Effects of more extreme precipitation regimes on maximum seasonal snow water equivalent

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Received 9 July 2012; revised 23 September 2012; accepted 30 September 2012; published 31 October 2012.

[1] Many climate change forecasts project more extreme precipitation regimes (MEPR) in the future, characterized by more intense but less frequent storms. Plausible impacts of MEPR have drawn considerable attention from hydrologists and ecologists, but the hydrological impacts of MEPR in snowfall-dominated regions are less clear. Here we quantify the impacts of MEPR on the maximum seasonal snow water equivalent (SWEmax) based on simulated snowpack dynamics. We show that between any two scenarios with the same amount of precipitation, the one with more intense snowfalls generally has larger SWEmax. Under a warmer climate, SWEmax increases enough with MEPR to partially offset higher melt rates and rain/snow ratios, especially in warm and dry winters. This study demonstrates how MEPR might affect seasonal snow water resources and potentially alleviate the decreasing trend in SWEmax caused by climate warming under specific conditions. **Citation:** Kumar, M., R. Wang, and T. E. Link (2012), Effects of more extreme precipitation regimes on maximum seasonal snow water equivalent, *Geophys. Res. Lett.*, *39*, L20504, doi:10.1029/2012GL052972.

1. Introduction

[2] Seasonal snow is an important natural water storage reservoir for most of the western United States and other snowfall-dominated regions. More than one-sixth of the Earth's population relies on melting snow or ice for their water supply [*Barnett et al.*, 2005]. Larger SWEmax can enhance seasonal peak flows and water availability in snowfall-dominated regions [*Yang et al.*, 2007; *Gottfried et al.*, 2002], and hence has broad implications for a range of coupled earth system processes. Numerous studies have reported the decline of SWEmax under warmer climate [*Mote*, 2003], however the effects of MEPR on SWEmax are an overlooked but important aspect of climate change. Extreme snow and rain events have become more frequent in the US [*Changnon*, 2007; *Knapp et al.*, 2008; *Figdor and Madsen*, 2007; *Groisman et al.*, 2001], and snowstorm-related costs have increased [*Changnon and Changnon*, 2006]. Heavy snowfall followed by melting may trigger serious hazards such as floods, landslides, and soil erosion [*López-Moreno and Vicente-Serrano*, 2011; *Kunkel*, 2003] and affect a suite of related earth system processes.

[3] To gain insight into how MEPR can affect SWEmax under a broad range of climatic conditions, we combine a stochastic precipitation model using the spell-length method [*Wilks and Wilby*, 1999; *Acreman*, 1990] with a 1-dimensional, 2-layer mass- and energy-balance snow model, SNOBAL [*Marks et al.*, 1998] to simulate snowpack dynamics. The two models have been used extensively in the western US [*Lall et al.*, 1996; *Mason*, 2004; *Marks et al.*, 1998]. Four simulations of changes to historical data were conducted to answer the following questions: 1) How do MEPR affect SWEmax, without any changes in the total precipitation? 2) How do MEPR affect SWEmax for different magnitudes of seasonal precipitation? 3) How do the effects of MEPR on SWEmax change for different air temperatures? and 4) How do the effects of MEPR on SWEmax change under a warmer climate for a range of seasonal precipitation and temperature? These questions are intended to assess the sensitivity of SWEmax to MEPR in different regions or years with different climate characteristics.

2. Data and Methods

[4] We used the long-term hourly meteorological data set from the Reynolds Mountain East (RME) watershed, a field laboratory in southwestern Idaho, for analysis. The site and model were selected because of the high-quality data [*Reba et al.*, 2011] and extensive validation of the SNOBAL model [*Marks et al.*, 1998; *Seyfried et al.*, 2009]. Four experiments were conducted with different climate characteristics, in addition to different precipitation intensity and frequency. The climate conditions were: 1) Fixed total precipitation; 2) A range of seasonal precipitation; 3) A range of temperatures; and 4) Different ranges of both seasonal precipitation and temperature. In each experiment, MEPR were represented by nine 'Scenarios' (enumerated from 1 to 9) with synchronized events and the same total amounts of precipitation, but with increasing frequencies of extreme events. Different fractions of rain vs. snow events, referred to as different 'Cases' in the four experiments, were also included to represent different rain/snow ratios in MEPR.

