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IMPLEMENTING EARTH OBSERVATION AND ADVANCED SATELLITE BASED ATMOSPHERIC SOUNDERS FOR WATER RESOURCE AND CLIMATE MODELLING

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ABSTRACT

This paper discusses preliminary remote sensing (MODIS) based hydrological modelling results for the Danish island Sjælland (7330 km^2) in relation to project objectives and methodologies of a new research project "Implementing Earth observation and advanced satellite based atmospheric sounders for effective land surface representation in water resource modeling" (2009-2012). The purpose of the new research project is to develop remote sensing based model tools capable of quantifying the relative effects of site-specific land use change and climate variability at different spatial scales. For this purpose, a) internal catchment processes will be studied using a Distributed Temperature Sensing (DTS) system, b) Earth observations will be used to upscale from field to regional scales, and c) at the largest scale, satellite based atmospheric sounders and meso-scale climate modelling will be used to study and verify the modelling of land surface hydrology processes.

1. INTRODUCTION

Climate, land cover and land use are changing, thereby imposing changes to the hydrological cycle which are affecting the access to water resources and increasing the frequency of extreme hydrological events, such as floods and droughts. Apart from directly affecting surface runoff and soil water percolation processes, land cover changes (with a side of > 10 km) also impact the local and meso-scale climate by changing the energy balance of the land surface [1]. In order to predict future freshwater availability and the vulnerability of ecosystems and society to floods and droughts, hydrological model tools are needed that are capable of accurately representing climate, land use and land cover at different spatial scales.

Important research tasks of the research project "Implementing Earth observation and advanced satellite based atmospheric sounders for water resource and climate modelling" are to

a) analyze and model internal catchment processes governing cumulative water inflow (including groundwater inflow) from the land surface to the stream using a Distributed Temperature Sensing (DTS) system (a thin fiber optic cable > 1500 m) and other spatial instream data
b) implement Earth observations (ie. MERIS, MODIS) of the land surface for modeling water and energy fluxes of Sjælland (Fig. 1)
c) develop methods for effective land surface hydrology representation at different spatial scales,
d) analyze and verify impacts of effective land surface representation using next-generation meso-scale climate modelling (WRF model) and satellite based atmospheric sounders (ie. AIRS, IASI) for Sjælland, and to
e) quantify the sensitivity of the new and verified models to land use change and climate variability

Figure 1. Land use map of Denmark (56°N, 10 °E). The island of Sjælland (7330 km^2) is located in the box. Source: AIS, NERI/Århus University.

The implementation of new advanced data technologies capable of representing different scales in hydrology, such as the distributed temperature sensing (DTS)

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system, multi-scale Earth observations, and satellite based large-scale atmospheric properties, will provide new valuable insight into the functioning and modelling of hydro-meteorological processes at multiple spatial scales.

2. LAND SURFACE HYDROLOGICAL MODELLING

There are two main approaches to model catchment hydrology: 1) the upward (spatial-deterministic) approach which consists of model cascades with each of the models representing sub-processes, and the downward approach which is based on the analysis of long runoff time series data. In the upward approach, impacts of land cover and land use depend heavily on interactions with site-specific smaller-scale soil and biophysical properties [2], whereas users of the downward approach find that land cover effects are strongly controlled by the flow paths in catchment systems that differ in their time scales and connectivity [3]. Even though there exist a good theoretical understanding of potential flow mechanisms in both the upward and downward approaches, knowledge of the mechanisms (flow parameters) in any one catchment is normally established through model calibration based on fitting simulations to discharge data recorded at the basin outlet. Problems are that estimation of many different internal catchment parameters are required, and that the effective (calibrated) model parameters are scale-dependent [4]. Despite the use of multiple Earth observations and successful matching with stream discharge data, the internal processes in the catchment may therefore not be modeled correctly [5, 6]. This means that predictions beyond the range of available observations can be highly dependent on model parameters and model structure which, in turn, are sensitive to the chosen calibration methods and model types [7, 8].

