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Discussions

Results from a full coupling of the HIRHAM regional climate model and the MIKE SHE hydrological model for a Danish catchment

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Abstract

In recent years research on the coupling of existing regional climate models and hydrology/land surface models has emerged. A major challenge in this emerging research field is the computational interaction between the models. In this study we present results from a full two-way coupling of the HIRHAM regional climate model over a 4000 km × 2800 km domain in 11 km resolution and the combined MIKE SHE-SWET hydrology and land surface models over the 2500 km^2 Skjern river catchment. A total of 26 one-year runs were performed to assess the influence of the data transfer interval (DTI) between the two models and the internal HIRHAM model variability of ten variables. In general, the coupled model simulations exhibit less accurate performance than the uncoupled simulations which is to be expected as both models prior to this study have been individually refined or calibrated to reproduce observations. Four of six output variables from HIRHAM, precipitation, relative humidity, wind speed and air temperature, showed statistically significant improvements in RMSE with a reduced DTI as evaluated in the range of 12–120 min. For these four variables the perturbation induced HIRHAM variability was shown to correspond to 47 % of the RMSE improvement when using a DTI of 120 min compared to a DTI of 12 min and the variability resulted in large ranges in simulated precipitation. Also, the DTI was shown to substantially affect computation time. The MIKE SHE energy flux and discharge output variables experienced little impact from the DTI.

1 Introduction

On a global scale the future climate is expected to experience a general warming due to the anthropogenic greenhouse effect, which will result in an increase in the frequency of extreme events such as heavy precipitation events and droughts (Solomon et al., 2007; Stocker et al., 2013). From a management perspective, knowledge of the future climate conditions in terms of both trends and extremes is essential. The ability to

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achieve realistic projections of both present and future climate depends largely on the ability to numerically simulate the processes of hydrology, energy and ecology and the related interactions between the atmosphere, the land surface and the subsurface. These processes are unambiguously tied together (Rodriguez-Iturbe, 2000; Sridhar et al., 2002; Overgaard et al., 2006; Wang et al., 2012), their interaction is highly complex (Pan and Mahrt, 1987; Pahl-Wostl, 2007; Bates et al., 2008) and further, it is paramount that the resulting prediction uncertainty must be taken into account (Giorgi, 2005; Collins et al., 2012).

The effort of modelling a combination of atmospheric, surface and subsurface processes has been performed in a broad range of studies over the years utilizing still more complex model codes. By coupling vegetation and hydrology processes using the Lund–Potsdam–Jena vegetation model (LPJ GUESS), Gerten et al. (2004) obtain more realistic global reproductions of evapotranspiration and runoff compared to stand-alone hydrological models, and argue that the coupling of processes can account for rising CO_2 levels not simulated when using hydrological models alone. Similarly Yan et al. (2012) successfully simulate global evapotranspiration with an energy based vegetation and water balance land surface model. Several studies deal with the influence of surface hydrology, vegetation and land use change on atmospheric processes. Seneviratne et al. (2006) show land-atmosphere coupling processes to be of significant importance to temperature variability for 2070–2099. Zeng et al. (2003) highlight the considerable influence of land surface temperature and moisture heterogeneities on simulated RegCM2 regional climate model sensible (H) and latent heat (LE) fluxes as well as the precipitation pattern, and Cui et al. (2006) show a substantial change in ECHAM5 general circulation model predictions as a consequence of projected changes in vegetation. Harding et al. (2011) puts these issues in a wider climate change perspective, identifying a grand challenge to the hydrological and climate communities to both reduce uncertainties related to how these findings impinges our understanding of the future and how to communicate them to a wider society.

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Current climate models include only a simplistic surface and subsurface description of hydrology processes and similarly hydrological models generally include atmospheric processes in a surface-near layer in the scale of meters. More recent studies have therefore focused on the effort to combine model codes each representing a component in the total simulation of atmospheric, land surface and subsurface processes as well as ocean processes. Of these, a few studies have focused on coupling a climate model with a combined land surface and hydrological model. Maxwell et al. (2007) study the coupling of the ARPS mesoscale atmospheric model (Xue et al., 2000, 2001) and the ParFlow hydrological model (Kollet and Maxwell, 2008) for a 36 h period over the Little Washita catchment in Oklahoma, USA, by using combined Parflow and CLM Common Land Model (Dai et al., 2003) runs for spinup. Rihani (2010) uses the same combination of models and catchment to address the effects of terrain, land cover etc. for a period of 4 days. In another study, Parflow is coupled with the WRF atmospheric model (Skamarock et al., 2008) and the NOAH land surface model (Ek et al., 2003) for 48 h idealized and semi-idealized runs (Maxwell et al., 2011). Rasmussen (2012) studies the HIRHAM regional climate model (Christensen et al., 2006) and the MIKE SHE hydrological model (Graham and Butts, 2005) with the SWET land surface scheme (Overgaard, 2005) in one-way coupled mode where output from the regional climate model is transferred to the hydrological model over the FIFE test domain in Kansas, USA, for the period May–October 1987. In that study over the FIFE domain, data is exchanged over an area represented by a single 0.125° HIRHAM grid cell. Two more recent studies couple the MM5 regional climate model (RCM) and the PROMET land surface model (Zabel and Mauser, 2013) and the CAM atmosphere model and the SWAT hydrology model (Goodall et al., 2013) respectively.

To our knowledge, no studies have been reported on long term simulations (more than a few days) with couplings between a regional climate model and a 3-D groundwater–surface water hydrological model using catchments larger than a single regional climate model grid point.

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An issue when systematically evaluating climate model results is the inherent model variability causing varying simulation outputs with only minor changes to the model setup either artificially induced by perturbing initial conditions such as the timestamp of model start, initial and boundary condition perturbations (Giorgi and Bi, 2000) or by altering the domain location (Larsen et al., 2013a). Giorgi and Bi (2000) show precipitation over regions in China, especially during the summer and for high precipitation events, to be highly sensitive to perturbations of initial and boundary conditions with a bias of 5–10 % of the average precipitation. Deser et al. (2012) stress that the high levels of climate model variability should be taken into account for 21st century climate projections. Similarly, Alexandru et al. (2007) used the CRCM Canadian regional climate model (Caya and Laprise, 1999) over five domains for twenty perturbed runs each to assess model variability in precipitation. In general at least 10 members were needed to reproduce correct seasonal means although this number was seen to be largely dependent on the domain size.

The current study utilizes a fully coupled model setup based on the HIRHAM regional climate model (RCM) and the MIKE SHE hydrological model combined with the SWET land surface model for the 2500 km^2 Skjern river catchment in Denmark. The coupled setup is developed to gain benefit from including the interactions between both modeling systems and is described in detail in Butts et al. (2013). As a new research task we have examined the specifics of the coupling of an RCM and a hydrological model with respect to the influence of the data transfer interval (DTI) between the two models since this strongly influences computation time. We also evaluated the importance of the internal HIRHAM model variability by assessing the sensitivity of the simulation results to perturbations of boundary and initial conditions.

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2 Method

2.1 Study area

The climate and hydrological models used in this study each covers areas within the range of their typical deployment. The data exchange between the models occurs at the overlapping grid cells with the hydrological catchment nested within the climate model domain (Fig. 1).

The HIRHAM regional climate model (RCM) version 5 (Christensen et al., 2006) covers a domain area of approximately 2800 km × 4000 km from northwest of Iceland to southern Ukraine (Fig. 1) and is in a resolution of 11 km on a rectangular grid. Approximately 60 % of the latitudinal stretch is located west of the Skjern catchment wherefrom most weather systems originate.

