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Hydrology and Earth System Sciences Discussions

Interactive comment on "Rain or Snow: Hydrologic Processes, Observations, Prediction, and Research Needs" *by* A. A. Harpold et al.

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We appreciate the reviewer's constructive and specific comments on the manuscript. We have addressed all the minor editorial comments and responded to the more detailed comments in the text below. We agree that the sign of a good review paper is creating something new from the gathered information, which was the objective of Section 5. We will bolster that effort by following the reviewer's recommendation about more details on the incorporation of atmospheric models into PPM and better explaining the importance/role of complex terrain.

2 Specific comments

2.1 Synopsis of remotely sensed information Section 3.2 and 3.3 are quite long indicating an emphasis on remotely sensed observations. After reading the two sections I

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feel that a synopsis is missing with general information about the applicability of those observations for PPM, which seems a bit lost in the detailed description in these long sections. I would suggest a summarizing paragraph, or an overview table with the following items, for example: description, coverage, availability, resolution, validated, references. The remotely sensed observations do also hardly appear in section 5 (Research Gaps), while the need to validate these products, was mentioned in the abstract. This synopsis can also be placed in the very short Conclusion section, in which the remotely sensed observations are also only very briefly mentioned (line 800).

We agree that a reader could get lost in the details of this section and not see the bigger picture. To improve this section, we have added both a brief overview at the beginning of section 3.2 and 3.3, as well as a table that more succinctly summarizes the technologies. The research gaps section did discuss remote sensing in section 5.2 and 5.5. Section 5.6 had the following sentence added on line 582: "Recent remote sensing platforms, such as GPM, may offer an additional tool to assess regional variability, however, the current GPM precipitation phase product relies on wet bulb temperatures based on model output and not microwave-based observations (Huffman et al., 2015)."

We also acknowledged that not only the PPM algorithms need improvement but also observations from remote sensing in the conclusions. The first paragraph of section 3.2 now reads "Ground-based remote sensing observations have been available for several decades to detect precipitation phase using bright band heights. Until recently, most ground-based radar stations were operated as conventional Doppler systems that transmit and receive radio waves with single horizontal polarization. Developments in dual polarization ground radar such as those that function as part of the U.S. National Weather Service NEXRAD network, have resulted in systems that transmit radio signals with both horizontal and vertical polarizations. In general, ground-based remote sensing observation, either single or dual-pol, remain underutilized for detecting precipitation phase and are challenging to apply in complex terrain (Table 2)."

The first paragraph is Section 3.3 now reads "Spaceborne remote sensing obser-

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vations typically use passive or active microwave sensors to determine precipitation phase (Table 2). While many of the previous passive microwave systems were challenged by coarse resolutions and difficulties retrieving snowfall over snow-covered areas. More recent active microwave systems have advantage for detecting phase in terms of accuracy and spatial resolution, but remain largely unverified. Table 2 provides and overview of these space-based remote sensing technologies that are described in more detail below."

The table has information on single polarized and dual-polarized ground radar, and spaceborne passive and active microwave sensors. The information in the table will include description, spatial resolution, temporal resolution, phase validation, and relevant references.

2.2 Incorporation of atmospheric information The authors describe well in section 4.2 the problematic scale issue between kilometer- scaled atmospheric models and processes influencing PP which act on a finer resolution. They emphasize that ". . .grid cells are averages requiring hydrological modellers to consider effects of elevation, aspect, etc. in resolving precipitation phase fractions for finer-scaled models." (l588ff). I think this is a very relevant topic and I would like to see this topic further discussed in the research gap section, maybe even with some conceptual ideas and/or reference to existing work, or – if not existent – references to similar work done by the downscaling community to represent unresolved variability on the sub-grid scale.

