Soil Initialization Strategy for Use in Limited-Area Weather Prediction Systems

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ABSTRACT

Three diverse methods of initializing soil moisture and temperature in limited-area numerical weather prediction models are compared and assessed through the use of nonstandard surface observations to identify the approach that best combines ease of implementation, improvement in forecast skill, and realistic estimations of soil parameters. The first method initializes the limited-area model soil prognostic variables by a simple interpolation from a parent global model that is used to provide the lateral boundary conditions for the forecasts, thus ensuring that the limited-area model’s soil field cannot evolve far from the host model. The second method uses the soil properties generated by a previous limited-area model forecast, allowing the soil moisture to evolve over time to a new equilibrium consistent with the regional model’s hydrological cycle. The third method implements a new local soil moisture variational analysis system that uses screen-level temperature to adjust the soil water content, allowing the use of high-resolution station data that may be available to a regional meteorological service.

The methods are tested in a suite of short-term weather forecasts performed with the Consortium for Small Scale Modeling (COSMO) model over the period September–November 2008, using the ECMWF Integrated Forecast System (IFS) model to provide the lateral boundary conditions. Extensive comparisons to observations show that substantial improvements in forecast skills are achievable with improved soil temperature initialization while a smaller additional benefit in the prediction of surface fluxes is possible with the soil moisture analysis. The analysis suggests that keeping the model prognostic variables close to equilibrium with the soil state, especially for temperature, is more relevant than correcting the soil moisture initial values. In particular, if a local soil analysis system is not available, it seems preferable to adopt an “open loop” strategy rather than the interpolation from the host global model analysis. This appears to be especially true for the COSMO model in its current operational configuration since the soil–vegetation–atmosphere transfer (SVAT) scheme of the ECMWF global host model and that of COSMO are radically diverse.

1. The problem of soil initialization

In numerical weather prediction (NWP) models, soil scheme initialization (especially the prognostic variables; i.e., the vertical profiles of soil temperature $T_g$ and moisture $w_g$) is not a straightforward task for a number of reasons. First, there are only sparse measurements for an operational analysis system. In situ observations are rare and heterogeneous. The Global Soil Moisture Data Bank project (Robock et al. 2000) is an example of the collection, dissemination, and analysis of gravimetric observations of soil moisture and temperature data from around 600 sites around the globe that until now has served to verify and initialize climate simulation tasks without addressing the requirements of real-time operational forecast usage. Remotely sensed surface soil temperature and moisture databases are available with mostly daily frequency, but the detected radiation is directly linked only to the model’s uppermost soil layer and therefore can only provide limited information. Moreover, soil moisture retrieval from microwave frequencies requires the accurate specification of the vegetation cover and soil type at the pixel location, which is not usually available with the desired precision. In

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addition to the lack of useful observations, the spatial heterogeneity and the consequential limited representativity of soil measurements is also problematic. Autocorrelation length scales for soil moisture can be as small as 10 m (Western et al. 1998).

The lack of accessible and reliable observations has been one primary cause for the employment of simplified strategies for soil initialization in numerical weather prediction models. In terms of their complexity, improvements in present soil analysis schemes fall well behind the impressive developments achieved in classic atmospheric data assimilation (Courtier et al. 1994; Evensen 2003; Ott et al. 2004). Soil initialization has the primary aim of integrating water and energy fluxes into the soil and snow buffers, and effectively determines the partitioning of surface fluxes between latent and sensible heat. It therefore has an immediate effect on the structure of temperature and humidity in the boundary layer, controlling the model prediction of the diurnal cycle, the timing and intensity of convection, and mesoscale circulations (Hammer 1970; Segal et al. 1995; Segal et al. 1988).

Soil initialization in limited-area models can follow several approaches, each of which has specific advantages and drawbacks. Direct interpolation of soil properties from the global host model is simple to implement. Nevertheless, care has to be taken with the approach; for example, it is important to ensure that the soil moisture values at each grid point are normalized to fall below the wilting point–field capacity interval of its own model before using this field in another model, if a change in soil type is expected in a grid point.

Initialization from a previous limited-area model run is another possibility (Smith et al. 1994; Macpherson et al. 1996). The quality of this approach mostly depends on the capability of the model to correctly predict mean moisture and energy sources, such as precipitation and incoming radiation. Soil moisture, for example, responds quickly to precipitation input, while taking time to release excess humidity through evaporation or transpiration. If either the soil type or precipitation is misrepresented, a feedback can result, leading to a model drift to excessively dry or wet equilibrium conditions. The advantage, compared to the previous option, is nevertheless that the soil properties are in near-equilibrium with the limited-area model physics, preventing shocks or spinup at the start of a model integration. If the soil scheme is realistic in representing the water and energy budget components such as runoff, percolation, capillarity, and soil conductivity for example, and the atmosphere produces the correct hydrological and radiative forcing, this method can in principle produce realistic soil field estimations.

