Validation of ELDAS products using *in situ* observations

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ABSTRACT

ELDAS soil moisture products from land-surface data assimilation (DA) systems designed at three European Weather Centres and implemented in online systems using the Soil-Vegetation-Atmosphere Transfer (SVAT) models ISBA (CNRM), TERRA (DWD) and TESSEL (ECMWF), respectively, are validated. Output from the three different SVAT models with DA system is compared to *in situ* observations from various databases. The present validation focuses on 1) soil moisture in the upper first meter of the soil, 2) net precipitation, that can be regarded as the main component of the soil hydrological balance in the validation period (May-October 2000) and 3) evaporative fraction. In the period considered here, the DA systems generally add water. This reduces bias in net precipitation, but without consistent reduction of the root mean square error. Evaporative fraction may be improved in dry conditions in particular, but is hardly affected in moist conditions. The amplitude of soil moisture variations is underestimated by the models. Fundamental land boundary conditions such as Leaf Area Index and soil characteristics are found to control the model results and the effect of the DA systems to a large extent. Depending on the application, improvement of the prescription of such characteristics in the models may have greater priority than further improvement of the DA system.

1. Introduction

The main objective of ELDAS (European Land Data Assimilation System) is to develop and test a system to generate high-quality estimates of regional (European) scale soil moisture. This paper describes the validation of the land data assimilation (DA) systems implemented in the context of ELDAS, by assessing the relation between model output and *in situ* observations. It is complementary to the ELDAS research efforts in which the background and behaviour of the DA system is analysed in great detail, like the research described elsewhere in this volume.

The land data assimilation systems validated here were designed at three European Weather Centres, and implemented in SVAT models (Soil-Vegetation-Atmosphere-Transfer) that are coupled to the main operational NWP-models of the centres. The first model, ISBA (Interactions between the Soil, Biosphere and Atmosphere; Noilhan and Mahfouf, 1996) has been developed at the National Centre for Meteorological Research (CNRM) at Météo-France. The second model, TERRA (DWD soil model) has been developed at the German Weather Service (DWD). The third model, TESSEL (Tiled ECMWF Scheme for Surface Exchanges over Land; Van den Hurk *et al.*, 2000) has been developed at the European Centre for Medium Range Weather Forecasts (ECMWF). Only some key-features of these systems relevant to the present validation study will be given in Section 2 of this paper. More details on the DA systems may be found in other contributions to this volume. The ELDAS products from the different models are validated using *in situ* observations from various databases. However, the information content of the datasets may be quite different, necessarily implying a different validation focus for the respective datasets (Section 3). Results for three focuses, soil moisture, net precipitation and evaporative fraction, are presented and discussed in Section 4. Finally, Section 5 summarizes our main conclusions.

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2. Key features of the models and setup of the data assimilation experiment

An overview of the SVAT schemes and the main layout of the DA experiment is given in Table 1. For each centre and SVAT-scheme the table shows the main land-surface database that was used for this validation study. While ISBA and TERRA have been run in a fully coupled mode, TESSEL has been run in a single-column mode (TESSEL-SCM). ISBA and TERRA construct their land-surface properties from the Ecoclimap database (Masson *et al.*, 2003), while TESSEL utilizes GLCC (Loveland *et al.*, 2000). For the forcings of the land-surface part, ISBA and TERRA rely on their model-derived precipitation (*P*), shortwave and longwave radiation (SW and LW, respectively). TESSEL uses the special ELDAS forcing databases for these quantities described elsewhere in this volume. The DA systems of the models use screen-level observations to diagnose deviations in the soil moisture fields. ISBA and TESSEL used temperature (*T*) as well as relative humidity (*RH*), while TERRA used *T* only. In the case of ISBA, an additional correction to soil moisture was applied to account for the difference between the model precipitation and the ELDAS precipitation. The present validation study is restricted to the period May-October 2000, for which output from all models was available.

Centre	SVAT	Land-surface database	Forcings	Soil Moisture Assimilation
CNRM	ISBA	Ecoclimap	Model P, SW, LW	(P), T, RH
DWD	TERRA	Ecoclimap	Model P, SW, LW	T
ECMWF	TESSEL-SCM	GLCC	ELDAS P, SW, LW	T, RH

Table 1. Experiment setup for the present validation study.

