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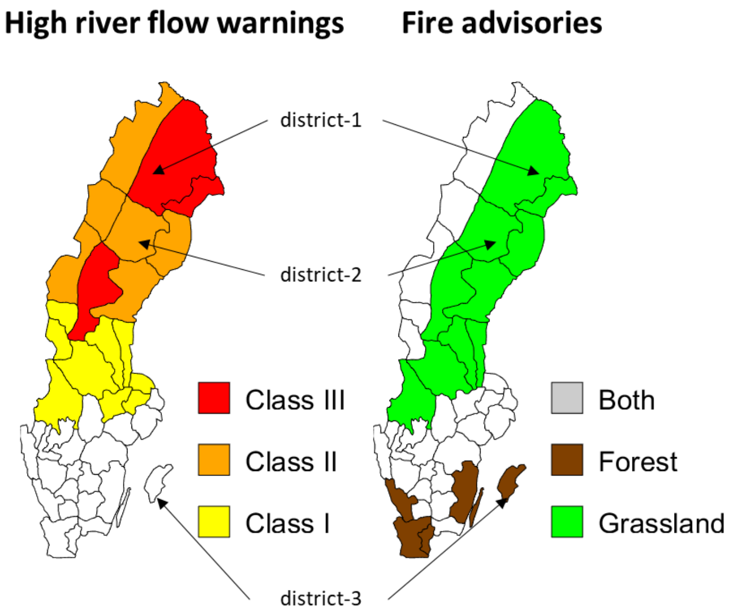

Front:
Example of a day with spatially overlapping high river flow warnings and fire advisories.

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Summary

Sweden is less affected by natural hazards compared to the most risk-prone regions in the world, however, it does experience several kinds of hazards that cause economical losses as well as increased mortality. Moreover, recent studies show that single natural hazards may be in different ways combined, leading to hazards that cause cascading or co-crowding effects and turn them into so-called “multiple” or “compound” hazards.

In this study we aim to view the natural hazards from a multiple perspective, in particular, those related to hydrology. We complied weather warnings and advisories (WA) issued by SMHI from 2011 to 2020 and conducted a comprehensive quality assurance. The studied WA cover the fields of meteorology, hydrology and oceanography. Four statistical metrics were designed and calculated as a basis to investigate the occurrences of single and multiple hazards in terms of their distribution in time (at daily level) and space (at warning district level). Combinations of up to four types of single hazards occurring on the same day and district have been explored, but we focused on two-type combinations (so-called double WA).

For single hazards, high river flow and heavy snowfall were found to be the most common warnings, in terms of the overall number of affected days and districts, followed by the warnings of strong wind gusts and high ocean level. Except for high temperatures, advisories were more frequently issued than warnings, with on average more than 1000 advisories issued per year (e.g. for risks of fire and water scarcity).

Analyses of hydrology-related multiple hazards (double WA) revealed that 1) districts along the west coast and the north-east coast were most affected, in particular during winter (December-February), 2) high river flow and strong wind gusts was the main warning combination including hydrology, ranked up high in all metrics, with most affected districts located along the west coast in southern Sweden, 3) high river flow warning combined with grassland fire advisory is the main hydrology-related combination of one warning and one advisory, and 4) water scarcity and forest fire stands out as the most frequent combination of two advisories.

Sammanfattning

Sverige är mindre påverkat av naturolyckor jämfört med de mest riskbenägna regionerna i världen, men upplever trots det flera typer av olyckor som orsakar både ekonomiska förluster och ökad dödlighet. Nyligen genomförda studier visar dessutom att enskilda naturolyckor kan på olika sätt sammanfalla, vilket kan leda till kombinerade effekter eller kaskadeffekter och omvandla dem till så kallade multipla eller samverkande naturolyckor.

