Validation of European Land Data Assimilation System (ELDAS) products using *in situ* observations

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ABSTRACT

Soil moisture products from land-surface data assimilation (DA) systems implemented at three European Weather Centers are validated. The DA systems are applied online, using the Soil-Vegetation-Atmosphere-Transfer (SVAT) models ISBA (Météo France), TERRA (German Weather Service) and TESSEL (European Centre for Medium-range Weather Forecasts), respectively. Output is compared to *in situ* observations from various databases. The present validation focuses on 1) soil moisture in the upper meter of the soil; 2) net precipitation, that is, precipitation minus evapotranspiration; 3) evaporative fraction. In the period considered here (May-October 2000) the DA systems generally add water. This considerably reduces bias in net precipitation, while the root mean square error of this quantity is slightly reduced as well. Evaporative fraction is improved in dry conditions in particular, but is hardly affected in moist conditions. The DA systems tend to cause underestimation of the amplitude of soil moisture variation. Properties of the land surface such as Leaf Area Index and water holding capacity of the soil are likely to control model results as well as the impact of the DA system. Depending on the application, improving the representation of such characteristics in the models may have greater priority than further improvement of the DA system.

1 Introduction

Soil moisture is a crucial state variable in Numerical Weather Prediction (NWP) models with realistic Soil-Vegetation-Atmosphere Transfer (SVAT) schemes. It controls to a large extent the partitioning of energy available at the surface between sensible and latent heat fluxes, and therefore the development of the atmospheric boundary layer (Ek and Holtslag, 2004; Santanello et al., 2005, Betts and Viterbo, 2005). However, typical time-scales of moisture changes in the upper meter of the soil are much longer than that of changes in tropospheric humidity. Incorrect initialization of soil moisture in NWP models may therefore result in systematic drift in the soil wetness state (Viterbo, 1996) and hence lead to poor model forecasts (Rhodin et al., 1999) (resilient errors).

At present, the complexity of the NWP systems precludes physically sound and yet feasible solutions to avoid drift of soil moisture in the SVAT schemes. Soil moisture assimilation is regarded as a pragmatic solution to repair biases in land – atmosphere interaction models related to soil wetness state (Van den Hurk and Ettema, 2007). In meteorological applications, the technique has been applied routinely since the mid-nineties (Mahfouf, 1991; Van den Hurk et al., 1997; Houser et al., 1998; Douville et al., 2000; Hess, 2001; Balsamo et al., 2004). Control of drift in soil moisture by land surface data-assimilation can considerably reduce forecast errors in screen-level temperature and humidity (Hess, 2001; Viterbo, 1996).

The research project "Development of a European Land Data Assimilation System to predict Floods and Droughts" (ELDAS) aimed to combine European expertise in the field of land-data assimilation and to develop and test a system to generate high-quality estimates of regional (European) scale soil moisture fields (Van den Hurk, 2002). It was related to the Global Land Data Assimilation System (GLDAS; Rodell et al., 2004) and the North American Land Data Assimilation System (NLDAS; Mitchell et al., 2004).

ELDAS systems were designed at three European NWP centers, and implemented in an online mode, that is, with full coupling to the NWP models. The latter feature is crucial, since it allows screen level observations to be used to drive the Data Assimilation (DA) system. It is necessary to include such indirect measures of soil moisture status, because direct soil moisture observations are not readily available on a routine basis (Van den Hurk and Ettema, 2007).

The DA systems were applied within the SVAT schemes that are incorporated in the main operational NWP models of the three centers involved in the present study. The first SVAT model, ISBA (Interactions between the Soil, Biosphere and Atmosphere; Noilhan and Mahfouf, 1996) has been developed at the National Centre for Meteorological Research (CNRM), Météo-France. The second model, TERRA (Doms et al., 2005) 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). Hereafter, the respective DA schemes will be named after the SVAT models applied at the NWP centers. For details on the DA and SVAT schemes the reader is referred to the cited literature.

The present paper describes a validation of the DA systems applied in ISBA, TERRA and TESSEL, respectively. Key-features of the SVAT and DA systems relevant to the present validation study will be given in Section 2. The systems are validated using *in situ* observations from 33 locations in Europe. The validation data originate from various databases that are briefly described in Section 3. The information content of these datasets varies widely among the locations, necessarily implying a different validation focus for the respective datasets. In order to focus the validation, three main topics were selected. Soil moisture, the quantity that is directly affected by the ELDAS system was selected as the first focus. Direct observations of soil moisture are only available from a limited number of sites. Therefore, as a second focus the behavior of net precipitation was chosen. Here, this quantity is defined as gross precipitation (P) minus evapotranspiration (E). For the validation period selected (May-October 2000), it is a major component of the soil hydrological balance, so that trends in P-E may be considered as a first-order approximation of trends in soil moisture. The third focus was chosen to be the energy partitioning at the surface, which plays a crucial role in meteorological models (see, e.g., Ek and Holtslag, 2004). Ultimately, land data assimilation systems are designed to yield a correct energy partitioning in the meteorological models. The results of the validation for the three main topics are presented and discussed in Section 4. Finally, Section 5 contains a general discussion and conclusions.

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

2.1 General

An overview of the SVAT schemes and the main layout of the DA experiment within ELDAS is given in Table 1. A full description of the physics of the SVAT schemes can be found in the cited literature. Here, only some key features of the DA experiment and characteristics that are crucial in the interpretation of the validation results are given.

The present validation study is restricted to the period May-October 2000, for which output from all models was available. ISBA and TERRA were run in their 3-dimensional mode. ISBA was run in the ARPEGE global model (Courtier et al., 1991), which has a Gaussian varying grid size ranging between 17 and 25 km over the ELDAS domain (Balsamo et al., 2005). TERRA is run in the Lokal-Modell (LM; Doms and Schättler, 2002) at a horizontal resolution of 7 km. The model output from ISBA-ARPEGE and TERRA-LM was post-processed to be projected on the ELDAS grid ("nearest neighbor"). The ELDAS grid extended from [35° N, 15° W] to [72° N, 38° E], with a horizontal resolution of 0.2x0.2 degrees. By contrast, TESSEL was run in a single-column (1-dimensional) mode (TESSEL-SCM) in which advection is prescribed as a lateral boundary condition to compensate for the lack of 3-dimensional feedback. The horizontal advection terms are derived from re-analyzed meteorological fields (ERA-40, Uppala et al., 2005). TESSEL-SCM was run specifically for gridpoints corresponding to the 33 validation sites.

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 relied on their model-derived precipitation (P), shortwave and longwave radiation (SW and LW, respectively). TESSEL used the special ELDAS forcing databases for the precipitation (Rubel et al., 2005) and radiation fields (Meetschen et al., 2004), respectively.

In the case of ISBA, a correction to soil moisture was applied to account for the difference between model precipitation and ELDAS precipitation forcing (Balsamo et al., 2004, 2005). All DA systems diagnose deviations in the soil moisture fields from forecast errors in screen-level observations. ISBA and TESSEL used temperature (*T*) as well as relative humidity (*RH*), but TERRA used *T* only.

2.2 Description of evapotranspiration in the models

All models compute the turbulent fluxes using the well-known resistance analogue. For evapotranspiration,

$$E = c_{veg} \frac{\Delta \rho_v}{r_a + r_s} \text{ [kg m}^{-2}\text{s}^{-1}\text{]} \tag{1}$$

where c_{veg} [-] is some measure of the vegetation cover, $\Delta\rho_v$ [kg m^{-3}] is the difference in water vapor density between the effective source height of water vapor and a reference level in the air, and r_a [s m^{-1}] and r_s [s m^{-1}] are the aerodynamic and surface resistance, respectively. In the present context, r_s has some special importance, because it incorporates the connection between soil moisture and the conditions at the screen level. For vegetation,

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

where $r_{s,min}$ [s m^{-1}] is the minimum stomatal resistance under optimal conditions, LAI [m^2 m^{-2}] is the leaf area index and $f(x_i)$ are dimensionless empirical functions that account for the effect of environmental conditions on stomatal aperture (Jarvis, 1976). Differences in r_s implied by differences in $f(x_i)$ will cause the main difference in the behavior of the modeled E. The function $f(\theta)$ describing the impact of soil moisture on r_s determines the sensitivity of screen level parameters to soil moisture conditions (Mahfouf, 1991). The performance of the DA schemes will therefore be sensitive to $f(\theta)$.

2.3 Coupling between soil moisture, evapotranspiration and screen level observations

The link between the screen level observations and soil moisture is provided by evaporative fraction, Λ, defined as

$$\Lambda \equiv \frac{\lambda E}{H + \lambda E} \tag{3}$$

where H [W m^{-2}] is the sensible heat flux and λ [J kg^{-1}] is the latent heat of vaporization. This link can be further examined by re-writing the sensitivity equation for λE to r_s given by Jacobs and De Bruin (1992) as:

$$\frac{\partial \Lambda}{\partial r_s} = \frac{-\Lambda}{(1 + s/\gamma) r_a + r_s} \tag{4}$$

which can readily be derived from the well-known Penman-Monteith equation. Here, s [kg kg^{-1}K^{-1}] is the slope of the saturation specific humidity versus temperature curve and γ[K^{-1}] ≡ c_p/λ is the psychrometric constant, where c_p [J kg^{-1} K^{-1}] is the specific heat capacity of the air. Equation (4) represents the change in Λ per unit change in r_s. In the models considered here, the response of r_s to soil moisture is modeled using in (2):

$$f(\theta) = \begin{cases} 0 & \theta < \theta_w \\ \dfrac{\theta - \theta_w}{\theta_c - \theta_w} & \theta_w \le \theta < \theta_c \\ 1 & \theta \ge \theta_c \end{cases} \tag{5}$$

where θ_w [m^3 m^{-3}] is the wilting point and θ_c [m^3 m^{-3}] a critical moisture content defining the transition between supply and demand limited transpiration. ISBA and TESSEL assume θ_c to be equal to the field capacity θ_{fc} [kg m^{-3}], by which the second member of (5) becomes equal to the Soil Water Index. In TERRA θ_c is the so-called turgor loss point which is computed dynamically as a function of the water holding capacity and the potential evaporation, following (Denmead and Shaw, 1962). By virtue of (5), r_s and Λ are sensitive to θ only in the range $\theta_w \le \theta < \theta_c$. Because of absence of synergy in (2), the modeled sensitivity of r_s to θ in this interval can to first order be written:

$$\frac{\partial r_s}{\partial \theta} = \frac{-r_s}{\theta - \theta_w} \tag{6}$$

so that

$$\frac{\partial \Lambda}{\partial \theta} = \frac{\Lambda}{\theta - \theta_w}(1 - \Omega) \tag{7}$$

with

$$\Omega \equiv \left[1 + \frac{\gamma}{s + \gamma}\frac{r_s}{r_a}\right]^{-1} \tag{8}$$

Ω is the decoupling factor (Jarvis and McNaughton, 1986), describing to what extent the surface and the conditions at a reference level are coupled. It attains values between 0 and 1 and is mainly influenced by the surface characteristics implicit in r_s and r_a. It is further modulated by temperature, through the dependence of s on temperature.

