Daily Streamflow Trends in Western vs. Eastern Norway and their Attribution to Hydro-Meteorological drivers

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Abstract

Climate change in terms of regional warming and modifications in precipitation regimes has large impacts on streamflow in regions where both rainfall and snowmelt are important runoff generating processes like in Norway. Hydrological impacts of recent changes in climate are usually investigated by trend analyses applied on annual, seasonal, or monthly time series. However, neither of them can detect sub-seasonal changes and their underlying causes. Based on high-resolution trend analyses (i.e., applying the Mann-Kendall test on 10-day-moving-averaged daily time series), this study investigated sub-seasonal changes in daily streamflow, rainfall, and snowmelt in 61 and 51 catchments in Western vs. Eastern Norway (Vestlandet vs. Østlandet), respectively, over the period 1983-2012. The relative contribution of rainfall vs. snowmelt to daily streamflow and the changes therein have also been estimated to identify the changing relevance of these driving processes over the same period. Detected changes in daily streamflow were finally attributed to changes in the most important hydro-meteorological drivers using multiple-regression models with increasing complexity. Results reveal a coherent picture of earlier spring flow timing in both regions due to earlier snowmelt. Other streamflow trend patterns differ between both regions: Østlandet shows increased summer streamflow in catchments up to 1100 m a.s.l. and slightly increased winter streamflow in about 50 % of the catchments, while trend patterns in Vestlandet are less coherent. The importance of rainfall for streamflow contribution has increased in both regions, and the trend attribution reveals that changes in rainfall and snowmelt can explain streamflow changes to some degree in periods and regions where they are dominant (snowmelt: spring and Østlandet; rainfall: autumn and Vestlandet). However, detected streamflow changes can be best explained by adding temperature as an additional predictor which indicates the relevance of additional driving processes for streamflow changes like increased glacier melt and evapotranspiration.

Keywords: *hydrological change, streamflow trend, climate change, hydro-meteorological driver, attribution, trend analysis*

1 Introduction

That the world has warmed since the 19th century has been unequivocally confirmed (Hartmann et al., 2013). Hydrological changes as a consequence of global warming and climatic change are important for human society since these changes have the potential to impact water supply, hydropower generation, and agriculture (e.g. Jiménez Cisneros et al., 2014). However, the impacts of climate change on hydrological conditions vary across different regions due to the hydro-meteorological regimes and the character of climate change in a specific region (Burn, Sharif, & Zhang, 2010). Mountainous and cold-climate regions, where snow and ice are an integrated part of the hydrological cycle, are particularly vulnerable to global warming since the cryosphere in these regions is rapidly declining, which will likely accelerate in the coming decades (Hock et al., 2019; Huss et al., 2017). In Western and Eastern Norway, where the roles of snowmelt and rainfall are highly relevant for regional streamflow regimes, the impacts of regional warming in interaction with changes in annual, seasonal, and sub-seasonal precipitation will be reflected by changes in the amount and timing of runoff (Bates, Kundzewicz, Wu, & Palutikof, 2008). This paper explores sub-seasonal changes in streamflow regimes in Western and Eastern Norway (Vestlandet vs. Østlandet) together with changes in the hydro-meteorological drivers, and aims to attribute observed changes in streamflow to these driving processes.

Over the last century, and particularly from the mid-1970s, mean annual temperature and mean precipitation have increased by 0.8 °C and 18 %, respectively, in the whole of Norway (Hanssen-Bauer et al., 2015). There are, however, seasonal and regional differences: the largest increases in both temperature and precipitation are found for winter/spring and autumn, and these increases are more pronounced in Østlandet than in Vestlandet. In contrast to other mountainous regions, higher-altitude areas (above 850 m a.s.l.) and colder inland regions have experienced positive trends in snow water equivalents and snow depth (Dyrrdal, Saloranta, Skaugen, & Stranden, 2013; Skaugen, Stranden, & Saloranta, 2012). However, at lower altitudes and in comparatively warmer regions these trends are negative. Future projections indicate that such trends will affect larger regions and higher altitudes, although some areas will likely still accumulate more snow during winter until the end of the 2050s (Hanssen-Bauer et al., 2015; Stewart, 2009).

Changes in the hydro-meteorological drivers will translate to streamflow changes via their direct influence on the most important streamflow generation processes in Norway, i.e. rainfall and snowmelt. Like in other mountainous regions, snow accumulation and -melt are integral parts of the hydrological cycle and important factors determining the hydrological regime in various catchments (Gottschalk, Jensen, Lundquist, Solantie, & Tollan, 1979). However, due to the location at the west coast of the Scandinavian Peninsula, Vestlandet receives large amounts of precipitation, especially during autumn, while precipitation sums in Østlandet are considerably lower with seasonal peaks during summer. Typically, streamflow regimes in Vestlandet and Østlandet are characterized by a low-flow period during winter which is followed by a prominent snowmelt induced high-flow period during spring and early summer, and another low-flow period during summer is followed by a secondary high-flow period during autumn and early winter. There are, however, regional variabilities ranging from pronounced pluvial to fully nival regimes mainly determined by latitude, altitude, and topography. In turn, the question arises whether the outlined changes in the hydro-meteorological drivers have led to changes in the relative importance of the streamflow generation processes and in streamflow regimes in Vestlandet and Østlandet over the last decades.

Studies that have focused on streamflow changes in the Nordic countries found positive annual as well as seasonal streamflow trends (Lindgren et al., 2017; Lindström & Bergström, 2004; Stahl et al., 2010; Wilson, Hisdal, & Lawrence, 2010), and trends in Norway are often consistent with the observed increases in mean precipitation outlined above (Wilson et al., 2010). Most notably, winter and spring streamflow has increased in the southern half of Norway, while summer streamflow has decreased. The significance and magnitude of these trends, however, vary considerably with the time period considered. Future changes in streamflow will be driven by both temperature and precipitation, while temperature changes will most likely have the largest effect in Norway (Beldring, Engen-Skaugen, Førland, & Roald, 2008). With reference to hydrological extremes, Wilson et al. (2010) identified tendencies towards more pronounced summer droughts in terms of volume deficits in southern and eastern Norway, although the percentage of stations showing significant trends in streamflow droughts are not as large as for summer season flows. Vormoor, Lawrence, Schlichting, Wilson, and Wong (2016) found that significant negative trends in flood magnitude can often be linked to a decreasing relevance of snowmelt as a flood generating process.

