ELDAS radiation and heating rates products using METEOSAT data

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Abstract

METEOSAT data have been used to create two ELDAS data bases: surface radiation using the ELDORADO system, and surface heating rates that is considered to contain information on soil wetness. ELDORADO data have been used in the data assimilation experiments of ECMWF, and are shown to behave properly. Heating rate data have been analyzed in terms of differences between low and high vegetation fractions, and between two years with different hydroclimate (2000 and 2003). Initial experiments with a limited area version of the ECWMF physical parameterization package showed a systematic low bias of simulated heating rates. Most of this bias has pragmatically been removed by updating the thermal roughness length in the model. Data assimilation experiments with the limited area model are imminent.

1. Introduction

The state of the land surface is clearly influenced by the amount of radiation reaching it. For land data assimilation – such as developed in the context of the European Land Data Assimilation System (ELDAS) project; see Van den Hurk, 2002 – errors in the radiative forcing may affect the quality of the resulting assimilation products severely. However, even with perfect radiative and precipitation forcings, the state of the soil in a routine Numerical Weather Prediction (NWP) system may deviate considerably from the truth. Even more seriously, due to the long-term memory of the soil system, accumulation of small but systematic errors in the surface fluxes may give rise to a severe drift of the land surface state. For this reason, many NWP-centres introduced some way of data assimilation on soil moisture using routine atmospheric synops observations. Since these observations are only indirectly related to the state of the land surface, and since the spatial density of the observation network is limited in many (remote) areas of the world, alternative sources of (satellite) data are being explored, both in the microwave and the thermal infrared spectral ranges.

This manuscript gives an overview of two data sets that have been derived from METEOSAT satellite observations and that are useful for soil moisture data assimilation: a surface radiation dataset (both longwave and shortwave), and a dataset of surface heating rates. The methodologies used to produce the data sets is presented and an overview of the properties of the data is given. Finally, an outlook of how the data should be used in present and future land data assimilation applications is discussed.

2. Surface radiation data: the ELDORADO system

Meetschen et al (2004) developed the ELDAS RADiation (ELDORADO) system and created a 15-month (Oct 1999 – Dec 2000) database of 3-hourly surface shortwave and longwave radiation at a spatial resolution of $0.2 \times 0.2°$ over Europe. First a brief outline of the system is presented, followed by a some validation experiments.

2.1. The ELDORADO system

ELDORADO is designed to combine the powerful properties of geostationary satellite data (high spatial resolution) and NWP radiative transfer modeling (detailed knowledge of the interaction between the vertical structure of the atmosphere (including clouds) and radiation). A four-step procedure is designed and implemented based on METEOSAT data and a limited area model RACMO (Lenderink et al, 2003) in which the ECMWF physical package of the 23R4 cycle (used in ERA40) is embedded.

In step 1 an apparent bias in METEOSAT net Top-Of-Atmosphere (TOA) shortwave radiation is removed. Multiple sources for observation errors can be defined, including radiometric calibration, misspecified surface albedo, sensor degradation and dependence of calibration on cloud cover. It is assumed that the largest errors in modeled TOA net shortwave radiation are caused by misspecification of clouds, and that cloud free pixels in RACMO have little bias. Therefore, a selection was made of cloud free grid boxes during daytime, and TOA calculations of these were used to calculate a monthly calibration factor for each time slot for the METEOSAT data. This correction is usually less than 10%.

Step 2 is used to create a new spatial distribution of the RACMO cloud field. For each grid box, observed TOA net shortwave radiation was compared to RACMO results in an array of nearby gridboxes. The entire RACMO column of the gridbox matching the observed TOA net shortwave radiation the closest was subsequently moved to the target location. This procedure is able to move, expand or contract cloud systems over a limited distance.

In step 3 a further correction to the cloud cover was applied, by comparing the RACMO total cloud cover field from the METCLOCK cloud detection algorithm (Feijt and de Valk, 2001). METEOSAT data are the main source for the METCLOCK system. In order to match the METCLOCK total cloud cover, the RACMO cloud cover profile was multiplied by a scaling factor which was constant with height.