Equation (7) provides a justification of DA approaches where forecast errors in screen level observations are used to diagnose soil moisture deviations and to improve the energy partitioning by adjusting the soil moisture. The required sensitivity is present in the models by virtue of stress function (5). Apart from the somewhat intuitive result that Λ should decrease with decreasing soil moisture, (7) shows that the impact of soil moisture changes on Λ is expected to be largest for well-coupled surfaces such as forests (high r_s, low r_a). The sensitivity is strongly enhanced by dry soils in two ways: 1) by decreasing the soil moisture content which reduces θ - θ_w; 2) by increasing r_s and therefore (1-Ω). Thus, (7) implies that a given soil moisture increment will have a larger impact on Λ in dry conditions than in wet conditions. Although the sensitivity represented by (7) will be modulated by feedback with the ABL (Jacobs and De Bruin, 1992; Ek and Holtslag, 2004) this equation can be used to interpret the main differences in the impact of the various DA systems on Λ.

2.4 Water holding capacity

In all cases, soil moisture is a relatively slowly varying variable. Of paramount importance is the water-holding capacity, defined here as the difference between field capacity and wilting point for a soil layer with depth 1 m. The water holding capacity depends on soil texture and differs considerably among the models, as shown in Table 2. The amount of water available for evapotranspiration is both a function of the water holding capacity as defined in Table 2 and of rooting depth.

The largest range in water holding capacity per unit soil depth is modeled 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 uses one uniform soil type.

The minimum sensitivity of Λ to soil moisture content is directly controlled by the water holding capacity, as can be seen from (7): the minimum sensitivity is obtained as $\theta \rightarrow \theta_{fc}$. Note that then $f^{-1}(x_n) \rightarrow 1$. For otherwise similar conditions the sensitivity is inversely proportional to the water holding capacity. Thus, under well-watered conditions and for similar rooting depth, the sensitivity of Λ in ISBA may be expected to be roughly twice that of TESSEL, and 2-3 times that of TERRA.

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

3.1 General

Figure 1 shows the locations of the 33 validation sites, that is, sites where observational data used in the present validation study were collected. The observations were performed in the context of different field campaigns, set up with different purposes. Therefore, the information content of the data sets varies widely among the locations. Also, a large range of climatic conditions is represented in the data.

At 24 out of the 33 validation sites, direct soil moisture observations were performed. These sites are henceforth called “soil moisture sites”. Some of the soil moisture observations show great detail in space and time. At all soil moisture sites precipitation is measured. Occasionally, other observations such as soil temperature are available, but at most of the soil moisture sites turbulent fluxes of latent and sensible heat were not observed.

At 14 out of the 33 sites micrometeorological observations of the turbulent fluxes were performed. These sites will be referred to as “flux sites”. The flux measurements were generally accompanied by observations of meteorological variables such as temperature, humidity, and radiation. At the majority of the sites, precipitation was observed as well. However, soil moisture was measured at a limited number of the flux sites only.

3.2 Validation data sources

In this study data from the following experiments were used:

a) The Danish Pesticide Leaching Assessment Programme (PLAP)

This programme was designed to monitor the leaching behavior of pesticides or their degradation products to groundwater. At six PLAP monitoring sites detailed observations of soil moisture and temperature profiles were performed. The observations in the soil were accompanied by observations of precipitation. For a detailed description of the sites and the measurements the reader is referred to Lindhardt et al. (2001).

b) *BALTEX-Estonia*

The Baltic Sea Experiment (BALTEX) is an international research initiative aimed at understanding the hydrological balance and energy exchange of the Baltic sea drainage basin (Raschke et al., 2001). For the ELDAS validation period, soil moisture content and precipitation data were made available for the Estonian region.

c) *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, obtained following prescribed experiment and data processing protocols (Aubinet et al., 2000). For the ELDAS year 2000, observations of H and λE were available at 13 forested sites, distributed over the European continent. Precipitation was observed at all but one of the CarboEuroflux sites used here. At some sites, soil moisture content was observed at depths below 20 cm and seasonal trends derived from these observations were included in the present analysis.

d) *Scintillometer observations in Spain*

For one site in Spain, flux observations were available from the large scale Energy and Water Balance Monitoring System project (EWBMS; Moene and De Bruin 2001). These measurements were performed with a Large Aperture Scintillometer (LAS), in an irrigated area near Badajoz in Spain. LAS can be used to measure sensible heat flux H over distances of 5-10 km and can even be applied to determine average fluxes over the various surface types within the scintillometer path (Meijninger et al., 2002). However, because the LAS only measures H directly, λE has to be derived from the surface energy balance:

$$\lambda E = Q_{*} - G - H \tag{9}$$

where Q_{*} [W m^{-2}] is the net radiation and G [W m^{-2}] is the soil heat flux. Observations of precipitation and the amount of irrigation in the scintillometer area were also available.

3.3 Validation focus and processing of the data

In accordance with the differing information content of the validation datasets, three main validation topics were chosen.

a) Soil moisture

Soil moisture is directly affected by the ELDAS systems and was therefore selected as the first focus. In order to avoid disparities due to the different discretization of the models, the moisture content in the upper 1m of the soil (θ_{1m} [m^3 m^{-3}]) was considered. At some validation sites θ_{1m} was observed directly. Analysis of detailed data from these sites showed that normalized trends of θ_{1m} can be approximated by normalized trends from observations below a depth of 20 cm. Therefore, such approximations of the trend in θ_{1m} were used for locations where direct observations of θ_{1m} were not available.

In order to ensure a fair comparison between observations and modeled soil moisture, normalized quantities are preferred and to this end, soil water index (θ - θ_w)/(θ_{fc} - θ_w) has often been used in the past (e.g., Dirmeyer et al., 2000). However, for the validation sites θ_{fc} and θ_w were often lacking. Another option is to compute an index from the maximum and minimum soil moisture value in a given period. However, this normalization is sensitive to rare extremes and exaggerates normalized trends in soil moisture. Moreover, dynamical differences are obscured, because any dataset will give normalized ranges between 0 and 1. For these reasons, it was decided to normalize the computed or observed values of the θ_{1m} using the 95-percentile value θ_{1m}^{95} of the validation period:

$$\hat{\theta} = \frac{\theta_{1m}}{\theta_{1m}^{95}} \tag{10}$$

This normalization is less sensitive to a few rare extremes, while still allowing an examination of differences in trends.

b) Net Precipitation, *P-E*

For none of the validation sites observations of natural drainage and runoff were available, which precluded analyses of the full soil hydrological balance. However, for the period under consideration gross precipitation and evapotranspiration, *P* and *E*, respectively, may be regarded as the major components of the soil hydrological balance at most validation sites. Therefore, the net input *P-E* was chosen as the second main focus of the present study. *P-E* can be used to evaluate the performance of the DA system as follows.

Within the model framework the soil hydrological balance of a layer with given depth for a given period of time of one day, say, is given by

$$\Delta W = P - E + \delta W - (R + D) \tag{11}$$

where W is the bulk soil moisture content, δW denotes the increments from the data assimilation system, R is runoff and D is drainage. For the observations δW is zero. Assuming (R+D) << (*P-E*), the effect of the DA system can therefore be assessed by comparing *P-E* from the observations with

P-E+δW and *P-E*, respectively, from the models. Because this analysis requires *E*, it could only be performed for flux sites. Cumulative values of *P*, *E*, and δW over periods of one month are considered. By resetting sums to zero each month, propagation of errors in early months to later months is avoided. Furthermore, specific seasonal features of the performance can be revealed.

Observed *P* was taken from the ELDAS precipitation database (Rubel et al., 2005). This database consists of 3-hourly precipitation sums for each gridpoint in the ELDAS domain, constructed from over 20000 rain gauge observations and radar observations in Europe. This data source is preferred over the local observations, because it guarantees high-quality observations of *P* to be available for all sites, at all times in the validation period. Furthermore, it matches the spatial scale of the model resolution and the quality of the ELDAS precipitation database is probably best in the period that is considered here (Rubel et al., 2005).

c) *Evaporative fraction,* Λ

The third major focus of the present validation study was chosen to be Λ, defined by (3). It is an important diagnostic in land-surface schemes (Ek and Holtslag, 2004; Betts and Viterbo, 2005), and may also serve as a soil-moisture indicator (Bastiaanssen, 1995). Λ quantifies the partitioning of available energy between heating and moistening the Atmospheric Boundary Layer (ABL). It controls to a large extent the ABL dynamics, including the formation of clouds within the ABL (Ek and Holtslag, 2004; Betts and Viterbo, 2005). Because it is a normalized flux, Λ allows a fair comparison between the model and the observations, independent of differences between prescribed and real surface characteristics. Also note that Λ is less sensitive to possible energy balance closure problems from the EC measurements.

Obviously, only data from flux sites could be used in this analysis. Data treatment from these sites needed special care in order to ensure meaningful analyses of Λ. Apart from the basic quality requirements within the CarboEuroflux community (Aubinet et al., 2000), the data were post-processed as follows.

Daily values of Λ were computed for every flux site (n=14) using only mean hourly values of H and λE between 10 and 15 UTC. For the sites considered here, the selected daytime period contains local noon in all cases. Observations were excluded if precipitation had occurred during the averaging period, and if the observed wind speed was less than 1 m/s. For both the model and the observations it was also required that H>-20 W/m^{-2} and λE > 10 W/m^{-2} (with upward fluxes taken positive). These requirements exclude extremely stable conditions under which Λ is a poor indicator of soil wetness and boundary layer dynamics. Finally, Λ for a specific day was included only if it could be computed from at least 4 out of 5 hourly flux values after the aforementioned data screening procedure.

