



Hydrological drought typology in cold climates

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Hydrological drought typology: temperature-related drought types and associated societal impacts

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Abstract

For drought management and prediction, knowledge of causing factors and socio-economic impacts of hydrological droughts is crucial. Propagation of meteorological conditions in the hydrological cycle results in different hydrological drought types that require separate analysis. In addition to the existing hydrological drought typology, we here define two new drought types related to snow and ice. A *snowmelt drought* is a deficiency in the snowmelt discharge peak in spring in snow-influenced basins and a *glaciersmelt drought* is a deficiency in the glaciersmelt discharge peak in summer in glacierised basins. In 21 catchments in Austria and Norway we studied the meteorological conditions in the seasons preceding and at the time of *snowmelt and glaciersmelt drought* events. *Snowmelt droughts* in Norway were mainly controlled by below-average winter precipitation, while in Austria both temperature and precipitation played a role. For *glaciersmelt droughts* the effect of below-normal summer temperature was dominant, both in Austria and Norway. Subsequently, we investigated the impacts of temperature-related drought types (i.e. *snowmelt and glaciersmelt drought*, but also *cold and warm snow season drought* and *rain-to-snow-season drought*). In historical archives and drought databases for the US and Europe many impacts were found that can be attributed to these temperature-related hydrological drought types, mainly in the sectors agriculture and electricity production (hydropower). However, drawing conclusions on the frequency of occurrence of different drought types from reported impacts is difficult, mainly because of reporting biases and the inevitably limited spatial and temporal scales of the information. This study shows that the combination of quantitative analysis of causing factors and qualitative analysis of impacts of temperature-related droughts is a promising approach to identify relevant drought types in other regions, especially if more data on drought impacts become available.

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1 Introduction

Socio-economic and ecological impacts of severe drought events (e.g. crop loss, wildfires, lack of drinking water, power shortage) are not directly related to meteorological drought, but indirectly, when persistent anomalous atmospheric conditions trigger soil moisture drought and hydrological drought (Fig. 1) (Wilhite and Glantz, 1985; Wilhite, 2000; Tallaksen and Van Lanen, 2004; Mishra and Singh, 2010). Therefore, besides good predictions of the meteorological situation, knowledge of the propagation of drought through the terrestrial hydrological cycle is crucial for drought management. Hydrological drought (drought in (sub)surface water storages and fluxes) can develop as a result of different processes (Fig. 1). These processes vary between regions with different climate and catchment characteristics. For example, in regions with high storage in aquifers, lakes and wetlands many small meteorological drought events can grow together into a multi-year hydrological drought event, and in regions with cold climates, in which snow accumulation plays an important role in the seasonal hydrological cycle, also anomalies in temperature influence hydrological drought development and recovery.

It is important to take these different drought propagation processes into account in statistical drought analysis, hydrological drought prediction and drought management. A hydrological drought typology is a useful tool because it classifies these processes and quantifies the relative influence of these processes in a specific drought event or in a specific catchment. Van Loon and Van Lanen (2012) distinguished six hydrological drought types (further called HDTs for brevity) by studying drought propagation processes in five contrasting catchments. These are *classical rainfall deficit drought*, *rain-to-snow-season drought*, *wet-to-dry-season drought*, *cold snow season drought*, *warm snow season drought* and *composite drought* (Fig. 2). From Fig. 2 and Table 1 (upper part), we can infer that for some HDTs anomalies in precipitation are the driver of the hydrological drought development (*classical rainfall deficit drought*, *rain-to-snow-season drought*, *wet-to-dry-season drought*) and for some HDTs anomalies

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in temperature play a more prominent role (*cold snow season drought, warm snow season drought*).

In Van Loon and Van Lanen (2012) we speculated that there might be other HDTs in climate zones that were not studied. Van Loon and Laaha (2014) applied the hydrological drought typology to a selection of catchments in Austria, testing this hypothesis, and discovered hydrological drought events that could not be explained by any of the processes in Table 1 (upper part). These unknown drought types were found in catchments with a pronounced influence of snow and glaciers on the hydrological regime.

In this paper we will define two new HDTs in cold climates and investigate their underlying processes and their socio-economic impacts. We will compare drought propagation processes between different regions with cold climates (the Alpine region and Scandinavia). Furthermore, we present an extensive search for impacts of hydrological droughts related to snow and ice from a collection of different sources (drought impact databases and historical archives). According to our knowledge this is the first time that such an integrated analysis of temperature-related droughts is presented, including a theoretical description, quantitative analysis of causing factors, and qualitative analysis of impacts.

For this research we have two hypotheses, namely (1) that for each region, the occurrence and severity of the new HDTs can be related to meteorological causing factors in specific seasons, and (2) that HDTs in cold climates have had socio-economic impacts in the recent and distant past. After presenting the theory of the new temperature-related HDTs (Sect. 2) we will first investigate hypothesis 1 by quantitatively analysing causing factors of these new HDTs in a number of catchments from two selected study areas (Sect. 3). Hypothesis 2 is investigated by qualitatively studying socio-economic impacts of temperature-related HDTs in the US and Europe in Sect. 4. In Sects. 5 and 6 both the quantitative and qualitative analyses are discussed and summarised.

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2 Temperature-related drought types: theory

The hydrological drought typology (Fig. 2 and Table 1, upper part), developed by Van Loon and Van Lanen (2012), was applied to a selection of Austrian catchments in Van Loon and Laaha (2014). Some drought events were characterised by deficits in the high-flow period: in spring in catchments with a clear snowmelt peak and in summer in catchments with a high percentage of glaciers. This led us to define two new HDTs, namely *snowmelt drought* and *glaciermelt drought* (Table 1, lower part). Their main characteristics are summarised in the following sections.

2.1 Snowmelt drought

A *snowmelt drought* is characterised by a deficiency in the snowmelt discharge peak in spring in snow-influenced basins (Fig. 3a – lower panel). This deficiency is due to a lack of snow accumulation during winter (Fig. 3a – second panel). In spring no distinct precipitation deficit occurs that can explain the discharge deficit (Fig. 3a – third panel). The processes resulting in deficiencies in snow accumulation during winter are, for example, a lack of precipitation during winter (Fig. 3a – third panel) or no buildup or partial melt of the snow cover due to high winter temperatures (Fig. 3a – upper panel). Consequently, the normal snowmelt peak is below normal or completely absent. Because discharges are normally high during the spring snowmelt season, deficit volumes of *snowmelt droughts* are generally high as well (Van Loon and Laaha, 2014).

Snowmelt droughts are multi-season droughts, because meteorological conditions in one season (winter) cause hydrological drought in another season (spring). This shows the difference with a *classical rainfall deficit drought* in which a precipitation deficit causes a hydrological drought directly or with a small lag (Van Loon and Van Lanen, 2012). In a *snowmelt drought* the influence of a precipitation deficit is delayed due to storage in the snow pack. Furthermore, the interaction between temperature and precipitation plays an important role in determining snow accumulation, melt, refreezing, infiltration, runoff, etc.

A *snowmelt drought* differs from a *cold snow season drought – type B* (Table 1) in the sense that in the latter the snowmelt peak is only delayed and not lower than normal. Equally, in a *warm snow season drought – type A* (Table 1) the snowmelt peak is only advanced and not lower than normal.

2.2 Glaciermelt drought

A *glaciermelt drought* is characterised by a deficiency in the glaciermelt discharge peak in summer in glacierised basins (Fig. 3b – lower panel), which is not caused by a precipitation deficit of similar magnitude (Fig. 3b – third panel). The most probable explanation for a lack of glacial melt in summer are low summer temperatures (Fig. 3b – upper panel). A deficit compared to the normal seasonal cycle can occur during the whole melt season or only during part of the melt season, for a longer or shorter period. Because discharges are normally high during the summer glaciermelt season, deficit volumes of *glaciermelt droughts* are generally high as well (Van Loon and Laaha, 2014), just as for the *snowmelt drought*.

In contrast to *snowmelt drought*, the *glaciermelt drought* is a within-season drought, because the meteorological conditions causing the drought and the drought event itself occur in the same season (summer). A *glaciermelt drought* can be confused with a *cold snow season drought – type B*, but a *cold snow season drought* is related to a delay of a (snow) melt peak, rather than a mutation of the (glacier) melt peak itself.

3 Temperature-related drought types: causing factors

We investigated the processes underlying the development of the newly-defined HDTs. We quantified the relative importance of different climate drivers (P and T) in different seasons on the development of these drought types. In this section, we describe the data, methods and results of our quantitative analysis of the causing factors of *snowmelt drought* and *glaciermelt drought* in Austria and Norway.