In a last step (step 4), a similar scaling was applied to the liquid water profile in the RACMO column. In this case, the scaling factor was defined as to minimize the difference between modeled and observed TOA net shortwave radiation. Since the evaluation of this quantity in step 2, cloud spatial and vertical distribution was altered in step 3, and by step 4 the consistency between modeled profiles and observed TOA fluxes was improved.

The final ELDORADO product consists of the surface downward shortwave and longwave radiation, produced by the RACMO model. Meetschen *et al* (2004) give a series of examples to evaluate the impact of each of these steps on the resulting model fields.

2.2. Validation of ELDORADO

Validation of ELDORADO products was carried out using a set of routine surface shortwave radiation measurements at 30 stations in The Netherlands, and comparison to two BSRN stations (Payerne and Lindenberg).

Figure 1 shows the comparison of summertime surface downward shortwave radiation, averaged over the Netherlands stations. Each symbol represents a single day during May and June 2000. Shown are the first guess results from RACMO (without any profile adjustment), direct ERA40 output and ELDORADO output. It can be seen that the first guess results show somewhat larger biases than ERA40, probably due to the absence of any data assimilation in the 24-hr RACMO forecasts forming the basis of the first guess data. However, the ELDORADO data outperform both of them, although some scatter is still remaining.

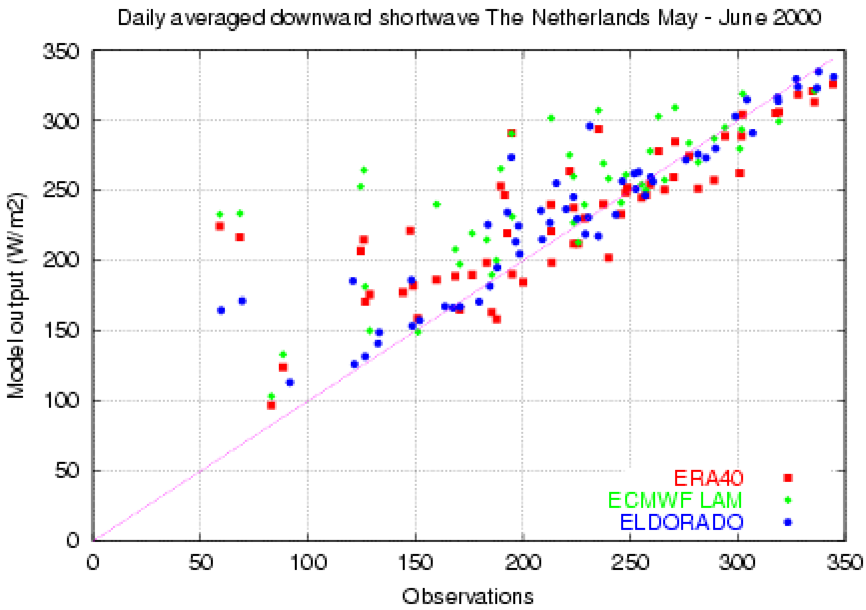

Figure 1: observed and modeled area averaged daily surface downward radiation. Observations are from 30 stations in The Netherlands; model data include the RACMO first guess, direct ERA40 output and the ELDORADO data. Each symbol represents a single day in the period 1 May – 30 June 2000.

The comparisons to data at two BSRN stations showed that longwave radiation was not affected very much by the ELDORADO system (neutral or slightly positive impact compared to the first guess), but that shortwave radiation errors were reduced considerably, especially during the summer season. Further details on the validation are discussed by Meetschen et al (2004).

3. Surface heating rate data from METEOSAT

The rate of change of the surface skin temperature depends on various processes at the land-atmosphere interface: incoming radiation, aerodynamic cooling, evaporation, and heat transport to the soil. The idea to use heating rate data in soil moisture assimilation is not new (Enthekabi et al, 1999; Kalma et al, 2001). Van den Hurk and The (2002) explored the assimilation of METEOSAT heating rate data during a 3 month summer season over Iberia. They used a similar but simpler set-up as discussed below, and showed an improvement of independent near-surface temperature and humidity scores when assimilating heating rates in a limited area model.