The implementation of new advanced data technologies capable of representing different scales in hydrology, such as the distributed temperature sensing (DTS) system, multi-scale Earth observations, and satellite based large-scale atmospheric properties, can provide new valuable insight into the functioning and modeling of catchment systems which is needed to advance the development of remote sensing based spatial water management tools.

2.1. Spatial catchment processes

The DTS system uses a long (1-2 km) thin fiber optic cable to provide spatial water temperature data with a resolution of 1 m. This technique, which was just recently introduced in hydrology, allows direct monitoring and quantification of groundwater inflow to streams [6, 9]. In combination with GIS (Geographical Information Systems) techniques and the use of spatial data (incl Earth observation) and hydrological modelling, downstream data (flow and temperature) can be analyzed and modeled in relation to the cumulative inputs from upstream contributing land areas (numerous subcatchments) at many scales

2.2. Satellite based atmospheric sounding

At the largest scales, new advanced satellite based atmospheric sounders (AIRS, IASI) provide very detailed high-quality vertical atmospheric profiles of air temperature, humidity, CO_2, and more which can be used to evaluate land surface hydrology processes and their feedback effects on climate. Because of the fast response time of atmospheric processes (much faster than groundwater responses), and the strong dependency of the energy balance on evapotranspiration and soil moisture availability, these measurements constitute a new opportunity to evaluate and verify the modelling of large-scale land surface hydrological processes. Impacts of land surface drying has a strong impact on convective processes and will be reflected in the atmospheric satellite data as 3-D changes in air temperature and air humidity.

3. MESO-SCALE CLIMATE MODELLING

Land surface heterogeneity and soil moisture gradients have a significant influence on atmospheric processes such as the development of convection and precipitation [10], and the important impact of land cover changes on climate development was also clearly demonstrated [1, 11]. However, a large portion of these processes occur on spatial scales too fine to be resolved by most climate models [12]. In order to relate the smaller-scale land surface processes to the atmospheric properties and fluxes at larger spatial scale, effective land surface hydrology schemes must be developed which can be used in meso-scale climate models to improve climate predictions [10, 13].

Numerical weather prediction (NWP) models are initialized and updated by assimilating radiosonde data representing atmospheric properties from the land surface to the top of the atmosphere, thereby indirectly representing land surface impacts. With the launch of new satellites, atmospheric infrared sounders are becoming available (AIRS in 2002; IASI in 2006) which are using thousands of channels to provide high vertical resolution radiosonde-like data (ie. air pressure, temperature, humidity, CO_2). These data are capable of resolving small-scale vertical features and to fill in spatial coverage of synoptic radiosonde measurements. Even though NWP models are not capable of fully exploiting the large amount of information contained in AIRS and IASI data [14], assimilation of AIRS in NWPs, such as the ECMWF system, improve weather predictions [15]. The data are considered to be of very high quality, and a very good comparison was also obtained between AIRS and synoptic radiosonde data in Denmark [16]. Indeed these data provide new opportunities to analyze and verify larger-scale land surface hydrology impacts on the atmospheric boundary layer development.

4. METHODOLOGY

In order to develop efficient land surface schemes for hydro-meteorological modelling, multiple spatial resolution Earth observations are used to upscale from plot to regional scale [17]. In addition, fiber-optical temperature cables will be used to identify and quantify the lateral inflows of groundwater to streams in a selected representative catchment. This new data technology will be used to improve the model representation of catchment hydrological processes in relation to the upstream land uses and soil types, thereby optimizing the use of Earth observations and other spatial data for predicting land use impacts on hydrological and climate processes. Important components of land surface hydrological models are seen in Fig. 2.

