Response to comments from Reviewer 5 on “*The evolution of process-based hydrologic models: Historical challenges and the collective quest for physical realism*” by Martyn P. Clark et al.

[Responses are in red font embedded throughout the review].

This is a synthesis paper for the special HESS issue honoring Eric F Wood. The paper is structured around three modeling “challenges” posed by Freeze and Harlan: (1) define suitable model equations – i.e. process parameterizations, (2) define adequate model parameters – i.e., the adequacy of data and the resulting uncertainty; and (3) cope with limitations in computing power – computational constraints. The paper is very successful in presenting historical modeling challenges and summarizing various approaches developed over the years to address the challenges, but less successful in offering a more comprehensive vision of moving forward.

Thanks for the constructive comments. We now define a clear path forward at the end of the paper (7 extended bullet points; see the detailed response below).

The review of the historical progress (and literature) is very comprehensive, and a student wanting to read about land surface modeling could spend a semester reading the paper and selected references, and really learn what has been done. I have one major comment related to areas 1: nothing is mentioned about the numerical schemes used to solve current LSM – especially those like Noah, VIC, Topmodel, mHM, etc. I think the papers by Dmitri Kavetski (e.g. WATER RESOURCES RESEARCH, VOL. 39, NO. 9, 1246, doi:10.1029/2003WR002122, 2003; or JH 320(1,SI)173 - 186 <arch 2006.) offers important insights that need to be included. Martyn probably know of other similar works, since he is the lead author on WRR 46, Art W10510, Oct 8, 2010 with Dmitri.

Thanks. We’ve now included discussion of the numerical solutions. In the section on model execution, we now state:

> *A second (related) solution to the computing challenge is to improve numerical solvers. In simpler models the need for robust numerical methods is often undervalued, and numerical errors in simple models contaminate model analysis and complicate model calibration [Kavetski et al. 2006b; Kavetski and Clark 2010, 2011]. For example, the “pits” in model parameter surfaces have been shown to be an artifact of numerical solution methods, requiring development of elaborate and time-consuming parameter estimation strategies that are not necessary in models with robust numerical solutions [Kavetski et al. 2006a; Clark and Kavetski 2010; Kavetski and Clark 2010]. In more complex models, advances in solution methods are an active area of research, with several recent advances in numerical solvers and parallelization strategies [Qu and Duffy 2007; Kumar et al. 2009; Kollet et al. 2010; Maxwell 2013]. Across all models there is a need to improve numerical solution methods, e.g., evaluate accuracy-efficiency tradeoffs, to support efficient model analysis and calibration strategies.*

Section 5 (Summary and next steps) was rather disappointing. The three points basically says the challenges remain, without any insights as to potential pathways forward. While the majority of the paper would really help students understand LSM developments over the last 40 years, the last section would offer no idea of where new research should go. To say that the key challenge is best posed by a quote by Wood (" What modeling experiments need to be performed to resolve the "scale" question and what is the trade - off among model complexity, the physical basis for land parameterizations and observational data for estimating model parameters? "), given the eminence of the author list, leaves this reviewer somewhat disappointed.

I would recommend that the authors augment this last section by listing potential pathways. Does SUMMA offer a framework for the modeling experiments Wood asks for? Can one develop a virtual reality (with or without SUMMA?), as called out by Wood (Wood, Eric F, Jan Boll, Patrick Bogaart and Peter Troch 2005. The Need for a Virtual Hydrologic Laboratory for PUB, Ch 16 in Predictions in Ungauged Basins: International Perspectives on the State of the Art and Pathways Forward . Eds. S Franks, M Sivapalan, K Takeuchi, and Y Tachikawa, IAHS Pub 301, Wallingford, Oxon. pp189 - 203), to explore " trade - off among model complexity, the physical basis for land parameterizations and observational data for estimating model parameters"? So I challenge the eminent authors of this synthesis paper to offer students and younger colleagues 'hints' on ways forward. It would make the paper much more impactful.

Fair comment. We have revised the conclusions to define a clear path forward:

> *We see several specific needs underlying these general research themes:*
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> *1. We need to improve the theoretical underpinnings of our hydrologic models [Clark et al. 2016]. Most discussions of inter-model differences focus on a discussion of algorithms rather than a discussion of processes. While there have been some calls in the past to improve the "dialog" between experimentalists and modelers [Seibert and McDonnell 2002], e.g., to focus more on processes, much of the interaction between experimentalists and modelers is focused on individual watersheds [e.g., Tromp-van Meerveld and Weiler 2008; Hopp and McDonnell 2009]. Much more work is needed to synthesize process explanations from research watersheds in order to develop more general theories of hydrologic processes [e.g., Tetzlaff et al. 2009], and test these alternative process descriptions in models.*
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> *2. We need to expand our prominence in community hydrologic modeling [Wood et al. 2005; Weiler and Beven 2015], both by providing accessible and extensible modeling tools, and also providing key research datasets and model test cases to scrutinize alternative modeling approaches. Such community activities will result in greater engagement of field scientists in model development and greater collaboration across diverse modeling groups, resulting in substantial improvements in the physical realism and predictive capabilities of hydrologic models. Advancing such community activities requires that we are much more effective and efficient in sharing data and model source code, not just by making models and data publicly available, but, critically, integrating models and data in widely-used analysis frameworks and developing model standards to simplify the sharing of source code in models developed by different groups [Clark et al. 2015b; Clark et al. 2016].*

3. We need to systematically and comprehensively explore the benefits of competing modeling approaches [Clark et al. 2015a; Clark et al. 2015b; Clark et al. 2016]. A key need is to systematically evaluate information gains/losses using models of varying complexity, exploring the interplay between changes in process complexity and changes in spatial complexity. These assessments will help identify useful model configurations for specific applications. Another need is to scrutinize models using data from research watersheds, both using data on internal states/fluxes and inter-variable relationships, in order to understand the benefits of competing process parameterizations. More generally, and as emphasized by Peters-Lidard et al. [2017], it is important to use applications of information theory to quantify how effectively models use the available information, i.e., to provide an estimate of system predictability, and identify opportunities to improve models.

4. We need to substantially advance the development of new modeling approaches that simulate the temporal dynamics of environmental change. Key challenges include predicting how energy gradients dictate landscape evolution, how natural selection favors plants that make optimal use of the available resources, and how the dynamic interactions between humans and the environment shapes the storage and transmission of water across the landscape [Rodríguez‐Iturbe et al. 1992; Eagleson 2002; Schymanski et al. 2009; Schymanski et al. 2010; Sivapalan et al. 2012; Harman and Troch 2014; Zehe et al. 2014; Clark et al. 2016; Grant and Dietrich 2017].

5. We must advance research on process-oriented approaches to estimate spatial fields of model parameters. The challenge is to estimate spatial variations in the storage and transmission properties of the landscape. Advances are possible through developing new data sources on geophysical attributes [Simard et al. 2011; Gleeson and Smith 2014; Fan et al. 2015; Chaney et al. 2016b; Pelletier et al. 2016; De Graaf et al., 2017], new approaches to link geophysical attributes to model parameters [Samaniego et al. 2010; Kumar et al. 2013; Rakovec et al. 2015], and new diagnostic approaches to infer model parameters [Gupta et al. 2008; Yilmaz et al. 2008; Pokhrel et al. 2012]. Such focus will give the parameter estimation problem the scientific attention that it deserves, rather than the far-too-common approach where parameter estimation is relegated to a "tuning exercise" in model applications. This focus on parameter estimation is necessary to improve the physical realism and applicability of process-based models.

6. We need to advance methods for model analysis, especially for complex models. As mentioned above, analysis of complex models is possible by both (a) developing surrogate models, i.e., models that emulate the behavior of complex models and run very quickly [Razavi et al. 2012]; and (b) applying computationally frugal model analysis methods that require a fewer number of model simulations [Rakovec et al. 2014; Hill et al. 2015]. These advances in model analysis are important because complex models are typically calibrated or analyzed using semi-manual or manual strategies, largely because of their immense computational cost (it is only possible to run a handful of simulations). We have very little insight process/parameter dominance and process/parameter interactions in very complex models, where such *information is desperately needed in order to inform meaningful parameter estimation strategies.*

7. Finally, and most important, we need to improve the construction of hydrologic models. Many of today's models have developed somewhat of a "shantytown" appearance, where a succession of students and post-docs bolted on new components to suit the needs of their particular project, and the overall construction of the model has become rather messy. Clark et al. [2015b] define some key requirements as: (a) impose modularity at the level of the individual fluxes, to enable greater model extensibility and code reuse, as it is straightforward to combine different flux parameterizations to form alternative conservation equations; (b) separate the physical processes from their numerical solution, to enable experimenting with alternative numerical solution methods, e.g., evaluating accuracy-efficiency tradeoffs; and (c) use hierarchal data structures, to enable representing spatial variability and connectivity across a range of spatial scales. Such improvements in model construction are a critical underpinning activity that is critical to accelerate advances in hydrologic science.

In addressing these research tasks is important to take a unified perspective. It is important to deliberately depart from previous debates on the "correct" approach to hydrologic modeling, and more effectively use the diversity of modeling tools in order to advance our collective quest for physically realistic hydrologic models.