Analysis of Soil Moisture Changes in Europe during a Single Growing Season in a New ECMWF Soil Moisture Assimilation System

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ABSTRACT

This study aims at stimulating the development of soil moisture data assimilation systems in a direction where they can provide both the necessary control of slow drift in operational NWP applications and support the physical insight in the performance of the land surface component. It addresses four topics concerning the systematic nature of soil moisture data assimilation experiments over Europe during the growing season of 2000 involving the European Centre for Medium-Range Weather Forecasts (ECMWF) model infrastructure. In the first topic the effect of the (spinup related) bias in 40-yr ECMWF Re-Analysis (ERA-40) precipitation on the data assimilation is analyzed. From results averaged over 36 European locations, it appears that about half of the soil moisture increments in the 2000 growing season are attributable to the precipitation bias. A second topic considers a new soil moisture data assimilation system, demonstrated in a coupled single-column model (SCM) setup, where precipitation and radiation are derived from observations instead of from atmospheric model fields. For many of the considered locations in this new system, the accumulated soil moisture increments still exceed the interannual variability estimated from a multiyear offline land surface model run. A third topic examines the soil water budget in response to these systematic increments. For a number of Mediterranean locations the increments successfully increase the surface evaporation, as is expected from the fact that atmospheric moisture deficit information is the key driver of soil moisture adjustment. In many other locations, however, evaporation is constrained by the experimental SCM setup and is hardly affected by the data assimilation. Instead, a major portion of the increments eventually leave the soil as runoff. In the fourth topic observed evaporation is used to evaluate the impact of the data assimilation on the forecast quality. In most cases, the difference between the control and data assimilation runs is considerably smaller than the (positive) difference between any of the simulations and the observations.

1. Introduction

Root zone soil moisture is a crucial variable in the climate system. Initial conditions in numerical weather prediction models of soil moisture for the upper meter of the soil are a crucial element in the forecast performance in midlatitudes spring/summer (e.g., Beljaars et al. 1996) and might extend predictability over land in the monthly to seasonal range (Koster et al. 2004). Root zone soil moisture affects transpiration, strongly influencing the partitioning of available energy into sensible and latent heat flux, and hence the evolution of lower atmospheric conditions. Soil moisture drifts are ubiquitous in NWP models, due to imperfect parameterizations of land surface and soil processes and failures in simulating precipitation and cloud cover. In many NWP centers, a correction to the model soil moisture is deemed necessary to avoid the systematic

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drift in the slow varying root zone soil moisture (Viterbo 1996).

Direct use of root zone soil moisture observations is hampered by the paucity (and representativity problems) of in situ–derived profile observations, or, in cases of (still only scarcely available) remotely sensed microwave soil moisture content, by the difficulty of inferring root zone soil water from a signal mostly sensitive to the first few centimeters of soil (Calvet and Noilhan 2000). To estimate soil moisture and reduce model drift, data assimilation systems making use of observations related to soil moisture [like atmospheric humidity or (infrared) brightness temperatures] have been tested since the mid-1990s in meteorological applications (Mahfouf 1991; van den Hurk et al. 1997; Houser et al. 1998; Douville et al. 2000; Boni et al. 2001; Seuffert et al. 2004; Drusch and Viterbo 2007) and applied routinely at forecast centers (Viterbo 1996; Douville et al. 2000; Giard and Bazile 2000; Hess 2001; Rodriguez et al. 2003; Bélair et al. 2003), leading to considerable reduction of short-range forecast errors of near-surface temperature and humidity.

Data assimilation can highlight deficiencies in the coupled land surface–atmosphere system but not necessarily their origin; analysis corrections can be applied in response to deficiencies in the formulation of the land surface scheme or in the atmospheric forcing of the land surface. For example, the corrections (also called increments) may emerge in response to deficiencies in the precipitation and/or radiation forcing, to a possibly inadequate partitioning of available water over runoff, soil storage, and evaporation in the land surface scheme, to errors in the modeling of near-surface quantities that are not related to the soil hydrology (e.g., boundary layer humidity), or to difficulties concerning the representativeness of observed near-surface quantities. Reichle et al. (2004) point out that model results may deteriorate when the actual soil moisture content is assimilated instead of an anomaly to a mean climatological state. However, this problem is mainly applicable when in situ– or satellite-derived soil moisture content is used to change the model equivalent variable, which indeed may be very different from the true state owing to misformulations of soil properties. Analyzed soil moisture should be considered as a model state that optimizes the (modeled) correspondence to the observed quantity under the given forcings, not necessarily comparable to in situ soil moisture observations. In the application discussed here, near-surface temperature and atmospheric humidity are the observed quantities whose model simulation is optimized by adjusting the soil moisture content. Drusch and Viterbo (2007) show that this procedure does indeed improve the simulation of surface turbulent fluxes of heat and moisture (strongly related to near-surface temperature and humidity) but does not necessarily produce soil moisture content values that are in closer agreement with in situ soil moisture observations.

Also, soil moisture data assimilation systems do not conserve soil water, since they add or remove water from the soil. This is not a property of soil moisture analyses only, but rather a general feature of data assimilation systems: in general, analysis increments for a state variable are neither energy nor mass conserving. Water conservation and confidence in the quality of the physical model formulation is particularly important for climate studies using long archives of meteorological analysis. The 15-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis archives (ERA-15) (Gibson et al. 1997) corrected soil water content depending on near-surface specific humidity using a simple nudging scheme, while the 40-yr ECMWF Re-Analysis (ERA-40; Uppala et al. 2005) used an optimal interpolation (OI) soil moisture data assimilation system depending on forecast errors of near-surface relative humidity and temperature. Betts et al. (1998a,b) showed that ERA-15 increments are systematic and a considerable portion of the surface water budget. Douville et al. (2000) and Mahfouf et al. (2000) showed that the introduction of a new land surface scheme into ERA-40 (van den Hurk et al. 2000) and the application of the OI scheme reduced the systematic soil water analysis increments (the difference between the a priori short-range forecast and the analyzed value) considerably in many regions of the world. However, these increments are still a nonnegligible part of the seasonal water budget in ERA-40. In most places, they dampen the seasonal cycle of soil water content and reduce the interannual variability in soil moisture and evaporative fluxes (Betts et al. 2003a,b; Guo et al. 2006; Ferranti and Viterbo 2006) due to the soil water increments providing a systematically positive supply of water in late spring and early summer. Also, in Europe systematic increments in these seasons are still fairly large after the land surface model update (Douville et al. 2000; Drusch and Viterbo 2007).

The evolution of total soil water, W, in a data assimilation system can be written as

$$\frac{\partial W}{\partial t} = P_l + M - E - R + I, \tag{1}$$

where t is time, P_l is the rainfall reaching the ground, M the snowmelt, E the sum of dewfall ($E > 0$), bare ground evaporation and root extraction by canopy ($E < 0$), R the runoff, and I the data assimilation in-

TABLE 1. Overview of topics addressed and model/observation tools used. The acronyms are explained in the text and Table 2.

