Widespread and Accelerated Decrease of Observed Mean and Extreme Snow Depth Over Europe

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Abstract Accumulated snow amounts are a key climate change indicator. It combines the competing effects of climate change-driven changes in precipitation and stronger snowmelt related to increasing temperatures. Here we provide observational evidence from a pan-European in situ data set that mean snow depth generally decreases stronger than extreme snow depth. Widespread decreases in maximum and mean snow depth were found over Europe, except in the coldest climates, with an average decrease of −12.2%/decade for mean snow depth and −11.4%/decade for maximum snow depth since 1951. These trends accelerated after the 1980s. This has strong implications for the availability of freshwater in spring, while extremes in snow depth, usually very disruptive to society, are decreasing at a slower pace.

Plain Language Summary Changes in snow accumulation are a climate change indicator. Global warming brings more extreme precipitation, and higher temperatures lead to less snow accumulation. Studies of the future climate indicate that under strong warming of the planet, extremes of snowfall will decrease less than the average snowfall. In this study, we show that snow accumulation is already dramatically decreasing over Europe, which has strong implications for the availability of freshwater during the melt period in spring. However, extreme snow accumulation, which is usually very disruptive to society, is decreasing at a slower pace.

1. Introduction

Changes in the availability of water resources by snowpack impact society and natural systems in many ways. With a growing snowpack in the cold season and release of water in the following spring, changes in precipitation and temperature can affect the storage and release of water, leading to increased dryness in summer due to decreased summer flows (Cayan et al., 2001), increased erosion in winter due to a shift from snow to rain (Kundzewicz et al., 2007; Lu et al., 2010), decreased groundwater recharge (Earman et al., 2006), changes in hydropower production (Golombek et al., 2012; Madani & Lund, 2010; Renöfält et al., 2010), and disruptions to winter tourism and local economies (Abegg et al., 2007; Beniston, 2012). Especially relevant are the snowfall extremes which can lead to high socioeconomic losses and casualties (Changnon, 2018; Changnon & Changnon, 2006; Rooney, 1967). Furthermore, the relation between discharge and snow is not well understood (Berghuijs et al., 2014), and in addition, the parameterization of snow storage and melt in hydrological models has been identified as one of the factors causing uncertainty in future discharge projections (Melsen et al., 2018). This further stresses the need to strengthen our understanding of the formation and melt of snowpack.

Projected increases in winter precipitation over middle and high latitudes and warmer temperatures have competing impacts on snow depth (Collins et al., 2013). Model projections of future climate for the 21st century indicate that increases in total precipitation are expected to outweigh the effects of warmer temperatures over the coldest regions and at high latitudes where temperatures in winter are still below the freezing point, thereby increasing snow depth (Kapnick & Delworth, 2013; Krasting et al., 2013; O’Gorman, 2014; Räisänen, 2008, 2016), but other studies demonstrate that this may not apply for high-altitude areas in Europe (Schmuki et al., 2017). In warmer regions, strong and widespread decreasing snow depth is expected, since the fraction
of below-zero temperatures will decrease, thereby decreasing the fraction of winter precipitation that falls as snow and increasing the amount of snowmelt (Diffenbaugh et al., 2013; Krasting et al., 2013). O’Gorman (2014) showed, using a physically based theory and Climate Model Intercomparison Project phase 5 (CMIP5) simulations, that heavy snowfall events will have smaller fractional decreases compared to mean snowfall at the end of the 21st century in the strong warming scenario Representative Concentration Pathway 8.5, and this was corroborated using regional climate models (Räisänen, 2016). Although snowfall obviously relates to snow depth, the two metrics cannot be compared directly. The accumulation of snowfall into snowpack and the effects of melt make snow depth a more integrative and perhaps more sensitive metric to climatic changes.

Local observations support the view that decreases are found in warmer climates and increases in colder climates. Decreases in snow depth have been found at lower altitudes and increases at higher altitudes in southern Norway (Skauangen et al., 2012). No or only slight changes in midwinter snow depth in the Swiss Alps are found for high-altitude stations, while negative trends were more pronounced for middle- and low-altitude stations (Laternser & Schneebeli, 2003; Marty & Meister, 2012; Scherrer et al., 2004). The same pattern was found in the Romanian Carpathians (Miciu, 2009) and in Russia (Bulygina et al., 2011; Zhong et al., 2018). However, observational evidence for a decrease in extreme snow depth has also been found, even at high altitude (Marty & Blanchet, 2012). The lack of consistent signal from regional-scale analyses calls for a continental-scale observation-based assessment. In this study, we analyze trends in mean and maximum snow depths in Europe. Here we use daily observed snow depth measurements sourced from the European Climate Assessment & Data Set (Klein Tank et al., 2002) and analyze data from the 1950/1951 winter to the 2016/2017 winter.

