Earth's Future

Key Points:
- Winter weather whiplash is defined as a rapid change in weather with temperature fluctuations above and below freezing
- Although rare, these events may have outsized impacts on coupled human and natural systems
- Identifying the occurrences of these events is critical in light of rapidly changing winter conditions

Supporting Information:
- Supporting Information S1

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Winter Weather Whiplash: Impacts of Meteorological Events Misaligned With Natural and Human Systems in Seasonally Snow-Covered Regions

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Abstract "Weather whiplash" is a colloquial phrase for describing an extreme event that includes shifts between two opposing weather conditions. Prior media coverage and research on these types of extremes have largely ignored winter weather events. However, rapid swings in winter weather can result in crossing from frozen to unfrozen conditions, or vice versa; thus, the potential impact of these types of events on coupled human and natural systems may be large. Given rapidly changing winter conditions in seasonally snow-covered regions, there is a pressing need for a deeper understanding of such events and the extent of their impacts to minimize their risks. Here we introduce the concept of winter weather whiplash, defined as a class of extreme event in which a collision of unexpected conditions produces a forceful, rapid, back-and-forth change in winter weather that induces an outsized impact on coupled human and natural systems. Using a series of case studies, we demonstrate that the effects of winter weather whiplash events depend on the natural and human context in which they occur, and discuss how these events may result in the restructuring of social and ecological systems. We use the long-term hydrometeorological record at the Hubbard Brook Experimental Forest in New Hampshire, USA to demonstrate quantitative methods for delineating winter weather whiplash events and their biophysical impacts. Ultimately, we argue that robust conceptual and quantitative frameworks for understanding winter weather whiplash events will contribute to the ways in which we mitigate and adapt to winter climate change in vulnerable regions.

Plain Language Summary Weather whiplash is a term used by researchers and the media to describe wild and rapid shifts in weather conditions. Here we investigate "winter weather whiplash" events, which are characterized by weather conditions swinging from frozen to unfrozen (or vice versa). These events have important consequences for ecosystems and communities, especially when they occur at unusual times of the year. Impacts of these events include tree damage, flooding, electrical outages, and crop damage. We use a series of case studies to explore the impacts of these events and analyze a long-term data set to demonstrate how they might be detected from weather data. Understanding winter weather whiplash events will help decision makers and planners adapt and mitigate these events in the future.

1. Introduction

Climate change is expected to increase the frequency and severity of extreme weather and climate events (IPCC, 2013), which are characterized by crossing the upper (or lower) threshold relative to historical baseline conditions (Alexander et al., 2006; Donat et al., 2013; Frich et al., 2002; Sheridan & Lee, 2018). Impacts of extreme events on natural systems and human communities may exceed those that occur because of regular normal variation in weather. For instance, extremely high maximum temperatures can lead to heat-related deaths (Vandentorren et al., 2004), intense winter storms can damage trees and result in widespread power

outages (Kloster et al., 2018), and catastrophic flooding can damage infrastructure and private property and negatively affect water resources as well as impacting nutrient loading to streams and lakes (Doocy et al., 2013; Wilson et al., 2019).

The impacts of extreme weather events depend on the human and natural context in which they occur. For instance, heavy rainfall occurring on already saturated soils may result in severe flooding (IPCC, 2013). Likewise, if this rainfall occurs immediately after fertilizer application in an agricultural area, the resulting runoff may degrade water quality (Carpenter et al., 1998). The chronology of extreme weather events is also critical for determining impacts. For example, when a heat wave overlaps with a multiyear drought, the cascade of events can exacerbate the effects on human and natural systems (AghaKouchak et al., 2014). Compound extremes are a special class of extreme events that can consist of two or more events happening simultaneously or in rapid succession, such as a severe drought coupled with a prolonged heat wave (Mazdiyasni & AghaKouchak, 2015; Zscheischler & Seneviratne, 2017). This term can also be used to categorize clustered multiple events that would not be considered extreme in isolation, but collectively lead to extreme impacts, such as if wildfire is followed by heavy rain that increases the risk of a landslide (Cannon & DeGraff, 2009).

Rapid reversals in extreme weather, such as swings from drought to deluge and hot to cold (or vice versa) may also fit within the definition of compound extreme events. Termed "weather whiplash" in the popular media, these extreme oscillations have the potential to induce unexpected impacts in associated coupled human and natural systems (Liu et al., 2007), resulting in substantial damage and costs (Douglas, 2013; Freedman, 2009; Jonnson, 2015; The Canadian Press, 2015). More recently, the term weather whiplash has been used in scientific literature, such as in studies describing water quality impacts of a rapid transition from drought to flood conditions on a seasonal timescale in the Midwest (Loecke et al., 2017) and on a monthly timescale in California (Swain et al., 2018).

To date, the concept of weather whiplash has largely focused on phenomena that typically occur during the warmer period of the year. However, rapid reversals in winter weather, both within and outside of the meteorological winter season of December, January, and February, are also relevant for understanding the impacts of climate change on natural and human systems (IPCC, 2013; U.S. Global Change Research Program, 2017). In northeastern North America, the past few decades have featured multiple examples of winter weather whiplash, both within and outside of winter, during which extreme swings in temperature above or below freezing, either alone or in combination with extreme precipitation, have produced extreme impacts. These include snowstorms and frost events that occurred in the "shoulder seasons" either prior to plant senescence or following vegetation green-up, such as the Storm of the Century in April of 1993 (Lott, 1993), the Easter Freeze of 2007 (Gu et al., 2008), the Halloween Snowstorm of 2011 (LeComte, 2012), and the False Spring of 2012 (Ault et al., 2013). Within winter, the combination of extreme temperature excursions and precipitation events has also resulted in catastrophic impacts including crop damage and electrical outages. The winters of 2017 and 2018 were emblematic of this kind of weather whiplash, when rapid seesawing from frozen to thawed and back to frozen conditions resulted in ice jams, flooding, and property damage (Brogan, 2018; Marcello, 2017; Wolfe, 2018). While none of these examples of shoulder season and wintertime events have previously been considered examples of winter weather whiplash, they all share three key features: (1) They happened over a short period of time of days to weeks, (2) temperature or precipitation conditions were misaligned with what is expected or typical for the system, and (3) they included unusual and rapid swings between above and below freezing temperatures. This third feature, crossing the hard physical threshold of 0 °C, may be especially important in exacerbating the impacts of extreme events such as winter weather whiplash on coupled human and natural systems.

