADO scheme on the estimated total cloud cover and TOA shortwave net radiation can be seen in Fig. 2. For 4 July 2000 the first guess field (Fig. 2a) suggests cloudy conditions for large parts of Central and North-East Europe, the British Islands, small parts of South and East Europe with cloud cover values ranging from 0.4 to 1.0. The Southern part of France, the Northern parts of Spain, Italy and most of East Europe are characterized by low cloud cover. The estimate from METEOSAT measurements (Fig. 2b) supports dense cloud cover for almost the whole of Europe north of 40°N intermitted by relative small cloud-free or weak covered areas in the Southern and Eastern part, Fennoscandia and Ireland. The “column moving” component of ELDORADO (step 2) reproduces the TOA shortwave net radiation pattern (Fig. 2h) as seen by METEOSAT (Fig. 2g) quite well showing many more fine scale structures than the first guess (Fig. 2f). But in large areas the total cloud cover (Fig. 2c) is lower than estimated from the Metclock data (Fig. 2b). The cloud cover adjustment (step 3) changes this quantity (Fig. 2d) leaving the TOA shortwave net radiation (Fig. 2i) almost unchanged. The cloud liquid water adjustment (step four in the ELDORADO scheme) results in comparably small changes in TOA shortwave radiation. However, in areas with less dense and fine structured clouds a better agreement in TOA shortwave net radiation (Fig. 2j) is visible, for example in Southern and Western France.

A more quantitative description of the impact of the ELDORADO scheme can be obtained through the comparison of TOA net shortwave radiation. In Fig. 3 TOA shortwave radiation as derived from Meteosat is compared to the corresponding values from the first guess field and the ELDORADO scheme. For July 2000 at 1200 UTC both data sets exhibit a positive bias when compared to the Meteosat values. However, the ELDORADO scheme reduces this bias from 66 $\mathrm{W\,m^{-2}}$ to 35 $\mathrm{W\,m^{-2}}$. The rms decreases from 84 $\mathrm{W\,m^{-2}}$ to 45 $\mathrm{W\,m^{-2}}$.

In spite of the Meteosat bias correction (see first step above) a systematic error remains present in the results. This is partially due to the assumption that the calibration correction applies similarly to cloudy and cloud-free conditions, and partly because the data integration procedure did not succeed in generating a model profile that results in a perfect match to the observations, for instance due to limitations in the relocation procedure or cutoffs applied to the increments to avoid unphysical model values. For an independent validation of ELDORADO we used 30 operational ground stations in the Netherlands measuring downward shortwave radiation. The observations are spatially integrated and compared to the corresponding ELDORADO / first guess product on a daily basis. Figure 4 shows the temporal evolution of the bias and rms for the period from October 1999 to December 2000. For the winter months from November to March both data sets are characterized by a slightly negative bias (-7 $\mathrm{W\,m^{-2}}$), and day-to-day variations are generally within ±20 $\mathrm{W\,m^{-2}}$. During the summer months the bias tends to be positive and strong variations are present. For the first guess field and the ELDORADO product the maximum values are $\sim$165 $\mathrm{W\,m^{-2}}$ and $\sim$120 $\mathrm{W\,m^{-2}}$, respectively. The ELDORADO scheme reduces the mean bias for the summer period from 21 $\mathrm{W\,m^{-2}}$ for the first guess field to 7 $\mathrm{W\,m^{-2}}$ for the final product. The annual cycle in the rms is caused by the stronger solar insolation during summer, which intensifies the difference between clear and cloud covered areas. In addition, small scale convective clouds, which are not well represented in NWP models, are more frequent in the summer months. However, the ELDORADO data set is characterized by a systematically lower rms. Average values of 74 $\mathrm{W\,m^{-2}}$ and 49 $\mathrm{W\,m^{-2}}$ were found for the summer period and the entire data set, respectively. The corresponding values for the first guess data are 102 $\mathrm{W\,m^{-2}}$ and 68 $\mathrm{W\,m^{-2}}$. It can be concluded that the ELDORADO scheme leads to a significant improvement in the derived downward surface shortwave radiation in the Netherlands.

