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Key Points:

- In extreme rain-on-snow floods, snowmelt continuously augmented precipitation
- Snowpacks seemed saturated and snowmelt was correlated in all snow-covered areas in extreme floods
- Snowmelt and precipitation pulses were synchronized at hourly to daily scales in extreme floods

Supporting Information:

- Supporting Information S1

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Precipitation-snowmelt timing and snowmelt augmentation of large peak flow events, western Cascades, Oregon

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Abstract This study tested multiple hydrologic mechanisms to explain snowpack dynamics in extreme rain-on-snow floods, which occur widely in the temperate and polar regions. We examined 26, 10 day large storm events over the period 1992–2012 in the H.J. Andrews Experimental Forest in western Oregon, using statistical analyses (regression, ANOVA, and wavelet coherence) of hourly snowmelt lysimeter, air and dewpoint temperature, wind speed, precipitation, and discharge data. All events involved snowpack outflow, but only seven events had continuous net snowpack outflow, including three of the five top-ranked peak discharge events. Peak discharge was not related to precipitation rate, but it was related to the 10 day sum of precipitation and net snowpack outflow, indicating an increased flood response to continuously melting snowpacks. The two largest peak discharge events in the study had significant wavelet coherence at multiple time scales over several days; a distribution of phase differences between precipitation and net snowpack outflow at the 12–32 h time scale with a sharp peak at $\pi/2$ radians; and strongly correlated snowpack outflow among lysimeters representing 42% of basin area. The recipe for an extreme rain-on-snow event includes persistent, slow melt within the snowpack, which appears to produce a near-saturated zone within the snowpack throughout the landscape, such that the snowpack may transmit pressure waves of precipitation directly to streams, and this process is synchronized across the landscape. Further work is needed to understand the internal dynamics of a melting snowpack throughout a snow-covered landscape and its contribution to extreme rain-on-snow floods.

1. Introduction

Much recent literature has addressed the changing character of mountain snowpacks and the consequences for water yield and timing at seasonal and longer time scales. Snowpacks also change character dramatically at shorter time scales, particularly during rain-on-snow events, when they may retain precipitation and dampen flood peaks, or melt and contribute to extreme floods. Yet it is not well-understood how snowpack dynamics contribute to extreme rain-on-snow floods [*McCabe et al.*, 2007; *Jones and Perkins*, 2010].

Rain-on-snow events occur widely in the temperate and polar regions, including New Zealand [*Fitzharris et al.*, 1999], the Andes [*Waylen and Caviedes*, 1990], the Himalayas [*Putkonen*, 2004], Alaska, northern Canada and Siberia [*Rennert et al.*, 2009; *Liston and Hiemstra*, 2011], Russia [*Ye et al.*, 2008], Great Britain [*Johnson and Archer*, 1973], Belgium [*Bauwens*, 1985], Germany [*Sui and Koehler*, 2001; *Garvelmann et al.*, 2014], Austria [*Singh et al.*, 1997], Switzerland (*Braun and Zuidema*, 1982; *Rössler et al.*, 2014], New England and the mid-Atlantic United States [*Anderson and Larson*, 1996; *Leathers et al.*, 1998; *Pradhanang et al.*, 2013], British Columbia [*Beaudry and Golding*, 1983; *Floyd and Weiler*, 2008], and California [*Kattelmann*, 1997], as well as the Pacific Northwest of the US [*Christner and Harr*, 1982]. Rain-on-snow events have the potential to generate devastating floods: the western Cascade Range of Oregon has produced some of the most extreme floods ever recorded in the United States [*O'Connor and Costa*, 2004]. These extreme floods were almost always regional rain-on-snow events, producing fatalities and high estimated damages [*U.S. Army Corps of Engineers (USACE)*, 1996; *Ashley and Ashley*, 2008].

Sixty years of research on rain-on-snow floods has provided limited insights into the internal dynamics of snowpacks during storm events. Much of the literature has focused on modeling the snowpack energy budget [e.g., *USACE*, 1956; *Harr*, 1981; *van Heeswijk et al.*, 1996; *Marks et al.*, 1998; *Rössler et al.*, 2014]. Other work has addressed how openings, such as those created by clearcutting, may augment rain-on-snow peak discharges [*Harr*, 1986; *Berris and Harr*, 1987; *Marks* et al., 2001; *Storck* et al., 2002]. Rain-on-snow peak

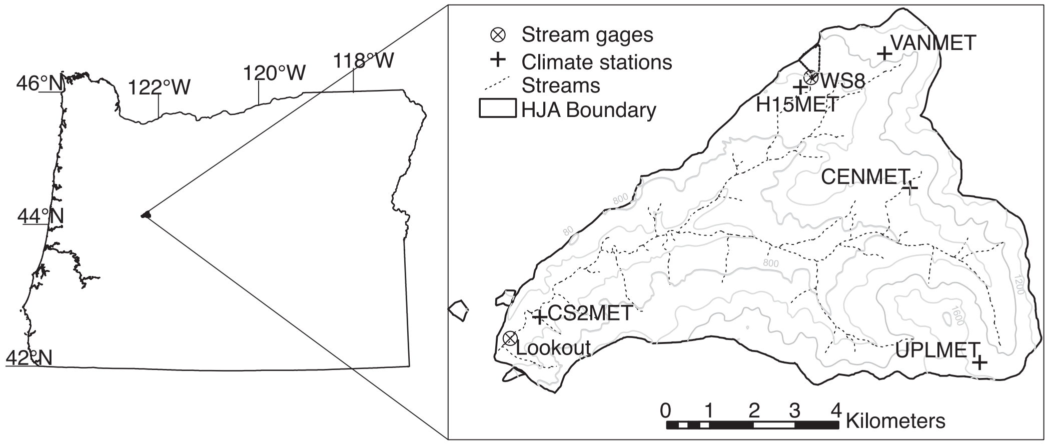

Figure 1. Location of study site (H.J. Andrews Experimental Forest) in Oregon, which includes the Lookout Creek drainage basin, and contains the 21.4 ha Watershed 8. Meteorological and gaging stations used in this study are shown on 200 m contours.

discharge cannot be predicted based on precipitation input alone [*Harr*, 1981; *Perkins and Jones*, 2008; *Jones and Perkins*, 2010], but precipitation increases snowpack water output and may affect streamflow [*Berris and Harr*, 1987; *Berg et al.*, 1991; *Singh et al.*, 1997; *Whitaker and Sugiyama*, 2005].

Multiple hydrologic mechanisms may be involved in extreme rain-on-snow floods. The snowpack may melt or accumulate, store or release water at various lags relative to precipitation, and become gradually saturated over multiple days. Hourly pulses of water from the snowpack may be coherent with pulses of precipitation, but out of phase, mitigating precipitation inputs. Alternatively, pulses of precipitation and snowmelt may be almost in phase, creating constructive interference and transmitting pressure waves through the near-saturated snowpack. The rain-snow transition zone may span large elevation bands, producing simultaneous melt throughout large areas. Twenty years of hourly snowpack outflow and matching meteorological and discharge data in the H.J. Andrews Experimental Forest in western Oregon provide the opportunity to examine these hydrologic mechanisms. Our objective was to identify the features of a rain-on-snow event that produce an extreme flood.

