Summary of Key Revisions

This document contains a summary of the revisions undertaken in response to key points from the two reviewers. Minor comments are also addressed in our revision but are omitted here for brevity; please refer to the prior author comments for discussions of detailed comments. We again would like to thank the reviewers for their time and consideration. Revisions will be shown in red, while reviewer comments will be italicized. In addition to these comments, the supplemental material has been significantly expanded to include more figures and animations in response to several of the reviewers' comments.

Major Comment #1: Provide detailed descriptions of model mechanisms, and use these to develop hypotheses regarding expected parameter sensitivities (Reviewer #1)

There are a number of issues that would improve the work from a good article to an excellent article. (1) The authors present a large amount of data presenting sensitivities at different temporal scales in a well structured way. However, the authors could make a clearer statements about their expectations on how sensitivities should compare across the different temporal scales and for what reason. When presenting the results, they could then check if these expectations hold. At the moment, comparisons across different temporal scales are limited and some differences which were surprising to me are not mentioned and not discussed (see comments 23, 28, 29).

(2) The authors could do an even better job in connecting results from the sensitivity analysis to hydrological mechanisms (in the model). This involves (a) a more detailed explanation of the concepts and intended mechanisms behind SAC-SMA. The method section should make clear, what different mechanisms will mean in terms of (spatiotemporal) parameter sensitivities

We agree with the need to provide a more detailed explanation of model mechanisms and expectations for parameter sensitivity. (Reviewer #2 has requested a similar expansion of the methods section). To address this issue, we have expanded Section 2.1 as follows:

> 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.
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> 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 metric chosen. For example, the sensitivity of the root mean squared error metric on a short timescale will emphasize transitions between quick-response processes, while a water balance error metric on a longer timescale will capture the integrated effects of interacting states and fluxes.

These expectations provide readers with more contextual support for our discussion of results in Sections 4.2 and 4.3. The results often match expectations – for example, the high sensitivity of upper zone and impervious area parameters during large events, compared to the more constant sensitivity levels of the lower zone parameters over time. However, there are a few surprises, such as the consistent (though small) sensitivity of the percolation parameters, as highlighted in the last paragraph of Section 4.2. One especially interesting result is the near-zero sensitivity of grid cells far from the outlet during large events, suggesting that hydrograph peaks do not depend on a significant fraction of the model (as discussed in

Paragraphs 2-3 of Section 4.1). Finally, the specific comments #23, #28, and #29 raise interesting points and will be discussed individually in the list of detailed comments.

Major Comment #2: Provide a specific example of the sequence of dominant parameters and compare to intended mechanisms, and connect this to the concept of hydrologic regimes (Reviewer #1)

(b) Moreover, for a selected number of periods, the spatio-temporal sequence of most influential parameters could be described and compared to the intended mechanisms of the model. (See also comment 17, 24, 25)

(3) A central point of the study is "identifying key transitions between modeled hydrologic regimes". The authors should be explicit about their definition of a hydrologic regime, how a transition between hydrologic regimes are detected and how this is connected to parameter sensitivity analysis. This is currently not made sufficiently clear and somewhat disconnected. During the presentation and discussion of results, the authors could make clearer when we observe such a transition between hydrologic regimes.

Comments (2b) and (3) are connected, because the spatio-temporal sequence of the most influential parameters is what we intended to convey with the term "modeled hydrologic regime". However, we agree that this terminology may be confusing for readers, since the unqualified term "hydrologic regime" suggests a connection to true watershed processes separate from our modeling efforts. We have replaced the term "modeled hydrologic regime" with "dominant parameters and processes" throughout the paper, including in the abstract, introduction, and discussion sections. This clarification has been added to the last paragraph of the introduction section:

> This study proposes high-resolution time-varying sensitivity analysis for a spatially distributed rainfall-runoff model, avoiding the biases introduced by representative event selection by identifying key transitions between dominant parameters and processes *a posteriori*. These parameters dominate the performance of the model at a particular time, distinct from the true dominant watershed processes independent of our modeling efforts.

Assessing the sequence of influential parameters at different times is the intent of Figure 9, which shows a qualitative summary of dominant parameters at increasing temporal resolution. In this work, the transitions between sets of dominant parameters and processes must be detected visually. There is, of course, a subjective component to the summarization of results in Figure 9, but it is important to note that this summary was compiled *a posteriori*, once the time-varying sensitivity results had been analyzed. This represents an improvement over a traditional *a priori* event selection, which may be biased by assumptions regarding the similarity between events without exploring the full dynamic variability of parameter sensitivity throughout the simulation.