For each flux site, average monthly differences between modeled and observed Λ were computed if in a particular month at least 50% of the noontime differences was available at that site. Next, for each month the mean differences were averaged over all sites with sufficient data in that month. October was excluded in all cases, because in that month Λ usually played no meaningful role as a soil moisture indicator anymore. Wet conditions due to precipitation often led to a stably stratified atmosphere in this month so that only a small number high-quality Λ values could be obtained.

4 Results

4.1 Soil moisture

Figure 2 shows the normalized soil moisture content $\hat{\theta}$ as defined by (10) typical of Vielsalm, Belgium, and El Saler, Spain. The general features of these cases are representative of moist and dry locations, respectively. It can be seen that the models are quite capable of simulating the situation in the moist case of Vielsalm. The amplitude of the variation in $\hat{\theta}$ is limited for both the observations and the models and amounts to, roughly, 0.40. Also, the timing of the variations is reasonably well simulated. In contrast, $\hat{\theta}$ is generally overestimated for the dry case of El Saler, except when a rainfall event causes the observed soil moisture to increase. Rapid increases in $\hat{\theta}$ due to rainfall events are observed, but not simulated by the models. An exception is the rainfall event on DOY (Day Of Year) 295 that has a clear impact on the output from ISBA and TESSEL. While the soil is observed to quickly dry out after a rainfall event, with values of $\hat{\theta}$ dropping to between 0.1 and 0.3, the models maintain the soil wetness at a high level with $\hat{\theta}$ between 0.6 and 0.8. Analysis of the soil hydrological balance after a rainfall event suggests that the high values are due to the addition of soil water by the DA system. Table 3 highlights the balance terms in the period between DOY 162 and DOY 191, just after the rainfall event on DOY 161. On DOY 162, $\hat{\theta}$ is about equal for the observations and the models. Hereafter, there hardly any precipitation is observed and the soil dries out. For all three schemes, the computed evapotranspiration is too high. However, in the case of ISBA, the output of soil water by evapotranspiration is fully compensated by input of water from the DA scheme and the soil water content increases. For TERRA, the compensation of evapotranspiration by the DA scheme amounts to 75%. This suggests that in these models, the amplitude of $\hat{\theta}$ is almost entirely limited by the DA scheme in the case of El Saler. For TESSEL, the compensation of evapotranspiration by the DA scheme is some 40%. However, the evapotranspiration term is overestimated much less than in the case of ISBA and TERRA. As a result, the modeled net loss of water from the soil (42 mm) corresponds quite well with the observed one (39 mm).

The underestimated amplitude of $\hat{\theta}$ at El Saler might be an important characteristic of the DA schemes investigated here. Therefore, the modeled and observed seasonal amplitude of $\hat{\theta}$ was compared for all validation sites where direct or approximated trend of θ_{lm} could be calculated (22 sites). The amplitude is computed simply as the difference between the normalized minimum and maximum of the daily $\hat{\theta}$ values in the validation period May-October 2000. Thus, it contains information on the amplitude of the seasonal cycle as well as on trends at shorter timescales such as induced by precipitation (see the El Saler example discussed above).

Results are shown in Figure 3. Amplitudes > 0.5 are quite common in the observed values. TERRA is the only model capable to mimic such amplitudes, with values up to about 0.65. However, inspection of a number of cases revealed that the timing of the minima and maxima was quite wrong (not shown here). Moreover, modeled amplitudes did not always match observed amplitudes for specific sites (Fig. 3). Amplitudes of ISBA and TESSEL remain below 0.3 for all sites.

It is concluded that the models tend to underestimate the amplitude of soil water content. The analysis for El Saler shows that this may be partly due to the influence of the DA scheme, which limits drying of the soil. In addition, soil physical characteristics may limit modeled amplitudes of soil moisture. The larger water holding capacity of TERRA (see Table 2) could explain the larger amplitude of the soil moisture simulated by this model.

For completeness, the non-normalized amplitude, expressed in mm of water per meter of soil, was also investigated. The results, shown in Figure 4 improved the comparison with the observations for ISBA and TESSEL, although there was still an underestimation on average, while there was a slight tendency to overestimate the amplitude in the case of TERRA. It is important to realize that discrepancies in the modeled soil hydrological balance do not necessarily imply a mismatch of evapotranspiration, due to compensating factors, such as a too small water holding capacity with too large rooting depth, or influence of drainage and runoff, which are not analyzed at present.

4.2 Net Precipitation

For the flux sites with direct observations of evapotranspiration (14 sites) observed P-E was computed for all months of the validation period (May-October). Figure 5 shows an example of P-E and P-E+δW for validation site Flakaliden in Sweden. The results for this particular site illustrate a couple of quite typical features of the ELDAS systems. Comparing the balance terms with and without δW shows that in some months the DA scheme improves the modeled soil hydrological balance, in others it does not. TESSEL performs rather well over the entire period and the increments improve the performance a little further. However, recall that P from ELDAS is one of the direct forcings of TESSEL. In contrast, the DA scheme of TERRA seems to deteriorate the output of this model. While the initial estimate of *P-E* agrees reasonably well with the observations the results for *P-E+δW* are much worse. This adverse effect of the DA scheme in TERRA was 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 as the assimilation was initially started from interpolated fields from a global model that has a free-running soil (Wergen et al., 2005). The output from ISBA is significantly improved by the DA scheme. However, the main improvement is due to the soil moisture correction based on the precipitation bias. The relatively poor estimate of *P-E* from ISBA was mainly due to the fact that *P* was quite far off in this case (*not* typical for all sites). These deviations triggered large *P*-related corrections in the ISBA scheme, that considerably improved the modeled soil hydrological balance. In some cases, this correction completely cancelled the increments due to the 2d-Var component of the DA scheme in ISBA.

For the flux sites, monthly cumulative observed *P-E* was compared to modeled *P-E* and *P-E+δW*, respectively, if the data coverage of observed *E* in a particular month was at least 67% (n=13 for May-June; n=12 for July-October). Mean monthly bias of *P-E* and *P-E+δW*, respectively, was computed as well as the root-mean-square-error (*rmse*) of the monthly sums from the differences at the validation sites. The monthly results are depicted in Figure 6. The averages over all months in the validation period are given in Table 4. A negative bias means that the model is too dry.

It can be seen that including the increments considerably reduced the bias in all models, in most months, suggesting a beneficial effect of the DA system on the soil hydrological balance. Only in October the DA system has hardly any effect on the bias in the monthly sums. In the case of TESSEL a gradual systematic decrease of the bias during the growing season can be seen. There is also a reduction of the *rmse*, of about 16% for ISBA, 15% for TESSEL but only about 5% for TERRA. This much lower improvement in the case of TERRA is related to the spin-up problems mentioned above and to the use of *P* from the model rather than from observations. The improvement in the case of ISBA is due mainly to the *P*-based correction. The effect on the *rmse* is much less systematic than the effect on the bias. Some months show a clear improvement with respect to *rmse*, others do not. Again, the largest improvement in the case of TESSEL is obtained in the first part of the validation period and gradually decreases towards October.

4.3 Evaporative Fraction

The *rmse* of Λ on a monthly timescale was computed from the monthly averaged differences per site. The result is shown in Figure 7 for the individual months and in Table 5 for the seasonal mean. In addition, because of the role of Λ as a diagnostic of relatively fast dynamic boundary layer processes in NWP models, for each site the *rmse* in a particular month was also computed from daily errors if at least 15 error estimates were available. The *rmse* on this daily timescale, averaged over all sites is also shown in Figure 7. Moreover, Table 5 shows the seasonal mean of the *rmse* on a daily timescale.

The average bias of the models varies between 0.06 and 0.09. These numbers correspond to 12-17% of the average observed Λ (0.50, range 0.31-0.71). The *rmse* varies between 0.20 and 0.23 on the monthly timescale, and between 0.23 and 0.27 on the daily timescale, which corresponds to 40-46% and 46-54% of the average Λ. During the validation period, a seasonal cycle can be observed in the bias, but not in the *rmse*. The trend in the bias seems to be somewhat similar for ISBA and TESSEL, with minimum deviations in July-August, but TERRA shows a reversed trend with a maximum deviation in June-July.

The influence of the DA system on the quality of Λ cannot be evaluated from the information given above. Only in the case of TESSEL a control run without data assimilation was performed. A limited screening of the effect was performed for this model by comparing the output from the control run and the DA run in a dry and a moist situation (see Van den Hurk and Ettema, 2007, for a more extensive discussion of the increments). The differences between dry and moist conditions should lead to quite different impacts of the DA systems (see Section 2.3). Figure 8 shows the 11-day moving average of the noontime Λ for El Saler (Spain, dry case) and Soroe (Denmark, wet case), respectively, for the observations, TESSEL with DA system, and the TESSEL control run. It can be seen that in the case of El Saler Λ is too small in the control run, apart from the start of the period. In the DA run Λ becomes too large. The overcorrection may be due in part to the high sensitivity of Λ to soil moisture under dry conditions, that is implicit in all the models because of the root functions chosen. By contrast, in the case of Soroe Λ is too high during most of the period. There is hardly any effect of the DA system on the performance of Λ in this case, especially when considering the end of the period. Even smaller impacts on Λ were found for other moist sites. The results are consistent with the conclusion from the sensitivity analysis that in the model context the sensitivity of Λ to soil moisture increases under dry conditions.

The surface characteristics in the model, such as LAI, albedo, roughness and water holding capacity, differ from the real surface characteristics. Given the sensitivity of Λ to such properties it may be argued that improvement of the modeled surface characteristics should be preferred over further improvement of the DA systems, especially under wet conditions where effects of the DA system are expected to be small (see Section 2.3). The possible impact on Λ of improving *LAI* is illustrated for a number of stations in the Estonia, were TERRA displayed a clear seasonality in Λ. For ISBA, the seasonal change of *LAI* is much smaller in this region, while TESSEL has a constant *LAI*.