A third possibility for deriving soil properties is to use indirect measurements. Especially in cases where there is strong radiative coupling between the surface and the atmosphere, the screen-level temperature and humidity are closely related to soil temperature and moisture content through surface fluxes. The idea followed in this case is therefore to use soil moisture as a tuning parameter to adjust the prediction of screen-level diagnostics (Rhodin et al. 1999; Hess 2001). Generally, the synoptic (hereinafter synop) database is a very dense measurement network that will not be covered by any representative soil moisture measurement system in the near future. Mahfouf (1991) tried both optimal interpolation and variational approaches to adjust the soil water content to minimize the distance between background and atmospheric synop observations with encouraging results. This method has to our knowledge been applied to the analysis of soil humidity, although Giard and Bazile (2000) proposed a simple correction additionally for soil temperature based on observed $T_{2m}$, which showed a clear benefit in the forecasts. The premise of this approach is that the atmospheric boundary layer thermodynamic properties are always related to soil moisture; however, this is not always necessarily the case. For instance, during the night, rainfall events, or days with low solar insolation, this method is likely to fail [as demonstrated in sensitivity studies by Bouttier et al. (1993), Giard and Bazile (2000), Drusch and Viterbo (2007) and Hess et al. (2008)], since the coupling between the soil and the boundary atmospheric layer weakens and the soil moisture estimation derived with this method is likely to diverge from reality. Moreover, if soil variables are merely considered to be a parameter to be tuned to compensate for various model biases, it is likely they will assume unrealistic values not suitable for hydrological applications, and will be highly dependent on the atmospheric model formulation.

The adopted strategy for soil initialization in regional-scale numerical weather prediction (R-NWP) models, especially if managed by small regional forecasting centers, is a compromise between ease of implementation and required minimal accuracy. In many cases running a local analysis is too demanding and, therefore, fields are either interpolated from a global model or from a previous model run (the so-called open-loop initialization). To help understand the relative merits of the various methods and also to quantify the quality of R-NWP analysis in subsequent applications, a diagnostic study is presented to compare the outlined initialization choices. The limited-area Consortium for Small Scale Modeling (COSMO) model is used as the regional weather prediction system while the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) model is employed as a global driving model. For a 3-month-long integration period spanning...
September–November (SON) 2008, the COSMO soil scheme TERRA (Schrodin and Heise 2001) is initialized in three different ways. The first uses a simple interpolation from the ECMWF soil moisture analysis. In the open-loop experiment, the COSMO model is initialized by its own previous analysis. Finally, in the last experiment, an adjustment to the soil moisture is computed using a variational scheme that converts differences in modeled and observed screen-level dry temperatures in soil moisture increments following Hess (2001) and Hess et al. (2008).

COSMO predictions are compared to independent local measurements collected at the San Pietro Capefiume (SPC) supersite and at several locations participating in the Assessment of the European Terrestrial Carbon Balance (CarboEurope) project (Papale et al. 2006). This analysis allows a quantitative assessment of the realism of the soil fields obtained with the three initialization methods. The chosen dataset include soil moisture and temperature data, as well as turbulent and radiative flux measurements. These data provide us with the possibility to verify the absolute quality of the various soil property analysis methodologies. Global diagnostics are derived from comparison to the synop network and using satellite-derived products.

2. Models and verification datasets

Since soil moisture analysis based on atmospheric observations is indirect and relies heavily on the underlying model, a brief summary of the main features of the land surface schemes used in the operational ECMWF model and in the COSMO model is given. The set of observations used for validation are taken from a collection of sites that provided nonstandard surface fluxes and soil measurements.

a. The COSMO model and its soil scheme

The COSMO model is a nonhydrostatic model based on the primitive atmospheric state equations (Steppeler et al. 2003). The prognostic variables are the wind vector, temperature, specific humidity, perturbation pressure, and five microphysical variables that describe the cloud phase. For the horizontal discretization, an Arakawa C grid on a rotated geographical system is used. In this study the COSMO implementation (COSMO-I7) is run with a mesh size of 7 km and the variables are computed on generalized terrain-following levels (see Fig. 1 for the integration domain). The model has a total of 40 layers, 15 of which represent the lower 1500 m. The surface-layer parameterization follows a stability-dependent drag-law formulation for momentum, heat, and moisture fluxes according to similarity theory (Louis 1979). A mass flux scheme for moist-convective processes based on Tiedtke (1989) is used, and a cloud microphysics scheme is implemented. The calculations of short- and longwave radiation fluxes and heating rates are based on the the two-stream approximation of the radiative transfer equation according to Ritter and Geleyn (1992).

COSMO-I7 uses as its surface vegetation atmosphere transfer (SVAT) module the TERRA scheme. The state variables of TERRA are the soil temperature profile, soil moisture profile, temperature and water content of the snow storage, and the amount of water in the interception storage. Soil temperature and moisture are stored at eight unevenly spaced model levels: 0.01, 0.06, 0.18, 0.54, 1.62, 4.86, and 14.58 m. This lowest level is set to monthly climatological values and does not evolve. Soil temperatures are interpreted as mean values of a layer. In addition to these prognostic surface state variables, the characterization of the COSMO surface is completed by the following set of time-constant or only seasonally varying fields: the fraction of land within the grid box \( c_{\text{land}} \), the soil type \( c_{\text{soil}} \), roughness length \( z_0 \), plant cover \( f_{\text{veg}} \), leaf area index \( f_{\text{LAI}} \), and root depth \( z_{\text{root}} \). These fields must be provided to initialize the model and are kept constant throughout each integration interval. Seasonal variations (e.g., of \( f_{\text{LAI}} \)) are considered by varying the initial data, but not by the forecast model itself. Using a lookup table (Schrodin and Heise 2001), each soil type (sand, sandy loam, loam, loamy clay, clay, ice, rock, and peat) is assigned to various physical material constants such as heat conductivity or pore volume. Subgrid-scale variability of all surface state variables is
neglected and homogeneous surface conditions are assumed within each grid box. Two surface types are treated differently, namely water and rock. Surface water is completely defined by surface temperature and roughness length. A second exception is that the surface of soil type “rock” is assumed to be impermeable for water. Therefore, no soil-moisture-related processes are considered at rock points and only the thermal heat equation is solved.