The MIKE SHE model setup covers the Skjern catchment area of 2500 km^2 (Fig. 1) located in the western part of the Jutland peninsula. Skjern River emerges in the central Jutland ridge at approx. 125 m a.s.l. and has its outlet into the Ringkøbing fjord. The Jutland ridge also constitutes the maximum elevation of approx. 130 m. Two general soil classes can be distinguished within the catchment, one being sandy soils generated by the Weichsel ice age glacial outwash, and the other being till type soils from the previous Saalian ice age. For the period 2000–2009 the average annual measured precipitation is 940 mm while the undercatch corrected precipitation (Allerup et al., 1998) amounts to 1130 mm. The corresponding mean annual air temperature is 9.3 °C whereas minimum and maximum monthly means reach 2.1–17.3 °C. The catchment land use is divided between 61 % agriculture, 24 % meadow/grass/heath, 13 % forest and 2 % other.

2.2 Observed input and validation data

Within the catchment measurements from three flux towers, placed over agricultural, meadow and forest surfaces, are used for calibration of the hydrological model.

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These all measure key climatic variables such as latent (LE), sensible (H), soil heat fluxes (G), radiation components, soil/air temperature, precipitation, wind speed, soil moisture and groundwater table. The latent and sensible heat fluxes is measured above the vegetation using eddy-covariance sonic anemometers, and the soil heat flux is measured using hukseflux plates at 5 cm depths. Latent and sensible heat fluxes are gap-filled and corrected according to data quality using the Alteddy software 3.5 (Alterra, University of Wageningen, Wageningen, the Netherlands) as described in Ringgard (2012) where up to 45 % of the data are replaced. For the periods 21 July–16 August and 24 August–28 October 2009, no data are recorded at the agricultural site and is therefore being replaced by data from the forest site. Discharge measurements (Q) from the three discharge stations Ahlergaarde (1055 km^2), Soenderskov (500 km^2) and Gjaldbaek (1550 km^2) are also used for point validation.

To drive the MIKE SWET module six climatic variables are needed. Daily precipitation (PRECIP) data are derived from gauge stations which have been kriging interpolated to a 500 m grid size as described in Stisen et al. (2011a) and further dynamically corrected to account for precipitation gauge undercatch (Allerup et al., 1998 and Stisen et al., 2011b). The remaining five variables; air temperature (Ta), wind speed (WS), relative humidity (RH), surface pressure (Ps) and global radiation (Rg) are based on climatic measurement stations which have been geographically and temporally interpolated to produce hourly 2 km datasets (Stisen et al., 2011b). For the validation of the coupled model setup the six distributed variables have been bilinearly interpolated to match the exact grid of the HIRHAM setup allowing for grid-by-grid calculations.

2.3 MIKE SHE

The present study uses the Windows-based MIKE SHE hydrological model capable of handling all key hydrological processes in the land-surface part of the hydrological cycle such as evapotranspiration, snow melt, channel flow (the MIKE 11 component), overland flow, unsaturated flow, saturated flow as well as irrigation and drainage (Graham and Butts, 2005).

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The SWET SVAT (Soil–Vegetation–Atmosphere Transfer) model component is included in the coupled setup. The SWET component is included to handle the vegetation and energy balance processes occurring in the land–surface interface stretching from the root zone and into the lower atmospheric boundary layer (Overgaard, 2005). The SWET energy-based model component is established on the basis of the Penman–Monteith equation (Penman, 1948; Monteith, 1965) but is modified to a two-layer system with resistance from both soil and canopy based on Shuttleworth and Wallace (1985) and also modified to include energy fluxes from ponded water and vegetation interception storage (Overgaard, 2005). A limitation to the current SWET model under Danish conditions is that snow accumulation/melt is not included.

In the current setup the MIKE SHE model is based on the Danish national water resources model (DK-model) (Stisen et al., 2011a, 2012; Højbjerg et al., 2013) in 500 m resolution using geology modifications according to Stisen et al. (2011a). The model setup includes eleven computational layers and an extensive river network and is implemented with a basic (maximum) time step of 1 h which is reduced by MIKE SHE during precipitation events. The setup was comprehensively calibrated against measurements from three discharge stations and latent and sensible heat fluxes at three measurement sites representing agriculture, forest and meadow surfaces as described in Larsen et al. (2013b). The calibration against these variables was performed for an optimal representation of the overall water balance as well as water and energy exchange with the atmosphere.

2.4 HIRHAM

The climate model used in the present coupling study is the HIRHAM regional climate model version 5 (Christensen et al., 1996, 2006) used by the Danish Meteorological Institute (DMI). HIRHAM is based on the atmospheric dynamics from the HIRLAM HIgh Resolution Limited Area Model used for operational weather forecasting (Undén et al., 2002) and physical parameterization schemes from the ECHAM5 general circulation

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model (Roeckner et al., 2003). HIRHAM is hydrostatic and is typically implemented in resolutions of 5–50 km – here 11 km as previously mentioned. HIRHAM model boundaries in the present study are constituted by ERA-Interim reanalysis data (Uppala et al., 2008) and the model time step was 120 s. The derivation of the domain is described in Larsen et al. (2013a) where seasonal precipitation and temperature were assessed for eight domains of varying size and resolution.

2.5 Coupling code

An obstacle in developing the coupling code in the present study was the differing computing platforms between MIKE SHE and HIRHAM based on Windows and Linux respectively. To facilitate communication across these platforms the Open Modelling Interface (OpenMI) code was used on the Windows workstation side and both MIKE SHE and HIRHAM were made OpenMI compliant. On the Linux side modifications to the HIRHAM code as well as an additional stand-alone code controlling the data exchange was developed. The OpenMI is created to facilitate the communication between existing time-dependent model codes running simultaneously and to handle differences in time step, model domain, resolution and discretization (Gregersen et al., 2005, 2007).

The OpenMI and Linux/HIRHAM coupling code served four general functions: (1) to serve as control on timing between models so that data is stored from one model waiting for the other to reach the point in time of specified data exchange. (2) To define which variables to be exchanged in both directions and to handle potential unit conversion factors, offsets and aggregation types. (3) To handle the spatial grid structure of each model and transfer the data based on a selected spatial interpolation mapping. (4) To collect and interpolate data for each separate model time step to be exchanged between models at each data exchange time step based on the differing time steps in the two model codes, including MIKE SHE's varying time steps during precipitation events.

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As both modelling platforms include numerous variables in 2 or 3 dimensions, the exchange of data between the models are selected within the modelling scope of using the HIRHAM climate forcing as input to MIKE SHE/SWET as well as transferring energy and water fluxes in the opposite direction. Therefore the HIRHAM to MIKE SHE transfer includes the driving variables necessary for the latter: PRECIP, RH, WS, Rg, Ta and Ps. From MIKE SHE the variables LE and surface temperature (Ts) is transferred of which Ts is used to calculate H within the HIRHAM code. The spatial mapping in this study was based on the weighted mean method where each grid cell contributes relative to the land share fraction.

The standard OpenMI method for data exchange is based on memory. However, due to safety regulations regarding network data exchange at the location of model execution, the current setup is constrained to the exchange of data files on a shared drive visible to both the Windows and Linux model setups. This network file transfer generates a significant increase in execution time when data exchange is made frequently (Butts et al., 2013). Therefore, there is a need to analyse the possible gain in the model coupling performance with increased data transfer interval (DTI) as a trade-off to the increase in computational load.

2.6 Simulations

All model simulations were performed for the one-year period from 1 May 2009 to 30 April 2010 with a spinup period from the beginning of March to 30 April 2009. A total of 26 model runs were used in the present study falling into four main simulation categories:

- Transfer interval (TI): eight two-way fully coupled simulations were performed varying the DTI between the HIRHAM and MIKE SHE models between 12 and 120 min. These DTI values were chosen within the limit of certain time step restrictions in MIKE SHE and the feasibility of executing model runs within the time

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slots allocated by DMI's supercomputing facility. The TI runs used 1 March 2009 as starting day.