Within winter, average trends toward warmer and wetter conditions at midlatitudes are expected to continue (Collins et al., 2013; Hayhoe et al., 2007). These milder winters that feature fewer, smaller snowstorms and more frequent rainfall may be interspersed with blasts of Arctic air that manifest as extended cold snaps as well as larger storms that drop more snow within a single event (Cohen, 2016; Cohen et al., 2018; Francis & Skific, 2015; Overland et al., 2016; Zarzycki, 2018), which together could indicate increased frequency of whiplash events within winter. Some studies have suggested reduced variance in midlatitude winter weather as polar sea ice cover decreases (Huntingford et al., 2013), while others have suggested an increasing frequency of midwinter temperature excursions and thawing events (Sheridan & Lee, 2018). Outside of winter, trends toward earlier canopy green-up (Monahan et al., 2016; Schwartz et al., 2006) may collide with random

occurrences of advective freezes, increasing the likelihood of "false springs" (Augspurger, 2013; Gu et al., 2008). Heavy spring snowfalls may also become more common as the Arctic warms (Cohen et al., 2018), though as with winter weather, the causal link between Arctic and midlatitude conditions during spring is uncertain (Overland & Wang, 2018).

Given the current lack of understanding of the causes and consequences of winter weather whiplash events, it is crucial to define and characterize these events in order to inform policy and management aimed at mitigating their risks to coupled human and natural systems, particularly in light of rapidly changing winter conditions. Here our goal is to address this knowledge gap by (1) defining winter weather whiplash, (2) developing a winter weather whiplash conceptual framework, (3) using four cases studies to illustrate our conceptual understanding, and (4) demonstrating quantitative methods for identifying winter weather whiplash events. We chose to focus our work in northeastern North America, a region in which climate change in both the U.S. and Canada is anticipated to be greater in winter as compared to summer (Bush & Lemmen, 2019; USGCRP, 2017). This area of focus lies against the backdrop of average milder winter temperatures and reduced snow cover and is thereby vulnerable to incursions of Arctic air that lead to sudden temperature swings from warm to cold (Cohen et al., 2018; Francis & Skific, 2015; Overland et al., 2016). Northeastern North America also includes a wealth of diverse gradients in climate, acid deposition, population density, infrastructure, and ecosystem services (e.g., water provisioning and filtration near urban areas, forestry, agriculture, and tourism in more rural parts of the region). These varied characteristics provide the context to explore how coupled human and natural systems interact with winter weather whiplash drivers as well as the impacts resulting from these events. Within this study region, we highlight four noteworthy winter weather whiplash events as case studies to illustrate how our conceptual understanding of winter weather whiplash might provide a new lens for seeing how extreme weather affects coupled human and natural systems.

We describe quantitative methods for delineating winter weather whiplash events and their biophysical impacts using the long-term hydrometeorological record at the Hubbard Brook Experimental Forest (HBEF). The identification of these events and their impacts on coupled human and natural systems is complex and requires harmonization of data from across biophysical disciplines (meteorology, phenology, hydrology, and biogeochemistry) as well as the social sciences (e.g., geography, resource management, and policy studies). A key challenge of this type of analysis is the mismatch of the spatial and temporal resolution of data sets, particularly since socioeconomic data are often site-specific and not collected at the scale of individual events. While this quantitative analysis is limited to the natural system of a single forested watershed, it represents a first step toward a framework that can be applied in future work encompassing a broader spatial domain and other types of data, including impacts to coupled human and natural systems.

2. Defining Winter Weather Whiplash Events

We define winter weather whiplash as a type of extreme event in which a collision of unexpected conditions produces a forceful, rapid, back-and-forth swing in winter weather and may induce an unexpected impact on coupled human and natural systems. Central to this definition is our focus on weather events, which occur over a period of days to weeks, as opposed to climate events, which describe multiseason or multiyear phenomena. Another key feature of our definition is the idea that winter weather whiplash events are misaligned with expected or typical conditions in coupled human and natural systems. In seasonally snow-covered regions, winters are generally characterized by below freezing temperatures and by precipitation that falls as snow, while the growing season typically features warm temperatures and precipitation falling as rain. Thus, winter weather whiplash occurs when air temperatures fluctuate above or below the 0 °C threshold, allowing for the phase change of water from solid to liquid (or vice versa). Crossing this physical threshold may mean that impacts to coupled human and natural systems are more damaging than warm or cold spells or precipitation events which do not feature swings between frozen and thawed conditions and may require unique responses to adapt to and mitigate against these events in the future. Given these key features of winter weather whiplash events and the suite of historically typical conditions in seasonally-snow covered areas, two types of winter weather whiplash events are possible: (1) extremely warm or rainy weather that takes place within the depths of winter, or conversely, (2) extreme cold or snowy winter conditions that occur during the shoulder seasons of spring and fall (Figure 1).
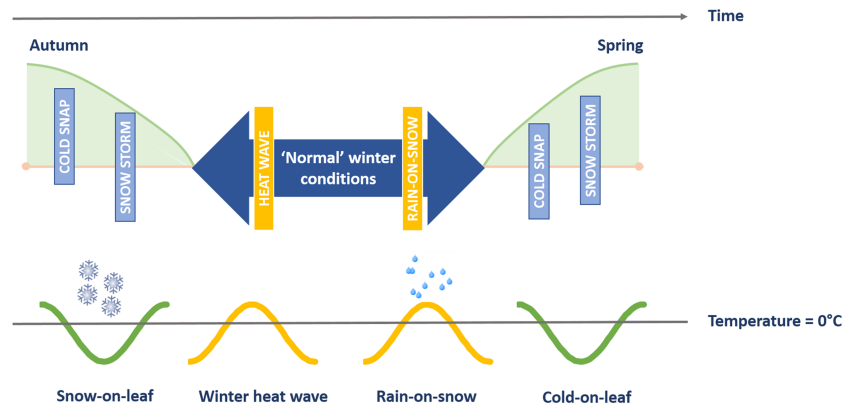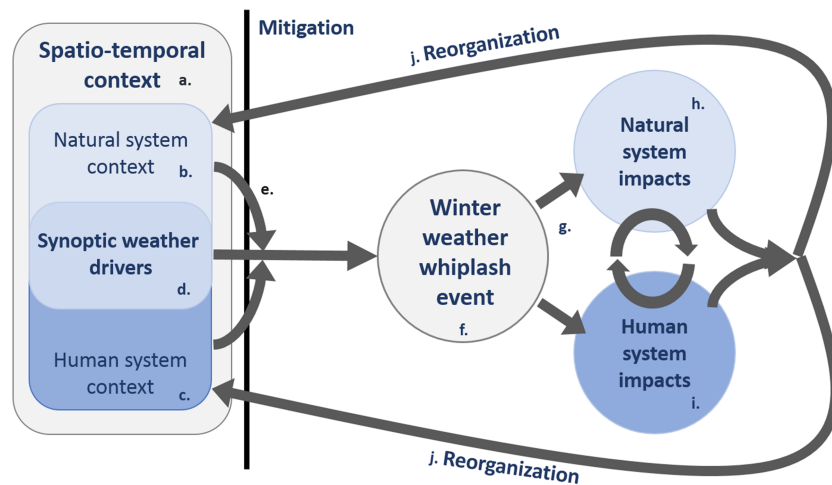
Figure 1. Diagram of winter weather whiplash events that can occur both within and outside of the winter season. The green shaded area represents photosynthetic activity of herbaceous and deciduous plants, which declines through the autumn and picks up again with the onset of spring. The four lower line graphs represent time series of air temperatures throughout winter weather whiplash events, with each one crossing the critical threshold of 0 °C. The *rain-on-snow* and *snow-on-leaf* events have the added dimension of precipitation occurring during the temperature excursion. Note that *snow-on-leaf* and *cold-on-leaf* events could occur during either the autumn or spring but are depicted only once for clarity.