Downward longwave radiation is another important component for the energy balance at the surface. Although the satellite measurements are almost insensitive to this quantity, the integration scheme updates this quantity.

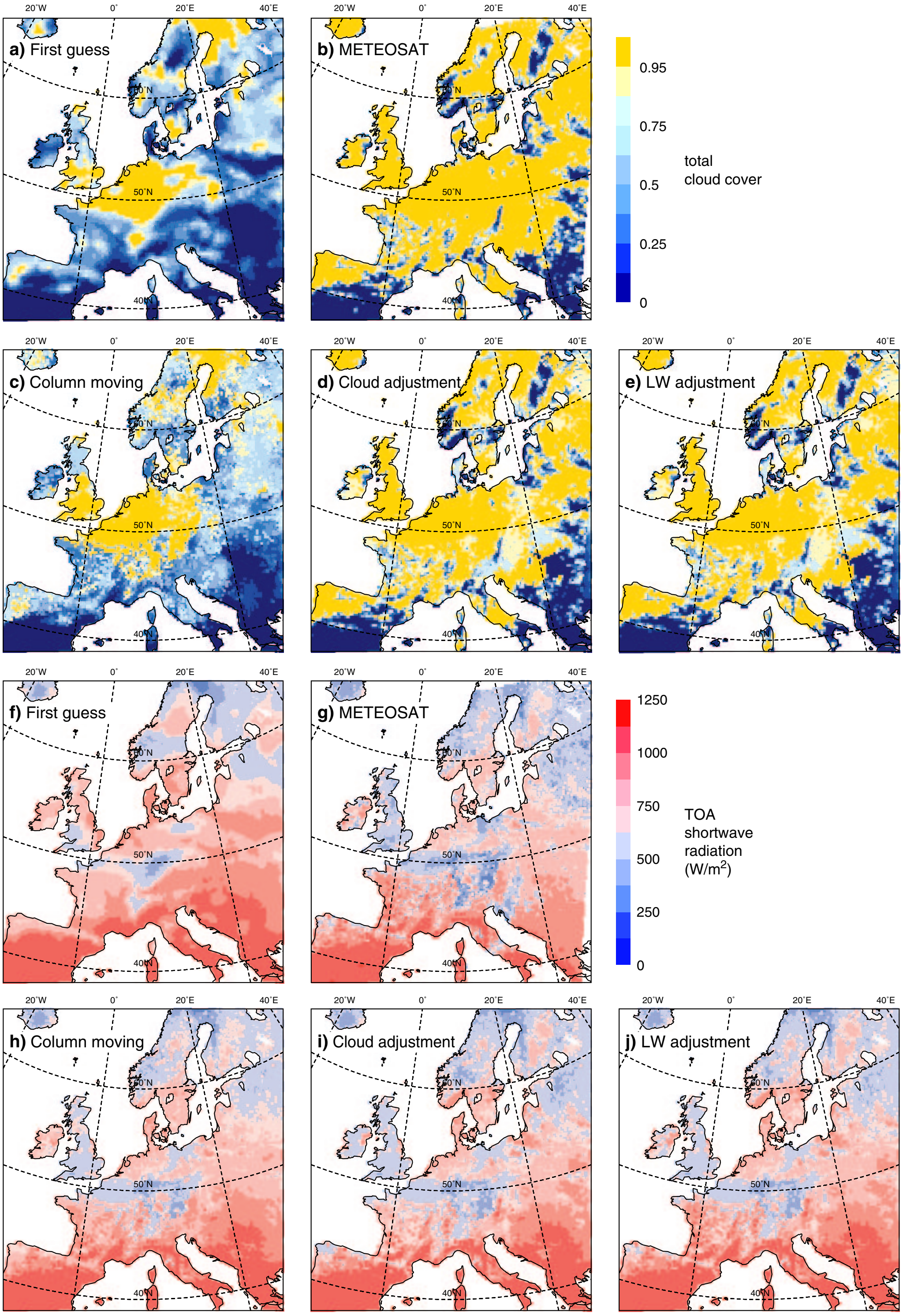

Figure 2: Example for the impact of ELDORADO on the estimated total cloud cover (a–e) and TOA shortwave net radiation (f–j) in RACMO for 4 July 2000 1200 UTC. First guess: Model run without any