[5] Nine precipitation scenarios were simulated using a variant of the spell-length model. The model identifies precipitation time series based on statistics of wet and dry periods, precipitation event amounts, and hourly weight fractions for precipitation during an event. Based on the precipitation data from 1984 to 2008 at RME, the precipitation event amounts, wet and dry periods, and hourly weight fractions were best fitted using the gamma, lognormal, generalized Pareto and beta distributions, respectively. Degrees of fit of distributions were evaluated using the chi-square test. The nine scenarios were then obtained by changing the coefficients (β_i and α_i) of the gamma distribution for precipitation

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0094-8276/12/2012GL052972

event amounts to N $\times$ β_i and α_i/N, respectively. This ensured that the simulated precipitation events for scenarios with different N had the same mean ($\alpha_i\beta_i$) but different variance (N$\alpha_i\beta_i^2$). Here N (N = 0.5, 1, 2, 4, 6, 8, 10, 12, and 14) is a scaling factor that was used to adjust the intra-seasonal variability of precipitation events to generate nine scenarios. Each scenario entailed 50 random realizations of a precipitation series during the cold season, and they were used to assess the average and variance changes in SWEmax. Simulated average SWEmax reached a steady state for 50 random series. The frequencies of extreme precipitation from Scenario 1 to 9 were 3.3%, 5.0%, 6.7%, 8.3%, 9.6%, 10.2%, 10.6%, 10.9%, and 11.0%, respectively. Here, extreme precipitation was defined as a daily amount larger than the 95th percentile in the base scenario (Scenario 2). In relation to the base frequency (Scenario 2), the frequency of extreme precipitation ranged from −35% (Scenario 1) to 120% (Scenario 9), generally within the range of change in reported extreme precipitation for the US [*Figdor and Madsen*, 2007]. The nine synthetic precipitation scenarios were then used to drive SNOBAL to simulate SWE. Other climate variables such as air temperature, vapor pressure and all-wave incoming radiation were modeled as a combination of two sine curves that describe their typical annual and diurnal variations, respectively. Parameters were estimated based on historical average of annual and diurnal cycles. To more accurately simulate actual storm conditions, variables (e.g., air temperature, vapor pressure, precipitation density) during storm durations were assigned fixed values in all four experiments. Wind speed and soil temperatures during the cold season were fixed at historical average values. These approaches enabled the assessment of the consequences of MEPR in isolation, without confounding effects of amount and temporal distribution of precipitation. Additional details regarding the generation of precipitation scenarios and SNOBAL structure are provided in the Text S1 in the auxiliary material.[1]

[6] The simulated precipitation and temperature time series based on historical records were considered as the base case that was then modified to generate a range of climatic conditions for the four experiments. In Experiment 1, three cases with 100%, 88%, and 74% of the precipitation events as snowfall were considered. Case 1 represented an all snow regime, Case 2 represented a precipitation regime with average fraction of snowfall events during the cold season being equal to the historical observations, and Case 3 represented the fraction of snowfall events considering a 2°C increase in temperature. The fraction of rain to snow in each month was assigned based on historical precipitation measurements. Precipitation events were classified as rain when the dew point temperature was above 0°C. In Experiment 2, the three cases in Experiment 1 were repeated for 12 different seasonal precipitation values. Different seasonal precipitation amounts were generated by rescaling the magnitudes of hourly precipitation in increments of 20% with respect to the base precipitation time series. In Experiment 3, 16 different average air temperature series were generated by rescaling the hourly air temperatures in 1°C increments with respect to the base temperature time series, except during storms. In order to identify the specific impacts of air temperature due to altered melt rate and precipitation phase, two cases were considered: Case 1, where all precipitation events were snow, and only the effect of changing temperature on the melt rate was considered, and Case 2, where changes in the fraction of snow events with increased air temperature were considered in addition to the effect on melt rate. Three cases were considered in Experiment 4: 1) Current average air temperature and fraction of snow events, 2) A 2°C increase in air temperature without any changes in precipitation phase, and 3) A 2°C increase in air temperature concomitant with a decrease in the fraction of snow events. The 2°C increase in air temperature was selected as an approximation of predicted changes 50 years into the future [*Coquard et al.*, 2004]. The increase in air temperature varied between different months, with a greater value in winter based on historical data sets [*Nayak et al.*, 2010]. The three cases were then repeated for a range of seasonal precipitation and air temperature conditions. The lower and upper range of seasonal precipitation approximated the driest and wettest years for RME in the period from 1984 through 2008. The lower and upper range of cold season average temperature ensured a precipitation regime varying from an all-snow (snow/precipitation ratio = 1.0) to a nearly rainfall-dominated (snow/precipitation ratio = 0.53) series. With a 2°C increase in average temperature, the snow/precipitation ratio for cold, moderate, and warm conditions became 0.98, 0.75, and 0.38, respectively.

