

The spatio-temporal influence of atmospheric teleconnection patterns on hydrology in Sweden

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ABSTRACT

Study region: Sixty-four river gauging stations distributed over Sweden.

Study focus: To investigate the influence of climate teleconnection patterns (TP) on streamflow in Sweden. Streamflow data is regionalized and the average hydrographs of each homogeneous region is divided into hydrological seasons. Thereafter the impact of different TPs on the streamflow, per homogeneous region and per hydrological season is analyzed.

New hydrological insights for the region: Five homogeneous regions are identified; three located in the north, where snow dominates the hydrological processes, and two located in the south, where rain dominates hydrological processes. The northern hydrographs are separated into three hydrological periods: low streamflow when snow is accumulated, high streamflow during the melting of the snowpack and a transition period in between. The southern hydrographs are characterized by streamflow above the yearly average during the winter and below during the summer. Hydrological periods in different homogeneous regions are influenced by diverse combinations of TPs. Arctic Oscillation, North Atlantic Oscillation and Scandinavian Pattern influence the streamflow in most of the regions during most hydrological periods. The further south and east the region is located, the more TPs influence the streamflow. The resulting streamflow variability is related to the interplay between different TPs both before and during each hydrological period. This interplay may enhance or decrease the individual influence of each TP on streamflow.

1. Introduction

The northern hemisphere climate circulation patterns, and their interactions, have a profound effect on the seasonal and annual temperature and precipitation patterns over Sweden by altering the transport of moist air masses over Scandinavia (e.g. Barnston and Livezey, 1987; Comas-Bru and McDermott, 2014; Hurrell et al., 2003; Rogers, 1997). This will, in turn, strongly influence also Scandinavia's hydrological processes in general and streamflow in particular. Sweden is characterized by a heterogeneous hydrological regime, with streamflow being dominated by snow processes in the northern two thirds of the country and by a mixture of rain and snow processes in the southern third (Krasovskaia and Gottschalk, 1992; Melin, 1970; Peel et al., 2007). In the snow dominated catchments, peak flows coincide with the snow melt in the spring, while in the rain dominated catchments, peak flows are associated with precipitation events and are more common in the cooler months from autumn to early spring.

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Teleconnection patterns (TPs) are a natural part of the chaotic movement of the atmosphere. They can be described as persistent and recurring patterns of circulation or air pressure anomalies that affect the climate over a large geographical area, by influencing the intensity and location of the jet stream and storm tracks and in turn temperature and precipitation. Consequently, TPs have a significant positive or negative correlation with the variability of a hydro-meteorological variable in a geographically separated region (Panagiotopoulos et al., 2002). This work concerns the northern hemisphere teleconnection patterns defined by Barnston and Livezey (1987), governing the long-term (> 1 month) variability of streamflow in many rivers in Sweden.

Although the connection between climate and streamflow is not new to researchers, it has traditionally been investigated at the local or river basin scale. The influence of remote drivers was generally not contemplated until the early 21st century when Enfield et al. (2001) and Barlow et al. (2001) related the climate variability to streamflows in the US. The relation between climate variability and rivers have since then been studied worldwide (e.g. Barros et al. 2004, for the Paraguay River basin, and Bonsal and Shabbar, 2008, in Canada). For Europe, Kingston et al. (2006a,b,2009) showed how the Icelandic Low, the Azores High and the difference between their pressure intensity (hence, the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO)) are connected to streamflow around North Atlantic Ocean. Their studies are clear in demonstrating that the higher the difference between the pressure fields, the higher the streamflows in Northern Europe. Trigo et al. (2004) also focus on the influence of NAO but on water resources in the Iberian Peninsula, showing that negative NAO was connected to the increase in water resources in that region. Giuntoli et al. (2013) showed that low flows in France were connected to the Atlantic Multidecadal Oscillation (AMO) as well as to NAO. Bierkens and van Beek (2009) used NAO as model input to predict winter discharge in major rivers in Europe. Ionita et al. (2012, 2014, 2015) and Ionita (2014, 2015) showed that river discharge in Europe is impacted by further TPs than NAO and AO, depending on the region and season.

For Scandinavia, despite the effects of climate variables on temperature and precipitation being well understood, the links between large scale climate patterns, land surface and hydrologic variability are not as well understood (Kingston et al., 2009). Changes in precipitation and temperature at the seasonal scale over Sweden have been showed to be connected to the low-frequency variations in the northern hemisphere teleconnection patterns (e.g. Wallace and Gutzler, 1981; Barnston and Livezey, 1987; Hurrell, 1995; Uvo, 2003) and these changes affect the nested cascade of processes that link the atmospheric and hydrological processes (Kingston et al., 2009).

Even though most of the Swedish rivers are regulated to some extent, the spatial and temporal variability of streamflow has noticeable societal impacts. Nearly half of Sweden's electricity comes from hydropower (SCB, 2014), but the uneven distribution of streamflow over the year, as well as its interannual variability, requires a skilful water management to control electricity production. Most of the hydropower plants in Sweden are located in the northern part of the country. Here, during the cold and dark winter months, when the electricity demand is highest, the streamflow is at its lowest because precipitation is stored in the form of snow. Conversely, during the warmer months, when demand is typically lowest, the streamflow is at highest due to the melting season (that typically occurs in early summer months) and somewhat high due to autumn rains. Consequently, water needs to be stored over the summer and autumn months to allow operators to meet demand during the winter, implying that timely and reliable forecasts of streamflow are invaluable to water resource managers. As climate is a large source of hydrological variability (Busuioac et al., 2001; Krasovskaia et al., 1994) the aim of this work is to identify and understand the climatic drivers behind the seasonal and interannual variability in Swedish streamflow.

In light of the complex and diverse hydrological regimes found in Sweden, as outlined above, our hypothesis is that different TPs govern the hydrology in different parts of the country as well as during different parts of the year. This is a first attempt to systematically investigating these connections, which are highly relevant both for understanding the impacts of natural climate variability but also for assessing climate change ones. To distinguish between the different hydrological processes, rivers in Sweden are initially divided into homogeneous hydrological regions which are used to identify and characterize the connections between time series of streamflow and teleconnection pattern indices. After establishing links to the most relevant TPs, a characterization of the underlying relationships is attempted by using wavelet analysis.

2. Data

Analyses were performed using time series of streamflow and of teleconnection pattern indices, as described below.

2.1. Streamflow

Observed daily streamflow data used in this study were collected from the Swedish Meteorological and Hydrological Institute (SMHI) database. Homogenization and quality control of the data was performed by SMHI before being made available in the public database (available online at: <http://vattenwebb.smhi.se/station>). Gauging stations were selected following the four criteria below.

- Degree of regulation: Stations with the least regulation were preferred to ensure that the streamflow was as near to natural as possible.
- Length of time series: Stations with longer time series were preferred to allow for more robust analyses.
- Number of missing data: Stations with fewer missing data were preferred to minimize data filling effects influencing the study results.
- Geographic location: Stations were selected to maximize the geographical coverage of Sweden.

Sixty-four unregulated or low regulated gauging stations, with daily streamflow data from January 1960 to December 2010, were

selected. Their distribution over the Swedish territory is shown in Fig. 1. Eleven time series had missing data, a total of 4836 days or 2.4%. A multiple linear regression of surrounding station data was used to infill those missing data. Daily streamflow data were averaged into monthly values. The Nash-Sutcliffe Efficiency values between the regressed time series and the target series ranged between 0.69 and 0.98 when the data is aggregated to monthly data. All series were standardized by subtracting their mean and dividing by their standard deviation prior of their use. The standardization allows the statistical comparison among series with large differences in absolute values. The standardized series were used in the clustering process and for calculating regional composite series (as described in Section 3.1).

2.2. Teleconnection patterns (TPs)

Monthly indices of selected TPs were collected from the Climate Prediction Center (CPC) (available online at: <http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml>) for the period January 1958 to December 2010.

The TPs used for analysis in this work are summarized in Table 1 and their known effects on temperature and precipitation in Sweden are briefly described. Other tested TPs, among them El Niño-Southern Oscillation and Pacific Decadal Oscillation, that generated inconclusive results, either due to insignificant correlations or because the available data period is too short for a robust physical analysis, were omitted from further analysis.