However, despite the promising information content on surface evaporation contained in surface heating rate data, the operational use in NWP land data assimilation systems has not yet been implemented anywhere. Practical problems remain present, including the strong dependence of heating rates on wind and aerodynamic coupling, and systematic biases in modeled skin temperatures and their dynamical evolution after sunrise (Trigo et al, these proceedings).

In the following first an overview is given of the procedure that is followed to produce a data set of METEOSAT heating rates covering most of the European area. After this, the modeled heating rate in the ECMWF land surface scheme is explored and an outlook for a data assimilation experiment covering the whole European area is discussed.

3.1. Derivation of METEOSAT heating rates

The definition of surface heating rates and the ways to derive it from available geostationary satellite observations is discussed by Van den Hurk and The (2002). The surface heating rate is defined as the surface temperature change after sunrise per unit of cos ζ, where ζ is the solar zenith angle. Owing to the thermal inertia of the soil the surface temperature generally lags behind the solar overpass. To avoid hysteresis only data before noon (and well after sunrise) are used. Atmospheric correction of surface temperature data is applied by running the MODTRAN radiative transfer code using first guess atmospheric profiles from the RACMO control simulations. The atmospheric correction varies over the day and thus affects the surface heating rate. To reduce computer cost, the atmospheric correction is calculated at a courser grid than the METEOSAT pixels and spatially interpolated.

A number of criteria are further formulated to detect valid METEOSAT heating rate pixels:

- Cloud screening is applied by defining a threshold on the residual error of a linear regression of surface temperature and shortwave reflectance on cos ζ. Time slots in which observations deviate considerably from this linear regression are flagged as cloudy and invalid
- The length of the consecutive cloud free period should be at least 3 hours, otherwise the heating rate of that pixel for that day is flagged invalid
- The temperature should rise with cos ζ: decreasing surface temperature is associated with cloud and flagged invalid
- cos ζ should be larger than 0.05 during the whole cloud free period.

These criteria generally leave 40-50% of the summertime days in Southern Europe intact. The percentage of valid summer days decreases with increasing latitude, to about 5 – 10% at 55°N. At higher latitudes no useful heating rate date can be derived from METEOSAT.

Heating rates are derived for two separate land use classes: areas dominated by tall vegetation (forests), and areas with no or limited forest cover. The ECOCLIMAP (Masson et al, 2003) database has been used to diagnose the dominant land use in each METEOSAT pixel. A further spatial aggregation was applied by averaging the heating rates of all METEOSAT pixels within every $0.2 \times 0.2°$ gridbox separately for the forest and non-forest pixels. Almost every gridbox was thus assigned a heating rate representative for low vegetation, whereas approximately 50% of all European gridboxes below 55°N also contained forest data.

Daily heating rate data were produced for central and southern Europe for two time periods: the main ELDAS time frame (1 Oct 1999 – 31 Dec 2000), and part of the summer in 2003 (1 Apr – 31 July 2003; Aug and Sep to be produced soon). The latter period enables the comparison of METEOSAT data to similar data derived from the Meteosat Second Generation (MSG). However, due to the late availability of calibrated MSG-data, heating rates have not (yet) been produced from MSG.

A preliminary analysis of the data has been carried out by plotting time series of average heating rates in eight European sub-areas, shown in Figure 2. Figure 3 shows time series of heating rates of the low vegetation land use component for each of these eight regions, both for 2000 and 2003.

As expected, in all areas the heating rates of forest vegetation is slightly lower than the low vegetation data (not shown). The differences are systematic but generally small, less than 4 K/cos ζ.

From figure 3 a clear annual cycle can be detected: relatively high values until March/April, a rapid decline to low values in early/mid spring, a gradual increase in summer and higher values later in the autumn, a reduction in late autumn/early winter by apparent wetting of the surface and a gradual increase until late winter again. Part of this is an artifact of the annual cycle of cos ζ and the associated reduction of number of valid cloud-free points in the winter season (concluded from the larger noise level in winter, and earlier springtime decline with decreasing latitude). The spring/summertime increase is the signal that is most interesting in the context of soil moisture data assimilation, since it is assumed to reflect the soil drying.