adjustment. METEOSAT: Estimate by Metclock. Column moving: After ELDORADO step 1 and 2. Cloud adjustment: After ELDORADO step 3. LW adjustment: After complete ELDORADO.

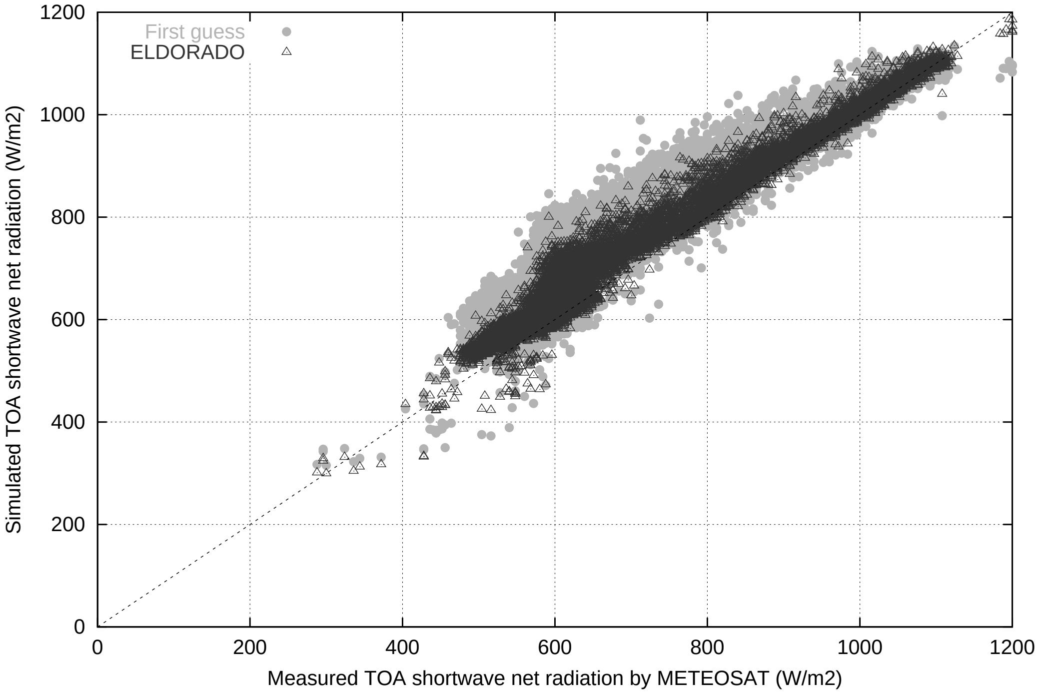

Figure 3: Scatterplot of Meteosat and RACMO TOA net shortwave radiation. Each point represents the daily average TOA radiation during July 2000 at a single grid box in the RACMO domain. Shown are results for the first guess and the ELDORADO outcome.