We agree that model scale is an important effect to consider and have added text to section 5.2 staring on line 750: "Historically, meteorological models have not been run at spatial scales capable of resolving convection (e.g. <2 km), which can exacerbate error in precipitation phase in complex terrain with a moisture neutral atmosphere. Coarse meteorological models also struggle to produce pockets of frozen precipitation from advection of moisture plumes between mountain ranges and cold air wedged between barriers. However, reduced computational restrictions on running these models at finer spatial-scales and over large geographic extents (Rasmussen et al., 2012) are enabling further investigations into precipitation phase change under historical and future climate scenarios. The suggests that finer dynamical downscaling is necessary to resolve precipitation phase is consistent with similar work attempting to resolve winter precipitation amount in complex terrain (Gutmann et al., 2014). A potentially impactful area of research is to integrate this information into novel approaches to improve precipitation phase prediction skill."

The authors also promote in section 5.5 (Develop spatially resolved products) the benefit of gridded products. Since these products probably suffer the same scale problems as mentioned in l588 for atmospheric models, the authors may discuss this aspect of including sub-grid variability here as well.

We agree and add this sentence in section 5.5 beginning on line 847: "Accurate gridded phase products rely on the ability to represent the physics of water vapor and energy flows in complex terrain (e.g. Holden et al., 2010) where statistical downscaling methods are typically insufficient (Gutmann et al., 2012)."

2.3 Specific conclusions for complex terrain The authors mention in the abstract that the manuscript ". . .conveys the advancements needed to improve predictions in complex terrain..." (l22f) and that in complex terrain robust observation networks are missing (l26f). I cannot find many details in the manuscript which allow formulating such a focus on complex terrain in the abstract. I suggest adding a paragraph in the research gap section summarizing specific issues in complex terrain.

The reviewer makes an important point that we address in numerous places within the manuscript. On line 188: "The rain-snow line predicted by atmospheric models is very sensitive to these microphysics (Minder, 2010) and validating these microphysics across locations with complex physiography is challenging." Line 203: "Few research stations, however, have this benefit, particularly in many remote regions and in complex terrain." On line 244: "However, if these observation systems were sufficiently simple they may have the potential to be applied operationally across larger meteorological monitoring networks encompassing complex terrain where snow comprises a large component of annual precipitation (Rajagopal and Harpold, 2016)." On line 298: "In general, ground-based remote sensing observation, either single or dual-pol, remain underutilized for detecting precipitation phase and are challenging to apply in complex terrain (Table 2)." On line 616: "These schemes vary greatly in their accuracy with "mixed phase" schemes generally having the best verifying simulations of precipitation in complex terrain where much of the water is supercooled (Lin, 2007; Reisner et al., 1998; Thompson et al., 2004; Thompson et al., 2008; Morrison et al., 2005; Zängl, 2007; Kaplan et al., 2012). Comprehensive validation of the microphysics schemes over different land surfaces types with a focus on different snowfall patterns (e.g. warm maritime, flat prairie, etc.) is lacking. In particular, in transition zones between mountains and plains or along coast lines the complexity of the microphysics becomes even more extreme as differing air mass characteristics become juxtaposed."

We add a new paragraph in at the beginning of the research gap section: "Similar intensive field campaigns are needed in complex terrain that is frequently characterized by highly dynamic and spatially variable hydrometeorological conditions. Such campaigns are expensive to conduct, but can be implemented as part of operational nowcasting to develop rich data resources to advance scientific understanding as was very effectively done during the Vancouver Olympic Games in 2010 (Isaac et al., 2014; Joe et al., 2014). The research community should capitalize on similar opportunities and expand environmental monitoring networks to simultaneously advance both atmospheric and hydrological understanding, especially in complex terrain spanning the rain-snow transition zone." We also add this sentence to section 5.1: "In complex terrain, air temperature can also vary dramatically at relatively small scales from ridgetops to valley bottoms due to cold air drainage (Whiteman et al., 1999) and hence can introduce errors into inferential techniques such as these." Multiple sentences are added to section 5.2: "Historically, meteorological models have not been run at spatial scales capable of resolving convection (e.g. <2 km), which can exacerbate error in precipitation phase in complex terrain with a moist neutral atmosphere. Coarse meteorological models also struggle to produce pockets of frozen precipitation from advection of moisture plumes between mountain ranges and cold air wedged between barriers. However, reduced computational restrictions on running these models at finer spatial-scales and over large geographic extents (Rasmussen et al., 2012) are enabling further investigations into precipitation phase change under historical and future climate scenarios. This suggests that finer dynamical downscaling is necessary to resolve precipitation phase which is consistent with similar work attempting to resolve winter precipitation amount in complex terrain (Gutmann et al., 2014)." And an additional sentence in section 5.5: "Accurate gridded phase products rely on the ability to represent the physics of water vapor and energy flows in complex terrain (e.g. Holden et al., 2010) where statistical downscaling methods are typically insufficient (Gutmann et al., 2012)."