3. Results and Discussion

3.1. How Do MEPR Affect SWEmax, Without Changes in the Total Precipitation?

[7] Figure 1 shows the mean SWEmax of 50 random precipitation series for each of the nine scenarios. Random timing of intense snowfalls can cause a large range of variation in SWEmax. However, larger SWEmax values are consistently more probable with an increase in MEPR (Figure 1, inset). On average, MEPR are likely to increase SWEmax. As the frequency of extreme snow events increases from Scenario 1 to 9, the mean SWEmax increases by almost 12.3%, from 552 mm to 620 mm (Case 1). The increasing trend is mainly due to the following three reasons: 1) Deeper snowpacks gain less cumulative net energy for melt during the accumulation season. Precipitation series with larger (i.e. more extreme) snow events cause increase in the accumulated snowpack lead to larger SWEmax values relative to less extreme series for the same amount of precipitation. This can be explained based on the thermodynamic comparison of melt between a relatively large and small snowpack under identical climate conditions. If two different snow masses are isothermal at 0°C (that is, the cold contents of both are zero) for identical amounts of successive energy gain or loss, the temperature of the larger snow mass over time will be greater than or equal to the temperature of the smaller mass because of its higher thermal capacity. The temperatures may be equal because the upper bound of the snow temperature is 0°C. This means that for identical amounts of energy gain or loss, the larger snowpack will have a higher average temperature. Higher average temperatures will cause the larger snowpack to receive less cumulative energy rather than identical amounts of energy gain or loss, yet still have a higher average temperature relative to the smaller snowpack (Text S2, Figure S2). The lower cumulative energy is because a warmer snowpack emits greater longwave radiation and has smaller

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL052972.

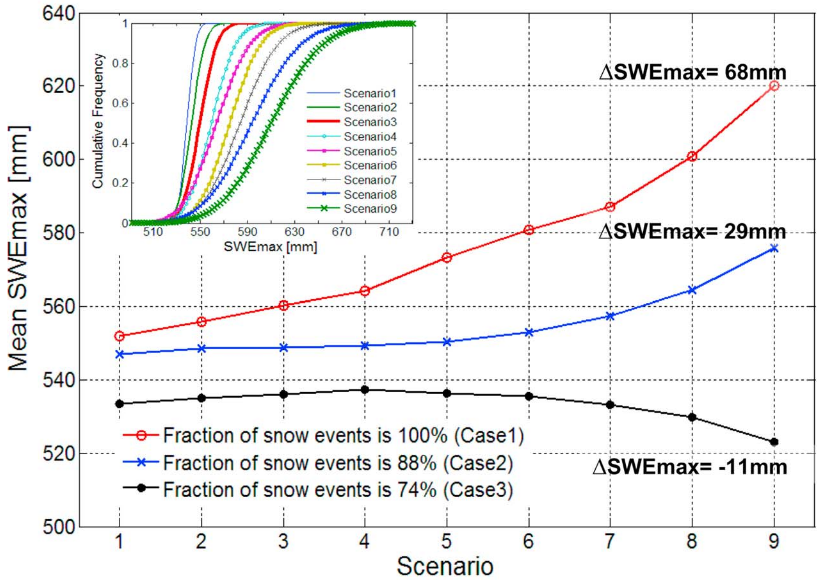

Figure 1. Mean of SWEmax for 50 random precipitation series for the nine scenarios. The nine scenarios have increasing frequency of extreme precipitation. ΔSWEmax is the difference in mean SWEmax between Scenarios 1 and 9. The embedded figure shows the cumulative frequency of SWEmax for Case 1.