Most of the studies mentioned above, as well as many other studies from all over the world, detect trends in hydro-meteorological observation data at annual (e.g. Durocher, Requena, Burn, & Pellerin, 2019; Hulley, Watt, & Clarke, 2019; Lindgren et al., 2017), seasonal (e.g. Birsan, Zaharia, Chendes, & Branescu, 2014; Déry, Stadnyk, MacDonald, & Gauli-Sharma, 2016; Lindgren et al., 2017) or monthly time scales (e.g. Makarieva, Nesterova, Andrew Post, Sherstyukov, & Lebedeva, 2019; Stahl et al., 2010; Xu et al., 2020). However, hydro-meteorological changes that affect streamflow often occur at the sub-seasonal scale, and these changes will be missed by trend analyses at broader temporal scales. Therefore, examining high-resolution (here daily) trends may be more advantageous than annual or seasonal trends (Déry et al., 2009; Kim & Jain, 2010; Kormann, Francke, & Bronstert, 2014; Kormann, Francke, Renner, & Bronstert, 2015). Indeed, when both an annual and high-resolution trend analysis is performed, it is revealed that some significant (sub)seasonal changes are detected where no significant annual change is found (Skålevåg, 2019). In addition, high-resolution trend analysis can help explaining underlying causes for detected streamflow changes (Kormann et al., 2014). This is particularly the case when detected trends in the most important streamflow generation processes (i.e. rainfall and snowmelt) are also available for the same time period and temporal resolution so that they can be linked with each other.

Besides accurately detecting recent changes in streamflow, the attribution of these trends to their specific causes is a challenge, which has received much attention in recent years (see Bindoff et al., 2013; Cramer et al., 2014). Trend attribution goes beyond identifying (in)consistencies between trends in streamflow and trends in potential hydro-meteorological drivers. It rather involves quantifying the evidence for a causal link between external drivers and changes in streamflow (Bindoff et al., 2013). This increases the confidence in observed hydrological changes and their particular drivers, which is also valuable for the understanding, prediction, and adaptation to expected future changes (Burn et al., 2012; DeBeer, Wheater, Carey, & Chun, 2016). However, various natural and human-induced drivers that may act simultaneously, interactively, and even over different time scales make the linkage of possible drivers to detected changes in streamflow a challenging task (B. Merz, Vorogushyn, Uhlemann, Delgado, & Hundecha, 2012). In this regard, a good spatial coverage of quality controlled streamflow data for a large set of pristine and near-natural catchments is beneficial and available in Norway. It ensures that detected streamflow changes result either from climate change or natural variability. Generally, two different types of attribution approaches are currently established: (i) model-based approaches, in which the underlying causes for detected trends are inferred from (physically-based) hydrological models that are able to reproduce trends in streamflow observations (e.g. Kormann, Bronstert, Francke, Recknagel, & Graeff, 2016; Zhai & Tao, 2017), and (ii) data-based approaches, which aim at establishing statistical relationships between detected changes in streamflow and their particular drivers (e.g. Duethmann et al., 2015; Kormann et al., 2015). Data-based approaches can be data-intensive, and the credibility of detected statistical relationships being due to physical cause-effect relationships needs to be assessed individually. However, the advantage of data-based approaches against model-based approaches is that they are quick and less affected by uncertainties resulting from model structure, parameterisation, and simplifications (Duethmann et al., 2015).

Our study aims at better understanding the dominant processes driving sub-seasonal streamflow changes in Western and Eastern Norway. In this regard, we examine highly-resolved (i.e. daily) trends in streamflow in 112 near-natural to pristine catchments in Vestlandet and Østlandet over three decades (1983-2012). Furthermore, we analyze daily trends in rainfall and snowmelt as the most important streamflow generation processes in both regions. As such, these trends should to a large extent explain the detected changes in daily streamflow. In this perspective, we also analyze trends in the relative contribution of snowmelt and rainfall to daily streamflow to investigate changes in the relative importance of both streamflow generation processes. Finally, we perform a data-based trend attribution approach based on multiple-linear regression to assess the extent to which detected changes in streamflow can be explained by trends in the hydro-meteorological conditions. Four specific research questions are addressed by this paper:

(i) What are the trends in daily streamflow and the most important hydro-meteorological drivers snowmelt and rainfall in Vestlandet and Østlandet during 1983-2012?

(ii) How has the relative contribution of rainfall and snowmelt to daily streamflow changed over this period?

(iii) What are the regional differences between the trends in Vestlandet vs. Østlandet?

(iv) To what extent can changes in the hydro-meteorological drivers explain trends in streamflow?

2 Study area and data

2.1 Hydro-climatological and runoff conditions

The study area spans a geographical range of 5-12°E and 59-63°N, and an altitudinal range of 0-2500 m a.s.l. (Fig. 1a). The area is divided into two regions, Vestlandet and Østlandet, which are located west and east of the water divide of the central Norwegian mountains, and correspond to two of the six Norwegian runoff regions as they are reported in the national science basis for climate change adaptation in Norway (Hanssen-Bauer et al., 2015). These runoff regions reflect general hydrological differences in terms of streamflow regimes in the country, although they primarily refer to watershed boundaries which are closely connected to administrative units as they are used for operational hydrological work by the Norwegian Water Resources and Energy Directorate (NVE) (Pettersson, 2012).

Due to their location west and east of the Scandinavian Mountain range, Vestlandet and Østlandet show remarkable hydro-climatological differences. While in Vestlandet annual precipitation is large and may exceed 3500-4000 mm, annual precipitation in Østlandet is much lower and may drop down to 300-400 mm in some valleys that are located inland in the rain shadow of the Scandinavian Mountain range. Vestlandet receives the largest precipitation volumes during autumn and winter, while summer precipitation is dominant in Østlandet. Mean annual temperature varies from about 6 °C at the west coast to about -3 °C in in the high-altitude areas in Østlandet. Due to the location at the west coast of Norway, annual temperature amplitudes in Vestlandet are considerably lower than in Østlandet, leading to mild and humid winters. Summer temperature is highest in Østlandet and winters are cold and comparatively dry.

Mean annual runoff generally reflects the patterns of annual precipitation, and runoff coefficients tend to be high due to low evapotranspiration. The illustrated differences in the seasonal and altitude-dependent temperature regimes, however, have impacts on snowpack volumes and the snow season which, in turn, leads to differences in the relative importance of snowmelt as a runoff generating process between and within the two regions: In higher altitude areas and east of the Scandinavian Mountain range, snowmelt during spring and early summer is particular important for the regional streamflow regime, while the role of snowmelt is decreasing towards the west coast, so that rainfall generated peak flows during autumn and winter are more prominent here. Still, both snowmelt and rainfall are relevant runoff contributors in both regions (Fig. 1b), though with differences in their relative importance.