– HIRHAM uncoupled variability (HUV): eight HIRHAM uncoupled simulations were performed each starting one day apart from 1–8 March 2009.

– Coupled variability (CV): eight two-way fully coupled simulations having a 60 min DTI were performed using the 1–8 March 2009 starting dates as above.

– MIKE SHE data source (MSDS): to assess the influence of data source on MIKE SHE performance two MIKE SHE simulations were performed. One in uncoupled mode using the PRECIP, RH, WS, Rg, Ta and Ps observation data and one in one-way coupled mode using HIRHAM model output with a 30 min DTI without data transfer back to HIRHAM.

The eight successive uncoupled HIRHAM runs will all show varying geographical and temporal patterns of, in particular, precipitation. With varying precipitation the water available for evapotranspiration and the energy balance also varies, and therefore attention should be given to which simulations are compared. For all models runs output from HIRHAM was assessed on the basis of the six climatic variables PRECIP, RH, WS, Rg, Ta and Ps since these were available and also used as MIKE SHE SWET input for uncoupled runs. Likewise, MIKE SHE simulation output was assessed on the basis of point measurement of LE, H and G at the agricultural, forest and meadow sites (Fig. 1) as well as discharge from three gauging stations.

Figure 2 outlines the data flow and simulation categories. As the Skjern Catchment exhibits an irregular shape as dictated by the flow patterns a varying level of overlap were seen between the HIRHAM grid cells and the hydrological catchment (Fig. 1). The PRECIP, RH, WS, Rg, Ta and Ps HIRHAM output analyses were therefore performed for five evaluation domains using distinct criteria to select these:

– Dom1: cells of 100 % overlap (9 cells)

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- Dom2: Dom1 + the cells of 50–100 % overlap (23 cells)
- Dom3: Dom2 + the cells of 0–50 % overlap (30 cells)
- Dom4: Dom3 + cells located immediately downstream of the catchment with regards to the dominant western wind direction (42 cells)
- Dom5: cells located downstream of the catchment alone with wind directions between north-west to south-west (4 cells)

For HIRHAM output the evaluation was performed on all five test domains by calculating a single root mean square error (RMSE) value for each full model simulation. For MIKE SHE output the RMSE was performed on the point data only. The RMSE was calculated on the basis of each hourly (RH, WS, Rg, Ta, Ps, LE, H and G) and daily (PRECIP and Q) simulation output against the corresponding observation for all six HIRHAM and four MIKE SHE variables:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i,t} (\mathrm{SIM}_{i,t} - \mathrm{OBS}_{i,t})^2}{n}} \quad (1)$$

where SIM and OBS are the simulated and observed values respectively, i and t are location and time respectively and n is the total number of data points. To assess the output variability from each of the three simulation groups involving HIRHAM (TI, CV and HUV) simulation box plots with the 25th and 75th percentiles including whiskers to the most extreme data were created.

Similar to the RMSE calculations the mean absolute errors (MAE) were assessed to gain more information on the expected improvements for simulations with a more frequent DTI:

$$\mathrm{MAE} = \frac{\sum_{i,t} |\mathrm{SIM}_{i,t} - \mathrm{OBS}_{i,t}|}{n} \quad (2)$$

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where the terms correspond to the RMSE calculations. The MAE calculations were performed for the TI simulations for each of the six HIRHAM variables at the five test domains and the four MIKE SHE variables at point scale. Least square fit linear trend lines were then fitted to the 12–120 min DTI MAE values for each of the test domains and point scale output and for each variable. The mean absolute and percentage change in MAE based on the trend lines from the 120 to the 12 min data points were then calculated. Also, correlation coefficients on the basis of the trend lines were calculated to detect statistical significance at a 95 % two-tailed level.

The HUV and CV simulation groups reflect similar initial conditions as induced by the perturbations, but differ by having the CV simulations including the two-way coupling. These simulations were therefore used to test for statistical significance of the coupling. A simple two-sample *t* test was performed for each of the test domains and variables for the HUV and CV simulations to test the hypothesis of these simulation groups having unequal means.

3 Results

3.1 HIRHAM output

3.1.1 Data transfer interval (DTI)

Of the six HIRHAM output variables, the four variables of PRECIP, RH, WS and Ta show a significant decrease in RMSE with decreasing DTI in the fully two-way coupled mode simulations whereas Ps RMSE results are less affected and Rg results are unaffected (Fig. 3). Of the four variables showing simulation improvements with decreasing DTI only some include substantial absolute RMSE improvements and exhibit a high degree of correlation in the range of DTI values. Based on the linear trend line averages, RMSE improvements of 1.1 mm day^{-1}, 1.1 %, 0.2 m s^{-1} and 0.3 °C. are seen for PRECIP, RH, WS and Ta respectively whereas the Ps RMSE improvement is

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0.1 hPa (Fig. 3). Corresponding values for MAE are 0.3 mm day^{-1}, 0.8 %, −0.1 m s^{-1}, 0.2 °C and 0.0 hPa. These absolute improvements correspond to changes between the 120 and 12 min simulations averaged for the four significant variables of 10.1 % for RMSE and 7.2 % for MAE with the highest relative improvements for PRECIP and Ta and the lowest for Ps (Table 1). The least square fit linear trend lines of these five variables show correlation coefficients between 0.58 and 0.98, whereof Ps is not significant, and Rg shows no correlation (−0.03) (Fig. 3). For the same five variables, PRECIP, RH, WS, Ta and Ps, there is a specific order in the resulting RMSE trend line locations with the largest RMSE values for Dom1, Dom2 etc., decreasing down to Dom5.

The coupled setup execution time as a function of DTI is shown in Fig. 4. Only a moderate increase in execution time is seen in the range of 60–120 min DTI values whereas a sharp increase is seen from DTI values of around 15–30 min.

3.1.2 HIRHAM model variability

Figure 5 shows the output variability for each of the TI, CV and HUV group runs for each of the five test domains Dom1–Dom5. For PRECIP, RH, WS and to some extent Ta the largest variability is seen for the two-way coupled runs (TI). The RH and WS 60 min DTI coupled (CV) and uncoupled (HUV) runs show almost negligible variability. The PRECIP and Ta simulations show a reverse pattern between HUV and CV where the largest variability is seen for the CV simulations for PRECIP whereas the opposite is seen for Ta with a larger HUV variability. For the same variables, PRECIP, RH, WS and Ta, a general decrease in RMSE is seen for the coupled TI and CV simulations with increasing test domain number from Dom1 to Dom5. For the HUV simulations this pattern is seen to some extent for PRECIP only. The Rg and Ps variables show comparable levels of variability between the TI, CV and HUV simulations groups. For Rg the RMSE values increase with test domain number whereas the opposite is the case for Ps.

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By comparing the 120–12 DTI improvement for the TI simulations based on the linear trend lines with the variability from the HUV simulations it is seen that the variability on average makes up 47 % of the TI improvement for the four variables PRECIP, RH, WS and Ta. The corresponding number when comparing TI with CV is 46 %.

For the two-sample t test between the HUV and CV Simulations the variables PRECIP, RH, WS and Ta all fulfilled the hypothesis of belonging to two separate populations with significance levels of 98.2 % or above. For these four variables, although all were highly significant, there was a clear pattern of falling significance with increasing test domain number corresponding to a lesser degree of coupling. Other than for the test for Ps at the Dom5 test domain showing a similar significance of 97.2 %, the hypothesis was rejected for the remaining variables (Rg and Ps) and test domains with significance levels of 48.3 % or below.