The first type of winter weather whiplash event, nonwinter weather taking place during the winter period (yellow boxes in Figure 1), may include atypically warm temperatures, or *winter heat waves*. Impacts from these events may include rapidly melting snow and flooding, disruptions to plant and animal phenology, and fewer opportunities for winter recreation (Penczykowski et al., 2017; Sui & Koehler, 2001; Tervo, 2008; Zhu et al., 2002). Non-winter weather inside of winter may also include *rain-on-snow* events that have many of the same effects as *winter heat waves*, although the hydrological consequences of *rain-on-snow* events can be more extreme given the increased input of liquid water and limited activity of vegetation during dormancy to retain water and nutrients (Casson et al., 2010; Surfleet & Tullos, 2013). Furthermore, winter rain events can be associated with freezing rain or ice storms, either at the beginning or end of the event, which have major consequences for forested ecosystems, electrical infrastructure, and road maintenance (Chang et al., 2007; Irland, 2000; Rhoads et al., 2002).

The second type of winter weather whiplash, winter weather outside of winter, occurs when a winter-like event (below freezing temperatures or precipitation falling as snow) happens outside of the winter season (blue boxes in Figure 1). Examples of these "winter outside of winter" events include early snowstorms that occur when leaves are still on trees (*snow-on-leaf* events), as well early autumn or late spring frosts (*cold-on-leaf* events) (Ault et al., 2013; Gu et al., 2008; Hufkens et al., 2012; Kane & Finn, 2014; Liu et al., 2018). Cold snaps or snowstorms occurring before plant senescence or after the ecosystem has started to green up can have particularly devastating impacts on vegetation and agricultural crops, due to direct tree mortality (stem breakage) or damage to buds, branches or roots (Barlow et al., 2015; Rigby & Porporato, 2008).

3. Developing a Winter Weather Whiplash Conceptual Framework

We draw on the ecological disturbance literature to conceptualize how winter weather whiplash events impact coupled human and natural systems (Figure 2). Disturbance is a well-studied phenomenon in ecology and is commonly defined as "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resource, substrate availability, or the physical environment" (Pickett & White, 1985). This concept has been broadly applied to coupled human and natural systems, both directly (Birkmann et al., 2010; Grimm et al., 2017) and indirectly through the study of concepts including resilience and adaptive capacity (Ostrom & Cox, 2010). Disturbances can be classified by characteristics of the event itself such as intensity, duration, severity or frequency (Schoon & Cox, 2012), although it is well recognized that system responses may depend not only on the characteristics of the event itself but also on the system properties (Peters et al., 2011). Both antecedent and co-occurring conditions, therefore, mediate the impact of the event on coupled human and natural systems. This is particularly evident in the context of extreme events which by definition need two simultaneous events in order to occur.

Figure 2. Conceptual model of the context, drivers, and impacts of winter weather whiplash events. The boxes and arrows are described in detail in the text.

We situate this concept of disturbance within the coupled human and natural systems framework (Liu et al., 2007) in order to explore how winter weather whiplash events affect the patterns and processes linking human and natural systems, to understand reciprocal interactions and feedbacks between humans and the environment and to investigate the ways in which regional-scale weather drivers can interact with local conditions and produce impacts at a range of temporal and spatial scales. This model also fits within the context of risk management theory, where risk arises from the combination of hazards, exposure, and vulnerability, and emphasizes the role that adaptation measures can play in mitigating the impacts of a whiplash event (e.g., IPCC, 2012). The supporting information features additional details on how our conceptual framework fits with ecological disturbance and coupled human and natural systems theory and literature.

The underlying spatiotemporal context of the event is indicated by box (*a*) on the left-hand side of the model (Figure 2). This spatiotemporal context includes both the antecedent environmental conditions, as well as the human baseline expectations for current weather events and those that will occur in the future based on historical memory. We acknowledge that human baseline expectations are shifting (Soga & Gaston, 2018), which may influence the social context within which an event occurs. Box (*a*) includes both the natural system contextual components (*b*) and the human system contextual components (*c*). Natural system contextual components include features like forest type/local vegetation, soils, climate normals, and hydrologic conditions. Human system contextual components consist of community-level factors such as infrastructure, social networks, level of social capital, or community cohesion, technology, and communication systems, as well as individual-level factors, such as household behaviors and decision making. In the context of winter weather whiplash events, this could include the age, placement, and maintenance of power grid infrastructure, as well as individual-level decisions about trimming vegetation near electrical infrastructure on personal property (Kloster et al., in press; Morzillo, unpublished data).

Overlying both systems, are synoptic—or large-scale—weather conditions (*d*) that, in conjunction with the coupled human and natural system context *(e)*, trigger winter weather whiplash events that include the crossing above or below the 0 °C threshold (*f*). The weather drivers may be one or more extremes that coincide with or follow one another. Alternatively, they may not be extreme themselves, but together may produce an extreme impact when interacting with a specific context in the natural or human systems (IPCC, 2012; Leonard et al., 2014). The events may be of short duration and local to regional in scope. The combination of synoptic conditions and natural and human system contexts result in impacts (*g*), to both natural (*h*) and human systems (*i*).