2.2 Streamflow records

Daily streamflow records from 112 streamflow gauging stations belonging to NVE's hydrometric observation network formed the basis for the trend analyses in this study. Out of these 112 stations, 61 catchments are located in Vestlandet, and 51 are located in Østlandet. Furthermore, 70 of these catchments are part of the Norwegian Hydrological Reference Network (HRN) and have been assessed as suitable for studying the effects of climate variability and hydrological change in Norway (Fleig et al., 2013). These catchments were selected according to the criteria defined by Whitfield et al. (2012), meaning that they are pristine or near-natural, with less than 10% of the area affected by basin development and the absence of significant hydrological alterations. The streamflow data from many of these stations have previously been used in hydrological trend studies both of Europe, the Nordic countries and Norway (Hisdal, Stahl, Tallaksen, & Demuth, 2001; Stahl et al., 2010; Vormoor et al., 2016). Further 42 streamflow records were added to those of the HRN. These catchments are affected by land use to a small degree, but still unaffected by major hydrological alterations so that they are suited for the purpose of this study. A total of 22 (13) catchments have a glaciated area larger than 5% (10%). The study period from 1983-2012 was chosen to ensure the best spatial and altitudinal coverage while covering a climate normal period of at least 30 years. The streamflow data is quality checked, and we further ensured that only streamflow records from catchments with less than 10% days missing in the chosen period were included in the analysis.

[Insert Figure 1]

2.3 Hydro-meteorological data

Daily data for the hydro-meteorological drivers, rainfall, snowmelt and temperature for each catchment stem from daily 1 x 1 km gridded datasets (seNorge data) covering the whole of Norway. The seNorge grids provide data for a range of hydro-meteorological variables from 01.09.1957 to present. This data is publicly available at www.seNorge.no and has been updated several times since its launch in 2006 (Engeset, 2016).

Precipitation and temperature data in the seNorge dataset (version 1.1.1) are interpolated from meteorological stations measurements, using triangulation and de-trended kriging respectively (see Mohr & Tveito, 2008). Precipitation is exposure and altitude corrected. During winter, precipitation usually accumulates as snow instead of directly contributing to runoff, which complicates the analysis of daily trends. Therefore, we only considered rainfall in this study, which was defined as precipitation on days with temperatures above 0.5 °C. To complement the rainfall data we used daily snowmelt grids, which is modelled with the seNorge snow model (version 1.1.1) (Saloranta, 2014). The model uses daily temperature and precipitation grids as input, and simulates various variables including snow depth, snow water equivalents, and snowmelt, employing a degree-day approach with an additional term related to the seasonal and zonal variation in incoming short-wave radiation (Saloranta, 2014).

Daily temperature, rainfall and snowmelt time series were extracted from the seNorge grids for each of the 112 catchments by taking the spatial mean. The fractions of snowmelt- and rainfall contribution to streamflow were estimated from the extracted time series of rainfall and snowmelt, respectively (see Methods).

3 Methods

3.1 Relative contribution of rainfall and snowmelt to streamflow

To determine the relative contribution of rainfall and snowmelt, respectively, to streamflow at each single day in the year, we applied a similar approach as described in Vormoor, Lawrence, Heistermann, and Bronstert (2015); Vormoor et al. (2016). They either modelled or estimated empirically the "normal flood duration" (NFD) for each catchment separately. The NFD is composed of the concentration and recession times of a maximum flood event within a specific catchment. The recession time of the NFD can be understand as the maximum time span a specific catchment needs to drain from full saturation to baseflow conditions. Consequently, the recession time marks the maximum time span in which runoff generation, concentration and routing processes can theoretically contribute to streamflow at a certain day. Hence, by accounting for rainfall and snowmelt dynamics over the recession time before a specific day, we are able to estimate the relative contribution of rainfall and snowmelt to discharge at this day. The number of days of the recession time of the NFD for the investigated catchments are taken from Vormoor et al. (2016) and usually range from 2 to 20 days, with four comparatively large catchments with a recession time of 35 days or higher.

The runoff R contributed by a variable X, here either snowmelt or rainfall, at time t (Eq. 1) describes the amount of water that theoretically can be contributed by X to streamflow at any given day.

$$R_{X,t} = \sum_{i=t-NFD}^{t} X_i \tag{1}$$

The relative contribution C of either snowmelt (SM) or rainfall (RF) at time t can therefore be defined as

$$C_{RF,t} = \frac{R_{RF,t}}{R_{SM,t} + R_{RF,t}} \; ; \; C_{SM,t} = \frac{R_{SM,t}}{R_{SM,t} + R_{RF,t}} \tag{2}$$

On days where neither snowmelt nor rainfall contributed to streamflow, which is common during the winter months, C was set to 0. It is assumed that baseflow is the dominant source of streamflow in these periods.

3.2 High-resolution trend analysis

Rather than examining the trends in aggregated monthly, seasonal or annual values, a high-resolution trend analysis approach, which determines trends for each day of year (DOY) was used to determine daily trends in streamflow (Q), rainfall (RF), relative rainfall contribution (RFC), snowmelt (SM), relative snowmelt contribution (SMC), and temperature (T) for each of the 112 catchments. The approach, a continuation of work by Déry et al. (2009), has been further developed and applied by Kormann et al. (2014, 2015) for analysing hydrological changes in the Austrian Alps. It has also been used to assess elevation-dependent temperature trends and their underlying mechanisms (Rottler, Kormann, Francke, & Bronstert, 2019), but has yet to be applied to a region other than the Alps.

Figure 2 shows the workflow of the high-resolution trend analysis, which can be summarised in three major steps:

[Insert Figure 2]

1. The original time series was smoothed with a centered 10-day moving average (10dMA) filter (Fig. 2a) to minimise the effect of transient storms on precipitation fluctuations (Whitfield et al., 2012) and to obtain similar hydrological responses from catchments of varying sizes (Déry et al., 2009). Furthermore, smoothing is required since the inter-annual variability of daily values, i.e. the variability in each DOY time series (Fig. 2) is high, which would impact the ability of the MK test to detect trends (Kormann et al., 2014). Kormann et al. (2014, 2015) used a 30dMA filter, but similar applications have applied a 3dMA filter (Kim & Jain, 2010), or used 5-day sequent averages (Déry et al., 2009). We opted for a 10dMA filter as a well-balanced compromise between a reasonable degree of smoothing and preserving intra-annual variability.

