Changing Characteristics of Snow, Precipitation and Drought in the Northeast U.S.

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The National Drought Mitigation Center investigated changing characteristics of drought and precipitation (especially winter precipitation) in the northeast U.S. (NEUS) to help address gaps in current research, in collaboration with the U.S. Department of Agriculture's Northeast Climate Hub. The work was funded through a cooperative agreement with the USDA's Office of the Chief Economist.

Key Takeaways:

- The results from this analysis support the observed and expected increase in winter and spring precipitation and heavy precipitation events in the NEUS.
- No clear signals emerged for recent changes in the number of dry periods in the NEUS. Future work could examine the maximum lengths of dry periods each year, rather than the number of periods that meet a certain threshold.
- Spring and annual snowfall has decreased across most of the NEUS, especially in the Appalachian regions of Pennsylvania, Maryland and West Virginia. It is possible that some increase in snowfall has occurred in northeastern parts of New England.
- Days with non-zero snow depth in February appear to be decreasing overall in the last 30 years when compared to the previous 30 years, though the robustness of this result is sensitive to the time periods analyzed.

Introduction

Climate change-driven alterations in winter temperature and precipitation, and consequent changes in the amount of snow and duration of snowpack, are a growing concern. This is particularly concerning in regions of the U.S. where snow plays a role in the economy, public health and culture.

In the U.S., research on changing snow regimes has largely focused on the western U.S., with less research in the NEUS (Krakauer et al., 2019; Xue and Ullrich, 2022). The Northeast chapter of the Fourth National Climate Assessment (Dupigny et al., 2018), which provided a regional synthesis of observed and projected changes in temperature, precipitation and extreme weather events, showed that winters in the NEUS have warmed three times faster than summers, leading to warmer late-winter and early-spring temperatures and a shorter snow season (Notaro et al., 2014 and Demaria et al., 2016). This combination of events has produced less early winter snowfall, leading to lower snow density and extent, and earlier snowmelt (Bormann et al., 2013; Burakowski et al., 2022; Nolin et al., 2021). The amount of winter precipitation falling as rain rather than snow has increased (Hayhoe et al., 2007; Nolin et al., 2021; Feng and Hu, 2007; Kunkel et al., 2009; Ning and Bradley, 2015; Huntington et al., 2003; Hatchett et al., 2022; Huang et al., 2017) as has the number of rain-on-snow events (Wachowicz et al., 2020). The earlier transition from winter to spring, coupled with shifts in snowfall amounts, has already resulted in earlier snowmelt-induced runoff and reduced springtime streamflows (Demaria et al., 2016; Dudley et al., 2017; Grogan et al., 2020).

The goal of this analysis was to evaluate trends in recent observed data pertaining to drought, precipitation and snow in the NEUS. To accomplish this, researchers performed a literature review and acquired hydroclimatic data, including precipitation data from the National Drought Mitigation Center's (NDMC) Drought Risk Atlas and snow depth data from the Applied Climate Information System (ACIS). Analyses of these datasets showed increases in winter, spring and summer precipitation in recent decades across the region, while snowfall has decreased in some areas in the last 30-40 years, especially in the western and southwestern parts of the region. Data from the NDMC's Drought Risk Atlas showed that days with heavier precipitation amounts also were increasing. Frequency of dry weeks decreased in some areas, though this pattern was inconsistent across the entire region. Finally, February generally has 10-20% fewer days with any snow depth in the 1990-2019 period compared to 1960-1989, though this result appears to be sensitive to the starting decade for the analysis (shorter, more recent periods do not typically show this result and even suggest the opposite trend in some areas.

For a full directory of figures produced during the project, please visit the "Changing Characteristics of Precipitation and Drought in the Northeast U.S." webpage. Please note that not all these figures were referenced in the results section herein (for instance, not all results were found to be noteworthy, but all of the figures developed from the analyses can be viewed at the aforementioned link).

Methods

To assess long-term trends in snowfall, snow depth, precipitation, the frequency of precipitation events, and the geographic variations in these patterns, a trend analysis was conducted using data from multiple station-based sources. The Mann-Kendall trend test, a widely used non-parametric test for trend in time series data, was used to evaluate statistical significance in trends. For more information on the Mann-Kendall trend test, please refer to the trends methodology from the NDMC's Drought Risk Atlas.

