Response to Reviewer #2

This publication presents the results of a spatially distributed sensitivity analysis using different spatial scales: (1) 6-month period, (2) three events and (3) a daily scale using always a 3h timestep. The results show that the aggregation into larger scales produces a loss of information and that the dynamics of the system can be appreciated using a high-resolution analysis. It is also shown how the sensitivities vary spatially depending on the precipitation patterns of individual events. The moving time window enables a clear identification of shifts in processes. It was clearly stated, that a posteriori selection of representative events based on the results of the continuous sensitivity analysis provides more concise results than a priori defined event analysis. The figures are informative and support the text significantly. The combined graphics with joint temporal and spatial distribution of rain depths or sensitivity metrics look nice. This is an interesting paper and I only have few minor comments and suggestions.

Thank you for your time and detailed comments to improve the clarity of our work. We have categorized and responded to all comments below.

Major Comment #1: Clarify role of parameters in SAC-SMA model

P10779_L24: Not everybody will be familiar with the details of the SAC-SMA model. Table 1 refers to some withdrawal rate parameters. Are these parameters constants or (non)linearly dependant to any state variable?

Table 1: Having information about the units for all parameters would be helpful. Please check the parameter values for the 4 parameters in which the unit is %. For example, is the upper bound for the riparian vegetated area 0.2% or 20% ?

In response to both reviewers, we have substantially expanded the explanation of the SAC-SMA model in the methods section of the paper. This revision will be detailed below.

We thank the reviewer for pointing out these issues with Table 1. We have added units for all parameters, and fixed the parameters which have percentage values.

> Herman et al. (2013b) showed that time-varying parameter sensitivity can be linked to the underlying mechanisms of a model. Here, studying the formulation of the SAC-SMA model allows the development of hypotheses regarding the expected parameter sensitivities, and how these might change in space and time. At each timestep, evaporation first occurs from the additional impervious store, both upper zone stores, and the lower zone tension store. In all cases, evaporation is proportional to the saturation level of the storage element. Next, direct runoff occurs from the impervious area, specified by PCTIM, and the additional impervious area due to saturation, specified by ADIMP. Precipitation not assigned to direct runoff enters the upper zone free water store. Gravity drainage occurs from the upper and lower zones according to the rate constants UZK, LZPK, and LZSK, and is linearly proportional to the amount of water in each respective store. Finally, runoff is also generated when the storage capacity of the upper

zone (UZFWM) is exceeded. The same process occurs when all of the lower zone storage capacities are exceeded (LZTWM, LZFPM, LZFSM), but otherwise excess from any of the lower zones will spill into another.

After the runoff generation mechanisms have occurred, each timestep of the model concludes with a redistribution of water between stores according to their saturation levels. First, any deficiencies in the upper and lower tension stores are filled by the free water in their respective zones. Next, percolation occurs from the upper zone free water store to the lower zone based on the saturation level of the lower zone. It is important to note that the lower zone controls percolation in the SAC-SMA model, unlike many other water balance models where percolation is equivalent to spillover from the upper zone. The amount of percolation varies with the parameters Z_{Perc}, the maximum percolation rate under dry conditions, and R_{Exp}, the unitless exponent of the percolation equation (Koren et al., 2004). Finally, the parameter P_{Free} determines the fraction of percolation that enters the primary and secondary free water stores in the lower zone.

From this description of model mechanisms, we can hypothesize which parameters might be most sensitive in space and time. During and immediately after precipitation events, the parameters associated with quick responses should be most sensitive. This includes the impervious area parameters and the upper and lower zone storage maxima, which can cause direct runoff via overflow. We might expect these sensitive parameters to be spatially concentrated near the outlet of the watershed, since only this area will have sufficient time to contribute to streamflow while the event is occurring. Between precipitation events, the primary streamflow generation mechanism will be drainage from the storage zones, controlled by the rate constants UZK, LZPK, and LZSK; we would expect these to be most sensitive in the time following an event, and with a broader spatial distribution to reflect their slower response. As found in prior work (Herman et al., 2013b), the percolation parameters are unlikely to be highly sensitive at any time, for two reasons. First, the amount of percolation is controlled by the moisture deficiency in the lower zone, so the parameter LZTWM (for example) has more influence on the magnitude of percolation than do the percolation parameters themselves. Second, the percolation parameters do not contribute directly to streamflow, so their signature may be obscured by intermediate processes. In general, we expect the lower zone parameters to exhibit higher sensitivity over the course of the simulation than upper zone parameters, because the lower zone deficiencies are filled first during the redistribution routine. It is important to note that the spatiotemporal parameter sensitivities will depend on the output metric chosen (e.g., the sensitivity of the root mean squared error metric will display a different signature than that of the water balance error).