Figure 9 shows the model results for the Jogeva site which is typical for the Estonian region. The Figure shows the modeled 11-day moving averages of Λ, constructed from at least 6 daily values within the averaging interval. Because no flux sites are available in this area, Λ was also computed using the well-known Priestley and Taylor (1972) approach, that gives reasonable estimates of λE for well-watered, dense grasslands and crops under optimal conditions. In spite of the temperature and radiation dependence, Λ from the Priestley and Taylor approach (Λ_{PT}) shows hardly any seasonal dependence. However, because the approach is valid for dense vegetation, it implicitly excludes the influence of a varying *LAI*. In the next step, a dependence on *LAI* was therefore included by scaling the Priestley and Taylor λE with the LAI variation in the models, that is, λE was reduced by a fraction LAI/LAI_m, where LAI_m is the maximum LAI of the season. This is consistent with increasing r_s in (2), like in the models. In this way, Λ_{PT} was scaled with LAI from ISBA and LAI from TERRA, by using their monthly LAI values, linearly interpolated to daily LAI values. The results are also displayed in Figure 9.

Accounting for the seasonal variation in LAI explains much of the differences between the models, especially at the start of the period investigated here. Indeed, the impact of LAI on Λ_{PT} was much larger than the impact of the DA system on Λ in the case of TESSEL. The 11-day moving average of Λ from the TESSEL control run for Jogeva was almost identical to the DA run and is therefore not included in Figure 9.

5 Discussion and conclusions

In the present study the performance of a soil moisture DA scheme implemented in three operational SVAT schemes, ISBA (Météo-France), TERRA (Deutscher Wetter Dienst) and TESSEL (European Centre for Medium-Range Weather Forecasts) has been assessed in the context of ELDAS. The schemes were validated for the period May-October 2000, using *in situ* observations from 33 sites in Europe.

Assuming that P-E is the most important part of the soil hydrological balance over the period considered here allowed assessment of the performance of the DA scheme with respect to the soil hydrological balance by comparing P-E or P-$E+\delta W$, respectively, to the observed P-E. The DA systems of ISBA, TERRA and TESSEL generally add water to the soil, thereby reducing the bias in P-E versus P-$E+\delta W$ by at least a factor of four (Table 4). In addition, the *rmse* of the monthly sums is reduced by 15-16% for ISBA and TESSEL, but only by 5% in the case of TERRA. For the latter model, the performance in the first one or two months of the simulations becomes worse, which may be attributed to spin-up, and adversely affects the overall improvement. The improvement of the ISBA soil hydrological balance is mainly due to the soil moisture correction based on the precipitation bias. On a monthly timescale, the impact of the DA increments based on screen level observations was much less and often almost neutralized by the precipitation corrections. The improvement of ISBA due to the precipitation corrections demonstrates the importance of high-quality precipitation fields. It also proves that assimilation of observed precipitation could be used to improve soil moisture fields in a physically consistent way.

The quality of the soil moisture simulations was assessed by considering soil moisture values normalized to the 95 percentile daily value of the validation period. The models underestimate the amplitude of the normalized soil moisture variations. As is demonstrated in the analysis of the soil water balance in El Saler (Fig 2, Table 3), this is partly due to the increments that keep the soils relatively wet. This result is consistent with the results of Bell et al. (2005), who found similar reductions of the amplitude in the context of a study on the effects of the DA system on river discharge.

Maximum normalized soil moisture variations are dictated by the water holding capacity of the soils incorporated in the models (Table 2). Because TERRA has the largest dynamical range in normalized soil moisture values between field capacity and wilting point, this model was capable of covering a major portion of observed soil moisture amplitudes. However, analysis of changes in non-normalized daily soil moisture values reveals that in many cases the total water exchange with the atmosphere may be much closer to the observed one than the amplitude of the normalized soil moisture values suggest. In a meteorological context, the exchange of water with the atmosphere is more important than the actual soil moisture status. Thus, in meteorological models the limited modeled soil moisture amplitude may still be considered acceptable.

Evaporative fraction Λ is an important quantity in meteorological models because it diagnoses the energy partitioning at the Earth's surface, which again affects the development of the Planatery Boundary Layer (Ek and Holtslag, 2004). For the purpose of validation, it is also an attractive parameter, since it is a normalized flux that partly removes the difference between the model surface characteristics and the real surface properties. Such differences would make a direct comparison of the turbulent fluxes, without normalization, unfair.

An average bias in Λ of 0.06 – 0.085 was found, which is typically about 15% of the average Λ. All three schemes displayed a seasonality of the bias. The cycle is different for TERRA than for ISBA and TESSEL, with the first model showing a maximum bias in June and July, and the latter models showing a minimum bias of about zero in July-August (Fig. 7). However, TERRA encountered spin-up problems in the first few months. The *rmse* was found to range between 0.2 and 0.23 on a monthly timescale (typically ~45% of Λ), and from 0.24-0.27 using daily noon values of Λ (~50%). The *rmse* showed no consistent trend during the validation period.

Implementing a DA system can be viewed as a practical approach to improve model forecasts. In the present study the effect of the DA system on Λ was assessed in the case of TESSEL, for moist and dry conditions, respectively. Hardly any improvement was found for the moist case, but Λ for the dry case showed a significant improvement. This is consistent with the sensitivity analysis of Section 2.3: the present parameterizations of the vegetation response to soil moisture imply only small effects on Λ of additional water under humid conditions. Rather than further improving the soil moisture assimilation system using observations that are only indirectly linked to Λ, improving the physics and basic parameter fields should be attempted.

Even zonally averaged evapotranspiration is sensitive to seasonal trends in *LAI* (Van Den Hurk et al., 2003). Indeed, our analysis for the Estonian region (Fig. 9) revealed that the impact of *LAI* on Λ exceeded the impact of the DA scheme on Λ. Therefore, under moist conditions, realistic prescription of *LAI* seems to be important. To improve evapotranspiration rates under dry conditions, alternative functions to describe water extraction by roots could be attempted. For example, including the ability of roots to actively deal with water shortage by increasing the capacity for water uptake (Teuling et al., 2006) would at least partially prevent Λ from dropping to low values too soon. In order to maintain realistic soil moisture behavior an improved description of the soil properties should be included. This option would not only be beneficial in a meteorological context, but also from the perspective of hydrological applications.

Only a few generalizations have been made here because of the following reasons. TERRA only used temperature as a diagnostic for deviations in soil moisture, while ISBA and TESSEL used temperature as well as relative humidity. Furthermore, the definition of soil and vegetation within the models was based on different databases and the forcings were different as well (see Table 1). Also, a single-column version of TESSEL was used that prescribes large-scale advection using results from the 3D model without the assimilation scheme. Thus, possible effects of the DA scheme on 3D interactions are implicitly ignored. The observation data base used to validate the DA schemes originated from different sources, implying large differences in their information content. At 24 out of 33 sites, direct soil moisture observations were available, often with very different characteristics in temporal and spatial resolution. At 14 out of the 33 sites flux observations were performed, but often no soil moisture observations were available. Also, most of the flux observations were performed over forest, and the sites tend to be located near the coast.

Because soil moisture is a crucial quantity in many models and parameterizations, direct validation of this quantity is preferred. Based on the experience in the present study, we would therefore strongly support the establishment of a network of standardized and quality-controlled soil moisture observations, preferably integrated in the existing flux-observation networks such as FLUXNET (Baldocchi et al., 2001).

In spite of the considerations given above, it is concluded that the soil moisture data assimilation systems can be regarded as a practical solution to improve model performance in some respects. From the meteorological point of view their effect is quite limited under humid conditions in particular. However, the impact of physical processes related to fundamental surface properties in the models, such as water holding capacity and *LAI*, suggests that improving such characteristics and the description of processes describing the water balance may be equally beneficial and may have greater priority than further improvement of the land surface data assimilation system.

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References

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P.H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grunwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., Vesala, T., 2000. Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology. *Advances in Ecological Research* **30**, 113-175.

Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X., Malhi, Y., Meyers, T., Munger, W., Oechel, W., Paw, K.T., Pilegaard, K., Schmid, H.P., Valentini, R., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem-Scale Carbon Dioxide, Water Vapor, and Energy Flux Densities. *Bull. American Met. Soc.* **82**, 2415-2434.

Balsamo, G., Bouyssel, F. and Noilhan, J., 2004. A simplified bi-dimensional variational analysis of soil moisture from screen-level observations in a mesoscale numerical weather-prediction model. *Q. J. R. Meteorol. Soc.*, **130**, 895-915.

Balsamo, G., Bouyssel, F., Noilhan, J., Mahfouf, J.-F., Bélair, S., Deblonde, G., 2005. A simplified variational analysis scheme for soil moisture: Developments at Météo-France and MSC, *ECMWF/ELDAS workshop on Land Surface Assimilation. ECMWF proceedings.* ECMWF, Reading, UK, 79-96.

Bastiaanssen, W.G.M., 1995. Regionalization of surface flux densities and moisture indicators in composite terrain : a remote sensing approach under clear skies in Mediterranean climates. Thesis, SC-DLO, Wageningen, 273 pp.

Bell, V.A., Blyth, E.M. and Moore, R.J., 2005. The use of soil moisture in hydrological forecasting, ECMWF/ELDAS workshop on Land Surface Assimilation. ECMWF - Proceedings. ECMWF, Reading, pp. 147-152.

Betts, A.K. and P. Viterbo, 2005. Land-surface, boundary layer and cloud-field coupling over the southwestern Amazon in ERA-40. *J. Geophys. Res.*, **110**, D14108, doi: 10.1029/2004JD005702.

Courtier, P., C. Freydier, J.F. Geleyn, F. Rabier and M. Rochas, 1991. The ARPEGE project at Météo-France. *Proc. ECMWF Seminar* **2**, 193-232.

Denmead, O.T. and Shaw, R.H., 1962. Availability of Soil Water to Plants as Affected by Soil Moisture Content and Meteorological Conditions. *Agron. Journal*, **54**: 385.

Dirmeyer, P.A., F.J. Zeng, A. Ducharne, J.C. Morrill and R.D. Koster, 2000. The sensitivity of surface fluxes to soil water content in three land surface schemes. *J. Hydrometeorology* **1**, 121-134.