For the verification of downward longwave radiation at the surface, data measured at two stations of the Baseline Surface Radiation Network (BSRN; Ohmura et al. 1998), namely Lindenberg (Germany) and Payerne (France), are processed. The results of the comparison between these in-situ measurements and the first guess / ELDORADO product are summarized in tables 1 (15 months) and 2 (summer 2000). Daily values form the basis for the calculations. For the shortwave radiation the rms in the ELDORADO product is significantly reduced for both stations. Generally, the rms values are comparable to those obtained for the stations in the Netherlands. The accuracy of shortwave surface radiation is increased when the integration system is applied. The rms values for longwave downward radiation during summer are hardly changed through the application of the ELDORADO scheme. The uncertainties of 7 $\mathrm{W\,m^{-2}}$ for Lindenberg and 10 $\mathrm{W\,m^{-2}}$ and Payerne in the first guess field are already low. The changes to 7 $\mathrm{W\,m^{-2}}$ and 9 $\mathrm{W\,m^{-2}}$ are probably within the accuracy range of the ground based observations. However, during summer time the longwave radiation component makes only a small contribution to the net downward radiation. The rms values calculated for the whole year show lower values for the ELDORADO data set. For Lindenberg the improvement is small and not significant, for Payerne station the rms is reduced from 20 $\mathrm{W\,m^{-2}}$ to 7 $\mathrm{W\,m^{-2}}$. From the limited number of observations it can be concluded that the ELDORADO scheme also has a positive impact on the derived downward longwave radiation.

4 Summary and conclusions

The main objective of ELDAS is the development of soil moisture assimilation strategies for operational NWP models. In order to minimize errors caused by incorrect forcing data sets, forcing radiation and precipitation fields are derived on the basis of observations. In this study, the ELDAS operational radiation system (ELDORADO) is presented, which has been developed to determine the downward surface radiation fields on a