All models rely on the well-known resistance analogue to compute the turbulent fluxes. For evapotranspiration, E,

$$E = c_{veg} \frac{\Delta\rho_v}{r_a + r_s} \tag{1}$$

where c_{veg} is some measure of the vegetation cover, $\Delta\rho_v$ is the difference (Δ) in water vapour density (ρ_v) between the effective source height of water vapour and a reference level in the air, and r_a and r_s are the aerodynamic and surface resistance, respectively. For vegetation, the latter quantity is usually computed as:

$$r_s = \frac{r_{s,\min}}{LAI} \prod_{i=1}^{n} f(x_i) \tag{2}$$

Where $r_{s,min}$ is the minimum stomatal resistance under optimal conditions, *LAI* is the leaf area index and $f(x_i)$ are empirical functions reaching values between 0 and 1, to account for the effect of suboptimal environmental conditions on stomatal aperture. In the present context, it is important to realise that differences in $f(x_i)$ between the models will cause the main difference in the sensitivity of screen level parameters to soil moisture conditions, and are therefore important to the performance of the DA schemes. Furthermore, these differences will cause the main difference in the behaviour of the modelled *E*. Also, these functions may obscure well-known relations between evapotranspiration and environmental factors, such as the one between *E* and shortwave radiation for vegetated surfaces.

In all cases, soil moisture is a relatively slowly varying variable. Of paramount importance is the water-holding capacity, defined as the difference between field capacity and wilting point for a soil layer with depth 1 m. The water holding capacity depends on the soil texture and differs considerably among the models, as shown in Table 2. The largest range in water holding capacity appears to be contained in TERRA. Although ISBA computes wilting point and field capacity from the textural composition of the soils, the actual range of water holding capacity (~80 mm) is small. TESSEL-SCM defines one soil type only. Note that the amount of water available for evapotranspiration is not only given by the water holding capacity as defined in Table 2, but also by rooting depth.

Soil	ISBA	TERRA	TESSEL-SCM
Sand	73	154	
Sandy loam	82	160	
Loam	88	230	152
Loamy clay	89	185	
Clay	85	206	

Table 2. Water holding capacity (mm) for different soil types in ISBA, TERRA and TESSEL-SCM, defined as the difference between field capacity and wilting point the for a 1-m deep layer of soil.

3. *In situ* observations and focus of the present validation study

Figure 1 shows the locations of the sites where observations used for validation of the ELDAS products originated (validation sites). For a total number of 36 sites data are available, but at two sites the observation period did not match the model output period. Also, in the present paper the validation data from one site did not correspond to any of the validation focuses defined below. Thus, the present validation is performed using data from the 33 sites indicated in the figure. The data were obtained in the context of different field campaigns, set up with different purposes. Therefore, the information content of the data sets differs greatly among the locations. We distinguish two main classes of sites:

3.1. Soil moisture sites

At these validation sites, soil moisture observations are pertinent to the experiments in which they were performed. These observations may show great detail in space and time or both, and in a number of cases several soil moisture profiles are available at one site. At all sites, precipitation is measured. Furthermore, other observed quantities such as soil temperature may be available. In general, at these sites no turbulent fluxes are observed.

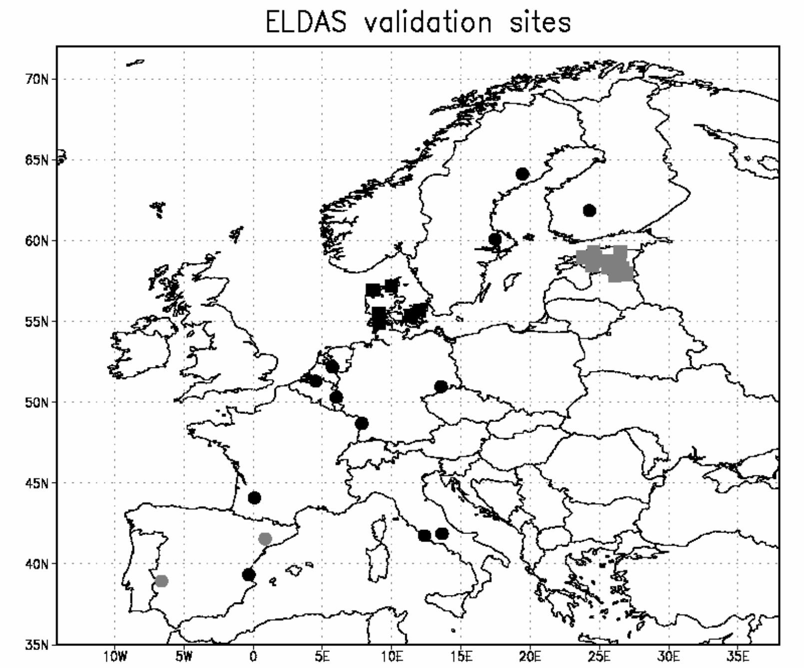

Figure 1. Location of the ELDAS validation sites. Black circles: CarboEurope sites; Grey circles: Scintillometer sites; Black squares: PLAP sites; Grey squares: BALTEX sites. See text for a further description of the sites.