Prior of use, hydrological data was detrended and then standardized by month to remove the influences of climate change, dimensionality and seasonality. It has been previously shown that runoff and teleconnection data can be autocorrelated and this can lead to overestimation of statistical significances in the case of series with considerable autocorrelation and thus they should be interpreted with care (e.g. Ptak et al., 2018; Yue et al., 2002). By breaking the data up into seasons and performing the analyses on each season independently reduces any influence autocorrelation might have on the results. Checks on these discharge data for the different hydrological periods showed that there are no significant autocorrelations. EA and PDO are found to have low (but significant) and considerable autocorrelations, respectively. The autocorrelations in the PDO data are not unexpected due to the robust nature of that teleconnection pattern.

3. Methodology

3.1. Hydrological characterization

To identify regions of homogeneous temporal hydrological variability, a cluster analysis was applied to the collection of 64 series of monthly averaged streamflow time series $Q(m)$ where m denotes month ($1 \leq m \leq 12$). Clustering is used for grouping variables into subsets that are linearly related to each other, conventionally illustrated by tree-like hierarchical diagrams – dendrograms – that show relations among all variables in a given set (Krumbein and Graybill, 1965). The correlation matrix is used as a basis for assessing the

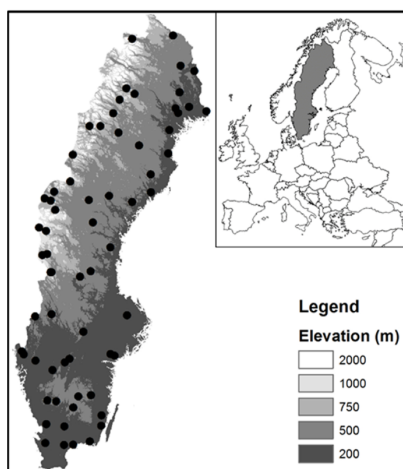


Fig. 1. Map showing the locations of the 64 gauging stations with records from unregulated rivers used in this study.

Table 1
Summary of the atmospheric teleconnection patterns considered in this study.

Teleconnection pattern		Centres of action	References
Abbreviation	Name		
NAO	North Atlantic Oscillation	North-south dipoles centred over Greenland and the North Atlantic between 35 °N and 40 °N	Hurrell (1995)
EA	East Atlantic	North-south dipoles, similar to the NAO, spanning the North Atlantic from east to west	Barnston and Livezey (1987)
EAWR	East Atlantic/West Russia	Height anomalies over Europe, northern China, North Atlantic and north of the Caspian Sea	Barnston and Livezey (1987)
SCA	Scandinavia	Primary circulation centre over Scandinavia, with weaker centres of opposite sign over western Europe and eastern Russia/western Mongolia.	Bueh and Nakamura (2007)
POL	Polar/Eurasia	Height anomalies over the polar region, northern China and Mongolia	Panagiotopoulos et al. (2002)
AO	Arctic Oscillation	A dipole between the polar cap area and the adjacent zonal ring centred along 45 °N	Thompson and Wallace (1998)

strength of the relationships occurring among the variables. One pair or more pairs of attributes are selected as highly connected, and connections between these pairs and the remaining variables are calculated to develop a hierarchy of interrelations showing the degree of connection within the dataset. The hierarchical cluster algorithm chosen for this work was Ward (Ward, 1963) due to its simplicity and broad practice.

Prior to applying the cluster analysis, the monthly streamflow data was filtered for noise by means of Principal Component Analysis (PCA) so that 90% of the original streamflow variance was kept, eliminating 10% of the variance that is expected to be related to noise in the data. The use of filtered data as input for the cluster analyses, as was done here, is common practice and convenient (e.g. Uvo and Berndtsson, 1996) to avoid connections being established based on noise in the data.

The resulting clusters were validated by means of three different methodologies: a) correlating the individual records with the cluster mean, and in this way ascertaining that all members in the cluster are well related to the cluster mean, b) by physical understanding of the geographical location of the clusters, and c) by using silhouettes. Silhouettes are a graphical aid based on the comparison of the dissimilarity of the members of each cluster and the mean silhouette width gives a measure for the clustering solution's validity (Forgy, 1965; Rousseeuw, 1987).

To represent the streamflow in each cluster, a composite monthly streamflow time series was created as the average of the time series from all stations composing the cluster. The composite series is denoted $\bar{Q}^c(m)$ where c stands for cluster. The benefit with using a composite is that it acts as a generalized time series for the entire cluster and thus is not biased toward any individual time series. To define hydrological periods, both the station time series $Q(m)$ and the cluster composite time series $\bar{Q}^c(m)$ were averaged into monthly mean annual hydrographs denoted $\bar{Q}(1:12)$ and $\bar{Q}^c(1:12)$, respectively, where 1:12 stands for calendar month.

The definition of different hydrological periods for each cluster was made predominantly based on visual inspection of the mean annual hydrographs from individual cluster members $\bar{Q}(1:12)$ superimposed over the cluster mean annual hydrograph $\bar{Q}^c(1:12)$. Periods of similar hydrological activity or state, hereafter referred to as hydrological periods, were defined by visual inspection of the hydrograph considering the intensity of the monthly flow. Five periods were defined: Accumulation Period, Spring Flow Period, Post

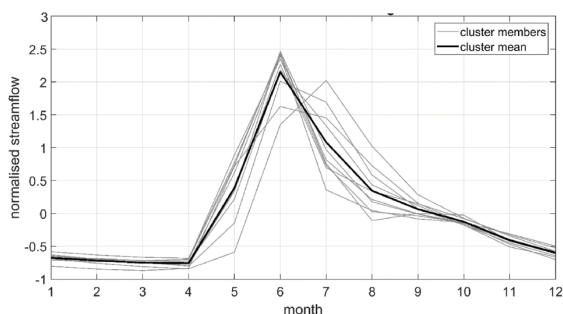


Fig. 2. Annual hydrographs $\bar{Q}(1:12)$ of all stations that compose cluster S^3 (grey lines) and the cluster mean annual hydrograph $\bar{Q}^c(1:12)$ (black line).

Flood Period, High Flow Period and Low Flow Period. The detailed description of the characteristics of these periods may be found in section 4.2. For analyzing the links to TPs, the composite streamflow series $\bar{Q}(m)$ were annually averaged over the hydrological periods into $\bar{Q}_{hp}(y)$, where hp denotes hydrological period and y denotes year ($1 \leq y \leq 51$).

Fig. 2 exemplifies how the hydrological seasons were determined for a cluster which is characterized by a snow dominated hydrology. The elevated hydrograph flows in August (that may be seen in Fig. 4) are mainly due to three sub-basins that, due to their geographical position, present a delayed signal from the others. In this case, we chose to not consider August as part of the spring flow period to minimize the risk of outliers from having a too strong influence in the analysis. As a result, the accumulation period is defined as November to April, Spring Flow Period as May to July and Post flow period as August to October.

3.1.1. Definition of hydrological periods

Based on the monthly composite hydrographs of each cluster, five hydrological periods were defined.

3.1.1.1. Accumulation period. Period during which precipitation is accumulated in the basin in the form of snow and the streamflow is below the annual mean. Streamflow during this period is almost entirely due to base flow which is the result of the meteorological conditions during the antecedent months. The accumulation period starts with a sharp decline in streamflow (typically through November and December) due to the little contribution from precipitation to the flow as the majority of it is intercepted and stored in the catchment in the form of a snowpack. The flow declines until it is in equilibrium with the base flow. After reaching this equilibrium, there is a slow but steady decline in streamflow until the onset of the spring flood due to the base flow storages being depleted over time.

3.1.1.2. Spring flow period. The month(s) after winter when the streamflow is significantly elevated compared to the rest of the year. The positive temperature in spring results in a relative rapid snowpack ablation, moreover, the occurrence of rain on snow might accelerate the ablation process. Snow melt is the majority contributor to streamflow during the spring flow period followed by the leading minority contributors: precipitation and base flow. However, towards the end of the period, the snowpack becomes depleted and rain events become the dominant contributor to streamflow. It is not uncommon to have some snow still on the ground in some areas at the end of the spring flow period due to the size of the initial snowpack, elevation and/or favorable meteorological conditions.

3.1.1.3. Post flood period. The months between the spring flow period and the accumulation period in the snow dominated clusters, when there is a steady decline in streamflow from the elevated levels during the spring flow period. The typically high streamflow of the spring flow period is receding and the majority contributors to streamflow during the post flood period are precipitation events, base flow and glacial ablation where glaciers exist. It is a combination of this glacial ablation, melt water from higher elevations and base flow that accounts for the extended tail of the spring flow period recession. Towards the end of the post flood period, when the temperature approaches freezing, there is a general decrease in both temperature and precipitation. This means that although there is a steady drop in streamflow there is also a drop in evapotranspiration rates that leads to a net increase in groundwater and lake levels.