2.4 Formality issues I would in general like to see page numbers to relevant sections when citing a book (or similar). One prominent example is the book authored by the U.S. Army Corps of Engineers, which regularly is available as a non-searchable pdf document or as a hardcopy. It contains various topics relevant to snow hydrology. To find the cited paragraph without mentioning page numbers is nearly impossible. I think this example shows that the standard of including page numbers when citing books and similar long references should be used. Similarly, the authors have not included access dates for all cited URL (e.g. line 200, line 1077 and others). Some cited references appear different than others (sometimes white spaces between ";" sometimes italic "et al.", sometimes with square brackets). More importantly, there are a few citations which do not appear in the reference list. These points are mentioned in my section "Comments line by line" below.

We appreciate the reviewer's attention to detail and have corrected these in the text and references.

2.5 Motivate Figures in the text Figure 1 and Figure 4 are hardly described in the text, although containing important information. I would suggest that the authors link their text closer to those Figures, especially to Figure 1 which shows the consequences of wrong PP in a hydrological model.

This is a good point by the reviewer. We add additional references to Figure 1 in the introduction. We also add this sentence to the beginning of section 5: “The cascading effects of incorrectly predicting precipitation phase lead to cascading effects on hydrological modeling (Figure 1).” We also better reference Figure 4 at the beginning of section 5 and within section 5.4.

2.6 Explain abbreviations and lines in Figure 2

It is not clear to me what the blue dotted line is (probably the mixing ratio). I would also suggest to add the used abbreviations for H, LE, f(sat), r etc in the caption. The arrow after H or LE should probably indicate that the energy of the hydrometeor is increasing because of a sensible heat transfer? Please clarify these uncertainties.

The following lines have been added to the caption for figure 2: “The blue dotted line represents the mixing ratio. H, LE, f(sat), and r are abbreviations for sensible heat, latent heat of evaporation, function of saturation and mixing ratio respectively. The arrow after H or LE indicate the energy of the hydrometeor either increasing (up) or decreasing (down) which is controlled by other atmospheric conditions.”

3 Comments line-by-line

Line 33ff: This sentence is the same as the previous.

This was deleted.

Line 200/208: Please use access dates with URLs. I suggest putting the links in the reference list.

This was corrected throughout the document.

Line 231: Lejeune not in reference list. This was incorrect and changed to L’hôte et al., 2005.

Line 265. Not clear which the comparison study is.

This was corrected to read: In a comparison study by Caraccioloa et al., (2006), the PARSIVEL optical disdrometer, originally described by Loffler-Mang et al. (1999) did not perform well against a 2DVD because of problems related to the detection of slow fall velocities for snow.

Line 354. The cited study is called Arkin and Ardanuy (1998).

This was corrected.

Line 411 and elsewhere: Kulie and Bennartz (2003) not in reference list

This was corrected.

Line 539: Froidurot wrongly spelled.

This was corrected

Line 945: no page numbers

This was corrected

Line 973: Krug (1995) and Bergström (1995) refer to the same document .

This was corrected

Line 978: Missing page numbers

This was corrected

Line 1037/1040: Please use McCabe and Wollock (1999a) and (1999b)

This was corrected

Line 1213: two times YE et al. (2013) in reference list

This was corrected

Line 1178: delete “publication info” and add page numbers

This was corrected

Table 1: McCabe and Wollock (2009) not in reference list.

This was corrected

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