Therefore, we will use the information from these sites to directly validate the soil moisture output from the models. Because soil moisture content cannot be directly compared among the models and the observations, we considered normalised trends in the evolution of soil moisture in the upper 1m soil layer. At some sites this quantity was observed directly. For other sites, observations sufficiently representative of normalised trends in this quantity were utilized, e.g., observations at 60 cm below the soil surface. To this end, data are available from three sources:

3.1.1. The Danish Pesticide Leaching Assessment Programme (PLAP)

This programme is designed to monitor the leaching behaviour of pesticides or their degradation products to groundwater. It was set up and run by the Geological Survey of Denmark and Greenland (GEUS), the Danish Institute of Agricultural Sciences (DIAS), the National Environmental Research Institute (NERI), and the Danish Environmental Protection Agency (DEPA), starting in the year 1999. At six PLAP monitoring sites, selected to represent the dominant soil types and the climatic variation in Denmark, detailed observation of, amongst other things, soil moisture and temperature profiles were performed. A detailed description of the sites and the measurements can be found in Lindhardt *et al.* (2001).

3.1.2. BALTEX-Estonia

These data were obtained in the framework of the Baltic Sea Experiment (BALTEX), an international research initiative aimed at understanding the hydrological balance and energy exchange of the Baltic sea drainage basin (Raschke *et al.*, 2001). Soil moisture measurements and precipitation data were made available for the Estonian region. These soil moisture observations are reported every decade or month, and are representative for the upper 20, 50 or 100 cm, or a combination of these layers.

3.1.3. CarboEuroflux

The major goal of the CarboEuroflux program is to improve the understanding of the magnitude and temporal and spatial variability of the carbon source and sink strengths of terrestrial ecosystems (Valentini *et al.*, 2000). The main data available from these sites are observations of the turbulent fluxes (see below). However, at some sites, soil moisture is observed at depths below 20 cm and these are included in the present analysis as well.

3.2. Flux sites

At the flux sites, micrometeorological observations of the turbulent fluxes are performed. These measurements are generally accompanied by observations of meteorological variables such as temperature, humidity, and radiation. At the majority of the sites, precipitation is observed as well. However, soil moisture is determined at a limited number of sites only. Therefore, a first focus will be on the net precipitation, P-E. For the period under consideration, this is the main component of the soil hydrological balance at most validation sites. Data on the other components of this balance (drainage and runoff) were not available, and appeared to be relatively small in the models (though sometimes not negligible). An assessment of P-E is regarded as a good first-order assessment of the behaviour of the soil hydrological balance and therefore of variations in soil moisture, albeit indirect. Considering the soil hydrological balance within the model framework for a layer with given depth and for a given period of time of one day, say,

$$\Delta W = P\text{-}E + \delta W - (R + D) \qquad (3)$$

where W is the bulk soil moisture content, δW denotes the increments from the data assimilation system, R is runoff and D is drainage, the effect of the DA system can then be assessed by comparing P-E from the observations with P-E+ δW versus P-E from the models.

The second major focus of the validation with data from flux sites is on evaporative fraction Λ, defined by

$$\Lambda = \frac{\lambda E}{\lambda E + H} \qquad (4)$$

where λ is the latent heat of vaporisation and H the sensible heat flux. This normalised flux is an important diagnostic in land-surface schemes, and may also serve as a soil-moisture indicator (Bastiaanssen, 1995). In addition, for validation purposes, normalisation is required in order to accommodate differences between the model surface and the true surface, as tiled output from the models is not available. There are two main data sources:

3.2.1. The CarboEuroflux network (Valentini et al., 2000)

In order to investigate the magnitude and temporal and spatial variability of the carbon source and sink strengths of terrestrial ecosystems turbulent fluxes are measured using eddy correlation devices mounted on tall towers. Flux measurement methods and calculations performed within the CarboEuroflux program are designed with the same hardware and software specifications at all sites. All data are quality-controlled and standard procedures for error corrections are prescribed. Details on the CarboEuroflux eddy correlation measurements and the processing of the raw data can be found in Aubinet *et al*. (2000). The flux measurements come along with various supporting observations, such as soil moisture observations, precipitation and radiation components. For the ELDAS year 2000, data are available at 13 forest sites, distributed over the European continent (see, Fig. 1).