Trends for two drought indices, the Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI), were calculated. To provide some consistency with start dates used in the DRA, trends on seasonal data were calculated from 1970, 1975, 1980 and 1985 through 2021 using the Theil-Sen slope estimator from Python's statsmodels package (see Theil, 1950; Sen, 1968). Trend magnitudes, inferred from the Theil-Sen slope, were expressed in units of index/year, and the Mann-Kendall Test was used to identify statistically significant trends. For more information on the seasonal trend methods for SPI and SPEI, please refer to the Drought Risk Atlas trends methodology.

Dry periods were identified by delineating consecutive days with less than 0.01 inches of precipitation on an annual basis. Trends in dry periods focused on the time periods from 1950, 1970, 1980 and 1985 through 2017 in the DRA for stations in the NEUS. For each year, the number of streaks per year exceeding thresholds of 3, 5, 7, 10 and 14 days were compiled, and Theil-Sen slopes and Mann-Kendall tests were evaluated for each station in the analysis. If a station had a data record of at least 35 years for the time frame being considered, earlier end years were allowed if station records did not go all the way to 2017.

Mann-Kendall trends and Theil-Sen slopes for the number of days with precipitation exceeding 0.10, 0.50 and 0.75 inches per year were taken from the DRA, with analysis periods spanning the periods 1970, 1975, 1980 and 1985 through 2017. Trends were also computed for climatological seasons (December-February, March-May, June-August, September-November). If a station had a data record of at least 35 years for the time frame being considered, earlier end years were allowed.

Daily snowfall data were downloaded from ACIS stations in the NEUS in June 2023. For each station, the record was reduced to periods of October through May, given that snowfall is most likely to fall within these months in the NEUS and that this period roughly aligns with the start of the water year used for assessing hydrologic resources in the western U.S. For periods beginning from 1950, 1960, 1970, 1975, 1980, 1985 and 1990 until 2020, the number of missing daily snow data points was compiled. For each of these time periods, when at least 95% of daily data were available, individual station data were analyzed for the respective time period. Total daily snowfall was calculated for each year (snowfall from October-December was included in the year in which the following January fell), and for the September-November, December-February and March-May periods. Mann-Kendall trends and Theil-Sen slopes were calculated for each of these for the periods beginning from the aforementioned start years until 2020. Differences in average snowfall (for the different climatological seasons) between 1961-1990 and 1991-2020 were also computed for stations that had at least 95% data completeness going back to 1960.

To analyze snow depth data, data integrity was calculated for stations in the same manner as snowfall data. Since the propensity for early melt-off was a metric of interest for this project, the annual number of days with snow depth greater than a trace in February, March and April was calculated for each station. The average values of the monthly snow depth days for the 1960-1989 period were subtracted from the 1990-2019 period. Differences for the 1970-1994 versus 1995-2019 periods, as well as 1980-1999 versus 2000-2019 periods, were also calculated. This was carried out to evaluate whether there have been changes in the number of snow depth days in recent decades compared to decades earlier in the analysis period.

Results

As discussed earlier, recent studies have found increases in extreme precipitation amounts and in annual precipitation in the NEUS (Krakauer et al., 2019). In particular, studies have shown that precipitation has increased in recent decades, with significant changes typically beginning around 1996 (Huang et al., 2017). Results from our analysis support this general pattern. Trends in SPI for winter months show statistically significant increases in precipitation (herein, “precipitation” refers to either liquid or frozen precipitation) across most of the NEUS (Figure 1), with some increase in SPI evident at almost every site analyzed with a start year of 1985. Spring (March-May) precipitation amounts, as analyzed by SPI trends, mostly exhibit increases since the 1970s and 1980s, with this trend being most consistent in western Pennsylvania, West Virginia, the Maryland Panhandle, and from New Hampshire through eastern Massachusetts and Rhode Island (Figure 2). Summer (June-August) precipitation amounts also exhibit many statistically significant increases, especially since 1985. In addition to overall increases in precipitation, moderately heavy (0.5 to 1.0 inches per day; Groisman et al., 2012) daily precipitation amounts during winter (December-February) have increased at most stations across the NEUS as well. Much of the region shows widespread statistically significant increases in calendar days with at least 0.5 inches of precipitation, especially since 1980 and 1985. Though slightly more muted, a similar pattern emerges for calendar days with at least 0.75 inches of precipitation during winter. Numerous increasing trends in spring days with at least 0.5 inches of precipitation were also observed since the 1980s, though this pattern was not as pronounced as during