2. Study Site and Data

The H.J. Andrews Experimental Forest occupies the fifth-order, westward-facing 6400 ha Lookout Creek basin, located on the western slope of the Oregon Cascades (Figure 1). Elevation ranges from 410 to 1630 m and slopes are typically steep (40% average), with subbasin slopes ranging from 25 to 60%. Miocene to Pliocene volcanism overprinted by Pleistocene glaciation and large, deep earthflows shape the geology and geomorphology [*Swanson and James*, 1975; *Swanson and Swanston*, 1977]. The climate is Marine West Coast with cool, wet winters and warm, dry summers. More than 80% of precipitation occurs between November and April. Mean annual precipitation (MAP) is 2200 mm at the CS2met station but varies with elevation from 1900 to 2900 mm as a result of orographic and rain shadow processes. Winter precipitation falls as a mix of rain and snow. Below 800 m, snowpacks rarely last longer than 2 weeks, but above 800 m (71% of basin area), snowpacks may last from early November to late June. Vegetation below 1050 m is dominated by Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*), with subalpine forest above 1050 m [*Franklin and Dyrness*, 1971]. Soils are highly porous Inceptisols and Andisols with infiltration rates >1 m h^{-1} and moisture storage capacity >0.5 m [*Brown and Parsons*, 1973; *Ranken*, 1974; *Dyrness*, 1969]. Overland flow does not occur except on roads or surfaces compacted by logging [*Harr*, 1977], and soils rarely freeze [*Jones and Perkins*, 2010]. Maximum daily streamflow in Lookout Creek (gage elevation 422 m, Figure 1) occurs in December or January, and minimum flow occurs in mid to late September. Rain-on-snow events typically occur between November and March [*Harr*, 1981, 1986; *Perkins and Jones*, 2008]. This study focused on Watershed 8 (WS8, Figure 1), a 21.4 ha, first-order, south-facing subbasin of Lookout Creek. Elevation in WS8 ranges from 970 to 1180 m and the average slope gradient is 25%. Vegetation is 150–500 year-old forest dominated by Douglas-fir, western hemlock, and Pacific silver fir (*Abies amabilis*) [*Dyrness and Hawk*, 1972].

This study used hourly data on streamflow from the Lookout Creek and WS8 gages; precipitation, air temperature, dewpoint temperature, and wind speed (at CS2met (482 m), H15met (909 m)); output from snowmelt lysimeters (at H15met, CENmet (1028 m), UPLmet (1298 m)); and snow water equivalent (SWE) (at CENmet, VANmet (1268 m), and UPLmet, Figure 1). All data were at hourly time resolution. Data were obtained from http://andrewsforest.oregonstate.edu/. We also used data from three Snowpack Telemetry (SNOTEL) stations within 30 km: Jump Off Joe (1070 m), McKenzie (1450 m), and Roaring River (1510 m).

Streamflow data were obtained from a trapezoidal flume with 5 min stage height readings (WS 8 (968–1182 m)) and a USGS gage (Lookout Creek (412–1631 m)). Precipitation data were obtained from a heated rain gauge at a 10 s resolution. Precipitation phase at H15met was determined following *Marks et al*. [2013]: precipitation was considered to be snow if dew point temperature was $\leq -0.5°C$, rain if dew point temperature was $\geq 0.5°C$, and mixed phase if dew point temperature was $> -0.5°C$ and $< 0.5°C$. Precipitation in the mixed phase was separated into rain and snow fractions assuming a 10% increase in rain for each 0.1°C rise above $-0.5°C$. Cumulative precipitation for each storm was calculated as the depth of precipitation (mm) accumulated up to time *t*. The runoff ratio was defined as streamflow divided by precipitation.

Air temperature and relative humidity data were recorded using Campbell HMP35C (12 March 1992 to 2 September 2002) and HMP45C (2 September 2002 to present) probes located 4.5 m above ground level. Dew point temperature was calculated from air temperature and relative humidity. Wind speed data were collected using a propeller-type anemometer located at 5 m above ground level. An analysis of 1 year of hourly data from colocated sonic (usonic) and propeller (uprop) anemometers at PriMet indicated that the two instruments were in strong agreement ($r^2 = 0.98$), although the propeller anemometer generally reported lower wind speeds than the sonic anemometer (usonic = uprop * 1.01 + 0.23).

Snowmelt lysimeter data were obtained from open-topped wooden boxes (2.3 m $\times$ 2.3 m $\times$ 0.3 m) installed at ground level. A hypalon rubber lining directs water ("snowpack outflow") to a drain in the lowest corner, which empties into a tipping bucket gage. Data are summarized at 5 min intervals, and recorded to the nearest 0.01 mm. Three snowmelt lysimeters are located at meteorological stations (Figure 1) in forest canopy gaps (diameter 100–250 m) surrounded by old-growth forest (80 m trees) (H15) or regenerating forest (10 m trees) (Cenmet, UPLmet). Water-year output (O) from the H15met lysimeter agreed with water-year precipitation (P) at the H15met precipitation gage located a few meters away ($O = 159 + 0.93 * P$, $n = 22$, $r^2 = 0.85$); differences are likely attributable to drifting snow or missing data.

Snowpack outflow is the sum of precipitation plus net snowpack outflow, measured at the snowmelt lysimeter. "Net snowpack outflow" was defined as snowpack outflow minus incoming precipitation, both measured at H15met (Figure 1). Net snowpack outflow expresses whether the snowpack is functioning as a sink or a source of water to the hydrologic system, although the pathways and phases of water within the snowpack could not be discriminated based on statistical or energy budget modeling. Incoming precipitation may enter the lysimeter as snow and then melt; enter as rain, freeze, and then melt; or enter as rain, percolate through the snowpack and exit without freezing. In addition, water vapor may condense as water on the surface of the snowpack, freeze and then melt, and percolate through the snowpack; and snow may sublimate, or water may evaporate, from the snowpack surface. Cumulative net snowpack outflow was calculated as the sum of net snowpack outflow up to time *t* and is the depth of liquid water (mm) released by the snowpack. When cumulative net snowpack outflow was negative, water was retained within the snowpack, and when it was positive, water was released by the snowpack.

3. Methods

We tested the following hypotheses: (H1) snowpacks produce continuous positive net snowpack outflow during a rain-on-snow event; (H2) the cumulative water released from the snowpack in the days leading up to the peak explains the magnitude of peak discharges; (H3) constructive interference between coherent pulses of precipitation and net snowpack outflow explains extreme peak discharges; and (H4) correlated snowpack outflow over most or all of the contributing watershed explains extreme peak discharges.