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3.1 Study areas

The thirteen Austrian and eight Norwegian catchments used in this study vary in climate and catchment characteristics (Fig. 4 and Table 2). The Austrian catchments are clustered according to geographical and thematic similarities by Gaál et al. (2012) and Haslinger et al. (2014) into four clusters Gailtal, Mühlviertel, Hoalp and Ötztal. Gailtal and Mühlviertel are low alpine and low mountain range clusters, respectively, with a distinct snowmelt discharge peak in spring. Average winter temperatures are close to 0 °C (respectively -5 and -1 °C). Clusters Hoalp and Ötztal consist of steep, glaciated alpine catchments with mainly summer discharge. In the Norwegian study area, four of the catchments are subcatchments of the Glomma basin in southeast Norway, in a typical subarctic climate with short summers and long winters. Akslen is the only glacier-influenced catchment in this area. Other glacierised catchments in Norway are Lovatn, Nigardsbrevatn, Gloppenelv, and Skjerdalselv. They are located in the mountainous regions of southwestern Norway. Glacier cover in the selected catchments ranges between 12 and 75 % (Table 2).

3.2 Data

Observations of discharge (Q), air temperature (T) and precipitation (P) and hydrological model simulation of snow water equivalent (SWE) were analysed for identification of possible key variables in *snowmelt droughts* and *glaciermelt droughts*. Daily P and T data were taken from a gridded dataset, both in Norway (Mohr and Tveito, 2008) (available from www.senorge.no) and in Austria (Haslinger et al., 2014), corrected for elevation differences between the grid cell and the catchment.

Model simulations were obtained from a semi-distributed conceptual hydrological model, similar in structure to the HBV model (Bergström, 1995). For Austria, a version of the HBV model was used that is developed by the Technical University in Vienna. A detailed description of the structure of this model is presented in Parajka et al. (2007). Snow accumulation is determined by air temperature thresholds used for splitting

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precipitation into snowfall, rainfall and melt, where the rate of snowmelt is calculated by a simple degree-day approach. The model was successfully applied in numerous regional studies in Austria in the past (e.g. Parajka and Blöschl, 2008; Merz et al., 2009). More details on the modelling setup, model input preparation and automatic model calibration procedure used in this study are presented in Merz et al. (2011). The Nash–Sutcliffe values for the Austrian catchments used in this study ranged between 0.6 and 0.9 with an average of 0.8. Nash–Sutcliffe values based on the logarithm of discharge were even higher.

For Norway, the “Nordic” HBV version was applied (Sælthun, 1996). Just as in the Austrian HBV version, snowfall is calculated when air temperature is below a threshold temperature and snowmelt is calculated with a degree-day approach. In both versions, glaciers are not modelled explicitly, because no validation data of glaciers were available. However, since we only used SWE from model output and not groundwater storage or simulated discharge, this was not regarded as a major issue. Nash–Sutcliffe values for the Norwegian catchments used in this study ranged between 0.56 and 0.9 with an average of 0.8. Nash–Sutcliffe values based on the logarithm of discharge were slightly lower.

3.3 Data analysis methods

For the analysis of the causing factors of *snowmelt droughts* anomalies in P and T in the snowmelt period and in the preceding snow accumulation period were needed and for *glaciersmelt droughts* anomalies in P and T in the glaciersmelt period and in the preceding snow accumulation period are relevant. The period of snow accumulation and snow/glacier melt are highly variable between catchments, dependent on location (Fig. 4) and altitude (Table 2). Therefore, we defined the seasons per catchment based on long term averages (regimes) for that specific catchment. In this way, the snow accumulation season is the period with below zero air temperature (like in Feyen and Dankers, 2009) and positive snow accumulation. This season is further called “winter”. For the snowmelt season, a similar approach was followed, starting at the end of winter

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(above zero air temperature and negative snow accumulation) and ending after the melt peak in discharge. This season is further called “spring”. The glaciermelt season is difficult to define based on processes because in glacierised catchments the snowmelt peak and glaciermelt peak cannot be distinguished. Therefore, we chose to use the definition of meteorological summer (June-July-August; JJA) for the glaciermelt period. This period we call “summer”. This resulted in a start of winter between 11 October and 5 December, an end of winter and start of spring between 1 March and 8 May, and an end of spring between 20 April and 21 June. Winter duration was on average 160 days (95–209 days) and spring duration 40 days (24–57). Summer duration was for all catchments 92 days. More information on this selection procedure and the regime plots are given in Ploum and Van Loon (2014).

For all seasons, the precipitation sum (e.g. P_{winter}), air temperature average (e.g. T_{spring}), and discharge sum (e.g. Q_{summer}) were calculated. Additionally, for the winter season, maximum snow accumulation (SWE_{winter}) and the number of days with air temperature above zero degrees ($PlusZero$) were calculated. To allow easy comparison between catchments, season sums and averages were standardised by dividing by the long-term mean of the variable for the specific catchment, resulting in dimensionless numbers with values around 1. If needed, T data was systematically increased (with 10°C in Austria and 15°C in Norway) before standardisation to avoid negative scales due to below zero winter averages and positive means or vice versa.

For visual inspection standardised spring and summer discharge (Q_{spring} and Q_{summer}) were plotted against standardised seasonal T and P including marked droughts. To quantify relations between discharge with a certain variable (e.g. T_{winter}), Pearson’s correlations R were calculated for each catchment and for each cluster of catchments (snow-influenced and glacier-influenced catchments in Austria and Norway). We also tested Spearman correlations, but that gave similar results.

From the time series of precipitation and discharge we identified droughts with the widely-used threshold level approach (Hisdal et al., 2004; Fleig et al., 2006; Van Loon, 2013), defining a drought when a variable falls below a pre-defined threshold. To reflect

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seasonality we used a variable threshold based on the 80th percentile of the flow duration curve of a 30 days moving window (Beyene et al., 2014). In this way we defined drought as water availability below the normal seasonal cycle. Drought deficit was calculated as the sub-threshold volume (Van Loon, 2013) as measure of the severity of an event. Drought deficit values were also standardised by dividing by mean drought deficit for the specific catchment.

We applied the typology of Van Loon and Van Lanen (2012), based on the time series of precipitation, air temperature, simulated snow and discharge for all catchments. Most of the drought events that could not be classified with the existing typology, were assigned to the new drought types *snowmelt drought* or *glaciermelt drought* based on the dominant propagation processes (Sect. 2 and Table 1 – lower part). A drought event was classified as *snowmelt drought* if the centre point of the drought was within the snowmelt period (spring) and no precipitation deficit in spring occurred with similar magnitude as the discharge deficit. A drought event was classified as *glaciermelt drought* if the centre point of the drought was within the glaciermelt period (summer) and no precipitation deficit in summer occurred with similar magnitude as the discharge deficit.

3.4 Results

In both Austrian and Norwegian catchments, most drought events (between 35 and 65 % of all events per catchment) were classified as *classical rainfall deficit drought* as was expected from the analysis in contrasting European catchments by Van Loon and Van Lanen (2012). No *wet-to-dry-season drought* were found, as seasonality in precipitation is negligible in these catchments compared to monsoon climates or Mediterranean climates. *Rain-to-snow-season drought*, *cold snow season drought* and *warm snow season drought* occurred in all catchments, on average about 9, 8 and 6 % of all drought events, respectively. The new HDT *snowmelt drought* occurred regularly in the Austrian clusters Gailtal and Mühlviertel and in the Norwegian Glomma catchments, ranging from 7 % of all drought events in one of the Mühlviertel catchments up to

28 % for one of the Glomma catchments with an average of 13 %. *Glaciermelt droughts* occurred regularly in the Austrian clusters Hoalp and Ötztal and in the central Norwegian catchments, with percentages around 20 % they were slightly more common than *snowmelt droughts*.

5 Visual analysis of scatterplots of discharge against possible causing factors (Figs. 5–8) revealed different patterns in Austria and Norway. *Snowmelt droughts* in Austria seem to be caused by a combination of factors (Fig. 5). For most events winter temperatures were above average (for about 70 % of all *snowmelt drought* events), winter precipitation was below average (for about 75 %), spring temperature was above average (for about 65 %), and spring precipitation was below average (for about 80 %).
10 The most extreme events mainly cluster in the low winter precipitation graph (Fig. 5 – topright panel). Additionally, a clear orientation is visible in all years (grey circles) indicating that spring discharge decreases (increases) with increasing (decreasing) temperature (winter and spring) and decreasing (increasing) precipitation (winter and spring).
15

Snowmelt droughts in Norway show a completely different pattern (Fig. 6). The meteorological conditions in spring do not seem to have any influence on spring discharge or droughts in spring (Fig. 6 – lower panels). Half of the *snowmelt droughts* in Norway have above normal T_{spring} and P_{spring} and half have below normal values. Also winter temperature preceding *snowmelt droughts* in Norway is indifferent (around 50 % above and below; Fig. 6 – topleft panel). Only winter precipitation shows a significant influence of decreasing discharge with decreasing precipitation and almost all *snowmelt drought* events (more than 90 %) were preceded by below-average winter precipitation (Fig. 6 – topright panel).
20

25 All *glaciermelt drought* events in Austria have below-average summer temperature (100 % of all *glaciermelt drought* events; Fig. 7 – bottomleft panel) and the severity of *glaciermelt drought* events increases with decreasing summer temperature. Summer precipitation plays a role as well (Fig. 7 – bottomright panel). Half of the *glaciermelt drought* events had above average summer precipitation, but these were events with

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relatively low deficit volumes. The more severe events (more than 5 times the catchment's average drought deficit) all had below-average P_{summer} . This points to a combined effect of a lack of glacier melt and a precipitation deficit. Meteorological conditions in the winter preceding *glaciermelt drought* events in Austria have less influence on droughts in summer. An orientation of decreasing summer discharge with decreasing winter precipitation can be observed, but interestingly severe *glaciermelt drought* events have above average winter precipitation (Fig. 7 – topright). *Glaciermelt droughts* in Austria also seem to have below-average winter temperatures preceding the event (90 % of all *glaciermelt drought* events; Fig. 7 – topleft). The physical process behind this pattern is unclear, but might be related to below-normal summer temperatures.

