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## **THE APPLICATION OF A DYNAMIC OPENMI COUPLING BETWEEN A REGIONAL CLIMATE MODEL AND A DISTRIBUTED SURFACE WATER-GROUNDWATER MODEL**

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To support climate adaptation measures for water resources, we have developed and evaluated a dynamic coupling between a comprehensive distributed hydrological modelling system, MIKE SHE, and a regional climate modelling system, HIRHAM. The coupled model enables two-way interaction between the atmosphere and the groundwater via the soil and land surface and can represent the lateral movement of water in both the surface and subsurface and their interactions as well as human interventions. The coupled model is applied to one-way and two-way coupled simulations for a managed groundwater-dominated catchment, the Skjern River, Denmark. The 2500 km<sup>2</sup> catchment model is embedded in a meso-scale (4000 km x 2800 km) climate modelling domain. By using the ERA Interim reanalysis as boundary conditions the coupling performance is evaluated against measurements of both climatic and hydrological variables, including local measurements of energy fluxes. The results presented here suggest that there may be important differences in the simulated water balances for this catchment created by introducing an alternative hydrological model into the RCM.

### **INRODUCTION**

The interactions between the atmosphere, the land surface and the subsurface hydrology play a key role in ensuring the sustainable development of water resources and terrestrial ecosystems. The evaluation of climate adaptation measures requires the ability to reliably simulate the impact of different anthropogenic effects on both the surface water and the groundwater under projections of future climatic conditions and variability. Groundwater is a widespread source of high-quality freshwater accounting for roughly a third of all freshwater withdrawals [1]. In

many cases, groundwater via baseflow maintains surface water flows during periods of low rainfall, ensuring both water supply and ecosystem health. However, the interaction between climate and groundwater are often neglected in climate models and climate assessment [2]. Few studies have investigated how groundwater systems will respond to climate change coupled with human activities.

While the hydrological modelling components within both global and regional climate models are continually evolving in many cases the groundwater is neglected or treated in a simplified fashion using conceptual models [3]. Several groups are addressing this gap but there are only a few instances in the literature where numerical solutions of the physics of groundwater flow are coupled to climate or atmospheric models and these are often applied to short periods of a few days or to hypothetical cases [4,5].

In this study we present the development and operational application of a fully dynamic coupling between two existing modelling systems; a comprehensive distributed hydrological modelling system, MIKE SHE, and a regional climate modelling system, HIRHAM. The coupled model enables two-way interaction between the atmosphere and the groundwater via the river and land surface and can represent the lateral movement of water in both the surface and subsurface. This means that feedbacks between the atmosphere and the land surface and between the groundwater and the atmosphere via the soil can be accounted for. In addition, by using a higher resolution in the hydrological model compared to the climate modelling grid the sub-grid variability in the energy fluxes due to shallow groundwater table effects and soil heterogeneity can be captured.

## **COUPLING OF THE CLIMATE AND HYDROLOGICAL MODELS**

The dynamical coupling between the regional climate model HIRHAM and MIKE SHE is performed using an energy-based SVAT (Soil Vegetation Atmosphere Transport) model [6,7] as a component within the MIKE SHE modelling framework [8].

### **Regional climate model - HIRHAM**

HIRHAM is a regional atmospheric climate modelling system [9] used at the Danish Meteorological Institute (DMI). This RCM was originally developed in collaboration between DMI, Royal Netherlands Meteorological Institute (KNMI) and Max-Planck Institute of Meteorology (MPI). HIRHAM combines atmospheric dynamics from the HIRLAM High Resolution Limited Area Model and the physical parameterization schemes of the ECHAM atmospheric general circulation model including its land surface scheme (LSM).

The current DMI-HIRHAM model code [9], HIRHAM5, is based on the HIRLAM (7.0) and ECHAM (5.2.02) codes with a number of extensions for, for example, integration into the high performance computing environment at DMI. HIRHAM has been widely used in regional climate modelling studies including the recent EU project ENSEMBLES [10] and its performance has been evaluated for a wide range of climatic conditions from the Arctic [11] to Africa [12].

### **Distributed surface water-groundwater model – MIKE SHE**

MIKE SHE is a process-based hydrological modelling system for representing flow, solute transport, water quality and other processes related to the land phase of the hydrological cycle at the catchment scale [8]. It represents the major flow processes including evapotranspiration, overland flow, unsaturated flow, groundwater flow, and channel flows as well as their

interactions including surface water/groundwater interactions [13,14]. MIKE SHE includes comprehensive river and channel modelling to represent flooding [15] and wetlands [16]. MIKE SHE has been applied in numerous hydrological studies over a wide range of climates and hydrological regimes [13] and is the modelling tool for the Danish national water resources model [17].