2. Data and Methods
2.1. Station Data
The European Climate Assessment & Data Set (ECA&D; Klein Tank et al., 2002) contains validated climate data from 63 European countries provided by the National Meteorological and Hydrological Services and other data holding institutes. At time of analysis (2018) the database holds in total over 10,600 stations throughout Europe and the Mediterranean with daily data from 12 essential climate variables observed at meteorological stations. Part of this data (78%) can be downloaded for noncommercial research and education; the remaining 22% is available at ECA&D as aggregated data or through the providing National Meteorological and Hydrological Service.

Data sets available through other channels, like the Global Historical Climatological Network (Menne et al., 2012) and the Global Telecommunication System, were also explored, but the quality of the snow depth records varies considerably per country (Figures S1 and S2 in the supporting information). This, together with the decision to use only ECA&D data due to the poor quality of the other data sets (see supporting information Text S1), led to substantial spatial inhomogeneity in the coverage of stations suitable for this study. Homogenization of the timeseries was not performed due to a lack of established methods to homogenize daily snow depth, but a quality control of the data prior to analyses was applied to minimize the impact of the low-quality series on the analyses. The quality control uses standard ECA&D approaches (ECA&D Project Team, 2012) and consistency between maximum daily snow accumulation and snowmelt rates (see supporting information Text S1). The altitudinal distribution and the total number of (valid, passed the quality control) stations can be seen in Figure S3. High-altitude stations are clearly underrepresented.

2.2. Aggregation of Data
The quality and availability of the data was best over the winter period (December-January-February, DJF) and from 1951 onward (Figure S4); therefore, focus is on this season and period only. Mean winter snow depth (Mean HS) is the average DJF daily snow depth. Maximum winter snow depth (Max HS) is the DJF 95th percentile of daily snow depth values because this metric is more robust than the actual winter maximum. It should be noted, however, that in cold climates such as northern Scandinavia, the annual maximum snow depth usually occurs in early spring. Aggregation of daily data to the seasonal level was done when a minimum of 85 days (out of 90 or 91 days in DJF) contained valid data. Trends are calculated for each station when a minimum of 70% valid data over the period considered is available (Klein Tank et al., 2009).

2.3. Trend Calculation
To estimate a trend, a distinction is made between increasing and decreasing trends. First, the trend sign is estimated using a least squares estimate of a simple linear regression. If the slope is positive, the linear regression coefficient is used to calculate the relative increase per decade using the mean of the period. If the
Figure 1. Spatial distribution of winter mean (a) and max (b) snow depth (HS) changes over 1951–2017. Significant trends (\( \alpha < 0.05 \)) are denoted with black circles around the colored point. Trends between -1% and 1% are denoted with crosses (+). The histograms under the maps show the trend distribution of all the displayed points. The trend averaged over Europe is -10.9% for Mean HS and -9.8% for Max HS.

slope is negative, a simple exponential model \( y = a \times e^{bx} \) is fitted to assess the magnitude of the trend. This is motivated by the physical reason that snow depth cannot reach negative values, a nonzero minimum threshold is unrealistic, and because some decreasing trends clearly showed nonlinear behavior. Figures S5 and S6 show example time series with their fitted trends, and Figures S7 and S8 support the choice of exponential models for decreasing trends and show that the results do not differ significantly from linear trends but are slightly smaller. Trend significance was assessed using the Mann-Kendall test with a 0.05 significance level (Şen, 2017).

The difference between mean and maximum snow depth trends was calculated for all stations. To test this difference for significance, the data set needed to be resampled. This aims to obtain a more homogeneous spatial distribution of stations across Europe. Applying standard significance testing routines to the full data set is not a valid approach, since the inhomogeneous coverage of the data set makes the countries with a dense network weigh in heavily in the testing. Additionally, the assumption that snow depth data from neighboring stations in such a dense network are independent cannot be maintained. For the countries with a high density of valid stations (i.e., Switzerland, Czech Republic, Germany, the Netherlands, Norway, and Slovakia), a reduced number of stations were selected randomly to match the density of snow depth stations of Sweden. Sweden is chosen as the coverage of snow depth stations in ECA&D (after the quality control) is more or less at the European average of ECA&D snow depth gauges. Linear correlation was then computed between Max HS and Mean HS trends to check if the slope of the correlation was significantly different from one. This process was repeated 1,000 times.

