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On the variability of cold region flooding

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SUMMARY

Cold region hydrological systems exhibit complex interactions with both climate and the cryosphere. Improving knowledge on that complexity is essential to determine drivers of extreme events and to predict changes under altered climate conditions. This is particularly true for cold region flooding where independent shifts in both precipitation and temperature can have significant influence on high flows. This study explores changes in the magnitude and the timing of streamflow in 18 Swedish Sub-Arctic catchments over their full record periods available and a common period (1990–2013). The Mann–Kendall trend test was used to estimate changes in several hydrological signatures (e.g. annual maximum daily flow, mean summer flow, snowmelt onset). Further, trends in the flood frequency were determined by fitting an extreme value type I (Gumbel) distribution to test selected flood percentiles for stationarity using a generalized least squares regression approach.

Results highlight shifts from snowmelt-dominated to rainfall-dominated flow regimes with all significant trends (at the 5% significance level) pointing toward (1) lower magnitudes in the spring flood; (2) earlier flood occurrence; (3) earlier snowmelt onset; and (4) decreasing mean summer flows. Decreasing trends in flood magnitude and mean summer flows suggest widespread permafrost thawing and are supported by increasing trends in annual minimum daily flows. Trends in selected flood percentiles showed an increase in extreme events over the full periods of record (significant for only four catchments), while trends were variable over the common period of data among the catchments. An uncertainty analysis emphasizes that the observed trends are highly sensitive to the period of record considered. As such, no clear overall regional hydrological response pattern could be determined suggesting that catchment response to regionally consistent changes in climatic drivers is strongly influenced by their physical characteristics.

1. Introduction

Cold environments are complex in that their hydrological systems interact with both climate variables and the cryosphere. Our understanding of drivers and effects of climate change on these systems is still limited, especially in terms of extreme events related to water resources such as floods and droughts. For flood extremes, this is worrisome as northern landscapes become more densely populated calling for risk mitigation and management strategies that can remain viable under a changing climate. Because there is growing concern about increased frequency and severity of extremes, the understanding of hydrological functioning and responses in cold regions is needed (Kundzewicz et al., 2014).

Recent studies have shown that flood extremes are shifting due to climate change but that changes vary with location (e.g. Burn et al., 2010; Wilson et al., 2010; Hall et al., 2014; Kundzewicz et al., 2014). Across Canada, for example, trends toward decreasing flood magnitudes and earlier flood occurrences have been detected for snowmelt-dominated catchments (Cunderlik and Ouarda, 2009; Burn et al., 2010). An ongoing shift in flow regime from snowmelt-dominated to rainfall-dominated coupled to the development of a bi-modal flow regime with two peaks in the annual hydrograph (one in late spring due to snowmelt and one in late summer due to rainfall events) has been found both in North America and northern Europe (Cunderlik and Ouarda, 2009; Dahlke et al., 2014). With regards to the magnitude and the occurrence of floods, variable spatial and temporal patterns have been

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detected for northern Europe (Wilson et al., 2010; Dahlke et al., 2012; Hall et al., 2014). Wilson et al. (2010) and Fleming and Dahlke (2014) showed that trends in annual and seasonal streamflow as well as changes in extreme events can be linked to precipitation and temperature trends, whereas the signal induced by temperature seems to be more clearly reflected in streamflow series. Consistent with this, increasing trends in minimum flows have been observed across much of northern Sweden emphasizing the importance of the cryosphere on hydrological system's response (e.g. Dahlke et al., 2012; Sjöberg et al., 2013).

Concurrent with these changes, climate in northern Sweden has changed over the 19th century. Mean annual air temperature has increased in general and, over the last century, fluctuations have been present (van der Velde et al., 2013). Increasing air temperatures have been measured in northern Sweden at the beginning of the 20th century until the early 1940s, followed by a decrease until the 1970s and an increase ever since to values higher than in the 1930s (Lindström and Alexandersson, 2004; Callaghan et al., 2010). The increase in air temperature is most pronounced in winter, whereas the temperature in summer did not rise significantly (Callaghan et al., 2013). Increasing extreme winter temperatures have been detected leading to enhanced snowmelt during winter and trends toward earlier snowmelt (Callaghan et al., 2010, 2013; Wilson et al., 2010; Hannaford et al., 2013). Mean annual and summer precipitation along with the variability of extreme precipitation events have constantly increased over the last century in northern Sweden (Lindström and Alexandersson, 2004; Callaghan et al., 2010). Enhanced winter precipitation, which mainly falls as snow, has been reported in the late 1980s and 1990s, whereas snow depth increased until the 1980s, but has since then decreased (Lindström and Bergström, 2004; Holmlund et al., 2005; Callaghan et al., 2013). Similarly, snow duration decreased significantly over the last century (Callaghan et al., 2013; Arheimer and Lindström, 2015).