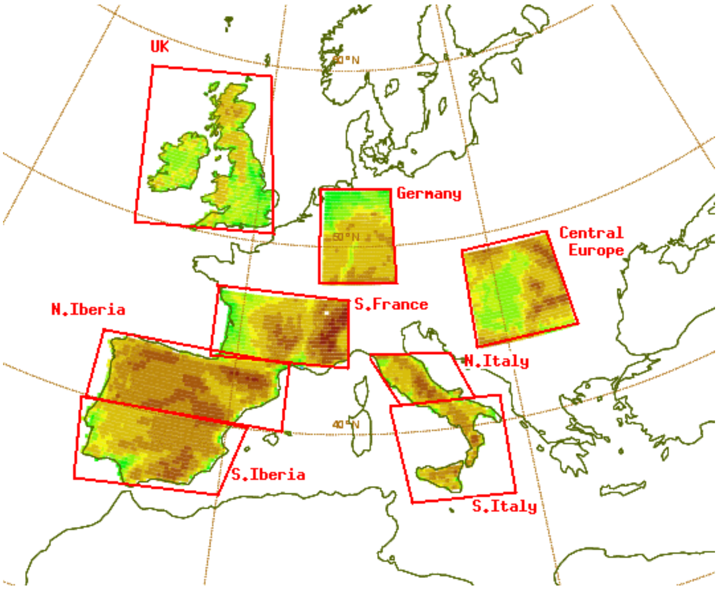

Figure 2: European sub-domains in which METEOSAT heating rates were averaged for time series plotting in figures 3 and 4.

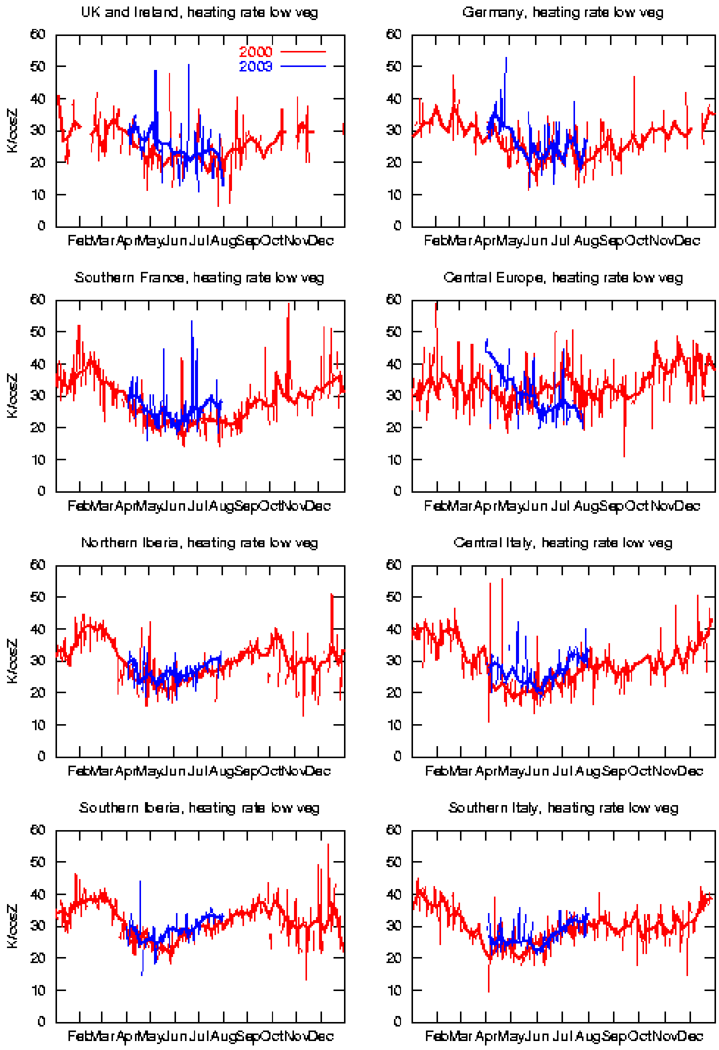

Figure 3: Time series of low vegetation heating rates in 2000 and 2003 for each of the eight regions denoted in figure 2. The areas are ordered roughly according to their geographic position: high latitude in top panels, continental areas in right hand side panels.