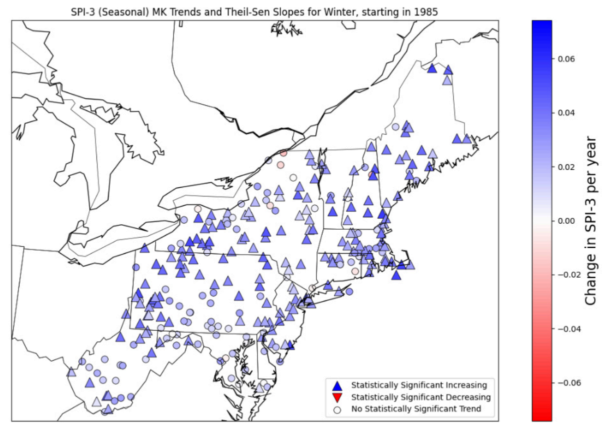

Figure 1: This map shows winter Standardized Precipitation Index (SPI) trends since 1985 in the NEUS, showing an overall increase in liquid and frozen precipitation across most sites. Statistical significance denoted by triangles is at the 95% confidence level.

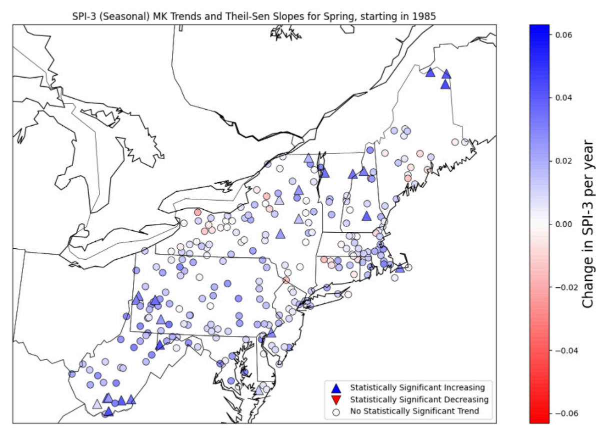

Figure 2: This map shows spring SPI trends since 1985 in the NEUS, showing mostly increases in spring precipitation across the region, with some variation.

the winter. For 0.75 inches precipitation thresholds during the spring, some statistically significant increases appeared for the start years 1970, 1975, 1980 and 1985, though they were more numerous for 1970 and 1975.

Although overall precipitation has generally increased in the NEUS, trends in drought have been variable. For example, Krakauer et al. (2019) found that although the frequency of drought (identified by periods of one month or more with SPEI less than -0.84) had decreased over the 1901-2015 period, the intensity and duration of drought had not changed appreciatively. Given overall precipitation increases alongside increases in the frequency of precipitation events, it can be reasoned that longer periods without precipitation would also be less common. Results from the DRA were analyzed for annual counts of 7- and 10-day dry periods. Statistically significant decreases in instances of 7-day dry periods were somewhat widespread for the 1980-2017 period, especially in Pennsylvania and New Hampshire. A similar pattern emerged for the 10-day dry period analysis, though this result was slightly less pronounced than for the 7-day analysis. A few areas, especially in parts of New York, showed less of this pattern, and there were a few stations suggesting increases in week-long dry periods from 1980 to 2017 (Figure 3).

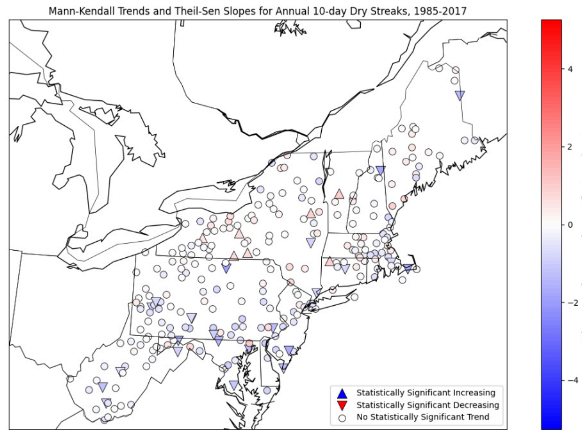

Figure 3: This map shows trends in the number of 10 day or longer consecutive dry days per year. An increase, denoted in red, would mean that more dry streaks of 10 days or longer are tending to occur more recently; the opposite would be true for the blue (decreasing) markers.