3.1.1.4. High flow period. The period with above average streamflow over the winter months in the rain dominated clusters, that typically starts in November and ends in March or April. Although precipitation might be in the form of snow during the high flow period, there is a higher likelihood that most of this snow will be lost during the high flow period due to thaw and rain on snow processes. During the high flow period the evapotranspiration rates are depressed, due to the average daily temperature being around zero, and there is a relatively high amount of precipitation. This results in higher soil moisture and lake levels that in turn, coupled with the precipitation, results in increased runoff.

3.1.1.5. Low flow period. The period with below average streamflow over the summer months in the R clusters, that typically starts in May or June and ends in October. Although there is a small increase in the amount of precipitation throughout the low flow period, the evapotranspiration rates are elevated due to the higher average daily temperature which cause the streamflow to drop below the annual means. The majority contributors to streamflow are precipitation events and base flow.

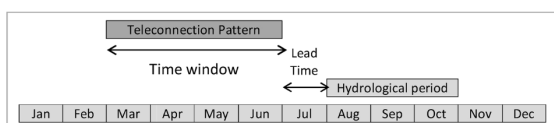


Fig. 3. Diagram showing how the TP periods are defined with regards to lead time (lt) and length of time window (wl). In this example the TP has a lead time of 1 month and a window length of 4 months.

3.2. Climatological characterization

3.2.1. Definition of teleconnection periods

Each series of monthly TP indices, $TPI(m)$, was averaged over time windows that were connected to the defined hydrological periods considering different lead times and windows lengths (Fig. 3). The time windows were either concurrent with the hydrological periods (which are listed above and detailed described in Section 4.2) or had a lead time to them. For clarification, Fig. 3 shows the example of a 4-month TP window with a 1-month lead time to the hydrological period Aug-Oct.

For each cluster and hydrological period, an ensemble of 145 TP windows were defined. One TP window was defined as concurrent with the hydrological period and its corresponding average indices denoted $\overline{TPI}_{hp}^c(y)$. The other 144 TP windows were a combination of different lead times lt ($0 \geq lt \geq 11$ months) to the hydrological period and window lengths wl ($1 \geq wl \geq 12$ months). The resulting average TP indices may be denoted $\overline{TPI}_{hp}^c(y, lt, wl)$ where lt is taken relative to the start of hydrological period hp for cluster c . In the following, for simplification, the expression $\overline{TPI}_{tw}^c(y)$ is used to denote the averaged TP indices over a certain time window tw which is related to a specific hydrological period in cluster c (see Fig. 3). $\overline{TPI}_{tw}^c(y)$ thus includes the averaged TP indices both in the concurrent hydrological period ($\overline{TPI}_{hp}^c(y)$) and prior to the hydrological period ($\overline{TPI}_{hp}^c(y, lt, wl)$).

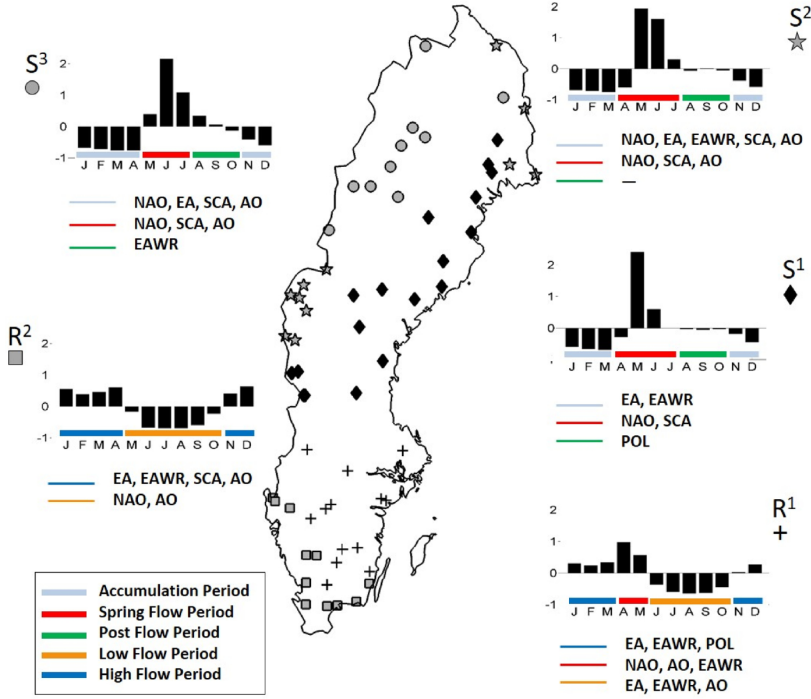


Fig. 4. Location of stations that compose the five clusters S^3 , S^2 , S^1 (snow dominated clusters), R^2 and R^1 (rain dominated clusters). Symbols that represent each cluster is placed under the name of the cluster. Black vertical bars are the cluster mean annual hydrograph $\overline{Q}(1:12)$ for each cluster, and coloured horizontal bars are the associated hydrological periods. For each cluster and hydrological period, the TPs (Table 1) that exhibit significant correlation ($p \leq 0.01$) with the streamflow and have a solid physical association to it are listed.

3.3. Linking hydrological regions and teleconnection patterns

PCA was used to determine connections between TPs and streamflow for every hydrological period and hydrological cluster. For each cluster and hydrological period, a PCA was applied to the data matrix composed by the time series of the streamflow composite, $\overline{Q_{hp}^c(y)}$, and the time series of the accompanying averaged TP indices, $\overline{TPF_{tw}^c(y)}$. A biplot of the first two PCA modes was used to identify within all TPs and time windows, the ones that were most strongly related to the streamflow composite of each cluster and hydrological period. In total 200 matrices were generated considering the five clusters, five hydrological seasons and all climate indices considered initially by this study generating 200 biplots that were analyzed. Some examples of such biplots may be found in the supplementary material (Fig S1 in the supplementary material). The accumulated explained variance of the first two modes ranged from 67% to near 100% with an average of 84%.

The Spearman correlation coefficient was calculated between $\overline{Q_{hp}^c(y)}$ and the TP time series $\overline{TPF_{tw}^c(y)}$ that were selected from the PCA biplot analysis. TP time windows for which correlation coefficients were not significant at the 0.01 level were disregarded from further analysis. Further, connections identified by significant correlations but without any discernible physical explanation (i.e. meteorological mechanism able to transfer the information from the teleconnection pattern to the local hydrology) were also discarded.

3.3.1. Temporal variability of the climate-hydrology connections

The temporal variability of the hydrological and climatological series was analyzed by means of continuous wavelet transform (CWT), the so-called wavelet power spectrum. CWTs were calculated for each streamflow composite time series $\overline{Q_{hp}^c(y)}$ and the corresponding TPs and time windows $\overline{TPF_{tw}^c(y)}$ that were found connected.

The wavelet analysis, first introduced by Morlet et al. (1982a, Morlet et al., 1982b and Grossmann and Morlet (1984), decomposes a time series into scale components allowing distinction between the oscillations that occur at different time scales. The wavelet analysis keeps information about the occurrence of non-stationary events in both time and frequency domains, highlighting localized intermittent periodicities (Grinsted et al., 2004).

The Morlet (Ψ_0) wavelet was used in this study since it is efficient in extracting features, maintaining a good balance between frequency and time information (Torrence and Compo, 1998; Grinsted et al., 2004).

To determine the connections between the temporal variability of the composite streamflow series $\overline{Q_{hp}^c(y)}$ and the associated TP averages $\overline{TPF_{tw}^c(y)}$, Cross Wavelet Transforms (XWT) were calculated (Grinsted et al., 2004). The XWT shows periodicities and time intervals in which the individual CWTs have common high power and a common local phase. To avoid the pitfalls of XWT analysis identified by Mauran and Kurths (2004), the wavelet transform coherence (WTC) was used. It is a measure of the coherence between the signals from the individual CWT, developed by Grinsted et al. (2004), and can be thought of as the local correlation between the wavelet transform of each time series used in the XWT.

The interpretation of the WTC as local correlation was explored in this work as a mean to identify different scales and time periods when composite streamflow time series and the associated TP averages were locally correlated. This is an attempt to overcome the non-linearity of the impact on streamflow that results from the interactions among different TPs. TPs may enhance or diminish each other's impact on streamflow depending on their state at the specific moment. This characteristic generates non-linearity in the signal that are not captured by simple correlation analysis between the discharge indices and one of the TPs.