As Reviewer #2 has noted, "The moving time window enables a clear identification of shifts in processes". This is the concept that we intend to convey with our discussion of transitions between sets of dominant parameters and processes. In order to clarify this point, we have augmented Section 4.3 with a discussion of the sequence of the most influential parameters in Figure 9 and how this can be used to identify transitions between dominant processes in the model:

> As Figure 9 shows, the dominant controls for the full aggregated period are a combination of lower zone parameters in the headwaters of the basin, and upper zone parameters near both the headwaters and outlet. The full period sensitivities are clearly influenced by the wet periods at the event scale, which exhibit the same responses, indicating that the aggregate period is biased toward these large events (a result consistent with the focus of the RMSE metric). By contrast, dry periods at the event scale exhibit very different sensitivity patterns, centered around slow drainage from the lower zone supplemental store. The summarized high-resolution sensitivity results in the bottom row of Figure 9 provide a more detailed understanding of model behavior than the full period or the event scale. In general, the parameters that appear most sensitive at the event scale are also the most active for the high-resolution moving window. These primarily include the upper zone parameters UZFWM and UZK and the lower zone parameters LZFPM and LZPK. This finding aligns with our initial hypotheses, since gravity drainage and overflow from exceeding storage maxima represent two of the primary runoff generation mechanisms in the model. The most sensitive cells during the rising and falling limbs of large events represent a decomposition of the event scale sensitivity during wet period, which may be particularly valuable depending on the part of the hydrograph being analyzed. As anticipated, the upper zone and impervious area parameters dominate model performance during and immediately following large events, since these create the quick response required to reproduce observed streamflow. The high-resolution dry period exhibits largely the same sensitivities as the event scale, which would be expected considering the lack of dynamic behavior during these dry periods. Finally, the small response reflects the common scenario in which quick runoff must be avoided to achieve good performance, a behavior which remains invisible at the event scale unless a small response event is explicitly chosen for analysis *a priori*.
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> The high-resolution results in the bottom panel of Fig. 9 can also be interpreted to identify transitions between dominant parameters and processes in the model. During the rising limb of streamflow events, the dominant processes in the model are typically direct runoff from impervious area, and overflow/drainage from the upper zone free water store. As might be expected, these processes are most dominant near the outlet of the watershed, reflecting the need for a quick response to match the observed hydrograph. During the falling limb, the model transitions to a dominant process comprising slower drainage responses from the upper and lower zone. These processes are dominant in the headwaters as well in addition to the cells near the outlet, since the longer time lag allows cells further from the outlet to contribute to streamflow. During small responses, the dominant process consists of direct runoff from impervious area and overflow from upper zone tension water, both of which must be properly attenuated to avoid overshooting the observed peak. Finally, during dry periods, a dominant process consisting of slow release from the lower zone often dominates model performance. These types of insights regarding transitions between modeled processes are not attainable from *a priori*

> selection of events assumed to be broadly representative. The coarser event scale sensitivities are typically obscured, and are not necessarily consistent even for seemingly similar events (as highlighted in Figures 4 and 5).
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> It should be emphasized that even though Fig. 9 represents a qualitative aggregation of the high-resolution sensitivity patterns, this aggregation is drawn *a posteriori* from the full range of dynamic parameter activation characterized using the three-hour moving window. The value of the high-resolution approach, as shown in Figs. 6-8, is its ability to isolate parameter activation in space and time while avoiding the potential biases introduced by *a priori* event selection and aggregation.

This clarifies the definition and interpretation of transitions between sets of dominant parameters and processes, which as Reviewer #2 notes is one of the primary strengths of the time-varying approach. The specific comments #17, #24, and #25 also raise important issues and will be discussed in the list of individual comments.

Major Comment #3: Clarify role of parameters in SAC-SMA model (Reviewer #2)

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 #4: Distinguish between “Full Period” and “Event Scale” analysis (Reviewer #2)

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
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> 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, […]

The reader may refer to the responses to individual author comments for a full list of detailed comments. Again, we thank the reviewers for their time and consideration to improve this paper.