3.2.2. Scintillometer observations in Spain

Flux observations were performed within the framework of the large scale Energy and Water Balance Monitoring System project (EWBMS), using Large Aperture Scintillometers (LAS; Moene and De Bruin 2001). The scintillometers applied here can be used to determine turbulent surface fluxes over distances of 5-10 km. Thus, observations from this instrument most closely match the spatial scale of the flux output from NWP models. Furthermore, in contrast with eddy correlation devices, these scintillometers can also be applied over heterogeneous terrain to yield average fluxes over the various surface types within the scintillometer path (Meijninger *et al.*, 2002). However, the LAS only measures sensible heat flux directly. Latent heat flux has to be derived from the surface energy balance, using net radiation and soil heat flux observations at or near the sites.

4. Results

4.1. Soil moisture

There is a myriad of options to normalise soil moisture values. Often, the soil water index is used, which is defined as the difference between the soil moisture content and the wilting point, normalised with the water holding capacity of the soil (see section 2). This index may be used explicitly in the resistance reduction functions $f(x_i)$ in equation (2). However, for the observations the required information was usually not available. Another option is to compute an index using the maximum value and minimum value in a given period, instead of the field capacity and the wilting point, respectively. However, this normalisation is sensitive to the occurrence of rare extremes, and may also exaggerate trends in soil moisture because any dataset will give normalised ranges between 0 en 1. For these reasons, we have chosen to normalise the computed or observed noon values of the upper 1m soil moisture content with the 95-percentile value of the validation period. This normalisation reveals trends, is less sensitive to a few rare extremes, while still allowing an examination of differences in trends. However, its interpretation is not straightforward in the sense that the amplitude of the soil moisture timeseries contains both the limits imposed by the water holding capacity, as well as a dynamic soil physical component.

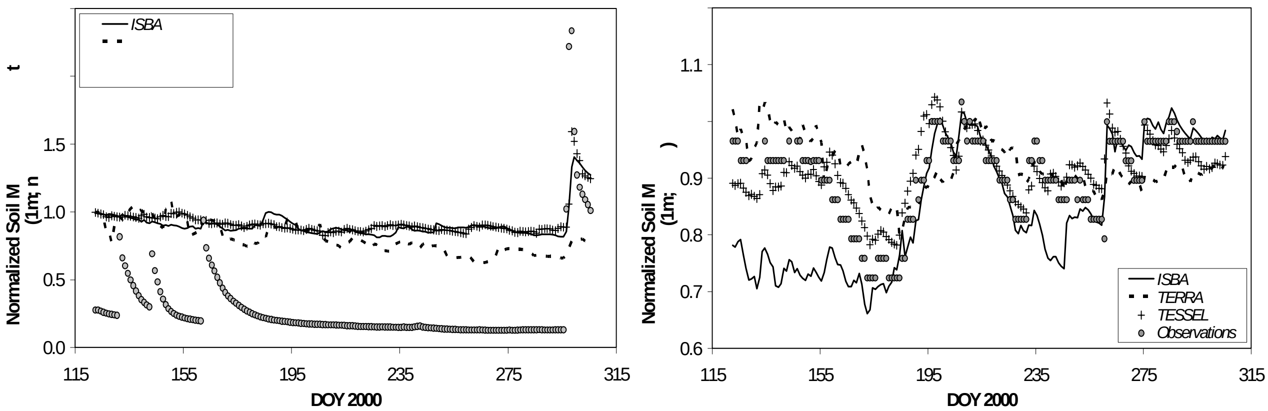

Figure 2. Normalised modelled and observed soil moisture content for the validation sites El Saler (left) and Vielsalm (right), respectively, during the validation period. Note the difference of the scale for the y-axis.

Figure 2 shows the normalised soil moisture content for a moist case and a dry case (Vielsalm, Belgium, and El Saler, Spain, respectively). It can be seen that the models are quite capable of simulating the situation in Vielsalm, but the soil moisture content seems to be overestimated for the dry case in El Saler. In the latter case, specific events after rainfall that are evident from the data can hardly be recognised in the model output. Inspection of the increments (not shown here) reveals that the models add between about 150 mm (TESSEL) and 300 (TERRA) – 350 (ISBA) mm of water to the soil, which limits to a large extent the amplitude of the soil moisture timeseries in this case. Note that one of the reason for the large input by the DA system might be the location of El Saler near the sea, with frequent occurrences of sea breeze.