Due to the complexity of cold region hydrological systems, however, a catchment's response can vary depending not only on climate forcing but also on catchment properties. As shown by previous studies, a region with a uniform climatic input can develop different streamflow responses depending on the state and the distribution of permafrost, storage capacity, glacial coverage, soil properties and a catchment's geomorphology and elevation (e.g. Birsan et al., 2005; Carey et al., 2010; Lyon et al., 2010; Walvoord et al., 2012; Tetzlaff et al., 2015). The cryosphere in general and permafrost in particular have significant impact on streamflow in cold environments by buffering the hydrograph through enhanced subsurface flow causing an increase in winter base flow and a decrease in spring flood magnitude (Dahlke et al., 2012; Walvoord et al., 2012; Sjöberg et al., 2013). The discontinuous permafrost zone is particularly important for a catchment's streamflow response due to the significant ice content in the ground, which influences infiltration and transit times (Lyon et al., 2010; Tetzlaff et al., 2015). Furthermore, snow is a significant feature of cold regions, where snow depth as well as snow duration play a crucial role for different hydrological signatures such as timing and magnitude of the spring flood, but also onset of snowmelt (e.g. Burn et al., 2010). Since these characteristics can differ on a local scale, variable streamflow responses on catchment scales can develop (e.g. Dahlke et al., 2012; Fleming and Dahlke, 2014).

Owing to the complexity of cold environments, a better understanding of the hydrology in sub-arctic catchments is needed. Decadal scale variability caused by atmospheric circulation such as the North Atlantic Oscillation brings about the need for long-term trend analysis to detect actual trends instead of natural variability in the system (Hannaford et al., 2013). This study focuses on examining trends and responsible mechanisms in the generation of high flow extremes (floods) in cold environments and their interactions with climate. Following the methodology in Dahlke et al. (2012) an emphasis is placed on changes in high flow extremes with consideration of trends and patterns across a range of flow characteristics. The goal of this study is to determine whether there are consistent regional patterns of change in streamflow records across the Swedish Sub-Arctic. This is accomplished by investigating 18 sub-arctic catchments in northern Sweden for changes in their hydrology. The consistency (or lack thereof) in spatial patterns of flooding has the potential to yield information about the evolution of hydrological responses across cold regions in general and northern Sweden specifically.

2. Methods

2.1. Study area

This study explored changes in 18 unregulated catchments located in the Swedish Sub-Arctic at latitudes ranging from 65 to 69°N (Fig. 1). The catchments considered have an area ranging from 100 to 10,000 km^2 and a mean elevation of 720 m a.s.l. (Table 1). Northern Sweden is characterized by the Scandinavian mountain range in the west and the Baltic Sea in the east. The Scandinavian mountain range denotes the border to Norway and has elevations up to about 2100 m a.s.l. in Sweden. The catchments considered all drain toward the Baltic Sea with the Scandinavian mountain range functioning as the regional water divide.

The glacial coverage in each of the catchments was estimated to be less than 2% of the catchments area (SMHI, 2013) and therefore not considered further in this study. The catchments are located in the continuous, discontinuous, sporadic or isolated permafrost zone, depending on latitude and elevation (Christiansen et al., 2010). The vegetation in the Swedish Sub-Arctic is mainly characterized by birch forests, tall shrubs, meadow, heath, and wetlands (Callaghan et al., 2013). These vegetation compositions are changing due to increasing air and soil temperatures and the thawing of permafrost resulting in an increase in tall shrubs and wetland graminoid vegetation (Callaghan et al., 2010). Northern Sweden is characterized by a cold and humid climate. The catchments considered have a mean annual air temperature between 0 and −8 °C with the lower values at higher elevations and latitudes. Above-average mean annual air temperatures have been reported in northern Sweden over the last decade (0.2–2.8 °C higher than multi-annual average 1961–1990) (SMHI, 2014a). Precipitation varies on an east–west gradient with annual values up to 2000 mm/year in the west (mountainous areas) and 500 to 700 mm/year in the east. Over the last decade, mean annual precipitation values varied year to year with ranges from 80% to 170% compared to the multi-annual average 1961–1990 depending on year and location (SMHI, 2014b). Years with above-average mean annual precipitation were in the majority.

Streamflow in northern Sweden is mainly snowmelt-dominated, with peak streamflow occurring in late spring and summer (May to July) when about half the annual streamflow occurs (Lindström and Bergström, 2004). The spring flood is approximately double the volume of the autumn flood caused by rainfall events (Arheimer and Lindström, 2015). Streamflow in northern Sweden can vary substantially at decadal scales as indicated by both the dry period in the 1970s and the wet period starting in the mid-1990s. Further, a higher than average increase in extreme values was reported over the entire 20th century starting in the 1990s with large floods both in 1995 and 2000 (Lindström and Bergström, 2004). Especially the flood in 1995 caused by enhanced winter precipitation was remarkable in northern Sweden, since it occurred in most catchments across the region (Lindström and Bergström, 2004; Holmlund et al., 2005). A loss in lake ice and a decrease in ice duration were reported over the