temperature gradients between snow and air, and snow and soil. This will cause a warmer snowpack to receive less net radiative, sensible, and ground heat fluxes. Less cumulative energy produces less melt during occasional warm periods during the accumulation phase, thereby leading to a larger SWEmax. 2) The second factor is the delay in the onset of occasional melt due to more negative advective energy associated with larger snow events. As noted earlier, extremely large events can cause a sudden increase in the accumulated snowpack. For identical snowfall temperatures, a larger accumulated snowpack requires more cumulative energy and hence time to initiate melt. In addition, the larger mass has a higher water storage capacity, which increases the possibility that melt will be retained and refreeze in the snowpack during intermittent cold periods. This reduces the rate of net mass loss from the larger snowpack. Both of these reasons may contribute to the increase of SWEmax under MEPR. 3) The third factor is the non-optimal use of available energy for snow melt. MEPR is characterized by more intense but less frequent precipitation events. The first two points indicate the consequences of extremely large snowfalls. This point highlights the impact of snow-free periods in the early deposition phase that happens before the occurrence of extreme snow events. Chance of intermittent snow accumulation and complete melt-out in the beginning of the snow season is higher for MEPR. Periods of no snow cover means that the energy that may be used for melting the same amount of snow in a less extreme regime remains unused for melt. This results in less melt during the early deposition phase, contributing to larger SWEmax. For a smaller fraction of snow events, increase in SWEmax due to MEPR is less (Case 2). This is because a decrease in fraction of snow events (and hence an increase in fraction of rain events) translates to a smaller difference in the frequency of intense snowfalls, and larger difference in the frequency of intense rainfall between the nine scenarios. Relatively larger water and energy pulses during intense rainfall increase the potential for the water holding capacity of accumulated snow to be exceeded, in contrast to small rain events that may be retained by the snowpack. More intense rainfall in MEPR equates to more runoff and contributes to decreased SWEmax. For an even smaller fraction of snow events (Case 3), SWEmax initially increases but subsequently decreases from Scenario 1 to 9. The decreasing trend is because higher proportions of intense rainfalls offset the increase in SWEmax caused by intense snowfalls.

3.2. Question 2: How Do MEPR Affect SWEmax for Different Magnitudes of Seasonal Precipitation?

[8] Experiment 2 assesses the sensitivity of SWEmax to MEPR, quantified by the difference in SWEmax between Scenarios 1 and 9 (ΔSWEmax), for different amounts of seasonal precipitation . For the 100% snowfall case, over a range of seasonal snow amounts from 289 mm to 1882 mm, the sensitivity of SWEmax to MEPR first increases and then decreases. The maximum ΔSWEmax of 107 mm occurs for 1013 mm seasonal precipitation representing a 14.6% increase in SWEmax between Scenarios 1 and 9 (Figure 2, Case 1). An important point to highlight here is the increase and then subsequent decrease in ΔSWEmax as the magnitudes of seasonal precipitation and extreme snow events increase. The rapid increase in the accumulated snowpack due to extreme events in the early period is larger for wetter years, resulting in a gradual increase in ΔSWEmax with increasing seasonal snowfall. The reversal of the trend in ΔSWEmax can be explained for similar reasons that were discussed for Experiment 1. For drier years, snow temperatures within the shallow snowpacks readily reach 0°C, irrespective of the MEPR scenario, hence resulting in smaller difference in cumulative energy and smaller ΔSWEmax values. Since the entire shallow snowpack is susceptible to melt in the accumulation period, differences in the onset of melt and length of snow free periods between MEPR scenarios are small, resulting in a small ΔSWEmax. With