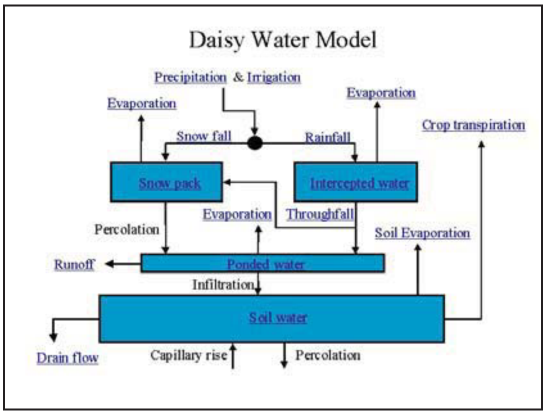

Figure 2. Components of the Land surface hydrology module of the Daisy model (http://code.google.com/p/daisy-model/)

At the larger scale (Sjælland), the land surface hydrological processes will be modeled and results evaluated through their impacts on the observed vertical distribution of atmospheric properties (ie. water vapour and temperature). For this purpose satellite based atmospheric sounding will be used, and meso-scale climate modelling (WRF model) will be applied using effective surface schemes developed for large spatial scale application [13]. The WRF model (Weather Research and Forecasting model) is a highly flexible next-generation meso-scale numerical weather prediction system which is applicable across scales ranging from meters to thousands of kilometers. It allows for system extensibility and is designed to serve both operational forecasting and atmospheric research needs.

4.1. Study area

The multi-scale land surface hydro-meteorological modelling experiment is carried out for Sjælland (Fig. 1). Sjælland (7330 km^2) is the main island of Denmark upon which the capital Copenhagen is also located. The island is characterized by multiple land cover types including agricultural fields (73 %), forest regions (14 %) and urban regions (10 %).

5. SOME RESULTS

5.1. Land surface hydrological modelling

A land surface hydrological model (using the Daisy model) was set up for Sjælland using multiple spatial resolution satellite images (Landsat TM and EOS/MODIS) and other spatial data sets describing the spatial distribution of climate inputs, soils (3 horizons) and lower boundary conditions [17]. A semivariogram analysis of high spatial resolution (30 m) Landsat NDVI (Normalized difference Vegetation Index) suggested that the lowest spatial resolution to adequately represent spatial vegetation dynamics at Sjælland is 500 m. The use of MODIS 500 m resolution NDVI data (Fig. 3) to represent Leaf Area Index (LAI) every 16^{th} day in land surface hydrological modelling were tested by comparing the spatial water balance model simulations with the higher spatial resolution predictions of a Landsat TM based model setup.

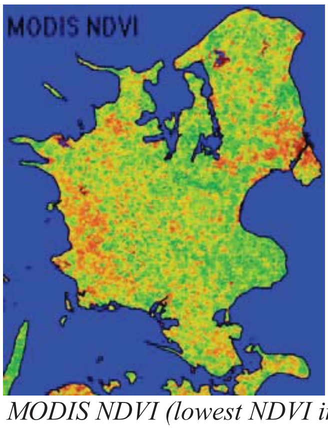

Figure 3. MODIS NDVI (lowest NDVI in red and highest NDVI in green colours). May 2001, Sjælland.

The impact of spatial resolution on water balance model results was assessed for a smaller representative catchment at Sjælland (Fig. 4). A good agreement was found which confirmed the use of 500 m spatial resolution for physically based land surface hydrological modelling at Sjælland [17]. Results also indicated that weather transition periods from humid to dry conditions require high temporal resolution climate input data to improve model accuracy.

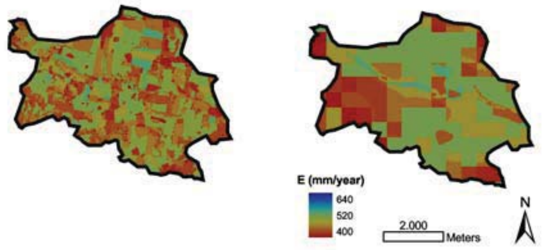

Figure 4. Simulated annual evapotranspirationfor the Skensved catchment in 2001 using Landsat TM (left) and EOS/MODIS data (right) respectively.