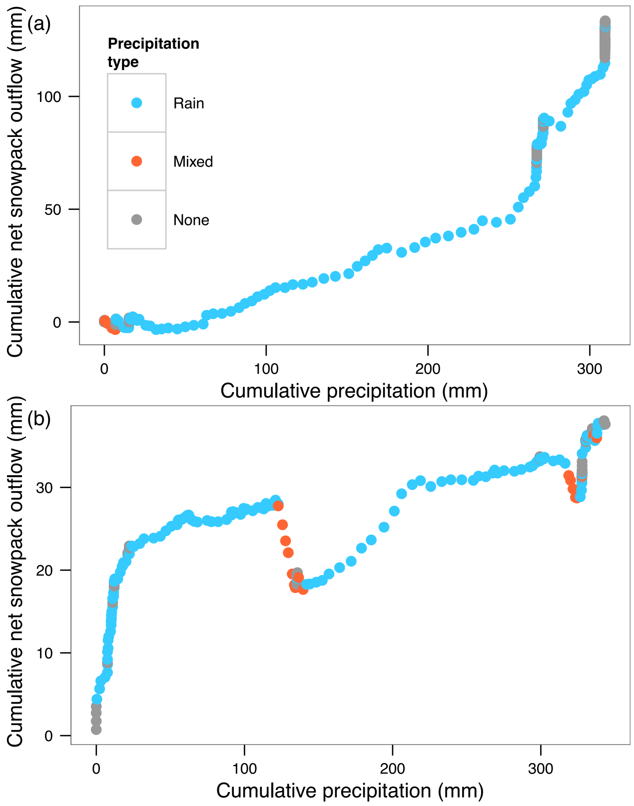

Figure 2. Cumulative net snowpack outflow as a function of cumulative net precipitation for storm events (a) 2 February 1996 and (b) 25 December 2005. During rain (defined as dew point T $\geq$ 0.5°C, blue points), snow was melting and cumulative net snowpack outflow increased with cumulative precipitation. During "mixed" rain and snow (defined as dew point T $<$ 0.5°C and >-0.5°C, orange points), melt ceased, and cumulative net snowpack outflow declined because water was retained by the snowpack or snow accumulated on top of the snowpack.

(H1) We identified 32 large storms over the period from 12 March 1992 to 15 September 2012 that had 3 day precipitation totals greater than 150 mm at CS2met and/or peak streamflow at Lookout Creek greater than 3.3 mm h^{-1} ($>$1 year return period). We used a subset (n = 26) of events, which had complete hourly data on discharge, precipitation, air temperature, relative humidity, dew point temperature, wind speed, and output from all three snowmelt lysimeters over a 10 day window centered on the peak on day 6 (supporting information Table S1). We tested how hourly net snowpack outflow rate categories were related to these independent variables using linear regression and one way analysis of variance (ANOVA), and we identified significant differences between pairs of categories using the post hoc Tukey-Kramer test [*Ramsey and Schafer*, 2012]. We conducted hourly energy balance modeling for selected events (supporting information).

(H2) We classified these storm events by plotting cumulative net snowpack outflow (*y*-axis) as a function of cumulative precipitation (*x*-axis) for each event and grouping these traces visually into five categories. Differences among categories were tested using ANOVA of total precipitation, rain and snow fraction, total net snowpack outflow, total snowpack outflow, and mean dew point temperature, with a post hoc Tukey-Kramer test.

(H3) We tested the hypothesis that the snowpack contribution to a rain-on-snow flood depends upon two aspects of the relative timing of pulses of net snowpack outflow and precipitation. We conducted wavelet coherence analysis [after *Grinsted et al.*, 2004] to assess (1) the strength of the relationship between precipitation and net snowpack outflow (hereafter "coherence") and (2) the temporal offset, or phase difference, between hourly scale pulses of precipitation and net snowpack outflow, over hourly to multihour time scales in each of the 26, 240 h storms. Wavelet analysis was performed using the biwavelet package for R [*Gouhier*, 2014], with the Morlet wavelet, following methods of *Torrence and Compo* [1998], *Grinsted*

Table 1. Mean Wind Speed, Dewpoint Temperature, Air Temperature, and Precipitation for Categories of Hourly Net Snowpack Outflow Rates in the 26 Storms in the Study (n = 6240 h)[a]

Net Snowpack Outflow Category	N (mm h^{-1})	n	Wind Speed (m s^{-1})	Dew Point T (°C)	Air T (°C)	P (mm h^{-1})	P_{t-1} (mm h^{-1})
None/gain	0	3579	0.1a	1.5a	1.7a	1.0a	0.8a
Low	$\leq$1	2196	0.2b	3.1b	3.5b	1.0a	1.1b
Medium	1–2	362	0.4c	4.0b	4.9c	2.3b	2.8c
High	2–3	77	0.5d	4.8b	6.0c	3.7c	4.7d
Very high	$>$3	26	0.5d	5.1b	6.3c	3.2c	6.1e

[a]Numbers in the same column followed by the same letter are not significantly different based on ANOVA followed by Tukey's highest significant difference test at $p < 0.05$. P = precipitation, P_{t-1} = precipitation in previous hour, T = temperature, N = net snowpack outflow.

