PROJECT TITLE

Title:	**Recent Changes in the Form, Frequency, and Amount of Cold-Season Precipitation in New England and Their Impact on Streamflow Dynamics**
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Summary

Rain-on-snow events are a major cause for winter flooding in the Northeastern U.S.. In the past several decades, warming has caused detectable changes of winter precipitation characteristics in the Northern Hemisphere middle and high latitudes, especially changes of rain-vs-snow contrast and snow melt. How the changing precipitation characteristics influence streamflow and what this may imply for winter flooding risks are not well understood. In this project, based on streamflow data, precipitation and temperature data, snow coverage and snow melt data, we investigate precipitation characteristics changes, streamflow changes, and their relationship in New England starting with Connecticut. As expected, wintertime rain frequency has increased and snow frequency has decreased due to the recent warming, and this change is faster along the coast than inland areas. Despite the increased rain frequency, the frequency of rain-on-snow events has decreased, as a result of snow coverage decrease more than compensating for the rain frequency increase. Since rain-on-snow events are an important cause for winter flooding in New England, this has significant implications on both pluvial and fluvial flood risks.

Most of the top ranked events for storm runoff (separated from base flow) at each streamflow station corresponded well with the top ranked events for watershed liquid input (defined as the sum of rainfall and snowmelt); with rare exceptions, rainfall is the dominant contributor to these storm runoff events, with rapid snowmelt accounting for a small fraction of the liquid input. As warming continues into the future, we expect even higher fraction of precipitation falling in liquid form, leading to higher winter flooding risks. It is worth noting that some of the findings may not hold in region at higher latitudes and should be further examined in regions beyond Connecticut.

Results from this project will be disseminated through an oral presentation at the American Meteorological Society Annual Meeting (Denver, CO, January 11, 2023) in the session "Linking Snow Hydrology and Society through Remote Sensing, Modeling, Data Assimilation, and Analytics" (https://ams.confex.com/ams/103ANNUAL/meetingapp.cgi/Session/61891) and through a manuscript still in the early stage of preparation for *Journal of Hydrology*. The project contributed to the training of four students in total: Koushan Mohammadi (ENVE PhD student, international, project-supported RA), Kyla Drewry (CEE undergraduate, supported by the project), Nickolas Morillo (CEE undergraduate, minority, supported by the CEE match to the project), and David Wang (high school senior, Groton School in Massachusetts, unpaid trainee exploring Environmental Engineering Major).

Introduction

Streamflow dynamics, including the sub-daily and day-to-day variability, seasonality, and extremes of streamflow, have significant impact on societal and ecosystem wellbeing. With the greenhouse gas-induced warming, major changes in streamflow dynamics have been observed or expected (Parr et al., 2015; Eleonora et al., 2016), including enhanced amplitude of seasonality, shifts in the flow timing, and an increase of both flood and drought risks. However, cold season flooding risks and how it changes in a warming climate remains relatively under studied.

Snowfall and snow pack play an important role regulating streamflow seasonality and water resources in general in the U.S. Northeast. For example, across unregulated river stations in New England, the winter/spring timing of high flow as reflected by the center of volume became significantly earlier as a result of earlier snow melting in a warmer climate (Hodgkins et al., 2003); in New York, majorities of annual peak flows resulted from Rain-On-Snow events (Pradhanang et al., 2013). The GHG warming causes a higher rain to snow ratio, greater frequency of rain-on-snow events and faster snow melting in the middle of winter, and earlier disappearance of snow pack in the spring. These threatens to increase winter floods and limit water resources during the growing season (e.g., Ahn et al., 2016; Eleonora et al., 2016; Davenport et al., 2020). However, most climatic assessments of precipitation focused on seasonal total amount or did not distinguish rain from snow (e.g., Diffenbaugh et al., 2012; Krasting et al., 2013; Seth et al., 2019; Wang et al., 2020), while the streamflow dynamics are sensitive to event-scale precipitation characteristics. Moreover, analyses of precipitation trend and changes were often conducted separately from those of streamflow. It is not clear how the winter streamflow changes are related to the changes of cold-season precipitation characteristics in a warming climate. This project attempts to fill the identified research gaps and focuses on deriving a predictive understanding of the role of winter rainfall and snowmelt in driving the changes of pluvial and fluvial flood risks based on observational data.

Objectives

The project objectives are 1) to characterize past changes of winter precipitation and storm runoff and 2) to understand how the observed changes of flood risks are related to changes of winter precipitation characteristics.