Natural system impacts (*h*) may include events such as branch breakage and tree mortality, crop stress and mortality, flooding, disruption of wildlife behaviors, frost heaving, and changes to carbon and nutrient cycling processes (Contosta et al., 2017, 2019; Enanga et al., 2016; Penczykowski et al., 2017; Rokaya et al., 2018; Rustad & Campbell, 2012). Human system impacts (*i*) may include occurrences such as

disruption of work/school activities, damage to property, increased municipal expenditures, disruption of basic essential services such as transportation and emergency services, loss of communication, and acute and/or long-term psychological and emotional stress (Bloesch & Gourio, 2015; Doherty & Clayton, 2011; Kloster et al., 2018; Martner et al., 2002). Feedbacks between these two systems may include snow-laden tree branches falling on power lines or personal property, disrupted cash flows to agricultural and natural resource-oriented businesses or selective removal of tree species susceptible to ice damage by municipalities leading to changes in forest species composition (Hauer et al., 2006).

Broader system level feedbacks (*j*) following from the winter weather whiplash event may restructure the coupled human and natural systems context of the system. For example, in the natural system, forest structure, and cover may change because of vulnerable tree species experiencing higher rates of mortality. In the human system, structural changes resulting from an event could include displacement of individuals and disruption of community cohesion, or changes in agricultural systems. Within and between each system (natural or human), system-level processes also act as feedbacks between event impacts and coupled human and natural systems context, shaping future winter weather whiplash events. Natural system processes such as carbon storage, hydrological flows, or nutrient cycling can be impacted and lead to future changes in ecosystem structure and function, as well as the provisioning of ecosystem services (Carpenter et al., 2009). The primary human system process is decision making, including strategies such as adaptive management, risk assessment, and policy changes, some of which result in active mitigation strategies designed to reduce the future influence of synoptic weather conditions. The success of these processes is dependent on the capacity of a community or jurisdiction to anticipate the need for adaptation, the rate of recovery and restoration following the event and the resilience of the community following the event (Linnenluecke et al., 2012).

4. Case Studies

We identified four case studies, one for each type of event described in Figure 1, to demonstrate the unique features of winter weather whiplash—rapidity, misalignment with expected conditions, and the crossing above or below the 0 °C threshold—as well as the impacts of these events on coupled human and natural systems. We selected these case studies by consulting a variety of government databases, popular media sources, and historical newspaper accounts. To illustrate winter events outside of winter, we examined the "Snowtober" nor'easter of 2011 and the "False Spring" of 2012 as illustrations of *snow-on-leaf* and *cold-on-leaf*, respectively. We also examined how the Rain-on-Snow of 2016 and the February "Winter Heat Wave" of 2017 exemplify nonwinter events occurring inside of winter. For each case study, we use our conceptual model (Figure 2) to illustrate the coupled human and natural systems contexts and drivers that led to the event, the impacts of the event on natural and human systems, and the resulting feedbacks within coupled human and natural systems.

4.1. Snowtober, 2011: An Example of a Snow-on-Leaf Event

In late October 2011, a severe snowstorm battered the northeastern U.S. and the Canadian Maritimes. The snowstorm came on the heels of two other major events: Hurricane Irene (August 2011), and a tornado outbreak (June 2011), during which seven major tornadoes occurred from Massachusetts to southern Maine. The storm was caused by a low-pressure system that formed off the east coast and converged with cold air out of Canada (LeComte, 2012). The early date of the snowstorm meant that leaves were still on the trees in many parts of the region (LeComte, 2012). This natural system context meant that trees were particularly vulnerable to storm damage because of the weight of the wet snow on top of the leaves (Ferc, 2011). The human system was similarly unprepared for a winter storm. Municipalities were not yet winter-ready with plows and other supplies (e.g., salt). Fall harvests of apple crops, which contribute to both agricultural and tourism revenue, were not complete (Barnard & Nir, 2011). The preceding hurricane and tornadoes meant that many residents had recently experienced significant power outages (Kloster et al., 2018). As the storm moved northward, heavy rains turned to wet snow that coated trees, many of which were still in leaf. The heavy snow loads and accompanying high winds snapped trees and broke tree limbs (Ferc, 2011).

Implications of the Snowtober 2011 event on the human system were substantial and far-reaching. Unseasonably low temperatures ruined remaining apple harvests. Towns such as Brookline, MA, and Hollis, NH canceled Halloween because of dangers related to downed trees and power lines (Barnard & Nir, 2011). Power outages were extensive; more than three million households and businesses lost

electricity (Ferc, 2011). This event, combined with subsequent hurricanes in the region (Irene in 2011 and Sandy in 2012), resulted in several state-level policies focused on oversight to reduce outages and restoration time and revised vegetation management specifications (Connecticut); restructuring of electric providers (New York); and enactment of penalties on utilities for inadequate response (Massachusetts) (Kloster et al., 2018). For example, utilities expanded enhanced tree trimming specifications to increase mileage of ground-to-sky clearing and tree removals and implemented new standards for vegetation management practices (Ferc, 2011).

Widespread tree mortality caused by storms such as Snowtober 2011 have numerous ecological consequences that may impact nutrient cycling (Houlton et al., 2003) and riparian vegetation structure (Millward et al., 2010). Some of the effects may be positive, in that gaps in the canopy are created and the forest is thinned, which can enhance the growth of residual trees, create wildlife habitat, and increase biodiversity (Ishii et al., 2004). In addition to direct damage to trees that occurred during the storm, these types of events can also make trees more vulnerable to mortality through indirect pathways such as pests and pathogens (Irland, 2000).

4.2. False Spring of 2012: An Example of a Cold-on-Leaf Event

In March of 2012, record-breaking high temperatures were observed across the United States and eastern Canada, with temperatures reaching up to 22 °C above normal at the peak of the event in some locations (Dole et al., 2014). These high temperatures occurred in the context of overall trends toward advancing spring onset (Contosta et al., 2019; Monahan et al., 2016; Schwartz et al., 2006). The warm spell was ultimately punctuated by a cold snap (Ault et al., 2013). Reconstructions and projections of future climate suggest that the risk of false springs is likely to increase dramatically in this new climate regime with warm springs followed by advective freezes (Augspurger, 2013; Gu et al., 2008).

Mild weather late in winter or early in spring can break dormancy of vegetation early, and a subsequent late frost can result in significant damage to vulnerable buds and flowers, as was the case in this event. Both the magnitude and timing of the false spring of 2012 (Karl et al., 2012) set the stage for major damage to apple and cherry crops, with first leaf, bud growth, and green-up all occurring anomalously early (Ault et al., 2013), including record-breaking early flowering in Massachusetts and Wisconsin (Ellwood et al., 2013).