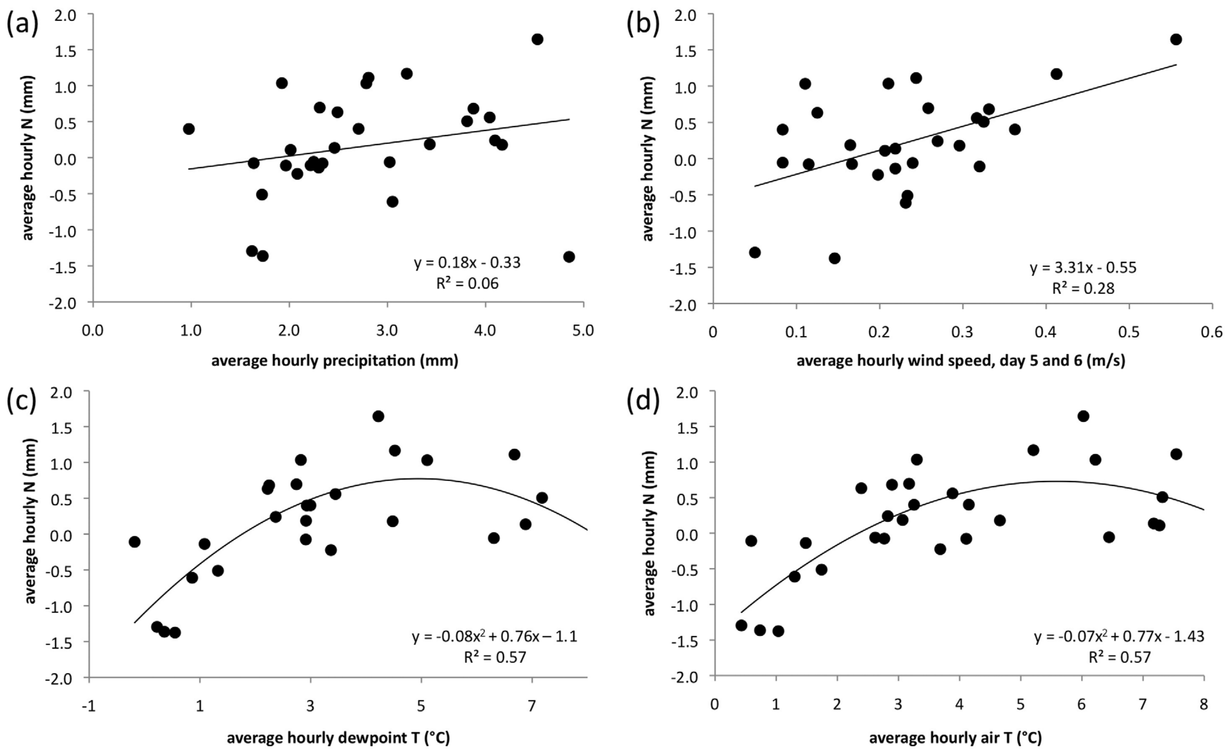

Figure 3. Response of average hourly net snowpack outflow (N) on the day prior to and the day of the peak for >1 year rain-on-snow events from 1992 to 2012 at WS 8 in the Andrews Forest, as a function of average hourly (a) precipitation, (b) wind speed, (c) dew point temperature, and (d) air temperature.

et al. [2004], *Labat* [2005], and *Cazelles et al*. [2008]. Significance values were computed using a Monte Carlo procedure with red noise and a lag-1 autoregressive model. We extracted phase differences for time scales of 12–32 h during the peak flow period (days 4–7) of each storm event, created plots of these phase difference distributions, and examined these distributions for evidence of a pronounced peak, indicative of synchrony between precipitation and net snowpack outflow pulses [*Cazelles and Stone*, 2003; *Schaefli* et al., 2007].

(H4) We correlated hourly snowpack outflow among pairs of snowmelt lysimeters (H15met, CENmet, UPLmet, Figure 1) located from 900 to 1300 m, which represents 42% of basin area.

4. Results

Although precipitation falling as rain and the presence of snow were not selection criteria, the largest floods in the study (26 storms from 1992 to 2012) were all rain-on-snow events, with an initial SWE > 0, more than 60% of precipitation falling as rain, and periods of snow accumulation and/or melt throughout the storm. On the day before and the day of these peak discharges, hourly precipitation intensity was low (2.7 ± 0.9 mm h^{-1}), air and dew point temperature were above freezing across a wide elevation range (4.1 ± 2.7 and 3.4 ± 2.7°C), and wind speed at 5 m above the ground was low (0.2 ± 0.1 m s^{-1}). Soils were not frozen: mean daily soil temperature at 10 cm depth was >0°C throughout all storms, at all four sites where soil temperature is measured (PRImet, CENmet, VANmet, UPLmet, Figure 1).

Snowpack outflow was not continuous during storms (H1), instead it responded to changes in precipitation from rain, to snow, to mixed rain and snow, depending on dew point temperature (Figure 2). Air temperature was similar at meteorological stations from 430 to 1294 m elevation in every event (supporting information); hence the entire Lookout Creek basin was generally either in, or out of, the rain-snow transition zone at various times during these events (supporting information). Hourly net snowpack outflow rate was positively related to dew point temperature, wind speed, and precipitation, and it was significantly higher when precipitation rate in the previous hour exceeded 4 mm h^{-1} (Table 1). Average hourly net snowpack

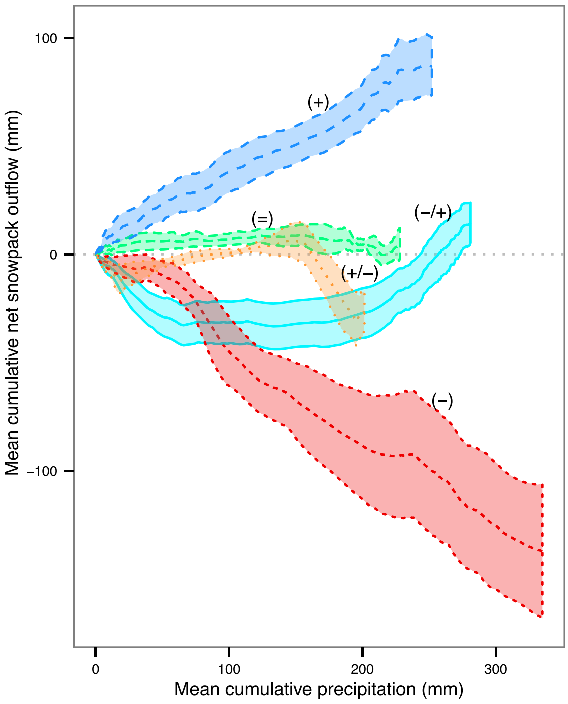

Figure 4. Mean (± standard error) cumulative net snowpack outflow as a function of cumulative precipitation for 26 10 day storm events divided into five categories: (+) persistent snowmelt (n = 7), (=) no net snowpack outflow or accumulation (n = 4), (−) persistent snow accumulation (n = 6), (+/−) late accumulation (n = 3), and (−/+) late snowmelt (n = 6). The horizontal extent of each group is based on the average cumulative precipitation in that category.

outflow on the day before and the day of the peak discharge was weakly related to wind speed ($r^2 = 0.28$) and dew point temperature and air temperature ($r^2 > 0.57$) (Figure 3). For >81% of the time for the 10 day storms, hourly net snowpack outflow rates were between −1 and +1 mm h^{-1}, precipitation was <2 mm h^{-1}, and total snowpack outflow was <2 mm h^{-1}. For >97% of the time during the day before and the day of the peak discharge, hourly net snowpack outflow was <3 mm h^{-1} and total snowpack outflow was <10 mm h^{-1}; this rate never exceeded 14 mm h^{-1}.

