HYACINTS

Hydrological Modelling for Assessing Climate Change Impacts at different Scales (09-063180-DSF)

FINAL REPORT

March 2014

1. Scientific Achievements

Project components and publications

HYACINTS has developed new methodologies and tools for assessing climate change impacts on water resources at different spatial scales. The main project components were:

- Coupling of DMI's regional climate model HIRHAM and DHI hydrological modelling system MIKE SHE and conversion of GEUS' national water resources model to run in the coupled system aiming at reducing simulation uncertainty ([1], [4], [5], [6], [10], [11], [14]).
- Development of methodologies for using a spatially refined model grid in parts of a model domain where more detailed descriptions of hydrogeological conditions are required ([21], [22]). An SME project on digital geological modelling was associated to this component ([2]).
- Development of methodologies for estimating precipitation and evapotranspiration from satellite data, particularly aimed at application in data poor regions in the world ([7], [12], [13]).
- Assessment of uncertainty propagation in the calculation chain (emission scenarios → global climate models → regional climate models → downscaling/bias correction methods → hydrological models → hydrological change) and identification dominating sources of uncertainty in projections of climate change impacts on water resources ([3], [8], [9], [15], [16], [17], [18], [19], [20]).

Coupled HIRHAM – MIKE SHE coupling and application to Denmark

The most challenging and risky HYACINTS research task was to establish a coupling between the HIRHAM regional climate model and the MIKE SHE hydrological modelling system. This coupling was successfully developed. HIRHAM is executed at DMI's linux based supercomputer, while MIKE SHE is run on a MS Windows PC (Figure 1). The two different software platforms make the coupling technically complicated, but the coupling approach allows the two codes to be otherwise almost unchanged. The coupling was tested with HIRHAM being run on an 8,000 km x 5,000 km domain while the MIKE SHE replaces HIRHAM's land surface scheme over the 2,500 km^2 Skjern Å catchment.

Previous studies have either been confined to surface water hydrological models (Goodall et al., 2013; Zabel and Mauser, 2013) or, in case of inclusion of groundwater, been limited to relatively small domains (up to a few hundred km^2) and short periods (a few days) both for the climate and the hydrological models (Maxwell et al., 2007; Kollet and Maxwell, 2008; Rihani et al., 2010; Maxwell et al., 2011). In this respect our results are novel by including an integrated groundwater-surface water hydrological model in the coupled climate-hydrology model simulation over several years and a large area. Based on model tests for one year periods, it is too early to conclude to which extent a coupled climate-hydrology model like HIRHAM-MIKE SHE will be able to reduce biases and uncertainties in climate model simulations. But we now have a powerful tool that is very suitable for such analyses.

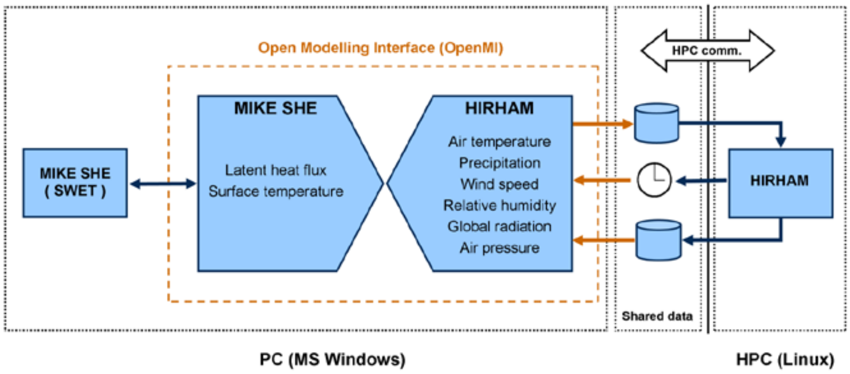

Figure 1. Schematic of the HIRHAM-MIKE SHE coupling. Both model codes have been extended with OpenMI Linkable Components, exposing selected variables to each other within the OpenMI platform. The MIKE SHE code runs on the same PC (MS Windows) as the OpenMI software, whereas the HIRHAM code runs on a massively parallelized Cray XT5 high performance computer system (HPC).

Scaling of hydrological models – refined grid modelling

The novelty and main achievement of the HYACINTS research in this field has been investigations with two different methodologies for using refined grid (telescopic mesh) around model sub-areas of particular interest and tests of the models in highly complex geologies. The two different methodologies were based on i) a new MODFLOW Local Grid Refinement module (MODFLOW-LGR) developed by Mehl and Hill (2007); and ii) a coupling of the MIKE SHE surface water processes (Butts and Graham, 2008) to a finite element groundwater code FEFLOW (Diersch, 2002).

