Status and needs for reanalysis: Land-Surface Processes

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1. Motivation

For a long time, land-atmosphere interactions over Europe have received comparatively little attention. While the importance of the land-surface schemes for the surface climate has clearly been demonstrated (e.g. Viterbo and Beljaars 1995), several studies have indicated that state-of-the-art general circulation models do not present any significant soil moisture-precipitation or soil moisture-temperature coupling over Europe (e.g. Koster et al. 2004). This would imply that initial soil-moisture data should merely play a minor role in a predictive framework.

Recent studies have also highlighted that land-surface schemes have made significant progress in representing surface fluxes of latent and sensible heat (see e.g. Betts 2004). However, it is important to note that the representation of the fluxes in a medium-range forecasting context does not test the longer-term (seasonal and interannual) properties of the coupled land-atmosphere system. Indeed, in the latter perspective it is imperative to represent the seasonal cycle of water storage in the terrestrial system. The importance of this cycle for the surface energy balance in semi-arid regions is well established: The drying of the soil during the summer season implies that net radiation must be balanced without an important contribution from evapotranspiration. However, until recently there was little awareness that this sequence of processes could be relevant on a European scale.

The record heatwave of the summer 2003 (Schär et al. 2004, Grazzini et al. 2004) has demonstrated that the aforementioned factors may be more than an element of the Mediterranean semi-arid climate. Studies using analysis data (Black et al. 2004) as well as direct observations (Zaitchik et al 2006) have highlighted the role played by pronounced continental-scale drying. Studies using global and regional models demonstrate that spring soil moisture anomalies have strongly contributed to the excess temperatures observed (Ferranti and Viterbo 2006, Fischer et al. 2006). Indeed, it has been suggested that European heatwaves may develop in absence of pronounced anomalies in surface net radiation, and that the anomalous partition of the surface fluxes in drought years may positively feed back to the upper-level circulation and thereby serve to sustain and enhance heatwave episodes (Fischer et al. 2006).

As the seasonal hydrological cycle strongly affects temperature extremes, it must also affect interannual surface temperature variability. This hypothesis has been investigated in several recent studies that have also addressed the role of climate change on European summer temperature variability. Climate models indicate that the interannual variability might considerably amplify in response to increased greenhouse gas concentrations (Schär et al. 2004). Intercomparison of climate models suggests that this effect is present in many or most global and regional climate change scenarios (Giorgi and Bi 2005, Vidale et al. 2006, Seneviratne et al. 2006). As regards the mechanism behind the amplification of interannual temperature variations, a recent modeling study – using simulations with a decoupled land-atmosphere system – demonstrates that most of this increase is due to land-atmosphere coupling (Seneviratne et al. 2006).

These recent results serve to stress the important role played by land-atmosphere feedbacks and surface hydrology in Europe, for the whole range of time scales involved (i.e. short and medium-range weather forecasting, seasonal forecasting, climate variability and climate change). An improved representation of the continental-scale hydrological cycle is thus highly desirable, both in modeling and data-assimilation systems.

2. The water balance in the ERA-40 reanalysis

Here we explore the quality of the water balance in the 40-year ECMWF reanalysis, and try to consider both its atmospheric and terrestrial branches. Combining the two branches yields a simple equation that links mean changes in terrestrial plus atmospheric water storage (averaged over large-scale river basins) with atmospheric moisture flux convergence and terrestrial runoff. Combining moisture convergence from atmospheric reanalysis with conventional runoff observations thus allows diagnosing terrestrial water storage variations (that reflect changes in soil moisture, ground water, surface water and snow storage). The so diagnosed variations may be integrated to obtain absolute estimates of terrestrial water storage. Of particular interest is the total amplitude of the seasonal cycle of terrestrial water storage, which is one of the key uncertainties in climate models and land-surface schemes.

The basic ideas behind the water balance approach have previously been pioneered using raw radiosonde data (e.g. Alestalo 1983) or earlier reanalyses (e.g. Trenbert and Guillemot 1995, Oki et al. 1995). Using ERA-40 data, the methodology has been revisited and applied to a series of mid-latitude river basins with areas between 50,000 and 3 million km^2 (Seneviratne 2004, Hirschi et al. 2006). The main results of these studies are:

1) For a domain covering the Illinois river basin (~200,000 km2), a detailed validation is feasible due to the availability of high-quality in-situ surface observations of soil moisture, ground water and snow cover. Validation shows that the seasonal cycle of terrestrial water storage (TWS) variations is well captured by the diagnostic approach, while the amplitude is slightly underestimated. Even monthly and interannual TWS variations correlate well with observations. This agreement implies that the ERA-40 atmospheric convergence data are of high quality and allow extending the approach to smaller scales than feasible with previous reanalysis products.

2) Depending upon the size of the river basin, there are long-term imbalances that imply drifts in the integrated TWS estimates. These imbalances derive from systematic biases in ERA-40 convergence data and/or in runoff observations. For river basins smaller than $2{\cdot}10^5$ km^2, the imbalances are mostly smaller than 0.5 mm/d. To remove this time-dependent drift in the diagnosed TWS data, a simple high-pass filter can be applied. In general the biases are not constant in time, but artificial inhomogeneities may result from changes in the global observing system used in the reanalysis. For some river basins these inhomogeneities are large. For instance, ERA-40 precipitation in Central Asia shows a pronounced increase in spring and summer precipitation around 1995 (see Schiemann et al. 2006), which may be related to the ERA-40 biases in tropical precipitation.

3) Intercomparison of diagnosed TWS variations against the corresponding internal ERA-40 variables (i.e., the sum of soil moisture and snow cover variations) shows considerable discrepancies. The terrestrial ERA-40 variables strongly underestimate the seasonal cycle in most mid-latitude river basins. The damping of the seasonal cycle is likely attributable to assimilation increments in soil water, which systematically supply water in summer and remove water in winter and early spring.

The derived diagnostic water balance data has been applied in several recent studies for the validation of regional climate models (Van den Hurk et al. 2005, Hirschi et al. 2006, work in progress) for process studies of the summer 2003 (Fischer et al. 2006) and for intercomparisons against GRACE estimates of TWS variations (Andersen et al. 2005, work in progress).

3. Outlook

The discussion in the previous section indicates that the ERA-40 atmospheric branch of the water cycle is much better represented than its terrestrial counterpart. This is not surprising and derives from two factors. First, a large set of atmospheric data enters the atmospheric assimilation and serves to constrain the atmospheric fluxes, while virtually no independent data is used that could constrain the terrestrial water balance. Indeed, ERA-40 soil moisture data are in essence obtained from a land-surface module driven by ERA-40 atmospheric forcing (including model-generated precipitation) and adjusted in response to assimilation increments in surface temperature and humidity (following the pioneering work of Mahfouf 1991). Second, the assimilation cycle does not contain any constraints that would try to minimize violations of water substance conservation. More specifically, the assimilation system may systematically add or remove soil moisture in the course of the seasonal cycle. In principle, the lack of conservation is typical for the whole assimilation systems (atmospheric conservation laws are not enforced either), but it appears that the violations of water conservation in the land-surface scheme are much larger in relative terms.

Improving on the current system will require (i) a more realistic representation of land-surface processes, (ii) use of additional observational data, and (iii) improved representation of water substance conservation. As regards the observational base, a series of satellite products (including gravimetric estimates of terrestrial water storage and microwave data of soil moisture) is available. However, it will be important to efficiently use the available precipitation data, as precipitation is the main driver of the terrestrial branch of the hydrological cycle.

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