Although snow melted at some time in all the 10 day events, continuous net snowpack outflow occurred during only seven events (Figure 4) (H1). During storms in the "persistent melt" (+) category, cumulative net snowpack outflow increased with cumulative precipitation throughout most of the storm event (n = 7). The (+) category included the rank 1, 3, 4, and 5 peak discharge events at WS8 and rank 1, 2, and 5 events at Lookout Creek (of 26 storms). During storms in the "late melt" (−/+) category, cumulative net snowpack outflow initially decreased (i.e., water was stored within the snowpack) and then increased (water was released) late in the event (n = 6). The (−/+) category included the rank-2 peak discharge event at WS8 and the rank 3 and 4 events at Lookout Creek. During storms in the "late accumulation" (+/−) category, cumulative net snowpack outflow initially increased, but then stalled or declined late in the event (n = 3). During storms in the "flat" (=) category, net snowpack outflow alternated with snow accumulation over the course of the storm event, and cumulative net snowpack outflow was less than 10% of cumulative precipitation (n = 4 storms). During storms in the "persistent accumulation" (−) category, cumulative net

Table 2. Significant Differences in Characteristics of Five Categories of Cumulative Net Snowpack Outflow Response to Cumulative Precipitation[a]

	(+)	(−)	(−/+)	(+/−)	(=)
n	7	6	6	3	4
Initial snow water equivalent (SWE)	375	161	206	120	225
Precipitation (P) (mm)	252ab	335b	281ab	201a	228a
Rain (mm)	247a	250a	255a	163a	226a
Rain fraction	1.0a	0.7b	0.9a	0.8ab	1.0a
Snow fraction	0.0a	0.3b	0.1a	0.2ab	0.0a
Net snowpack outflow (mm)	87b	−137c	14a	−25a	5a
Snowpack outflow (mm)	339a	198b	296a	177b	233ab
Snowpack outflow (P)	1.3b	0.6c	1.1a	0.9a	1.0a
Dew point temperature (°C)	3.0a	1.0a	2.4a	1.6a	3.6a
Air temperature (°C)	3.3a	1.1a	2.6a	1.8a	4.1a
Wind speed (m s^{-1})	0.2a	0.1a	0.2a	0.1a	0.2a
WS8 peak flow (mm h^{-1})	3.6a	2.1a	2.7a	1.7a	1.9a
Lookout Creek peak flow (mm h^{-1})	5.3a	2.9a	3.8a	2.0a	2.3a

[a]Numbers are averages of total values for the 10 day period of storms in each category, except for temperature, which is the average value for each storm. (=) = no net snowmelt or accumulation; (+) = persistent snowmelt; (−) = persistent snow accumulation; (−/+) = late snowmelt; (+/−) = late snow accumulation. Numbers in the same row followed by the same letter are not significantly different based on ANOVA followed by Tukey's highest significant difference test at $p < 0.05$. SWE sample size was too small for ANOVA.

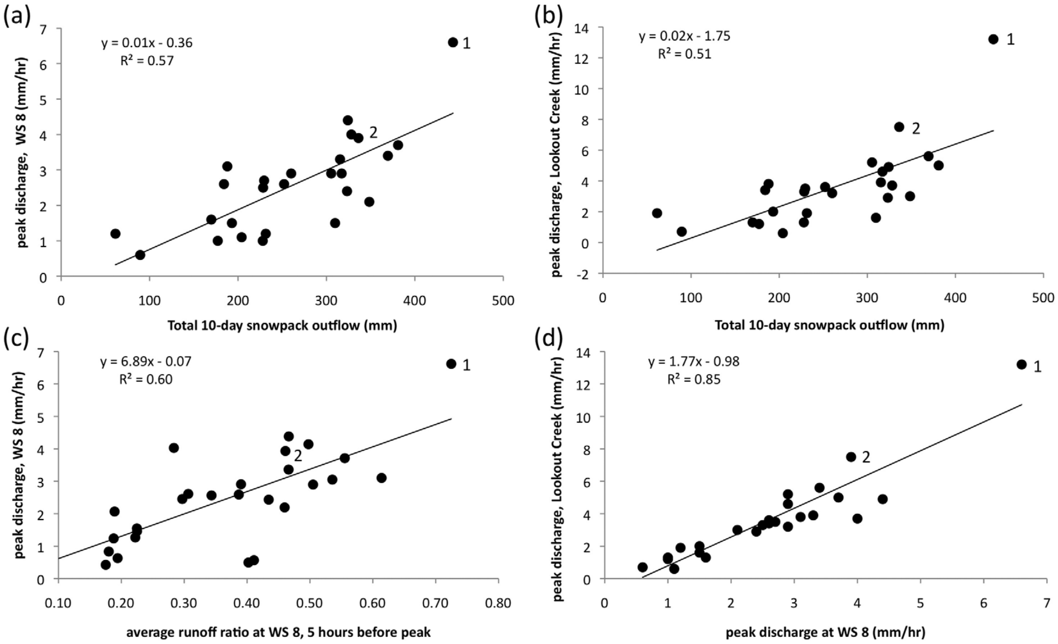

Figure 5. The 10 day snowpack outflow at the snowmelt lysimeter at H15met station was related to peak discharge (a) at the nearby 21.4 ha WS 8 and (b) in the 64 km^2 Lookout Creek. Peak discharge at WS 8 was related to (c) the average runoff ratio (discharge/precipitation) at WS 8 during the 5 h preceding the peak and (d) peak discharge in Lookout Creek. (n = 26 storm events). Points labeled 1 and 2 are the first and second-ranked peak discharge events at Lookout Creek in the study period: 1 = February 1996; 2 = January 2011.