2. The trend in each DOY time series was estimated separately (i.e. the trends in the values of January 1st, 2nd, ..., December 31st over all years; Fig. 2b-c). The Mann-Kendall (MK) test (Kendall, 1975; Mann, 1945) was used for the detection of trends and for the determination of the significane of these trends both at the local α_{local} and the global (field) level α_{field}. The MK test is is a non-parametric trend test for the detection of monotonic trends (Chandler & Scott, 2011; Helsel & Hirsch, 1992) and widely applied in hydrology for the detection of significant trends in time series (Burn et al., 2012). Potential autocorrelation (serial correlation) in the time series may lead to a disproportionate rejection of the null hypothesis, i.e. that no trend is detected by the MK test (Yue, Pilon, Phinney, & Cavadias, 2002). Therefore, where a significant ($\alpha = 0.05$) lag-1-autocorrelation was detected with the Ljung-Box test (Ljung & Box, 1978), the prewhitening procedure according to Wang and Swail (2001) was applied to the DOY time series

$$W_t = \frac{Y_t - cY_{t-1}}{1 - c} \tag{3}$$

where Y_t is the original time series, c the auto-correlation coefficient, and W_t the modified time series. However, due to the independence of the values in the DOY time series, autocorrelation was rarely present and prewhitening only needed in 4-9 % of cases (dependant on variable investigated). The MK test was then applied to the (prewhitened) DOY time series and the significance of a trend at the $\alpha_{local} = 0.1$ level was determined.

Hydro-climatological data from different sites located in the same geographical area are often cross-correlated (Renard et al., 2008; Wilks, 2006). The field significance can be used to determine whether detected trends at multiple sites are significant at the field (global) significance level α_{field}, and not purely detected by chance (Burn & Hag Elnur, 2002). Where a field significant trend is detected, it is assumed that a significant change has occurred across the region. The field significance ($\alpha_{field} = 0.1$) for each DOY in a region was calculated using a bootstrapping approach proposed by Burn and Hag Elnur (2002). Bootstrapping shuffles the temporal structure of the individual DOY time series, but preserves any cross-correlation in the original dataset. The MK test was then applied to the bootstrapped time series. This procedure was repeated N times, and the percentage of catchments with a significant trend in each resampling was combined to create a distribution ($N = 600$). The critical value p_{crit} is defined as the $1 - \alpha_{field}$ percentile of this distribution. If the percentage of catchments with significant trends exceeded p_{crit}, the trend was deemed to be field significant, i.e. likely not caused by randomness and not significantly impacted by cross-correlation.

Trend magnitudes were estimated using the Theil-Sen (TS) estimator (Sen, 1968; Theil, 1950), which is the median of the slopes of all data point pairs. As a non-parametric approach, the TS estimator is robust against outliers and works better than linear regression on heteroscedastic and skewed data (Wilcox, 2010), of which the latter is common in environmental data.

3. The trend magnitude for each DOY time series is aggregated into a yearly trend cycle, i.e. daily resolved trends throughout the year (Fig. 2d). These daily trends of each catchment are then compiled to a regional trend array ordered by median catchment altitude (Fig. 2e). That is, in Figure 2e, we are looking from above at the daily resolved trend curve (Fig. 2d) for each investigated catchment, while positive and negative trends (i.e. hills and valleys above/below zero) are colour coded in blue and red respectively. Non-significant trends ($\alpha_{local} = 0.1$) are tagged by a hatched pattern, and the top bar indicates periods with field-significant ($\alpha_{field} = 0.1$) in yellow.

3.3 Data-based trend attribution with multiple linear regression

Having estimated daily resolved trends in streamflow and its hydro-meteorological drivers, we aimed to attribute changes in daily streamflow to their particular drivers. Due to the large number of catchments, we opted for a data-based attribution approach using ordinary least squares multiple regression, rather than a model-based approach. Such a multiple-regression approach establishes a quantitative relationship between trends and their possible drivers (Duethmann et al., 2015). We assessed to what degree various combinations of daily trends in snowmelt (SM), rainfall (RF) and temperature (T) explains daily trends in streamflow (Q) for each of the 112 catchments. The relationship between the trends was assessed for the entire annual cycle, but also per season, i.e. winter (DOY 335-59; Dec-Feb), spring (DOY 60-151; Mar-May), summer (DOY 152-243; Jun-Aug), and autumn (DOY 244-333; Sep-Nov). All daily trends, both significant and non-significant were included in the attribution analysis.

The streamflow trend in each DOY time series is assumed to be proportional to the trend in the hydro-meteorological drivers (Eq. 4). As illustrated above, RF and SM are the most important runoff generation processes, and thus, trends in these variables should explain a large part of the streamflow trends. Trends in T can serve as a proxy for glacial melt and/or evapotranspiration (ET). We gradually increased the number of predictors to investigate which drivers explain best the detected (seasonal) trends in daily streamflow (Table 1). That is, we first established the relationship between trends in streamflow with trends in only rainfall and snowmelt, respectively. Then we established the relationship of trends in streamflow with trends in rainfall and snowmelt, before we also considered trends in temperature to end up with the full multiple-regression model displayed in Eq. 4.

$$Q_{trend}[m^3 s^{-1}\ yr^{-1}]\ \sim\ SM_{trend}[mm\ yr^{-1}] + RF_{trend}[mm\ yr^{-1}]\ + T_{trend}[^{\circ}C\ yr^{-1}] \quad (4)$$

The extent to which trends in hydro-meteorological drivers explain trends in streamflow was evaluated with the coefficient of determination R^2. To ensure that any improved results from including more independent variables in the multiple regression are not the result of overfitting, we compared the Akaike Information Criterion (AIC) of the models.

[Insert Table 1]

All analyses and visualisations were performed with Python 3.7 (Python Software Foundation, 2018). The MK test and TS estimator were obtained from USGS's "trend" module (Hodson, 2018).

4 Results

The results are assessed as follows: Matrix-plots illustrate daily resolved trends in streamflow (section 4.1) and in rainfall and snowmelt as the most important hydro-meteorological drivers for streamflow, including the changes in their relative contribution to daily resolved streamflow (section 4.2). Maps and a summary table illustrate to what extent detected trends in daily streamflow can be explained by changes in the hydro-meteorological drivers at the annual and seasonal scale (section 4.3).