Glaciermelt droughts in Norway behave similarly in the sense that the influence of low summer temperatures is dominant (more than 90 % of all *glaciermelt drought* events had below-normal T_{summer} ; Fig. 8 – bottomleft panel). However, the relation of increasing drought severity with decreasing summer temperature, as found for the Austrian catchments, was not as well visible. Summer precipitation (50–50 %), winter precipitation (50–50 %) and winter temperature (35 % below-average vs. 65 % above-average) do not seem to be causing factors for *glaciermelt drought* development in Norway.

Table 3 quantifies the relationships observed in Figs. 5–8. Correlations above 0.5 have only been found in Austria (Q_{spring} and P_{spring} , Q_{summer} and T_{summer} , Q_{summer} and P_{summer}). For *snowmelt droughts* we expected a relationship with SWE or PlusZero, but neither Austria nor Norway showed a significant relationship (Table 3). Correlations with drought deficit in stead of discharge were also calculated, but did not result in any significant relationship.

When calculating the correlations per catchment independently we found interesting patterns. The correlation between Q_{summer} and T_{summer} increased with increasing glacier cover (Fig. 9): catchments with low glacier cover had a negative correlation because a high temperature is related to low Q due to high evapotranspiration, catchments with medium glacier cover had no correlation, and catchments with high glacier

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cover had positive correlation because a high temperature is related to high Q due to high glacier melt. The correlation between Q_{summer} and P_{summer} did not show any increase or decrease with increasing glacier cover, but it does confirm the difference between Norway and Austria, with Austrian catchments showing an effect of precipitation on glacier melt droughts (Fig. 9).

For *snowmelt drought* we could not find a catchment characteristic that similarly explained the differences between catchments. Both correlations with P and T did not show any clear relation with long-term average temperature or snow cover (Fig. 10).

4 Temperature-related drought types: socio-economic impacts

Temperature-related drought types, like *snowmelt drought* and *glacier melt drought*, but also *rain-to-snow-season drought*, *cold snow season drought* and *warm snow season drought* (see Table 1), are expected to have various socio-economic impacts. In the regions used in the first part of this study, Norway and Austria, for example the winter of 2013–2014 was very warm and dry, resulting in wildfires in Norway¹ and lack of snow in ski resorts in Austria². In Norway also the severe *rain-to-snow-season drought* in 2002–2003, can be found in media sources impacting hydropower production and drinking water supply³.

Descriptions of the socio-economic impacts of droughts, in the media or in government reports, are an important source of information. They can contribute to the understanding of the occurrence, severity and spatial distribution of temperature-related drought types. In this section, we present the data, methods and results of our qualitative assessment of drought impacts. Unfortunately, the consistent collection, accessibility, and consolidation of these data sources is still in its infancy. Therefore, not enough

¹robertscribbler.wordpress.com/2014/01/30

²www.planetski.eu/news/5896

³http://www.nve.no/en/Water/Hydrology/Flood-and-drought/

information was available to do this analysis for Norway and Austria, but we extended our study to the entire Europe and the USA.

4.1 Data and methodology

Impacts of drought were not systematically collated before the last decade. In 2005 the National Drought Mitigation Center (NDMC, Lincoln, Nebraska) launched the Drought Impact Reporter (DIR), which was the USA's first comprehensive database of drought impacts (NDMC, 2014). Recently, the European Drought Observatory (EDO) has started to collect ongoing drought impacts in the European continent (JRC, 2014) through an automatic search of a wide range of sources. Parallel to this the DROUGHT-R&SPI project has developed a European Drought Impact report Inventory (EDII), which is being filled with information on thousands of drought impacts that occurred in Europe, mainly over the last decades (Stahl et al., 2012). In this study we summarise drought impacts associated with temperature and snow conditions from: (i) historical archives, and (ii) the drought impact databases EDII and DIR.

4.1.1 Historical archives

Historians provide information on drought impacts beyond the instrumental record (e.g. earlier than mid 19th century when a more systematic monitoring of precipitation and river flow started). Different written sources are consulted and the information usually is hidden in the margins of the documents (e.g. Camuffo et al., 2010; Garnier, 2010a, b; Garcia de Cortazar-Atuari et al., 2010; Garnier et al., 2011). Diaries drafted by private persons (priests, middle-class persons, aristocrats), municipal chronicles and the archives of the Roman Catholic Church are particularly useful. Indications for drought events in the archival information are for instance: (i) phenology (state of the vegetation, fires), (ii) food prices on markets, and (iii) elements of social expression (scarcity, riots, religious processions pro pluvia) that sometimes were combined with visual observations (water marks on bridges, ferry houses).

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Up to the 17th century, droughts observed by historians are both “socio-economic drought” and “hydrological drought” (Fig. 1). Archives report low-water marks of rivers, death of fish, interruption of navigation, processions “pro pluvia”, epidemics, etc. However, from 1750, historians can access instrumental data produced by the first scientific and meteorological European societies like the Royal Society of London, the Royal Society Medicine of Paris or the “Societas Meteorologica Palatina” of Mannheim (Germany). These instrumental data allow historians to include “meteorological drought” (Fig. 1) thanks to precise daily meteorological observations.

In this study, we extracted information on historical drought events related to anomalies in temperature or snow from French and English archives for the period 1500–1925. The descriptive information of each event has been converted into a severity class (Table 4) and a HDT.

4.1.2 Drought impact report database (EDII)

A pan-European Drought Impact report Inventory (EDII) has been set up in the framework of the EU DROUGHT-R&SPI project (Fostering European Drought Research and Science-Policy Interfacing, www.eu-drought.org). An online database infrastructure with a standardised input interface has been created on the website of the European Drought Centre (www.geo.uio.no/edc). It allows submission of impact reports for the purpose of cross-disciplinary research on drought vulnerability and risk. The inventory contains data from the period 1904–2011 and it reveals a large variety of drought impacts and response measures across Europe (Stahl et al., 2012). Currently, EDII stores 4245 drought impact reports (state: 7 July 2014) and this number is still increasing. For this study, we queried the database for all years, all countries, all impact categories and all sources. Afterwards, we searched for the keywords snow, glacier, frost, winter and freeze and did a visual selection of drought events based on their description. We classified the selected drought events in HDTs.

4.1.3 Drought impact reporter (DIR)

The National Drought Mitigation Center has collated impacts from drought impacts that have occurred in the USA since 2004. In total 17 195 impacts have been reported in the last ten years (state: 7 July 2014). Impact reports come, for instance, from media, Community Collaborative Rain, Hail and Snow network (CoCoRaHS), National Weather Service and private persons. Different categories have been distinguished, e.g. agriculture, business and industry, energy, fire, plants and wildlife, tourism and recreation, water supply and quality. For this study, we again used all impact categories and all sources. We queried the database for the keywords snow, glacier, frost, and winter. Results were so numerous that visual selection of events and application of the hydrological drought typology were not possible. Therefore, only a statistical analysis was performed on the DIR impacts.

4.2 Results

4.2.1 Historical archives

Historical archives in England and France covering the period 1500–1925 were studied to obtain information on drought connected to snow processes. Table 5 provides selected drought events that mention terms as snow, frost, freezing conditions, exceptionally cold or warm weather during the winter season. The estimated duration varies between 2 months and 1 year. The events are sometimes preceded by a dry summer or continue into the following summer, which results in a more severe drought event (e.g. the 1614 drought in Britain and the 1719 drought in Rhône-Alpes, Table 5). The severity class of all selected drought events ranges from 3–5 (Table 5), meaning negative impacts on navigation and water resources due to below-normal water levels up to exceptionally dry conditions resulting in water shortage, forest fires, and food problems (Table 4).

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A bit more than half of the reported events are classified as *cold snow season drought* (Table 5 and Fig. 11). The remaining events had above normal winter temperature and were therefore classified as *warm snow season drought*. All *cold snow season droughts* were of subtype C and all *warm snow season droughts* of subtype B, because winter temperatures in France and England are normally around zero (Van Loon and Van Lanen, 2012). Unfortunately, this type of archival information was not available for Austria and Norway (the case study areas used in Sect. 3) or for other regions with winter temperatures far below zero, which could indicate historical occurrence of the other *cold and warm snow season drought* subtypes, *rain-to-snow-season drought*, *snowmelt drought*, and *glaciermelt drought*. Nevertheless, the impact reports for France and England show that negative impacts of drought due to anomalies in temperature have already been documented for centuries.