For all validation sites with soil moisture observations representative for the 1m bulk value (22 sites) the amplitude of variations in the normalised soil moisture content was examined. The amplitude was computed simply as the difference between the normalised minimum and maximum daily value in the validation period. It often contains information on the amplitude of the seasonal cycle, but it may also reflect strong variations on shorter timescales such as for El Saler in the case of strong precipitation (Fig. 2). The result, shown in Figure 3, suggests that TERRA is the only model capable to mimic amplitudes up to about 0.65, which are quite common in the observations. However, inspection of a number of cases revealed that the timing of the minima and maxima may be off, and values did not always match the values for specific sites. Nevertheless, we conclude that the models tend to underestimate the amplitude of variations in soil water content. The case for El Saler shows that this may be partly due to the influence of the DA scheme, which limits the drying of the soil in that case. Another part of the explanation may be the physical limits imposed on the water holding capacity by the prescription of the soil properties, as is evident from Table 2. Scaling the amplitude with water holding capacity improved the amplitude of the ISBA output (not shown here). The non-normalised amplitude, expressed in mm of water per meter of soil, improved the comparison with the observations for ISBA and TESSEL, although there was still an underestimation on average, while there was slight tendency to overestimate the amplitude in the case of TERRA. This indicates that water vapour exchange with the atmosphere might match the observed exchange in spite of the discrepancies between the observed and modelled soil hydrological balance, perhaps due to compensating factors or errors, such as a (too) small water holding capacity and (too) large rooting depth. On the other hand, drainage and runoff, not analysed here, may also influence this amplitude.

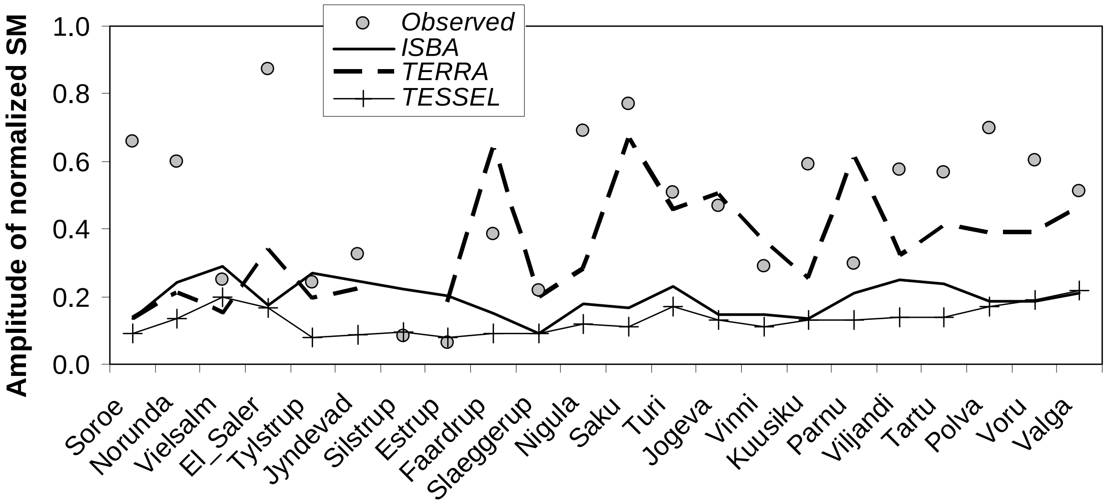

Figure 3. Amplitude of variations in the normalised soil moisture content of the upper 1 m of soil (SM). Labels on the x-axis denote the validation sites. The model outputs are connected by a line to facilitate comparison with the data.

4.2. Net Precipitation

The net precipitation, *P-E*, was computed for the flux sites with observations of evapotranspiration in all months of the validation period (12 sites). Observed precipitation can either be taken from the local observations, or from the ELDAS precipitation database that represents averages for the model grid boxes. Here, we choose to take the ELDAS precipitation, because this guarantees *P* to be available for all sites, at all times in the validation period. However, because TESSEL is driven by this forcing, the comparison between observed and modelled net precipitation is in fact a comparison between observed and modelled evaporation in this case. In some cases, the difference between the two observations may be quite large, even if expressed as cumulative monthly values. Note that the uncertainty in the ELDAS precipitation database is probably smallest in the summer (see elsewhere in this volume).