Results and Discussion

Our analysis focused on analyzing streamflow and precipitation in Connecticut, and we plan to expand the analysis to New England in Year 2. Main results are summarized under two topics pertaining to the two project objectives:

1) Warming and Precipitation Characteristics Changes

Warming has caused a shift of precipitation form, with an increase of rain frequency and a decrease of snowfall frequency (Figure 1). This temporal trend is consistent with the negative spatial correlation between snow frequency and winter average temperature (Figure 1). Winter total precipitation amount has increased, and this increase was primarily a result of rainfall increase. Total snowfall amount changed little or event decreased.

The frequency of rain-on-snow events during winter shows a weak negative trend. Analysis on the relationship between rain-on-snow frequency and several relevant variables (including snow cover, snow water equivalent depth, rain frequency, snow frequency, and temperature) produced evidence that the reduction of rain-on-snow frequency resulted from the reduction of snow cover and snow frequency. That is, although rain frequency has increased, there was simply not enough snow on the ground to make it a "rain-on-snow" event.

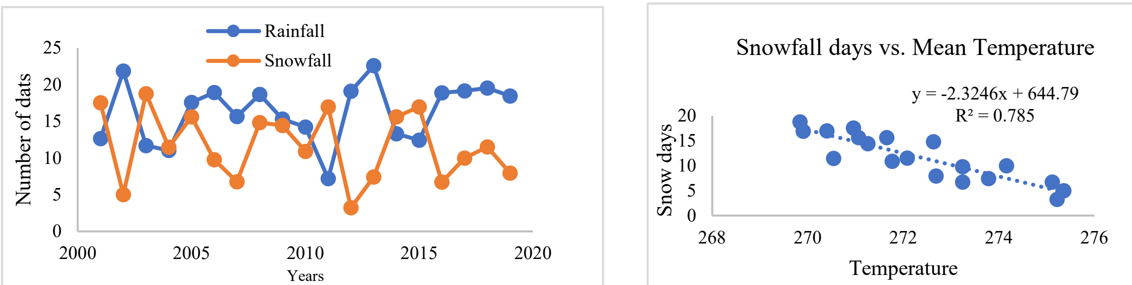

Figure 1: (left) Days with rain and snowfall during winter (DJF, December-February), averaged across Connecticut; (right) Snowfall days varying with mean temperature in DJF.

2) Major Storms: Storm Runoff and Equivalent Rainfall

Our flood risk analysis at each station/watershed focused on the top ranked events: from each year we chose the top three events for input (rain plus snowmelt, referred to as "equivalent rainfall") and top three events for output (storm runoff after removing baseflow). This analysis was done at the station level. At each station, base flow separation is applied to streamflow time series, and the resulting storm runoff hyetograph is used to identify the top three storm runoff events; for each station, the corresponding drainage basin is delineated based on DEM data, and rainfall, snowfall, temperature, and snow cover over this drainage basin are used to derive the "equivalent rainfall". Judging from the timing of these events (Figure 3), not surprisingly, most of top three storm runoff events correspond to the top three equivalent rainfall events. Among these top events, the primary contributor was rainfall; snow melt accounted for a small fraction of the total liquid input (Figure 3).

The peak storm runoff did not show a clear increasing signal; neither did the annual maximum liquid input. However, the duration of the high flow event showed an increasing trend. Based on the sample distribution of high flow duration (Figure 4), among high flow events posing a flood risk, the most often observed were 1-day events during the 1st decade of the data record and multi-day events during

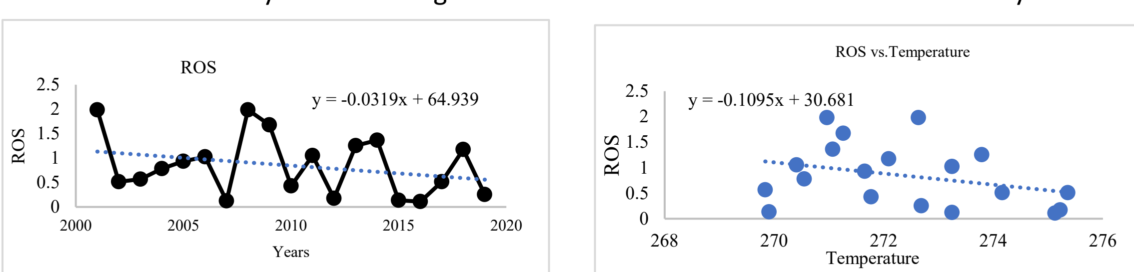

Figure 2: (left) Rain-on-snow frequency time series, averaged across Connecticut; (right) Rain-on-snow frequency varying with mean temperature during DJF season.

the last decade. This increase of flood duration is consistent with findings from past studies based hydrological models driven with future climate projections (Parr et al., 2015). This duration and frequency analysis at individual stations is limited by the limited inventory of events; currently we are lumping data from multiple stations to test the robustness of this result.