Topic	Question	Model/data assimilation systems used	Observations used
a	Effect of precipitation bias in ERA-40	ERA-40, OFFL	ELDAS precipitation
b	Signature of increments in new data assimilation system using observed forcings and 24-h time window	SCM-DA minus SCM-CTL, OFFL	ELDAS precipitation and radiation
c	Soil water budget terms affected by data assimilation	SCM-DA, SCM-CTL	ELDAS precipitation and radiation
d	Comparison to observed evaporation	SCM-DA, SCM-CTL	In situ evaporation measurements

crement per assimilation cycle. All terms on the right-hand side are fluxes expressed in units of water per unit time (mm day^{-1}). In a land surface model without data assimilation the water budget is closed without increments.

As explained before, the increment I can compensate for deficiencies in (a) the forcing of precipitation or radiation, (b) the model formulation of the partitioning of precipitation into evaporation, runoff, and soil storage, (c) the modeling of near-surface quantities due to vertical or horizontal transport, or (d) the representativeness of observed or analyzed near-surface atmospheric conditions. In a coupled land–atmosphere system many of these terms are mutually interacting, and disentangling the sources of errors is not a trivial task. Formal statistical methods to trace systematic and random model errors from data assimilation experiments (e.g., Schubert and Chang 1996) fail when in situ observations of soil moisture are absent or incomparable to the model state.

In the following we focus on the seasonal evolution of the soil water budget terms by integrating Eq. (1) over time and analyzing the cumulative time series. This allows a focus on the systematic increments, since random fluctuations at daily or weekly time scales are averaged out. We address four separate topics that help expose the systematic signature of soil moisture analysis increments, focusing on 36 European sites during a 15-month period (October 1999–December 2000). The first topic addresses the question how much of the systematic increments at these European locations in ERA-40 can be explained by a systematic (spinup) bias in ERA-40 precipitation. This bias is quantified using observed precipitation and is consecutively related to the magnitude of the analysis increments. A subjective measure for an "expected" magnitude of a random seasonally accumulated increment is derived from multiyear simulations with an offline version of the ERA-40 land surface model, where an estimate of the interannual variability of the soil water storage change is chosen as reference. The second topic addresses the signature of the soil moisture increments in a newly developed data assimilation system, in which observed precipitation and radiation are used and observed near-surface quantities over a 24-h time period are used to update the soil moisture content. Particularly, it is analyzed whether the use of observed forcings removes the systematic component of the increments or not. The third topic compares the water balance of the model with data assimilation to the water balance of an "open loop" simulation with the same model (but without data assimilation), to explore which balance terms in the soil are affected most by the data assimilation. And in topic d we compare the resulting surface evaporation simulations to observations at a subset of the European sites to assess whether the data assimilation procedure leads to an improvement or not. Table 1 gives an overview of the topics addressed and the model tools used for this analysis, which are described in detail in section 2.

For this analysis we used the following components:

- ERA-40 data,
- single-column model (SCM) runs with a version of the ECMWF physical parameterization, including the option to apply soil water corrections and bypass modeled radiation and precipitation,
- offline uncoupled multiyear simulations with the ECMWF land surface model, and
- in situ observations of evaporation at a subset of locations.

This work is carried out in the framework of a collaboration project on European Land Data Assimilation Systems (ELDAS; van den Hurk 2002).

The main aim of this paper is to stimulate the further development of soil moisture data assimilation systems into a direction where they can provide both the necessary control of slow drift in operational NWP applications and support the physical insight in the performance of the land surface component in NWP and climate modeling systems. First we will discuss the available tools and observations and subsequently will

TABLE 2. Overview of the modeling systems and their labels used in this study.

Label	Description	Time period	Configuration	Precipitation and radiation forcing
ERA-40	Reanalysis archive of soil hydrological budget terms [Eq. (1)]	Apr 2000–Oct 2000	Increments calculated 6-hourly from analyzed near-surface temperature and humidity	From atmospheric model
SCM-CTL	Control run with SCM without data assimilation	Oct 1999–Dec 2000	Atmospheric profiles reset to analysis daily; no reset or data assimilation of soil moisture	From ELDAS database
SCM-DA	Data assimilation run with SCM	Oct 1999–Dec 2000	Atmospheric profiles reset to analysis daily; soil moisture increments calculated daily using analyzed near-surface temperature and humidity	From ELDAS database
OFFL	Offline land-surface-only simulation	1980–2000	No reset or data assimilation of soil moisture; first year repeated 3 times to spin up soil moisture	From ERA-40, but precipitation corrected using ELDAS database

address the four topics, followed by a general discussion of the results.

2. Methodology and models

Table 2 gives an overview of the variety of modeling systems and their labels used for the analyses in this study. In brief, research topic a uses ERA-40 data and a new precipitation analysis based on a large collection of rain gauge data to quantify the precipitation bias affecting soil moisture increments. Soil moisture increments are compared to the estimated interannual variability of soil moisture storage changes generated by a multiyear offline land surface model simulation (OFFL). The effect of using observed precipitation and another data assimilation approach (topics b and c) is assessed by means of a set of SCM experiments, both with (SCM-DA) and without (SCM-CTL) applying soil moisture corrections. Also the OFFL simulations are used to assess whether the accumulated increments are systematic or not. Comparison to observations of evaporation (topic d) is done using a collection of experimental data. A more extensive discussion about the various methodologies is given subsequently in section 3, which presents the four research topics.

All model simulations and comparisons refer to 36 European locations displayed in Fig. 1: ERA-40 data are extracted only from the grid boxes collocated with these sites, whereas the remaining simulations are only applied for these sites. All the modeling systems have in common the Tiled ECMWF Land Surface Scheme for Exchange over Land (TESSEL; van den Hurk et al. 2000), which will be described first. The second subsection describes ERA-40 and the products that have been used for examining the impact of a systematic precipitation bias. The third subsection gives details on the structure and simulations with the SCM and the new precipitation and radiation forcings used therein. The

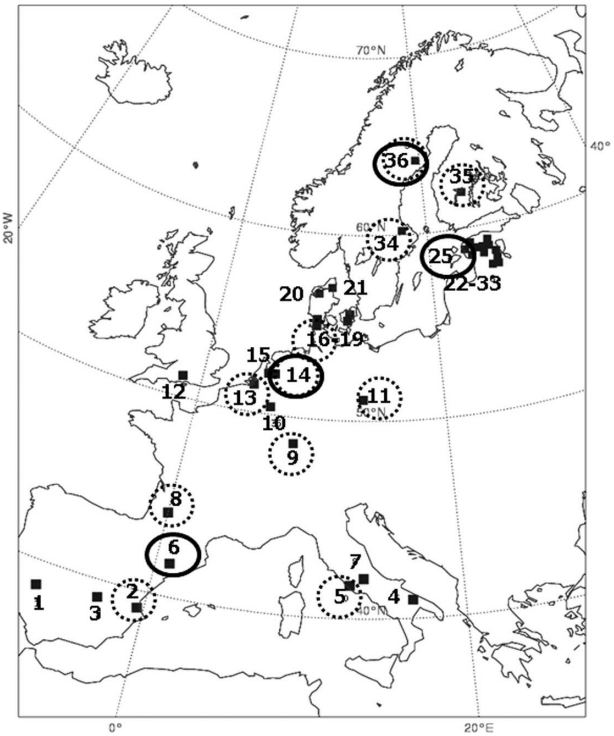

FIG. 1. Location of the test sites (for details see Jacobs et al. 2007, manuscript submitted to *Tellus*). The numbering refers to the labels used in Figs. 5–7, ranked according to geographical latitude. Sites serving as examples in Figs. 2 and 4 are encircled with solid circles, whereas the sites with evaporation observations are encircled with dashed circles.