Although the temperatures of the hard freeze in April were normal for the northeastern and midwestern United States, the anomalously early leaf-out of fruit trees (apple and cherry) that preceded it led to major damage to these important crops (Ault et al., 2013). Economic damages were $500 M for fruit trees in the state of Michigan (Knudson, 2012) and $71 M for fruit trees and berries in the Northeast (Kunkel, 2013). Following the historic "false spring" of 2012, agricultural researchers and extension specialists have developed potential adaptations to avoid similar losses in the future. Crop treatments in development or use include preventing early bud break by using mist cooling or frost fans in fields to delay bud break, or keeping trees warm when frost is predicted (Hu et al., 2018; Rijal, 2017). Each of these potential adaptations has implications for ecosystem health, including water use, energy consumption, smoke emissions, or herbicide use, which each also have feedbacks to climate change. In the northeastern United States, new risk management tools include interactive maps that overlay critical time periods for bud and flower development with weather data to identify periods of risk (Northeast Regional Climate Center, 2019). Such linkages between phenology and weather and climate data will allow more sophisticated understanding of the ecological effects of whiplash events that result from a mismatch between early season plant phenological development and late season frosts.

4.3. Winter Heat Wave of 2017: An Example of a Winter Heat Wave Event

In late February 2017, anomalously high temperatures swept across central and eastern North America. The hot weather started in the midwestern United States on 22 February and spread into the eastern United States and southwestern Ontario over the next several days. It was the second hottest February on record in the contiguous United States (NOAA National Centers for Environmental Information, 2018) and February temperature records were broken across North America (LeComte, 2018). The event ended in early March when temperatures went back below freezing, and thunderstorms followed by heavy snow swept through the eastern United States. While short term, 1 to 2 day warming events are relatively common

during the winter; the duration of the February 2017 event was significant in that it persisted for more than a week at many locations (Ladwig et al., 2019).

Unseasonably warm conditions wrought havoc on winter recreational activities, and the event received a great deal of media attention. There were reports of ski areas struggling (Kummer, 2017) and deaths in the northeastern United States due to snowmobiles falling through ice on lakes (Esch, 2017). The impacts of long-term trends in rising temperatures and declining snow cover on winter recreation have been well documented, but the impact of discrete winter events has received comparatively less attention (Scott et al., 2008). Snowmobiling may be particularly sensitive to winter weather whiplash events, given the lack of snowmaking on snowmobile trails (Scott et al., 2008).

The ecological impacts of the Winter Heat Wave of 2017 were numerous. Temperatures were high enough to elicit a phenological response in many plant species. In a study from a botanical garden in Wisconsin, approximately half of the plant species under consideration showed advance stages of bud break following 6 days of extreme high temperatures, and the effect was particularly pronounced in species with weak dormancy requirements (Ladwig et al., 2019). Winter thaws, such as the 2017 event, can also have profound effects on other biotic and abiotic components of ecosystems. Sudden loss of snowpack can release large quantities of melt water to ice-covered lakes and streams and potentially elicit downstream flooding. Soils without an insulating snow cover are more vulnerable to freezing when the cold returns, and soil frost may damage fine roots and tubers and increase the risk of flooding during the spring if melt water is unable to infiltrate frozen soil (Cleavitt et al., 2008; Shanley & Chalmers, 1999). Wildlife may not be able to forage effectively in frozen soil, and insects that over-winter beneath an insulating snow cover may suffer greater winter losses (Penczykowski et al., 2017). For example, over-winter colony losses of honey bees have been associated with increased winter weather variability (Switanek et al., 2017). These impacts can be significant and further detrimentally affect elements of social systems (e.g., commerce and municipal activities).

4.4. Rain-on-Snow of 2016: An Example of a Rain-on-Snow Event

A particularly large *rain-on-snow* event affected much of eastern Canada and Vermont on 25 February 2016. According to the Canadian Disaster Database (https://www.publicsafety.gc.ca/cnt/rsrcs/cndn-dsstr-dtbs/index-en.aspx), heavy rain and thunderstorms trailed behind the freezing rain resulting in total rainfalls of up to 68 mm and ice accumulation on buildings and trees up to 25 mm. The combination of rain and mild weather melted ice and snow and resulted in localized flooding for numerous communities. Multiple local states of emergency were declared in the Eastern Townships of Quebec where ice breakup resulted in the flooding of local rivers.

Rain-on-snow events can facilitate particularly severe and destructive flooding when they result in ice jams, both because of the early nature of the flooding and because subsequent cold weather can amplify the damage (Beltaos, 2002). This was the case during the 2016 event, when local authorities commented that damage would have been less extensive had the event occurred during the spring, when milder temperatures and stronger stream flows would have broken up the ice and lessened flooding due to ice jams (CBC News, 2016). This amplification of damage is like the False Spring of 2012 example above, where the extent of damage was related to the timing and duration of the cold event relative to the stage of crop development. In this case, substantial snowmelt and rain water influx to ice-covered rivers resulted in a larger flood response. Flooding of this type can be extremely costly, with damages reaching tens or hundreds of millions of dollars depending on the location and severity of the flood (Rokaya et al., 2018).

Ecosystem consequences of *rain-on-snow* events are widespread and well documented in the literature. These rare events can deplete the snowpack resulting in earlier and smaller spring melts (Freudiger et al., 2014) and have a disproportionately large effect on water quality, including pulses of acidity (Eimers et al., 2007) and nitrogen export in streams (Casson et al., 2012; Crossman et al., 2016; Kurian et al., 2013). *Rain-on-snow* events can also impact soil temperatures and increase the incidence of soil freezing (Putkonen & Roe, 2003). Ice storms and freezing rain, both of which are sometimes associated with *rain-on-snow* events, can result in tree mortality and forest damage (Irland, 2000).

5. Developing Quantitative Metrics of Winter Weather Whiplash Events

We used hydrometeorological time series data from the HBEF to illustrate how our qualitative classification scheme and conceptual framing of winter weather whiplash might be translated into quantitative metrics of extreme whiplash events and their impacts. This represents a first step in quantitatively detecting these events and their impacts, and the goal is to develop a framework that can be adapted for larger scale analyses which can incorporate other types of data, particularly human system data. The HBEF is a 3,160-ha reserve in the White Mountain National Forest in central New Hampshire (43°56′N, 71°45′W). It was established by the U.S. Forest Service in 1955 as a center for hydrologic research in the Northeast. Within the HBEF, there are nine intensively monitored small watersheds that range in size from 12 to 77 ha. Streamflow is measured at the outlets of these watersheds and meteorological data (e.g., air temperature, precipitation, and snow water equivalent) are collected within and around these watersheds, with records that date back to the inception of the study site. For our analyses, we use data from Watershed 3, which is a 42-ha reference watershed with predominantly northern hardwood tree species.