Doms, G., J. Foerstner, E. Heise, H.-J. Herzog, M. Raschendorfer, R. Schrodin, T. Reinhardt and G. Vogel, 2005. *A description of the Nonhydrostatic Regional Model LM, Part II: Parameterization.* 140 pp. DWD, Offenbach. Also: http://cosmo-model.cscs.ch/public/documentation.htm#p2

Doms, G. and U. Schättler, 2002. *A Description of the Non-Hydrostatic Regional Model LM, Part I: Dynamics and Numerics.* 134 pp. Also: http://cosmo-model.cscs.ch/public/documentation.htm#p1.

Douville, H., Viterbo, P., Mahfouf, J.F. and Beljaars, A.C.M., 2000. Evaluation of the optimum interpolation and nudging techniques for soil moisture analysis using FIFE data. *Mon. Weather Rev.* **128**, 1733-1756.

Ek, M.B. and Holtslag, A.A.M., 2004. Influence of Soil Moisture on Boundary Layer Cloud Development. *J. Hydrometeorology* **5**, 86-99.

Hess, R., 2001. Assimilation of screen level observations by variational soil moisture analysis. *Meteorol. Atm. Phys.* **77**, 145-154.

Houser, P.R., Shuttleworth, W.J., Famiglietti, J.S., Gupta, H.V., Syed, K.H., Goodrich, D.C., 1998. Integration of soil moisture remote sensing and hydrologic modeling using data assimilation. *Water Resour. Res.* **34**, 3405-3420.

Jacobs, C.M.J. and De Bruin, H.A.R., 1992. The Sensitivity of Regional Transpiration to Land-Surface Characteristics - Significance of Feedback. *J. Clim.* **5**, 683-698.

Jarvis, P.G., 1976. The interpretation of leaf water potential and stomatal conductance found in canopies in the field. *Phil. Trans. R. Soc. Lond. B.* **273**, 593-610.

Jarvis, P.G. and McNaughton, K.G., 1986. Stomatal Control of Transpiration - Scaling up from Leaf to Region. *Adv. Ecol. Res.* **15**, 1-49.

Lindhardt, B., Abildtrup, C., Vosgerau, H., Olsen, P., Torp, S., Iversen, B.V., Jørgensen, J.O., Plauborg, F., Rasmussen, P., Gravesen, P., 2001. *The Danish Pesticide Leaching Assessment Programme. Site Characterization and Monitoring Design.* Geological Survey of Denmark and Greenland, Copenhagen, 74 pp.

Loveland, T.R., Reed, B.C., Brown, J.F., Ohlen, D.O., Zhu, Z., Youing, L., Merchant, J.W., 2000. Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. *Int. J. Remote Sensing* **21**, 1303-1330.

Mahfouf, J.F., 1991. Analysis of Soil-Moisture from near-Surface Parameters - a Feasibility Study. *J. Appl. Meteorol.* **30**, 1534-1547.

Masson, V., Champeaux, J.-L., Chauvin, F., Meriguet, C. and Lacaze, R., 2003. A Global Database of Land Surface Parameters at 1-km Resolution in Meteorological and Climate Models. *J. Clim.* **16**, 1261-1282.

Meetschen, D., van den Hurk, B., Ament, F. and Drusch, M., 2004. Optimized surface radiation fields derived from Meteosat imagery and a regional atmospheric model. *J. Hydromet.* **5**, 1091-1101.

Meijninger , W.M.L., Green , A.E., Hartogensis , O.K., Kohsiek , W., Hoedjes , J.C.B., Zuurbier , R.M., De Bruin , H.A.R., 2002. Determination of Area-Averaged Water Vapor Fluxes with Large Aperture and Radio Wave Scintillometers over a Heterogeneous Surface – Flevoland Field Experiment. *Boundary-Layer Meteorol.* **105**, 63-83.

Mitchell, K.E., Lohmann, D., Houser, P.R., Wood, E.F., Schaake, J.C., Robock, A., Cosgrove, B.A., Sheffield, J., Duan, Q.Y., Luo, L.F., Higgins, R.W., Pinker, R.T., Tarpley, J.D., Lettenmaier, D.P., Marshall, C.H., Entin, J.K., Pan, M., Shi, W., Koren, V., Meng, J., Ramsay, B.H., Bailey, A.A., 2004. The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. *J. Geophys. Res.* **109**, D07S90, doi:10.1029/2003JD003823.

Moene, A. and De Bruin , H.A.R., 2001. Sensible heat flux data derived from the scintillometers. *In: Z. Su and C. Jacobs (Editors), Advanced Earth Observations - Land Surface Climate, Final Report*. BCRS Reports. Ministry of Transport, The Hague, 85-90.

Noilhan, J. and Mahfouf, J.-F., 1996. The ISBA land surface parameterisation scheme. *Global and Planetary Change* **13**, 145-159.

Priestley, C.H.B. and Taylor, R.J., 1972. On the Assessment of Surface Heat Flux and Evaporation Using Large-Scale Parameters. *Mon. Weather Rev.* **100**, 81-92.

Raschke, E., Meywerk, J., Warrach, K., Andrea, U., Bergstrom, S., Beyrich, F., Bosveld, F., Bumke, K., Fortelius, C., Graham, L.P., Gryning, S.-E., Halldin, S., Hasse, L., Heikinheimo, M., Isemer, H.-J., Jacob, D., Jauja, I., Karlsson, K.-G., Keevallik, S., Koistinen, J., van Lammeren, A., Lass, U., Launianen, J., Lehmann, A., Liljebladh, B., Lobmeyr, M., Matthaus, W., Mengelkamp, T., Michelson, D.B., Napiorkowski, J., Omstedt, A., Piechura, J., Rockel, B., Rubel, F., Ruprecht, E., Smedman, A.-S., Stigebrandt, A., 2001. The Baltic Sea Experiment (BALTEX): A European Contribution to the Investigation of the Energy and Water Cycle over a Large Drainage Basin. *Bull. Amer. Met. Soc.* **82**, 2389-2413.

Rhodin, A., Kucharski, F., Callies, U., Eppel, D.P. and Wergen, W., 1999. Variational analysis of effective soil moisture from screen-level atmospheric parameters: application to a short-range weather forecast model. *Q. J. R. Meteorol. Soc.* **125**, 2427-2448.

Rodell, M., Houser, P.R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J.K., Walker, J.P., Lohmann, D., Toll, D., 2004. The global land data assimilation system. *Bull. Amer. Met. Soc.* **85**, 381-394.

Rubel, F., Brugger, K., Skomorowski, P. and Kottek, M., 2005. Daily and 3-hourly Quantitative Precipitation Estimation for ELDAS, *ECMWF/ELDAS workshop on Land Surface Assimilation. ECMWF - Proceedings*. ECMWF, Reading, 19-32.

Santanello, J.A., Friedl, M.A. and Kustas, W.P., 2005. An empirical investigation of convective planetary boundary layer evolution and its relationship with the land surface. *J. Appl. Meteorol.* **44**, 917-932.

Teuling, A.J., Uijlenhoet, R., Hupet, F. and Troch, P.A., 2006. Impact of plant water uptake strategy on soil moisture and evapotranspiration dynamics during drydown. *Geophys. Res. Let.* **33**, L03401, doi:03410.01029/02005GL025019.

Uppala, S.M., Kallberg, P.W., Simmons, A.J., Andrae, U., Bechtold, V.D., Fiorino, M., Gibson, J.K., Haseler, J., Hernandez, A., Kelly, G.A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R.P., Andersson, E., Arpe, K., Balmaseda, M.A., Beljaars, A.C.M., Van De Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Holm, E., Hoskins, B.J., Isaksen, L., Janssen, P., Jenne, R., McNally, A.P., Mahfouf, J.F., Morcrette, J.J., Rayner, N.A., Saunders, R.W., Simon, P., Sterl, A., Trenberth, K.E., Untch, A., Vasiljevic, D., Viterbo, P., Woollen, J., 2005. The ERA-40 re-analysis. *Q. J. R. Meteorol. Soc.* **131**, 2961-3012.

Valentini, R., Matteucci, G., Dolman, A.J., Schulze, E.D., Rebmann, C., Moors, E.J., Granier, A., Gross, P., Jensen, N.O., Pilegaard, K., Lindroth, A., Grelle, A., Bernhofer, C., Grunwald, T., Aubinet, M., Ceulemans, R., Kowalski, A.S., Vesala, T., Rannik, U., Berbigier, P., Loustau, D., Guomundsson, J., Thorgeirsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrieff, J., Montagnani, L., Minerbi, S., Jarvis, P.G., 2000. Respiration as the main determinant of carbon balance in European forests, 2000. Respiration as the main determinant of carbon balance in European forests. *Nature* **404**, 861-865.

Van Den Hurk, B.J.J.M., 2002. European LDAS established. *Gewex Newsletter* **12**, 9.

Van Den Hurk, B.J.J.M., Bastiaanssen, W.G.M., Pelgrum, H. and Van Meijgaard, E., 1997. A new methodology for assimilation of initial soil moisture fields in weather prediction models using Meteosat and NOAA data. *J. Appl. Meteorol.* **36**, 1271-1283.

Van Den Hurk, B.J.J.M., Viterbo, P., Beljaars, A.C.M. and Betts, A.K., 2000. *Offline validation of the ERA40 surface scheme.* Technical Memorandum 295, ECMWF, Reading, 42pp.

Van Den Hurk, B.J.J.M., Viterbo, P. and Los, S.O., 2003. Impact of leaf area index seasonality on the annual land surface evaporation in a global circulation model. *J Geophys Res-Atmos* **108** (D6), 4191, doi:10.1029/2002JD002846.

Van den Hurk, B.J.J.M., and Ettema, J., 2007. Analysis of Soil Moisture Changes in Europe during a Single Growing Season in a New ECMWF Soil Moisture Assimilation System. *J. Hydromet.* (in press).

Viterbo, P., 1996. *The representation of surface processes in general circulation models*, ECMWF, Reading, 201 pp.

Wergen, W., Hess, R. and Lange, M., 2005. Variational soil assimilation at DWD, *ECMWF/ELDAS workshop on Land Surface Assimilation. ECMWF - Proceedings*. ECMWF, Reading, 69-77.