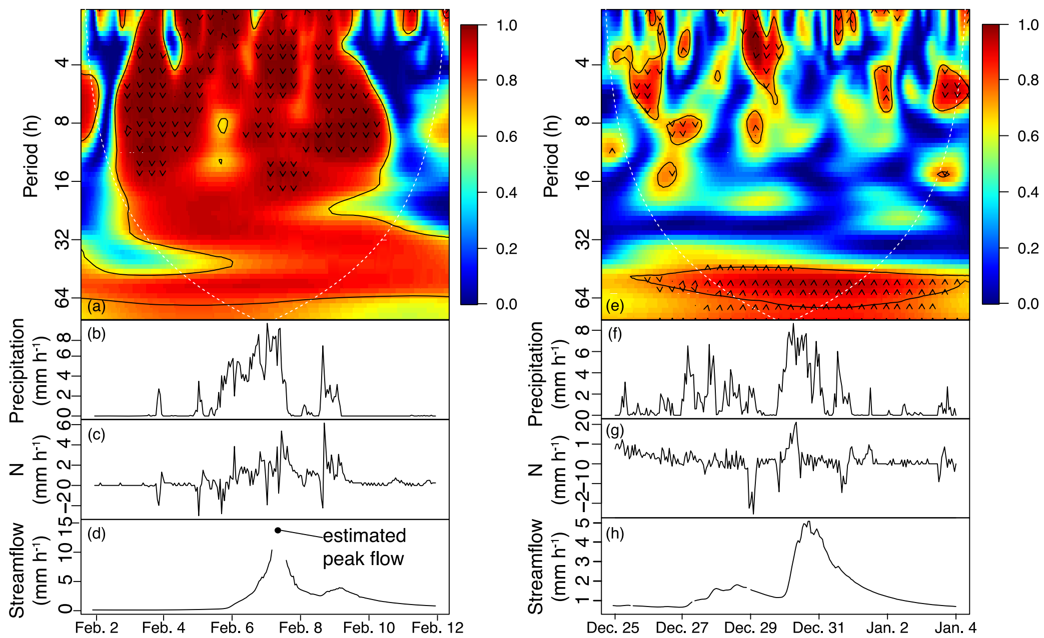

Figure 6. Wavelet coherence (a, e) and hourly precipitation (b, f), net snowpack outflow, N (c, g), and Lookout Creek streamflow (d, h) for 10 day storm events of (a, b, c, d) 2 February 1996 and (e, f, g, h) 25 December 2005. The colors in the wavelet coherence plots correspond to the power to the right of each plot where values approaching 1 represent a high degree of coherence between pulses of precipitation and net snowpack outflow. The black contours enclose areas of statistically significant wavelet coherence. The phase difference between the continuous wavelet transforms of precipitation (x) and net snowpack outflow (y) is depicted by black arrows in Figures 6a and 6e. Each black arrow refers to a particular time and temporal scale. Similar phase differences are shown when all arrows point in the same direction in a region of Figure 6a or 6e. The arrows point right when the *x* and *y* are in phase, left when they are in antiphase, down when *x* leads *y*, and up when *y* leads *x*. The phase relationship is indicative of the physical processes occurring during the storm event. When power is increasing in *x* (precipitation) and in *y* (net snowpack outflow), and *x* is leading, the snowpack is contributing net outflow, and precipitation is preceding snowpack outflow. This is shown by downward-pointing arrows, which indicate a phase difference of $\pi/2$. When power is increasing in *x* and decreasing in *y*, the two variables are in antiphase; precipitation is increasing while net snowpack outflow is decreasing, and precipitation is being stored in the snowpack. This is shown by leftward-pointing arrows, which indicate a phase difference of $+/-\pi$.

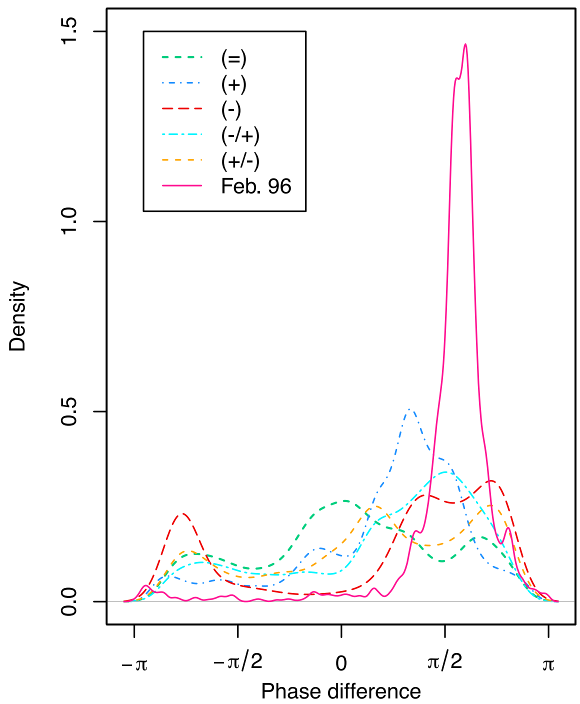

Figure 7. Density plot showing the distributions of phase differences for the midstorm time frame (4 days surrounding the peak flow) and intermediate time scale (12–32 h) for the five response categories and the February 1996 extreme event. Values on the *x*-axis represent the phase difference between the precipitation and net snowpack outflow waveforms. The higher and narrower the distribution, the greater is the synchrony between precipitation and net snowpack outflow at a given phase difference. Figure 6 provides further explanation on the hydrologic implications of the different phase differences.

snowpack outflow decreased (snow and meltwater accumulated) with cumulative precipitation throughout most of the storm event ($n = 6$).

Overall, storm events in the (+) category had significantly higher total net snowpack outflow than other categories (Table 2) (H2). Categories did not differ significantly in snow water equivalent, mean air temperature, dew point temperature, wind speed, or peak discharge with this small sample size (Table 2). Hourly energy budget modeling indicated that net longwave radiation dominated the energy budget, and that heat advected by precipitation was larger than sensible and latent heat exchange (supporting information).

Although peak discharge was not related to instantaneous or average precipitation rate for the prior 5 h ($r^2 < 0.24$), peak discharge was related to measures of basin wetness (H2): the 10 day total snowpack outflow ($r^2 = 0.57$ for WS8, $r^2 = 0.51$ for Lookout Creek, Figures 5 a and 5b) and the runoff ratio for the 5 h preceding the peak ($r^2 = 0.60$, Figure 5c). Peak discharges at Lookout Creek and WS 8 were strongly related ($r^2 = 0.85$, Figure 5d). However, measures of basin wetness underpredicted peak discharge in the two largest peak discharge events in the study (Figure 5).

The two largest peak discharge events at Lookout Creek in this study (2 February 1996 and 11 January 2011) displayed significant wavelet coherence at multiple time scales over several days (H3), indicating a tightly linked relationship between precipitation and snowpack outflow. During the extreme flood of 2 February 1996 (the event of record for this site and a persistent snowmelt (+) event), precipitation and net snowpack outflow displayed significant wavelet coherence at scales of 2–64 h over several days at the time of the peak discharge (Figures 6a–6d). In contrast, other storms in the persistent melt (+) category (e.g., 25 December 2005), which were not extreme floods, lacked the coherence between precipitation and net snowpack outflow at multiple time scales over multiple days (Figures 6e–6h).

Moreover, in the largest event in this study, precipitation pulses were quickly followed by pulses of positive net snowpack outflow at the 12–32 h time scale, producing constructive interference (H3), as shown by the peak at $\pi/2$ in the phase difference distribution for the 2 February 1996 event (Figure 7). Constructive interference, in this case, indicates that precipitation was augmented by net snowpack outflow, producing larger fluxes of water from the snowpack. Other storms in the persistent melt (+) category had less peaked phase difference distributions at the 12–32 hour time scale (Figure 7). Although storm events in the late melt (−/+) and late accumulation (+/−) categories also displayed significant wavelet coherence between precipitation and net snowpack outflow [*Jennings*, 2014], they lacked consistent phase differences (Figure 7). Storm events in the flat (=) category displayed significant wavelet coherence only in small, disconnected regions [*Jennings*, 2014]. Thus, coherence and constructive interference between hourly precipitation and net snowpack outflow explained differences in peak discharge between storms with similar cumulative snowpack outflow: the 2 February 1996 event had a much higher peak discharge than the 25 December 2005 event (Figures 6 and 8).