The MODFLOW-LGR method was tested against a hypothetical setup with complex geology and on Aarhus Water's well field in Ristrup, which is an area with buried valleys and complex geology. The HYACINTS results suggest that the LGR routine can have so long execution times for models with complex geologies that the benefit of using it often may disappear. Furthermore, results show that decisions on how to design the grid refinement may have substantial implications on results when applied for projecting climate change impacts on groundwater.

The MIKE SHE-FEFLOW coupling was developed and has been successfully tested against a sequence of hypothetical cases of surface water-groundwater interactions for which there are known analytical/numerical solutions. (Yamagata et al., 2012a,b). The current testing this technology for catchment-scale set-ups indicate that care is needed to match the surface water and groundwater grid sizes to properly capture the interactions between surface water processes and the time steps when there is strong dynamical interaction such as during surface water flooding The strength of this approach is that we extend the capabilities of both models to address new problems such as the effect of climate change on saltwater intrusion or radioactive waste disposal.

The digital geological software tools being developed in the associated SME project includes new and improved functionalities to handle complex geologies fully three-dimensionally in a manner that makes it easy to use the geological information in groundwater modelling.

Application in data sparse areas

HYACINTS research has produced new knowledge on use of satellite data for estimating precipitation and evapotranspiration and use of these data in hydrological modelling. The methods have been successfully tested on cases from Western Africa and China.

Uncertainty

HYACINTS has in a number of case studies assessed how uncertainties in climate modelling interact with uncertainties in geological and hydrological modelling when projecting climate change impacts on water resources (Figure 2). The analysis of uncertainties on climate models was based on results from the ENSEMBLES project that is available through a database hosted by DMI. Daily climate data from 11 combinations of global General Circulation Models (GCMs) and Regional Climate Models (RCMs) were downloaded for the entire Denmark for the period 1950 – 2100. The data were made ready for use in hydrological models by two different bias correction methods. The 11 different climate model projections were then imposed on six different geological conceptualisations for the Lejre area (HOFOR well fields, water supply to Copenhagen, 465 km^2) and on three different refined grids for the Ristrup area (Aarhus Water well field, 18 km^2).

From the case studies it was concluded that the inherent natural climate variability together with climate models constitute the dominating sources of uncertainty for precipitation projections, while uncertainty due to bias correction methods typically amounts to 10-20% of the climate model uncertainty. When propagating climate uncertainty through hydrological models the climate uncertainty may, depending on the projection variable and the site specific regime, be amplified or reduced and become larger or smaller than the uncertainty originating from the hydrological model. We found in our two cases that climate uncertainty dominates over geological uncertainty and model uncertainties related to numerical discretization and geological resolution for projection of groundwater heads and streamflow, while the opposite is the case for projection of well field capture zones.

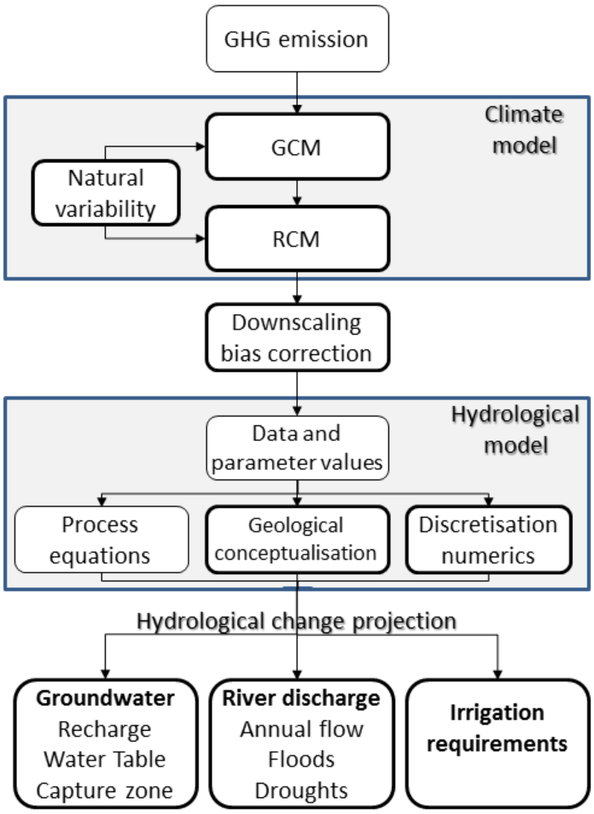

Figure 2. The uncertainty cascade from emission scenarios to hydrological change projections. The elements studied in HYACINTS are marked with bold frames.