Table 1. *Summary of the setup of the ELDAS DA experiment.*

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

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

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

Table 3. *Components of the soil hydrological balance of the upper meter in the soil at validation site El Saler, given as sums over the period DOY 162-191. P is the precipitation; E is the evapotranspiration; δW represents the increments due to the data assimilation; ΔS_{1m} is the storage change of water in the upper 1 m of the soil; "Other" includes runoff, drainage and changes in water storage of layers below 1 m.*

	DATA	ISBA	TERRA	TESSEL
P (mm)	2	3	3	0
E (mm)	-41	-116	-107	-69
δW (mm)		122	80	27
ΔS_{1m} (mm)		7	-17	-32
Other		-2	7	10

Table 4. *Mean monthly bias (model-observations) and rmse in* P-E *and* P-E+δW, *respectively, for ISBA, TERRA and TESSEL, computed for the period May-October 2000.*

	Bias P-E (mm)	**Bias P-E+δW (mm)**	**rmse P-E (mm)**	**rmse P-E+δW (mm)**
ISBA	-24.7	-6.0	53.4	44.6
TERRA	-33.6	-5.8	55.5	52.7
TESSEL	-13.1	-0.9	28.1	24.0

Table 5. *Seasonal mean of bias and rmse in* Λ *from errors on a monthly timescale as well as the seasonal rmse in* Λ *from errors on a daily timescale. Months included are May-September.*

	Bias Λ(monthly)	***rmse* Λ(monthly)**	***Rmse* Λ(daily)**
ISBA	0.085	0.23	0.27
TERRA	0.060	0.21	0.24
TESSEL	0.066	0.20	0.24

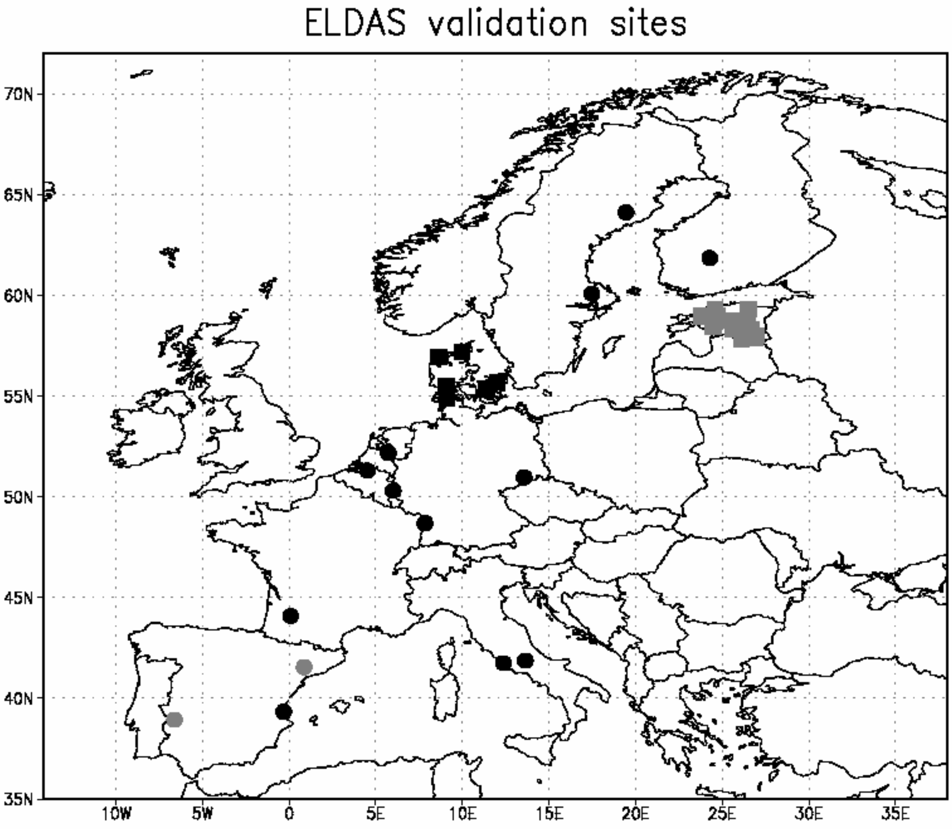

Figure 1. Location of the ELDAS validation sites Black circles CarboEurope sites; Grey circles: Scintillometer sites; Black squares: PLAP sites; Grey squares: BALTEX sites. See text for a further description of the sites.

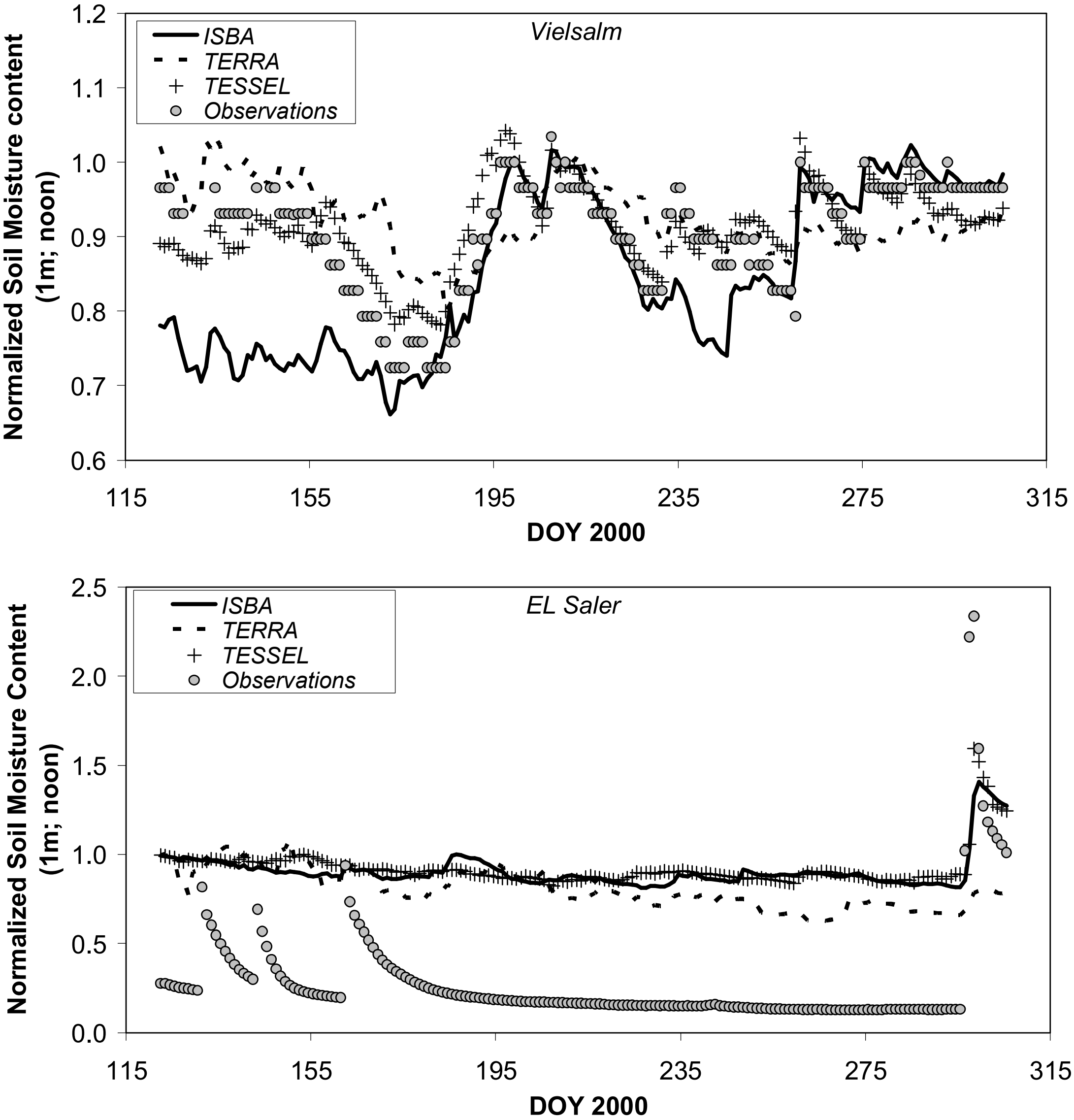

Figure 2. Normalized modelled and observed soil moisture content $\hat{\theta}$ for the validation sites El Saler (upper) and Vielsalm (lower), respectively, during the validation period. Note the difference in scale.

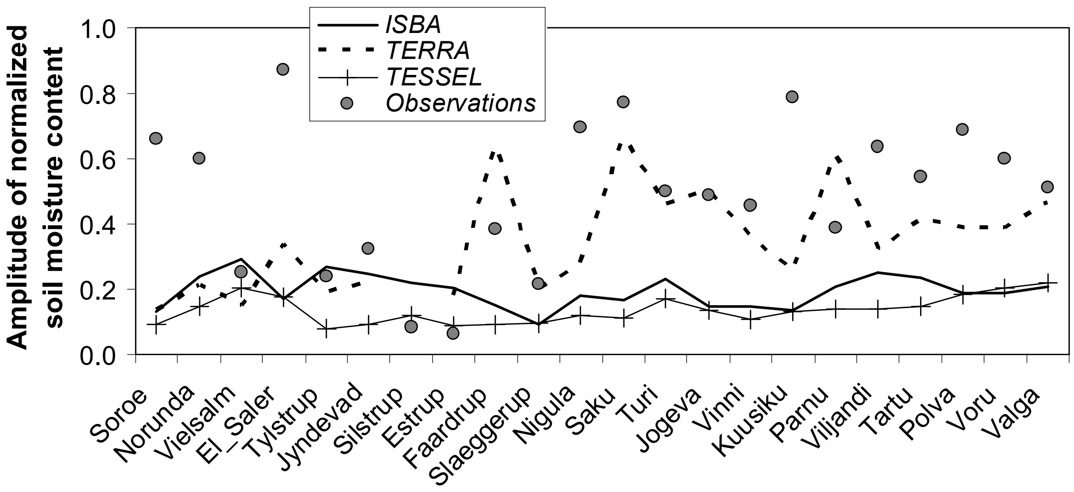

Figure 3. Comparison of observed and modelled amplitudes of the normalized soil moisture content $\hat{\theta}$. Labels on the x-axis denote the validation sites. The model outputs are connected by a line to facilitate comparison with the data.