4.1 Daily resolved streamflow trends

Figure 3 displays the detected trends in streamflow for Vestlandet (a) and Østlandet (b). The most obvious seasonal pattern, which can be observed for both regions, is a positive streamflow trend in spring (approximately DOY 70-110). This positive trend in daily streamflow with magnitudes up to 78 (Østlandet) and 57 (Vestlandet) % per decade is detected for almost all catchments at every altitude level (y-axis), except for the lowest elevated catchments in Vestlandet (25-160 m a.s.l.). These positive trends are followed by a band of negative trends in late spring (approximately DOY 105-170) in both regions, while this pattern is more pronounced and the magnitude of these negative trends is larger in Østlandet than in Vestlandet (on average 21 % per decade vs. 14% per decade) and larger in lower elevated catchments as compared to high-altitude catchments. In Østlandet, some altitude-dependency regarding the timing of this positive-negative trend sequence is detected, with an earlier onset of this sequence at low altitudes. In Vestlandet, this altitude-dependency is not visible.

During the other seasons (summer to winter), the regions differ quite considerably from each other. In Østlandet, there is a clear increase in summer streamflow (DOY 180-250) by up to more than 30% per decade for catchments with altitudes up to 1071 m a.s.l.. Above this altitude, the positive trends are considerably smaller and not consistently present in all catchments. During autumn, there are small negative streamflow trends across all altitude levels in Østlandet, followed by mostly positive streamflow trends during winter, although this is only supported by about 50% of the catchments, while the other catchments show no trends or trends in the opposite direction. The streamflow trends in Vestlandet during summer, autumn, and winter are less coherent than in Østlandet. During the second half of the year (DOY 200-10), there are two successions of positive and negative streamflow trend phases that occur simultaneously across all altitudes. In magnitude these trends vary between -25% per decade to +30% per decade. During January to February, there is a mixture of both negative and positive trends, with slightly more dominant negative trends. However, since streamflow during winter is generally low, the absolute change is still small, which is particularly the case for Østlandet. A remarkable difference between both regions is also found with regard to trends throughout the year (indicated by the colored bars at the very right of each plot in Figure 3): these colors indicate whether the annual sum of daily trends is positive (green), as it is dominantly the case for Østlandet, or negative (magenta), as it is dominantly the case for Vestlandet.

[Insert Figure 3]

Regarding the significance of trends, Figure 3 shows that most of the presented trends are not significant ($p \geq 0.1$) at the local scale (dashed lines). The strongest coherent signal of local significance can be found for the positive trends during spring in both regions, where almost every catchment between DOY 70 and DOY 110 shows some days with significant trends. During this season, the detected trends are also field-significant. Regarding the other seasons of the year, trend significance is rare and catchment-dependent, although the major patterns (summer in Østlandet, summer and autumn in Vestlandet, and spring in both regions) are field-significant.

4.2 Daily resolved trends in rainfall and snowmelt and their contribution to streamflow

Figure 4 shows the detected trends in (i) absolute snowmelt and (ii) in the relative contribution of snowmelt to streamflow in Vestlandet (Fig. 4a, c) and Østlandet (Fig. 4b, d). Detected trends in absolute rainfall and in the contribution of rainfall to streamflow are displayed in the same configuration for both regions in Figure 5.

Regarding changes in snowmelt, a clear and consistent signal towards earlier snowmelt is detected for both regions (Fig. 4a, b), which coincides with the timing of positive streamflow trends in both regions as shown in Figure 3 (DOY 70-110). In both regions, this increase in snowmelt is detected for the same period where we also found significantly positive temperature trends (not shown). Regarding altitude dependency, both regions show that the onset of this trend occurs with a temporal delay towards higher altitudes. The lowest elevated catchments in both regions, however, do not show any trend during this time span, which indicates the low importance of snow cover at this altitude. Another common pattern for both regions is found during autumn (around DOY 280), where slightly negative snowmelt trends occur in catchments above 700 m a.s.l. (Vestlandet) and 1000 m a.s.l. (Østlandet), which indicates more rainfall instead of snowfall during this period. Overall, negative trends in snowmelt are larger than positive trends which results in a net negative trend throughout the year for most catchments in both regions.

Focusing on changes in the contribution of snowmelt to streamflow, the patterns in in Figure 4c and 4d reflect the impact of earlier snowmelt in spring on streamflow. Negative trends between DOY 100 and 200 are, however, more pronounced in Vestlandet than in Østlandet which indicates the overall decreasing role of snowmelt contribution to streamflow in this region. This is also reflected by mainly negative trends throughout the year in Vestlandet. In Østlandet, in contrast, the signal of positive trends in snowmelt contribution to streamflow in earlier spring is more pronounced and larger in magnitude as compared to Vestlandet. This results in an overall increasing role of snowmelt contribution to streamflow in many catchments, particularly at altitude levels between 600 to 1000 m a.s.l. Another remarkable difference between both regions is that positive trends in snowmelt contribution are found for many catchments below 1200 m a.s.l. during January and February (DOY 0-60) in Vestlandet, while these trends are rarely present in Østlandet.

[Insert Figure 4]

With reference to trends in rainfall (Fig. 5a, b), the two regions show clear differences. In Vestlandet there are trends in both directions almost throughout the entire year, with overall slightly positive trends in the first half of the year, and dominantly negative trends in the second half of the year (particularly between DOY 270-300 by more than -2 mm per decade). This leads to mixed overall annual trends; about one half of the catchments show overall negative and positive trends, respectively, without any altitude-dependent patterns. In Østlandet, detected trends occur mainly between DOY 100 to 300 showing overall positive trends (up to +1.5 mm per decade) across all altitudes. Only around DOY 160, 250, and 280, some slightly negative trends across all altitudes are detected. Therefore, for every catchment in Østlandet, trends in rainfall throughout the year are consistently positive. In contrast to snowmelt, altitude-dependencies regarding the timing of any trend are not detected.

The relative contribution of rainfall to streamflow throughout the year increases during 1983-2012 in most catchments in both Vestlandet and Østlandet (Fig. 5c, d). There are though some intra-annual differences between the regions: While the temporal patterns during spring generally reflect the inverted picture of snowmelt contribution for both regions, there are opposite patterns regarding the direction of trends in rainfall contribution to streamflow in November and December (DOY 300-365). In Vestlandet, rainfall contribution is decreasing which matches with the negative trends in rainfall sums during this time period (Fig. 5a). In Østlandet, the relative contribution of rainfall increases although no trends in rainfall sums have been detected so that this refers to the decreasing importance of snowfall/snowmelt during this time period. Note, however, that the detected changes are still small (±10% per decade).