A more detailed plot of the simulated PRECIP for each run, for each of the TI, HUV and CV simulation groups and for each test domain is shown in Fig. 6. Several tendencies are evident: as seen in Fig. 3 the PRECIP decreases with increasing domain number for all three simulation groups. This decrease is strongest for the two-way coupled TI and CV simulation groups which also show the highest PRECIP levels compared to the uncoupled HUV simulations. Compared to the observation period with the PRECIP sum of 892 mm across the test domains, TI and CV consequently overpredict PRECIP with mean period sum values across both simulations and domains of 1004 mm and 1027 mm respectively, whereas HUV underpredicts with a period sum of 868 mm. With regard to timing there is a tendency for the main part of the TI simulation variability to derive from events in the fall months of 2009 whereas most of the HUV and CV variability occurs in early 2010 events.

In addition to comparing simulation statistics and precipitation sum curve plots, the HIRHAM output variables for all 24 TI, HUV and CV simulations are simply plotted against time to assess and compare their temporal patterns. An example is shown in Fig. 7 with hourly values for the period 10–18 July 2009, except for precipitation with daily values for all of August 2009. A large spread is seen for precipitation amounts

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for individual days increasing with the mean intensity especially for 3 and 20 August whereas reasonable agreement is seen between the simulations in the prediction of most dry days. For the remaining five variables, RH, Ta, Ps and especially WS and Rg, the period with low pressure and precipitation, 10–12 July, exhibits a fair amount of spread between the individual simulations, whereas the remaining period, 13–18 July, shows a higher degree of consistency within each simulation group (TI, HUV and CV) especially in terms of dynamics. For the PRECIP, RH, WS and Ta variables the coupled simulations groups of TI and CV clearly deviates from the HUV simulations in terms of the timing, dynamics and absolute levels. Of these, the most noticeable difference is the daytime RH and night time Ta which are notably higher and lower, respectively, for the HUV simulations.

3.2 MIKE SHE output

As for the HIRHAM simulations, the MIKE SHE RMSE results are plotted as a function of DTI (Fig. 8). LE shows a general improvement in RMSE with a higher frequency of exchange (smaller DTI), strongest for agriculture and forest. Corresponding correlation coefficients between RMSE and DTI of 0.83, 0.55 and 0.13 are seen for agriculture, forest and meadow respectively. Conversely H shows general decreases in RMSE results with increased DTI and with correlation coefficients of −0.80 to −0.83. To some degree LE and H thereby reflects an inverse signal which could be expected for a situation of no overall improvement since these components together are the major contributors to the energy balance. No clear trend between DTI and RSME results is seen for neither G nor Q and the corresponding correlation coefficients are generally low.

For LE an absolute improvement of 1.9 $\mathrm{W\,m^{-2}}$ in both MAE and RMSE is seen from the 120 to 12 min trend line average data points corresponding to 6.9 and 4.5 % for MAE and RMSE respectively (Table 1). Overall the one-way coupled and uncoupled MSDS simulations are superior to the TI simulations with the exception of agricultural LE and G and meadow G. The HIRHAM climate model variability as represented by the

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CV simulations produces a resulting MIKE SHE RMSE total output span of 1.5 $W m^{-2}$, 1.5 $W m^{-2}$, 0.7 $W m^{-2}$ and 2.2 $m^3 s^{-1}$ for LE, H, G and Q as an average of the three surfaces and the three discharge stations (Fig. 8). By comparison the TI simulations induce a spread in the corresponding results of 3.7 $W m^{-2}$, 3.8 $W m^{-2}$, 4.5 $W m^{-2}$ and 1.3 $m^3 s^{-1}$ respectively.

The variations in the MIKE SHE output for four variables LE, H, G and Q for the CV and TI model runs are shown in Fig. 9. Also here there is no distinct pattern distinguishing the TI and CV simulation group results. The 10–12 July period shows larger variations in predicted flux output reflecting the variability in the HIRHAM simulations. Using either observation data or HIRHAM data as driving input for MIKE SHE (MSDS runs) however resulted in substantial variations in the results. As expected due to the change in driving data, the uncoupled (observation data input) runs resulted in shifts in LE, H and G values for both peaks (daytime) and lows (night time) most obvious for G. The one-way coupled run output (HIRHAM data input) to some extent, especially for night time LE and G, however resembled the observation data input run more than the TI and CV runs.

4 Discussion

4.1 Impact of coupling

The motivation for performing this coupling study is to include the land surface-atmosphere interaction between the RCM and the hydrological model. Our hypothesis is that the RCM will benefit from the more detailed representation of the surface and subsurface processes provided by the dedicated hydrological model as compared to the much more simple land surface schemes on which climate models usually rely. Similarly, we expect that the hydrological model would benefit from the better representation of the horizontal redistribution processes in the atmosphere offered by the dynamic coupling with the climate model. In this regard, the results in the present study show a statistically significant impact for four of six climate variables in using a fully two-way coupled climate–hydrology model setup compared to the individual models alone. The degree of coupling impact is related to the degree of coupling with the highest significance levels occurring centrally in the catchment (Dom1) and a smaller effect downstream (Dom5).

4.2 Performance of coupled vs. uncoupled model

As shown above the performance of the coupled model simulations (TI and CV) is generally poorer than the uncoupled model simulations (HUV). This is not surprising. Even though it is based on basic physical principles the HIRHAM RCM has been refined over the years to better reproduce observations. Moreover, the model configuration (domain extent and grid size) with the best performance in terms of simulating precipitation and air temperature as well as in representing the atmospheric circulation patterns has been selected in Larsen et al. (2013a). Likewise, MIKE SHE SWET has been subject to rigorous inverse modelling to assess parameter values (Larsen et al., 2013b). With the coupling the existing land surface scheme in HIRHAM is replaced by MIKE SHE SWET over the Skjern catchment. Calibrating complex models comprising several processes often introduces compensational errors (i.e. providing the right answer for the wrong reason) in the different model components in order to ensure that the model fits observational data as well as possible. When the existing land surface scheme in HIRHAM is replaced by MIKE SHE SWET it will inevitably provide different results and as the new coupled model is not calibrated simulation results are likely to be poorer. The ability of model calibration to compensate for biases in other model components is well documented (Graham and Jacob, 2000; Stisen et al., 2012). The question of how to calibrate a complex coupled climate–hydrology model system as presented here, in a two-way coupled mode, is outside the scope and time-frame of this work. This task is computationally extensive and would require a far-reaching coding effort to include automatic inverse modeling. Even with manual calibration improved coupled simulations results may possibly remain inferior

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to the uncoupled results. That said the fact that the coupled model performance is poorer when the land surface scheme is replaced by an elaborate scheme (MIKE SHE SWET) that is well calibrated against observational data suggests that some of the other HIRHAM components could be improved. This should be investigated further, as there is a perspective here in learning from the coupled model to improve the HIRHAM parameterisations.

4.3 Test domains

There is a clear tendency, for the coupled HIRHAM output (TI) from the five test domains of increased RMSE levels with a higher fraction of coupled cells (Fig. 3), with the exception of Rg results. An important consideration in this regard is however the specific location of each of the domains within Denmark (Fig. 1). For the uncoupled HUV simulations the pattern of increased RMSE values with the same test domains as for the TI simulations is seen for PRECIP. Therefore it is not possible to directly relate the share of MIKE SHE influence on the HIRHAM simulations to the results. An additional cause of the pattern of higher RMSE levels for test domains located in central Jutland (Dom1 – Dom4) as compared to the eastern Dom5 could be related to certain geographical biases in the precipitation as often seen in RCM's, including HIRHAM (Jacob et al., 2007; Polanski et al., 2010). Corresponding biases for temperature have also been found (Kjellström et al., 2007; Plavcová and Kyselý, 2011). Van Roosmalen et al. (2010) showed the HIRHAM model (version 4) to produce higher precipitation and temperature biases over the central Jutland ridge compared to the rest of Denmark and also found HIRHAM to locate simulated rainfall maximum too far towards the North Sea compared to the observation maximum more inland in Jutland. Proximity to the coastline has also been shown to affect precipitation results from HIRHAM (Larsen et al., 2013a) and thereby the available water affecting the energy balance budget. In this regard the test domains Dom2 and specifically Dom3-Dom4 is located close to Ringkøbing Fjord which could also contribute to the higher RMSE levels of these compared to Dom5.