fourth subsection describes the offline simulations, and in situ sites and evaporation observations are detailed in the fifth subsection.

a. The land surface model TESSEL

TESSEL (Viterbo and Beljaars 1995; van den Hurk et al. 2000) has four soil layers (0.07, 0.21, 0.72, and 1.89 m) where the top three layers contain most of the root zone for all vegetation types, topped by a skin layer without heat capacity. The skin layer is divided in up to six fractions (bare ground, low vegetation, high vegetation, intercepted water, snow under high vegetation, snow on ground, and on low vegetation), and for each of these a separate surface energy balance is solved. The vertical water transport in the soil layers follows Darcy's law with free drainage at the bottom. The same soil characteristics, corresponding to a loam type, are specified globally. For the SCM and OFFL simulations, land surface characteristics (vegetation types and coverage, albedo, roughness length, etc.) are taken from the operational ECMWF surface climatology database, which is also used in ERA-40 (ECMWF 2007).

b. The ERA-40 system and quantities used

For the locations analyzed here we extracted all hydrological budget terms from the ERA-40 archive for the growing season in 2000 (April–October), including the 6-h forecasted evaporation, precipitation, and runoff, and the 6 hourly states of the soil water and snow components. Soil moisture analysis increments were calculated as the difference between the analysis and first guess at a given time. Note that due to the close proximity of some locations in Fig. 1, the same ERA-40 grid boxes are considered representative for multiple sites, leading to a reduced ERA-40 sample of 33 locations.

The soil moisture data assimilation system used in ERA-40 is based on OI analysis as described by Douville et al. (2000). Soil moisture corrections are only applied in the root zone, defined as the top three layers. The corrections are a linear combination of the 6-h forecast errors in the screen-level relative humidity and temperature. Under atmospheric conditions with strong surface–atmosphere coupling, the root zone soil moisture exerts a considerable control over the screen-level fields through evaporation (Mahfouf et al. 2000). Assimilation of these parameters based on OI prevents soil moisture from drifting and improves the simulation of land surface energy fluxes and screen-level humidity and temperature (Mahfouf 1991). Nonetheless the OI analysis applied in ERA-40 is prone to a number of shortcomings, as pointed out for instance by Seuffert et al. (2004) and Balsamo et al. (2004): the system lacks flexibility to accommodate new observations or additional control variables, and an empirical masking procedure is required to eliminate conditions where near-surface atmospheric quantities are not informative about soil moisture.

c. The single-column model setup with soil moisture assimilation and observed forcings

For this study an SCM version of the coupled land–atmosphere ECMWF model cycle 23r4 is used. This is a hydrostatic model based on the primitive equations incorporating 60 atmospheric levels with a well-resolved boundary layer. It uses the comprehensive physical package of ERA-40, including TESSEL as land surface scheme. Atmospheric dynamical forcing terms (advection, subsidence, and pressure gradient force) and initial state of the soil on the first simulation day (1 October 1999) were generated from a high-resolution (spectral truncation T511, with quasi-uniform resolution of ~40 km) 24-h forecast, starting from ERA-40 initial conditions. The atmospheric forcing was taken from the closest grid point every 3 h. Every 24 h, at 0000 UTC, the full atmospheric profile was replaced by the profile taken from the T511 run. Precipitation and incoming shortwave and longwave radiation fluxes are prescribed from 3-hourly interpolated observations to reduce forcing errors to the land surface scheme (see below).

In the control simulations (SCM-CTL), soil water evolves without analysis ("open loop"). In the data assimilation experiment with a 24-h window (SCM-DA), soil water adjustments take place at 0000 UTC every day, and during the subsequent 24 h the water content in the entire soil column evolves according to the formulation of the land surface scheme, the prescribed dynamical forcing, and the observation-based precipitation and radiation fluxes.

The data assimilation is carried out with a newly developed simplified version of an Extended Kalman Filter (EKF) system (Seuffert et al. 2004), based on the original design by Hess (2001). The soil moisture in the upper three soil layers is updated by minimizing a cost function, optimally combining the information from the model prior forecast and 6-hourly screen-level observations in a subsequent 24-h time window. Assuming a quasi-linear relationship between soil moisture and observable quantities in a small soil moisture range, the minimum of the cost function can be obtained directly by performing one additional perturbed forecast for soil moisture content in each of the three layers in which the initial value is modified slightly. A Kalman filter is used for time propagation of the background

error of the modeled soil water content. A full description of the simplified EKF data assimilation system using a synergy of observations (screen-level parameters, heating rates, and brightness temperatures), a comparison to the OI analysis as used in ERA-40, and tests using field data are given by Seuffert et al. (2003, 2004).

Six-hourly temperature and dewpoint temperature data assimilated at the grid points were retrieved from the daily T511 24-h forecast simulations. Comparison to ERA-40 analyses and local station data revealed a very small random error in these quantities (not shown).

Soil water increments do not only originate from systematic errors in the hydrological components of the land surface model, but also from deficiencies in the atmospheric forcing, in particular precipitation and downward radiation. Datasets of both parameters are produced for the period October 1999–December 2000 over Europe. Daily precipitation analyses at a spatial resolution of $0.2° \times 0.2°$ are produced using over 20 000 gauges. The daily values are disaggregated in 3-hourly intervals using radar reflectivity data in large portions of the domain, and with ECMWF forecast products from ERA-40 where radar data were not available (see Rubel et al. 2004 for details). At the same spatial resolution, a 3-hourly database of surface longwave and shortwave downward radiation was prepared as described by Meetschen et al. (2004). Surface radiation fluxes are calculated using the previous ECMWF radiative transfer code (Morcrette 1991) while atmospheric profiles of cloud cover and water vapor content are adjusted in order to match top-of-atmosphere reflectances with Meteosat satellite data. Validation using over 30 surface ground stations revealed a slightly smaller bias and root-mean-square error of particularly the shortwave radiation than the unadjusted calculations with the ECMWF forecast model (Meetschen et al. 2004). The precipitation and radiation data described here are referred to as the ELDAS precipitation and radiation datasets in the rest of this paper.

d. Multiyear offline land surface simulations

The magnitude of seasonally accumulated soil moisture analysis increments depends strongly on the magnitude of all terms in the soil water budget equation. It is therefore of interest to relate these increments to a measure of what one could expect from natural variability of the soil water storage change. Here we subjectively defined this "natural variability" as an estimate of the interannual variability of the accumulated storage change generated by a multiyear offline simulation of TESSEL. For this we ran TESSEL for the 36 European locations using ERA-40 6-hourly interpolated fields of (bias-corrected) precipitation, radiation, near-surface (2-m height) air temperature, humidity, and wind speed for the period 1980–2000. An initial state was obtained by running the model three times through the first year, after which equilibrium was reached. Since precipitation is a major driver for interannual variability of soil water, a simple correction procedure was followed to remove the bias in the ERA-40 precipitation data using the precipitation observations for the year 2000. For each month in 2000, an average bias of the ERA-40 data was evaluated against the ELDAS precipitation data. The resulting correction factor was applied similarly to all years. Atmospheric temperature was corrected for height differences between ERA-40 and the grid point in the simulations with the SCM, using an adiabatic lapse rate (6.5 K km^{-1}). Specific humidity was corrected accordingly by assuming relative humidity to be constant with height. Ten-meter wind speed was extrapolated to 2-m height using a neutral wind profile. Surface pressure was corrected by assuming an average pressure gradient of 10 Pa m^{-1}. The other ERA-40 driving fields (wind speed, radiation) were left unchanged.