The XWT and WTC were calculated and displayed using the cross wavelet and wavelet coherence toolbox for MATLAB provided by A. Grinsted (<http://www.giaciology.net/wavelet-coherence>). The wavelet spectrum was calculated and displayed using the wavelet software provided by C. Torrence and G. Compo (<http://atoc.colorado.edu/research/wavelets/>).

4. Results and discussion

Fig. 4 is a compilation of the main results achieved by this work. It displays the location of the stations that compose the different clusters of homogeneous hydrological variability, the standardized composite hydrograph for each cluster, the identified hydrological periods, and the TPs that have a statistically significant ($p \leq 0.01$) correlation with the streamflow variability of each cluster. Each cluster occupies a mutually exclusive and distinct geographical region; however, due to the limited number of stations, it is not possible to exclude the possibility of intrusions along the boundaries between the clusters.

4.1. Hydrological clusters and their characteristics

The hierarchical clustering of the 64 monthly streamflow time series resulted in the five unique clusters represented by different symbols in Fig. 4. The robustness of this result is supported by the average silhouette width for the clusters being 0.52, indicating that a reasonable structure was found (Struyf et al., 1997), and by the time series of the individual cluster members showing high correlations (0.79 ± 0.025 ; $p < 0.01$) with their cluster mean time series.

Three clusters are located in the snow dominated northern part of Sweden. These clusters are named S^1 , S^2 and S^3 where S refers to snow dominate and the numbers 1, 2 and 3 representing the relative intensity of this hydrological characteristic from least to most intense. The stations that constitute the S^3 cluster (circles in Fig. 4) are located in the mountainous highlands and forested inland plains in the northern third of the country. This is the only cluster that does not include any stations near the coast. The S^2 cluster (stars in

Fig. 4) is split into two separate regions: one in the mountainous highlands in central Sweden, south of cluster S³, and one along the Finnish border, from the inland plateau in the north down to the coast. This spatially discontinuous cluster is in agreement with clusters found in Uvo (2003) when examining the variability in precipitation over northern Europe. The stations in cluster S¹ (diamonds in Fig. 4) are mostly located along the northern coastline and inland plains. At its southernmost part, the stations in S¹ also extend up into the mountainous highlands south of S². In common, the annual hydrographs of the S clusters present a well-defined melting season characterized by peak flows. More detailed descriptions of the hydrographs are presented in Section 4.2.

Two clusters are located in the rain dominated southern part of Sweden: R¹ and R². In this case, R refers to rain dominated and the numbers for the intensity of this characteristic. R¹ (plusses, Fig. 4) extends from low-lying areas north of Stockholm, down to the south-eastern coast into the southern highlands and up to the Norwegian border. The stations in cluster R² (squares, Fig. 4) are located in a band that extends along the western and southern coastlines and a short way up the eastern coast. Although R¹ falls under the rain-dominated category, its composite hydrograph displays a snow process related signal in the form of a distinct snow melt period in April and May. The hydrograph for the cluster R² displays only a minor snow process related signal with a weak signal of snow melt in April (Fig. 4). The relatively mild winter temperature (around 0 °C) typical of these regions results in several snow melt events as well as rain-on-snow events (that most often result in the snow melting) during the winter and consequently only limited periods with snow accumulation on the ground, typically from a few days to some weeks, as expressed by the normal number of days with snow cover below 75 days (average 1961–1990) presented by SMHI (2019a).

Some statistics such as number of gauging stations per cluster, elevation of the gauging stations, the upstream catchment area and the percentage of this area covered by water bodies are summarized in Table 2.

Previous cluster analyses of river streamflow in Sweden were made by Gottschalk (1985) and, for the southern part of Sweden, by Kingston et al. (2011). The choice to remake the analysis in this work is based on the fact that the data set used here spans a longer period of time that includes different climatic characteristics, as compared to the dataset used by Gottschalk (1985). The current dataset (1960–2010) includes the climate shift observed during the 1970's (Baines and Folland, 2007), which is characterized by an important and simultaneous change of phase in several TPs. Among others, the climate shift separates a period of predominantly very negative values of NAO during the 60's and 70's from the predominantly very positive NAO period that was most intense during the 1990's (Hurrell, 2017). Moreover, a different clustering methodology was used in this study. Instead of analyzing all catchments at once, Gottschalk (1985) analyzed streamflows in small and large catchments separately and used correlation coefficient and p-space Euclidian distance, without data pre-filtering. While Kingston et al. (2011) used a similar method as the one used here, their study area included only a few Swedish stations, located exclusively in southern Sweden.

Gottschalk (1985) identified seven clusters for small basins and three for large ones within Sweden. The five clusters identified here are an intermediary solution, coherent with his results. Additionally, these results are also coherent with the northern North Atlantic hydrological regions identified by Kingston et al. (2011). They found that Sweden's hydrology was coarsely divided into two groups; one group in the southern third and another in the north.

4.2. Hydrological periods

The annual streamflow in the snow dominated clusters is characterized by three distinct hydrological periods: the *accumulation* period during winter months, *spring flow period* at melting season and the *post flood period* through November and December, as seen in the S¹, S² and S³ hydrographs in Fig. 4.

Accumulation period exists only in the snow dominated clusters and is defined as November to March in clusters S¹ and S² and November to April in cluster S³. The start of the spring flow period in the snow dominated clusters ranges from mid to late April for S¹ and early to mid-May for S³. S¹, which is the closest cluster to the coast and lowest in both elevation and latitude, shows the earliest start (Fig. 4 - S hydrographs).

The northern clusters, S³ and S², have a longer time from the start of the spring flow period to the spring flow peak if compared to the S¹, due to their geographic locations. Basically, spring temperature take longer time to rise in those latitudes. Cluster S¹ has the most distinct spring flow peak, that approaches 2.5 standard deviations of the annual mean flow (Fig. 4 - S¹ hydrograph), as its catchments have smaller snowpacks and a more rapid rise in daily temperatures in spring (SMHI, 2019b).

Cluster R¹ has a shorter spring flow period (Figs. 4 - R¹ and R² hydrographs) as compared to the S clusters. The lack of spring flow period in R² is related to the small and intermittent presence of snow in the catchments so that no snowpack is formed during winter. The higher elevations and latitudes of the catchments in R¹ result in the generation of a more substantial snowpack and a later timing of the spring flow period, typically during April and early May.

Table 2
Elevation and area statistics for the different clusters.

Cluster	Number of stations	station elevation (m)			upstream area (km ²)			lake area (%)		
		min	mean	max	min	mean	max	min	mean	max
S ³	10	208	387	489	418	1 942	6 056	0	9	15
S ²	11	21	374	825	65	4 853	18 752	0	5	12
S ¹	18	4	183	641	294	2 524	11 851	1	6	13
R ¹	13	19	141	443	40	824	2 382	2	8	18
R ²	12	6	60	155	5	624	3 665	0	5	16

The post flood period begins in July for S^1 and in August for S^3 and S^2 . The slow fall in the average daily temperature as the summer turns into autumn, and a slight increase in precipitation during the autumn months (mostly in S^2), results in a slow-down, stabilization, and rise in streamflow in the S clusters.

The hydrographs of the rain dominated clusters are characterized by only two distinct periods: the *high flow period* with above annual average flows in winter and the *low flow period* during the warm months, characterized by below annual average flows (see the R^1 and R^2 hydrographs in Fig. 4). This “binary” hydrograph is due to the mild temperatures in the southern parts of Sweden during the winter period. This results in the low characteristic evapotranspiration rates, and an increased likelihood of liquid precipitation and freeze/thaw events if compared to colder regions, especially in catchments with low elevation and close proximity to the sea.