I denna studie betraktar vi naturolyckorna ur ett multipelt perspektiv, med särskilt fokus på de som är relaterade till hydrologi. Vi sammanställde vädervarningar och meddelanden (VM) utfärdade av SMHI från 2011 till 2020 och genomförde en omfattande kvalitetskontroll. De VM som studerades omfattar områdena meteorologi, hydrologi och oceanografi. Fyra statistiska mått utformades och beräknades som underlag för att undersöka förekomsten av enskilda och multipla naturolyckor i termer av deras fördelning i tid (på dygnsnivå) och rum (på varningsdistriktsnivå). Kombinationer av upp till fyra typer av enskilda olyckor som inträffar på samma dag och i samma distrikt har undersökts, men vi fokuserade på kombinationer av två typer (s.k. dubbel VM).

För enskilda naturolyckor visade sig höga flöden och snöfall vara de vanligaste varningarna, sett till det totala antalet förekomster över alla dagar och distrikt, följt av varningarna för vind och högt vattenstånd. Förutom för höga temperaturer utfärdades meddelanden avsevärt oftare än varningar, med i genomsnitt mer än 1 000 meddelanden per år (t.ex. för brandrisk och risk för vattenbrist).

Analyser av hydrologirelaterade multipla naturolyckor (dubbel VM) visade att 1) distrikten längs västkusten och norra ostkusten var mest drabbade, särskilt under vintern (december-februari), 2) höga flöden och vind var den främsta varningskombinationen som inkluderar hydrologi, högt rankad i alla statistiska mått, med de mest drabbade distrikten belägna längs södra västkusten Sverige, 3) varning för höga flöden kombinerat med meddelande om gräsbrandrisk var den främsta hydrologirelaterade kombinationen av varning och meddelande, och 4) vattenbrist och skogsbrandrisk var den vanligaste kombinationen av två meddelanden.

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1 Introduction

There is a growing interest in risk assessment of natural hazards that are in some way combined. In Zscheischler et al. (2020) a typology of compound weather and climate events was proposed, in which the compound events are categorized into four types:

- **preconditioned events**, where a weather-driven or climate-driver precondition triggers a hazard;
- **multi-variate events**, where an impact is caused by multiple drivers and/or hazards;
- **temporally compounding events**, where a cascade of hazards leads to an impact; and
- **spatially compounding events**, where hazards that co-occur in connected locations cause an aggregated impact.

For example, sea level extremes in particular in the Baltic Sea can be considered as preconditioned events. Many of these extremes occur as storms hit the basin when the mean sea level is already elevated (Suursaar and Sooäär, 2007). Wildfire is a kind of multi-variate event. The climate conditions such as precipitation, temperature, wind speed and relative humidity as well as fuel conditions determine whether the risk exists for a certain location. The hazards involved in the temporally compounding events can be of the same hazard (e.g., heatwaves) or different types of hazards (e.g., a flood followed by a heatwave). They however refer to a succession of hazards that affect the same geographical location. In a spatially compounding event, multiple, neighbouring locations are affected by the same or different types of hazards in a limited time window.

Recently, Gustafsson et al. (2021) provided an overview of multiple natural hazards in Sweden. Their study addressed that there were connections amongst different natural hazards and concluded that natural hazards need to be viewed more from a multiple perspective.

Natural hazards are highly unusual phenomena and therefore generally hard to find in observational data sets, both because these observations often do not extend very far back in time and because observations may be limited to specific locations. Furthermore, there is no complete and updated data base of different kinds of natural hazards that have occurred in Sweden. An alternative to study observations is to use modelling, and in that way identify and analyse situations with high risk of multiple hazards. Modelling has the advantage of full spatial coverage as well as long continuous simulation periods, e.g. by using results from climate models to force impact models (for e.g. floods or fires).

In this study we use warnings and advisories (hereafter abbreviated WA when used in a general sense) issued by SMHI to investigate the risk of multiple hazards, i.e. when different types of WAs are likely to co-occur in space and time. A WA is issued when a specific forecasting model signals that some kind of critical level will be exceeded sometime in the future. For some hazards, e.g. intense rainfall, the forecasting time horizon is hours up to 1-2 days whereas for other hazards, e.g. drought, the horizon is weeks or months. A limitation with using modelled data for studying the risks of hazards is that the issued WAs themselves do not provide any information about the actual outcome, i.e. whether the (multiple) hazard actually occurred or not (although evaluation of some WAs is routinely made). Even so, the WAs, combining modelling outputs with expert judgement, provide us a possibility to assess the risks of the multiple natural hazards. Furthermore, an analysis of issued WAs has a clear link to societal impacts, as they are the alerts that county boards, rescue services, etc., need to act on and respond to, regardless of the actual outcome.