For each year of the 21 yr of offline simulations, the daily difference of the total soil water content from its value on 1 April was accumulated over the year. The resulting 21 annual time series of daily accumulated soil water difference were averaged over 10-day intervals, and for each interval the standard deviation $\sigma(W)$ of the 21 simulations was calculated. This is a measure of the interannual variability of the soil water change from the start of the growing season, due to the interannual variability in precipitation and evaporation. Note that the simple precipitation correction procedure may affect the resulting calculated interannual variability of the storage change, which should therefore be considered as an estimated proxy of the true interannual variability.

e. In situ locations and observations

The sites shown in Fig. 1 are selected in the ELDAS project owing to the presence of validation data at nearby stations, either data on soil moisture content (e.g., the group of locations in Estonia), data on energy balance or surface flux variables, or a combination of these (Jacobs et al. 2007, manuscript submitted to *Tellus*). On a subset of 11 sites surface evaporation measurements were collected. At the CarboEuropeFlux network sites (Valentini et al. 2000) the eddy correlation technique was used, and the observations mainly represent forest sites. Observations collected at the Energy and Water Balance Monitoring System project (EWBMS; Moene and De Bruin 2001) consist of measurements of sensible heat flux using large aperture

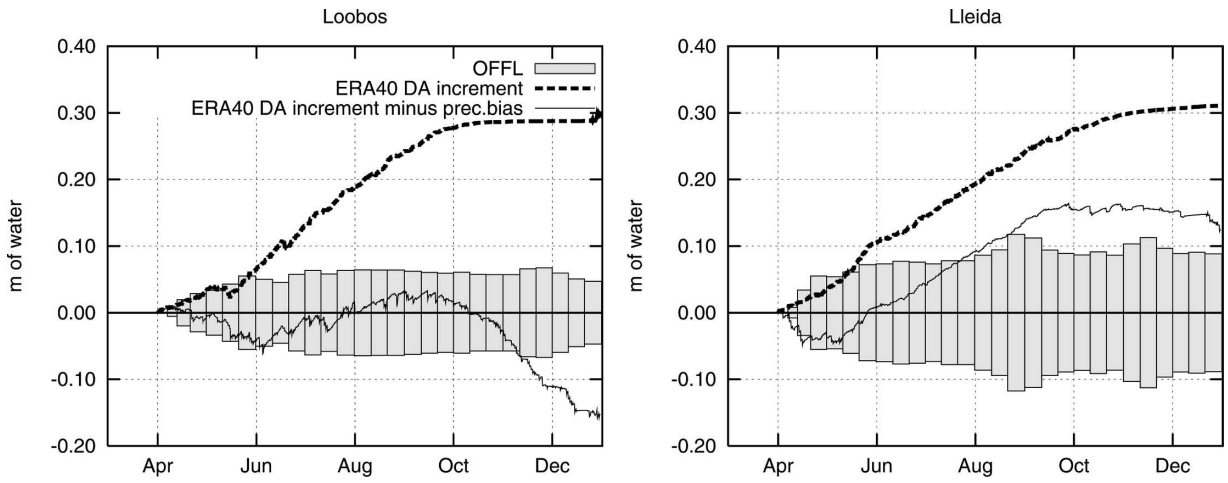

FIG. 2. Time series for the year 2000 of cumulative soil water increments generated by the ERA-40 system (heavy dashed) for (left) Loobos (the Netherlands; point 14 in Fig. 1) and (right) Lleida (Spain; point 6 in Fig. 1). Also shown (light solid) is the ERA-40 cumulative increment reduced by the known precipitation bias and (shaded bars) for each location the standard deviation of the interannual change of cumulative total soil water difference relative to 1 Apr 2000 from the multiannual OFFL uncoupled land-only simulation.

scintillometers, net radiation, and soil heat flux. Latent heat flux was obtained as a residual. The flux sites are indicated in Fig. 1.

3. Analysis and results

a. Topic a: Impact of a systematic (spinup) precipitation bias in ERA-40 soil moisture increments

For each of the 36 aforementioned locations, the soil water balance produced by ERA-40 was collected as a cumulative time series since the start of the 2000 growing season (1 April 2000 until 31 December 2000). Examination of increments in the autumn and winter seasons prior to 1 April 2000 revealed a very inactive data assimilation system, consistent with a weak coupling between the land surface and 2-m observations under low radiation conditions.

Figure 2 shows the evolution of the accumulated daily total soil water increments in ERA-40 since 1 April 2000 for two rather typical locations. The bars in Fig. 2 are a measure of the estimated soil moisture interannual variability produced by the OFFL simulations (see section 2d).

The left panel in Fig. 2 at Loobos in the Netherlands is typical for the European midlatitude area between 45° and 60°N. In ERA-40 the cumulative increments clearly exceed the estimated interannual variability of soil water content. A considerable portion of the increment is considered to originate from the use of the short-range (6 h) precipitation forecast as land surface forcing in the ERA-40 data assimilation. The precipitation values in ERA-40 at midlatitudes are known to suffer significantly from a spinup problem (Hagemann et al. 2002), giving rise to systematic underestimation at short forecast intervals. We used the daily observed precipitation forcing to estimate the precipitation bias in ERA-40. Subtracting this bias entirely from the actual ERA-40 increment significantly reduces this quantity. Removing the precipitation bias may reduce the data assimilation increment in (1). However, if the higher precipitation amount had been included originally, then evaporation and runoff likely would have changed, too. However, it may be considered as a first-order estimate of the impact of the precipitation bias on the magnitude of the soil moisture increments as shown in Fig. 2.

Also, for a point located in northeast Spain (Lleida, right panel in Fig. 2), the ERA-40 increments are roughly similar as for the Loobos site. Here the precipitation bias is much smaller and can only explain part of the large values of I in ERA-40. The large increment may be related to a systematic positive radiation–cloud feedback that promotes excessive surface drying (e.g., Viterbo 1996). Some stations closer to the coastline (e.g., Bari, point 4 in Fig. 1) show a much larger ERA-40 increment (and a much smaller impact of the precipitation bias correction). Up to 60 cm of water is added there during the 2000 growing season (not shown). This may be related to a representivity problem of the analyzed atmospheric humidity and temperature used for the soil moisture data assimilation

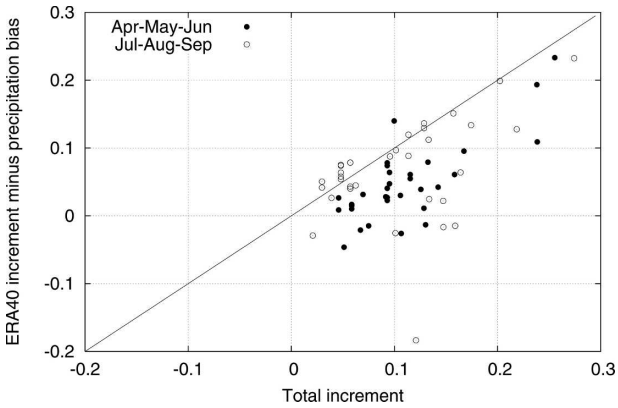

FIG. 3. Cumulative increment in ERA-40 in two different 3-month periods compared to the increments from which the ERA-40 precipitation bias was subtracted. The periods are April–June 2000 (filled symbols) and July–October 2000 (open). Each data point represents one location of Fig. 1.