Major Comment #2: Distinguish between “Full Period” and “Event Scale” analysis

P10780: It is mentioned that the analysis will be done for the three events and using a high resolution window. It should be also said that the average sensitivities for the 6 month period will be shown. Chapter 4.1 named “Event-scale sensitivity analysis” shows the results for the whole period besides the results for the three events. If the whole period is also considered to be “event scale”, then this should be explained somewhere.

Fig 4 and 5: Consider changing the title of the plots “Event-scale sensitivity” if the full period is not considered to be at the “event-scale”.

P10787_L19: “.. the sensitivities shown in Fig 4 and 5 are strongly influenced by a few large events..” refers probably only to the first row of plots, since the plots in rows 2 and 3 show the results for single events.

We agree that this issue could be confusing for readers, and we thank the reviewer for pointing it out. We do not consider the full period analysis to be “event scale”. We have modified the text in Section 2.2 (formerly p.10780, in regard to the reviewer’s first comment):

> We begin by computing parameter sensitivity over the full simulation period. Then, in order to explore the potential consequences of event scale diagnostics, we select a priori three sub-periods to represent watershed dynamics. These are highlighted in Fig. 2 for further analysis: (1) a large rainfall event with the highest intensity precipitation focused in the headwaters; (2) a large rainfall event with similar cumulative precipitation but uniform intensity throughout the basin, and (3) a prolonged dry period with low flow. Figure \ref{Fig-3} shows the spatial distribution of forcing for each of the three selected sub-periods. We utilize these three sub-periods to explore the relationship between parameter sensitivities over the full period and those derived for shorter events. We then advance this comparison by computing spatially distributed parameter sensitivities at a high-resolution moving window with a 3-hour timestep. In summary, the experiment consists of sensitivity analysis at three temporal resolutions: the full 6-month period, three representative sub-periods, and the high-resolution moving window. We seek to understand the similarities and differences in dominant model behavior at each of these resolutions. In the absence of process-level watershed data, our diagnostic analysis focuses on the transitions between dominant modeled processes under changing hydrologic conditions.

Furthermore, we have revised the title and first sentence of Section 4.1:

> 4.1 Full Period and Event-Scale Sensitivity Analysis
>
> The sensitivity indices for the root mean squared error (RMSE) metric are shown in Figure 4 for the full simulation period and the three selected events. […]

In response to the second comment, we have modified the titles of Figures 4 and 5 to read “Full Period and Event-Scale Sensitivity”, to ensure clarity for readers. Finally, in response to the third comment, we have clarified the sentence in question as follows:

> Consequently, the sensitivity indices shown in Figs. 4 and 5 for the full simulation period are strongly influenced by only a few large events, […]

Detailed Comments

P10787_L4: In “...this measure of performance succeeds in activating a larger spatial area of the model...”, it would be better to speak of “...succeeds in extracting information from a larger spatial area...”.

This is a valuable clarification. We have made the suggested edit.

P10787_L10: “... will cause a similar concentration of sensitivity ...“ is not clear

P10787_L11: “... whereas distributed precipitation ...”, maybe “ ... homogeneously or uniformly distributed ...” would be better ?

We agree that this sentence was unclear in the original manuscript. We intended to say that when precipitation is spatially concentrated, the sensitivity of model parameters is likely to appear in a similar pattern in the grid cells where precipitation occurred. We have revised as follows:

> These findings align with previous work: spatially concentrated precipitation will cause parameter sensitivity to appear in a similar pattern as the precipitation, whereas uniformly distributed precipitation will cause sensitivity in cells near the outlet […]

P10790_L16: “The parameters ... play a small role in model performance, but they are dominated by the upper and lower zone parameters ... ” is not clear.

Here we are referring to the four parameters whose sensitivities are shown in Figure 8, since they do not strictly fall into the “upper” or “lower” zone categories. These parameters have a moderate, but non-zero, level of sensitivity throughout the simulation. However, the upper and lower zone parameters demonstrate much stronger signatures, meaning that these remaining parameters are rarely controlling model performance. To clarify this issue, we have revised the sentence as shown below.

> The parameters shown in Figure 8 play a small role in model performance, as evidenced by their moderate but non-zero sensitivities through time. However, the sensitivities of the upper and lower zone parameters are typically much larger (see Figures 6 and 7) and thus these remaining parameters rarely control model performance. This result suggests a potential identifiability problem for these less-sensitive parameters, as they are rarely activated in any of the model grid cells.

The movies are nice! Since the word “movies” appears in the title it could be a good idea to add 1-2 sentences about their existence in the text.

Yes, we have included a pointer to the supplement in the first paragraph of Section 4.2. We have also added many more animations to the supplement in this revision.

> While these figures are designed for journal format, animations of time-varying sensitivity indices are available as a multimedia supplement.

We would like to thank Reviewer #2 once more for the time and consideration required to provide these comments.