[Insert Figure 5]

Regarding the significance of all these trends, similar overall patterns as reported in section 4.1 can be observed, i.e. mostly weak local significance, and slightly larger global significance.

4.3 Attribution of streamflow trends to hydro-meteorological drivers

Figure 6 presents the spatial distribution of the results achieved by the annual and seasonal multiple regressions (columns); the complexity of the regression models increases from bottom to top (rows). Table 2 provides a summary of the results according to the number of catchments that achieved a certain R^2 score for the respective regression models at the annual scale.

[Insert Table 2]

Focusing on the two simplest models (QRF and QSM; see Table 1), we generally see that neither trends in rainfall nor snowmelt alone can explain the detected trends in streamflow very well at the annual scale (R^2 dominantly below 0.2; Table 2). Trends in rainfall, though, explain the detected streamflow trends considerably well during autumn for many catchments in Vestlandet (R^2 up to 0.8; Figure 6). Trends in snowmelt, on the other hand, explain considerably well the detected streamflow trends during spring for many catchments in Vestlandet and for the most mountainous catchments in Østlandet (R^2 up to 0.8). Consequently, combining trends in snowmelt and rainfall as predictors (QSMRF) leads to improved R^2 at the annual scale (R^2 mostly between 0.2-0.8; Table 2). Still many catchments, particularly in the very east of Østlandet show low R^2 scores around 0.2.

[Insert Figure 6]

The highest R^2 scores are achieved by adding temperature as an additional predictor to the previous regression model (QSMRFT; Table 1; top row in Figure 6). For most of the catchments the R^2 scores still range from 0.2-0.8. However, the number of catchments within the group of lowest R^2 scores has been reduced by 50% (Table 2). The improvements by adding temperature as an additional driver are also illustrated in Figure 7. The largest improvements at the annual scale are found for catchments in the North of Vestlandet close to the border between both regions (Fig. 6). These catchments show glacier coverages by more than 10% percent (Fig. 7), so that temperature can be seen as a proxy for glacier melt as a runoff generating process. However, improvements are also found for many unglaciated catchments in both Vestlandet and Østlandet. A comparison of the AIC between the models including/excluding temperature trends as additional drivers reveals little to no difference, which indicates that the detected improvements by adding temperature trends is not the result of overfitting the multiple regression models. The catchments with the lowest R^2 scores are found for catchments in the very East of Østlandet, irrespective of the season and model complexity considered.

[Insert Figure 7]

5 Discussion and conclusions

Revisiting our proposed research questions, the results are discussed as follows: Changes in daily streamflow and their (in)consistencies with changes in daily rainfall and snowmelt including the regional differences are discussed in 5.1. Changes in the relevance of rainfall- and snowmelt contribution to daily streamflow are discussed in 5.2. Finally, 5.3 discusses the results of the data-based attribution of daily streamflow changes in Vest- and Østlandet.

5.1 Trends in daily streamflow, rainfall, and snowmelt

Many of the detected trends in daily streamflow show large consistencies with the trends in daily snowmelt and rainfall as presented in this study. The most obvious and mostly significant pattern in daily streamflow trends, observed in both regions, is related to changes in the timing of snowmelt. Earlier snowmelt leads to an earlier onset of spring high flows; negative streamflow trends immediately afterwards are then due to absence of large snow covers. It is important to note that, when comparing multi-annual hydrographs in many catchments, the detected changes in daily snowmelt rates are not large enough to change the timing of the snowmelt-induced streamflow peak, but rather to flatten the spring flow curve (see Skålevåg, 2019). However, snowmelt generated flood events often show significant earlier occurrence (Vormoor et al., 2016). Similar patterns of earlier onset of snowmelt coupled with overall slower snowmelt rates has been observed in the Northern Hemisphere (Wu, Che, Li, Wang, & Yang, 2018) and western North America (Musselman, Clark, Liu, Ikeda, & Rasmussen, 2017). Earlier timing snowmelt and associated runoff has been detected in several mountainous and cold-climate regions around the world (Clow, 2010; Déry et al., 2009; Maurer, Stewart, Bonfils, Duffy, & Cayan, 2007; Morán-Tejeda, Lorenzo-Lacruz, López-Moreno, Rahman, & Beniston, 2014; Stewart, 2009; Vincent et al., 2015) and can be considered as the most robust signal of climate change impacts on streamflow in such environments (Hock et al., 2019; Jiménez Cisneros et al., 2014).

The altitude-dependency of these streamflow trends during spring and early summer, meaning the temporal delay of earlier snowmelt in catchments at higher altitudes as compared to lower altitudes, is not as pronounced as one might have expected. For catchments in the Alps, Kormann et al. (2015) found much more pronounced altitude-dependent streamflow patterns during spring and summer. However, due to the different altitude ranges of the Alps and the Scandinavian mountains, the catchments they considered cover much higher altitudes (up to > 3100 m a.s.l. mean catchment altitude) than the catchments considered in this study (up to 1546 m a.s.l.). Still, the altitude-dependency of snowmelt trends during spring is more pronounced than the altitude-dependency of streamflow trends for the same season. This might be explained by 'snowmelt-compensation-effects' as described by (Rottler et al., 2021). They argue that, at a certain day, meltwater in streamflow which previously stem from lower elevation bands is now replaced by meltwater from higher elevation bands. This explains why altitude-dependent trends in the timing of snowmelt itself are more prominent than trends in the timing of snowmelt-dominated streamflow.

The prominent and mostly significant increasing streamflow trends during summer in Østlandet are consistent with detected positive trends in summer rainfall which agrees with reported seasonal precipitation trends in this region (Hanssen-Bauer et al., 2015). It disagrees, though, with seasonal streamflow trends reported by Wilson et al. (2010) who did not find any trends for catchments in Østlandet for the period 1961-2000. However, although rainfall trends are positive in all catchments throughout the entire altitude range, positive streamflow trends were only found for catchments up to 1100 m a.s.l. Above this altitude, the increasing relevance of rainfall does not translate to positive streamflow trends due to the decreasing relevance of summer snowmelt in many of these high-altitude catchments.