2 Aims and limitations

This study aims to:

- extract or digitize the available hydrological, meteorological and oceanographic warnings and advisories (WAs) that have been issued by SMHI during the period 2011-2020;
- improve understanding of all issued and recorded WAs via data preparation;
- provide a general picture of potential single and multiple hazards in the 10-year period;
- identify risk-prone regions at national level.

This study is considered as a preliminary work prior to more in-depth studies of compound events and their impacts. It aims to explore single hazards and several kinds of potential multiple hazards in Sweden. In particular, we focus on spatial and temporal distribution patterns, i.e. when and where single hazards and/or multiple hazards may occur.

All single natural hazards included in SMHI data base, i.e. hazards associated with WAs, are being studied:

- **warnings**: heavy rainfall, heavy snowfall, strong wind gust, thunder, high river flow, high lake level, high ocean level, high temperature;
- **advisories**: grassland fire, forest fire, high temperature and water scarcity (i.e., low river flow) in watercourses. The latter is limited to a predicted low flow in rivers, advisories based on low groundwater level is not part of the study.

Note that (1) high temperature is a natural hazard associated with warnings as well as advisories but using different criteria, and (2) a warning of “mountain weather” issued in the five districts enclosing the Scandinavian mountains only is not included in this study. It is noted that the warning of “mountain weather” replaces the warnings of strong wind gusts there but using different criteria. Furthermore, it contains unique warnings for wind combined with low temperature or precipitation. As this rather special type of warning is issued only in a specific part of Sweden, it was excluded in this national study.

3 Data and impact modelling

3.1 Extraction from the KEPS database

We compiled warnings and advisories (WAs) from the internal database at SMHI, KEPS (replaced by the TOVE database since October, 2021). The KEPS database is a primary system for automatically storing meteorological, hydrological and oceanographic WAs issued by SMHI.

Figure 1. An example of an entry in the KEPS client showing the spatial distribution of the 40 warning districts on land (black lines), neighbouring waterbodies along the Swedish coast (green line) and affected districts with an active high river flow warning (yellow area).

In KEPS, the WAs can be searched with criteria on time, type of WA, severity and location. The WAs are displayed on a map where the affected districts are highlighted together with the descriptive text that was published by SMHI (e.g., Figure 1). The detailed information about land districts and water bodies is available in Appendix E. From the web interface it is also possible to export the result of a query as a text file. This text file contains spatial and temporal information, the start and end time of the WA together with its type, severity and district where it was issued. The descriptive text (as shown in Figure 1) is not part of the text file but only available in the KEPS client.

3.2 Warnings and advisories of natural hazards

Tables 1 and 2 lists the criteria and consequences of single natural hazards included in the SMHI warning system in operation until October 2021, after which a new impact-based system is in use. As the focus of the report is on hydrologically related WAs, these are somewhat more comprehensively described.

3.2.1 Warnings

All warnings are available for the period of 2011-2020, except the warning of high temperature that was introduced in 2014. The warning of high ocean level was issued for waterbodies along the Swedish coast, for both high ocean level and low ocean level.

The forecasts of high river flow in Sweden have been generated based on the hydrological HBV model (Hydrologiska Byrån Vattenbalans; Bergström, 1976, 1992; Lindström et al., 1997) since the early 1970s. Since 2014, the HYPE model (Hydrological Predictions for the Environment; Lindström et al., 2010), a semi-distributed, physically based catchment model have been in operation in addition to the HBV. Daily mean flow in 10-day forecasts, together with (near) real-time observations as well as expert knowledge, are usually used as a basis for issuing warnings for a high flow situation with consideration of forecast reliability and lead time. The model's forcing data are taken from different sources of forecasts, primarily the so-called PMP meteorological forecast, which is based on deterministic and ensemble forecasts from the ECMWF as well as other forecast centers. The model's initial conditions are updated to the forecast date with observations (weighted stations or gridded precipitation and temperature) if possible.