We expanded the hydrometeorological data set from Watershed 3 to include additional variables that would facilitate the detection of winter weather whiplash events. The variables include daily simulated snow depth, simulated daily snowfall and rainfall values, and daily modeled phenology. We simulated daily snow depth as snow water equivalent (SWE) using a degree-day snowmelt model (Buttle, 2009; Crossman et al., 2016; Kokkonen et al., 2006) implemented in R (R Core Team, 2017) using the *snow.sim* function (Kokkonen et al., 2006) within the *hydromad* package (Andrews et al., 2011). Additional details on parameterization and validation of the degree-day snowmelt model are provided in the supporting information and in Contosta et al. (2019). Using the temperature thresholds that best predicted SWE, we then partitioned daily total precipitation into snowfall (as liquid equivalent) and rainfall. We applied the degree day phenology model of Richardson et al. (2006), which was developed based on field observations at the HBEF, to model canopy phenology of the three dominant species in the northern hardwood forest community at the HBEF: sugar maple (*Acer saccharum* Marsh.), American beech (*Fagus grandifolia* Ehrh.), and yellow birch (*Betula alleghaniensis* Britt.). For this model, a phenology index (PI) that ranges from 0 to 4 quantifies canopy development and senescence, where 0 indicates dormancy and no leaves while 4 represents a full, green canopy (Richardson et al., 2006). We averaged phenology indices across all three species to have a single PI for the forest for each day of our study period.

We combined our definition of winter weather whiplash with the meteorological approach of identifying weather extremes to flag occurrences of winter weather whiplash events. Because a key feature of winter weather whiplash involves the crossing of the 0 °C threshold in a way that is out of sync with expected conditions, we first stipulated that an event within winter could only take place if daily maximum temperature was above freezing. Conversely, an event outside of winter could only happen if daily minimum temperature was below freezing. In keeping with the meteorological identification of weather extremes, we also used threshold-based criteria for determining the extent to which weather conditions deviated from normal. This approach identified winter weather whiplash events as crossing the upper (or lower) end of a threshold relative to historical baseline conditions (Alexander et al., 2006; Donat et al., 2013; Frich et al., 2002). Because we did not know a priori what an appropriate threshold might be for determining the occurrence and severity of a winter weather whiplash event, we determined the daily 1st, 5th, 10th, 90th, 95th, and 99th percentiles over the entire historical record for each variable in our data set. We thus used our percentile-based thresholds in combination with our 0 °C temperature criteria to flag occurrences of each of four winter weather whiplash event types, resulting in six possible determinations of event frequency for each type (supporting information Table S1). This approach allowed us to explore how event frequency might change depending on whether the percentile-based criteria were broadly or narrowly applied. For example, we were able to compare the frequency with which *winter heat waves* took place if defined as occurring when daily maximum temperatures that were above 0 °C exceeded the 1st, 5th, 10th, 90th, 95th, or 99th percentile of historical values. Because our typology of winter weather whiplash events requires that nonwinter conditions must occur within winter or winter conditions must occur outside of winter, we also delineated the winter and nonwinter periods using our simulated PI. Here, winter was defined as the period when the PI was <0.5, which was prior to bud swelling in the spring or subsequent to the majority of leaf fall in autumn (Richardson et al., 2006). For winter events that occurred outside of winter, we also used the PI to isolate the "shoulder

Table 1

Total, Median, and Range of the Annual Occurrences of Four Types of Winter Weather Whiplash Events Occurring From 1956 to 2017 (Flow Data 1963 to 2015) at the Hubbard Brook Experimental Forest

Event	Threshold criteria	Total occurrences in record	Median occurrences per year	Range of occurrences per year	Number of winter maximum flow events in record	Number of annual maximum flow events in record
Snow-on-leaf	90th percentile	90	1	(0, 7)	n/a	n/a
	Literature	14	0	(0, 2)	n/a	n/a
Cold-on-leaf	90th percentile	16	0	(0, 5)	n/a	n/a
	Literature	3	0	(0, 2)	n/a	n/a
Rain-on-Snow	90th percentile	12	0	(0, 3)	0	0
	Literature	144	2	(0, 6)	14	13
Winter heat wave	90th percentile	693	12	(0, 28)	18	15
	Literature	39	1	(0, 2)	1	1

Note. For each event type, seven criteria were used to flag an event as taking place. Six of these criteria were based on the crossing of a threshold relative to a historical baseline, and one criterion was derived from scientific literature. Here we present two of the threshold-based criteria for visual clarity: the 90th percentile and the literature-based threshold. To illustrate the impact of winter weather whiplash events, we show the number of winters on record for which *rain-on-snow* and *winter heat wave* events resulted in (1) winter maximum daily flow and (2) annual maximum daily flow. Statistics for all six threshold criteria are in supporting information Table S2.

season" that marks the transition between winter and the growing season to avoid false identification of events during the summer. In this case, the PI had to be ≥0.5 and ≤ 3.5.

Recognizing that the occurrence of a winter weather whiplash event may also require a specific set of conditions irrespective of historical thresholds (McPhillips et al., 2018), we also developed a seventh criterion for each event type based on our best understanding of scientific literature describing the drivers and antecedent conditions that would have the potential to produce an extreme impact. Thus, we defined a *snow-on-leaf* event as occurring when daily minimum temperature was below 0 °C and at least 10 mm of SWE falls during the growing season (PI ≥0.5), where the 10-mm threshold is based on the minimum amount of snowfall that must occur to cause a societal impact within the northeastern United States (Squires et al., 2014). Our literature-based threshold for a cold event when leaves are still on the trees (*cold-on-leaf*) was derived from Augspurger (2013), who combined field observations of tree phenology with meteorological data to model the suite of temperature conditions most likely to trigger a late spring frost event. In this case, warm air temperatures in March must combine with cold air temperatures in April for frost damage to occur (Table 1). For *rain-on-snow*, we used the criteria of Freudiger et al. (2014), who defined such events as occurring when both ≥3-mm rain falls on a snowpack with ≥10-mm SWE and the amount of liquid in the rainfall comprises at least 20% of the resulting melt. For *winter heat waves*, we determined that an event would occur when winter temperatures exceeded the heating-degree day threshold of 18 °C, above which indoor home heating is not necessary (Quayle & Diaz, 2002) and then returned to more normal winter temperatures within 5 days of the cold-on-heat event. Having temperatures return to winter conditions is required to avoid flagging warming associated with spring onset, and to fit our definition of winter weather whiplash as a back-and-forth process.