The high flow period starts in November, for both R^1 and R^2 , with an increase in streamflow through December followed by a drop

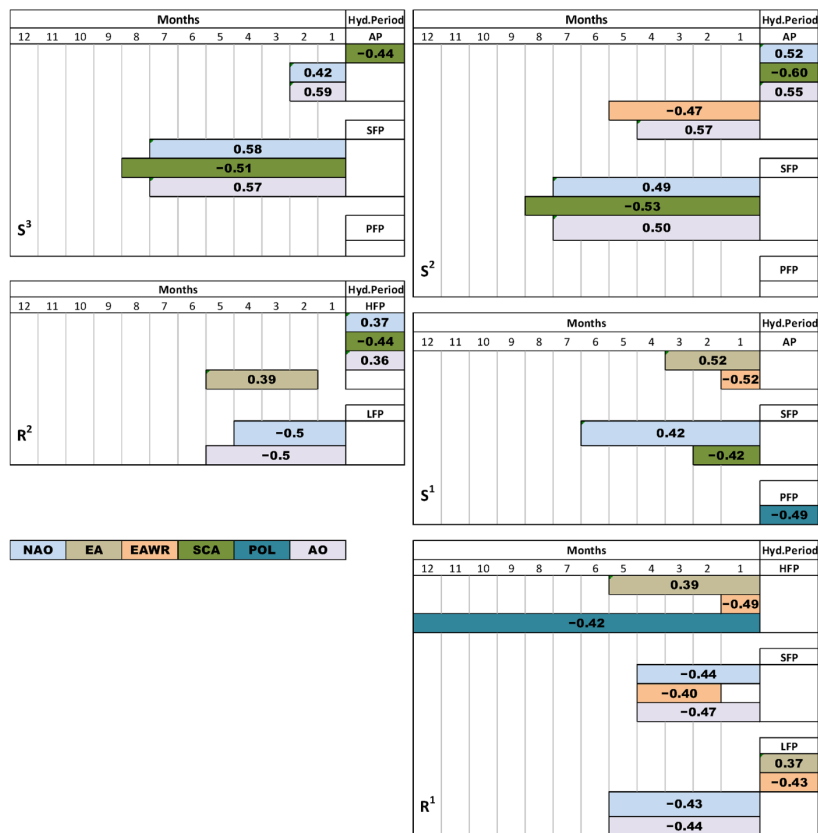


Fig. 5. The horizontal bars represent the TPs (bar colour) and time windows that were found connected to the composite streamflow in each cluster (snow dominated S^3 , S^2 and S^1 , and rain dominated R^2 and R^1) and hydrological period (AP for accumulation period, SFP for spring flow period, PFP for post flood period, HFP for high flow period, and LFP for low flow period). The number in the bar is the Spearman rank-order correlation coefficient between streamflow and TP index. The gap between the hydrological period and the bar indicates the lead time lt (a bar within the hydrological period is concurrent with the hydrologic period) and the length of the bars represent the TP time window length wl .

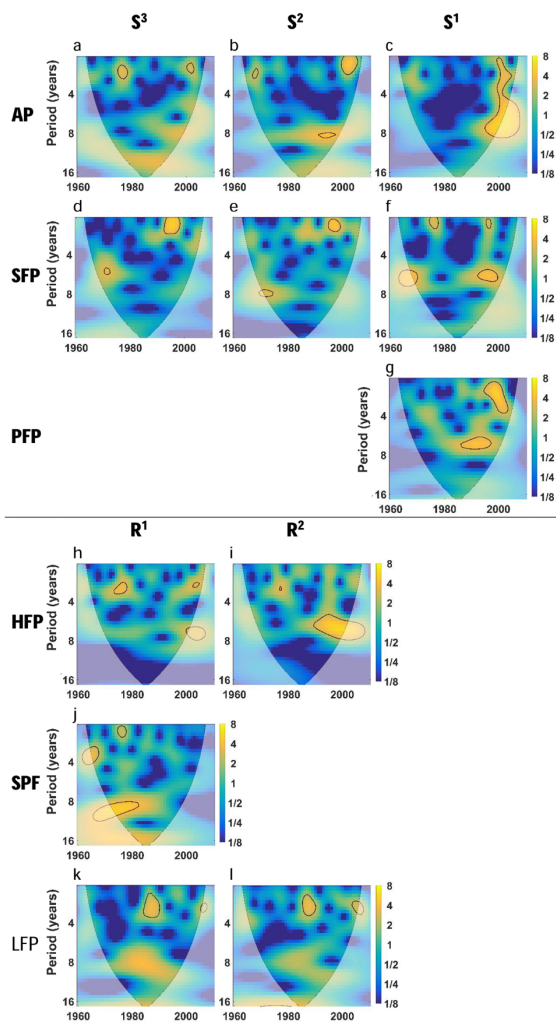


Fig. 6. Continuous Wavelet Transform (CWT) of streamflow per cluster (columns) and hydrological period (rows) that presented correlation with at least one TP as presented in Fig. 5. Statistical significance of 95% is represented by a bold black continuous line and the cone of influence by faded colours. The power of the transform is indicated by colours as in the colour bar to the right of each figure row. Here AP stands for Accumulation Period, SFP for Spring Flow Period, PFP for Post Flow Period, HFP for High Flow Period and LFP for Low Flow Period.

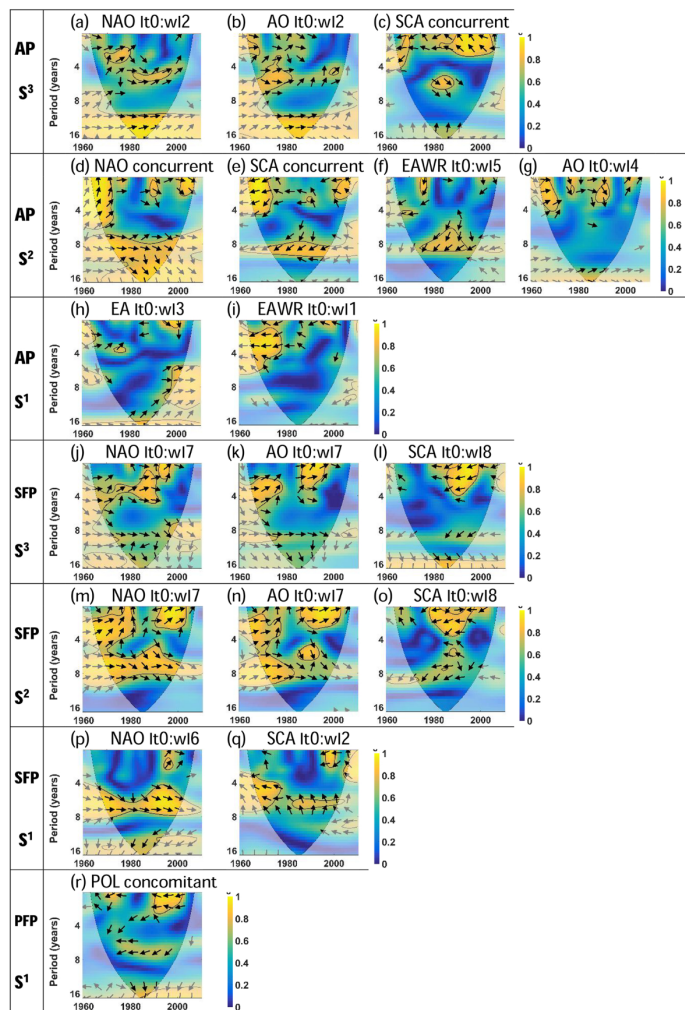


Fig. 7. Squared Wavelet Transform Coherence (WTC) between streamflow and TPs for different snow dominated clusters, hydrological periods (rows) and TPs (columns). Statistical significance of 95% is represented by a bold black continuous line and the cone of influence by faded colours. Intensity of the coherence is represented by the colours (right bar) and the arrows represent the relative local phase angle. Here AP stands for Accumulation Period, SFP for Spring Flow Period, and PFP for Post Flow Period.

in February and March due to decrease in precipitation. Similar to the pattern seen in the S clusters, there is a delayed reaction in R¹ streamflow due to its higher elevation and latitude, and consequently, lower temperature.

The low flow period starts in May in R² and June in R¹ with decreasing streamflow until August, after which it increases again as the average daily temperature and evapotranspiration decreases.

In the following, the five hydrological periods identified in the analysis of monthly composite hydrographs from each cluster are described and discussed.

4.3. Climate-streamflow connections

Fig. 5 presents the combinations of TPs and associated time windows that are significantly correlated to each cluster and hydrological period. The choice of TPs and periods tested was made based on the biplots that resulted from the PCA analysis (examples on Figure S1) applied on a matrix containing time series of TPs and streamflow in different hydrological periods. The presented selection is based on both correlations significant at ≥ 0.01 level and a clear physical explanation that supports the correlation. In an attempt to simplify visualization, Fig. 5 is divided in five panels corresponding to the five clusters in Fig. 4. The panels are positioned and named similarly to the clusters in Fig. 4. For example, Fig. 5 S³ shows that for the S³ cluster, located in north-west Sweden, the streamflow during accumulation period is negatively correlated (-0.44) to the SCA index averaged over the same period, and positively correlated to NAO (0.42) and AO (0.59) with zero-month lead time and a 2-month time window.