Table 1. Criteria and consequences of single hazards used at SMHI until October, 2021.

Hazard	**Criteria**	**Consequences**
Heavy rainfall	Class I: rainfall amount > 35 mm/12 hours or > 70 mm/24 hours	Risk of large water volumes; may cause overflowing stormwater pipes and flooded basements.
	Class II: rainfall amount > 70 mm/24 hours	Very high risk of flooding in basements, storm-water systems and smaller watercourses. Risk of flooded roads.
Heavy snowfall	Class I: snow amount > 5 mm/6 hours	Snowfall.
	Class II: snow amount > 20 mm/12 hours, or snow amount > 12 mm/12 hours and wind speed > 8 m/s	Strong snowdrift.
	Class III: snow amount > 35 mm/12 hours, or snow amount > 25 mm/12 hours and wind speed >8 m/s	Extra strong snowdrift.
Strong wind gusts	Class I: wind speed 21 m/s - 25 m/s.	The wind can cause problems for tall vehicles.
	Class II: wind speed 25 m/s - 30 m/s.	Storm/hurricane. Damage to buildings with a risk of flying objects. Major damage to forests and risk of traffic disruptions as well as electricity and telecommunications supply.
	Class III: wind speed > 30 m/s.	Storm/hurricane. Damage to buildings with a risk of flying objects. Dangerous to stay out. Extensive damage to forests and buildings with very large disruptions in traffic and electricity supply.
High ocean level	Class I: [1] > 80 cm in RH2000; [2] > 90 cm in RH2000; [3] > 75cm in RH2000; [4] > 70cm in RH2000	
	Class II: [1] > 120 cm in RH2000; [2] > 130 cm in RH2000; [3] > 110cm in RH2000; [4] > 100cm in RH2000	

[1]Skagerack, Kattegatt

[2]Öresund, Södra Östersjön, and Bottenviken

[3]Mellersta Östersjön, Norra Östersjön, Ålands hav

[4]Södra Bottenhavet, Norra Bottenhavet, Norra Kvarken.

Table 1 (continued). Warning level of single hazard used at SMHI until October, 2021.

Hazard	**Criteria**	**Consequences**
Thunder	Class I: frequency of lightning > 500 times/1h Class II: frequency of lighting > 800 times/1h	
High river flow*	Class I: High river flow in watercourses at a level that occurs on average between every 5 - 25 years.	May cause minor flood problems.
	Class II: Very high river flow in watercourses at a level that occurs on average between every 25 - 50 years.	Flood problems in exposed areas.
	Class III: Extremely high river flow in watercourses at a level that occurs on average every 50 years.	Causes serious flood problems.
High lake level	Defined for lake Vänern, Vättern, Mälaren, Hjälmaren, Storsjön and Siljan.	
High temperature	Class I: Maximum daily temperature ≥ 30 ºC for 3-4 consecutive days.	An increased stress on the body, which can cause problems, especially for risk groups.
	Class II: Daily maximum temperature > 30 ºC and > 5 days in a row. Alternatively, Daily maximum temperature > 33 ºC for 3 days in a row.	An increased stress on the body, which can cause problems for risk groups.

*New criteria and consequences were in use since February, 2021.

3.2.2 Advisories

The grassland and forest fire advisory were incorporated in the KEPS system from 2016 onwards. Two models are used to issue the advisories of wild fire: wildfire models developed at SMHI (HBV_forest and HBV_grass) and the Fire weather Index (FWI) developed in Canada.

The HBV_forest describes the risk of fire ignition by an index. It is based on the HBV hydrological model and is today used at SMHI as a basis for fire risk prediction (e.g., Gardelin, 1996, 1997, 2001; Gardelin and Sjöö, 1999). The FWI focuses on rating the moisture content in different fuel layers in a common standardized forest type, from which several relative indices of fire behaviour potential are generated (van Wagner, 1987). It describes the risk of fire with respect to ignition risk and fire spread.