4.2.2 Drought impact databases

The keywords snow, glacier, frost (freeze), and winter were mentioned slightly more than 300 times in the European Drought Impact report Inventory (EDII). The term winter appeared in about 90 % of these selected impact reports. Clearly, not all drought impact reports with the term winter were related to winter processes, for example below-average winter wheat yield could be related to a rainfall deficit in spring. Therefore, we visually selected from these 300 entries the reports that were related to winter processes (anomalies in winter temperature, snow accumulation, etc.). The drought of 1972, for example, was “predominantly a winter and spring drought event. Beginning with low accumulated precipitation from the previous fall, the drought intensified due to low precipitation during the winter. The hydrological drought peak occurred March 1972 and was centred in Poland. According to Bradford (2000) drought in 1972 affected particularly the USSR with extreme low river levels. Alesund and other areas in Norway were affected by water use restrictions because of water shortage in 1972 (Aftenposten 7 March 1972)”. A more difficult one was, for example, the impact report of the 1947

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drought, which occurred in a large part of Europe, amongst others in Romania, which states:

The winter of 1946/1947 was particularly severe, by the spring this led to flooding and this was then followed by one of the driest and hottest summers on record during 1947. Much of central Europe had then suffered lower than normal harvests for three years. In some parts of eastern Europe, such as north-eastern Romania, more than 90 % of the population was suffering from hunger after crop failures. This led to food aid from the US and instigation of the Marshall Plan (Sheffield and Wood, 2011).

Here, a combination of a *cold snow season drought* and a *classical rainfall deficit drought* caused the described impacts. These impact reports were taken into account in this study.

The keyword snow turned up in about 5 % of the entries of the EDII. For example, the 1949 drought in Switzerland is related to snow anomalies:

During the complete hydrological year 1948/1949 streamflows were exceptionally low in Switzerland, which led to a significant drop in hydropower production of about 12 % to a year of normal (average) streamflow conditions. This reduction was a result of a summer drought but also a consequence of unusually low snow resources from the winter period. Already in December 1948 a ban on electrical room heating was imposed, followed by further restrictions (e.g., regarding lighting) in consequence of the extremely dry conditions in January and February. Those restrictions kept in force until the beginning of April (Schorer, 1992).

The visual selection of the 300 impact reports resulted in 30 reports that could be attributed to one of the temperature-related HDTs, representing 15 separate events (many drought events were reported more times in different countries). Figure 11 (lower graph) shows these selected drought events retrieved from the EDII that were related to temperature and snow. Reported impacts are for example strongly reduced tree

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growth and reduced crop yields due to cold spring, higher energy prices and energy use restrictions due to deficits in hydropower production, water use restrictions due to low flows, low reservoir levels and dry wells.

The drought events have different underlying processes and are classified as *cold snow season drought*, *snowmelt drought*, and *rain-to-snow-season drought*. The selected drought impacts show that these HDTs have occurred often in the last century. In 40 % of the selected drought impacts a combination of HDTs occurred (Fig. 11). Especially, the combination of a *snowmelt drought* in spring and a *rain-to-snow-season drought* in summer and winter resulted in very severe socio-economic impacts. Also a *cold snow season drought* followed by a *snowmelt drought* was reported to have a large effect on reservoir levels and, consequently on drinking water and electricity production. Some temperature-related drought events occurred in a large region (e.g. the droughts in 1947, 1973 and 1996), but their impacts are diverse, partly because of the different physical circumstances depending on local temperature and snow thresholds (even resulting in different HDTs in different parts), and partly because sectors are impacted differently in different regions because of socio-economic circumstances.

Additionally, we queried the US Drought Impact Report (DIR) with the same keywords as the EDII. The keywords snow, glacier, frost and winter were reported slightly more than 1300 times in the impact database coordinated by the National Drought Mitigation Center (NDMC, 2014). Each of these impacts was classified into one or more categories. Most temperature-related drought impacts were reported with the category “Agriculture”, about 3.5 % of all impacts in the DIR and 57 % of the temperature-related impacts (Table 6). However, most of these impacts were again related to winter wheat and not always to a snow-related drought in winter. Other important categories are Water supply and quality (mentioned in 27 % of the impacts), Plants and wildlife (26 %), and others (e.g. Society and Public health; 28 %). Most temperature-related impacts are reported by the media and the CoCoRaHS, but also many reports are from local farmers.

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Many temperature-related drought impact reports in DIR are from the previous winter (2013–2014) when it was extremely cold in large parts of the USA. These impacts relate to a *cold snow season drought*. In other parts of the country (e.g. California) the warm and dry winter resulted in a *warm snow season drought* with impact reports on wildfires, water use restrictions, closing of ski resorts (“Snowfall has not been so low at the 25 ski resorts in California since the 1971–1972 season.”), low reservoir levels and irrigation problems. The 7 impacts with the keyword “glacier” (Table 6) were all related to drought events in Glacier County and Glacier National Park. From the description it was unclear whether the mentioned drought impacts had any relation with temperature, snow or glaciers.

In the DIR also some positive events can be found, for example “Oregon Department of Transportation has saved money on snow removal” in January 2014 and a report of “less foundation damage in Sioux City, Iowa, due to little moisture in soil” on April 2014. (“Below normal precipitation in Sioux City this winter reduced the number of “frost heave” incidents this spring. Fluctuating freezing and thawing events can lead moisture to be drawn up to the soil surface when the ground finally thaws in the spring and can damage concrete basements.”) In the EDII only negative consequences of drought are included (Stahl et al., 2012).

5 Discussion

In the quantitative analysis of causing factors of temperature-related droughts in Norway and Austria (Sect. 3) we found patterns in scatterplots of discharge vs. meteorological variables per region, but these patterns were not confirmed by the statistical analysis. A reason for that can be that severe and minor droughts are equally taken into account in the statistical analysis, while in the scatterplots the eye focuses on the more severe drought events. In Ploum and Van Loon (2014) significant statistical relationships were found when selecting the eight most severe drought events in glacierised

catchments, with T_{summer} being the most important explaining variable for Q_{summer} and *glaciersmelt drought* deficit.

Another reason can be that differences between catchments are too large to cluster the catchments and derive general relationships per region. Ploum and Van Loon (2014) found, for example, that in Gailtal (Fig. 4 and Table 2) droughts in the snowmelt period were related to P and T in spring, while in Mühlviertel (Fig. 4 and Table 2) winter conditions (snow accumulation and occasional melt due to high T in winter) had more influence. This shows that the interaction between meteorological variables in different seasons is complex and can hardly be generalised. Therefore, processes underlying drought types should ideally be studied per (small) catchment. The disadvantage of that is that droughts do not occur regularly and time series are often too short to detect enough drought events for statistical analysis. In this study, we performed a first order statistical analysis. More elaborated analyses of the causing factors of drought types in different regions and climates, might be an interesting next step.

Also uncertainties in data can be (part of) the reason for limited statistical relationships. We used well established datasets of catchments in Austria (Parajka and Blöschl, 2008; Merz et al., 2011; Haslinger et al., 2014) and Norway (Mohr and Tveito, 2008; Engelhardt et al., 2012; Fleig et al., 2013) that were thoroughly quality-checked and used in other scientific studies. However, measurement errors, uncertainties in the estimation of gridded data from station data, and issues of representativity can still occur, especially in mountainous catchments. Furthermore, in drought analysis and classification subjective choices cannot be avoided. For applying the hydrological drought typology unfortunately no automatic procedure is available (yet).

Regimes of snowmelt and glaciersmelt are different in regions around the world and even differ per catchment and within catchment, because altitude influences the temperature regime and therefore snow accumulation (Marsh and Woo, 1981). Weingartner et al. (2013) showed this variability by presenting a diagram with the effects of seasonality in precipitation and increasing snow cover on the discharge regime. In this research we only compared driving processes for *snowmelt drought* and *glaciersmelt*

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drought under Alpine and Scandinavian conditions. For Alpine basins our results correspond to the conclusions in Collins (1987) and Chen and Ohmura (1990), where annual discharge showed a clear year-to-year variation in relation to summer temperature and this relation was stronger in basins with a higher percentage glacier cover. Also the larger spread in the relationship above 30 % ice cover found by Collins and Taylor (1990) for Alpine basins is reproduced in this study (ca. 40 % in Fig. 9). For Norway the importance of winter precipitation is confirmed by e.g. Nesje (2005). Engelhardt et al. (2014) found that for a number of glacierised catchments in Norway strong correlations with annual discharge changed from annual and winter precipitation for the most maritime glacier to summer temperature for the most continental glacier.

The results of this study are too specific to be directly transferable to other regions with cold climates. For example, in part of the Himalayas, summer precipitation is more important than summer temperature in determining summer discharge, because of the summer monsoon (Thayyen and Gergan, 2010). In this region *glaciermelt droughts* are probably very rare as discharge is hardly affected by summer temperature. Almost all summer droughts in this area are probably *classical rainfall deficit droughts* (Table 1). Spring discharge in the western Himalayas is mainly explained by winter precipitation (Pal et al., 2013), so *snowmelt droughts* in western Himalaya might have similar causing factors as *snowmelt droughts* in Norway. Snowmelt contributions to discharge differ, however, widely over the Himalayas: from up to 50 % in the far western catchments, 25 % in far eastern catchments, and less than 20 % elsewhere (Bookhagen and Burbank, 2010).