The information provided by the Spearman rank correlation analysis is complemented by the wavelet analysis, in order to highlight the temporal distribution of the relationship between the composite hydrographs $Q_{hp}^c(y)$ and the associated mean TP indices $TP_{tw}^c(y)$, along the time span of the data set. The objective is to quantify the local correlation between streamflow and TP over time, which reflects the degree of (possibly nonlinear) association between the inter-annual variability of the streamflow and the TP, respectively.

4.3.1. Snow dominated clusters

4.3.1.1. Accumulation period. Fig. 5 shows that S³ streamflow during accumulation period is negatively correlated with the average SCA⁻ index over the same period (concurrent) and positively correlated with the average NAO⁺ and AO⁺ indices for lead time lt zero and two months' window length wl (lt0:wl2) to the accumulation period (hereafter, the superscript sign following the TP acronym indicates the sign of the correlation).

The CWT of S³ accumulation period streamflow (Fig. 6) highlights that its interannual variability has two preferred bands of oscillation: 2–4 year and 8–16 year. The 2–4 year oscillation was most active during the second half of the 1970's and the first half of 2000's and was particularly inactive during late 1980's. The 8–16 year oscillation was present during most of the study period, even if it does not show as statistically significant at 95% on the wavelet spectrum diagram (Fig. 6a). The WTC of S³ accumulation period streamflow and different TPs (Fig. 7a, b and c) clarifies that the 2–4 year oscillation is locally correlated, in anti-phase, with the concurrent SCA, along the time span, with the strongest intensity from mid-1980's to mid-2000's. Whereas the 8–16 year oscillation is locally correlated, in phase, to both NAO lt0:wl2 (Fig. 7a) and AO lt0:wl2 (Fig. 7b) during the whole time span of the series. The phase of the local correlation is in agreement with the impact of the climate mode represented by the index on the precipitation and temperature over Scandinavia. A high SCA index is commonly associated with a decrease in precipitation, and thus discharge, over Scandinavia, which results show to be in anti-phase with SCA. The opposite is true for NAO, which results show to be in phase with discharge. This will be discussed further and in more detailed discussed later in this section.

It should be emphasized that the high powers showed by the CWT at 2–4 year periodicity (Fig. 6a) are connected to different TPs. During 1975–1980 S³ accumulation period streamflow is locally correlated to NAO and AO, on the other hand, during 1995–2005, SCA is the TP to which the streamflow is locally correlated.

For the S² cluster, the mean streamflow during the accumulation period is correlated with the average indices of NAO⁺, SCA⁻ and AO⁺ during the concomitant season and with the average indices of EAWR⁻ and AO⁺ in the four and five months prior to the accumulation period, respectively (Fig. 5 S²).

The CWT clarifies that interannual variability of the streamflow at S² during accumulation period presents two preferred bands of oscillation. The 2–4 year band was most active during late 1960's and late 1990's to mid-2000's, but also evident during late 1970's and 1990. The 8–10 year band, is clear throughout the whole data time span, but most active during the 1990's (Fig. 6b). The WTC of S² accumulation period streamflow and TPs (Fig. 7d, e, f and g) reveals that the 2–4 year oscillation is locally correlated (in-phase) similarly with the average NAO (Fig. 7d) and AO (not shown) concurrent to accumulation period before 1970's, between 1985–1990 and between 2000–2005 and with AO prior (lt0:wl4) to accumulation period, during the same years but not after 1995 (Fig. 7g). Moreover, it is locally correlated (in anti-phase) with the concomitant SCA before 1975 and after 2000.

The oscillation on 8–10 year band is locally correlated with NAO and AO (in-phase) and SCA (anti-phase) at the concomitant period along the whole time span (Fig. 7d and e), as well as to EAWR lt0:wl5 (out of phase) during 1975–1995 (Fig. 7f).

Noticeable for the accumulation period streamflow in S² is that it clearly shows that the variability in streamflow may result from the interaction between different TPs, either during short time intervals (as for the 2–4 year band oscillation) or for long time spans (as for the 8–16 year band).

The accumulation period streamflow in S¹ is correlated with the average EA⁺ and EAWR⁻ indices in the three and one months prior to the accumulation period, respectively (Fig. 5).

The CWT shows that S¹ accumulation period streamflow did not show any period of preferred oscillation. Statistical significant

power is only present between 1990 and 2010 spanning from 2 to 10 year periodicity (Fig. 6c). Such power showed, on WTC, to be locally correlated to EA l0:w13 (in-phase) in the longer band of oscillation. The negative Spearman correlation found with EAWR may be related to a local correlation (in anti-phase) at periods < 4 years before 1980 (Fig. 7i).

4.3.1.2. Spring flow period. The spring flow period streamflow in S^3 and S^2 are both correlated with the average NAO⁺, SCA⁻ and AO⁺ indices during the seven, eight, and seven months prior to the spring flow period, respectively (Fig. 5 S^3 and S^2). The long time window prior to the spring flow period clearly indicates the impact of the TPs on the amount of snow that is stored in the basin during winter, as the main contribution to the streamflow during spring flow period comes from snow melt.

The CWT of the streamflow in S^3 during the spring flow period shows one centre of statistically significant power at about 2-year band of oscillation active during the 1990's, and one at the 4–8 year around mid-1970's (Fig. 6d). The WTCs of the S^3 spring flow period show that both centers of action are locally correlated (in-phase) with NAO l0:w17 and AO l0:w17 (Fig. 7j and k). In addition, the activity centre at about 2-year periodicity is locally correlated, in anti-phase, with SCA l0:w18 (Fig. 7l). Clearly, the centre of high power at the 2-year band is a result from the interaction among several climate modes of variability (TPs AO, NAO and SCA).

The wavelet spectrum for the S^2 spring flow period streamflow presents different characteristics than the one for S^3 spring flow period flows, despite similar rank correlations with AO, NAO and SCA. It indicates that the ~2-year oscillation is present during most of the study time, however statistically significant only during the second part of the 1990's (Fig. 6e). A centre of significant power at 8-year oscillation is present around early 1970's. The WTC charts show that the short period oscillation is locally correlated (in-phase) with NAO l0:p7 and, in a similar way, with AO l0:w17 (Fig. 7m and n). At the same time, this oscillation is locally correlated (in anti-phase) with SCA l0:w18 (Fig. 7o). The 8-year oscillation is, however, locally correlated (in-phase) mostly to NAO l0:w17.

The spring flow period in S^1 is correlated to the mean NAO⁺ and SCA⁻ indices six and two months prior to the spring flow period, respectively (Fig. 5 S^1). The CWT of the S^1 average streamflow during spring flow period (Fig. 6f) shows a preferred oscillation of about 6–8 year periodicity that was distinctly active during the 1960's and from the mid 1980's to the early 2000's. The WTC clarifies that the active period in the 1960's is locally correlated to NAO l0:w16 (in-phase), whereas, the one from the mid 1980's to the early 2000's is locally correlated, in-phase, with NAO l0:w16 and in anti-phase with SCA l0:w12 (Fig. 7p and q). A 2-year period oscillation active during the late 1970's is also evident in the CWT of S^1 spring flow period streamflow. This, however, is not locally correlated to any of the TPs considered in this work.

This example again underlines that different TPs may be connected to streamflow at different periods and time spans but also that other causes beyond the known climate modes of variability may be related to streamflow variability.

The interesting opposite influence that NAO/AO and SCA exert on the spring flow deserves to be further discussed. Positive (negative) NAO/AO increases (decreases) spring flow, and the oppositely for SCA. The meteorological processes connected to this opposing behavior may be clarified as during positive (negative) AO/NAO conditions, the north Atlantic storm track is shifted northwards (southwards) over Scandinavia (southern Europe) and the polar jet is stronger (weaker) and more zonal (meridional) in nature (Hurrell, 1995). This increases (reduces) the transport of mild and moist air masses from the Atlantic towards Scandinavia and limits (enhances) the intrusion of a cold polar trough over the region.

On the other hand, a positive SCA is associated with a decrease of the number of extra-tropical cyclones in northern Europe, resulting from a weak storm track located northward of the normal track and to a blocking high pressure over Scandinavia (Mailier et al., 2006; Vitolo et al., 2009). Moreover, a positive SCA is also associated to a reduced frequency of winter atmospheric rivers towards northern Europe (Lavers et al., 2012), that is an important source of moisture to the region. Indeed, Comas-Bru and McDermott (2014) suggests that SCA has an additive effect on the NAO-precipitation relationship over the southwest coastal region of Sweden, and a subtractive one on the rest of the country, when the TP indices have the same signs. When the TP indices have opposite signs there is a general additive effect on the NAO-precipitation relationship over the entire country. It is argued that this is due to the shifting of their net centers of activity in the Atlantic-Eurasian domain.