The grassland fire advisory describes fire danger in grassland with a temperature index calculated by the HBV_grass model. The onset/offset of grassland fire season and the physical processes differ from that of the forest fire risk. Seven-day accumulated temperature difference between actual temperature and snow melting dew temperature reveals the moisture content in the grass, which is designed to determine the start of grassland fire season. In practice, the advisory of grassland fire is issued as long as grass from previous year exists. As soon as grass from this year comes the risk of grassland fire

Table 2. Advisory level of single hazard used at SMHI until October, 2021.

Hazard	**Criteria**	**Consequences**
High temperature[1]	Maximum daily temperature ≥ 26 ºC for 3 consecutive days	
Forest fire	- HBV-index ≥ 4 (4 - big, 5 - very big, 6 - extremely big) - HBV-index and FWI index > 3 - In case only one of indices > 3, extra criteria will be taken, for example, persistence, influencing area, etc.	Large or very large ignition risk and fire is spread easily in forest.
Grassland fire	- No snow cover during the grassland fire season and the vegetation is dominated by the dead grass from last year - Influencing area ≥ 1000 km2 - Grassland fire index ≥ 4	
Water scarcity	- Low[2] flow in large or medium-sized basins (upstream catchment area > 200km^2) and critical rivers identified by County Boards, when there is a 75% probability of river flow being among 5% of the lowest historical flows (since 1961) during the coming 4-week period (SMHI). - Low groundwater levels in small reservoirs, when a significant part of the county with unusually low volume and expected to remain low over the next 30 days (SGU). - Low groundwater levels in large reservoirs, when a significant part of the county has levels that are unusually low and are expected to remain low over the next 60 days for large reservoirs (SGU).	Low flows in watercourses, together with high water temperatures can affect wildlife and the environment. For households with own well low groundwater levels in small reservoirs can lead to a lack of water and affect water consumption. Low groundwater levels in large reservoirs can lead to a shortage from municipality water supply.

[1]The advisory was first issued in 2016.

[2]Unusually low means that flow is among 5% of the lowest historical flows during the comparison period from 1961.

decreases. The soil moisture in the most superficial soil layer of the HBV model (ca 1 cm) is a key determining factor.

The advisory of water scarcity is designed to concern the “scarcity of water” in watercourses and the shortage of water in groundwater reservoirs at county level. It is an advisory that has been produced in cooperation between SMHI and the Geological Survey of Sweden (SGU) since 2017. The advisory was not issued directly through the KEPS system but by using a separate procedure at the forecast and warning service. In this study we focus on analysing low flow in watercourses from a hydrological perspective (see section 2).

It is noted that during the season 2016 and/or until the season 2017 the strategy to issue the advisories for forest and grassland fire was changed to facilitate the communication with the users. This change might have had some impact on the number of issued advisories during the fire season of these particular years.

4 Methods

The evaluation process consists of two main steps: 1) data preparation and 2) spatial and temporal analysis of single and multiple natural hazards. We started with investigating single hazards from available warnings and advisories (WAs), followed by an analysis from a multiple natural hazard's perspective. The spatial and temporal distribution as well as the frequency of occurrence of single and multiple hazards are of our interest. Although our main focus is hydrological warnings and multiple hazards including hydrological hazard (i.e. high river flow), a complete overview of all warnings and advisories is provided.

4.1 Data preparation

The analysis period is 2011-2020 because 1) most types of warnings and advisories in the KEPS database are available from 2011 and 2) a new impact-based warning system is in use since October, 2021. There were some shortfalls and limitations of the data in KEPS that needed to be addressed. Further some of the advisories needed to be retrieved from other sources. The required steps to complete the data set were as follows:

- Paper copies of fire advisories archived until 2014 were digitized as the fire advisories were included in KEPS from 2016 (we were unable to locate any advisories issued during 2015). The paper copies only included the final advisories that were described in a different way from those in KEPS. A wide range of expressions were used to describe the spatial extension, e.g. "south-eastern Norrland", "east coast from Småland to Västerbotten" and "Götaland except Skåne and western coast". In total 170 expressions were used and all of these were manually associated with their corresponding warning district(s). This mapping inevitably introduces some uncertainty, and single days and districts might have been differently classified if issued through the KEPS system, but we assume (and believe) that this uncertainty will not have a significant impact on the final results.
- Advisories of water scarcity were retrieved from the archive and converted into the same format as the other WAs. They are issued on warning district level but only once a week, thus the same affected district(s) are considered at risk until the next weekly update.
- Manual work was needed in order to fill in with information either from map images displayed in the KEPS client (e.g., Figure 1) or PDF archive up to 2015, as quite a lot of the high river flow warnings in 2011-2013 lacked spatial information.
- The warnings of high ocean level are issued for the green bordered ocean districts as shown in Figure 1. They are transferred to the land districts that have a part of their coast line adjacent to the sea district with the warning, in order to study the co-occurrence of them with the other land district warnings. For example, the warnings in Skagerrak is attributed to Bohuslän and Göteborg as it is the only land district by Skagerrak. Other sea districts can have several land districts next to them.

Next, basic quality controls have been applied to the complete data for analysis at a daily time scale. “False” WAs needed to be addressed before any analysis could be performed. They are generated when the descriptive text is updated shortly after the WA has been issued, which will produce what looks like a new WA in the automated KEPS system, even though no new WA was issued. In these cases, the database appears to contain very brief WAs but in reality, they are thus only updates of the same WA, probably either due to fixing of a typo or some other kind of mistake. False WAs are therefore often generated for the same event.

For some WA types, short-duration WAs are clearly false, e.g. high river flow which is a slow process with many hours between warning updates in the general procedure. For other types, e.g. rain- or snowfall, wind gusts and thunder, short-duration WAs may be “true” as they represent short-lived meteorological events (see Figure 2). Based on an analysis of WA durations described in Appendix A, it was decided to use 2 hours as a cut-off to identify false WAs, i.e. WAs with a duration shorter than 2 hours were discarded.

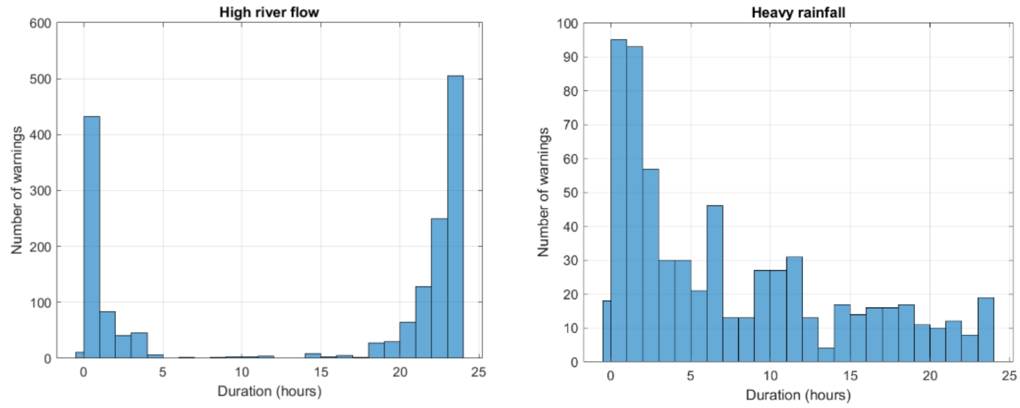


Figure 2. Number of warnings of high river flow (left) and heavy rainfall (right) with a duration of less than 24 hours. The narrow bars to the left of 0 is the number of warnings of negative duration, i.e. the expiration time is before the starting time. Those were discarded from the analysis.