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4.4 Scale of variables

An essential consideration in the analysis of the HIRHAM performance is the local to regional scale in which the atmospheric variables are affected by the land surface. The Skjern River catchment covers an area of approximately 70 km × 50 km. In this study the hypothesis is that areas in the proximity of the catchment and up to 25 km downstream of the catchment (in relation to the dominant wind direction) may be affected by the model coupling. This corresponds to atmospheric scales from smaller mesoscale to microscale. It could be argued however that the effect of the coupling, although tested on regional scales below 100 km, could likely be imposed regionally on top of larger scale atmospheric phenomena such as larger mesoscale and synoptic scale features. In this regard global incoming solar radiation (Rg), by and large affected by cloud cover and therefore upstream larger meso- and synoptic scale conditions, shows no effect of the coupling scenario as the RSME pattern resembles a somewhat random pattern as a function of DTI, test domain and model variability (Fig. 3). Kaas and Frich (1994) however show changes in cloud cover to be correlated to surface temperature. Similarly surface pressure (Ps) would be connected with larger scale weather systems and sea surface temperatures (Køltzow et al., 2011) and is seen to be constrained to some degree by lateral boundary conditions (Seth and Georgi, 1998; Diaconescu et al., 2007; Leduc and Laprise, 2009) but is highly influenced by domain characteristics (Larsen et al., 2013a). It is thus likely that the Ps RMSE improvement with DTI, although modest in absolute terms, is connected to small scale coupling effects imposed on larger scale atmospheric patterns. The variables RH, WS and Ta all vary in spatial scales down to microclimate far below the resolution of HIRHAM and even MIKE SHE and the improved results with a more frequent DTI is therefore anticipated to some extent. Also PRECIP, in particular convective rainfall, can be seen at grid scales below the HIRHAM resolution (Casati et al., 2004).

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4.5 Data transfer interval (DTI)

As most variables in the present study exhibit some degree of improvement with a lower DTI the relation between computation time and DTI (Fig. 4) is highly relevant for studies of longer periods, as improved performance of the coupled setup is constrained by a corresponding increase in computation time. Similar to this study Maxwell et al. (2011) tested the transfer timing of data between the Parflow hydrological model and the WRF atmospheric model in a 48 h idealized constructed setup. The simulations were performed by using four transfer intervals of 5, 10, 60 and 360 s, where WRF used a constant time step of 5 s (nonhydrostatic model) and the time step in Parflow varied with the transfer interval. Good water balance results were obtained for transfer rates up to 12 times that of WRF (60 s) whereas the results for transfer interval of 360 s deteriorated. Even though a smaller time step was used in WRF than in HIRHAM in the present study (5 s compared to 120 s) the results of Maxwell et al. (2011) correspond reasonably to our results where a transfer rate of 12 times that of HIRHAM would correspond to a 24 min DTI.

4.6 Perspectives for further use

In this paper we demonstrate the feasibility of a full dynamical coupling between a regional climate model (HIRHAM) and a distributed hydrological modelling system (MIKE SHE) at very different scales. Scientifically, the current prototype gives us an adequate tool to investigate how improved representations of surface and sub-surface processes impacts projections of atmospheric circulation and vice versa for a wide range of problems, e.g. with respect to extreme dry and wet periods in a present and future climate as well as the hydrological response to climate change scenarios when feedbacks are considered. The long-term perspective of these efforts naturally points towards the development of comprehensive regional earth system models with improved and more physically consistent descriptions of regional climate processes than current climate models, potentially leading to better and more realistic regional

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climate change projections. A particularly important aspect of modelling, not only the influence of climate onto the hydrological regime but also the anthropogenically induced changes may be assessed, which have been shown to have a substantial effect on the local to regional climate (Durieux et al., 2003; Cui et al., 2006). A next incremental step would therefore be to explore the effect of land use change using the coupled climate–hydrological model system, which is able to include interaction and feedback mechanisms of the entire water and energy cycle, rather than to rely on existing statistical measures in the assessment of causes and effects. In most cases such analyses are likely to involve much larger hydrological model catchments. While there are no technical limitations to this task, this is equally likely to incur an increase in the hydrology model construction and calibration effort. On the other hand, this study clearly indicates that using the described methodology there could be significant advantages in applying the coupled model approach on a larger geographical scale than as shown. Extending the coupled domain in size would for example serve to minimize inconsistencies at the edge of the shared model domain, caused by uncoupled and semi-overlapping grid cells which blend the physical descriptions of the coupled model setup and HIRHAM, respectively. This might in turn improve the simulation of Rg, the only variable in this work showing little or no change due to the coupling, due to improved larger-scale surface temperature descriptions known to affect cloud cover (Kaas and Frich, 1994).

Computationally, we show that it is feasible to run simulations using coupled models dedicated to different types of computing systems, in this case a high performance computer and a personal computer. Moreover, we have demonstrated that transient coupled climate–hydrology simulations at the decadal scale or longer are well within reach. The present prototype implements a number of technical decisions inherent to the computing environment available for this study and more work is needed in order to reduce computation times, e.g. implementation of a more efficient memory-based data transmission schemes as prescribed in the OpenMI standard. In its current

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form the coupling approach, however, may easily be generalized to other computing environments.

In terms of further model development this work suggests that several steps may be undertaken to improve the coupled model performance. Firstly, better calibration of the full two-way coupled modelling system is needed. Hydrology models are generally highly calibrated based on detailed present-day measurements and long-term projections of the hydrological response in a future climate are thus likely to push the hydrology models out of their comfort zone. Conversely, climate models are, in general, not strongly calibrated, creating a mismatch across both scales and accuracy, which might be offset by improved inter-model calibration for more physically consistent model output and ultimately for improved confidence in climate–hydrology projections. Secondly, while in this study we directly link model variables using an OpenMI interface, the present framework could easily be extended by imposing empirical downscaling and bias correction methods to further improve model compatibility across time and spatial scales. Lastly, as mentioned above, to improve model performance during winter time as well as the applicability of the coupled system to other climatic regions, snow melt could be included in the MIKE SHE/SW ET module, which in turn should induce an obvious improvement in winter periods with snow.

The 75–99 mm and 52–134 mm spans in total period PRECIP amounts from the HUV and CV simulations respectively, differing within groups only by perturbated starting conditions, clearly reflect the high variability in simulated PRECIP as also shown in several studies (Casati et al., 2004; van de Beek et al., 2011; Larsen et al., 2013a). Future studies within the field of coupling a regional climate model and a hydrology model therefore require an assessment of the amount of impact truly induced by the coupling as opposed to that caused by climate model variability. In this regard, even though this study as of now is the only full scale real catchment case climate/hydrology study to use a full year evaluation period, further benefit is gained by longer period simulations to include a range of conditions.

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5 Conclusions

This study presents the performance of the fully two-way coupled setup between the HIRHAM RCM and the combined MIKE SHE/SWET hydrological and land surface models. Especially the influence of the data transfer interval between the models (DTI), the domain of coupling influence and the HIRHAM model variability were assessed.