### Soil Vegetation Atmosphere Transport component

This work builds on the development and application of an energy-based SVAT (land-surface) model [6,7] as a component within MIKE SHE. This component is based on the two-layer soil–canopy system with some modifications to treat ponded water on the soil surface and water intercepted by vegetation. The model is referred to here as MIKE SHE SWET and has been applied and evaluated at plot scale, landscape scale and catchment scale [18].

### Skjern River catchment

The study area is the 2500 km<sup>2</sup> Skjern river catchment located on the western coast of the Jutland peninsula of Denmark, Figure 1. The catchment is predominantly agricultural with the following land use distribution: grain and corn (55%), grass (30%), forest (7%), heath (5%), urban (2%) and other (1%). Since 2007 the catchment has served as a hydrological observatory with comprehensive field data have been obtained through a broad range of often novel measurement techniques including eddy-correlation flux measurements [19]. The distributed hydrological model was constructed using 11 computational groundwater layers and horizontal discretization into 500 m grids. The soil data have been obtained from 250 m distributed soil maps and the land use data have been obtained from agricultural statistics. The distributed hydrological model and calibration approach are described in Larsen et al. [19].

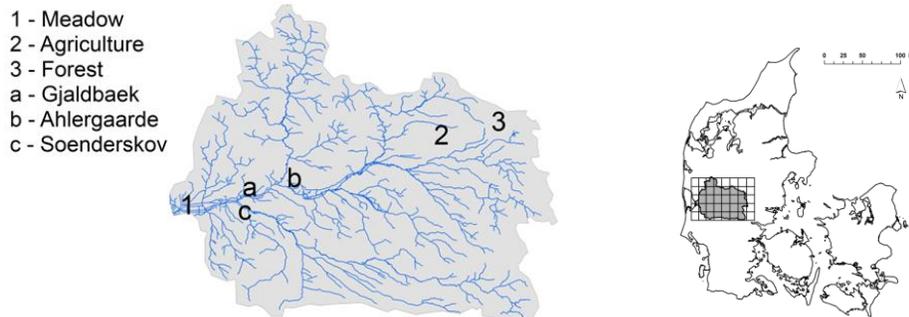


Figure 1. The locations of the Skjern river catchment, the river network and point observations of discharge and energy fluxes.

### Coupling methodology

The coupling of MIKE SHE and HIRHAM is based on the Open Modelling Interface (OpenMI) developed within the water modelling community. The standard is however more general, enabling linkages between different kinds of models developed in different scientific disciplines as demonstrated here. The OpenMI Standard defines an interface that allows time-dependent models that are running simultaneously to communicate at each time step across differences in time step, spatial resolution, and discretization [20].

While MIKE SHE is fully compliant to the OpenMI standard, a number of extensions and modifications had to be implemented into the HIRHAM code to simulate OpenMI compliancy for the purposes of the present study. The data exchange is restricted to a limited number of variables necessary to describe the exchange of water and energy between the two models. Specifically, the latent heat flux (evapotranspiration) and surface temperature are simulated by the MIKE SHE SWET on request by HIRHAM, where they replace values calculated in its LSM, see Figure 2. HIRHAM calculates the radiation and sensible heat components of the energy balance. The simulated air temperature, precipitation, wind speed, relative humidity global radiation and air pressure simulated by HIRHAM, within the shared domain, are passed to MIKE SHE SWET.

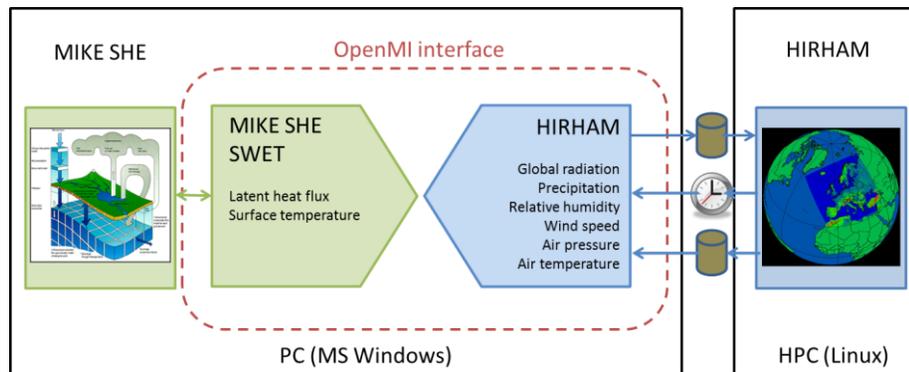


Figure 2. Schematic of the HIRHAM-MIKE SHE coupling approach. The MIKE SHE code runs on a PC (MS Windows) together with OpenMI. The HIRHAM code runs on a massively parallelized Cray XT5 high performance computer system (HPC).