Glacierised catchments in North-America often show behaviour comparable to glacierised catchments in Europe. For example, Naz et al. (2014) found that for the Bow catchment in Canada glaciermelt contribution to summer discharge is between 15 % in cold years and 47 % in warm and dry years. In USA, Hall et al. (2012) found a strong relationship between spring discharge and snow covered area in winter.

In tropical regions with glaciers, such as in the tropical Andes, relationships between meteorological conditions and droughts are different than those in the regions

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described above. Due to year-round constant temperatures there is no seasonality in glaciermelt (e.g. Juen et al., 2007). Precipitation will therefore have a larger effect on interannual variation in discharge. The opposite is the case for Antarctica with 100 % glacier cover and a strong relationship with temperature. For example, Doran et al. (2008) found up to 6000-fold increase in annual streamflow in a warm year compared to a cold year. For each of these regions, similar analyses as in this paper can be performed to investigate the occurrence and causing factors of *snowmelt droughts* and *glaciermelt droughts*.

In scientific literature, no studies were found that focus specifically on the causing factors of a lack of snowmelt or glaciermelt. The opposite, however, is investigated often: snowmelt floods, for example the Pacific Northwest flood of 1996 (Marks et al., 1998), and record glaciermelt in warm summers, for example in 2003 in Europe (Paul et al., 2005; Koboltschnig et al., 2009).

In this study we assumed no major trends in hydrometeorological variables. That assumption does not completely hold. We noticed that in some catchments *snowmelt drought* events were clustered in the end of the period. Expected increasing temperatures in the future will probably lead to more *snowmelt droughts* and less *glaciermelt droughts*. Climate change is also expected to change the relative influence of temperature and precipitation in different seasons (Barnett et al., 2005; Stewart, 2009) and, consequently, the governing processes underlying drought types. An interesting follow up to this research would be an investigation of changes in the distribution over drought types and changes in causing factors per drought type over time. As was also mentioned before in Van Loon and Van Lanen (2012), the effects of climate change on HDTs is distinctly different between regions with winter temperatures around zero and regions with winter temperatures far below zero.

Knowledge of the causing factors of drought in spring and summer in snow-influenced and glacier-influenced basins can be useful for drought forecasting. For example, in catchments where winter conditions are dominant for spring/summer drought development, prediction of winter conditions is crucial. Recent developments in making

winter meteorological predictions more accurate (Scaife et al., 2014) are also promising for multi-seasonal drought forecasting. However, more research is needed before this is possible.

The (mostly qualitative) analysis of socio-economic impacts of temperature-related droughts in Europe and the USA (Sect. 4) is limited, mainly because the data sources are not complete, not in time nor in space. For this study, historical archives were, for example, only available from France and the UK. The EDII is Europe-wide, but does have a bias towards certain countries (e.g. Germany) (Stahl et al., 2012). Furthermore, both EDII and DIR are recent databases and are still in the process of being filled. Currently, entries are biased towards later years. This type of information also suffers from language issues, at least in Europe compared to the USA. Therefore, a quality check on drought impact reporting or drought impact media searches is always needed, which makes collecting this data very time-consuming.

There are some initiatives for extending drought impact databases. The European Drought Observatory (EDO) has started to collect ongoing drought impacts (JRC, 2014) and the UCL Global Drought Monitor is in process of adding a Drought Impact Reporter. These initiatives provide opportunities to repeat the analysis of impacts of temperature-related droughts with more information. Because drought is an extreme event with a low frequency of occurrence it is important not only to look at current drought impacts, but also to put some effort in collecting historical impact information, both from the recent (last century) and distant past.

From the impact reports we could see that most severe impacts occur after a combination of a number of (different) drought types. For example a *cold snow season drought* in winter and spring followed by a *classical rainfall deficit drought* in summer is a devastating combination for crop production. The combination of the *rain-to-snow-season drought* and a *snowmelt drought* causes record low water level in rivers, lakes and reservoirs. This makes it important not only to look at the frequency of occurrence of HDTs, but also at their timing and sequence.

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Both in the historical analysis and in the impact databases no *glaciers melt droughts* were found. There can be several reasons for that: (i) *glaciers melt droughts* do not occur, (ii) *glaciers melt droughts* do not have socio-economic impacts, (iii) *glaciers melt drought* impacts are not reported in EDII and DIR, because there is a lack of entries from glacierised regions, and in developed countries (like Switzerland) impacts are compensated by large storage reservoirs, (iv) *glaciers melt drought* impacts are not reported because a lack of glacier melt is not called a drought in public discourse and newspapers. We did not find *glaciers melt droughts* in the historical archives either, but, as mentioned before, the historical archives were not investigated in countries with severe winters, continuous snow accumulation, and glaciers (e.g. the Alpine region or Scandinavia).

The documented impacts in EDII cluster towards the end of the investigated period (Fig. 11). In contrast to our conclusion from the quantitative analysis (see above), this is likely not related to effects of climate change, but mainly a reporting and documentation bias. The effect of climate change on drought impacts can only be investigated if numbers of drought impact reports in the databases are significantly higher.

6 Summary and conclusions

In this paper we investigated hydrological droughts related to temperature anomalies and anomalies in snowmelt and glacier melt. We added two new hydrological drought types to the hydrological drought typology developed in Van Loon and Van Lanen (2012). A *snowmelt drought* is a deficiency in the snowmelt discharge peak in spring in snow-influenced basins and a *glaciers melt drought* is a deficiency in the glacier melt discharge peak in summer in glacierised basins.

From a detailed analysis of meteorological conditions related to *snowmelt droughts* and *glaciers melt droughts* in 11 snow-influenced and 12 glacierised catchments in Austria and Norway, we found that possible causing factors are different in Austria and Norway. In Austria, *snowmelt droughts* are related to warm and dry winters, but also

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spring conditions seem to have an effect. In Norway, winter precipitation is the dominant factor in explaining *snowmelt droughts*. All *glaciermelt drought* events in Austria and almost all in Norway had below-average summer temperature. In Austria below-average summer precipitation was additionally important for the most severe drought events, whereas it did not play a role in Norway. Only the effect of summer temperature and precipitation on *glaciermelt drought* in Austria could be confirmed with statistical analysis. For Norway and for the other drought types and meteorological conditions no significant statistical relationships were found.

Our hypothesis that for each region occurrence and severity of the new hydrological drought types can be related to meteorological causing factors in specific seasons was partly confirmed and partly rejected. We did find differences in occurrence and severity for drought types in Austria and Norway and could visually related them to meteorological conditions in the seasons preceding and at the time of the drought event, but these relationships were not always statistically significant. In other snow or glacier-influenced regions around the world the balance between temperature and precipitation in winter, spring and summer can be different resulting in different (combinations of) causing factors for *snowmelt droughts* and *glaciermelt droughts*. This can be investigated using the type of analysis presented in this paper. This is especially interesting in the light of the effects of climate change.

In the last part of this paper we investigated whether temperature-related drought types were of any relevance to socio-economic factors using both historical archives and recent drought impact databases. Many impacts were found for various temperature-related drought types. *Cold and warm snow season droughts* were abundant in historical archives of the UK and France in the period 1600–1800. *Cold snow season droughts*, *snowmelt droughts* and a number of combined temperature-related droughts were found in the European Drought Impact report Inventory (EDII) in the period 1925–2011. The keywords snow, glacier, frost (freeze), and winter were mentioned over 300 times in the EDII and over 1300 times in the US Drought Impact Reporter (DIR). In the DIR the dominant categories were Agriculture, Water supply and quality,

and Plants and wildlife. The EDII reports were visually selected and finally represent 15 distinct drought events that mainly impacted hydropower production and crop yield in various countries in Europe.

Our second hypothesis that hydrological drought types in cold climates have had socio-economic impacts in the recent and distant past, was mostly confirmed. Only for *glaciers melt droughts* no related socio-economic impacts were found. This is likely to be caused by a reporting bias (lack of glacierised areas in databases, other terms used to describe glacier melt deficiency), so hopefully continuing efforts to improve and extend drought impact databases and historical drought research will also provide information on the socio-economic impacts of *glaciers melt droughts*.

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Table 2. Catchment characteristics of selected catchments in Austria and Norway, per cluster (min–max per catchment).

cluster (no. of catchments)	period of sim.	area [km ²]	elevation [m]	mean annual air temperature [°C]	mean annual precipitation [mm]	glacier cover [%]
Gailtal (4)	1976–2008	140–940	491–2734	2.8–5.1	1260–1430	0
Hoalp (2)	1976–2008	40–65	1494–3560	–0.5–0.3	1420–1430	27–42
Mühlviertel (4)	1976–2008	120–255	496–1346	7.0–7.4	930–1120	0
Ötztal (5)	1976–2008	60–785	952–3770	–2.2–0.6	1090–1110	17–43
Glomma (4)	1958–2013	120–1830	170–2460	–3.1–1.7	700–960	0–12
Central-Norway (4)	1958–2013	24–235	50–2070	–0.7–2.5	2310–5270	19–75

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Table 3. Correlation between Q_{spring} and possible related meteorological factors for *snowmelt drought* and between Q_{summer} and possible related meteorological factors for *glaciersmelt drought*.