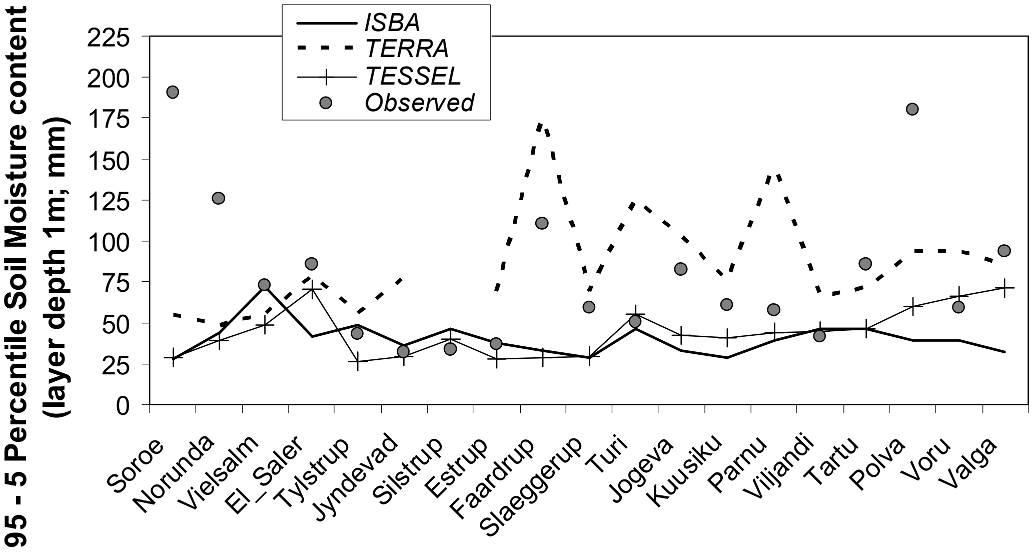

Figure 4. Comparison of observed and modelled amplitudes of the soil moisture content in the upper meter of the soil. In contrast with the amplitude shown in Fig. 3, the amplitude is defined here as the difference between the 95 and 5 percentile daily values, respectively, in the validation period (May-October 2000) . Labels on the x-axis denote the validation sites. The model outputs are connected by a line to facilitate comparison with the data.

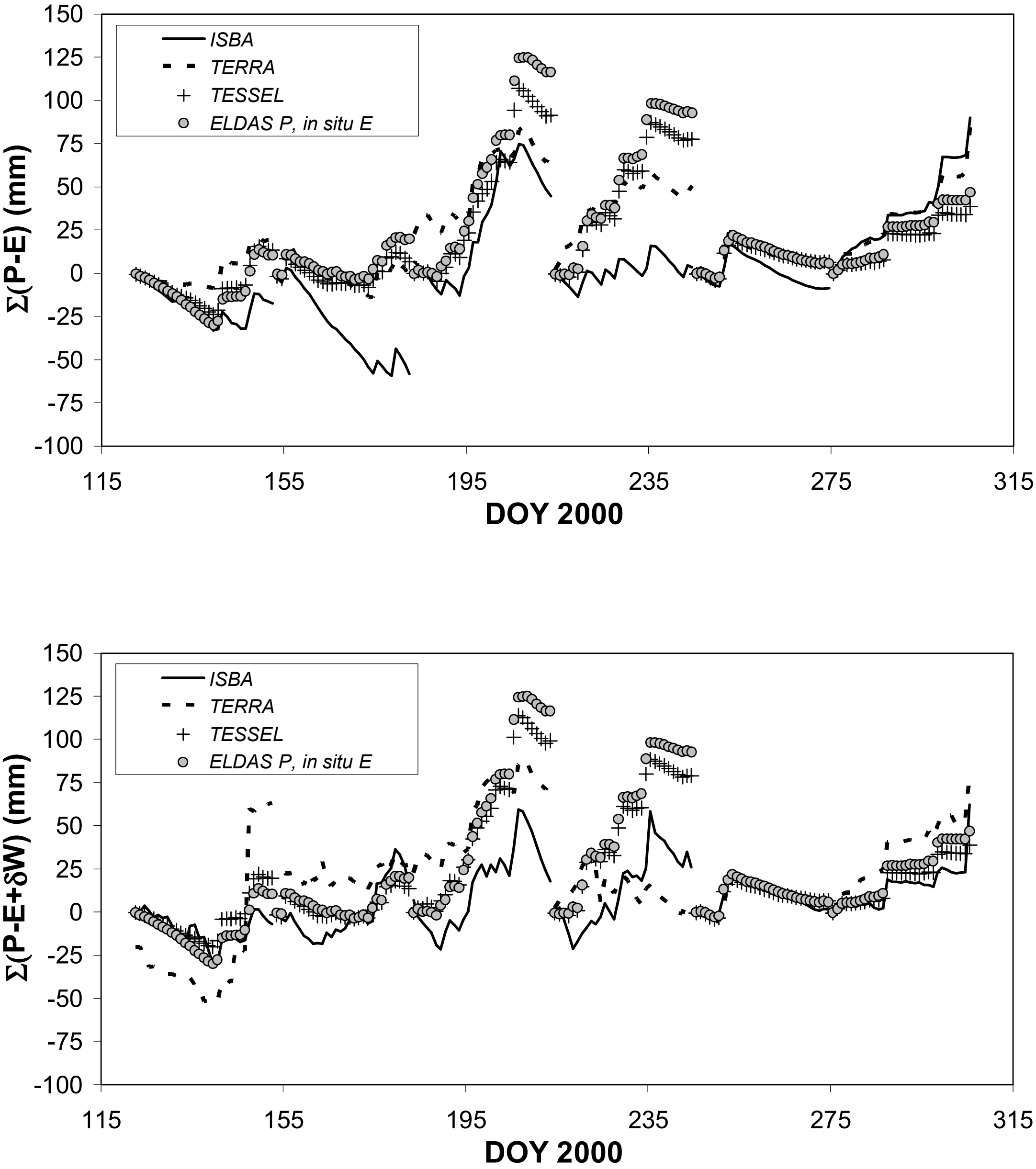

Figure 5. Illustration of the effect of the data assimilation increments on the soil hydrological balance. Case study Flakaliden (Sweden). Upper: P-E; Lower: P-E for the data and P-E+δW for the models. δW denotes the contribution from the data assimilation. Values shown are cumulative values, reset to zero at the start of each month.

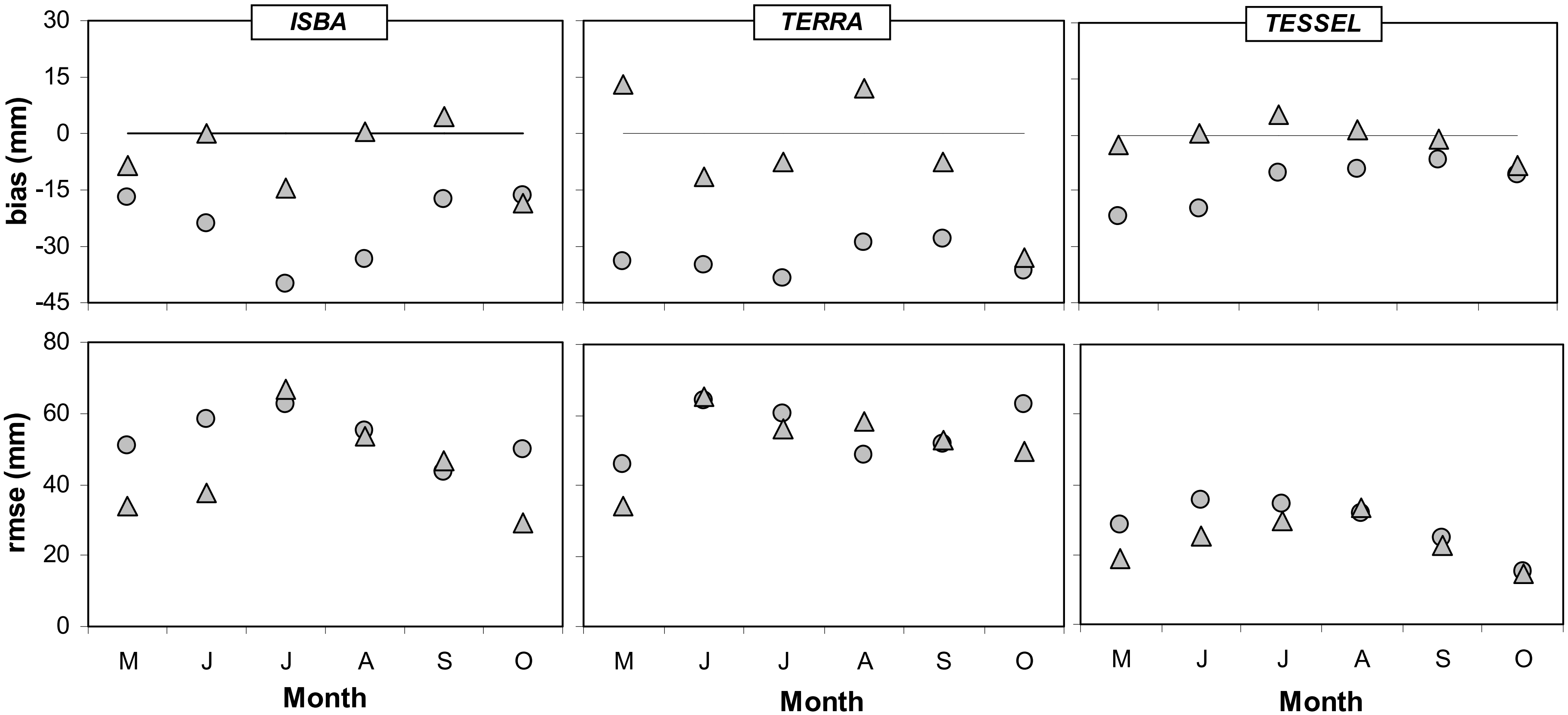

Figure 6. Bias (model-observations) and rmse of monthly sums of P-E (circles) and P-E+δW (triangles) for ISBA (left), TERRA (middle) and TESSEL (right), respectively.