Soil temperature profile evolution is prognosed using the extended force–restore method for each soil layer and, if existing, for the snow layer. The temperature of the interception store is assumed to be equal to the soil surface temperature, and no separate heat budget equation is necessary for this store. The basic equation for the temperature prediction is the heat conduction equation:

$$\frac{\partial T_g}{\partial t} = \frac{1}{(\rho c_p)} \frac{\partial}{\partial z} \left( \lambda \frac{\partial T_g}{\partial z} \right),$$  \hspace{1cm} (1)

where \( T_g \) is soil temperature, \( \rho c_p \) is heat capacity, and \( \lambda \) is heat conductivity. The lower boundary condition for the solution of (1) is provided by a climatological temperature prescribed in the lowest layer. This temperature is kept constant during the integration time. At the upper boundary the coupling between soil (or snow) and the atmosphere is by radiation and by sensible and latent heat fluxes. In addition the effects of the melting of falling snow, freezing of rain, freezing of water in the interception store, melting of snow in the snow store, and freezing (melting) of water (ice) in the soil layers are considered, as described in Doms et al. (2004).

The hydrological element of TERRA provides a prediction of soil moisture for two stores at the surface (interception and a snow store) and for the eight soil layers. The soil gains water from precipitation, snow, rim, and dew, whereas evaporation, transpiration, and runoff deplete water from the stores and soil layers. To determine the evaporation from bare soil and the transpiration by plants, the model uses the BATS scheme of Dickinson et al. (1986). Processes such as capillary ascent, percolation, and infiltration are parameterized to describe the vertical exchange and transport of water between the different stores and soil layers. Infiltration is limited by the maximum infiltration rate, which depends on the soil type and on the soil moisture conditions: dry and sandy soils can infiltrate water faster than, for example, moist soils with a high clay content. If the potential infiltration rate is higher than this limit, the excess is converted into surface runoff and removed from the model’s hydrological cycle. Runoff is calculated for each layer in the individual columns but does not allow for lateral transport between neighboring soil columns.

Surface temperature and soil moisture provided by TERRA are then used to calculate the turbulent fluxes and to determine the surface energy balance of COSMO (Schrodin and Heise 2001). The scheme calculates sensible \( H \) and latent heat \( L_E \) fluxes and the momentum flux using the transfer coefficients for momentum and heat derived from Monin–Obukhov similarity theory with the iterative method of Louis (1979):

$$H = -c_p \rho u_T T_*$$ and $$L_E = -\lambda \rho u_T q_*,$$ \hspace{1cm} (2)

where \( \rho c_p \) is the air heat capacity at constant pressure, \( \lambda \) is the latent heat of evaporation, \( u_T \) is the friction velocity. In addition, \( T_* \) and \( q_* \) are the surface fluxes of temperature and water vapor, respectively, and are defined as

$$T_* = -C_h^d |v_h| (\theta \pi_{sfc} - T_{sfc})$$ and $$q_* = C_q^d |v_h| (q^v - q_{sfc}^v),$$ \hspace{1cm} (4) \hspace{1cm} \hspace{1cm} (5)

with \( C_h^d \) and \( C_q^d \) the bulk aerodynamic transfer coefficients for turbulent heat and moisture exchange at the surface and \( |v_h| \) the absolute wind speed at the same level. We set \( \theta \) and \( \pi_{sfc} \) as the potential temperature at the lowest grid level and the scaled pressure at the ground, respectively. Finally, \( \theta \pi_{sfc} - T_{sfc} \) and \( q^v - q_{sfc}^v \) represent the gradient of the temperature and specific humidity between the ground and the lowest atmospheric level.

The COSMO model includes an optional soil moisture analysis scheme based on a variational approach outlined in Lange (2009) and here briefly recalled. Analysis increments at 0000 UTC are produced using observations in the preceding 24-h time window. First, a \( T_{2m}^{\text{obs}} \) observed field is obtained by optimal interpolation of synop observations and model background resulting from a +24-h forecast run \( T_{2m}^{\text{background}} \). Then, background increments \( \Delta T_{2m} \) are calculated as \( T_{2m}^{\text{obs}} - T_{2m}^{\text{background}} \) at two specific times (12, 15 h) around noon. Finally, \( \Delta T_{2m} \) are converted into moisture increments \( \Delta w_{gi} \) at the various levels \( i \) using a parameterized form of the Jacobian \( \partial w_{gi}/\partial T_{2m} \), which is a function of the latent heat. The choice of calculating background errors \( \Delta T_{2m} \), only at two instants, is due to the assumption of maximum soil–atmosphere coupling. One should therefore expect that the major benefit from the soil moisture analysis arises primarily in situations for which the scheme is designed...
(i.e., correcting forecast errors at the time when the observations are assimilated around noon). If the bias does not change its sign, the scheme should nevertheless be able to improve the screen-level errors caused by mis-specification of the Bowen ratio at other lead times. In cases in which the soil is characterized by a substantial soil heating during the daytime and cooling during night, as occurs in very dry soil conditions, then the application of this kind of soil moisture correction can exacerbate the reduction in soil thermal inertia with a consequent worsening of the biases during nighttime. It will be shown that this is an important aspect of this approach.

b. The IFS soil analysis

The IFS soil scheme is the Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land (HTESSEL; Viterbo and Beljaars 1995; Van den Hurk et al. 2000; Van den Hurk and Viterbo 2003). It has four prognostic soil layers for moisture and temperature, with free drainage and a zero heat flux condition at the bottom of the deepest layer. It also includes a precipitation interception layer and a skin temperature level. From the surface to the bottom, the layer thicknesses are, respectively, 0.07, 0.21, 0.72, and 1.89 m. The top three layers correspond to the root zone with a total depth of 1 m. The root density decreases exponentially with depth. The surface evaporation has a bare soil fraction controlled by soil moisture in the top layer and a vegetation fraction. The role of the vegetation is represented explicitly, through a transpiration term and an interception loss term corresponding to the evaporation of dew and intercepted rain at the potential rate. The transpiration is controlled by the leaf area index and the stomata conductance, which is regulated by the water availability in the root zone (top three layers) and the photosynthetically active solar radiation.