When using either the threshold-based or literature-based criteria to identify a winter weather whiplash event, we flagged all possible occurrences of the event. Figure 3 visually depicts our approach to quantitatively identifying winter weather whiplash events at the HBEF. It displays all instances when conditions crossed the literature or 90th percentile threshold of historical conditions while also highlighting four notable synoptic winter weather events that we feature in our case studies above: the 2011 Snowtober Halloween Snowstorm, the False Spring of 2012, the Rain-on-Snow of 2016, and the Winter Heat Wave of 2017. Threshold-based criteria, literature-based criteria, or both detected each of these four winter weather whiplash events, though they did not always overlap. In some cases, 90th percentile threshold-based criteria detected the same event as the literature definition, as in *snow-on-leaf* for Snowtober of 2011. In others, the 90th percentile threshold flagged a greater number of occurrences than literature-based criteria, as in the False Spring of 2012 and the Winter Heat Wave of 2017. In the case of the 2016 Rain-on-Snow event, only the literature-based threshold flagged the event, not the 90th percentile criterion. This lack of coherence in the detection of winter weather whiplash among event types suggests that correctly identifying these events may at times require indices that combine the approach of the meteorological community, which focuses on
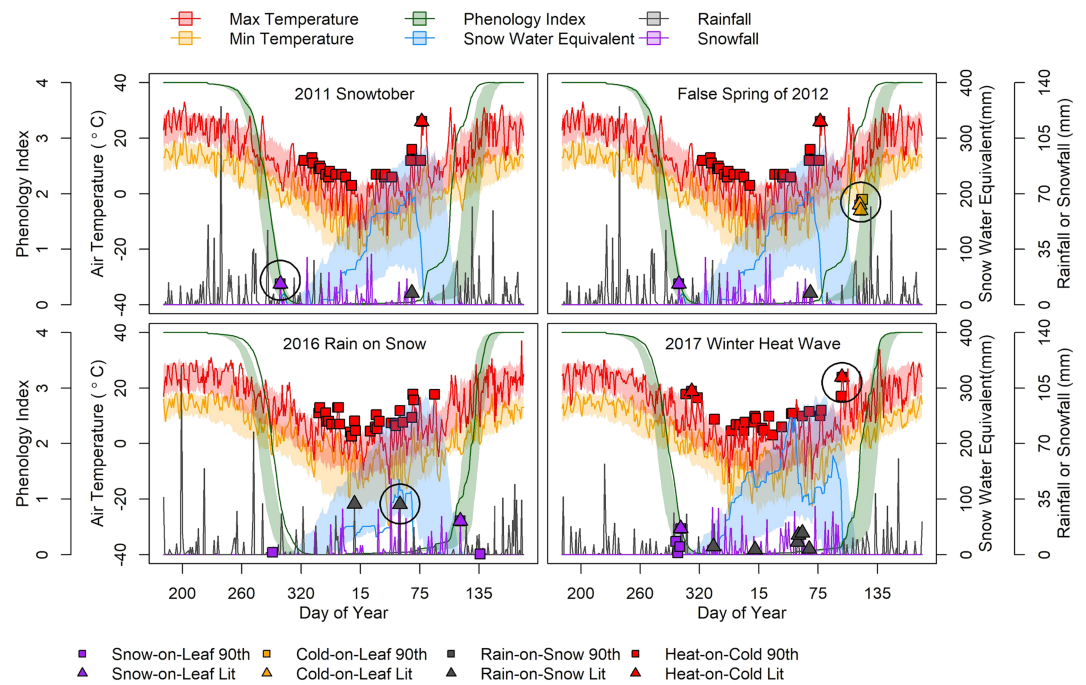
Figure 3. Notable synoptic winter weather events at the Hubbard Brook Experimental Forest that were regional weather systems affecting much of northeastern North America: the 2011 Snowtober Halloween Snowstorm, the False Spring of 2012, the Rain-on-Snow of 2016, and the Winter Heat Wave of 2017. Each time series begins on 1 July and ends on 30 June to allow the winter season to appear in the middle of the panel. Variables include daily maximum and minimum temperatures, simulated daily rainfall, snowfall, snow depth (as snow water equivalent or SWE), and modeled daily phenology. Lines indicate daily values for temperature, precipitation, snowpack, and phenology. Shaded areas depict the range of values that fall within the 90th and 10th percentiles calculated for each day of the historical record (1956–2017). Square points indicate the crossing of the 90th percentile threshold of historical conditions ("90th"). Triangular points indicate the crossing of a threshold as defined by the literature ("Lit"). In keeping with our definition of winter weather whiplash, "*snow-on-leaf*" and "*cold-on-leaf*" indicate snowfall and extreme cold, respectively, during autumn or spring when foliage is present. In contrast, *rain-on-snow* and *winter heat wave* represent non-winter conditions inside of winter. All events that occurred based on crossing the 90th and literature-based thresholds are depicted in each panel to illustrate their frequency. Case studies are highlighted with a circle in each panel.

temperature and precipitation conditions (Brown et al., 2010; Donat et al., 2013; Karl et al., 1999), with those of the hydrologic community, which also emphasizes antecedent conditions such as snowpack and soil water content, to understand and predict the impact of extreme storms (McMillan et al., 2018). Quantification of the successive, temporal ordering of weather events using Markov chain estimation (Sedlmeier et al., 2016) may also enable a more rigorous detection of winter weather whiplash events that may not be simultaneous but in combination result in an extreme impact.