2. Commercial and Societal Results

HYACINTS results have already been applied in many societal contexts. This is particularly the case with the downscaled climate projection data and the uncertainty assessments of climate change impacts. Key examples of applications by HYACINTS partners include:

- The assessment of climate change impacts on groundwater conditions carried out for Koordineringsenheden for Klimatilpasning (KFT) and now available at www.klimatilpasning.dk provided by the Nature Agency and aiming at being used by municipalities for screening purposes (Henriksen et al., 2012). A follow-up study included assessment of changes in extreme river discharges under future climate conditions (Henriksen et al., 2013). The assessment tool has supported municipalities to establish climate change adaptation plans, a task that had to be completed by the end of 2013.
- Climate proofing of the design of the Silkeborg motorway (Troldborg et al., 2011).
- IDA's climate change adaptation strategy for Denmark (Mark et al., 2012).
- The climate basis for the INTERREG projects CLIWAT and BaltCiCa as well as projects for municipalities and regions.
- Advisory functions to the Ministry of Environment.

The new knowledge generated in HYACINTS will strengthen the specialised consultancy services within the water sector both in Denmark and internationally that is offered by the HYACINTS partners ALECTIA and DHI. In addition, the two new coupling technologies developed for DHI's software will contribute to new functionalities of DHI's modelling software. The HIRHAM-MIKE SHE coupling is a valuable and innovative research tool being used by Danish researchers but is not, as yet, fully mature as a commercial product. The MIKE SHE – FEFLOW coupling is already being applied commercially as a consultancy tool and potential software product in DHI consultancy projects in Sweden and Singapore.

In addition, the downscaled climate projection data are today being used by consulting companies in a variety of water resources projects.

HYACINTS results have been disseminated via many articles in Danish popular scientific journals such as Vand & Jord as well as public presentations at a large number of professional meetings. A key message promoted throughout the HYACINTS period has been that climate change adaptation requires a paradigm shift compared to traditional water management in order to suitably handle the major uncertainties in climate change projections. Advocacy for such paradigm shift requires many years of continuous oral and written presentations and discussions supplemented by new illustrative examples. HYACINTS results have been crucial and very instrumental in this respect.

3. Research Education

Four PhD students have successfully completed their studies. Three of the candidates are today employed as postdocs at AU, RUC and DTU, while the fourth candidate works in the consulting company Envidan. A fifth PhD student (at GRAS) terminated his study after a year, and the remaining resources were successfully converted to a postdoc position at GRAS.

Four postdocs received research training of varying lengths (between 1 and 2½ years). The two postdocs from private companies (ALECTIA and GRAS) are today still employed at the same company, while the two postdocs at DMI and GEUS today are employed at permanent positions at DTU and the Danish Road Agency. The two postdocs with 2½ and 2 years duration (ALECTIA and GRAS) conducted separate research tasks and each contributed with two first-authored papers plus some co-authored papers, while the two postdocs with shorter durations (GEUS, DMI) primarily had tasks supporting PhD students in the HIRHAM- MIKE SHE coupling and contributed with co-authored papers.

HYACINTS arranged and co-sponsored one PhD course: “Assessment and Propagation of Uncertainty in Spatially Distributed Environmental Modelling” held at GEUS in September 2009 with 25 participants. The external teachers were Dr. Gerard BM Heuvelink, Wageningen University, The Netherlands and Dr. James D Brown, National Weather Service, NOAA, USA. In addition, HYACINTS contributed to the PhD course “Adaptive management in relation to climate change” held at University of Copenhagen in August 2011 with 15 participants.

4. Collaboration

HYACINTS has resulted in strengthened and new collaborations both nationally and internationally. *Nationally*, the collaboration between the partners has been substantially strengthened. This has materialised in new tools and joint publications. The mutual learning between the climate modelling community and the water resources community (both researchers and practitioners) has been very significant during the six years project period. The importance of this intangible knowledge dissemination cannot be overestimated.

Internationally, HYACINTS partners have exploited and strengthened existing collaborations. In addition new collaborations have been established:

- China: Peking University (Prof Chunmiao Zheng) and Institute of Remote Sensing Application, Chinese Academy of Science (Dr. Bingfang Wu) related to testing of remote sensing technologies and integrated hydrological modelling. (GEUS, ALECTIA, GRAS).
- Germany: University of Bonn (Prof Clemens Simmer) and Forschnungszentrum Jülich (Prof Stefan Kollet) related to coupled climate hydrology modelling (GEUS, University of Copenhagen, DMI, DHI).
- USA: US Geological Survey (Dr. Steffen W Mehl) related to the refined grid modelling (AU).
- SKB – Swedish Nuclear Fuel and Waste Management Co concerning surface water and groundwater interactions in radioactive waste disposal (DHI).

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