4.2 Characterization of single and multiple hazards

4.2.1 Single hazards

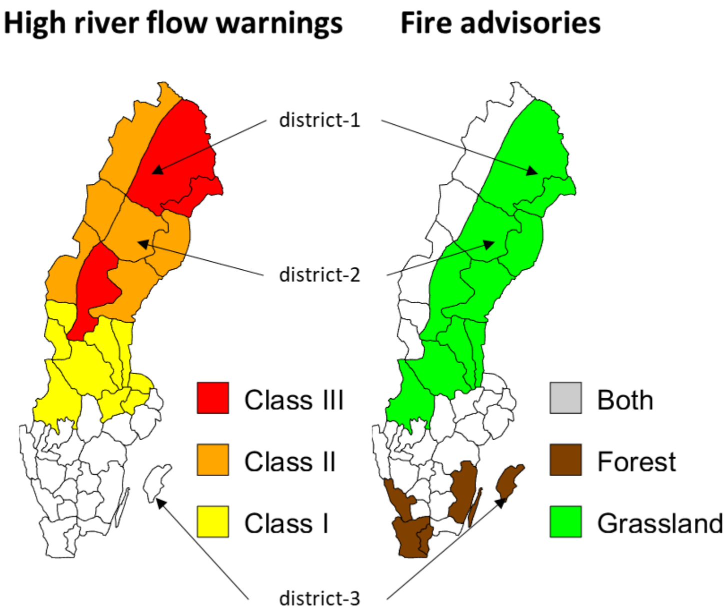
To facilitate analysis, the single WAs are converted to *daily* and *district* level, using a binary approach. Thus, for a certain warning district, even if a certain WA is active only a part of a day, or if there is more than one active WA on a day, that day will be registered as an “active WA day” for that type of WA. Similarly, for a certain day, even if only a part of a warning district is affected (e.g. such as always is the case for high river flow warnings), or if there is more than one WA in a district, the district will be registered as an “active WA district” for that type of WA.

This thus means that the KEPS data are converted into so-called indicator matrices (with binary entries, i.e. 0 or 1), as illustrated in Figure 3. In the top of the figure, the high river flow warnings and fire advisories issued on 2018-05-14 are shown as an example. Warnings of high river flow (of different classes) were issued in central and northern Sweden, whereas forest fire advisories were issued in the south and grassland fire advisories in the central and north of Sweden. In the bottom of the figure, these warnings and advisories are presented as an indicator matrix for the same day. For example, the Class III warning of high river flow and the grassland fire advisory in district 1 are represented by “1” in the corresponding columns. Similar columns are used for all warnings and advisories and similar matrices are made for each day 2011-2020.

In a mathematical notation, we denote by $S_{tc}(i,j)$ the complete set of indicator matrices for a certain single WA with:

- tc representing the WA type and, when relevant, class (e.g. high river flow of Class III);
- i representing day ($1 \leq i \leq 3653$; 10 years of data 2011-2020);
- j representing district ($1 \leq j \leq 40$).

Thus, for a WA of type *t* and class *c*, if there was at least one "true" occurrence sometime during day *i* somewhere in district *j*, $S_{tc}(i,j) = 1$, otherwise $S_{tc}(i,j) = 0$.



District	Date	High river flow			Forest fire	Grassland fire
		Class I	Class II	Class III	Fire advisory	Fire advisory
1	2018-05-14	0	0	1	0	1
2	2018-05-14	0	1	0	0	1
3	2018-05-14	0	0	0	1	0

Figure 3. An example figure with a part of an indicator matrix for 14 May, 2018, with corresponding values of variable $S_{tc}(i,j)$ in the table at the bottom. The index *i* (2681) represents the date (14 May, 2018) and *j* represents the three different districts (1-3).

To investigate the occurrence of single natural hazards in each district, the number of single-type WAs are summed and averaged over calendar months and years. This allows us to identify (1) inter- and intra-annual variations of individual WAs as well as specific years with the lowest and highest number of WAs, and (2) regional differences and hot-spot districts. Different time periods are used depending on the data availability for the different WAs.

To characterize and quantify the occurrences of single WAs, four different and complementary metrics, $NumDD_{tc}$, $NumDays_{tc}$, $NumDistricts_{tc}$ and $AvgDistricts_{tc}$, were used.