Across the entire October-through-May period, long-term decreases in snowfall were observed from 1950 and 1960 through 2020 across most of the NEUS. The trend is less robust for start years in the 1970s and 1980s. Increases (numerically, though not significant at the 0.05 level) in season-wide snowfall were observed in parts of eastern New England (Figure 4). Since 1990, snowfall in West Virginia and the Maryland Panhandle, and central New York, especially southeast of Lake Ontario, generally decreased. Spring snowfall has generally decreased since 1950 and 1960, especially for areas in western New York, central and western Pennsylvania, and West Virginia. From 1990 onward, the primary trend was toward lower snowfall, especially in New York, central Pennsylvania and the West Virginia/western Maryland Panhandle region. A few sites in northeast Maine showed increasing snowfall, though not at a statistically significant level.

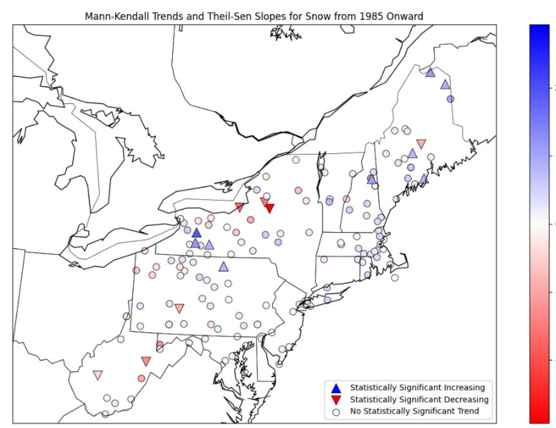

Figure 4: NEUS snowfall trends from October through May since 1985 show a mix of decreases and increases in snowfall. The primary area of decreasing snowfall is in the Appalachian region of western Pennsylvania, western Maryland, and West Virginia.

Recent studies have suggested earlier snowmelt is occurring, as inferred from the timing of vernal streamflow increases (Dudley et al., 2017). Days with non-zero snow depth were analyzed for February, March and April for the 1960-1989 versus 1990-2019 periods to evaluate trends in the timing of snowmelt at the end of the cold season. The percentage of days in February with non-zero snow depth generally decreased across the region, especially in western New York, western Pennsylvania and West Virginia, where some sites saw decreases up to 20% (Figure 5). Notably, for a shorter-range comparison (with smaller comparison windows), from 1980-1999 to 2000-2019, this pattern becomes more difficult to detect, even reversing in some areas, suggesting that the year-to-year variance is substantial and that the trend is sensitive to how long of an analysis time frame is considered (Serinaldi et al., 2017). For March, decreases in snow depth days, while not substantial, appear in western Pennsylvania independent of the time frames considered. Decreases in snow depth days were also observed in parts of southern New England for the analysis starting in 1960, though this pattern reversed when trends were analyzed from 1980 onward. Other snow depth day counts were also considered. For instance,

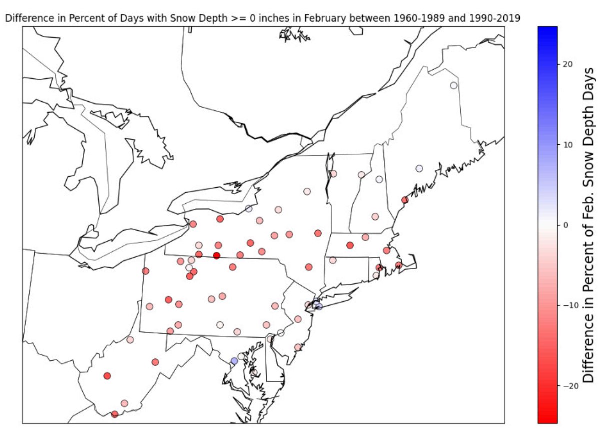

Figure 5: This map illustrates the difference in the percentage of days in February with measurable snow depth at sites in the NEUS, comparing 1990-2019 with 1960-1989. Comparisons between these two time periods indicate widespread decreases in the number of February days with snow on the ground.

the snow depth threshold used for counting snow depth days did not make a significant difference in the February trend for most locations (2-inch, 4-inch and 6-inch thresholds were also used for each month). With some local variation, the same result held for March snow depth days, independent of the threshold used.

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