In Vestlandet, most trends outside spring are insignificant (for all variables). The pattern of alternating bands with positive and negative trends in rainfall and streamflow might be explained by a 'stochastic drift', caused by natural variability or simply by the random occurrence of autumn storms, which heavily impacts precipitation in this region. Therefore, this pattern is not necessarily connected with climate change. Unlike as in Østlandet, the annual sums of daily trends in rainfall are mixed and catchment dependent. This agrees with regional observations for annual precipitation, which show the lowest percentage changes (slight increase) during recent decades and the largest uncertainties (Hanssen-Bauer et al., 2015). Seasonally, large decreases in autumn rainfall are also reflected by our results. However, large increases in spring precipitation in Vestlandet as shown by Hanssen-Bauer et al. (2015) are not fully reflected by our results based on daily trend analysis. This may be due to our focus on rainfall instead of general precipitation, so that we have missed intra-seasonal increases in snowfall during early spring, particularly in the high-altitude catchments.

The results of this study demonstrate the benefit of high-resolution trend analyses. Assessing trends at a daily resolution allows for the detection of sub-seasonal trend clusters, including changes in the timing of trends, and it enables a direct comparison of trends in streamflow and their dominant drivers. That is, it accounts for information that may not be perfectly caught by seasonal or monthly trend analyses. For instance, the detected trend patterns of earlier snowmelt (and related streamflow) across the elevation range would not have been correctly identified for all catchments by seasonal or monthly analyses since the end of the month March (DOY 90) cuts right through the sequence of positive-negative trends between DOY 70-140 particularly in Østlandet.

5.2 The changing relevance of rainfall and snowmelt on streamflow

Estimating the relative contribution of rainfall and snowmelt to daily streamflow allows for gaining deeper insights into the changing relevance of the most important runoff generating processes on streamflow in Norway. Our results point towards a generally increasing (decreasing) importance of rainfall (snowmelt) on streamflow contribution in both regions. This is in line with findings by Vormoor et al. (2016), who identified the increasing role of rainfall for flood generation in Norway over the last decades. It may also be seen as the onset of a development that will intensify in the future (Vormoor et al., 2015) and potentially lead to systematic shifts in streamflow regimes in Norway (Beldring et al., 2008) as it is generally predicted for areas where much of winter precipitation currently falls as snow (Bates et al., 2008). Similar results on the decreasing importance of snowmelt induced event runoff have also been presented for catchments in other parts of world where snowmelt is an important runoff generating process (e.g. Burn & Whitfield, 2016, 2017; Sikorska-Senoner & Seibert, 2020). However, it is important to note that, during most parts of the year, rainfall is already the most important driver of streamflow throughout the data period for all catchments considered (see Figure 1b). Still, the increasing (decreasing) role of seasonal rainfall (snowmelt) may rearrange the relative importance of the peak flow periods during spring and autumn in many catchments which currently are characterized by mixed flow regimes.

Catchments in Østlandet at altitude levels between 600-1000 m a.s.l., with increasing annual net contribution to streamflow by both rainfall and snowmelt, have also been identified by this study. In these cases, the increasing relevance of both rainfall and snowmelt contribution to streamflow at different times within the year aggregate to positive annual trend sums. Here, the net positive snowmelt contribution can be explained by generally positive trends in winter precipitation in Østlandet and temperatures that are still low enough to ensure considerable snow storage throughout winter (Hanssen-Bauer et al., 2015; Skaugen et al., 2012).

Winter streamflow was found to increase for many catchments in both regions, although more pronounced in Østlandet than in Vestlandet. However, these changes are small in absolute terms and often insignificant. This is particularly but not exclusively the case in catchments which are characterized by dominant winter baseflow conditions (i.e. none of both drivers is dominant; Figure 1b). The detected increase in winter streamflow is line with significant positive trends at the monthly scale for Norwegian catchments with winter low flow regimes (Stahl et al., 2010). For some of our study catchments, the increase in winter streamflow can be explained by either increased winter rainfall contribution (instead of snowfall and –storage) or intermediate snowmelt contribution due higher winter temperatures. However, there is no obvious link between increased winter streamflow and changes in rainfall and snowmelt (contribution to streamflow) for most of these catchments. This might also explain comparatively low predictive skills of the multiple-regression approaches for the attribution of winter streamflow changes (Fig. 6), which will be further discussed in section 5.3.

To our knowledge, this is the first data-based attempt to evaluate changes in the contribution of rainfall and snowmelt as the most important runoff generation processes to daily streamflow in Norwegian catchments. This approach has originally been developed for the classification of peak flow events in Norway. The simple distinction between rainfall and snowmelt is comparatively straightforward since their contrasting roles for event runoff generation are very prominent compared to other regions where more complex event classification (e.g. R. Merz & Blöschl, 2003) is necessary. For daily streamflow including low flow periods, however, additional drivers and catchment state variables are relevant as it has been indicated by the results of the statistical trend attribution. These have not been explicitly considered by this study. Still, this simple approach proved to be valuable to distinguish between rainfall and snowmelt as important contributors to daily streamflow and their changing relevance over time.

5.3 Attribution of streamflow trends to hydro-meteorological drivers

The two simplest regression models (QRF and QSM; see Table 1) showed that rainfall and snowmelt as isolated drivers can explain streamflow changes to some degree in periods and regions where they are dominant (snowmelt: spring and Østlandet; rainfall: autumn and Vestlandet). The combination of both drivers into a more complex multiple-regression approach (QSMRF) considerably improved the predictability of streamflow changes during all seasons and in both regions. This confirms the importance of both processes for the streamflow regimes in Vest- and Østlandet. Notably, detected streamflow changes can be best explained by adding temperature as an additional predictor.