(Balsamo et al. 2004). Possibly the inland advection of nearby relatively cool and moist marine layer air is not picked up appropriately by the atmospheric analysis, leading to an overestimation of the atmospheric moisture deficit promoting positive soil moisture increments. However, systematic analyses of the effects of positive feedbacks or distance to the coastline have not been explored for the inhomogeneous distribution of 36 European locations available here.

A summary of the possible effect of the ERA-40 precipitation bias on analysis increments is shown in Fig. 3, where for all 36 locations a comparison is made between the total increments (horizontal axis) and the increments minus the precipitation bias (vertical axis) for two 3-month periods in 2000: April–June and July–September. The distance of each point below the 1:1 line is an indication for the hypothetical contribution of the precipitation bias to the analysis increment. In particular, early in the growing season the precipitation bias explains a large portion of the increment, on average in the order of 45%. Later in the season, when precipitation on many locations is lower, the bias contributes less to the soil increment. Note, however, that the irregular spread of locations over Europe (Fig. 1) does not allow considering Fig. 3 as a representative estimate for the European-wide effects.

b. Topic b: Magnitude of increments in the new simplified EKF data assimilation scheme

In this section we present results from the SCM-CTL and SCM-DA runs to provide a picture of the magnitude and temporal behavior of soil water analysis increments in an assimilation system using precipitation forcing having relatively little bias. In both the SCM-CTL and SCM-DA simulations for each of the 36 point locations, all soil water balance components were accumulated starting from 1 April 2000 as the start of the growing season, considering the prior 6 months since 1 October 1999 as a spinup period. The cumulative time series from the CTL run were subtracted from the DA time series, to generate time series of the DA-minus-CTL differences in components of the accumulated water balance components (see Fig. 4). Time series of the accumulated increments I are derived from the SCM-DA runs solely. The remaining budget terms are discussed in the next subsection. Here we focus on the analysis increments and discuss the possible background of the observed phenomena.

Figure 4 displays DA-minus-CTL difference time series, together with the OFFL soil moisture variability for a number of locations, each representing a rather "typical" class of locations. The selection allows a discussion of the major features of the data assimilation effects. The upper two panels shown in Fig. 4 coincide with the examples shown in Fig. 2 (i.e., the Loobos site in the Netherlands and Lleida in northeast Spain). The lower left panel displays an example from north Sweden, while on the lower right an Estonian example is shown.

For the Loobos site the overall accumulated increment over the 6 months starting from April 2000 is fairly modest, approximately 50 mm. Based on comparison with the Loobos result in Fig. 2, the use of observed precipitation in SCM-DA probably has a strong beneficial impact on the magnitude of the increments. Although the cumulative increment is smaller than one σ of the estimated interannual variability, it is systematically positive in the summer season. On midlatitude locations with a similar behavior, the positive summer increments are often preceded by a (smaller) removal of soil water (negative increment) in late spring. This behavior was also shown by Seneviratne et al. (2004), who analyzed the annual cycle of terrestrial water storage in ERA-40 over the Mississippi River basin. They observed a strong damping of this annual cycle and too-high summertime soil moisture content owing to the soil moisture data assimilation. This behavior is noted for the locations spread around the midlatitude European domain away from the Mediterranean area (Spain and Italy). Douville et al. (2000) hint at an overestimation of springtime canopy transpiration owing to the lack of seasonality of leaf area as a possible cause for this phenomenon, but other processes that are not well represented by the model may also be responsible for generating too much evaporation in

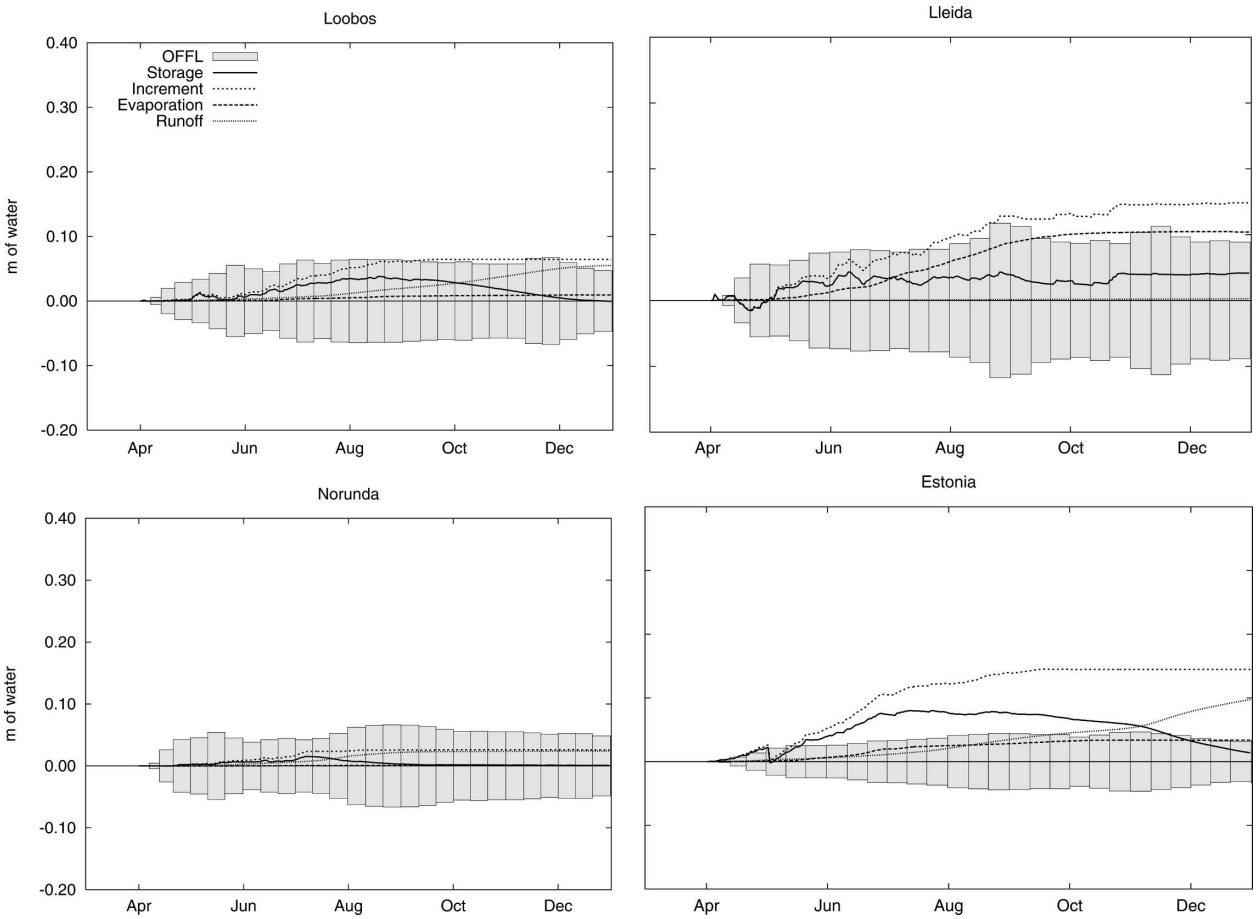

FIG. 4. Time series of differences DA – CTL of cumulative water balance terms: difference in stored water (solid), the DA increment (small dash), difference in cumulative evaporation (large dash), and difference in cumulative runoff (dotted) for four example points: (upper left) Loobos (the Netherlands; point 14 in Fig. 1), (upper right) Lleida (Spain; point 6 in Fig. 1), (lower left) Norunda (Sweden; point 36 in Fig. 1), and (lower right) Estonia (point 25 in Fig. 1). Also shown (shaded bars) for each location is the standard deviation of the estimated interannual change of total soil water content, relative to 1 Apr 2000, from the multiannual OFFL uncoupled land-only simulations.

spring. The quick depletion of the soil reservoir needs to be compensated in summer by adding soil water.