The IFS model implements a soil moisture analysis that employs an optimal interpolation (OI) method proposed by Mahfouf (1991). Similar to the COSMO model analysis scheme, it is based on analysis increments of 2-m temperature and relative humidity. Every 6 h, corrections applied in each soil layer (analysis increments) are linear combinations of atmospheric increments of 2-m temperature and relative humidity. The details of the method can be found in Douville et al. (2000), while Viterbo and Beljaars (1995) provide full details on the quality of the IFS soil scheme and a comparison with observations.

c. The verification dataset

The verification dataset is composed of four sources; measurements collected by the European Union (EU) funded CarboEurope Integrated Project (CEIP), data from the Agenzia Regionale Prevenzione e Ambiente dell’Emilia Romagna’s (ARPA) Servizio IdroMeteoClima (SIMC) station located at San Pietro Capofiume (SPC) in the middle of the Italian Po Valley, the standard network of synop surface stations that cover the COSMO-I7 domain, and satellite-derived soil products from the Advanced Microwave Scanning Radiometer for Earth Observing System (EOS) (AMSR-E) sensor.

The CarboEurope project has the main aim of quantifying the relationship between carbon fluxes and vegetation characteristics. Therefore, great attention has been paid to locating observing stations over different land-use/cover types. Measurements (data available online at http://ce-atmosphere.lsce.ipsl.fr/DATA_RELEASE/index.php) have been recorded since 2004 half-hourly by more than 100 eddy flux stations over Europe. The collected dataset therefore potentially possesses a good representativeness of fluxes over different ecosystem types. The location and the vegetation characteristic of the stations that fall into the COSMO-I7 domain and were active during the validation period (SON 2008) are reported in Table 1.

SPC is an intensive observation meteorological station managed by ARPA-SIMC. In addition to the conventional meteorological measurements, including SYNOP and TEMP variables, since 2007 a time-domain reflectometer (TDR) has been in operation that measures soil water content and temperature profiles at eight unevenly spaced levels below the ground between 10 and 100 cm. At the time of the experiments the SPC was not provided with instrumentation for surface fluxes measurements; thus, CarboEurope sites are used for this purpose.

Finally, global diagnostics are calculated using the synop network, which comprises more than 400 surface stations over land and the level-2B land surface product from AMSR-E instrument on board the Aqua satellite, which includes daily measurements of surface soil moisture with a nominal resolution of 25 km (Njoku et al. 2003).

A map of the location of the ground stations used for the comparisons is reported in Fig. 1. Table 1 summarizes the available in situ observations.

3. Experiment strategy

A set of single-column experiments is first carried out to understand the capability of the SVAT module TERRA to correctly simulate soil hydrological and energy budget evolution. To this end, the soil-state and the turbulent fluxes at the soil–atmosphere interface are derived by forcing the SVAT module in a one-way
Initialization by interpolation from the ECMWF soil climatology (Commission of the European Communities 1995). The bottom-layer soil temperature and humidity are the same and are taken from an external database/ climatology (Hess et al. 2008 and Lange 2009). The soil moisture is rescaled to a nondimensional index according to soil texture. During the interpolation procedure, the soil moisture is vertically interpolated in the atmosphere by applying a correction based on a regression of the free-air vertical profile when the target model surface height is lower than the input one. Afterward, the vertical temperature gradient between the lowest model layer and the surface is used to recompute the surface temperature on the target model grid. Finally, temperatures in the deeper soil layers are corrected accordingly, thus, preserving the original model vertical structure of the field.

- **Open-loop soil initialization (hereafter the COSMO experiment).** The initialization is performed using the soil moisture and temperature fields from the previous COSMO run. After a spinup period (the fields for the first initialization are interpolated from the ECMWF model) the soil moisture of this experiment represents the equilibrium between the source terms (precipitation, dew, rime, snow) and the sink terms (evaporation from bare soil, transpiration from plants, runoff). The temperature profile is instead a “solution” of the energy budget at the surface. The vertical soil temperature profile is therefore a direct consequence of the atmospheric model radiative forcing and the assumption on the thermal conductivity of the soil type at the grid-point location.

