

Improved scenario prediction by using coupled hydrological and atmospheric models

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Abstract The hydrological model MIKE SHE, provided with a new energy-based land-surface module, has been dynamically coupled to the non-hydrostatic model ARPS. Using data from the FIFE experiment, both the land-surface module and a 1-D coupling of the models have been validated. Subsequently, a hypothetical scenario, where grassland is turned into agriculture, was investigated by running the model system in both uncoupled and coupled mode. It was found that the uncoupled system significantly over-predicts the change in evapotranspiration caused by the land-use change in comparison to the coupled model results, which emphasizes the importance of taking feedback effects at the land surface into account.

Key words land-surface modelling; coupled models; land-atmosphere feedback

INTRODUCTION

Currently our understanding of the nature of hydrological change is at an early stage. The prediction of the effects of future change (and validation of these predictions) has barely begun (Beven, 2000). Furthermore, predictions of the hydrological impact of climate and land-use changes are subject to considerable uncertainty. In the context of climate change and land-use change, process-based models are still the most promising approach. The alternative of trying to predict changes in catchment-scale bulk parameters that represent the interaction of different processes does not seem viable.

Modelling the effects of land-use change or climate change on the hydrological cycle requires a proper understanding of the water and energy exchange between the atmosphere and the land surface. In particular, the two-way coupling between the two systems can have a significant impact on the hydrological predictions for land-use and climate change. Traditionally, the hydrological impacts of climate change have been based on driving hydrological models with the output of regional climate models. There is an inherent contradiction in this approach as climate models include their own hydrological model component. Furthermore, while most of these hydrological components describe the canopy and root zone in great detail, the interactions between groundwater, the root zone, and surface water are normally neglected, which may lead to inaccurate model predictions in areas where the groundwater and surface water are closely connected (Overgaard *et al.*, 2006; Chen & Hu, 2004; York *et al.*, 2002). However, more importantly, the feedback between the two systems is neglected in this approach. Previous studies have shown that this lack of feedback may potentially lead

to errors when dealing with changes in hydrological and land-surface properties (Jacobs & de Bruin, 1992; Brubacker & Entekhabi, 1996; Kim & Entekhabi, 1998).

The aim of this paper is to present a framework for the investigations of the interactions and feedback mechanisms between the terrestrial component of the hydrological cycle and the atmosphere, and to investigate the significance of feedback on the impact of land-use and climate change studies.

DYNAMIC COUPLING OF THE HYDROLOGICAL AND ATMOSPHERIC MODELS

To provide comprehensive hydrological modelling while addressing to the need to include the feedback mechanisms between the atmosphere and the land surface, a dynamically coupled hydrological and atmospheric model system has been developed. Such a coupled system provides a unique framework for investigation of land surface–atmosphere interactions at hydrological scales. A comprehensive hydrological modelling system, describing the terrestrial component of the hydrological cycle, MIKE SHE, has been modified to allow coupling to a local-scale non-hydrostatic meteorological model, ARPS. The coupling exploits the European Open Modelling Interface and Environment (OpenMI) to link the two models.

The atmospheric model

The Advanced Regional Prediction System (ARPS) developed at the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma was selected to represent the atmospheric component in the coupled modelling system. ARPS is a three-dimensional non-hydrostatic model formulated in terrain-following coordinates. The governing equations of ARPS include conservation equations for momentum, heat, mass, water (vapour, liquid, and ice), sub-grid-scale turbulent kinetic energy, and the state equation for moist air. A detailed description of ARPS is given by Xue *et al.* (2000, 2001).

The hydrological model

The distributed, hydrological model MIKE SHE was selected to represent the hydrological component in the coupled modelling system. MIKE SHE is an integrated hydrological model that simulates all the major components of the land phase of the hydrological cycle, as well as the mutual interactions between the components (Abbott *et al.*, 1986a,b; Graham & Butts, 2006). It is based on a discretized horizontal network of grid squares covering the model domain. In each surface grid square the model solves for land-surface fluxes, overland flow and infiltration. The unsaturated zone is represented by a number of computational nodes in the vertical direction within each grid square. Here the unsaturated flow is described by the one-dimensional Richards' equation. The groundwater component of MIKE SHE provides a fully three-

dimensional simulation of flow in a heterogeneous aquifer allowing for shifting between confined and unconfined conditions. It uses an iterative coupling procedure to compute the soil moisture and water table dynamics near the interface between the saturated and unsaturated zone.