Model simulations for all Sjælland (500 m resolution) were evaluated using discharge data from 30 catchments [17], and the spatial simulations were also compared with predictions of the National Water Resource Model [18] which is a coupled surface water-ground water model based on the MIKE SHE code. In general, the remote sensing based runoff simulations were in good agreement with the fast-flow component of the observed stream flow. The fast-flowing stream component is insensitive to groundwater abstraction and most sensitive to the spatial land surface representation. In order to include groundwater dynamics and their interaction with stream flow in hydrological modelling, it is necessary to use a spatially distributed hydrological model like MIKE SHE.

The remote sensing based simulations (Fig. 5) generally provided much larger spatial variability in water balance predictions than those of the National Water Resource Model which is not using remote sensing data. Despite *seasonal* differences in net precipitation inputs (precipitation minus evapotranspiration) between the 2 different models, there was a good agreement in the simulated *annual* water balances for Sjælland [20]. The findings suggest that better understanding and a more consistent modelling of internal spatial catchment processes is required.

In the coming years, the DTS system will be applied to study and verify the modelling of internal catchment processes by assessing the groundwater inflow to streams. The DTS system uses a long (2 km) thin fiber optic cable to provide spatial water temperature data with a resolution of 1 m. This technique, which was just recently introduced in hydrology, allows direct monitoring (and quantification) of groundwater inflow to streams [6, 9]. In combination with GIS (Geographical Information Systems) techniques and the use of Earth observations and hydrological modelling, downstream data (flow and temperature) will be analyzed and modeled in relation to the cumulative inputs from upstream contributing land areas (numerous subcatchments) at many scales.

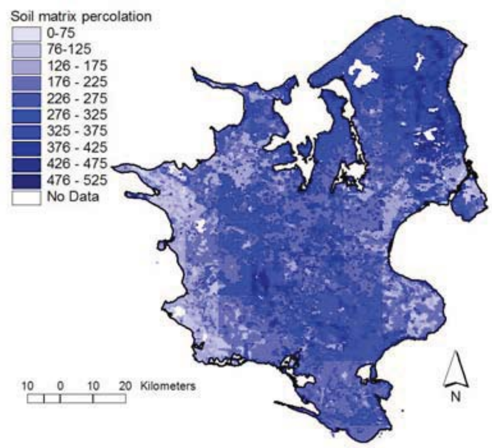

Figure 5. Remote sensing based simulation of annual soil water percolation to groundwater (mm/year), Sjælland 2001.

5.2. Meso-scale climate modelling

The coupled meso-scale model WRF-ARW (Weather Research and Forecasting – Advanced Research WRF) will be used in the project, such that the feedbacks from the land surface on the atmospheric boundary layer dynamics can be assessed. A new and more sophisticated surface scheme will be implemented, and in addition, we will focus on the effect of land surface sub-grid scale heterogeneity on parameters such as the aerodynamic roughness, the LAI and the albedo. The WRF model is currently set up and running for Sjælland using a 2 km spatial resolution. Several techniques will be used for verification of the modeling results: 1) using daily atmospheric sounders from satellites (AIRS, IASI), and 2) using land-based remote sensing technique for wind profile (with a LiDAR) and atmospheric boundary layer height estimation (with a ceilometer). The quality of sounding data will be extracted and compared with radiosonde data locally available at Sjælland. Preliminary results on selected days show an excellent agreement for air temperature profiles and a good agreement for atmospheric profiles of precipitable water content (16).

6. CONCLUSION

The development of model tools applicable at different spatial scales is particularly important to assess relative impacts of climate and land use change. Integrating physically based distributed hydrological models and energy based water temperature simulations will extend the capability of hydrological models to use Earth observations for predicting climate and land use (incl. groundwater abstraction) impacts on water resources.

Furthermore, land surface spatial aggregation techniques developed within the project for large scale evaluation are also needed to evaluate hydrological feedback effects on climate.

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