All components used in the present analysis (P, E and δW) are considered on the time scale of one month, that is, we computed cumulative values over periods of one month and reset the sums to zero at the start of subsequent months. As an example, *P-E* and *P-E+δW* are plotted in Figure 4 for validation site Flakaliden in Sweden. The figure illustrates the importance of the precipitation correction of ISBA. In this case, the ELDAS monthly P-estimates compared reasonably well with the local observations (not shown). Because

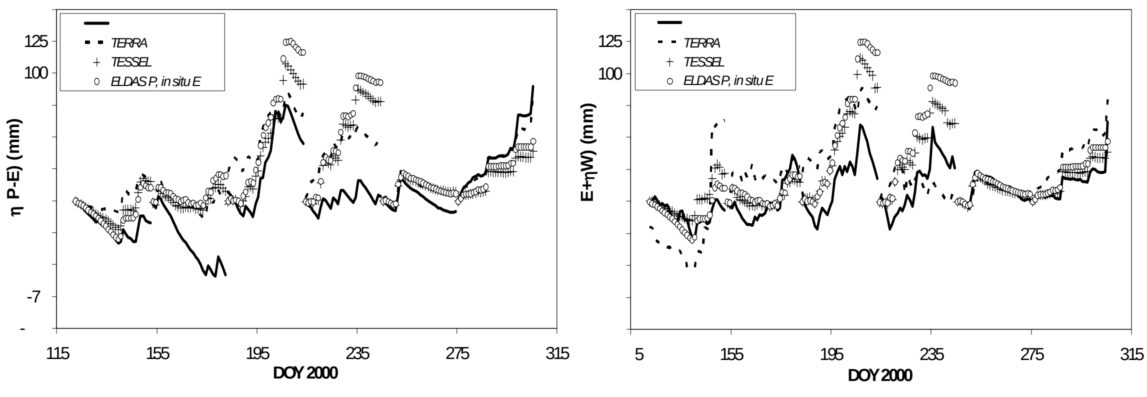

Figure 4. Illustration of the effect of the data assimilation increments on the soil hydrological balance. Case study Flakaliden (Sweden). Left: P-E; Right: P-E for the data and P-E+δW for the models. Values shown are cumulative values, reset to zero at the start of each month.

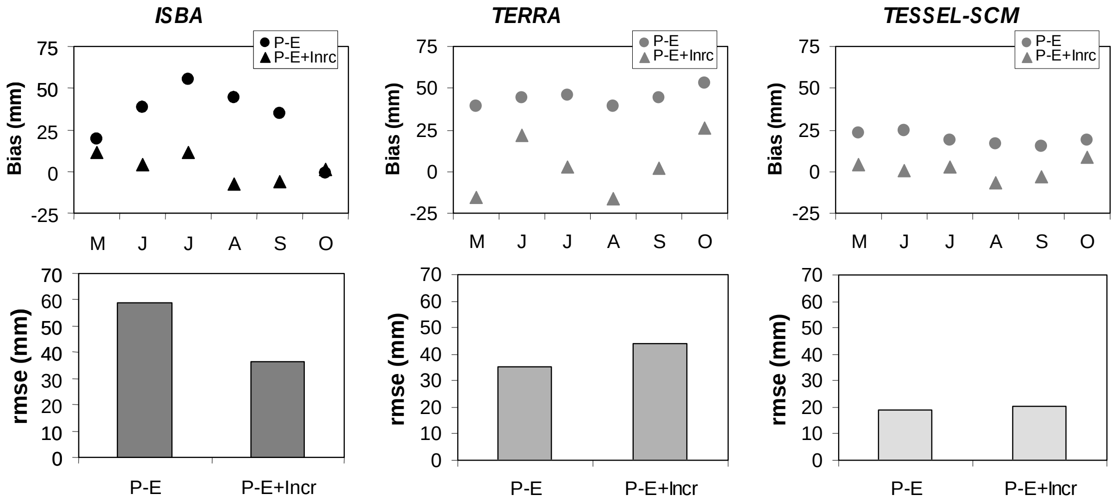

Figure 5. Bias (observations-model) and rmse of monthly sums of P-E and P-E-δW for ISBA (left), TERRA (middle) and TESSEL-SCM (right), respectively.

ISBA was quite far off in this case (not typical for the entire dataset) large corrections are required that considerably improve the modelled soil hydrological balance. In some cases, this correction cancelled the moisture input from the 2d-Var component of the assimilation scheme. The figure also illustrates the deterioration of the model output by the DA in the context of the TERRA scheme. While the initial estimate of P-E agrees quite reasonably with the observations as well as with TESSEL, the results for P-E+dW are worse for TERRA, while TESSEL shows a slight improvement. The adverse effect of the DA scheme in TERRA is found in a number of other cases as well, and seems to be typical for the first one or two months, not for the third and subsequent months. This is probably an effect of spin-up.