Dynamic coupling

The coupling between the atmospheric model ARPS and the hydrological model occurs through the land-surface module (LSM). To achieve a consistent coupling, a new energy-based LSM was implemented in MIKE SHE (Overgaard, 2005). This energy-based evapotranspiration component consists of a two-layer soil-canopy system of the Shuttleworth-Wallace type (Shuttleworth & Wallace, 1985) with some modifications to treat ponded water on the soil surface and water intercepted by vegetation (Overgaard, 2005). A single, semi-transparent canopy layer is located above the substrate, such that the only way for heat and moisture to enter or leave the substrate layer is through the canopy layer; see Fig. 1.

In this framework, the land-surface model in the ARPS model is not used. Instead at each time-step, ARPS provides MIKE SHE with all relevant climate parameters, i.e. precipitation, net long and short wave radiation, the humidity, and wind speed; see Fig. 2. The MIKE SHE LSM calculates the latent heat flux, the sensible heat flux and the momentum flux. These fluxes are returned to ARPS, where they provide the lower boundary condition for the next time-step (explicit coupling procedure). While such a

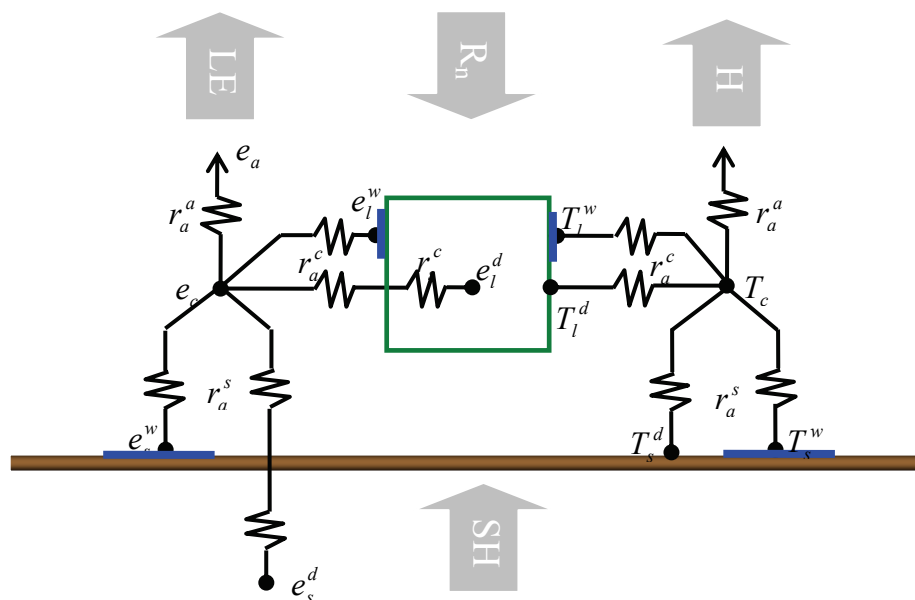


Fig. 1 The land-surface model (LSM) implemented in MIKE SHE. The box represents a leaf. Temperatures and humidity at the wet and dry (superscript w and d , respectively) surfaces (subscript l : leaf surface; s : soil surface; c : mean canopy level) are denoted T and e . The transport of latent heat (LE) and sensible heat (H) is illustrated on the left- and right-hand side of the figure, respectively. R_n is net radiation, and SH is soil heat flux. The resistances are denoted r_n .

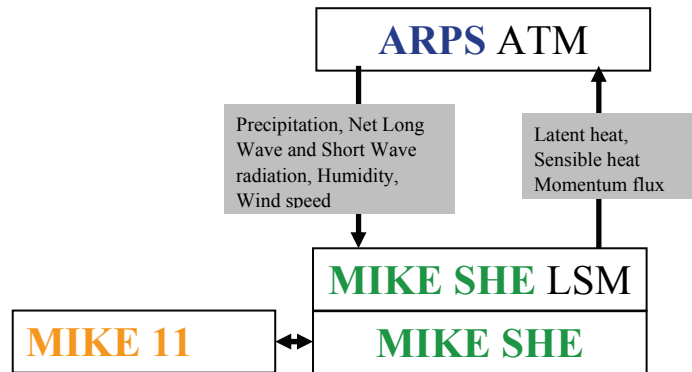


Fig. 2 Dynamic coupling of MIKE SHE and ARPS via the MIKE SHE land-surface model (LSM).

coupled model system probably will be too computationally expensive to be used for long simulations of large domains, it has the potential to provide important insight on the interactions between the land surface and atmosphere in areas where the parameterizations of the land-surface models implemented in atmospheric models do not. This model structure allows MIKE SHE to be used in both coupled and uncoupled mode.