A Mediterranean behavior is depicted by the Lleida site in the upper right panel of Fig. 4. Compared to the OFFL-estimated interannual variability, larger annual increments (up to nearly 150 mm for the location shown) are produced, governed by a large atmospheric evaporative demand particularly in the summer season. The increment is about half the value found in ERA-40 for this location (cf. Fig. 2). Observed precipitation did not show large differences with ERA-40 precipitation. The atmospheric moisture and temperature fields entering the data assimilation system are very similar to ERA-40, although in SCM-DA a 24-h time window is used instead of a single time slot in the ERA-40 OI system. In addition, the use of observed radiation may avoid a strong positive feedback cycle driving the soil depletion, and we speculate that this is responsible for at least part of the reduction of the accumulated increment. Springtime increments are generally small. The analysis increments in summer exceed the winter- and springtime values. The difference with the midlatitude locations is, apart from the magnitude of the accumulated increments, the relatively large effect of the data assimilation on accumulated evaporation, which will be addressed later.

A third example is seen in the lower left panel of Fig. 4, where negative increments occur during a short episode late in spring. The site is located in central Sweden. The data assimilation is active during a short period in spring as soon as the soil water has melted and liquid water movement occurs. Since near-surface forecast errors are assumed to primarily result from erroneous evaporation rates, the amount of melted water

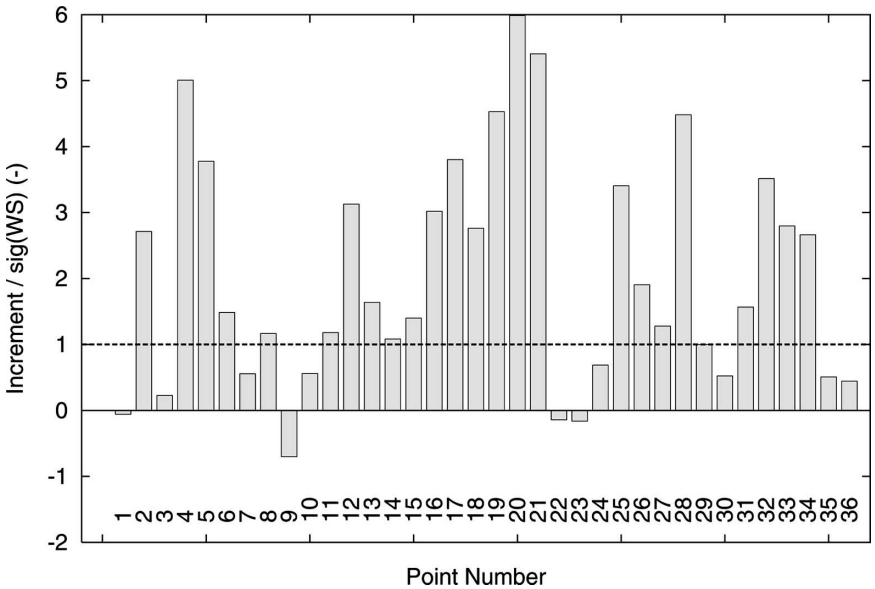

FIG. 5. Total increment between 1 Apr and 1 Oct 2000, normalized by the standard deviation of soil water change in the same period derived from the multiyear OFFL runs. The sites are ordered from low to high latitude.

that infiltrates in the soil results in an overestimation of the surface evaporation. The forecast errors of near-surface temperature and/or humidity could also be due to a misrepresentation of the snow cover or of the melting process, rather than an error in the soil wetness.

The final example shown in the lower right panel of Fig. 4 is located in the Estonian area, where a dense network of soil moisture field sites is located. The accumulated increments for these sites have values in between those of Loobos and Lleida as seen in the two upper panels. The ratio between the cumulative change of evaporation and the increments is fairly low (order 30%) and resembles the situation in the Loobos site. The relatively large increments compared to the estimated interannual variability in combination with a low evaporation response (see next subsection) is typical of the set of locations in the northern part of the Estonian area. In the southern locations the increments are generally smaller.

Figure 5 shows the relative size of the accumulated increments at each location between 1 April and 1 October 2000, normalized with the value of $\sigma(W)$ calculated from the OFFL runs at 1 October. A value of $I/\sigma(W)$ lower than one applies to locations where the data assimilation does not give rise to substantial changes of the soil water budget compared to the estimated interannual variability of soil water content. Four out of the 36 locations have negative increments, eight have increments lower than one standard deviation, and the rest (24 locations) exceed one standard deviation, up to more than sixfold. For these locations the increments are more than random corrections to noisy errors in the forcings or surface scheme parameters. This will be discussed in more detail below.

c. *Topic c: Changes in the soil water budget due to the moisture increments*

Figure 4 also shows the time response of the remaining terms in Eq. (1) to the supply or removal of soil water. The evolution of soil water content initially tends to follow the increments, followed by a more or less pronounced change of runoff and evaporation. Later during summer the soil water content generally starts to return to the value simulated in the control runs, and the other components compensate the surplus or shortage induced by the increments.

Runoff in the model consists mainly of deep drainage depending on soil water content in the lowest soil layer. It is a steep function of soil water content at high water levels, and fairly insensitive to the amount of soil water under dry conditions. The runoff response in the SCM-DA runs lags the soil water increments, since it takes time for the increments—which are applied to the top three levels only—to reach the deepest soil level. During the following autumn changes of the cumulative evaporation and the cumulative increments are generally insignificant. Eventually the increments are removed as runoff in the subsequent autumn and winter season.

Evaporation and soil water increments are positively correlated without a time lag, since evaporation is the main component of the water balance that is directly sensed by the forecast errors in screen-level temperature and humidity as used in the data assimilation. However, for many locations the induced changes in evaporation are relatively small compared to the other terms of the water balance. In the Swedish locations shown in Fig. 4 the significant (negative) peak of soil water increment is greatly compensated by a sharp decrease of runoff. After this short episode of active data assimilation the soil state is hardly changed anymore. In the Estonian example the evaporation response to the relatively large increments is also small.

At each location, changes to the components of the water balance induced by soil moisture increments have been examined. Figure 6 shows the modifications in evaporation, runoff, and soil water storage normalized by the total increment over a given period. Two periods have been considered: the first three months after 1 April (upper panel) and the total 6-month growing season (lower panel). The sites are ranked from low to high latitude of the location shown in Fig. 1.