Next, cumulative values of P-E and P-$E+\delta W$ from the models were compared to the observed P-E on a monthly timescale. For every month and per site the model value was subtracted from the observed values. The deviations were averaged over all sites with sufficient flux data (12), giving a mean monthly bias in the soil hydrological balance (Figure 5). It can be seen that the positive bias is reduced considerably for all models, in most months. The root mean square error (rmse) over the entire validation period was also averaged for the 12 sites. Only in the case of ISBA, the rmse decreased after including the increments in the soil hydrological balance. This improvement is due mainly to the precipitation correction. TERRA showed an increased rmse, which is probably related to the spin-up problems mentioned above. The rmse in the case of TESSEL was almost the same with and without δW. However, recall that ELDAS precipitation was used to force TESSEL. We conclude that on a monthly timescale the DA schemes add water and reduce the bias in an important component of the soil hydrological balance, net precipitation, but that there is a tendency to increase the rmse, except if precipitation corrections are part of the DA system. The latter conclusions stress the importance of the availability of high-quality precipitation observations.

4.3. Evaporative Fraction

Daily values of Λ were computed for every site using mean hourly values of H and λE between 10 and 15 UTC. For the model as well as for the data we required H>-20 W/m^{-2} and λE > 10 W/m^{-2}. Furthermore, data were excluded if precipitation had been observed in the averaging period, and if the wind speed was less than 1 m/s. Furthermore, Λ for a specific day was excluded if less than 4 hourly averages for the fluxes were available. Next, the monthly averages of Λ were computed for the models as well as for the data. For every month, the average bias for all flux sites with sufficient flux data (12) was computed. However, October was excluded because in many cases, Λ plays no meaningful role anymore as a soil moisture indicator and shows large scatter. Also the rmse over the period May-September was computed on the monthly as well as on a daily timescale. The latter exercise was performed because of the role of Λ as a diagnostic of relatively fast dynamic boundary layer processes in NWP models. The results are shown in Figure 6. It can be seen that the average bias of the models varies between -0.04 and -0.10, indicating an overestimation of Λ on average. The rmse varies between 0.08 and 0.15 on the monthly timescale, and between 0.23 and 0.28 on the daily timescale.

The effect of the DA system on Λ cannot be evaluated from this information. An indication of the possible impact was obtained by comparing the output from TESSEL-SCM for the ELDAS-run with DA system to a similar control run, without DA system. The results suggested that for the TESSEL scheme the DA system had hardly any effect on Λ under moist conditions, but were improved under dry conditions. However, more general and definite conclusions require an analysis of the other models as well. Furthermore, to draw more definite conclusions on Λ, it is required that the model output matches the data as closely as possible. This requires tiled output from the models, or spatially averaged observed fluxes, for example from scintillometers.

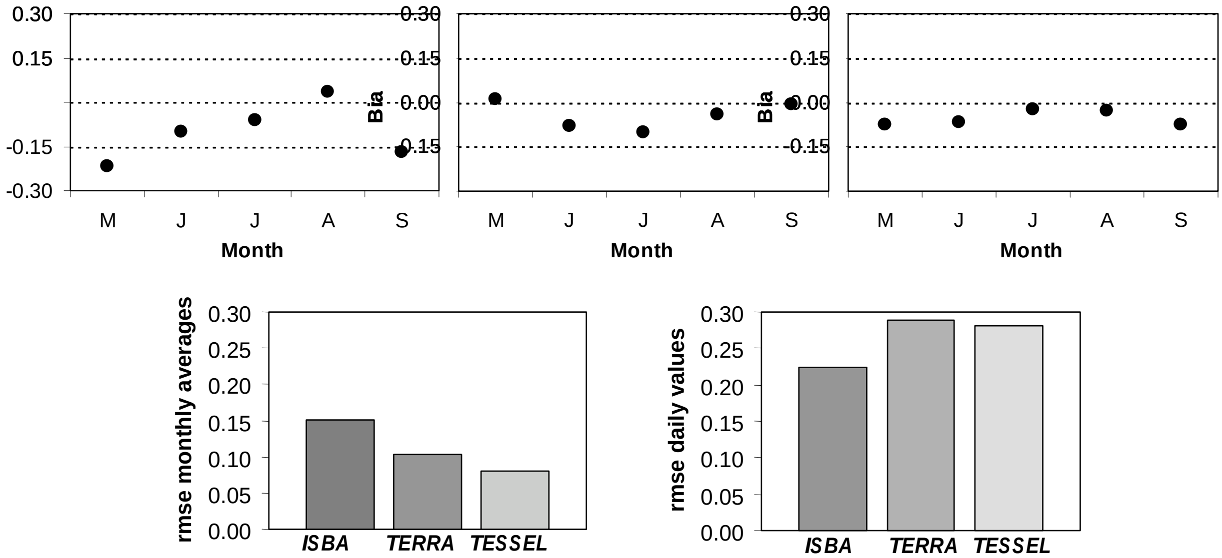

Figure 6. Bias (observations – model) in monthly averaged evaporative fraction, Λ (May-September, upper panels) and rmse of the monthly means (lower panel, left) and daily values (lower panel, right) respectively.