The exchange of data needed to couple MIKE SHE and ARPS is carried out using the OpenMI protocol. The Open Modelling Interface and Environment (OpenMI) is a set of standardized interfaces and classes that have been developed within the EU Fifth Framework project, HarmonIT, (<http://www.openmi.org>). OpenMI allows the models to communicate at run-time, across differences in time step, and spatial resolution, although in this case the atmospheric and hydrological models use the same surface grid size. OpenMI was developed in an attempt to provide a widely accepted unified method designed to simplify linking of hydrology-related models, both legacy codes and new ones (Gregersen *et al.*, 2005). It is based on direct access of the model at run-time, thus not using files for data exchange. To achieve the above dynamic coupling both models were made OpenMI compliant by developing the appropriate interfaces. These interfaces allow for run-time and time step control to an outside entity and provide access to internal state variables and parameters.

Evaluation of the land-surface model

Prior to using the LSM in the coupled modelling system it was validated against both column and distributed field data, (Overgaard, 2005). The distributed evaluation of the model was carried out for a 10 km² agricultural field site in western Denmark where eddy covariance measurements and remote sensing based estimates of latent heat surface fluxes were available (Boegh *et al.*, 2004). Initially, the model was evaluated at the plot scale using measured fluxes of latent heat. Field data from four flux-sites representing three of the four vegetation classes identified in the area were used to evaluate the model at the plot scale. The model was found to perform reasonably well at all flux-sites in two distinct evaluation periods (Fig. 3).

A comparison between simulated latent heat fluxes and latent heat fluxes derived from satellite remote sensing showed that the model accurately simulated the spatial

distribution, as well as area mean. An underestimation of the small-scale variability did, however, give rise to some deviations at the pixel scale, see Fig. 4. Overgaard (2005) presents a more detailed evaluation using additional field data sets. This includes verification of the coupled atmospheric–hydrological framework using measured fluxes together with concurrent radiosonde data from the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) (Sellers *et al.*, 1992).

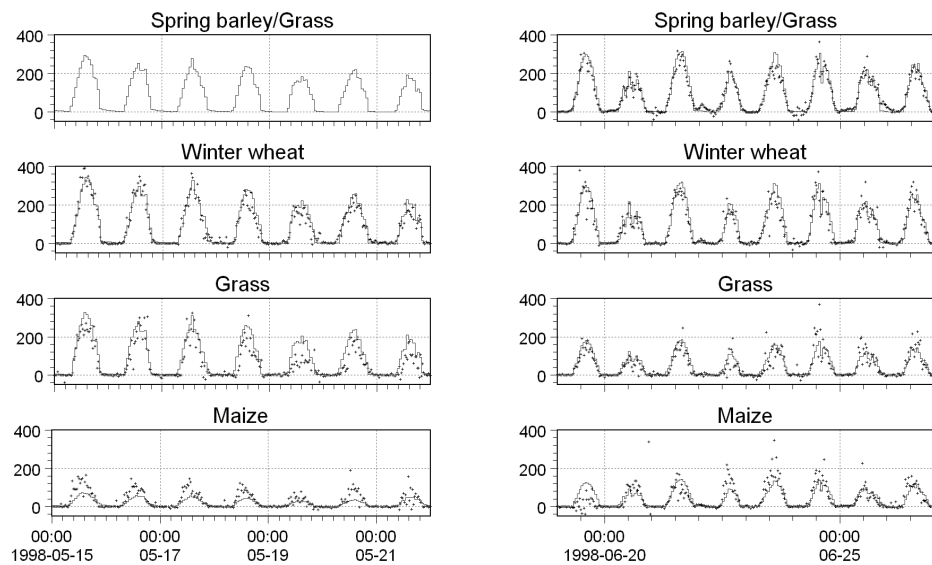


Fig. 3 Result of the plot-scale evaluation. The line is the simulated fluxes (W m^{-2}) and the dots indicate 30-minute averages of measured fluxes. No observations were available for the barley field in May.