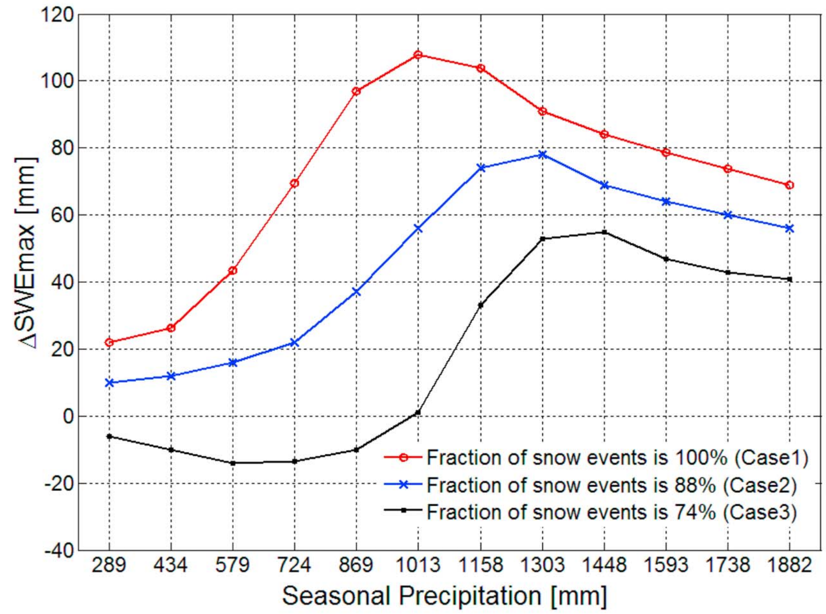

Figure 2. The variation in ΔSWEmax with increasing seasonal precipitation. The seasonal amount of precipitation changes from 289 mm to 1882 mm in steps of 145 mm (20% of the base seasonal precipitation of 724 mm).

increasing seasonal precipitation, difference of cumulative net energy between MEPR scenarios increases and then decreases (Text S2, Figure S6). For intermediate seasonal precipitation, snowpacks are deeper, and hence reach 0°C less frequently. This leads to larger differences in the cumulative net energy input and melt between MEPR scenarios, resulting in larger ΔSWEmax values. Differences in the onset of melt and snow free periods between MEPR scenarios are larger, contributing to an increase in ΔSWEmax. For wet years, snow temperature fluctuations are small irrespective of the MEPR scenarios, because of the higher thermal capacity of the deeper snowpacks. This results in a smaller difference in the melt amounts between MEPR scenarios, and hence smaller ΔSWEmax. In addition, larger early snow events ablate less frequently and tend to cause smaller ΔSWEmax As the fraction of snow events decreases, ΔSWEmax decreases as described in Experiment 1. However, ΔSWEmax increases and then subsequently decreases with increasing seasonal precipitation for most of the rain/snow cases (Figure 2). Notably, In Case 3, as the seasonal precipitation increases from 289 mm to 579 mm, ΔSWEmax decreases. Negative ΔSWEmax indicates that SWEmax is smaller under MEPR scenarios. This is because extreme rain events dominate over extreme snowfall events causing smaller SWEmax for drier seasonal conditions.

3.3. Question 3: How Do the Effects of MEPR on SWEmax Change for Different Air Temperatures?

[9] Experiment 3 shows that ΔSWEmax initially increases but subsequently decreases with increasing average cold season air temperatures. For Case 1, as the average air temperature in the cold season changes from −8.2°C to 5.8°C, ΔSWEmax varies from 5.3 mm to 181 mm, with a peak difference of 260 mm at 3.8°C, representing a 331% increase in SWEmax between Scenarios 1 and 9, for a moderate precipitation amount (Figure 3a, Case 1). The reasons for the varied sensitivity are similar to the ones discussed above: 1) For the lower average air temperatures, snow temperatures for all MEPR scenarios are less likely to reach 0°C during the winter and hence difference in cumulative energy is relatively small. With increasing air temperatures, the likelihood of melt events increases, resulting in larger difference in cumulative energy. However, once the air temperatures exceed a threshold value, melt events occur so frequently in all nine scenarios, that SWEmax is less sensitive to MEPR and difference in cumulative energy decline (Text S2, Figure S7). 2) Similarly, the second reason is that for the highest air temperatures, the entire snowpack is susceptible to melt, while for the lowest air temperatures, negligible snow melt occurs. Both cases resulted in relatively small differences in both the onset of melt and period of no snow cover between different MEPR scenarios, hence resulting in smaller relative ΔSWEmax values.

[10] If changes in the fraction of snow events for different air temperature conditions are considered, the variation in ΔSWEmax with increasing temperature is notable, although less pronounced. The maximum ΔSWEmax of 126 mm occurs at 2.8°C, corresponding to a 149% increase in SWEmax from Scenario 1 to 9 (Figure 3a, Case 2). For drier and wetter years, the maximum response of SWEmax to MEPR occurs at lower and higher air temperatures, respectively (Figures 3b and 3c).