Of the six HIRHAM output climate variables, precipitation, relative humidity, wind speed and air temperature (PRECIP, RH, WS and Ta) showed significant improvements in RMSE with a reduced DTI in the evaluated range of 12–120 min DTI's. Statistically significant differences by performing the coupling were also seen for these same four variables as they were shown to derive from two different populations when comparing similar perturbed runs of HIRHAM uncoupled runs (HUV) with two-way coupled HIRHAM runs (CV). The improvement for precipitation is highlighted with regard to the potential in the coupled setup as this is considered one of the most difficult variables to simulate. Going from a DTI of 120–12 min decreased the average RMSE for these significant variables with 10.1 %. In this regard, the computation time was shown to increase rapidly with a lower DTI as a model month corresponds to 4–5 real hours with a 60 min DTI where the corresponding duration is 10–16 h for 12–24 min DTI values. The global radiation and surface pressure variables (Rg and Ps) were shown to have little to no impact from the coupling. Little to no improvement in the MIKE SHE output variables is seen for decreased DTI values as the improvement in latent heat flux (LE) is in the same range as the sensible heat flux (H) decline.

The uncoupled and coupled HIRHAM model variability as induced by perturbing the HIRHAM runs with varying starting dates were shown to correspond to 47 and 46 % respectively of the average improvements in RMSE and MAE for the four significant variables when going from a 120 min to a 12 min DTI. Similarly significant variations were seen in the simulated precipitation where the eight two-way fully coupled simulations with 12–120 min DTI values (TI) produced precipitation spans during the one year period of 108–170 mm for the five test domains. Similarly the

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uncoupled (HUV) and coupled (CV) simulations with model variability induced by perturbation showed precipitation spans of 75–99 mm and 52–134 mm respectively. For all of these, the resulting span increased with a higher degree of coupling, whereof a certain share of this pattern may be attributed to well-known geographical HIRHAM bias over the central Jutland ridge. The HIRHAM model variability as transferred to the MIKE SHE model in the 60 min DTI CV simulations was substantially higher for discharge than for the LE, H or soil (G) heat fluxes.

In general the coupled modeling results (TI and CV) are generally poorer than the uncoupled results (HUV). This is not surprising as each of the models over the years, also prior to the study, have been separately refined or calibrated to reproduce observations. These calibrations are likely to have compensated for errors in the separate and complex model components to ensure a proper data fit. We propose that the replacement of the land surface scheme in HIRHAM, as introduced by MIKE SHE, and the change in data input in MIKE SHE, as introduced by HIRHAM, causes this deterioration. The calibration of the coupled setups is outside the time-frame and scope of the present paper, however we see a great potential for further improvements when these are applied.

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Table 1. Absolute and percentage change in MAE and RMSE between the largest (120 min) and smallest (12 min) DTI based on the average value of the linear trendlines of either the five test domains (HIRHAM output) or the measurement sites (MIKE SHE output). Also shown is the absolute variability from the CV and HUV runs defined as the minimum value subtracted from the maximum for the 60 min DTI averaged between test domains (HIRHAM output) or measurement sites (MIKE SHE output) for each tested variable.

	Variable	MAE absolute change	MAE percentage change	MAE CV variability	MAE HUV variability	RMSE absolute change	RMSE percentage change	RMSE CV variability	RMSE HUV variability
HIRHAM output variables	PRECIP (mm day^{-1})	0.3	8.3	0.2	0.2	1.1	16.4	0.7	0.6
	RH (%)	0.8	7.9	0.3	0.1	1.1	8	0.3	0.2
	WS (m s^{-1})	0.1	5.4	0.0	0.0	0.2	5.8	0.5	0.1
	Rg (W m^{-2})	−0.1	−0.2	2.6	1.3	−0.1	−0.1	6.0	3.2
	Ta (°C)	0.2	10.1	0.1	0.1	0.3	8.8	0.1	0.2
	Ps (hPa)	0.0	1.8	0.1	0.1	0.1	2.7	0.2	0.2
MIKE SHE output variables	LE (W m^{-2})	1.9	6.9	0.9	–	1.9	4.5	1.5	–
	H (W m^{-2})	−2.3	−7.4	0.5	–	−3.1	−6	1.5	–
	G (W m^{-2})	−0.1	−3.1	0.2	–	−0.7	−7.9	0.7	–
	Q (m^3 s^{-1})	−0.4	−12.2	0.7	–	0.1	−0.1	2.2	–

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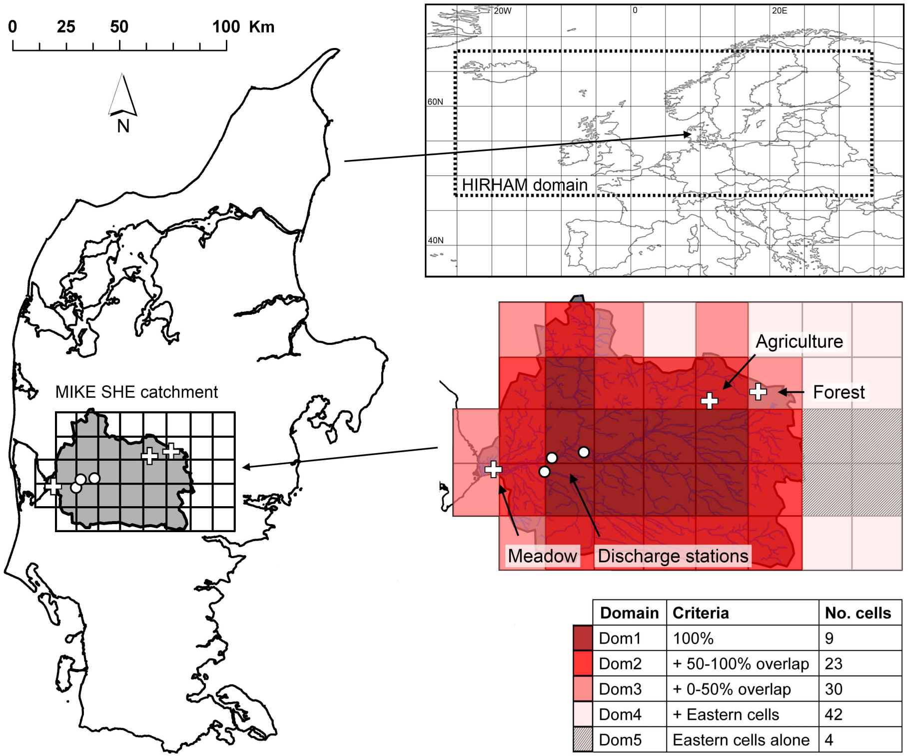

Fig. 1. Location of HIRHAM regional climate domain within Europe, MIKE SHE catchment within Denmark, three point measurement sites, and location of five evaluation domains.

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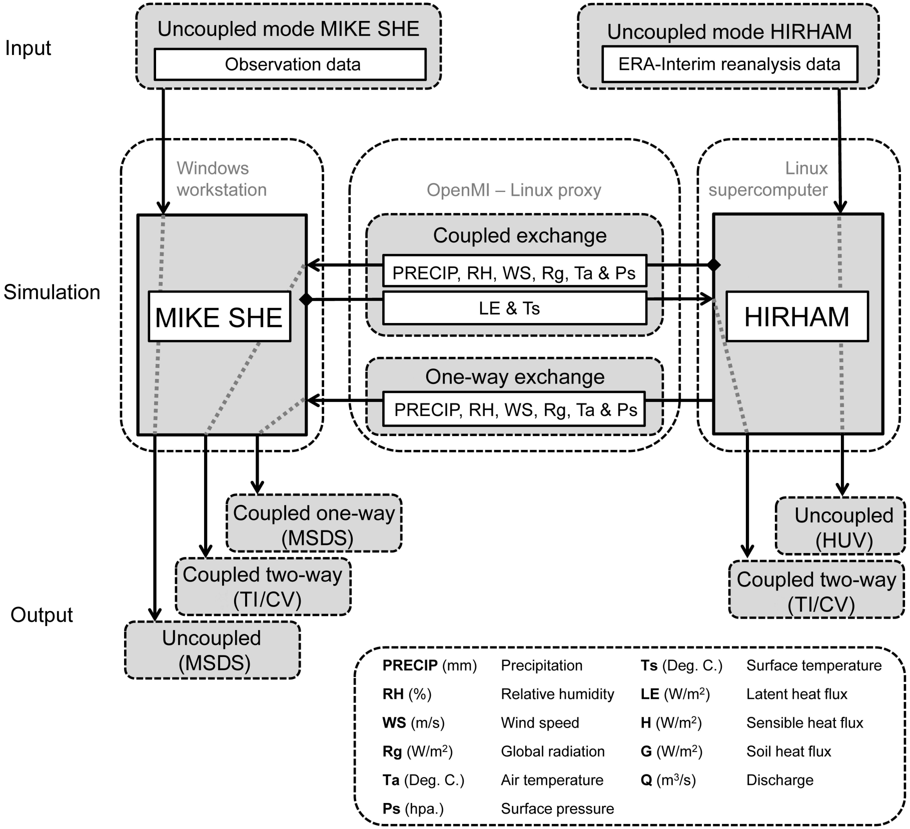

Fig. 2. Flow chart of the data flow and analyses performed in the present study and a legend of the variables mentioned in the study.