Apart from 2000, also the limited time frame in 2003 has been plotted. Although the true drought of that year was experienced mainly in the later half of the 2003 summer (August & September, especially in the continental areas), it can be seen that most areas experience a somewhat higher heating rate increase in the early summer than in 2000. This is well explainable from the climatological anomaly of that particular year. Processing of the remaining 2003 summer months is underway.

3.2. Modeled heating rates

Preparations are being made to carry out an extensive data assimilation experiment using the RACMO model, carrying the ECMWF physical parameterization. In order to be able to compare the results to future processed MSG-data, the 2003 time frame was selected for this experiment, in spite of the fact that for this period no ELDAS radiation and precipitation databases have been compiled.

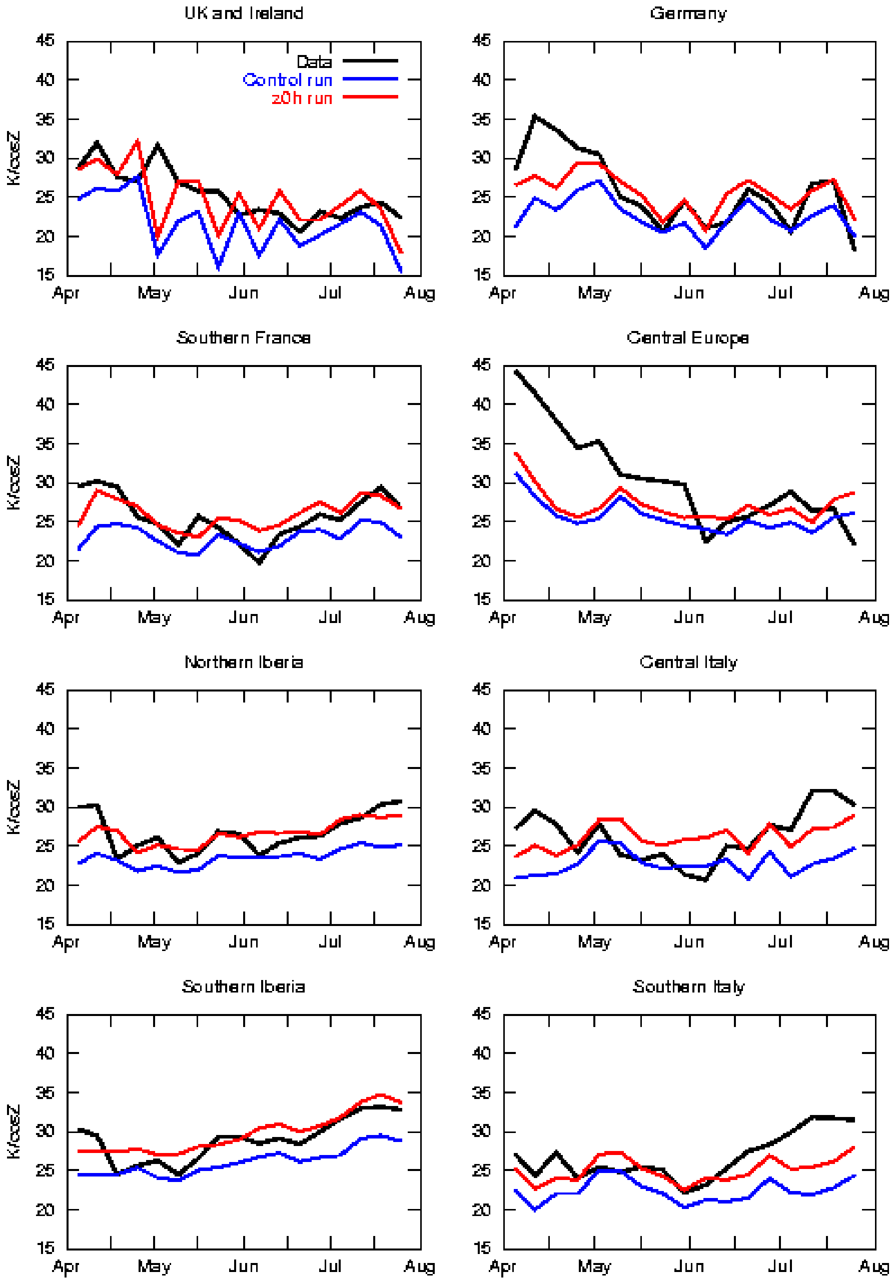

Figure 4: Observed and modeled surface heating rates for low vegetation for the 2003-period. Shown are weekly averages from the observations (black line), the control simulation (blue line) and a simulation with updated thermal roughness (red lines). Panels are for the eight sub-regions depicted in figure 2.