3.4. Question 4: How Do the Effects of MEPR on SWEmax Change Under a Warmer Climate for a Range of Seasonal Precipitation and Temperature?

[11] Experiment 4 explores the potential impacts of MEPR on SWEmax under a warmer climate for a range of temperatures (Figure 4, rows) and precipitation (Figure 4, columns). For the wide ranges of seasonal precipitation and air temperatures considered in Experiment 4, an increasing trend in SWEmax from Scenario 1 to 9 was consistently present (Case 1). A 2°C increase in average air temperature intensified the increasing trend in SWEmax with MEPR for most conditions

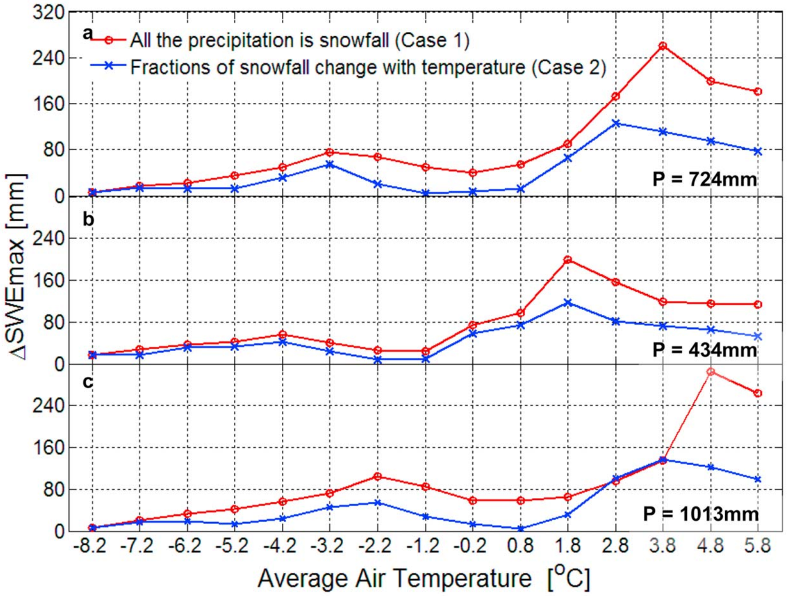

Figure 3. The variation in ΔSWEmax with increasing average air temperatures during the cold season. Case 1 considers the effect of temperature only on the melt rate; Case 2 considers changes in fraction of snow events with increased temperature in addition to the effect on melt rate. (a, b, and c) Shown are the responses of ΔSWEmax to increased temperature for different seasonal precipitation amounts (P).