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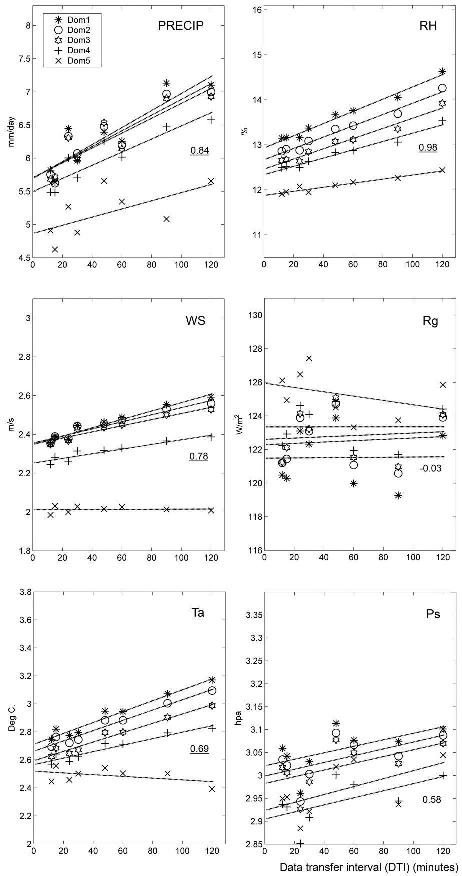

Fig. 3. HIRHAM output RMSE statistics for each of the test domains for the coupled TI simulations. Linear trend lines are shown with RMSE as a function of DTI as well as the average trend line correlation coefficients where the significant correlations on a two-sided 95 % confidence level are underlined.

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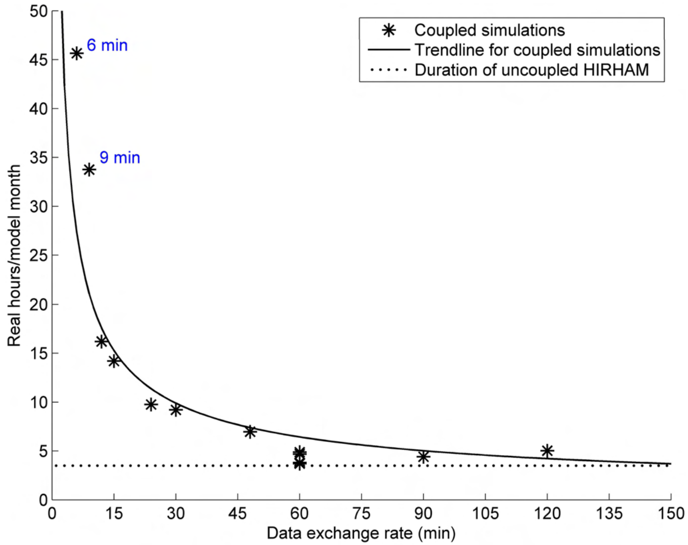

Fig. 4. Model execution time in hours of wall time as a function of DTI. DTI steps of 6, 9, 12, 15, 24, 30, 48, 60 (eight CV runs), and 120 min were used whereas 6 and 9 min DTI values were extrapolated from unfinished runs. For comparison the dashed line is the execution time for the uncoupled HIRHAM runs (HUV). The figure originates from Butts et al. (2013).

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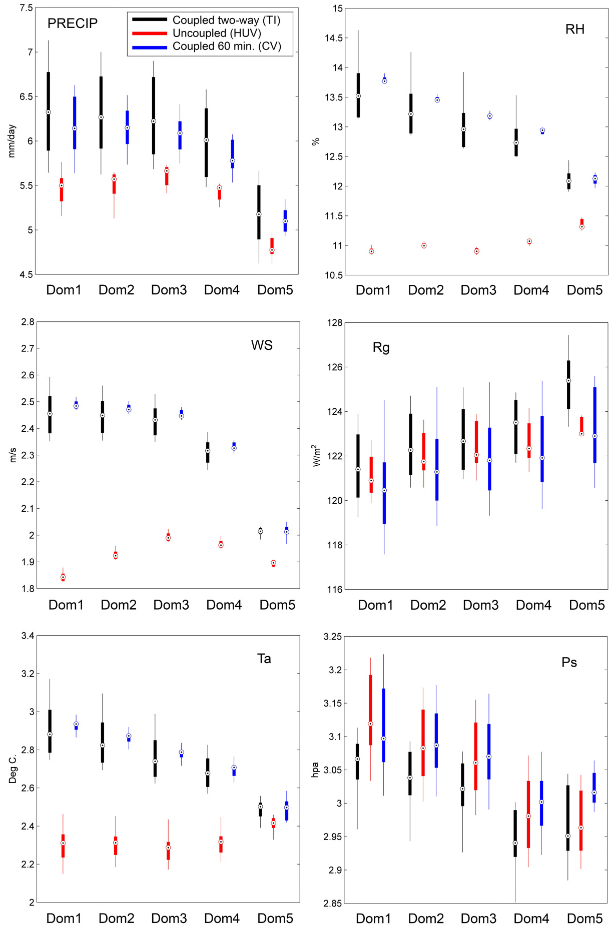

Fig. 5. RMSE variability for the TI, HUV and CV simulations for each of the five test domains. The dots represent the median value, the box plots represent the 25–75th percentiles and the whiskers represent the entire data range.

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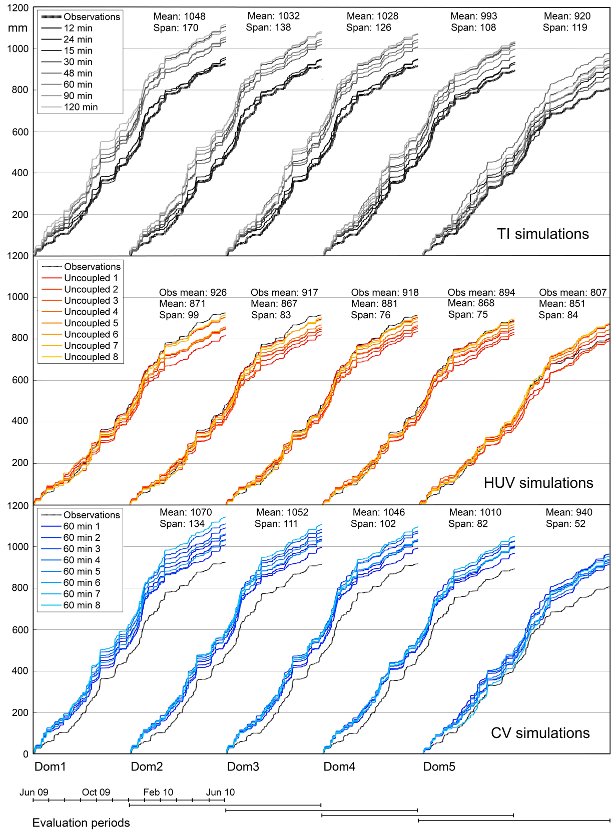

Fig. 6. Precipitation sum curve for the evaluation period 1 May 2009 to 30 April 2010 for the five test domains and the TI, HUV and CV simulations as well as the observations. Also given are the simulated mean values, the span in the period sum for each plot group (minimum value subtracted from maximum value) and the observed mean values.