- **Open-loop soil initialization plus variational soil moisture analysis using surface 2-m synop observation (SMA experiment)** A local soil moisture analysis is performed using the variational scheme from Hess et al. (2008) and Lange (2009). The soil moisture is adjusted to minimize the distance between the background and $T_{2m}$ synop observations. The temperature is instead initialized from the previous COSMO run as in the COSMO experiment. Nevertheless, as the soil heat capacity and the conductivity are functions of the

<table>
<thead>
<tr>
<th>ID</th>
<th>Name</th>
<th>Network</th>
<th>Measurements used</th>
<th>Height (m)</th>
<th>Land cover</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITAmp</td>
<td>Roccarespampiani2</td>
<td>CarboEurope</td>
<td>$H, L_E$</td>
<td>223</td>
<td>Oak</td>
<td>—</td>
</tr>
<tr>
<td>ITCz</td>
<td>Castelporziano</td>
<td>CarboEurope</td>
<td>$H, L_E$</td>
<td>68</td>
<td>Forest</td>
<td>—</td>
</tr>
<tr>
<td>ITRen</td>
<td>Renon</td>
<td>CarboEurope</td>
<td>$H, L_E$</td>
<td>1730</td>
<td>Spruce</td>
<td>—</td>
</tr>
<tr>
<td>SPC</td>
<td>San Pietro Capofiume</td>
<td>ARPA-SIMC</td>
<td>$w_g$, $T_g$ (at 10, 25, 45, 70, 100, 135, 180, 1458 cm), RR</td>
<td>11</td>
<td>Grass</td>
<td>—</td>
</tr>
<tr>
<td>Synop</td>
<td>—</td>
<td>Synop</td>
<td>$T_{2m}$, $T_{dew2m}$</td>
<td>[5; 3100]</td>
<td>Various</td>
<td>Various</td>
</tr>
</tbody>
</table>
soil moisture, a temperature profile is predicted that is in general different from that of the COSMO experiment. Moreover, a different soil moisture produces a different radiative coupling with the atmosphere. As in the ECMWF experiment, since the soil moisture is adjusted independently of the soil temperature, energy conservation can be violated.

All the experiments are performed for 3 months starting on 1 September 2008 (SON period). Each assimilation cycle lasts 24 h, starting at 0000 UTC. In Table 2, a brief summary of the experiments is reported.

### 4. Results

#### a. Problem diagnosis

The main motivation for investigating a different soil moisture initialization strategy compared to the simple ECMWF interpolation is found in the systematic annual biases in screen-level temperatures and humidity. As soil variables were initially interpolated from the IFS model, it was often observed that in the Po Valley, in early spring, temperatures were systematically too high while in summer they were too low. Figure 2 shows the diagnosis of the various problems to be faced. The seasonal variation of the outgoing longwave radiation clearly shows a shift in the annual phase, which is superimposed on a delay in the diurnal cycle. On the one hand, the soil model appears to be unable to represent the increase in the thermal energy seasonal response to the thermal forcing. On the other hand, the diurnal cycle is delayed by a couple of hours and its weak amplitude causes a warm nighttime bias and a cold daytime bias. The former prevents the establishment of stable stratified PBL conditions typical of fog formation, while the latter inhibits strong daytime mixing with delay in the triggering of local convection. The underlined problems are clearly related to an incorrect prediction of soil temperature.

### Table 2. Summary of the main characteristics of the experiments performed. Single-column experiments use the SVAT module TERRA forced by observations in single-point observational stations (1Dexp). The 3D model integrations are performed with COSMO using a different soil initialization strategy (3Dexp).

<table>
<thead>
<tr>
<th>Expt</th>
<th>Temperature</th>
<th>Soil moisture</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERRA forced by OBS (1Dexp)</td>
<td>TERRASPC</td>
<td>Observed profiles from TDR</td>
<td>Atmospheric forcing provided in terms of observed $T_{2m}$, RH$<em>{2m}$, rain rate, $u</em>{10m}$, downward SW radiation, and downward LW radiation at SPC</td>
</tr>
<tr>
<td></td>
<td>TERRACRB</td>
<td>Interpolated from IFS</td>
<td>Atmospheric forcing provided in terms of observed $T_{2m}$, RH$<em>{2m}$, rain rate, $u</em>{10m}$, downward SW radiation, and downward LW radiation at CarboEurope locations</td>
</tr>
<tr>
<td>TERRA forced by COSMO (3Dexp)</td>
<td>ECMWF Interpolated from IFS</td>
<td>Interpolated from IFS</td>
<td>Bottom layers from IFS; first initialization from IFS</td>
</tr>
<tr>
<td></td>
<td>COSMO</td>
<td>From the previous COSMO run</td>
<td>Bottom layers from IFS; first initialization from IFS</td>
</tr>
<tr>
<td></td>
<td>SMA</td>
<td>From the previous COSMO run</td>
<td>Bottom layers from IFS; first initialization from IFS</td>
</tr>
</tbody>
</table>

**FIG. 2.** Seasonal vs daily OLR at SPC (top) as measured by the CNR1 radiometer (Kipp and Zonen, Delft, the Netherlands) and (bottom) as predicted by the COSMO-I7 model. The data are averaged over 2 yr (2007-08).
and humidity. Moreover, the two diverse time scales (seasonal and daily) indicate that the errors are associated with deeper soil layers as well as the upper soil levels.

The September–November 2008 period chosen for verification was a typical autumn season with an intermittent series of heavy precipitation events and dry spells. Figure 3 shows the daily averaged observed precipitation and \( T_{2m} \) at San Pietro Capofiume. The first 10 days of October experienced no precipitation and have been marked as “dry periods.” Between 24 October and 2 November, several rainbands moved eastward from a low pressure minimum located in the middle of the Mediterranean Sea. Ten days of almost continuous precipitation were then recorded and have been marked as a “wet period.” Figures 4 and 5 show the 3-hourly 2-m temperature and relative humidity for the 10 days during the dry period and the wet period, as predicted by the set of full 3D integrations (3Dexp). As expected, the largest model discrepancy with the observations is at night during the dry period. These biases are exacerbated in the relative humidity due to the fact that the model is evidently also slightly dry. During dry conditions, the best performance during daytime is achieved by the SMA initialization, as one would expect. Under strong solar forcing, the screen-level temperature, used as a predictor, strongly depends on the soil moisture content. Soil moisture increments are calculated during daytime and this is when the scheme works at its best. If, as is the case with the COSMO model, the daytime bias has an opposite sign to the nighttime bias, the SMA approach will tend to further dry the soil, which is already too dry, exacerbating the nighttime bias. This is clearly visible, for example, at day 38 in Fig. 4 when the correction to the maximum predicted temperature at noon leads to a worsening of the minimum night temperature estimation. The limitation depicted is inherent in the methodology, which applies increments calculated at “noon” when the soil–atmosphere coupling is at its maximum in the whole assimilation window.