It should be emphasized that different TPs that are connected to the same homogeneous region and hydrological period very often have opposite impacts on the streamflow. In this way, the impact of diverse TPs may strengthen or cancel each other, enhancing or decreasing the effect of individual TPs in a linear or non-linear manner. Such dynamics of opposing influences have been described before by e.g. Ionita (2014) and Lim (2015) as well as for the impacts of SST on precipitation (e.g. Uvo et al., 1998, for precipitation in Northeast Brazil).

When these relations are analyzed in more detail by means of wavelets, it becomes clear that the strong CWT powers for spring flow in the S clusters (Fig. 6, second row) shows to be locally correlated to both NAO/AO and SCA, as seen by the corresponding WTC (Fig. 7j to q). However, when examining the different periodicities of oscillation, it shows that in S^3 and S^2 , the high power with about 2-year periodicity is locally correlated to the three TPs, but that the long-periodicity oscillations (8–16 years) are only locally correlated to NAO/AO. On the other hand, in S^1 , only the power at 8 to 16-year periodicity is locally correlated to NAO and SCA. This is probably due to the eastern placement of S^1 that makes the Baltic Sea its main source of moisture. The R¹ cluster presents a shorter and less marked spring flow period. The variability in the mean spring flow period streamflow is clearly connected to the variability of AO and NAO on longer periodicities and to EAWR on shorter, less active, ones. This example provides us with the perspective that the influences of different TPs, and the consequences of their interaction, may also happen in different oscillation periodicities that might accentuate the resulting non-linearity in the interannual streamflow variability.

From Fig. 5, it is noticeable that the streamflow during spring flow period in the northern, snow dominated S clusters is influenced by TPs during longer time windows than the southern, rain dominated R clusters. This characteristic is in agreement with the longer time during which snow is accumulated in the northern clusters and increases the possibility of long-term forecasting.

4.3.1.3. Post flood period. In the post flood period, the contributions to streamflow from base flow and snow processes are matched or exceeded by the contribution from precipitation events. Consequently, no TP showed a significant teleconnection with the post flood period in S^3 and S^2 . However, the S^1 post flood period streamflow is correlated with the average POL^- index in the concomitant period (Fig. 5 S^1)

The CWT for S^1 post flood period streamflow shows preferred oscillation periodicities at 2–4 year and 6–8 year bands. The shorter period oscillation was most active from the mid 1990's to the mid 2000's and the longer, most active from mid-1980's to early 2000's (Fig. 6g). The WTC reveals that both oscillations are locally correlated (in anti-phase) with the concurrent POL index (Fig. 7r). This result suggests that the activity of the POL may modulate the precipitation in S^1 during summer and autumn.

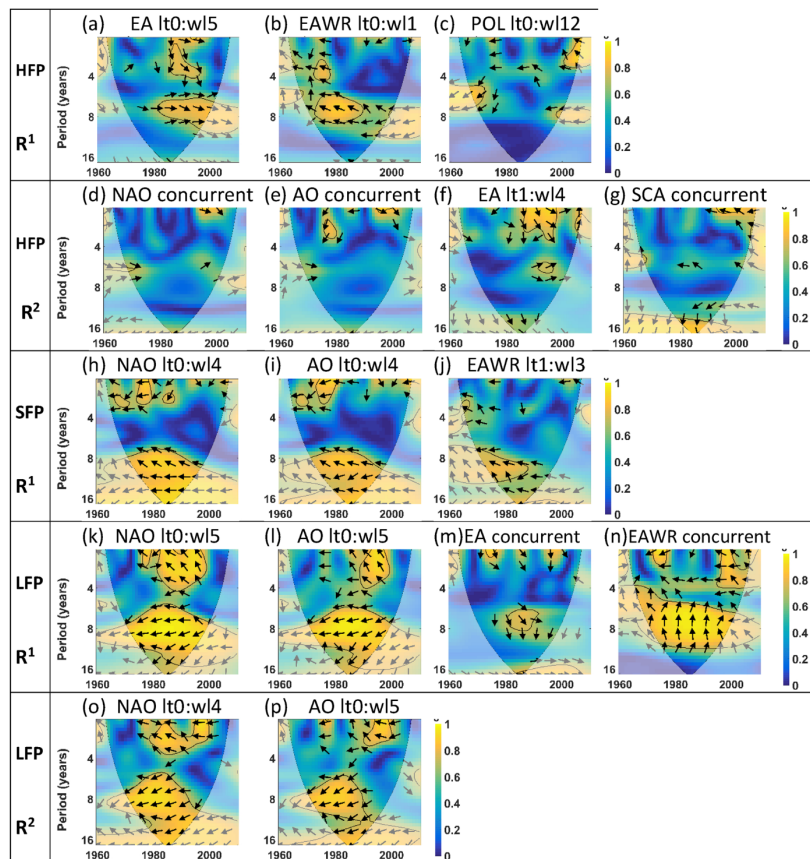


Fig. 8. Same as in Fig. 7 but for rain dominated clusters. Here HFP stands for High Flow Period, SFP for Spring Flow Period and LFP for Low Flow Period.

4.3.2. Rain dominated clusters

4.3.2.1. High flow period. The high flow period in R^1 is correlated with the average EA^+ , $EAWR^-$, and POL^- indices in the five, one, and twelve months prior to the high flow period, respectively (Fig. 5 R^1).

The CWT analysis of the R^1 high flow period streamflow (Fig. 6h) indicates oscillations in two preferred periodicities, 2–4 year and ~8-year bands. The oscillation at 2–4 year band was most active during the 1970's and 2000's. The WTC of R^1 high flow period streamflow and different TPs showed that the activity during the 1970's is locally correlated in anti-phase with $EAWR$ lt0:w11 (Fig. 8b) while the activity during 2000's was locally correlated in anti-phase with POL lt0:w12 (Fig. 8c). These results, once more, highlight the impact of two different modes of climate variability on the streamflow at different times.

The oscillation of about 8-year periodicity was active during the 2000's. Despite being under the cone of influence, the WTC shows that it is locally correlated with EA lt0:w15 (in-phase), $EAWR$ lt0:w11, and POL L0:P12, the last two in anti-phase (Fig. 8a, b and c), which is in agreement with the rank correlation coefficients found.

The R^2 high flow period streamflow (Fig. 5 R^2) is correlated with the concurrent average NAO^- , SCA^+ and AO^- indices and the average EA index in the four months period with a lead time of one month (lt1:w14) as seen in Fig. 5 R^2 .

The CWT (Fig. 6i) suggests two preferred oscillation periodicities: 2–4 year and 6–8 year. A clear strengthening of the activity of the 2–4 year period oscillation happens at about every decade; however, its power was significant only during late 1970's.

The WTC of R^2 high flow period streamflow and the different TPs evidenced that the shorter oscillation is locally correlated with the concurrent AO , EA (lt1:w14) and concurrent SCA (in anti-phase) (Fig. 8e, f and g). However, the phase of the first two WTCs varies significantly along the time span, which indicates that the local correlations might not be physically supported. In agreement with that, no significant correlation was found between R^2 high flow period streamflow and EA index and the correlation coefficient between AO index and R^2 high flow period streamflow is the lowest presented in Fig. 5.

The 6–8 year oscillation was most active from late 1980's to late 2000's (Fig. 6i). Despite its strong power, the WTC analyses show that it is only weakly locally correlated with the EA lt1:w14, in-phase (Fig. 8f). None of the analyzed TPs exhibit a clear connection to the power and oscillations showed by the CWT.

In general, AO and NAO are linearly correlated (0.01 level) to streamflow in all clusters and all hydrological periods, except for the post flood period in the northern group. However, the correlations found between NAO/AO and flows during high flow period in R^2 (0.37) is, despite being statistically significant, not supported by the results from the wavelet analyses (WTC Fig. 8d, e, f and g). These are inconclusive with respect to local correlation as they present both few areas of significant local correlation and arrows pointing to different directions within each of the few significant periods. This lack of or low correlation between NAO/AO and flows in the southernmost clusters is supported by the findings of Uvo (2003), who found that winter precipitation in southern Sweden has very little (near zero) of its variability explained by NAO .