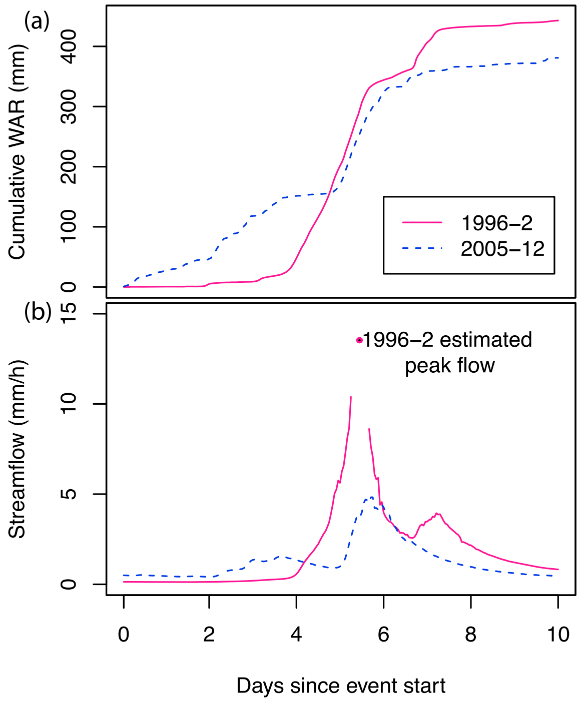

Figure 8. Time series plots for storms of 2 February 1996 and 2 December 2005 showing (a) cumulative total snowpack outflow (water available for runoff, or WAR) and (b) streamflow.

In addition, during the two extreme rain-on-snow floods (7 and 13 mm h^{-1} at Lookout Creek, Figure 9), hourly snowpack outflow rates over the 10 day storm were very strongly correlated ($r > 0.85$) among pairs of snowmelt lysimeters (H15met, CENmet, UPLmet, Figure 1) located from 900 to 1300 m, and representing 42% of basin area (H4). However, for smaller peak discharges hourly snowpack outflow rates were much less correlated ($0.3 < r < 0.8$) for pairs of lysimeter at elevation above 1000 m (Figure 9). Thus, during extreme floods, the snowpack liberated water synchronously throughout the entire snow-covered basin area.

5. Discussion

Results of this study are consistent with the interpretation that during an extreme rain-on-snow flood the snowpack melts and becomes increasingly saturated, to the point that pulses of precipitation become synchronized with pulses of net snowpack outflow and produce constructive interference, and that this process occurs simultaneously across the entire snow-covered area of the basin (Figure 10). Pulses of precipitation on an increasingly saturated snowpack may produce pressure waves that push water from the snowpack continuously at multiple timescales over several days coinciding with the peak discharge.

How these processes contribute to an extreme peak discharge is not clear. Rain-on-snow events were frequent, but extreme rain-on-snow floods, by their nature, were rare. Although models indicate that soils were near saturation during large rain-on-snow events [*Perkins and Jones*, 2008], observed rates of precipitation and snowpack outflow (< 10 mm h^{-1}) were insufficient to produce infiltration-excess runoff in these unfrozen soils, and the cumulative snowpack outflow (less than 300 mm over 10 days) was insufficient to overwhelm the water storage capacity of these soils and produce saturation-excess runoff. Alternatively, water in a melting snowpack may move through lateral preferential flow pathways rather than as Darcian flow [*Wankiewicz*, 1978; *Marsh*, 1999; *Kattelmann and Dozier*, 1999; *Eiriksson et al.*, 2013]. Or, precipitation pulses may push meltwater through the snowpack and through the basin as a pressure wave, as suggested by *Jones and Perkins* [2010] based on work of *Torres et al.* [1998], *Torres* [2002], and *Ebel and Loague* [2008]. Results presented here indicate

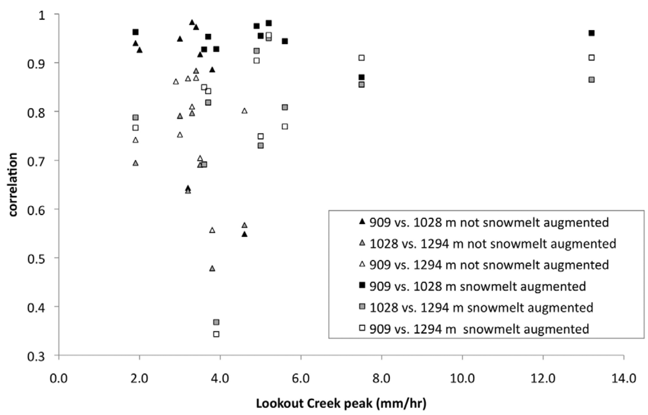

Figure 9. Correlations of hourly snowpack outflow between pairs of snowmelt lysimeters at H15met (909 m), Cenmet (1028 m), and Uplmet (1294 m) over the 10 day (240 h) period for each of 26 storms as a function of peak discharge in the Lookout Creek watershed. High correlations for events > 6 mm h^{-1} indicate that snowpack outflow was highly synchronized across the landscape during extreme floods. Correlations of 0.3–0.9 for events of < 6 mm h^{-1} indicate that snowpack outflow was not consistently synchronized during these events, especially above 1000 m. *X*-axis is peak discharge at the mouth of Lookout Creek (64 km^2). See Figure 1 for station locations and supporting information Table S1 for complete storm data.