In global and European temperature records, the warming of the climate has become more pronounced since the 1980s (Hartmann et al., 2013; Klein Tank & Können, 2003; van der Schrier et al., 2013), although a drastic change in precipitation regime may have occurred slightly later (Marty, 2008). This motivates to consider a possible change in trend magnitude around the 1980s by assessing the trends in snow depth over two nonoverlapping periods, with eight different split years (from 1978 to 1985) to test for the robustness of the
split. The probability distribution of the two resulting periods (1951-split and split-2017) was then plotted for the eight different split years. Example time series are shown in Figure S9.

3. Results

3.1. Decreasing Snow Depth Trends

Figure 1 shows that a widespread decrease in mean and maximum snow depths is observed over Europe, except in the coldest climates. Trends in winter snow depth are calculated over the 1951–2017 period. Despite the lack of available high-quality data for some countries, a spatially homogeneous pattern of decreasing mean snow depth and maximum snow depth trends across Europe is observed. The average of decreasing trends in mean snow depth is $-12.17\%$/decade (40.5% of all stations are significant; Figure 1a), while the average of decreasing trends in maximum snow depth is $-11.37\%$/decade (36.4% of all stations are significant; Figure 1b). For stations in the more temperate regions, decreases exceeding 20%/decade are observed. The average decreases in mean snow depth are stronger than for maximum snow depth (Table 1), and the difference is more pronounced for high latitudes where snow is more common in winter. The stronger average decreasing mean snow depth is also observed when the averages are computed based on the resampled data set as detailed in section 2.3, although the differences between decreases in mean and maximum snow depths are smaller (see supporting information Table S1).

Further analysis of the difference between mean and maximum snow depth trends (Figure 2) shows that observations show a smaller change in maximum compared to mean snow depth. This behavior resembles the contrasting trends in mean and extreme snowfall identified in model studies to occur at the end of the 21st century (O’Gorman, 2014; Räisänen, 2016), although it should be noted that the dynamics between contrasting trends in mean and maximum snowfall and snow depths are not the same. Negative differences dominate the map (65% of the stations), indicating that for most stations maximum snow depth decreases less strongly than mean snow depth over the 1951–2017 period. The remaining 35% stations that show positive differences (Max HS trend larger than Mean HS trend) appear to be related to extreme snow depth events that have occurred in the early part of the record and melted rapidly, amplifying the trend in maximum snow depth while the trend in mean snow depth remains unaffected (Figure S6). Figure 2 shows that the negative difference between mean and maximum trends is more spatially homogeneous in Scandinavia than in western and central Europe.

The steep decrease in mean snow depth can be related to a combination of decreases in mean snowfall, less days with snowfall, and stronger snowmelt which (combined) lead to shorter periods with snow cover. To assess the importance of the drivers in the changes in snow depth, mean and maximum snow depths are calculated for the days where snow depth is at least 1 cm. This approach relates to the Simple Daily Intensity Index used for precipitation (Klein Tank et al., 2009) and cancels the effect of the shortening of the periods with snow cover. A trend analysis of these modified snow depth indices (Figure S10) shows that the distribution of the trend differences has its median indeed at less negative values than the one in Figure 2, but decreases in Mean HS are still slightly dominant over decreases in Max HS. This indicates that the shorter periods with snow cover strongly influence the steep decrease in mean snow depth.

3.2. Increasing Snow Depth Trends

In contrast to the many stations showing decreasing mean and maximum snow depth trends (1,131 stations, representing 89.13%), a few stations show increasing trends for both metrics (88 stations, representing 6.93%), mainly located in northern and inland Scandinavia, Russia, and the Czech Republic. These positive trends range from $+1\%$/decade to $+10\%$/decade, although only 12.5% of the trends for mean snow depth and 12.8% of these trends for maximum snow depth are significant. It should be noted that 3.47% of all stations showed
decreasing mean snow depth and increasing maximum snow depth, while only 0.47% showed the opposite. In addition, some positive trends are observed in regions where snowfall barely occurs, like in the southwest of the Netherlands or in Ireland, where an occasional heavy snowfall event in the recent part of the record produced high snow depth maxima (Figure S6), amplifying the trend in maximum snow depth.