Meteorological variable	Hydrological variables			
	Q_{spring} Austria	Q_{spring} Norway	Q_{summer} Austria	Q_{summer} Norway
Twinter	−0.178	−0.342	0.26	0.205
Pwinter	0.377	0.236	−0.039	0.166
SWEwinter	0.266	0.02	−0.032	0.126
PlusZero	0.239	−0.092	0.005	0.184
Tspring	−0.105	0.325		
Pspring	0.549	0.135		
Tsummer			0.537	0.417
Psummer			0.767	0.07

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Table 4. Severity classes and description for 16th–19th century drought events (Garnier, 2010a, 2014).

Index	Description
5	exceptional drought: no possible supply, shortage, sanitary problem, very high prices of wheat, forest fires
4	severe low-water mark: impossible navigation, layoff of wheat mills, search for new springs, forest fires, death of cattle
3	general low-waters (difficulties for navigation) and water reserves
2	local low-waters of rivers, first effects on vegetation
1	absence of rainfall: rogations, evidences in texts
–1	insufficient qualitative and quantitative information but the event is kept in the chronological reconstruction

Table 5. Selected drought events in England and France that are connected to anomalies in winter temperature, snow, and/or frost.

Site	Year	Starting date	Ending date	Remark	Relative duration	Severity index	Source	Typology
Britain	1614	Jan	Aug	It began to snow and freeze on 16 Jan, and the frost continued unbroken, with occasional snow, until 7 March, by which time the depth of snow was greater than in any other year within "living memory". When the thaw came there was a great flood, but without rain, and the drought continued until 20 August. Great scarcity of hay and corn.	240 days	5	Annals of Cambridge, volume 3	cold snow season drought – type C
Britain	1691			Rainfall were only 72 % of normal, or less than 3/4. Autumn was an extraordinary dry and hot season, and winter was exceeding dry and calm; "no rain for many months past".	150 days	3	Annals of Cambridge, volume 3	warm snow season drought – type B
Rhône-Alpes	1719	Jan	Jul	The drought is preceded by very dry summer, 1718 and without rain. The winter, 1719 is very soft and dry (less than 2 frost days). The agricultural consequences are important: no hay, the harvest of the wheat begins on 12 June, almost no vegetables in gardens. The Loire and the Rhône are very low and the epidemics (bad quality of water) spread.	1 year?	5	Archives municipales de Lyon, BB 292	warm snow season drought – type B
Britain	1731	Dec	Oct	It opened with a great frost and some snow in winter, but the summer was hot, especially September, which was also exceptionally dry.			Annals of Cambridge, volume 3	cold snow season drought – type C
Britain	1740	Dec 1739	Jul 1740	The drought began, as often, with a frost. The Thames was frozen over in December 1739, and a famous frost-fair was held on the river from Christmas Day of that year until 17 February 1740. A printing-press was set up on the ice, on which mementoes of the great frost were printed. The winter, besides being exceptionally cold, was very dry; archives declare "not 3 h continued rain from the beginning of November until the following April and the drought lasted with unabated severity until the end of July.	240 days	3	Annals of Cambridge, volume 3	cold snow season drought – type C
Britain	1742	Feb	Dec	The greater part of January was mild and fairly rainy. February, March and April were dry and cold, especially March, during which month both Plymouth and Lyndon were practically rainless. December 1742 closed with 3 weeks of very severe frost without snow. The year as a whole had 80 % of the standard normal rainfall over England.	330 days	3	James Woodforde's Diary	cold snow season drought – type C
Rhône and Loire valley	1742	Jan	Apr	The drought lasts between January and April 1741, period in the course of which it rains not at all. The North wind ("bise" in French) blows constantly from January in 15 April. Grapes are very damaged in Beaujolais and in the Monts du Lyonnais.	120 days	3	Archives départementales Rhône, 5 Mi 345	cold snow season drought – type C
Lyonnais	1779	Christmas 1778	Feb 1779	December, January and February are very hot. There are neither snow nor rain. The harvests are reduced (in particular potatoes) and destroyed by cockchafers.	60 days	3	Journal de Claude Bellod, p. 91	warm snow season drought – type B
France	1921	Autumn 1920	Jul 1921	The hottest and the driest year in Paris since 1873. It falls only 270 mm (against 625 mm on average). The drought begins in autumn, 1920 and increases in February (no rain drop on Beauce, the South of the Champagne and Jura). In Paris, June is the dry since 1813. Between 22 May and 11 July, it falls only 2 mm to Paris. The drought is European: Holland, England and Russia which knows a famine.	270 days	4	Bulletin municipal officiel de Paris	warm snow season drought – type B

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Table 6. Number of reported impacts for selected keywords and categories in the Drought Impact Reporter in the USA since 2004.

Keywords	no. of impacts	Categories							
		Agriculture	Business and industry	Energy	Plants and Fire	Tourism wildlife	Water supply and recreation	and quality	Others
Snow	272	98	39	8	53	80	75	89	100
Glacier	7	3	0	0	3	0	0	0	4
Frost	54	37	1	1	6	15	0	13	14
Winter	979	609	39	12	121	250	63	249	243

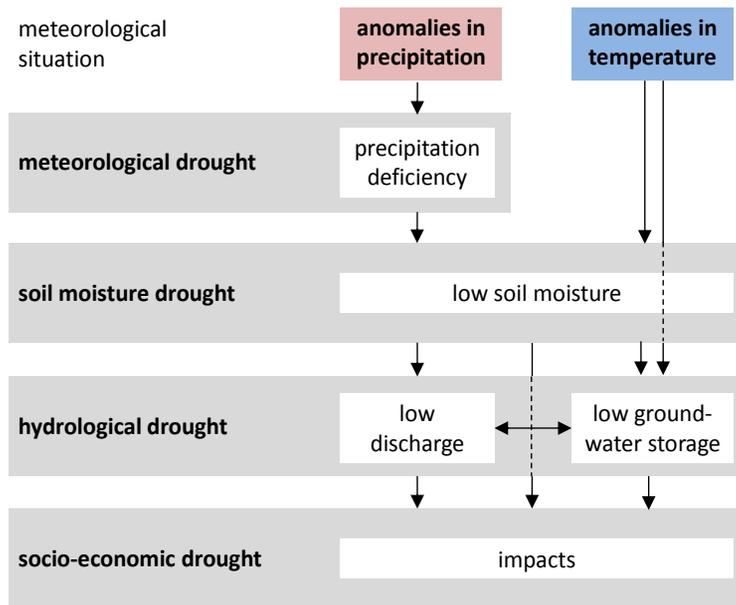


Figure 1. Scheme representing drought propagation (adapted from Fig. 8.1 of Van Loon, 2013).

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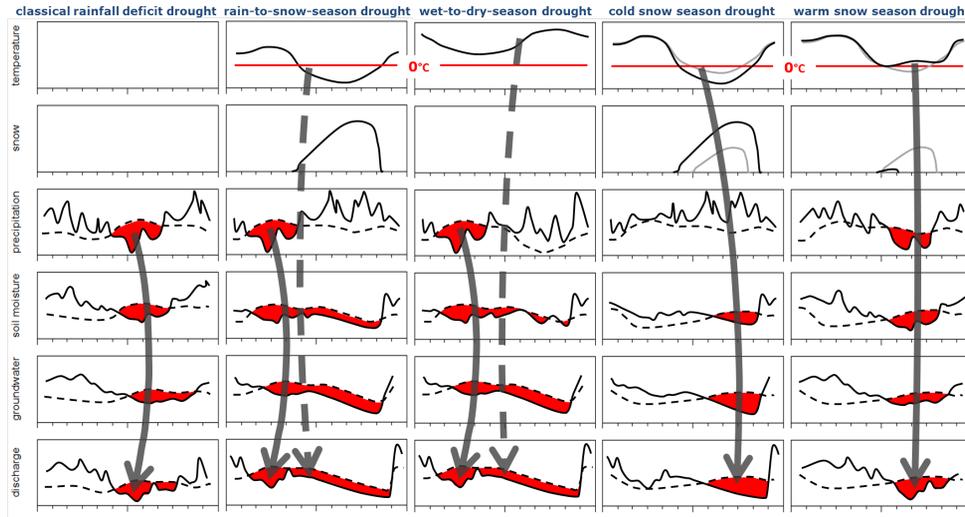


Figure 2. Synthetic time series representing the propagation of a meteorological anomaly (precipitation and/or temperature) through the terrestrial hydrological cycle per hydrological drought type (HDT) (adapted from Fig. 8.2 of Van Loon, 2013). The x-axis represents one year and the tick marks indicate the months. The black lines are the time series of each hydrometeorological variable, the grey lines in the upper two rows are long-term averages of air temperature and snow, the dashed lines represent the threshold levels, and the red surfaces indicate drought events. Propagation of drought events is indicated by the arrows, dashed arrows represent a lack of recovery of the hydrological drought (meteorological drought ceased). The *cold snow season drought* is *subtype C* and the *warm snow season drought* is *subtype B*. For description, see Table 1.