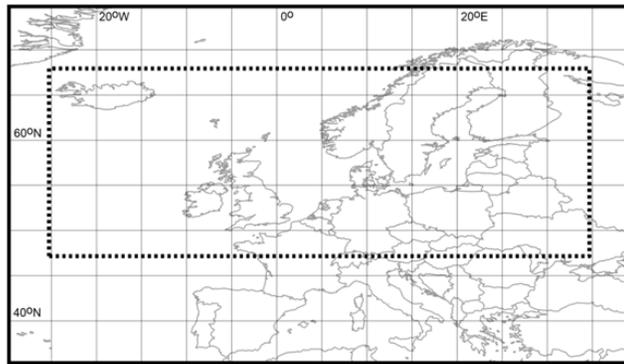


Figure 3. The HIRHAM RCM model domain (dashed line) used in this study.

The HIRHAM set-up uses the parameters derived in Larsen et al. [21]. Boundary forcings were based on ERA-Interim reanalysis data applied every 6 hours. The RCM simulations were performed using a resolution of 11 km with regular grids and the time step used was 2 minutes but data is exchanged between the models at 30 min intervals. The HIRHAM model domain size, location and resolution were selected based on a systematic investigation of model performance [21] and covers an area of approximately 4000 km x 2800 km from Iceland in the north-west to Ukraine in the south-east. The domain is extended towards the west of the Skjern catchment to where the majority of weather systems originate, Figure 3.

## COUPLED SIMULATION RESULTS

The results presented here are derived from simulations for an entire year, covering the period May 1 2009 to April 30 2010. Detailed comparisons have been made between a number of climate variables (global radiation, surface pressure, wind speed, relative humidity, temperature and precipitation) and hydrological variables (discharge, evapotranspiration, sensible heat flux and soil heat flux) elsewhere [22,23]. In this paper we present selected results focusing on the temporal and spatial behaviour of evapotranspiration (latent heat flux) at the observation points (Figure 4) and across the catchment (Figures 5 & 6).

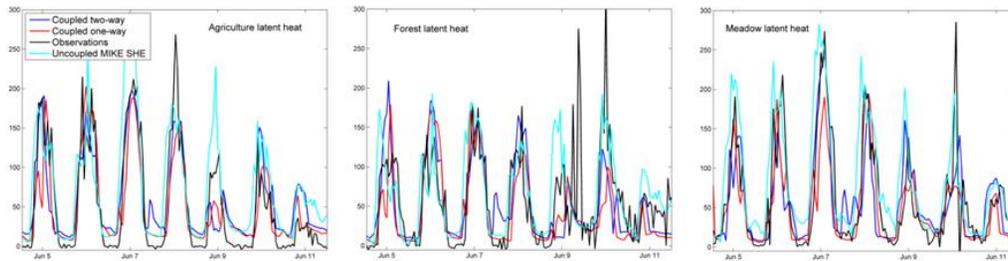


Figure 4. Comparison of measured and simulated latent heat (evapotranspiration) for a one week period in June 2009. The curves show the 1) eddy flux measurements 2) simulations from the distributed model driven by observed climate variables [uncoupled MIKE SHE] and the coupled model where 3) the hydrological model is driven by the climate variables simulated by HIRHAM [coupled one-way] and 4) fully dynamic [coupled two-way] coupling between MIKE SHE and HIRHAM.