The wet period is characterized by smaller biases, with the exception of day 59, when all of the three model simulations missed completely the observed precipitation. It is worth noting that in this wet regime when the soil moisture is close to its field capacity value, the SMA experiment produces unrealistic warm increments.

![Fig. 3. Observed daily precipitation at SPC during SON 2008.](image)

![Fig. 4. Time series of 3-hourly 2-m temperature and RH for the 10 days during the dry period. Observations are provided by rain gauges while COSMO model predictions are from the three different initializations.](image)
This is a side effect produced by the missing strong coupling between the soil and the boundary atmospheric level. Indeed, care has to be taken regarding the applicability of a soil moisture scheme when the information content at the screen level is weak. Some thinning is therefore recommended to exclude synoptic situations with weak coupling between the soil and atmosphere and when horizontal coupling between neighboring grid points is weak (cloud free, weak advection) (Hess et al. 2008).

b. Soil temperature and humidity prediction

To understand how TERRA diagnoses the soil temperature and humidity evolution patterns, comparisons are performed locally with the TDR observations available at the SPC meteorological station. The 1Dexp simulation uses TERRA initialized by the observed TDR profiles in the levels where data were available and climatological values, otherwise. The SVAT model is then driven with a set of observed variables (specifically, $T_{2m}$, RH$_{2m}$, $u_{10m}$, RR, downwelling SW, and IR radiation). Figure 6 shows the time transect of soil moisture and temperature during the whole experimental period. The TDR measurements are available between 10- and 100-cm depths into the soil. Unfortunately, the deepest TDR sensor was faulty and the soil temperature is unavailable for the period. The most striking feature is the presence of a water reservoir at roughly 100 cm (and probably below), which is completely absent in the

FIG. 5. As in Fig. 4, but for the wet period.

FIG. 6. Evolution of soil moisture and temperature vertical profiles during the whole SON 2008 period, as predicted by TERRA forced by observed data. The comparison is performed at SPC, where a TDR instrument provides the observed soil moisture and temperature profiles at specified levels.
model forecast even if present in the initial fields used to start the forecast. The water reservoir is in the root zone where the most water is available for evapotranspiration. This is certainly due to the presence of an impermeable layer, which accumulates water and highlights how a poor description of soil pedology and lithology produces a misrepresentation of the model hydrological budget. In current operational SVAT models, the soil type is constant with respect to the soil depth; so in addition the soil texture associated with that soil type does not change. Vertical stratification of soil types is therefore not accounted for.

The soil evolution predicted by TERRA when fully coupled with the COSMO model is reported in Fig. 7. The ECMWF experiment shows, in general, an overestimation of soil moisture in the upper levels while the SMA tends to become too dry during the dry period (between days 30 and 40). The cause of this has already been discussed in the previous section and is due to the change in the bias between daytime, when soil moisture increments are calculated, and nighttime. After the first 10 days required for the open-loop experiment to reach its own equilibrium, the soil temperature prediction shows substantial changes when passing from the ECMWF to the COSMO and SMA experiments, with a deeper warm layer in the ECMWF initialization, which is not present in the other two cases. The groundwater detected by the TDR is not predicted by the coupled experiments. This deficiency is clearly independent of the accuracy with which the atmospheric model is capable of predicting the water sources (precipitation, dew, rime, snow). Nevertheless, the presence of a water reservoir can strongly influence the soil response to the atmospheric forcing. Figure 8 shows the composite analysis of precipitation and soil moisture in the first 10 cm at the San Pietro Capofiume station for the 1Dexp.

Figure 9 reports the same plot but for the fully coupled experiments (3Dexp). For each day for which the 24-h accumulated rain is greater than 1 mm (day 0), the soil moisture increments with respect to it are calculated for increasing and decreasing lags of up to 5 days. Soil moisture responds quickly to precipitation inputs. In fact, most of the soil moisture increments already occur at day 0 and the simulations are in agreement with the observations. After the rainy event the soil takes time to release excess water through evaporation or transpiration and, probably due to the impermeable layer or the slower percolation; at day +1 a positive soil moisture increment can still be observed. The soil's slow drying is nevertheless not represented in any of the experiments even, in the "perfect" scenario which is driven by observations (Fig. 8). The abrupt decrease of the soil water content affects, therefore, not only the absolute estimation of the soil humidity, but also its dynamical response to the atmospheric forcing. It has to be noted that the heat capacity of the soil, which controls the seasonal and daily cycles of the model net outgoing LW radiation, is a linear function of the soil water content. Since each of the 3Dexp runs overestimates $w_g$ in the first 10-cm depth and underestimates it in the root zone, heat capacity and thermal inertia are also overestimated in the upper levels and underestimated in the lower ones. As a consequence, the uppermost soil temperature cycle, which controls the diurnal variation, is delayed, while the lowermost soil temperature cycle, which controls the annual wave, is too advanced. We will see in the following section that this can have important consequences on the predictions of the daily evolution of the turbulent fluxes.
c. **Satellite validation**