Averaged trends over the stations, which show increases in both mean and maximum snow depths, show that the mean increases more (4.12%/decade) than the maximum (3.43%/decade); an opposite behavior to stations showing decreasing trends.

3.3. Difference Between Mean and Maximum Snow Depth Trends

The difference between trends in mean and maximum snow depths over Europe is analyzed further in Figure 3a, which shows the scatter plot for trends in mean and maximum snow depths. The slope of the regression line is 0.91, indicating the less steep decrease in Max HS compared to Mean HS averaged over Europe. To test the significance of this result, bootstrapping is used as outlined in section 2.3, to produce 1,000 resampled data sets. Figure 3b shows the histogram of the slopes of the regression lines constructed by this bootstrapping approach. It also shows the lower bound of this slope at the 5% significance level. These figures show that for nearly all resampled data sets the trend in the Mean HS is stronger than in the Max HS and that this also holds for the lower bounds in these slopes. This strengthens the view that the decrease in mean snow depth is stronger than the decrease in maximum snow depth and that this contrast is statistically significant.

Interestingly, the offset of the regression line in Figure 3a is very close to zero (0.09%/decade), suggesting that also for positive trends, the trend in Mean HS is stronger than in Max HS. However, the bootstrapping shows that the uncertainty in the value of the offset is large. The number of stations showing significantly increasing trends in Mean and Max HS is simply too few to establish a robust relation.
3.4. Acceleration of Snow Depth Trends

Trend analysis over periods before and after the 1980s using piecewise linear regression shows an acceleration of snow depth trends. The analysis was repeated for all splitting years in the period 1978–1985 in order to account for possible impacts of interannual variability in snow depth. For the Mean HS, trends are clearly stronger for the more recent period (Figure 4a), and both positive and negative tails of the trend distribution move to smaller values, indicating that negative trends become more negative and positive trends less positive. The acceleration is more pronounced for the Mean HS than for the Max HS (Figure 4b), which makes that for the most recent period the difference between the trends in Mean and Max HS becomes more negative for the stations where trends in Mean and Max HS are decreasing (Figure 4c) and less positive for stations which...
have increasing trends in Mean and Max HS (Figure 4d). This shows that for the recent — warm — period trends in Mean and Max HS become more negative (or less positive) regardless of the sign of the trend (examples of typical stations are shown in Figure S9), and the decreases are clearly stronger for the Mean than for the Max HS when comparing the early and recent periods.

4. Discussion and Conclusion

With global warming, the fraction of precipitation that falls in the form of snow decreases and snowmelt is stronger. In addition, the amount of precipitation is projected to increase for middle and high latitudes and the conditions where the strongest snowfall events occur (close or just below 0°C) will be similar in both the present and the future climates (O’Gorman, 2014; Räisänen, 2016). Snow depth integrates these competing effects. Here we show that both mean and maximum snow depths show widespread decreases in Europe, except for the coldest regions. The winter mean snow depth relates to variations in frequency and severity of snowfall and snowmelt, and the results indicate that for the areas in Europe where mean snow depth decreases, the decreasing time period for which snow cover is present strongly contributes to the decrease in mean snow depth. In the regions with a decrease in mean snow depth, the maximum snow depth generally decreases as well but less fast than the mean snow depth. Averaged over Europe, the trends in maximum snow depth are about one tenth weaker than the mean snow depth trends.

For the coldest areas in Europe, an increase in mean and maximum snow depths is observed. Here the increase in precipitation, probably associated with the warming climate, dominates any snowmelt signal in the mean snow depth. For these areas, the reduced number of significant trends observed makes it difficult to study whether trends in mean and maximum snow depths show contrasting behaviors.

The spatial coverage of good quality data is poor and very inhomogeneous. More than, for example, temperature or precipitation, snow depth relates strongly to topographic features such as slope and aspect of the mountain in complex and often nonlinear ways. This stresses the need for making the existing high-density observation networks accessible for research and that these snow depth data require a strong validation before their value in climate research can be fully exploited.

The observations in this study clearly show that mean and maximum winter snow depths are decreasing over Europe, that the decrease is widespread, and that the decrease has accelerated since the 1980s in parallel with stronger warming. Generally, snow depth extremes are decreasing on a slightly smaller rate than the mean snow depth, and this contrast has become stronger in the last few decades.

Acknowledgments

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References


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