Figure 4 shows the modeled heating rates for the low vegetation fraction in the ECMWF land surface scheme. As in the observations, the modeled heating rates for the forest component is slightly lower than for the low vegetation, but the differences are a bit smaller than in the observations (not shown). This is likely due to the fact that the ECMWF land model assigns a similar roughness length to both the low and high vegetation fractions. The small difference between the two fractions is caused by the dominant contribution of completely forested gridboxes (with associated higher roughness length) in the calculated mean heating rate of tall vegetation.

From figure 4 it can clearly be seen that the control simulation gives rise to a strong underestimation of the heating rate early in the growing season for all areas, and a smaller than observed increase during the summer months in the southern areas. This is at least partly due to a strong sensitivity of the modeled heating rate on the specification of the aerodynamic coupling of the skin layer to the atmosphere, which is partially dependent on a parameterization using the thermal roughness length z_{0h} which has a high uncertainty. Experiments with different values of z_{0h} revealed that strong (but not unrealistic) reduction of this variable improves the correspondence to observed heating rates considerably. Assuming that misspecification of soil drying does not yet cause a strong heating rate biases during the first half of April 2003, this period was used to derive a map of z_{0h} that optimizes the mean correspondence between modeled and observed heating rates. This map is consecutively fixed in time and used to rerun the RACMO model. The change of z_{0h} generally slightly increased the surface evaporation at the cost of a small reduction of sensible heat transfer. To enable a clean evaluation of the effect of change z_{0h} on the RACMO simulations, the rerun was carried out using daily integrations starting from initial soil conditions generated in the control run. Figure 4 shows the results in terms of heating rates of low vegetation. The correspondence with observations in early April is not always perfect, but the systematic model bias is greatly reduced.

3.3. Future activities

Owing to time constraints a full data assimilation experiment has not yet been carried out with this heating rate data set. It will, however, likely be completed in the near future, allowing an evaluation of the added value of using satellite derived heating rate data for soil moisture assimilation. Only heating rate data will be assimilated, and the performance of the system is evaluated from inspection of model biases of independent synops observations (near surface temperature and humidity).

4. Conclusions and outlook

Two ELDAS datasets have been compiled using METEOSAT data: a surface radiation data base (containing both longwave and shortwave radiation), and a surface heating rate data base. The latter has been produced both for the general ELDAS time frame (Oct 1999 – Dec 2000) and part of the 2003 growing season. The radiation data have successfully been used in the ECMWF data assimilation experiments (see Ettema and Viterbo, these proceedings). Although their quality generally outperforms first guess model results, the direct added value of the radiation data to the quality of the assimilated soil moisture product is probably not excessive. The soil moisture data are shown to be very susceptible to misspecification of precipitation and the treatment of the water exchange processes within the soil model, and these sensitivities may obscure possible beneficial impacts from using ELDORADO radiation instead of first guess model products.

The heating rate data have not yet been used in a regional scale ELDAS data assimilation experiment. It remains yet to be explored what is the most optimal specification of the observation error, but it is likely that the sensitivity to this specification is small compared to the systematic heating rate bias in the model.

In this study, heating rate data are used to eliminate part of this systematic bias by adjusting the thermal roughness length in a static fashion. There is, however, no clear evidence that z_{0h} is indeed a static variable (Verhoef et al, 1997). This implies that METEOSAT data should be used to correct simultaneously for misrepresentation of the aerodynamic coupling to the atmosphere and for soil wetness errors, which violates the available number of degrees of freedom. In fact, METEOSAT data should be used in concordance with other data containing information on aerodynamical coupling and/or soil wetness (like air temperature or –humidity). Alternatively, low frequency fluctuations of the data should be separated from the faster oscillations, and these two frequency ranges should be used to address separate variables in the data assimilation system.

5. References

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