The uncoupled MIKE SHE simulations were performed in a conventional manner, using a calibrated hydrological model [21] driven by measured climate variables. The results show that the SVAT model (MIKE SHE SWET) is able to capture satisfactorily the temporal behaviour of the evapotranspiration at the point scale for the 3 sites (agriculture, forest and meadow). In the coupled simulations, the climate variables simulated by HIRHAM are used to drive the calibrated MIKE SHE model. It is most interesting to compare the results of the one-way coupling with the two-way coupling where there is feedback between the groundwater system and the atmosphere. While there are some differences in both dynamics and levels of evapotranspiration (ET) for this period these are not particularly significant. The uncoupled MIKE SHE simulations of ET are generally higher for this period. The results shown, however, cover only a limited period. It is more appropriate in the context of climate change to examine the seasonal differences in evapotranspiration, Figure 5. The MIKE SHE-HIRHAM model simulates consistently higher levels of ET than the HIRHAM RCM. Both however generally simulate higher levels during the summer (June-August).

There are several possible explanations for these differences. The most important differences between the ways evapotranspiration is simulated in the two cases shown in Figure 5 are 1) the HIRHAM LSM is replaced by the MIKE SHE SWET 2) the spatial resolution used for MIKE SHE SWET is higher and 3) the effects of shallow groundwater are included. This is highlighted in Figure 6 which shows the importance of downstream riparian areas in determining the level and spatial distribution of evapotranspiration. In these areas the groundwater is close to the surface and can supply water to evaporation. This effect is expected to be more important in the summer where evapotranspiration might be limited by water supply.

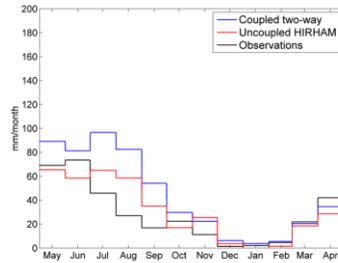


Figure 5. Comparison of measured evapotranspiration with simulations using 1) the uncoupled HIRHAM RCM and 2) the coupled MIKE SHE- HIRHAM model with two-way coupling.

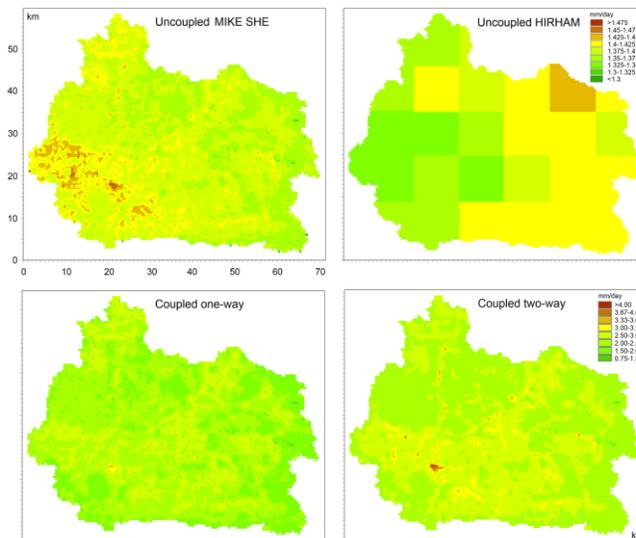


Figure 6. The simulated spatial distribution of mean daily evapotranspiration for the period June 5-11, 2009, see Figure 4.

The uncoupled MIKE SHE simulations driven by observed climate data exhibit generally higher fluxes as was also seen in Figure 4. While the spatial patterns of the one way and two way coupling are similar, higher evaporation rates are found for the two-way coupling. While groundwater is present in both these cases, there is feedback to the atmosphere from groundwater in the two-way coupling of HIRHAM and MIKE SHE.

## CONCLUSIONS

In this paper we present the development of a fully dynamic two-way coupling between a comprehensive hydrological modelling system MIKE SHE, and a regional climate modelling system, HIRHAM together with some results of the evaluation of this new tool for a managed groundwater-dominated catchment, the Skjern River, Denmark. By embedding the 2500 km<sup>2</sup> catchment within a regional scale climate modelling domain it is possible to represent both the meso-scale weather producing phenomena including ocean-atmosphere interactions that are important for Denmark. At the same time by coupling HIRHAM to MIKE SHE using a higher resolution we are able to include the interaction between groundwater and the atmosphere and

are better able to capture the variability particularly due shallow groundwater levels in the riparian areas. The evaluations presented here for evapotranspiration indicate that the coupled model provides plausible results when compared to point observations. Compared to the original RCM, the coupled model simulates a different spatial distribution and larger evapotranspiration (latent heat) fluxes during the summer. Further work is required to properly account for these differences. However, these results suggest that there may be important differences in the simulated water balances for this catchment created by introducing an alternative hydrological model into the RCM.

#### ACKNOWLEDGEMENTS

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