Given that several winter whiplash events feature the interaction between precipitation, temperature, and snowpack, we used daily flow data from Watershed 3 at the HBEF to illustrate the hydrologic impact of winter weather whiplash events (Figure 4). We focused on *rain-on-snow* and *winter heat wave* events on the assumption that they would be more likely to impact flows as compared to *snow-on-leaf* or *cold-on-leaf*, which would be more likely to affect vegetation. Using the Wilcoxon signed-rank test, we observed that *rain-on-snow* coincided with significantly greater flows ($p < 0.01$) than *winter heat wave* events. Both winter weather whiplash conditions (*rain-on-snow* and *winter heat wave* events) had significantly ($p < 0.001$) greater flows than normal as compared to when neither of the above conditions were met. Median daily flows during *winter heat wave* events (5.2 mm) were approximately five times greater than that of normal flows (0.96 mm), while median daily flows during *rain-on-snow* events (13.0 mm) were approximately an order of magnitude greater than normal flows. Over the course of the daily flow data record (1963 to 2015) there were 14 winters (144 days) for which the maximum flow for that winter was coincident with a *rain-on-snow* event, while no winter maximum flows occurred during a *winter heat wave* event (Table 1).
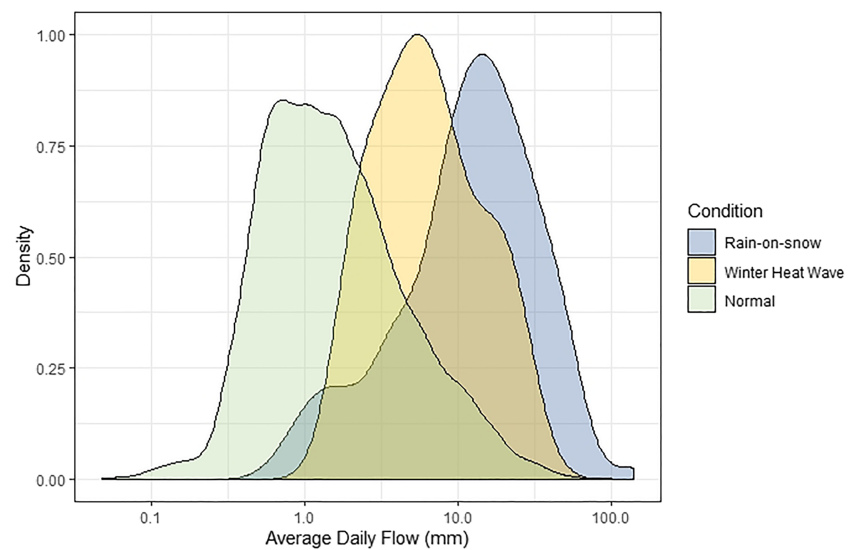
Figure 4. Kernel density plot of daily winter hydrological flows (mm) for Watershed 3 at the Hubbard Brook Experimental Forest from 1963 to 2015 under three conditions: (i) *rain-on-snow* events, shown in blue, during which ≥3 mm of rainfall occurs over a snowpack of ≥10-mm SWE (Freudiger et al., 2014); (ii) *winter heat wave* events, shown in yellow, during which the daily maximum temperature ≥ 18 °C during winter and then subsequently returns to historically normal winter temperatures within five days of the cold-on-heat event; and (iii) "normal" winter flows, shown in green, during which neither of the above conditions are met. "Winter" is defined here as when the phenology index was <0.5, a period following the majority of leaf fall in the autumn and prior to bud swelling in the spring.

The quantitative responses outlined here demonstrate the potential biophysical impacts of some winter weather whiplash events. Even in a small, forested ecosystem like HBEF, the potential to shift the major runoff event from the expected spring melt period to an earlier *rain-on-snow* or *winter heat wave* event has important consequences for water quality (Casson et al., 2014), aquatic ecosystem structure (Sickman et al., 2003) and moisture limitation during the subsequent growing season (Barnett et al., 2005). In larger river systems, winter floods represent a major challenge for communities and infrastructure, particular because they can result in ice jams (Beltaos, 2002). This analysis also provides an example of the ways in which quantitative metrics can be used to identify events and measure impacts. *Cold-on-leaf* and *snow-on-leaf* events, which may be more likely to impact vegetation or net primary production, might be detected using remote sensing of forest cover or eddy covariance measurements as opposed to the hydrologic metrics we have applied here. Identifying the coupled human and natural systems impacts of winter weather whiplash may present more of a challenge due to the infrequency of these events and the variability in both event dynamics and impacts (Smith, 2011). Furthermore, the infrequency of events makes detecting change over time at a single site with a decades-long record challenging. Since long records are uncommon, it may be necessary to use data sets with broader geographic coverage in order to generate enough statistical power to detect trends through time. However, such quantitative approaches are needed in order to both understand the societal consequences of winter weather whiplash events and to predict the vulnerability of systems to extreme impacts given the combination of the coupled human and natural system context and winter weather conditions.

6. Conclusions and Future Research Directions

Winters are changing rapidly across snow-covered regions of the world (Contosta et al., 2019). In addition to monotonic trends such as increases in average temperatures and earlier onsets of the spring season, there is increasing evidence that climate change will result in changes to the intensity and distribution of extreme winter weather (Francis & Vavrus, 2012). Here we introduce, define, and investigate winter weather whiplash events, a class of extreme events characterized by rapid, back-and-forth changes in winter weather that have the potential to result in outsized and unexpected impacts on coupled human and natural systems. A key feature of these events is that air temperature crosses the 0 °C threshold, and therefore, the phase of water changes from frozen to liquid (or vice versa). Crossing this hard physical threshold may mean that

impacts to coupled human and natural systems are more damaging than other types of events and that unique responses are needed to adapt and mitigate against these events in the future. While attribution of winter weather whiplash is challenging, we argue that a robust understanding of the ways in which antecedent conditions in both human and natural systems respond to weather that rapidly fluctuates above and below freezing is critical for developing mitigation and adaptation strategies in seasonally snow-covered communities.

The causes and consequences of winter whiplash events cross disciplinary boundaries and therefore require analyses that span biophysical disciplines (meteorology, phenology, hydrology, and biogeochemistry) as well as social sciences (geography, resource management, and policy studies). In this manuscript, we lean on quantitative, biophysical data to identify the occurrence of winter weather whiplash and its hydrologic impacts but do not directly address the socioeconomic consequences of these events. Quantitative data regarding climate and ecosystem conditions may be more readily available at broad spatial scales during winter whiplash events, whereas economic and social data are more challenging to acquire and are often collected at spatiotemporal resolutions that do not match the scope of a weather event. Harmonizing meteorological, environmental, and socioeconomic data may lead to an integrated understanding of these incidents, providing stakeholders with more usable information for planning and response purposes. It is clear that winter whiplash events often carry serious and profound consequences with practical implications for human societies and thus uniting this initial work with existing models of mitigation and adaptation would be valuable in order to minimize detrimental and negative repercussions.

While our work makes broad strides toward standardizing a methodology for identifying and quantifying winter weather whiplash events, our threshold-based methods may not fully capture the variability in their duration, magnitude, and impacts. For instance, while our methods highlighted the February Rain-on-Snow event in 2016, it also indicated that another event occurred in January; yet the January event did not produce the same hydrological effect. This is in large part due to the importance of antecedent conditions in determining the magnitude of system response to a winter weather whiplash event, but the difficulty in incorporating these conditions into a quantitative framework. Using a multi-indicator definition and considering antecedent conditions such as runoff and snowpack over a broader temporal window may lead to a more robust identification of events. There have been calls to combine phenology data with meteorological data to identify the onset of spring (Ault et al., 2013), recognizing that lags between biophysical and ecological phenomena can have important consequences for natural and human systems (Contosta et al., 2017). A similar, multidisciplinary approach to identifying winter weather whiplash events is needed to produce a fulsome picture of when and where these events occur, what the impacts are, and how distribution may change in the future.

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