A realistic spatial prediction of soil moisture can have important uses as, for example, in hydrological and climate applications. Soil moisture has a strong impact on climate simulations through a soil–atmosphere feedback process by which an increase in evapotranspiration directly or indirectly amplifies precipitation (Budyko 1974; Beljaars et al. 1996; Schär et al. 1999). It is therefore interesting to verify if any of the methods is actually able to produce a suitable description of the soil water content and of its evolution at the global scale. An extensive validation of soil moisture can only be performed using satellite-derived products, which in principle can provide the desired spatial coverage. Here, a tentative comparison is performed using the daily averaged soil moisture product from AMSR-E. There are a number of caveats nevertheless to bear in mind. Considering the nominal spatial resolution of only 25 km of the satellite dataset and the low spatial representativity of soil moisture measurements, this comparison can only be considered to be an indication of the distance between the model predictions and satellite-derived products. Moreover, AMSR-E soil humidity retrievals have already been shown to produce inaccurate estimates over highly vegetated areas (Crow et al. 2001). Finally, the comparison can only be performed for the uppermost soil level since no information is available at root zone depth. Figure 10 shows the cross correlation of the soil hydric content over the whole domain at different lag times between the observation dataset and the model prediction. The maximum correlation between the datasets occurs at day 0, which shows the right timing of the precipitation offset. The SMA experiment produces the best correlation to
the observations but only slightly improves the COSMO experiment. This general feature is nevertheless a very low correlation between the predicted \( w_g \) and that observed, with the ECMWF soil moisture analysis even being anticorrelated with respect to the AMSR-E product. Even if the accuracy of the AMSR-E dataset is in places questionable, this result also highlights the poor quality of NWP-derived soil moisture per se.

d. Turbulent flux prediction

Biases of up to \(-4\) K in the \( T_{2m} \) and of 20% in the RH\(_{2m}\) are primarily due to erroneous estimations of both turbulent surface fluxes, which are diagnosed by the TERRA scheme. Figure 11 shows the mean-day sensible and latent heat fluxes at one of the CarboEurope stations taken as an example averaged over 10 days during the dry and wet periods identified earlier. Since the other sites show very similar results, in the interest of brevity, they have not been included. On average, sensible heat flux is underestimated while latent heat flux is overestimated, nevertheless, during nighttime there is a substantial overestimation of both turbulent fluxes. The nighttime bias is especially marked in the ECMWF experiment as diagnosed by the excess in the outgoing longwave emission in Fig. 2. The soil–atmosphere interface is too warm and prevents the formation of nighttime stratified stable boundary layer conditions.

The diurnal cycle, which is shifted in the ECMWF experiment, is significantly improved by both the COSMO and SMA experiments. The flux prediction highlights the main danger of external interpolation from global models as a strategy for surface initialization. In fact, TERRA in its present implementation is very conductive during dry periods due to an approximation built into the scheme that uses a mean conductivity value between the field capacity and the permanent wilting point. Heat conductivity in the soil instead is usually predicted by empirical fits of observed data as a function of the soil moisture (Van Wijk and De Vries 1966; Benoit 1976) and Fig. 12 shows, for example, the empirical fit of the observed data of the heat conductivity of the soil and the prediction from the TERRA scheme. Its value is, therefore, underestimated if the soil is close to field capacity while it is overestimated if it is closer to the permanent wilting point. Therefore, during the dry period of the experiment, the deeper soil levels lose heat to the upper layers very efficiently, determining a warm bias in the soil temperature at the surface. Another consequence of this approximation is that during daytime the soil upper layers effectively act to store heat, which is then released only later in the evening. As a consequence, the outgoing longwave diurnal cycle is smoothed and shifted some hours forward in time, as observed in the diagnosis of the operational COSMO-I7 implementation (Fig. 2). This approximation is not present in the IFS SVAT scheme, which, during the autumn period therefore, has a much lower conductivity. As a result, a completely different profile of soil temperature is produced by this model, as also shown in Figs. 7 and 13, where the daily variation of the ground temperature is shown.

At two different model levels the three assimilation cycles provide different estimations. Despite the fact that SMA and COSMO have a more pronounced diurnal cycle, the most striking feature is the very high temperature predicted by the ECMWF experiment in the deeper ground level. The use of this value in the TERRA scheme probably causes the unrealistic nocturnal heating diagnosed in Fig. 14. Most of the improvements are achieved when passing from the ECMWF experiment to the COSMO one, since most of the differences are connected to the soil temperature prediction. The SMA initialization only adds a marginal benefit to the prediction of surface fluxes. This example also suggests that a correct initialization in the soil temperature can be more relevant than the subsequent correction of soil moisture, at least during dry conditions. In other words, when the soil is close to its wilting point, it is hard to estimate the dominating effect between thermal inertia and radiative cooling, and it is possible that simply running the forecast model can furnish the zero-order correction to the soil initialization problem. Near-surface variable biases are strongly dependent on the soil conditions. Schemes that by design only correct for errors on a selective basis
(i.e., when there is strong radiative coupling) can therefore only produce a “conditional” correction.