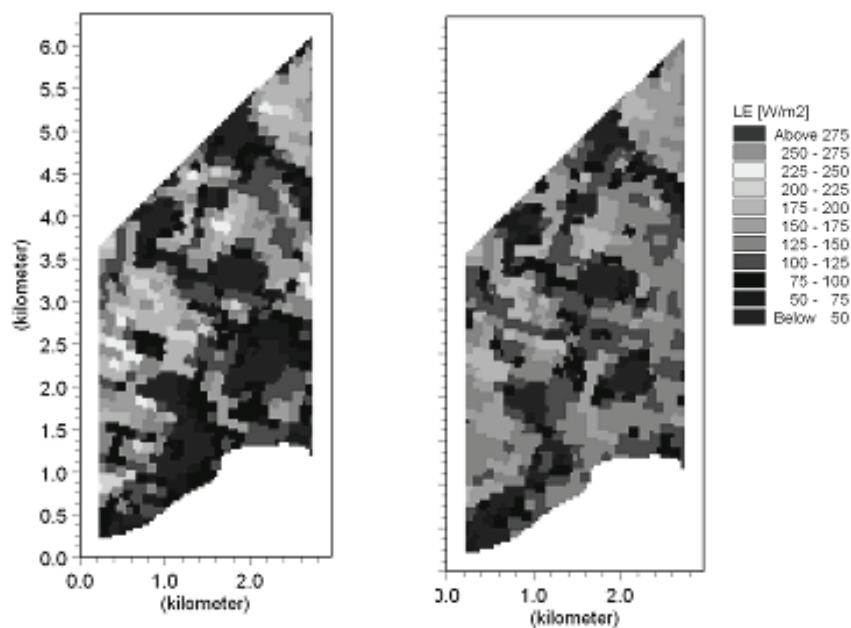


Fig. 4 Latent heat flux derived from remote sensing (left), simulated latent heat flux (right).

LAND-USE CHANGE IN COUPLED AND UNCOUPLED SYSTEMS

To explore the impact of using coupled and uncoupled models, the above framework was applied to a hypothetical scenario, where a grassland area is converted to agriculture using climatic conditions from the FIFE experiment. To evaluate the impact of replacing grassland with agriculture, the model parameters corresponding to grassland are replaced with parameters corresponding to agriculture (Table 1). An uncoupled agriculture scenario simulation is carried out using the climate time series extracted from the coupled grassland scenario. A fully coupled agriculture scenario is carried out as well. Any differences between the simulated impacts will be due to feedback.

The sum of the errors of soil evaporation and transpiration makes up the error of the simulated impact of total evapotranspiration, which is approximately 16 W m^{-2} (Fig. 5). Relative to the simulated coupled impact on total evapotranspiration (40 W m^{-2}), this is approximately 40%. Hence, the impact of replacing grassland by agriculture is overestimated by 40%, if atmospheric feedback is not taken into consideration.

Table 1 Land-surface parameters used in MIKE SHE. The parameters for grassland are used for the evaluation, and parameters for agriculture are used in the scenario simulations.

	Unit	Grassland	Agriculture
Unstressed stomata resistance	s m^{-1}	110	90
Leaf width	m	0.02	0.02
Soil surface roughness	m	0.03	0.03
Root depth	m	0.5	0.8
Leaf area index: 6 June	–	1.7	4
11 July	–	1.1	–
Vegetation height	m	0.5	0.8
Albedo	–	0.23	0.23
Light extinction coefficient	–	0.7	0.7

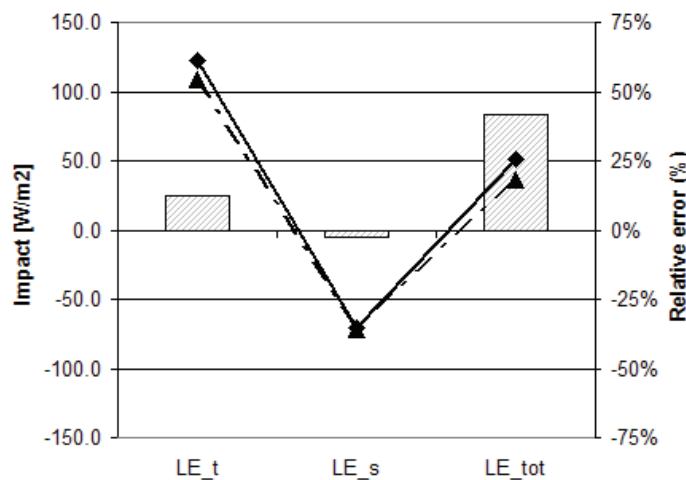


Fig. 5 Effect of feedback in a grassland-to-agriculture scenario simulation (LE_t: transpiration; LE_s: soil evaporation; LE_{tot}: total evapotranspiration). The triangles and diamonds indicate the coupled and uncoupled impact, respectively, in absolute values (left axis). The relative error is indicated by bars (right axis).

CONCLUSIONS

A dynamically coupled modelling framework has been developed to investigate the effects of feedback between the atmosphere and land surface on changes in the hydrological system, including land-use and climate change. The framework consists of the dynamic coupling of an atmospheric model ARPS and a distributed hydrological model MIKE SHE sharing a common land-surface model (LSM). The OpenMI protocol is used to perform this coupling. The LSM was satisfactorily evaluated against field data including both eddy correlation data at the plot scale and remote sensing data at the landscape scale. This tool has been used to investigate the effect of feedback on predictions of the impact of land-use change on evapotranspiration processes. Significant errors may arise by not taking account of feedback. In a hypothetical grassland-to-agriculture scenario, it was shown that neglecting atmospheric feedback led to a 40% overestimation of the change in evapotranspiration.

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