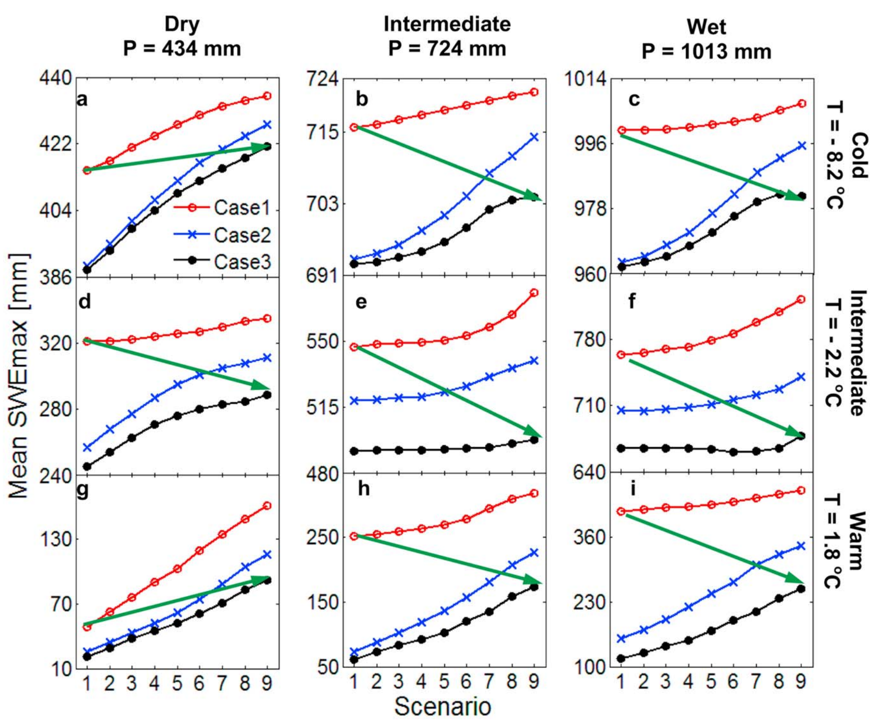

Figure 4. Ensemble mean of SWEmax for (a–i) the nine MEPR scenarios under different seasonal precipitation (P) and air temperature (T) conditions. Case 1 represents the baseline average air temperature and fraction of snow events ($\Delta T = 0°C$, $\Delta Fs = 0$); Case 2 represents a 2°C of increase in air temperature without any changes in precipitation phase ($\Delta T = 2°C$, $\Delta Fs = 0$), and Case 3 represents a 2°C increase in air temperature concomitant with a decrease in the fraction of snow events ($\Delta T = 2°C$ & $\Delta Fs \neq 0$). The arrow indicates the general trend in SWEmax for a warmer climate when the combined effects of MEPR, higher air temperatures and larger rain vs. snow fractions are considered.

(Case 2). A concomitant decrease in the fraction of snow events with warming (Case 3) decreased the slope of the increase in SWEmax relative to Case 2, but increases in SWEmax with MEPR persisted for almost all conditions. For cold winters, changes in SWEmax under warmer temperatures and MEPR are small (note differing y-axis scales in Figure 4), however changes in SWEmax are more significant in warmer winters. A very important result is that the decreases in SWEmax due to warming and decreased fraction of snow vs. rain events were in some cases negated by increases in SWEmax due to MEPR. For example, for the warmest and driest condition, SWEmax for Scenario 9, Case 3 exceeded SWEmax for Scenario 1, Case 1 by about 29 mm (Figure 4g). This result is especially notable because regions characterized by these conditions are frequently challenged by limited water resources and are particularly susceptible to changes in cold-season hydrological processes driven by climatic warming. The result also highlights that it is critically important to consider changes in both amount and intra-annual variability of precipitation when assessing the impacts of climate change on snow-dominated systems.

4. Conclusions

[12] This study explored the responses of SWEmax to both more and less extreme precipitation regimes. It can be inferred from modeling results that as the frequency of extreme snowfall increases, the average SWEmax increases. The rate of increase in SWEmax caused by MEPR changes with air temperature, seasonal snow amount and precipitation phase. With reported declines in SWEmax and shifts in snowmelt timing, many studies have focused on the impact of climate warming on water availability and related processes that are tightly coupled to the hydrologic cycle. This work shows that it is critical to consider both the effect of warming and more extreme intra-annual precipitation variability when conducting assessments of such impacts. Increases in SWEmax caused by MEPR could partially offset the reported decline in SWEmax, especially in warmer and drier winter conditions. Increases in SWEmax due to MEPR could also increase spring melt for instances when and where MEPR is not concurrent with warmer temperatures. It is also possible that in actual basins, the amount of SWEmax changes may be either enhanced or reduced by spatiotemporal heterogeneity in hydrometeorological variables, hence the effects of MEPR using spatially distributed models are needed to further enhance our understanding of the hydrologic effects related to climatic variability. Even though the use of an extensively validated physically based model and physically plausible explanations lend credence to the result, the experiment does not account for uncertainty in the magnitude of changes in SWEmax because of model structure. Further studies focused on multi-model ensemble comparisons can be used evaluate the uncertainty. This study also provides a basis for further exploration of the effects of MEPR on the timing of snowmelt runoff, another very important determinant in water resources management, and the spatially-explicit quantification of SWEmax alterations due to MEPR.

[13] **Acknowledgments.** This study was supported by the Duke University start-up grant and NSF-CBET Award No. 0854553. We would like to thank Danny Marks, Adam Winstral and Michele L. Reba for providing us access to data set from RME and to SNOBAL. We thank Jeff Dozier and Jessica Lundquist for constructive comments that greatly improved this paper.

[14] The Editor thanks Jeff Dozier and Jessica Lundquist for their assistance in evaluating this paper.

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