Reply letter to Anonymous Referee #1

P2, L17-L29: Kurtz et al. (2014), WRR assimilated piezometric heads and groundwater temperatures.

The suggested literature is included in the revised manuscript (P2,L2).

P4, L22-L23: How is the irrigation handled then?

For computational efficiency and due to the fact that the exact irrigation both in terms of location and amount is not known, the irrigation module is not activated in the model. When assimilating soil moisture we exclude the sites which are subject to irrigation (this only concerns some of the agriculture sites and can easily be detected from the abrupt increases in observed soil moisture). This is explained in the revised manuscript (P4,L26-27 and P15,L5-7)

P6, L5-L9: Is this a realistic perturbation of the forcings? Spatial correlation is excluded and therefore the perturbations have less influence than in case larger grouped areas would get either a positive or negative perturbation of the precipitation.

The forcing grid size (10 km for precipitation and 20 km for ET) is much larger than then the model grid size (200 m). In the present study, the spatial correlation is kept relatively simple. When perturbation is added to each forcing grid, all model grids within this grid will receive a perturbed value of observed precipitation. More realistic and refined schemes for perturbation of precipitation may be considered in the future.

P11, L1: If this would be the case, it would be better not to use localization at all. Was the optimal localization length used, and how was it determined? Was the correlation length of hydraulic conductivity taken into account?

In the univariate assimilation, we did see better result without using localization at all. In the present study, we tested different localization lengths, and determined the optimal localization length empirically. We agree that the correlation length of hydraulic conductivity could be considered to decide the optimal localization length.

P11, L24-L27: Can this be related to Non-Gaussian distributions as soil moisture is Non-Gaussian distributed? At this point, it would be good to know whether soil moisture or pressure is updated in the data assimilation. MIKE-SHE calculates internally with pressure, so probably pressure was updated in/after the data assimilation procedure. This implies that soil moisture data have to be transformed to pressure for which soil hydraulic properties are needed. In addition, pressure shows in general strongly non-Gaussian distributions, especially under drought conditions. If instead the data assimilation is done in terms of soil moisture, and soil moisture is updated, I wonder how piezometric head is assimilated. For those cases, and the grid cells affected (the grid cell with the groundwater level and the grid cells below the groundwater level), soil moisture could be set equal to porosity. Was this done? It would be good to have some more detail here as this also affects non-linearity/non-Gaussianity in the DA and therefore affects the results.

The model state vector consist of groundwater levels and soil moisture. However, the groundwater level and soil moisture states are not updated directly by the Kalman filter. Instead, the groundwater level and soil moisture corrections are transferred into sink/source terms in the numerical solutions to the saturated and unsaturated zone, respectively. This is done to provide a more stable solution.

In MIKE SHE, the saturated and unsaturated zones are explicitly coupled (run in parallel). This is done to optimize modelling time steps used in the unsaturated (minutes to hours) and saturated (hours to days) zone, respectively. The flux between the unsaturated and saturated zones is then calculated by an iterative procedure that conserves mass for the entire column. This means that the assimilation of soil moisture has an effect on groundwater levels, and assimilation of groundwater levels on soil moisture, via the explicit coupling. Thus, there is no need to explicitly set the soil moisture equal to the porosity below the groundwater table.

Section 4.3: Further increase of ensemble size could improve results further. In my opinion, the ensemble size is an unresolved issue.

We completely agree that larger ensemble size could improve the result further. The ensemble size used in the study is a compromise between assimilation performance and computational time. The applied ensemble size is found feasible for operational use of data assimilation with the current model setup.

P13, L14-L15: Is pressure perturbations also transferred to the surface water domain? This could generate the observed stronger perturbations in one of the simulation experiments in the discharge.

Perturbations in groundwater levels will influence the river-aquifer interaction, and hence have an impact on the river discharge. Groundwater level perturbations can also influence drainage flow to the river.

P17, L7-L8: Would a coarser model but a much larger ensemble size not be better? The number of grid cells could for example be reduced by a factor of 4 (half of current resolution) and increase the number of ensemble members by a factor of 4.

When setting up the model, we did find a reduced model performance using a coarser model (500m). However, it is not known whether this can be compensated by increasing ensemble size. We think this is very interesting and can be explored in future studies.