As most present SVAT schemes are based on ad hoc assumptions, this exercise shows how simple interpolation from a global to a regional scheme can be a poor strategy if the two soil models have different approximations. Bearing these caveats in mind, it is nevertheless important to assess the global performance of the three methods. Figure 14 shows the comparison between $H$ and $L_E$ at two CarboEurope locations for the three TERRA–COSMO coupled experiments as compared to the observations for the whole period. The fit across the data is performed locally. That is, for the fit at given point $x$, the fit is made using points in a neighborhood of $x$, weighted by their distance from $x$ following Cleveland et al. (1991). These diagnostics are calculated for the whole period, so different soil conditions are sampled. On average, the model underestimates both the sensible and latent heat during daytime and nighttime. It is clear that even on domain mean statistics the improvements produced by the COSMO experiment with respect to ECMWF interpolation largely

Fig. 11. (top) Comparison of model and observed mean day sensible and latent heat fluxes for the dry period under study. (bottom) As in the top panel, but for the wet period. Similar results have been found at the other CarboEurope sites (not shown).
offset the additional benefits of also performing a soil moisture analysis.

e. 2-m temperature and humidity prediction

Two-meter diagnostics are used worldwide as a metric to assess NWP model quality near the surface and as direct forecast products. Global temperature diagnostics are evaluated using the synop network over the whole COSMO-I7 domain and the daily bias for dry and dewpoint temperatures is reported in Fig. 15. The largest cold error in the ECMWF experiment occurs at noon and is strongly reduced by both the COSMO and SMA experiments. The dry humidity bias is almost constant during the day. The SMA experiment is the only one able to produce a reduction of the global bias.

5. Discussion and conclusions

Given the lack of any representative soil measurement network and the often insufficient knowledge of surface pedology, lithology, and vegetation characteristics, over the past few years soil analysis has often been considered a tuned lower boundary condition to drive, at its best, lower level atmospheric processes. The first and more obvious consequence of this approach is that soil outputs from atmospheric models are not appropriate for driving hydrological models, as the absolute soil moisture content strongly depends on the design of the soil model (Teuling et al. 2009). In this study we have outlined the effects on NWP accuracy, which directly stem from this. Different soil initialization methods have been compared in the quest for the best strategy to provide a soil analysis in regional models.

First, there are serious problems in trying to use soil analyses derived from a global model in a limited-area model if the two soil models are different in their underlining assumptions. While this is certainly a suitable option for the atmospheric fields, which to some extend represent the true atmospheric state, the method loses validity for the soil prognostic variables if, as is presently the case, they only represent parameters to be tuned to compensate for various model errors. It is clear that SVAT models with different characteristics will also adjust to different thermal and hydrological equilibria with little connection to reality. If the soil schemes of the global model and the regional one have varying assumptions, the consequences on the surface fluxes estimation can be severe especially under specific circumstances of dry conditions, limited horizontal advection, or high levels of cloud cover, to name a few examples. In our study we found, for example, that initializing the regional model COSMO SVAT module TERRA by interpolation from the global IFS model induces in COSMO a strong warm nighttime bias and a weakening of the diurnal cycle in both latent and

FIG. 12. Empirical fit of soil conductivity measurements as a function of soil moisture, as reported in Van Wijk and De Vries (1966) and Benoit (1976).

FIG. 13. Mean day temperature at two model levels as predicted by the three initialization schemes. The average is performed during the dry period at the Collelongo station.
sensible heat surface fluxes. The cause was identified as the different specification of the soil thermal conductivity between the two models. Thus, an appropriate approach (i.e., “tuned”) for the IFS model is apparently not optimal when incorporated into another model with different physics.

Due to the current configuration of the COSMO model and of its soil analysis, it appears that an open-loop configuration can avoid these imbalances and has an overall better level of performance on 2-m forecasts especially when the soil is close to its wilting point. This condition is particularly challenging since higher amplitudes in soil heating during daytime and cooling during night are expected.

The correct prediction of the soil vertical temperature profile was found to be fundamental. Soil temperatures profiles that are at least in balance with the soil scheme produced a zero-order correction to surface flux estimations. Any subsequent improvement in the soil moisture estimation, performed, for example, using indirect measurements such as $T_{2m}$, only adds a marginal benefit. This apparently striking result is justified by the design of current soil moisture schemes, which, using near-surface observations as predictors for soil moisture increments, assume that the atmosphere contains information pertaining to the state of the soil moisture. However, forecast errors of atmospheric temperature and humidity do not always contain useful information. For instance, during
rain, at nighttime, and with low solar insolation, this method is likely to fail.

A possible, and already proposed solution (Hess et al. 2008), would be a selective application of soil moisture increments only on those cases for which the underlying hypotheses are rigorously verified. This is nevertheless again an ad hoc solution that would not provide a substantial improvement on the absolute quality of the soil analysis. The use of other observations such as precipitation and satellite-derived surface soil moisture will certainly help to mitigate these deficiencies in the future. In the short term a substantial benefit can nevertheless arise from including temperature as a control variable in the assimilation scheme.

The COSMO model is used by a wide community, including many European weather forecasting centers; the ECMWF model is one of the most frequently used to initialize regional NWP systems; and TERRA represents the state of the art in SVAT schemes, implying a wider application of the study. It is nevertheless important to highlight that to generalize these conclusions an intercomparison exercise employing several NWP models coupled to different SVAT schemes would be a logical development of this research. As a first step in this direction, the Short-Range Numerical Weather Prediction Programme (SRNWP) of the Network of European Meteorological Services (EUMETNET) has already promoted the collection of verification datasets especially devoted to the measurement of surface variables (information on the C-SRNWP data collection can be found online at http://www.cosmo-model.org/srnwp/content/default.htm). This data pool, when employed to drive offline simulations, will provide more detailed information on the baseline performance of current SVAT models and of SVAT plus atmosphere coupled systems. The ongoing effort should identify where and possibly how improvements to the SVAT models can be made, which may ultimately lead to improved soil analyses (Jacobs et al. 2008).

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