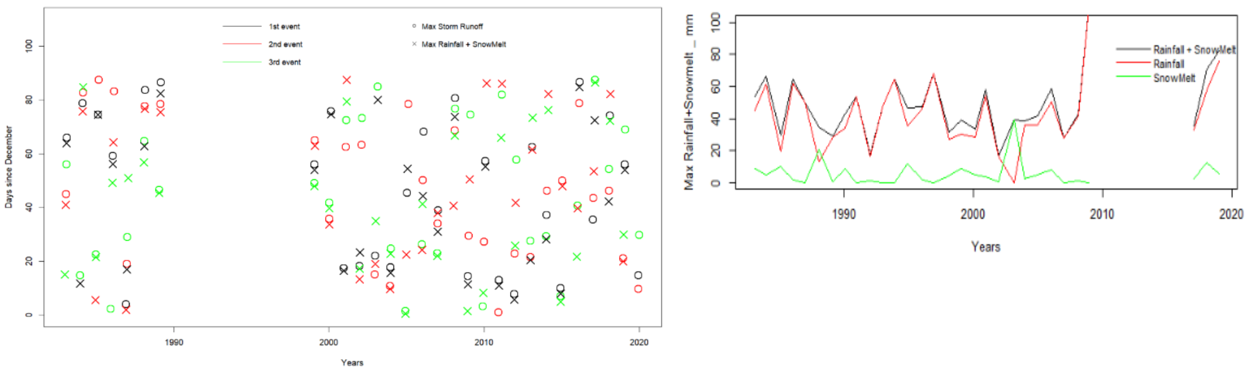

Figure 3: (left) Timing of the top three input and output events, using Quinebaug River at West Thompson (CT) as an example; (right) Sum of rainfall and snowmelt time series for the annual maximum event and the contribution from rainfall and snowmelt, using Pequabuck at Forestville (CT) as an example.

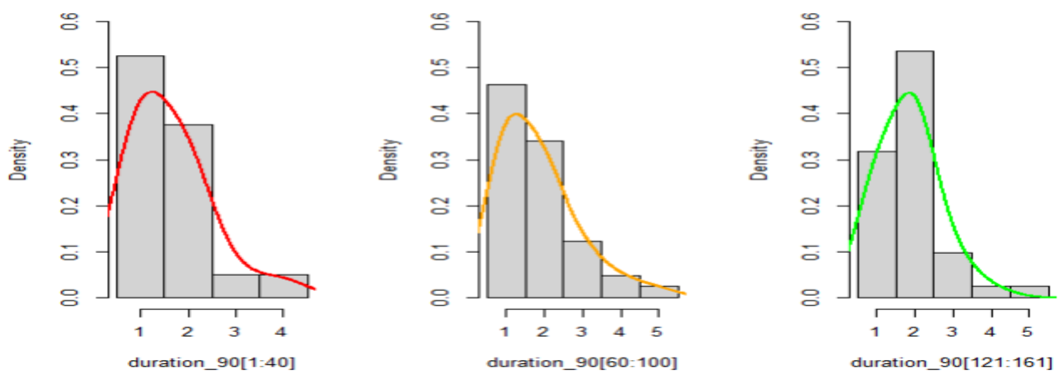

Figure 4: Sample distribution of the duration of high flow events in the first, middle, and last decade, using Quinebaug River at West Thompson (CT) as an example. High flow events became longer from early decade to late decade of the observational record.

Conclusions

Warming in the past several decades has already caused changes of winter precipitation characteristics, including the straightforward changes towards more rainfall than snowfall and unexpected changes such as the reduced frequency of rain-on-snow events. With rare exceptions, rainfall (as opposed to rapid snow melt) is the primary cause for major storm runoff events in winter; contribution from snowmelt is minor in most events. As warming progressed, major storm flow events have become longer-lasting.

Some of the findings may be latitude-dependent. For example, the decrease of rain-on-snow events may only hold in warmer regions of the Northeast; at higher latitudes such as Vermont or New Hampshire where snow cover is more prevalent, rain-on-snow events may increase as rainfall becomes more frequent. Findings from this project should be examined in other regions of the Northeast. Relative to summer flooding events that are almost entirely determined by precipitation, temperature plays a more important role in streamflow dynamics through its impact on precipitation form and snow melting, which increases the complexity of winter time flood prediction. How temperature, rainfall/snowfall, and snowmelt may interact to influence streamflow is challenging to tackle with conventional statistical analysis. Machine learning is an attractive alternate approach owing to its ability to extract useful information from a large amount of feature data with poorly understood dependence. Follow up research should explore the use of machine learning in winter streamflow forecast.

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