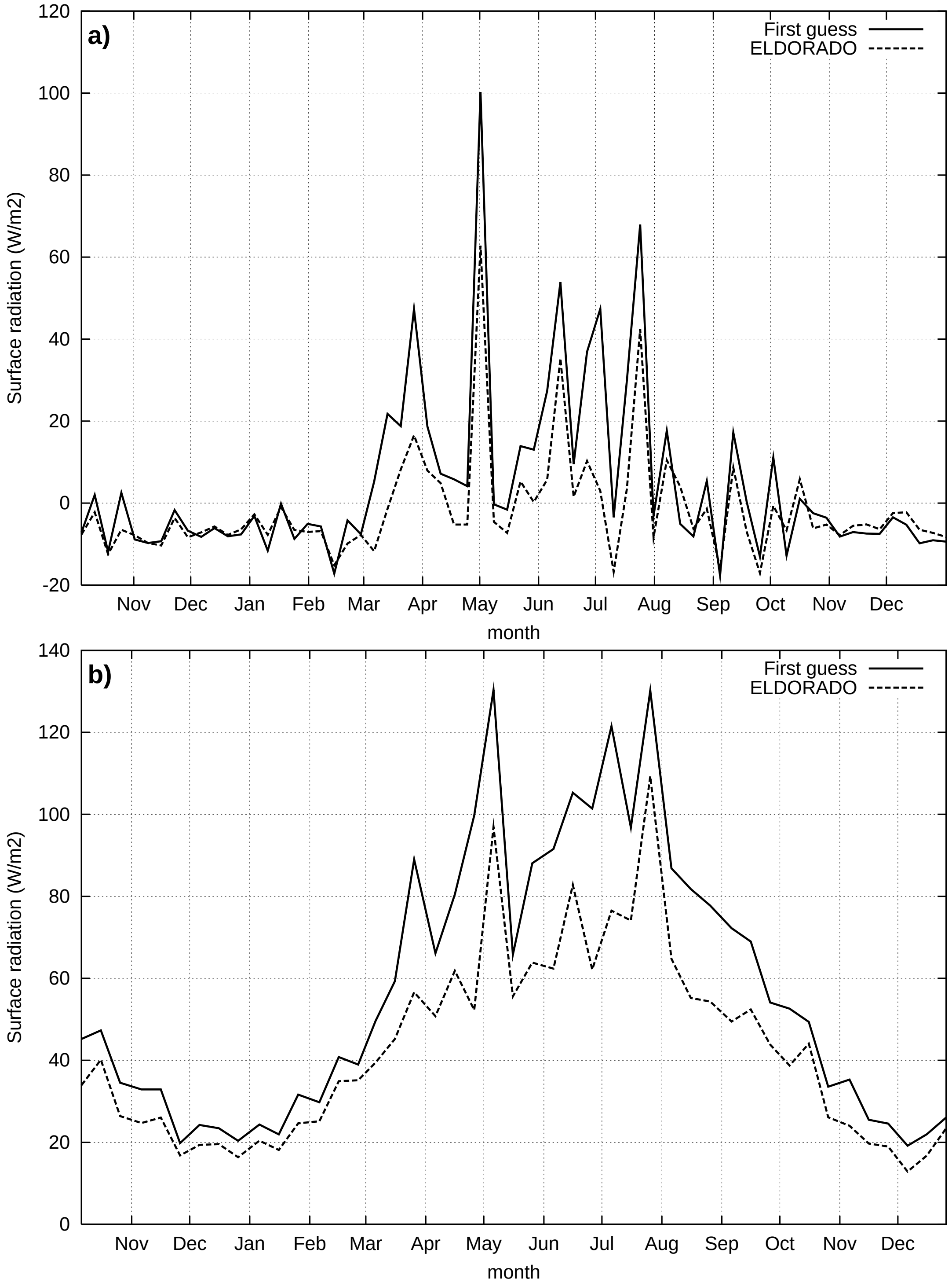

Figure 4: Time series of daily bias (a) and rms (b) of surface downward shortwave radiation for the first guess and the ELDORADO field, compared to approximately 30 radiation stations distributed across the Netherlands.

continental scale. A demonstration data base covering Europe during more than one seasonal cycle has been produced.

The sources of input for ELDORADO and its computational expenditure were restricted by the desire for an operationally working system. Meteosat visible and infrared measurements comply with these boundary conditions. Previous studies indicate that it is possible to detect 89% of the clouds over land during daytime from the two channels available (Feijt et al. 2000). Because Meteosat measurements contain only little information on the vertical structure of clouds, output of the limited area NWP model RACMO is used as a first-guess. ELDORADO modifies the first-guess to derive cloud fields with radiative properties, which match the METEOSAT observations.

ELDORADO is not a full assimilation scheme, which combines the different datasets according to their error statistics in a statistically optimal way. Consequently, shortcomings in the NWP model (including the radiative transfer scheme), errors in data sets like the aerosol climatology and errors in the observations may result in erroneous updates of the cloud amounts. As already mentioned above, cut offs to the increments had to be applied to avoid unphysical values for the cloud amounts in some cases. In the current set up, the scheme is limited to the derivation of surface radiation and can not be used in NWP to update cloud amounts. In order to extend the scheme towards a statistically optimal system for NWP applications, it would be necessary to derive reliable error estimates for the surface albedo, the aerosol climatology, the observations and the NWP model. This is a challenging task, which can not be performed within the framework of land data assimilation studies. For the offline simulations within NLDAS and ELDAS retrieval schemes as described in Pinker et al. (2003) or integration schemes like ELDORADO have to be used.

In order to validate cloud cover fields derived from Meteosat, the Metclock product is compared to observations at 950 European synoptic stations during the seven months study period in the year 2000. The average bias was found to be -0.006. For the rms errors values between 0.2 and 0.3 are obtained. Given the differences in spatial resolution and representativeness between ground truth and satellite derived cloud cover estimates, this performance is acceptable for the application in ELDORADO.

The redistribution of clouds according to these estimated cloud cover fields through ELDORADO results in finer structured cloud fields and sharper borders between overcast and cloud free areas. This improvement is confirmed by the verification of TOA shortwave radiation at 1200 UTC based on Meteosat data for July 2000. Compared to the first guess fields the rms was reduced from 84 $\mathrm{W\,m^{-2}}$ to 45 $\mathrm{W\,m^{-2}}$. In both fields TOA shortwave radiation is overestimated. However, the bias is reduced from 66 $\mathrm{W\,m^{-2}}$ to 35 $\mathrm{W\,m^{-2}}$.