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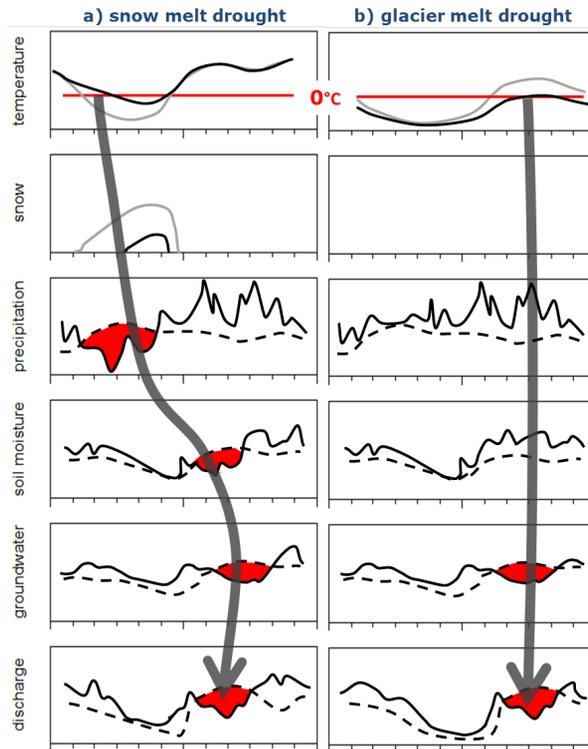


Figure 3. Synthetic time series representing the propagation of a meteorological anomaly (precipitation and/or temperature) through the terrestrial hydrological cycle for the new hydrological drought types (HDTs), **(a)** *snowmelt drought* and **(b)** *glaciermelt drought*. (Legend: see Fig. 2.)

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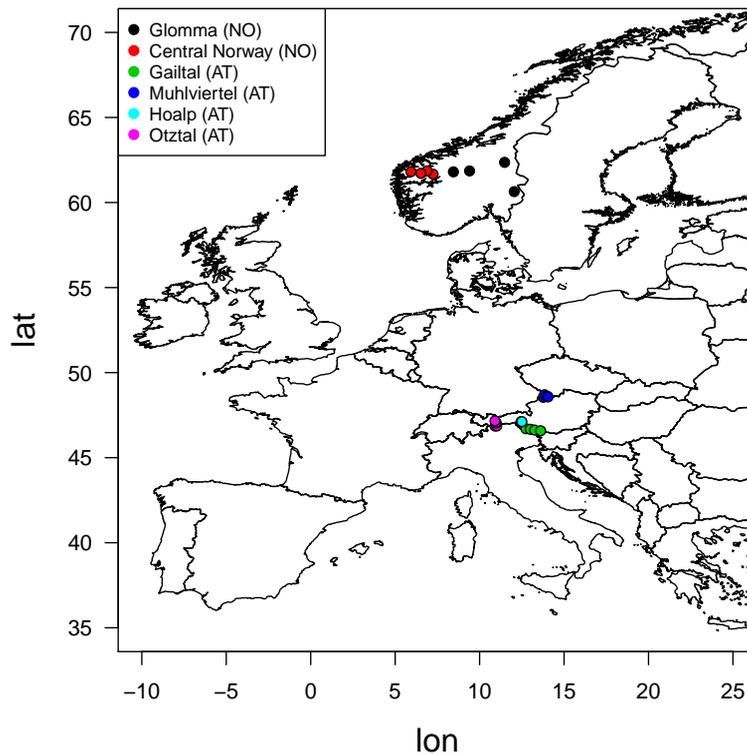


Figure 4. Selected catchments in Norway and Austria.

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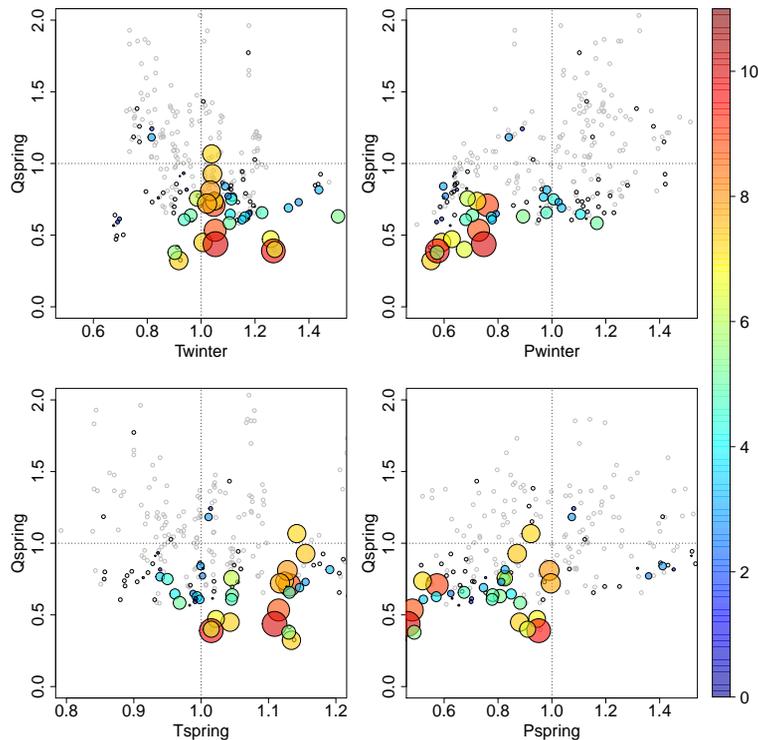


Figure 5. *Snowmelt drought events in Austrian catchments: standardised spring discharge (Q_{spring}) [-] against standardised causing factors (T_{winter} , P_{winter} , T_{spring} , P_{spring}) [-]. Below 1 = below average, above 1 = above average. Grey circles: all years, black circles: all drought years, coloured circles: *snowmelt drought* years (size and colour of dots is dependent on standardised drought deficit [-], scale on right side of figure).*

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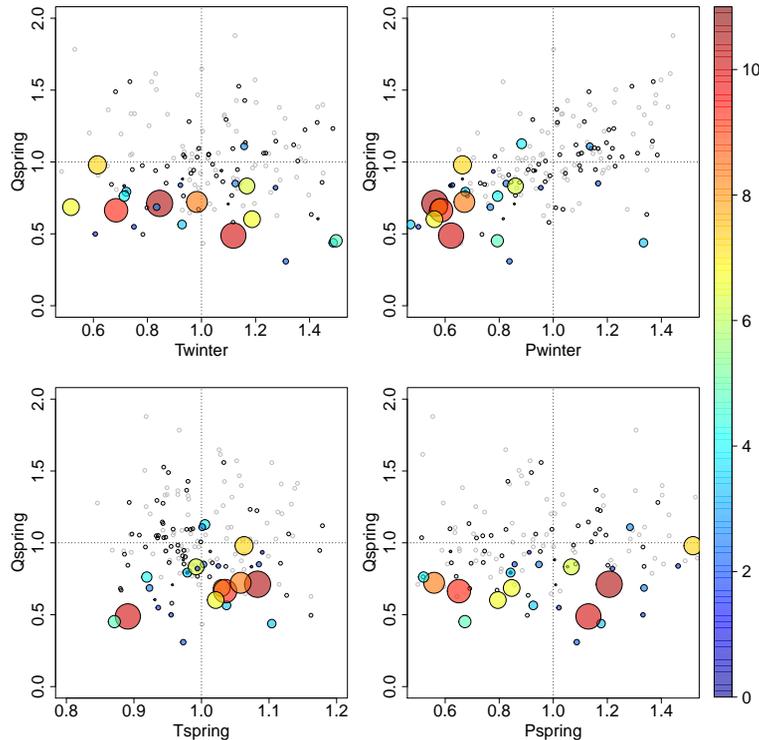


Figure 6. Snowmelt drought events in Norwegian catchments: standardised spring discharge (Q_{spring}) [-] against standardised causing factors (T_{winter} , P_{winter} , T_{spring} , P_{spring}) [-]. Below 1 = below average, above 1 = above average. Grey circles: all years, black circles: all drought years, coloured circles: snowmelt drought years (size and colour of dots is dependent on standardised drought deficit [-], scale on right side of figure).