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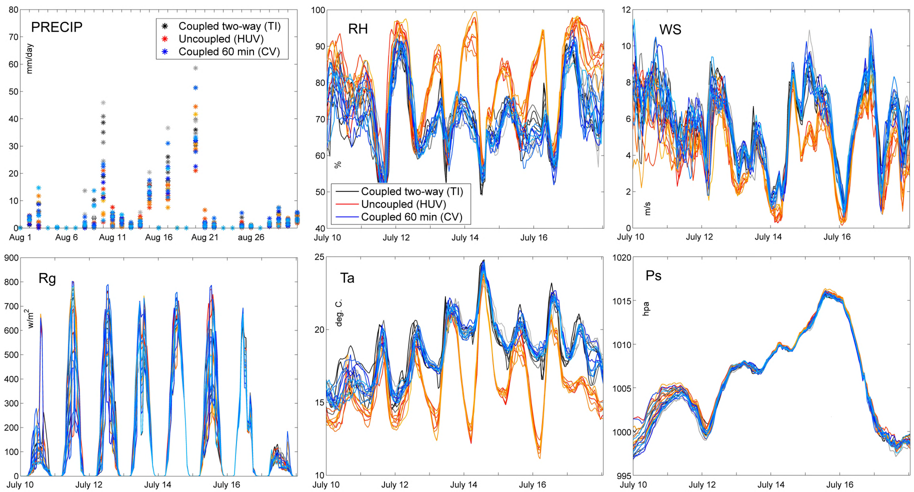

Fig. 7. The six HIRHAM output variables assessed in the present study in the 10–18 July period (precipitation is 1–31 August to match the period in Fig. 9 with a higher dynamic in discharge) for all 24 TI, HUV and CV runs and for Dom1 (nine cell mean). The legend colouring reflects the overall simulation group (TI, HUV or CV) whereas each simulation is in the colour shade as in Fig. 6.

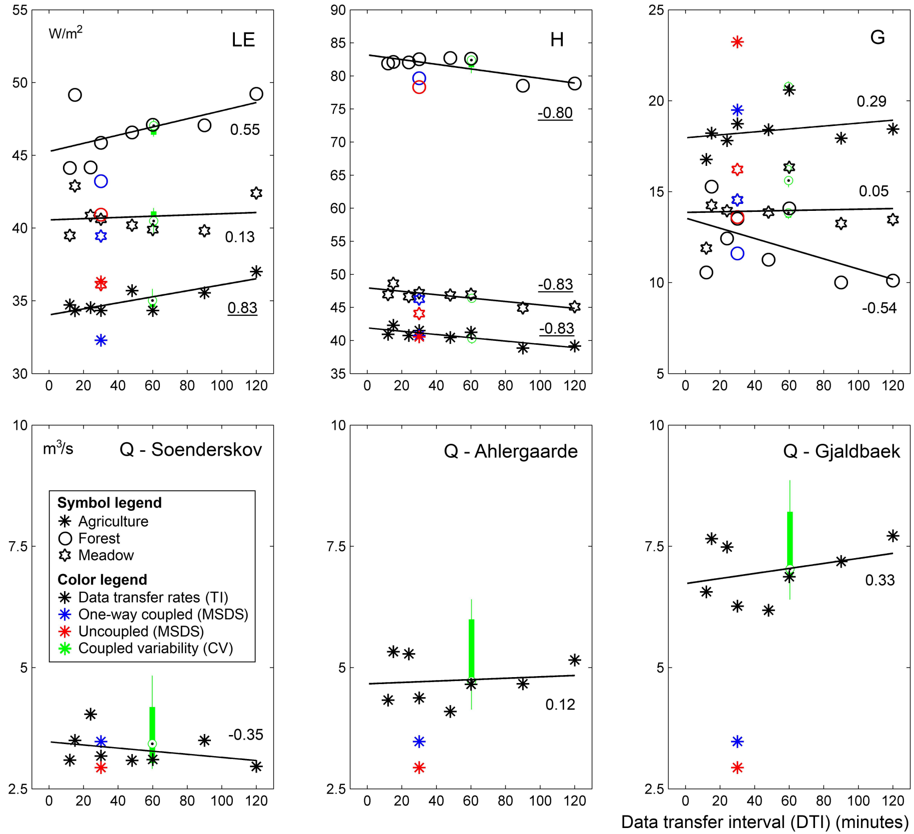

Fig. 8. MIKE SHE output RMSE statistics for each of the three flux tower measurement sites and the three discharge stations for the TI, MSDS and CV simulations. For the TI simulations linear trendlines are shown with RMSE as a function of DTI as well as the average trendline correlation coefficients where significant correlations on a two-sided 95 % confidence level are underlined. Also, the variability of the perturbed CV simulations is shown.

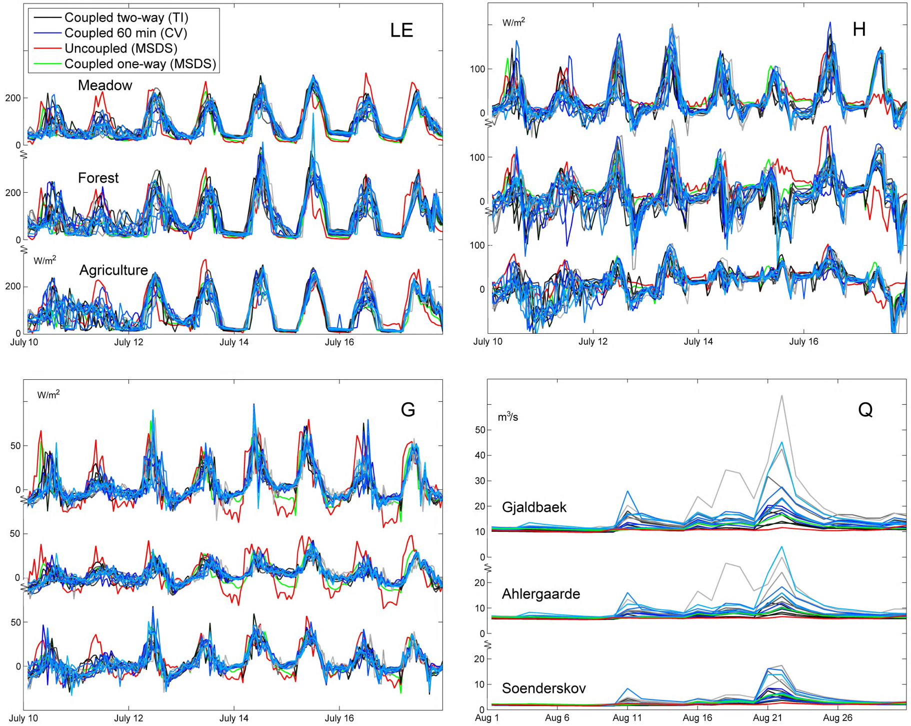

Fig. 9. Four MIKE SHE output variables for the period 10–18 July (discharge is 1–31 August) for the TI, CV and MSDS runs and for Dom1 (nine cell mean). The legend colouring reflects the overall simulation group (TI, CV and MSDS) and each simulation has the same colour shade as in Fig. 6. The individual flux sites are shown for LE only. Notice the *y* axis shifts to accommodate more sites.

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