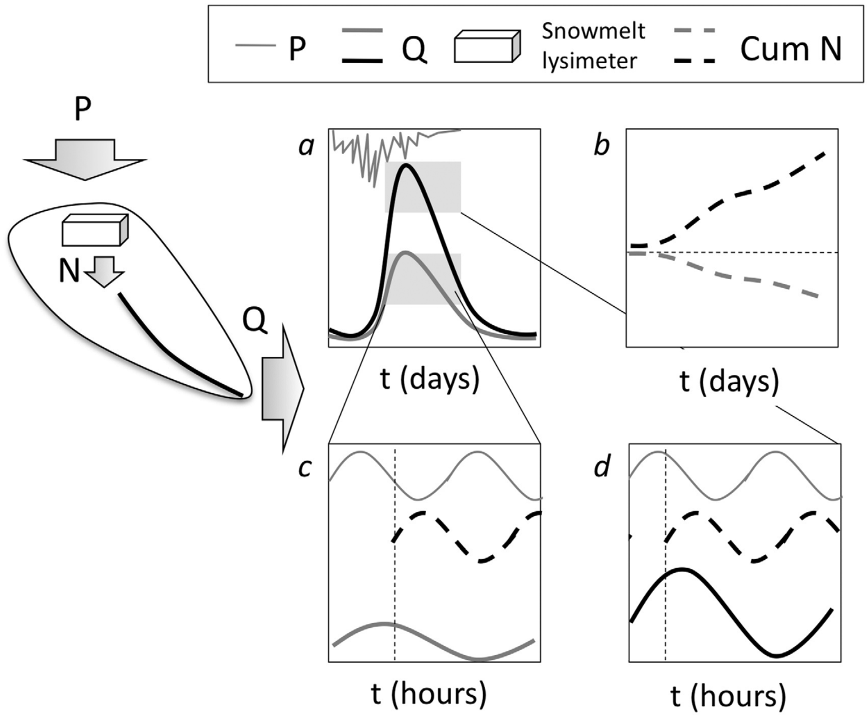

Figure 10. Conceptual model of snowmelt influences on the magnitude of rain-on-snow floods. The snowmelt lysimeter provides information on how net output from the lysimeter (net snowpack outflow, N) influences the relationship between incoming precipitation (P) and discharge (Q) from a watershed at two temporal scales (days and hours). (a) At the multiday timescale, large amounts of incoming P may produce a moderate or large flood (thick grey line), or an extreme flood (heavy black line). (b) During a moderate flood, the snowpack absorbs or does not augment incoming P (cumulative net snowpack outflow is negative or zero—thick dashed gray line) over multiple days. During large and extreme floods, the snowpack augments incoming P continuously and becomes increasingly saturated over multiple days (cumulative net snowpack outflow is positive—thick-dashed black line). (c) In moderate floods, hourly scale pulses of incoming P are counteracted by pulses of net snowpack outflow that are displaced by π radians, producing destructive interference, resulting in a damped waveform of Q. (d) During large floods, fine-scale pulses of incoming P are augmented by pulses of net snowpack outflow that are almost in phase (displaced by $\pi/2$ radians), producing constructive interference, resulting in a higher amplitude waveform of Q, but this process occurs only intermittently during the storm event. In an extreme flood, P and net snowpack outflow are almost in phase at multiple temporal scales for multiple days coinciding with the peak.

that during an extreme peak discharge, snowpack and soil may be sufficiently saturated to effectively transmit pressure waves from the snowpack surface through soil and the stream network.

Energy advected to the snowpack by incoming pulses of precipitation appeared to be a key driver in producing extreme peak discharges (see supporting information). Many studies have emphasized the role of turbulent fluxes (latent and sensible heat exchange) in warm, wet winds as a driver of snowmelt during storm events [e.g., *Harr*, 1981; *Berris and Harr*, 1987; *van Heeswijk* et al., 1996; *Marks* et al., 1998]. Although heat advected from rainfall typically comprises a small portion of the rain-on-snow energy budget [e.g., *USACE*, 1956; *Harr*, 1981; *van Heeswijk* et al., 1996], it accounted for 29–44% of the energy budget in persistent melt events in this study, indicating that precipitation enhanced snowmelt in snowpacks that were near the melting point. *Whitaker and Sugayama* [2005] attributed high snowpack outflow to rain moving through the snowpack without inducing melt. However, *Berman et al.* [2009] used isotope signatures of outflow from a snow core subjected to artificial rain to show that initial outflow was precipitation moving through the snowpack, but subsequent outflow increasingly resembled the snow isotopic signature, indicating progressive melt. The dynamic feedbacks between precipitation, melt, snowpack saturation, and snowpack transmission of precipitation pulses during storms are not well understood.

Climate change is expected to reduce snowpacks in the western U.S. [e.g., *Mote* et al., 2005; *Nolin and Daly*, 2006; *Sproles et al*., 2012] and increase winter streamflow in western Oregon [*Jung and Chang*, 2011; *Surfleet and Tullos*, 2013]. However, climate change effects on rain-on-snow floods are harder to predict [*Hamlet and Lettenmaier*, 2007; *McCabe et al*., 2007]. This research indicates that the rain-snow transition zone is highly dynamic in space and time during alternating cold and warm fronts responsible for the rain-on-snow phenomenon, which is not well represented by current climate models. As climate warming increases snowpack temperature and exposes snowpacks to rain, rain-on-snow events will expand into areas that are currently in the seasonal or permanent snow zone [*Ye et al*., 2008; *Rennert et al*., 2009]. These changes may generate extreme rain-on-snow floods in locations where such flooding has not previously occurred.

In the 1980s, snowmelt lysimeters were installed in several locations in the Andrews Forest to better understand snowpack behavior during rain-on-snow events [*Berris and Harr*, 1987]. Thirty years later, with the accumulated high temporal resolution, spatially coincident, long-term records of snowmelt from lysimeters, as well as precipitation, air and dew point temperature, wind speed, and discharge, this research has drawn novel inferences about the behavior of a melting snowpack during storm events, and the possible mechanisms that produce extreme flooding. Yet these results also reveal major challenges for understanding extreme rain-on-snow flooding. Current concepts and terminology are inadequate: "rain-on-snow" conditions only rarely lead to extreme floods, and the transient snow zone implies a static area, when in fact the area undergoing melt is highly dynamic during storm events. New sensors are needed to track dynamic temperature, pressure, and water content in snowpacks during storm events; remote sensing analyses are needed to track hourly or daily changes in snowpack area; and hourly scale models are needed to represent the internal dynamics of snowpacks over large areas.

6. Summary and Conclusions

The 26 largest events in the 20 year study period, which were selected based on precipitation and discharge magnitude, were all rain-on-snow events involving an initial snowpack, snowmelt, and/or accumulation, and more than 60% of precipitation falling as rain over the 10 day storm window. Only seven of these events involved continuous net snowpack outflow, and only two of the persistent melt events produced extreme floods, which were associated with landslides and debris flows in the Lookout Creek watershed [*Snyder* 2000; *Wemple et al*.; 2001]. The two extreme events were distinguished from all other large rain-on-snow events by the presence of significant wavelet coherence between precipitation and net snowpack outflow at scales ranging from 2 to 64 h for several days coinciding with the peak discharge, as well as by pulses of precipitation and net snowpack outflow that were consistently almost in-phase (net snowpack outflow followed precipitation by $\pi/2$ wavelengths) throughout this same period. During extreme flood events, hourly snowpack outflow was highly correlated throughout the snow-covered area of the basin, but total snowpack outflow never exceeded 14 mm h^{-1} and rarely exceeded 10 mm h^{-1}. Extreme rain-on-snow floods occurred only when pulses of precipitation and net snowpack outflow were strongly synchronized, with net snowpack outflow lagged behind precipitation, at subdaily to weekly temporal scales throughout almost the entire event.

Circumstances necessary to generate an extreme rain-on-snow event develop over multiple days. The recipe for an extreme rain-on-snow event includes persistent, slow melt within the snowpack, which appears to produce a near-saturated zone within the snowpack throughout the landscape, such that the snowpack transmits pressure waves of precipitation directly to streams, and this process is synchronized across the landscape. Persistent low-intensity precipitation and net snowpack outflow, strong coherence between precipitation and net snowpack outflow at a range of time scales coinciding with the peak discharge, and constructive interference between pulses of precipitation and subsequent pulses of net snowpack outflow occurred during the largest peak flows at WS8 and Lookout Creek, including the 7 February 1996 flood that caused widespread damage across western Oregon. However, it is unclear how internal snowpack characteristics foster precipitation-net snowpack outflow synchrony or how this synchrony observed at a point (a snowmelt lysimeter) contributes to basinwide or landscape-scale extreme flood response. Further work is needed to better understand the internal dynamics of a melting snowpack throughout a snow-covered landscape and its contribution to extreme rain-on-snow floods.

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