Shortwave radiation at the surface are validated against 30 operational ground stations in the Netherlands. In comparison with the first guess, ELDORADO reduces the bias for the whole study period from 21 $\mathrm{W\,m^{-2}}$ to 7 $\mathrm{W\,m^{-2}}$ during summer. The already small bias of -7 $\mathrm{W\,m^{-2}}$ during winter time is not reduced by the system.

		Lindenberg		Payerne	
		RMS [$\mathrm{W\,m^{-2}}$]	Correlation	RMS [$\mathrm{W\,m^{-2}}$]	Correlation
shortwave	First guess	32.0	0.92	41.8	0.91
	ELDORADO	21.4	0.96	25.1	0.97
longwave	First guess	12.5	0.94	19.6	0.85
	ELDORADO	11.9	0.95	7.0	0.91

Table 1: Correlation and rms of shortwave and longwave radiation estimations of RACMO first guess and ELDORADO for Lindenberg and Payerne from October 1999 to December 2000.

		Lindenberg		Payerne	
		RMS $[\mathrm{W\,m^{-2}}]$	Correlation	RMS $[\mathrm{W\,m^{-2}}]$	Correlation
shortwave	First guess	42.8	0.74	54.1	0.80
	ELDORADO	28.6	0.88	29.0	0.95
longwave	First guess	6.9	0.94	10.3	0.89
	ELDORADO	7.3	0.94	8.7	0.93

Table 2: Correlation and rms of shortwave and longwave radiation estimations of RACMO first guess and ELDORADO for Lindenberg and Payerne from June to August 2000.

In a second comparison, measurements of shortwave and longwave downward radiation are analyzed for two European BSRN stations . The shortwave radiation rms is significantly reduced when compared to the value obtained for the NWP forecast. For downward longwave radiation ELDORADO slightly improves the accuracy. To decide whether this improvement is significant the analysis has to be extended to a larger number of stations, which may become available in the future.

Surface shortwave radiation budgets for NLDAS generated by Pinker et al. (2003) have also been compared to ground measurements. On the daily timescale the rms error was between 22 and 29 $\mathrm{W\,m^{-2}}$ for different ground station networks during one year. These values are comparable to the results obtained in the ELDORADO validation. The comparison of the complete NLDAS forcing data with ground stations (Luo et al. 2003) is based on hourly quantities, which make the resulting rms errors and correlations not comparable with the daily values examined in this study. A similar remark applies for the instantaneous values compared by Yucel et al. (2003).

The accuracy of downward shortwave radiation derived from the radiative transfer model approach proposed by Gautier and Landsfeld (1997) is slightly higher than the values presented in this study. However, the values presented in Gautier and Landsfeld (1997) are based on measurements at the ARM site in Oklahoma. Since the prevailing weather conditions and the surface properties differ significantly from those at the sites used in this study, it is difficult to compare the rms errors and bias directly. The correlations between ground based observation and satellite derived shortwave radiations are similar (0.96 for Lindenberg, 0.97 for Payerne, and 0.98 for ARM/Oklahoma). However, it has to be noted that the model of Gautier and Landsfeld works with a constant surface albedo. Consequently, the authors concede that they expect problems for snow surface conditions, which are common in large areas of the ELDAS study domain. Changes of the surface albedo are monitored and explicitly treated by ELDORADO. Its performance under snow conditions is included in the data analysis presented in this study. The Lindenberg station had a closed snow cover during 34 days (7.4% of the whole study period), in which the errors for this station are not different from those obtained at the Netherlands stations, which had much less snow at that time. From 25 to 31 December 2000, the Netherlands were covered by snow. Bias and rms of the ELDORADO derived radiation fields do not deteriorate during this period.

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