Two sites in Fig. 6 show values of $\Delta E/I > 1$. For these locations the effect of the increments on other terms in the water budget (the runoff) is negative: positive increments lead to a reduction of runoff. These runoff responses are delayed adjustments to small but negative increments in the period prior to 1 April 2000. They are both located in Spain (see Fig. 1).

The four locations for which more than 70% of I is returned as evaporation are all located in the Mediterranean area, where the evaporative demand of the atmosphere is large, radiative energy is not the limiting factor for evaporation, and soil water anomalies are closely correlated to evaporation. In these areas the soil moisture assimilation system is most active (on average 170 ± 132 mm is added during the six months in the growing season).

In the largest group of locations, soil water storage is the term having the strongest response to the increments early in the season (upper panel in Fig. 6), but accumulated over the growing season (lower panel) a significant fraction of the increments is eventually removed by a runoff increase. The most striking feature of this group is the relatively small fraction of the increments that is returned to the atmosphere as evaporation. On average 100 ± 70 mm is added by the data assimilation in this group of sites, but on average the evaporation is changed by less than 18% of this amount in the same period. This is remarkable, given the fact that the assimilated observations are assumed to contain information on evaporation rather than on any other quantity related to the hydrological budget of the land surface.

A limited response of evaporation on soil water increments may be understood from the experimental setup of the SCM runs. Although the coupling of the land surface to a full atmospheric column allows a considerable degree of freedom of the surface evaporation to affect near-surface moisture content, the lateral forcing and daily reset of the atmospheric moisture profiles reduce this control. Similar to experiments with offline land surface models driven by fixed atmospheric conditions (like the OFFL simulations used in this study) the lack of full land–atmosphere interaction imposes a severe limitation on the variability of the evaporation in response to soil wetness variations. Comparison to a full 3D model environment equipped with the EKF data assimilation system should be carried out to confirm this constraint.

Also the land surface scheme itself constrains evaporation variability more than runoff. Like many land surface models, TESSEL is formulated essentially as a moisture reservoir with limited water holding capacity, and strong anomalies in either precipitation or soil moisture increments are easily "spilled over" the reservoir, thus preferably changing the runoff rather than the evaporation budget. Analysis of the (estimated) interannual variability of all terms in the OFFL simulations supports the notion that evaporation is much stronger constrained (showing less interannual variability) than runoff (not shown). This is confirmed by analyses of effects of varying precipitation forcings in an ensemble of offline model simulations in the context of the Global Soil Wetness Project (Schlosser and Houser 2007). Runoff acts as the "kitchen sink" in the case of anomalous precipitation, as it is the only term in the water balance that is not constrained by atmospheric demand (evaporation) or storage capacity (soil water).

d. Topic d: Comparison to in situ evaporation observations

At a subset of the locations used in this analysis (nearly) continuous evaporation measurements have been carried out, allowing an evaluation of the hydrological budgets in the SCM-CTL and SCM-DA runs.

Figure 7 shows the observed and modeled cumulative evaporation during the growing season (April–September) for these locations. Modeled evaporation rates are only accumulated when valid observations are available. For one location the data assimilation deteriorates the relatively good match between observations and the

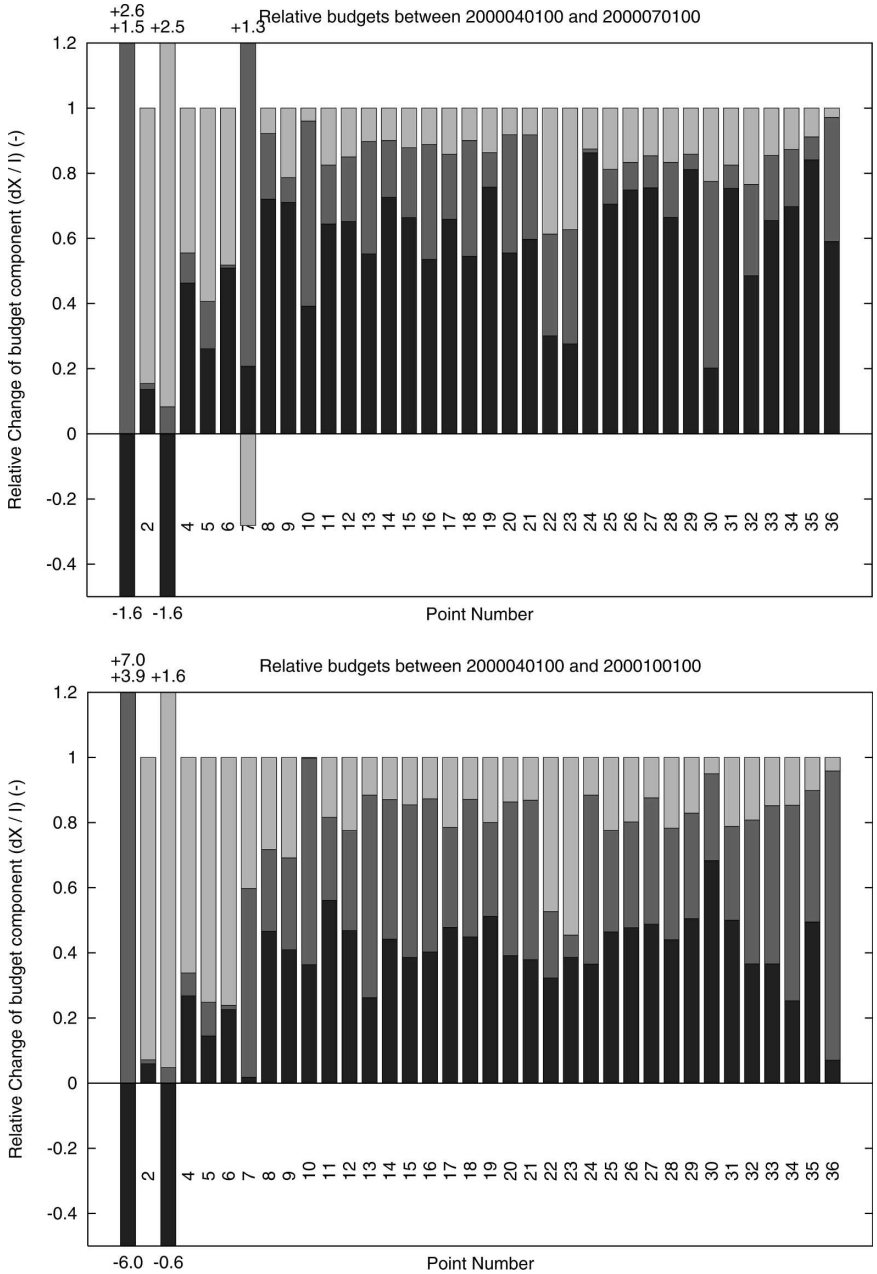

FIG. 6. Change of the soil water balance terms: evaporation (light shading), runoff (middle shading), and soil water change (dark shading) relative to the overall magnitude of the accumulated soil water increment for each location. Each column represents one location, ranked from low to high latitude. Columns larger than one indicate compensation of negative fractions by other terms in the balance. The budget changes in (top) April–July 2000 and (bottom) April–October 2000. Values of clipped bars are indicated in the margin.