We have shown that temperature obviously serves as a proxy for glacier melt in catchments that show some glacier coverage (particularly in Vestlandet). That is, glacial melt water contribution to streamflow is indirectly considered by adding temperature as a predictor to the attribution approach. However, considerable improvements were also found for unglaciated catchments in both regions. Here, it is assumed that temperature serves as a proxy for increased evapotranspiration, meaning that water losses to the atmosphere are also indirectly considered by the approach. This appears reasonable since the improvements are not only found for the summer season (glacier melt) but also for spring and autumn where evapotranspiration may already/still impact the water balance of the catchments. A limitation of assuming temperature trends as proxies for both glacier melt and evapotranspiration trends, is that an increase in each will have the opposite effect on streamflow. Thus, it is possible that the effect of both drivers on streamflow are masked by each other in glaciated catchments. In this context, negative summer streamflow trends in Romania have been attributed to increased temperature and evapotranspiration (Birsan et al., 2014), and in the Austrian Alps, Kormann et al. (2016) found positive evapotranspiration trends during spring and summer, which however, could not be identified as a major driver for streamflow changes due to the dominance of other drivers. Trend analyses for different parts of the world reveal that evapotranspiration has increased at many locations over the last decades (e.g. Duethmann & Blöschl, 2018; Ukkola & Prentice, 2013). Annual ET trends during the study period, estimated from water budget in unglaciated catchments, are generally positive to non-significant in Østlandet and negative to non-significant in Vestlandet (Skålevåg, 2019). Although the relative importance of evapotranspiration on streamflow in Norway is small, it will probably increase in the future due to projected warming and (related) changes in vegetation characteristics like longer vegetation periods, upward migration of species in mountainous areas and land use changes (Bryn, 2008; Bryn & Potthoff, 2018). At the same time, water limitations (for ET) are not supposed to become a general issue in Norway due to an overall projected increase in precipitation in future years (Hanssen-Bauer et al., 2015).

Finally, we need to emphasise that even with our most complex multiple-regression model some streamflow changes could not be sufficiently explained. This is particularly the case for some catchments in the high-mountain areas of Vestlandet and some catchments in Østlandet close to the Swedish border. It is also the case for winter streamflow changes in many catchments as discussed in section 5.2. A general limitation of data-based attribution approaches is their inability to identify exact reasons for (poor) predictive performances. Regarding winter streamflow changes, one reason might be due to our classification of rainfall, which is defined as precipitation that falls at $\geq 0.5°C$ average catchment temperature. This approach is especially uncertain in winter: some of the precipitation at days with $> 0.5°C$ may still fall as snow, or rainfall may freeze on the ground. In both cases, the precipitation defined as "rainfall" does not immediately contribute to streamflow. This may partly explain why rainfall and snowmelt trends explain streamflow trends during winter so poorly (Rizzi, Nilsen, Stagge, Gisnås, and Tallaksen (2018)). A more general reason might be due a missing predictor (i.e. driver) for the attribution of streamflow changes. However, since human interventions do not play any role in the study catchments, and since the attribution with the considered drivers works well for other catchments, it is hardly possible to identify any missing major driver in our statistical attribution approach. Uncertainty in streamflow, rainfall, and snowmelt data may be an issue that leads to poor attribution results for some catchments, particularly at the daily scale and catchment-averaged snowmelt (modelled), rainfall and temperature (interpolated) values considered in this study. In this perspective, complementary hydrological model-based attribution attempts may (i) help identifying the influence of all these speculative reasons on the predictive performance of the multiple-regressions and (ii) possibly improve the attribution and understanding of hydro-meteorological drivers to detected changes in daily streamflow where the statistical models perform poorly.

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Tables

Table 1: Overview of attribution models

Model abbreviation	Model equation
QSMRFT	$Q_{trend} \sim SM_{trend} + RF_{trend} + T_{trend}$
QSMRF	$Q_{trend} \sim SM_{trend} + RF_{trend}$
QSM	$Q_{trend} \sim SM_{trend}$
QRF	$Q_{trend} \sim RF_{trend}$

Table 2: Overview of attribution results for the entire yearly trend cycle (annual). Number of catchments within the R^2 range, with the distribution between the two regions indicated in brackets (Vestlandet; Østlandet).

Model	$R^2 < 0.2$	$R^2 =$ 0.2-0.4	$R^2 =$ 0.4-0.6	$R^2 =$ 0.6-0.8	$R^2 > 0.8$
QSMRFT	12 (4; 8)	39 (21; 18)	35 (23; 12)	25 (13; 12)	1 (0; 1)
QSMRF	24 (14; 10)	36 (18; 18)	27 (17; 10)	24 (12; 12)	1 (0; 1)
QSM	50 (32; 18)	39 (21; 18)	13 (3; 10)	5 (1; 4)	0 (0; 0)
QRF	71 (30; 41)	23 (19; 4)	11 (10; 1)	1 (1; 0)	0 (0; 0)

Figure legends

F1_studyarea.eps

Figure 1: Location of the investigated streamflow gauging stations and the median altitude of the corresponding catchments (a) and the dominant contributor to daily streamflow for catchments in Vestlandet and Østlandet sorted by altitude (b). A streamflow contributor is dominant if on average more than two third of the runoff volume at a certain day over 1983-2012 stem from rainfall or snowmelt, respectively (see section 3.1).

F2_flowchart.png

Figure 2: Flow chart illustrating the daily trend analysis approach. With reference to the main text: step 1 (a-b), step 2 (c-d), step 3 (e).

F3_streamflowTrends.eps

Figure 3: Streamflow trends in Vestlandet (a) and Østlandet (b). The trend magnitudes are presented in percent change relative to the mean streamflow at each DOY. Non-significant trends are overlain with a hatched pattern. The top bar shows periods where the trends are field significant (yellow). The bar on the right indicates whether the trends throughout the year are mainly positive (limegreen) or negative (magenta), without any distinction regarding magnitude.

F4_snowmeltTrends.eps

Figure 4: Snowmelt trends in Vestlandet (a,c) and Østlandet (b,d). The trend magnitudes are presented in mm per decade at each DOY. Non-significant trends are overlain with a hatched pattern. The top bar shows periods where the trends are field significant (yellow). The bar on the right indicates whether the trends throughout the year are mainly positive (limegreen) or negative (magenta), without any distinction regarding magnitude.

F5_rainfallTrends.eps

Figure 5: Rainfall trends in Vestlandet (a,c) and Østlandet (b,d). The trend magnitudes are presented in mm per decade at each DOY. Non-significant trends are overlain with a hatched pattern. The top bar shows periods where the trends are field significant (yellow). The bar on the right indicates whether the sum of daily trends throughout the year is positive (limegreen) or negative (magenta).

F6_attribution.eps

Figure 6: Results of data-based attribution. The coefficient of determination R^2 indicated by colour. The first two rows show the differences between the two main models, with RF trend, SM trend (and T trend) as drivers, for the entire yearly trend cycle (annual) and for each season (winter, spring, summer and autumn).

F7_QSMRFTvsQSMRF.eps

Figure 7: Effect of the inclusion of temperature trends on R^2. Catchments with glaciated areas > 5 (10) % are indicated by grey (black) circles.