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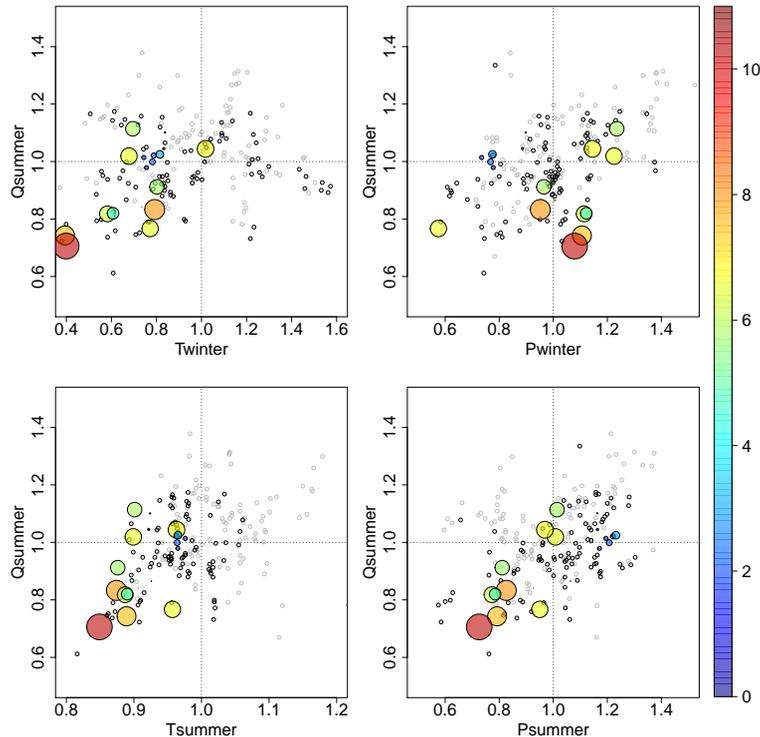


Figure 7. *Glaciermelt drought* events in Austrian catchments: standardised summer discharge (Q_{summer}) [-] against standardised causing factors (T_{winter} , P_{winter} , T_{summer} , P_{summer}) [-]. Below 1 = below average, above 1 = above average. Grey circles: all years, black circles: all drought years, coloured circles: *glaciermelt drought* years (size and colour of dots is dependent on standardised drought deficit [-], scale on right side of figure).

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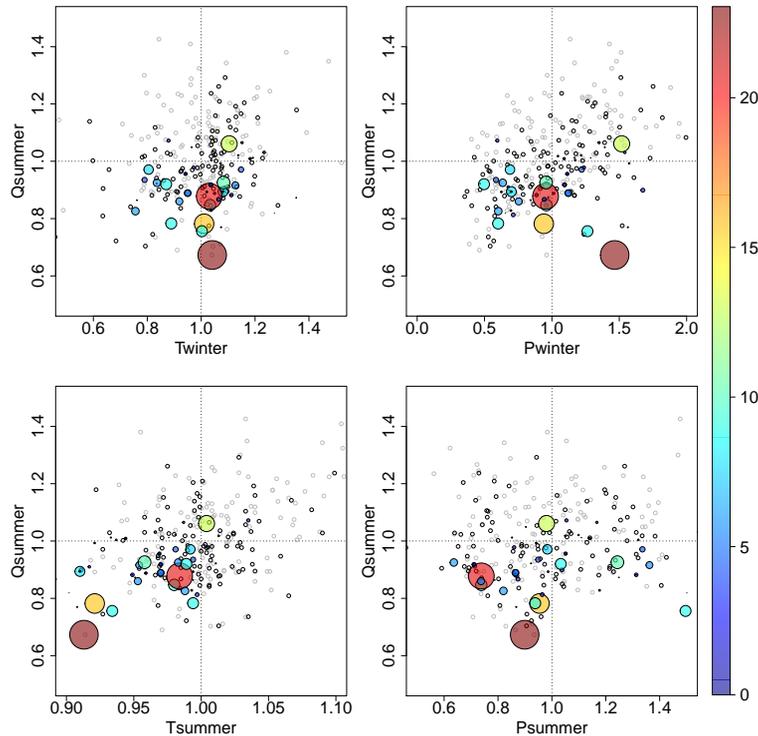


Figure 8. *Glaciermelt drought* events in Norwegian catchments: standardised summer discharge (Q_{summer}) [-] against standardised causing factors (T_{winter} , P_{winter} , T_{summer} , P_{summer}) [-]. Below 1 = below average, above 1 = above average. Grey circles: all years, black circles: all drought years, coloured circles: *glaciermelt drought* years (size and colour of dots is dependent on standardised drought deficit [-], scale on right side of figure).

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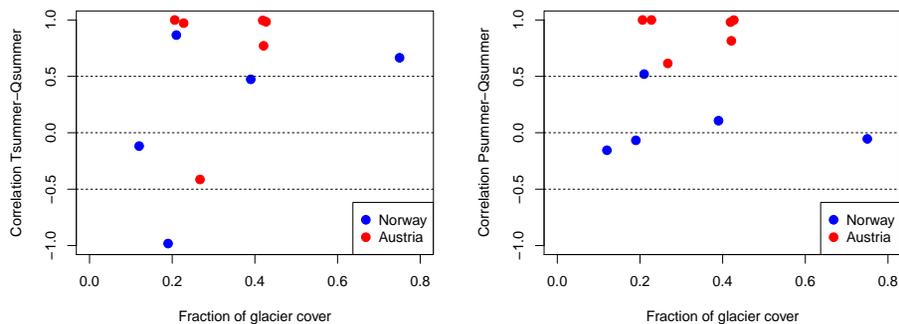


Figure 9. Correlation between Qsummer and Tsummer and Psummer for *glaciersmelt drought* events in Austrian and Norwegian catchments in relation to fraction of glacier cover per catchment.

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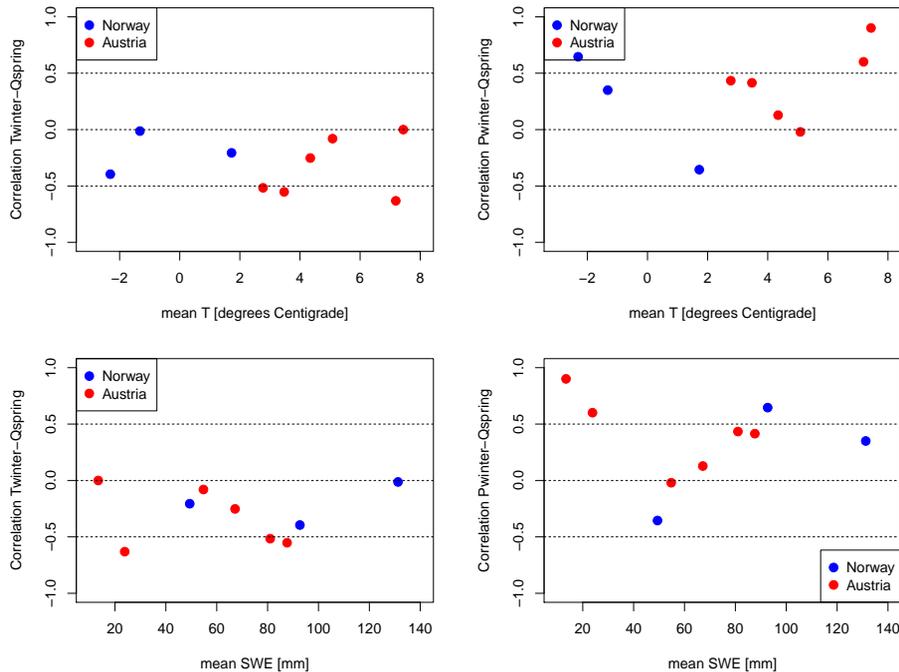


Figure 10. Correlation between Qspring and Twinter/Pwinter for *snowmelt drought* events in Austrian and Norwegian catchments in relation to catchment mean air temperature and snow cover.

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Hydrological drought types in cold climates

A. F. Van Loon et al.

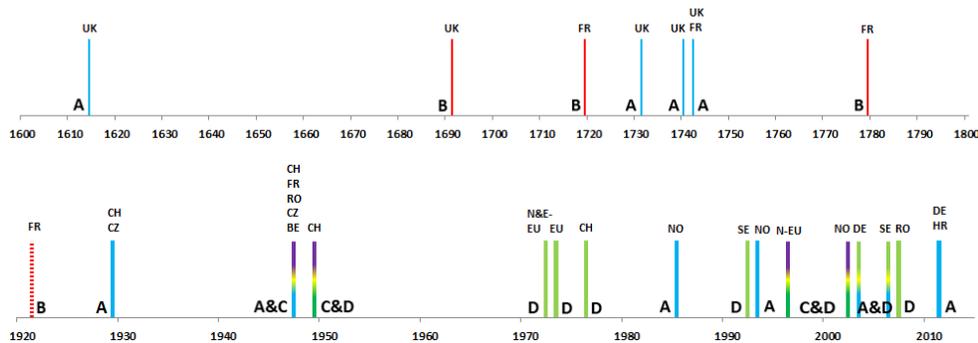


Figure 11. Selected drought events that are connected to winter temperature anomalies obtained from historical archives (upper graph) and the EDII (lower graph). **(A)** (blue): *cold snow season drought*, **(B)** (red): *warm snow season drought*; **(C)** (purple): *rain-to-snow-season drought*, and **(D)** (green): *snowmelt drought*. Abbreviations represent countries in Europe (EU).

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