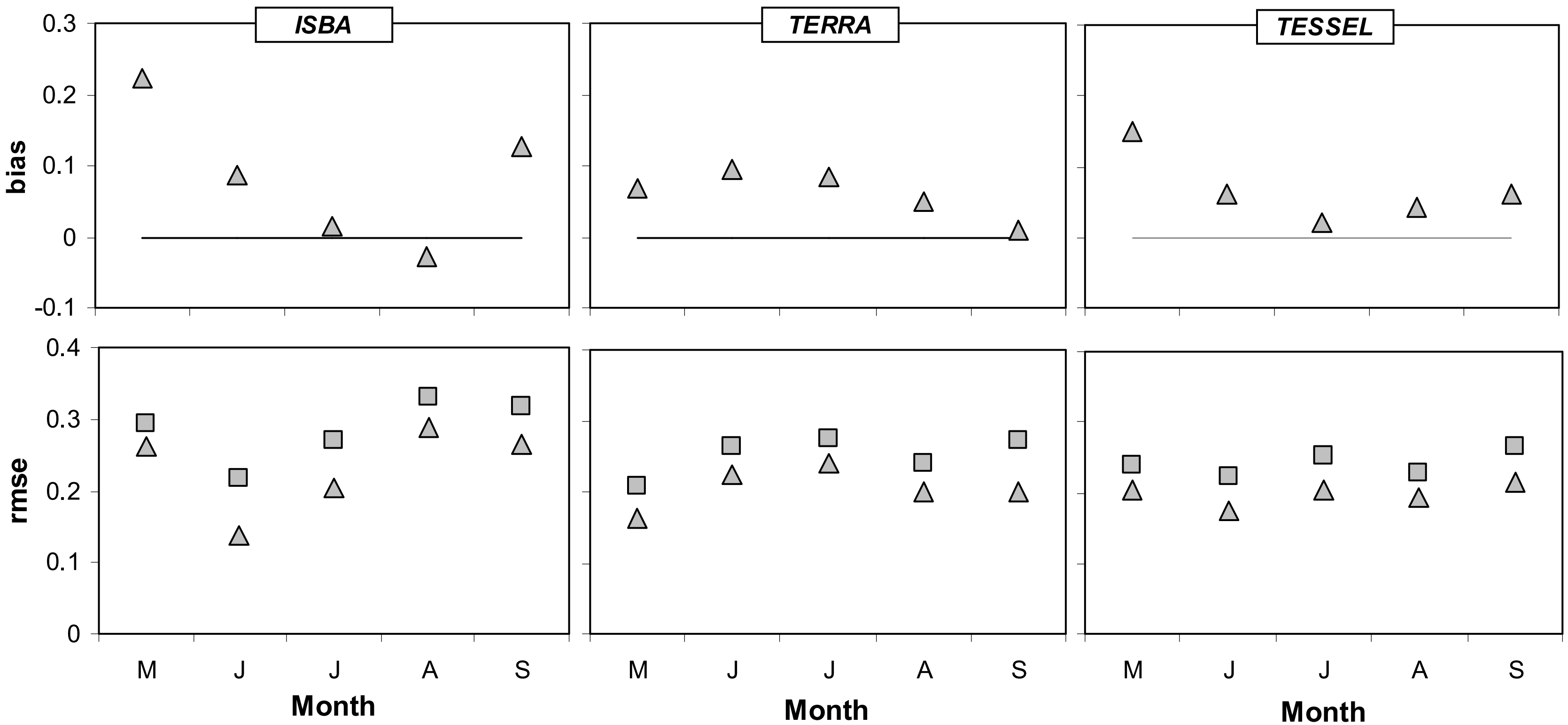

Figure 7. *Bias (model-observations) and rmse of the evaporative fraction Λ on a monthly timescale (triangles) for ISBA (left), TERRA (middle) and TESSEL (right), respectively. Also shown in the lower panels is the rmse of Λ on a daily timescale (squares).*

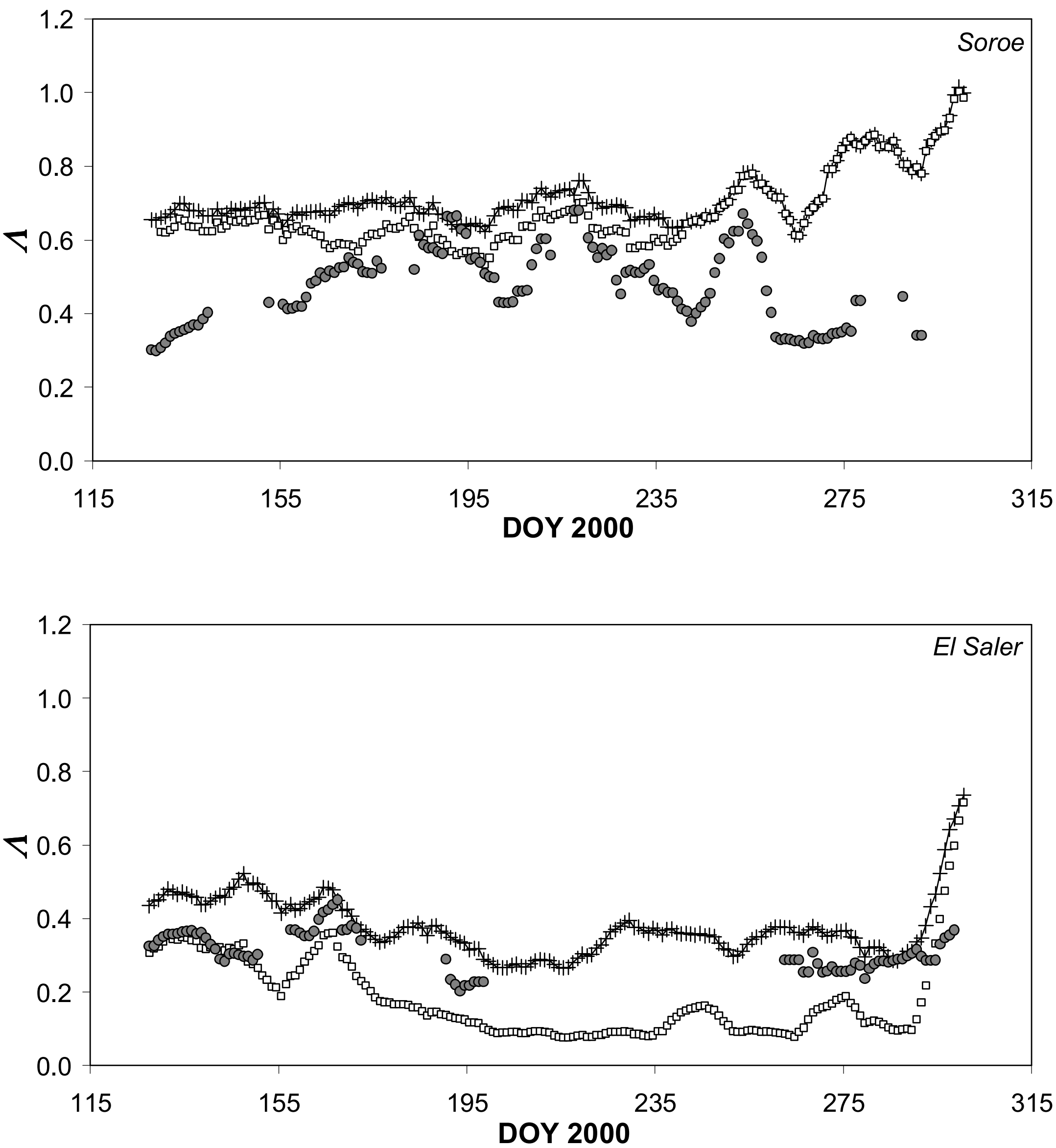

Figure 8. Illustration of the impact of the TESSEL DA system on the evaporative fraction Λ for a typical moist and dry case, respectively. Upper panel: moist case (Soroe, Denmark); Lower panel: Dry case (El Saler, Spain). Filled circles: observations; pluses: TESSEL with DA system; squares: TESSEL

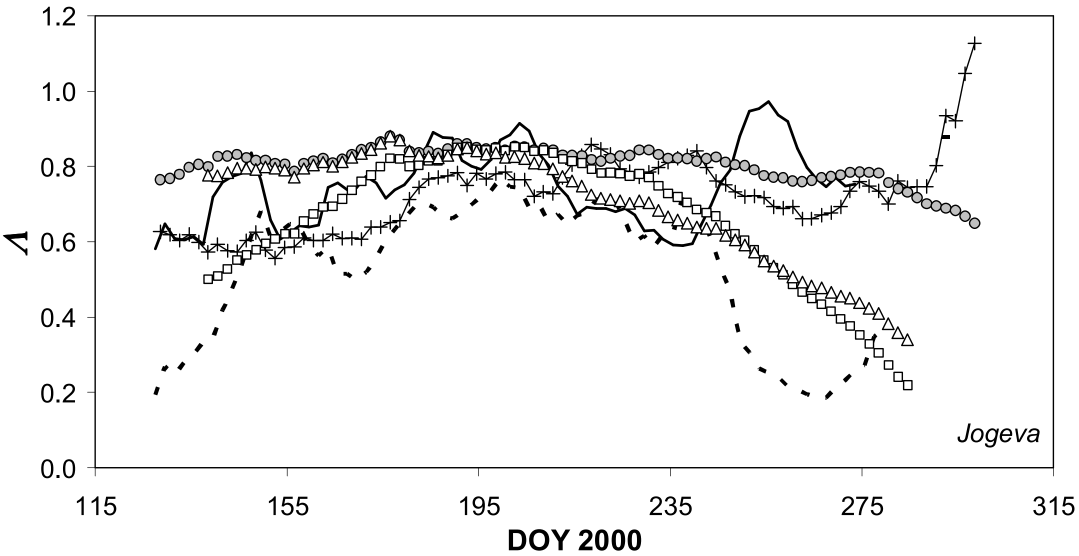

Figure 9. Illustration of the possible impact of surface properties on model output for Λ, case Jogeva, Estonia. The curves show 11-day moving averages of the evaporative fraction Λ around noon (see text). Black line: ISBA; dashed line: TERRA; pluses: TESSEL; open circles: Λ_{PT}*; triangles:* Λ_{PT} *multiplied by* LAI/LAI_m *from ISBA; horizontal dashes:* Λ_{PT} *multiplied by* LAI/LAI_m *from TERRA .*