The importance of the surface characteristics is also illustrated in a case typical for the Estonian region, depicted in Fig. 7. Here, the 11-day moving averages of Λ, constructed from at least 6 daily values within the averaging interval, are shown for the models. The TERRA output shows a clear seasonal cycle as opposed to the output from TESSEL and ISBA. Because no flux sites are available in this area, Λ was computed using evapotranspiration according to the well-known Priestley and Taylor (1972) approach, that gives good estimates of λE for well-watered, dense grasslands and crops under optimal conditions. In spite of the temperature and radiation dependence the Priestley and Taylor approach also shows hardly any seasonal dependence. However, including a dependence on LAI using the TERRA LAI scaled to the maximum value of the period (cf. Eq. 2) does introduce a seasonal variation. Some seasonal variation, though much smaller, is also obtained if the ISBA LAI is used. Because TESSEL-SCM uses a constant LAI no change in the seasonal trend will be obtained if LAI from TESSEL is used. Accounting for the variation in LAI thus explains the differences between the models to a large extent. We conclude that fundamental surface properties may have a large impact on evaporative fraction. Such an impact may be even larger than the one of the DA system or its further improvements, at least in moist regions.

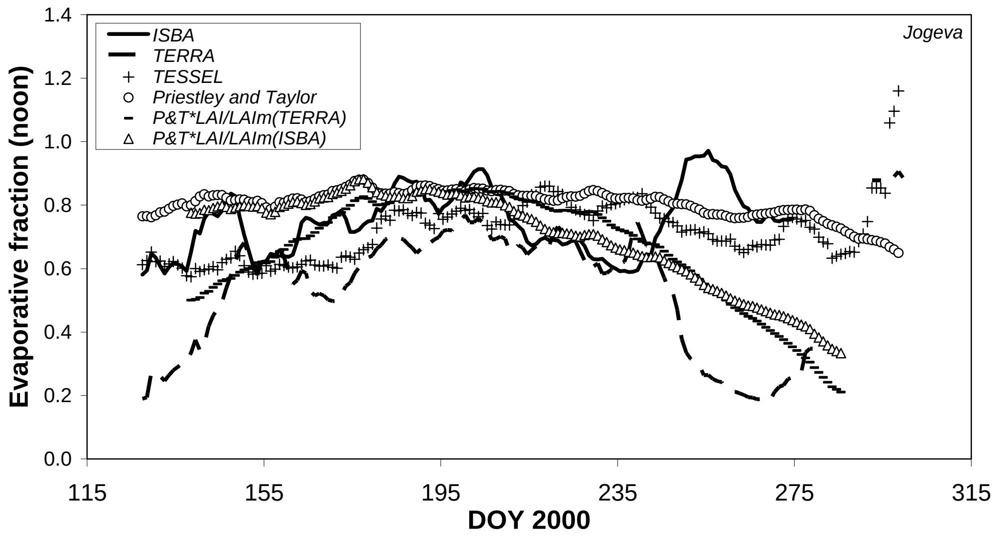

Figure 7. Illustration of the possible impact of surface properties on model output for Λ (case Jogeva, Estonia). The curves show 11-day moving averages (see text). Grey line: ISBA; dashed line: TERRA; pluses: TESSEL-SCM; open circles: Priestley and Taylor estimate of L (P&T); triangles: P&T multiplied by normalised LAI from ISBA; horizontal dashes: P&T multiplied by normalised LAI from TERRA .

5. Conclusions

For the validation period considered in the present study (May-October 2000), the land surface data assimilation systems of ISBA, TERRA and TESSEL generally add water to the soil. On average, this results in a smaller bias of the net precipitation, *P-E*, but without consistent reduction of the root mean square error. The results from ISBA in this case demonstrate the importance of high-quality precipitation observations. Also, the evaporative fraction is increased, which seems to improve the model performance for this quantity in dry areas. On the other hand, evaporative fraction of moist areas is hardly affected, or overestimation of evaporative fraction tends to increase somewhat. The models underestimate the amplitude of the soil moisture variations, which is partly due to the addition of water by the DA system, and partly to the soil characteristics prescribed by the models. The land data assimilation systems can be regarded as a practical solution to improve model performance at least in some respects. However, the control on physical processes of fundamental surface characteristics in the models, such as water holding capacity and Leaf Area Index, shows that improving such characteristics may be equally beneficial and may have greater priority than further improvement of the land surface data assimilation system.

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