Authors' reply to Short Comment by Albrecht Weerts

We thank Dr Weerts for his time in commenting on our discussion paper. We provide responses to each individual point below. For clarity, comments are given in italics, our responses in plain text.

My main concern is the introduction and the analysis of the results. Especially, the section on time delay (p 9536 line 6-23) and EnFK. The main problem may stem from the way a time lag is modeled (e.g. for instance an unit hydrograph) which cause that states at time t not only depend on the states of time t-1 but also t-2, t-3 etc depending on the concentration time). For example, by using a physically based model for the routing, the time delay and attenuation are modeled more realistically. In this way the states and discharge at time t only depend on the states of time t-1 (see Rakovec et al, 2012) and there is no problem in applying EnKF or (lagged) Particle Filtering. However, as shown by Rakovec et al (2012) the EnKF filter will mainly affect the states of the physically based model for the routing (kinematic wave) which makes sense. A similar issue/problem (the way a time lag is modeled) as mentioned above seems to be present in the saturation-excess runoff part of the model of Clark et al. (2008, see A6), this was also noted by Mendoza et al (2012).

Thank you for drawing our attention to the paper by Rakovec, which we had not previously cited. The paper describes state updating in a distributed hydrological model using the Ensemble Kalman Filter, and we will comment on the findings in our revised paper.
The model that we used (TopNet) allows for two contributions to time lag. The first is through a delay introduced to surface storage, which depends on the distribution of distances to the stream, and the overland flow velocity, which can be calibrated. That is the saturation-excess runoff part referred to in the model of Clark et al. (2008), and occurs only within the subcatchments of the distributed model. The second part is through a kinematic routing scheme (also described by Clark et al., 2008), which routes outflow from all subcatchments to the catchment outlet. Time lags in this part are controlled by reach length, slope, hydraulic geometry and Manning's n. Hence we believe that this is a physically-based routing model as recommended by Dr Weerts.
In our implementation of the REnKF, we update soil moisture, depth to water table, and surface storage. However we do not update water quantity in the kinematic routing scheme. Updating this store produces a fast change in flow at the gauging site, and so is more suitable for the EnKF, as commented. However it does not produce the desired correction to the model states such as soil moisture or depth to water table, and so the model improvement is short-lived (as noted by Li et al. (2011) which we cited). We also note the HESSD comment to the Rakovec paper which questions their approach which does not include the physically realistic lagged relationship between hydrological model states and runoff at the catchment outlet. In all, we believe that our method provides a more physically realistic and sustained correction to model states. In our discussion paper we also cited other systems which update the routing store (e.g. Randrianasolo et al., 2010). This is clearly an important methodological decision and in our revised paper we will discuss these different approaches in greater detail.

Another important issue is the way the hydrological model is made stochastic (perturbed) (Bouttier and Courtier, 1999, page 21) and how it affects the outcome. Unrealistic perturbation (for instance spatially or independent/uncorrelated perturbation to model states/parameters) may cause spurious correlations to occur in the Kalman filter scheme and subsequently erroneous updates. However, for practical applications spurious correlations can be suppressed (see Mitchel and Houtekamer, 2001 or more readable Sorensen et al., 2004).

We agree with Dr Weerts that perturbations to the model states should be correlated in both space and time in order to simulate the physical system. In our implementation of the REnKF, we achieve this by using Gaussian random fields parameterised by the decorrelation time and the correlation length (described in Section 2.2.3). Figure 1 shows an example in the case of spatial correlation of

rainfall perturbations. We followed the recommendations of Clark et al. (2008) in setting the decorrelation times and correlation lengths.

We also agree that suppression of spurious correlations by imposing distance limits is an option when implementing Kalman filter schemes. In the hydrological modelling cases we used, we felt it was reasonable for all parts of the catchment to influence the gauged flow, however in more complex scenarios (e.g. assimilating multiple flow measurements where the upstream area of some gauges is limited), this approach might be beneficial. We also noted in our paper that an experiment to increase the soil moisture perturbations degraded the model performance (P9549 L10), and discussed a non-causal relationship (i.e. spurious correlations) as a possible explanation. We will add a comment on reducing the support of the correlation function to our revised paper.

To get a better handle on what is going when applying EnKF ("numerical artefacts") the paper needs to include one or more twin experiment(s). In this manuscript, it remains unclear what the main cause (not explicit treatment of time delay by model or spurious correlation due to the model perturbations or other cause) of this behavior is. Additionally, the experiments carried out should be described clearly in the material and methods section (separated from the results). Also I would expect the results to include an analysis of the forecast improvements as a function of lead time (and maybe relevant other verification statistics).

In our paper, we performed four experiments for each subcatchment, i.e. (1) Control deterministic run (2) Free-running Ensemble (3) EnKF (4) REnKF. The results are tabulated in Table 3, and presented graphically for one subcatchment in Figure 6. We agree that we could improve the clarity for the reader on which experiments were undertaken. To this end, and as suggested by Dr Weerts, we will add a section at the end of the Methods, to describe concisely which experiments will be used and presented in the Results section.

It is not easy to interpret the exact cause of the artefacts under the EnKF, although we believe we already provided physically realistic representations of time delay (kinematic routing) and time/space correlated perturbations, so these are less likely to be the cause. In Figure 13 we showed that the oscillations in the ensemble median flow under the EnKF were due to water being added/removed from the water table in that case (and this was replicated in other cases; not shown). Since the problem is corrected by use of the REnKF, we interpret that the artefacts are removed due to explicit representation of the lag time, and the iterated application of the EnKF. However, we agree that this is a likely explanation rather than a proof of the cause of the artefacts, and we will change the wording to reflect this. We thank Dr Weerts for the suggestion to include an analysis of forecast performance as a function of lead time, as also suggested by Reviewer 1, and we will include this analysis in our revised paper. We also plan to include other relevant verification statistics.

One other issue is to include a discussion why variational methods are not considered in the present study.

Variational methods are an alternative to Kalman Filter methods, as we noted in the introduction (p9535 L16). In the revised paper we will extend our comment on the differences between these two approaches.