control simulations (location 5 in south Italy), while in two other cases (location 2 located near Valencia, Spain, and to a lesser extent location 8 in south France) the data assimilation clearly improves on the results. In the other cases the difference between the observations and either the SCM-CTL or SCM-DA run is (much) larger than the change of simulated evaporation between SCM-CTL and SCM-DA. For these locations the comparison between the observations and model output does not give a clear indication on which simulation is better. It only confirms the earlier finding that the impact of the data assimilation on the simulated evapo-

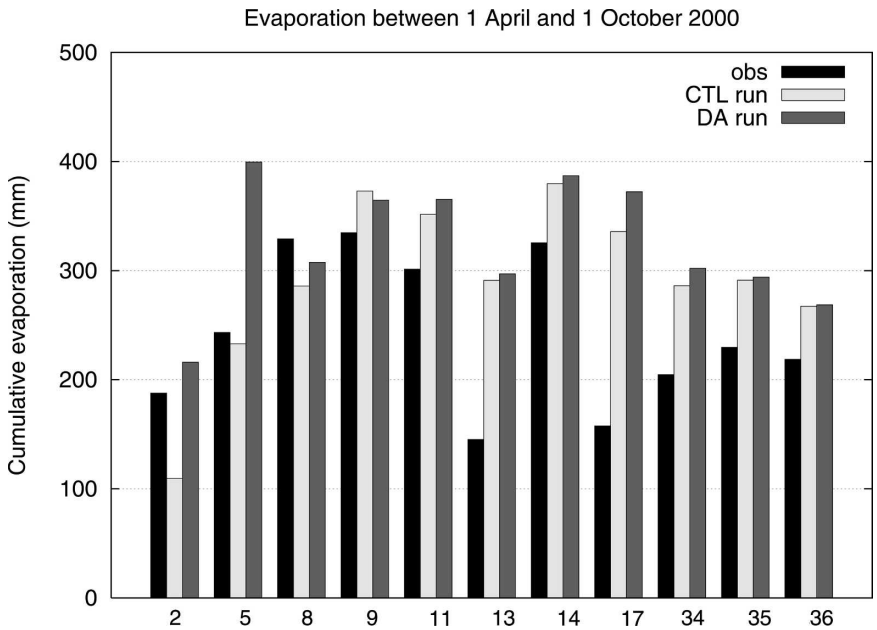

FIG. 7. Observed and modeled cumulative evaporation between 1 Apr and 1 Oct 2000 for a subset of locations. Modeled evaporation is accumulated only for the days where observed evaporation rates were available.

ration rate is small, at least compared to the (generally positive) bias in the modeled evaporation. Note, however, that apart from factors affecting the data assimilation (soil moisture, atmospheric temperature, and humidity) other model characteristics may be responsible for the disagreement between observed and modeled evaporation. Jacobs et al. (2007, manuscript submitted to *Tellus*) argue that the discrepancy between observed and modeled land surface characteristics (like constant versus varying value of LAI, or an albedo representative for grassland or forest) may be responsible for the evaporation bias.

4. Discussion and conclusions

Cumulative ERA-40 soil water budgets (including the contribution from the soil moisture data assimilation) were analyzed for 36 locations across Europe during the growing season April–October 2000. For many cases the increments are systematically positive. However, accounting for the ERA-40 precipitation bias (derived using observed precipitation) reveals that on average nearly half of the size of the accumulated increment can be attributed to this bias. Part of the low precipitation bias over Europe is associated with a spinup of the atmospheric data assimilation (Hagemann et al. 2002). The effect of this spinup on the soil moisture assimilation could be reduced when instead of the first guess precipitation forecast a somewhat longer forecast lead time would be used (for instance the precipitation from the +6- to +12-h forecast range).

Observed precipitation (and radiation) obviously should be given preference in soil moisture data assimilation applications. In the context of the ELDAS project a new data assimilation system is designed and tested, in which observed precipitation and radiation replace the quantities generated by the atmospheric model. In addition, a simplified extended Kalman filter is used to assimilate near-surface quantities in a 24-h time window and to propagate the background error forward in time. In an ECMWF SCM system, this data assimilation package was added as an option, and the comparison between the SCM-CTL and SCM-DA experiments allowed a further analysis of the size and effects of systematic soil moisture increments.

Despite the use of precipitation and incoming radiation derived from observations, analysis increments were still systematically applied in the SCM-DA runs. Accumulated over the most active part of the annual cycle (the growing season between April and October) they added to values in the same order or larger than one standard deviation of the estimated interannual variability of soil water change for many locations. Locations near coastlines displayed larger increments, which hints at a misrepresentation of land–sea differences or circulations in the model driving the data as-

similation, rather than systematic biases in the soil water content. Most of the points displaying relatively large increments in Fig. 5 [$I/\sigma(W) > 1.5$] appear to be located close to the coast. This should be analyzed with a gridded Europe-covering version of the presented data assimilation system.

The 36 locations were subdivided in a number of broad classes, according to the signature of the partitioning of the analysis increments over runoff, evaporation, and stored soil water. The largest group of locations generally located between 45° and 60°N showed small or negative increments in winter and spring, but larger positive increments in summer. Although evaporation was considered the main process governing the increments (Beljaars et al. 1996), for locations away from the Mediterranean, evaporation changes received only a small portion of the analysis increments. The main fraction of the increments for the non-Mediterranean locations is eventually removed as runoff, after initially increasing the amount of stored soil water. This can at least partially be understood from the constraint on evaporation imposed by the setup of the SCM experiments, where lateral advection and daily reset of atmospheric profiles limit the degrees of freedom of the land surface evaporation to change the actual atmospheric moisture content. A more extreme group of locations with summertime positive increments were located in the Mediterranean area. Here more than 70% of the increments actually returned as evaporation. Comparison with evaporation observations at two locations gave conflicting results on the question whether the data assimilation improved or deteriorated the simulated evaporation rate. For one location in south Italy the control run already showed a fairly good match and the data assimilation caused a strong overestimation of evaporation, while at a location near Valencia the correspondence to observations was significantly improved by the soil moisture corrections.

However, even with the present experimental setup it may be desirable to increase the sensitivity of evaporation to soil moisture increments in order to reduce the relative magnitude of the increments in the seasonal water balance overall. This can probably be realized by modifying the land surface model in order to reduce springtime water loss due to evaporation or runoff, sustain higher evaporation levels at lower soil moisture values in summer, and reduce annual runoff to avoid water loss.

In the current practice of soil moisture data assimilation, systematic model biases related to these processes are mitigated by changing the state of the prognostic soil water content, thereby adding an extra term to the soil water balance equation. Alternative methods to constrain model results by observations exist, like the multiparameter estimation methodology currently being addressed in various studies [see, e.g., Liu et al. (2004, 2005) and the PILPS San Pedro project, available online at http://www.sahra.arizona.edu/pilpssanpedro]. Given the results presented here, adjusting the sensitivity of evaporation as function of soil water content ($\partial E/\partial W$) as control variable will likely allow larger portions of analysis increments being returned to the atmosphere, resulting in smaller systematic corrections to the soil moisture content. For cases where near-surface biases point at shortcomings in the treatment of soil thaw or snowmelt (van den Hurk and Viterbo 2003), changes to the formulation of the dependence of infiltration and runoff on (partially frozen) soil water content will probably also lead to smaller increments.

It seems desirable in a future work to evaluate a modified version of the land surface scheme in the simplified EKF system, even though the experimental setup and the limited number of test sites analyzed here do not allow to draw firm conclusions on its current weaknesses.

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