Streamflow during the high flow period is a combination of base flow, lake out-flows and concurrent meteorological conditions. EA and POL are the TPs connected to the high flow period in R^2 whereas only EA is connected in R^1 . Their connection to R^1 and R^2 high flow period streamflow is possibly connected to groundwater and lake storage levels as EA positively (negatively) influences the recharge of these storages in R^1 and R^2 by transporting mild and moist air masses over (away from) Sweden, resulting in milder and wetter (cooler and dryer) conditions. On the other hand, the concomitant conditions of SCA , AO and $EAWR$ influence high flow period streamflow by driving the meteorological conditions during the period. The wavelet analysis is inconclusive in showing local correlation between TPs and high flow period flows in R^2 , except for EA at shorter periods of oscillation (2-years). In R^1 , local correlations are distinct at longer periodicities of oscillation with EA and $EAWR$, with opposite phases (Fig. 8a, b and c). Also, in this case, an interaction of TPs (EA and $EAWR$) with a resulting strengthening or weakening of their effect on streamflow is suggested. $EAWR$ is negatively correlated with precipitation over southern Sweden and the coastal northern region during winter and most of the country during the summer (e.g. Ionita, 2014; Lim, 2015). This is due to the blocking influence of the anticyclonic centre of activity over the North Sea between Scandinavia and the United Kingdom and the resulting north-westerly circulation over the Scandinavian Peninsula.

4.3.2.2. Spring flow period. The spring flow period in R^1 is correlated with the average NAO^- and AO^- indices in the four months prior to the spring flow period and the average $EAWR^-$ index in the three month-period with a one-month lead-time to spring flow period (Fig. 5 R^1).

The CWT for the R^1 SPF streamflow suggests two preferred oscillation periodicities, both active mostly during the first half of the study span. The WTC analysis clarifies that the oscillation of 2–4 year periodicity is locally correlated in anti-phase to both AO lt0:w14 and NAO lt0:w14. The 8+ year oscillation is locally correlated in anti-phase with AO/NAO lt0:w14 (Fig. 8h and i) as well as with $EAWR$ lt1:w13 (Fig. 8j).

4.3.2.3. Low flow period. The low flow period in R^1 is correlated with the average EA^+ and $EAWR^-$ indices over the low flow period and the average NAO^- and AO^- indices in the four months prior to the low flow period (Fig. 5 R^1).

The CWT for the R^1 low flow period streamflow suggests two preferred oscillation periodicities: of 2–4 year periodicity, most active during the mid-1980's to the early 1990's and in the mid-2000's, and a ~8 years periodicity most active from the mid-1970's to 2000, however, not statistically significant (Fig. 6k).

The WTC suggest that the active period of 2–4 year oscillation in the mid-1980's to the early 1990's is locally correlated with AO/NAO L0:P5 in anti-phase (Figs. 8k and l), whereas the activity during the mid-2000's is locally correlated, in anti-phase, with the concurrent $EAWR$ (Fig. 8n). The WTC analysis supports that the ~8-year oscillation, even if not statistically significant at the CWT, is

locally correlated with both NAO Ito:w15, in anti-phase, and the concurrent EAWR, which leads the oscillation by 90° (as represented by the vertical arrows pointing down in (Fig. 8m)).

The low flow period in R^2 is correlated with the average NAO⁺ and AO⁺ indices in the four and five months prior to the low flow period respectively (Fig. 5 R^2). Its CWT (Fig. 6l) shows a 2–4 year oscillation most active during 1985–1990 and during the 2000's. This oscillation is connected in anti-phase to AO Ito:w15 and NAO Ito:w14 (Figs. 8o and p).

As well as the post flood period for the S clusters, the low flow period for the R clusters are periods when the streamflow is strongly related to rainfall. Interestingly, in these periods average streamflow is connected to different TPs (EAWR, POL, NAO, AO and EA), or even not connected to any of the studied TPs (S^2). The wavelet analysis show that most of the local correlations with the different TPs are associated with long-periodicity oscillations (8–16 years).

The analysis of the relation between the interannual variability of streamflow and TPs, developed here by means of rank correlation and wavelet analysis, clarifies that different TPs affect the streamflows in different homogenous hydrological regions – clusters – during different hydrological periods.

AO/NAO before the spring flow period are positively correlated to streamflow during the spring flow period in all snow dominated clusters (S clusters). On the other hand, AO/NAO is negative correlated to streamflow during the low flow period and the spring flow period in R^1 . In all clusters, SCA is negatively correlated to the streamflow both prior and concurrent to most of the hydrological periods. EA, at time windows prior to the high flow period, showed to be positively correlated to streamflow in R^1 and R^2 and to the accumulation period in S^1 . POL showed negative correlations with accumulation period in S^2 and S^3 and the spring flow period in R^2 . Finally, EAWR showed negatively correlation to high flow period long prior the hydrological period in R^1 .

The spring flood, resulting from the melting of snow accumulated during the accumulation period, showed to be most influenced by NAO, AO and SCA, up to eight months prior spring flow period, in the S clusters. As the spring flood is responsible for refilling dams, this knowledge opens up new possibilities for seasonal hydrological forecasting to support decision-making in the hydropower industry (e.g. Olsson et al., 2016; Foster et al., 2018). Also, for forecasting hydrological droughts this knowledge might be a key factor, as summer droughts are conditioned on the winter and spring climate (Laaha et al., 2017).

5. Conclusions

The work described here allows the conclusion that in terms of streamflow natural variability, as represented by data from 64 gauging stations in unregulated systems, the Swedish territory may be divided into five homogeneous regions. Three of these regions are characterized by the dominance of snow processes in their hydrology (the northern group; clusters S^1 , S^2 , S^3) and two by rain processes (the southern group; clusters R^1 , R^2). The hydrographs of the snow dominated group are characterized by three hydrological periods classified as Accumulation Period, Spring Flow Period and Post Flood Period. For the rain dominated group, the hydrographs show two half-year periods; one with streamflow below the annual average (Low Flow Period) and one with flows above the average (High Flow Period).

The variability of the streamflow in each of the homogenous regions and hydrological periods is influenced by diverse teleconnection patterns (TPs) that can affect the streamflow individually or in combination by defining the climatic/meteorological conditions prior to or during each hydrological period. The location of the homogeneous hydrological region is largely governing how the streamflow is influenced by climate. Despite uncertainties connected to averaging TP indices, it is possible to conclude that streamflow in the snow dominated regime of cluster S^3 is influenced mostly by Arctic Oscillation (AO), North Atlantic Oscillation (NAO) and Scandinavian Pattern (SCA). The influence of climate begins up to eight months prior to the hydrological period. Similar conditions are observed for the S^2 cluster; however, in this case, East Atlantic (EA) also influences streamflow. Interestingly, no significant connection to the TPs was found for the flows during the Post Flow Period in this cluster. The streamflow of S^1 cluster is influenced by fewer TPs than the other S clusters. Unique for it is the influence of the Polar/Eurasian Pattern (POL) on its Post Flow Period. The further south and east the cluster is located, the more TPs influence the streamflow. Streamflow in the R^1 cluster, that is located mostly to the south and east, is influenced not only by AO, NAO and SCA but also by EA, POL and East Atlantic – Western Russia Pattern.

The impact of the different TPs, which are connected to the same homogeneous region and hydrological period, on streamflow is often in conflict with each other. This suggests that the interplay between these TPs may have a net positive or negative effect on their activity which in turn would enhance or reduce their individual influence on streamflow in a linear or non-linear manner.

To conclude, all clusters exhibit a distinct influence of TPs on their streamflows by defining the meteorological conditions prior to the start of the hydrological period. This creates a clear potential for the development of seasonal hydrological, as it is the behavior of certain TPs, months in advance, that governs the average streamflow in the hydrological periods. This is especially true for the spring flow period in the northern group where the influence of NAO, AO, and SCA begins up to eight months prior to the hydrological period. This potential, however, does not exist in all hydrological periods. Especially the periods that are simultaneous with the autumn (low flow period and post flood period) have their average flow closely connected to the meteorological evolution during the period itself, i. e. no connections to the previous climatic conditions were evident.

CRedit authorship contribution statement

Cintia B. Uvo: Conceptualization, Methodology, Visualization, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition. **Kean Foster:** Methodology, Formal analysis, Visualization, Writing - original draft, Funding acquisition. **Jonas Olsson:** Funding acquisition, Methodology, Writing - review & editing, Funding acquisition, Project administration.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.ejrh.2021.100782>.

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