Table 3. Definition of metrics: $NumDD_{tc}$, $NumDays_{tc}$, $NumDistricts_{tc}$ and $AvgDistricts_{tc}$

	Definition	**Question to be answered**	**Mathematical expression**
$NumDD_{tc}$	Total nr. of occasions with WA of type *t* and class *c* over all days and all districts	How common is this WA?	$\sum_{j=1}^{40}\sum_{i=1}^{3653} S_{tc}(i,j)$
$NumDays_{tc}$	Total nr. of days when WA of type *t* and class *c* occurred in at least one district	How often does this WA occur anywhere in Sweden?	$\sum_{i=1}^{3653} S_{tc}(i,j) \vert j \geq 1$
$NumDistricts_{tc}$	Total nr. of districts where WA of type *t* and class *c* occurred on at least one day	How many districts experience this WA?	$\sum_{j=1}^{40} S_{tc}(i,j) \vert i \geq 1$
$AvgDistricts_{tc}$	Avg. nr of affected districts on days when WA of type *t* and class *c* occurred.	When this WA occurs, how many districts are typically affected?	$NumDD_{tc}/NumDays_{tc}$

4.2.2 Multiple hazards

To study the simultaneous occurrence (i.e. overlaps) of two different types of WAs, we need to examine combinations of days and districts experiencing more than one type of active WA. As an example of a multi-hazard event, on 2018-05-14 both a Class III high river flow warning and a grassland fire advisory were issued in district 1 (Figure 3). Thus, there was a risk of having to manage both flooding and grassland fire on the same time in the same location.

In a mathematical notation, identifying multiple-hazard events amounts to identifying days *i* and districts *j* where $S_{tc}(i,j) = 1$ for more than one WA type/class *t* for any class *c*. This was attained by defining multiple-hazard indicator matrices $M_{t12}(i,j)$ for every combination of two types of WAs, with *t1* and *t2* representing the two different types.

Thus, the combination of high river flow and grassland fire in district 1 in Figure 3 makes $M_{t12}(i,j) = 1$ for this combination, day (i=2681, corresponding to 2018-05-14) and district (j=1). Note that in this multiple-hazard analysis the warning class *c* was not considered, as the main interest is the overlap of different types *t*, regardless of severity, as well as to obtain enough cases for meaningful analysis. For example, in Figure 3 the combinations of high river flow and grassland fire in districts 1 and 2, respectively, were registered in the same “high river flow (*t1*) and grassland fire (*t2*)” category even though the high river flow warnings are of different classes (Class III in district 1 and Class II in district 2).

For the case of multiple, overlapping hazards, “multiple versions” of the metrics described above for single WAs (section 4.2.1) were formulated as shown in Table 4.

Table 4. Definition of metrics: $NumDD_{t12}$, $NumDays_{t12}$, $NumDistricts_{t12}$ and $AvgDistricts_{t12}$

	Definition	**Question to be answered**	**Mathematical expression**
$NumDD_{t12}$	Total nr. of occasions with combinations of WA types *t1* and *t2* over all days and all districts	How common is this WA combination?	$\sum_{j=1}^{40}\sum_{i=1}^{3653} M_{t12}(i,j)$
$NumDays_{t12}$	Total nr. of days when WA type *t1* and *t2* co-occurred in at least one district	How often does this WA combination occur anywhere in Sweden?	$\sum_{i=1}^{3653} M_{t12}(i,j)\|j \geq 1$
$NumDistricts_{t12}$	Total nr. of districts where WA types *t1* and *t2* co-occurred on at least one day	How many districts experience this WA combination?	$\sum_{j=1}^{40} M_{t12}(i,j)\|i \geq 1$
$AvgDistricts_{t12}$	Avg. nr of affected districts on days when WA types *t1* and *t2* co-occurred.	When this WA combination occurs, how many districts are typically affected?	$NumDD_{t12}/NumDays_{t12}$

5 Overview of results for all hazards

For all WAs, except weather in mountainous areas, the same types of analysis have been applied. However, we give more attention to the hazards associated with warnings than those associated with advisories. Section 5.1 presents results related to the single natural hazards. There, the natural hazard with the most frequently issued WAs, together with warnings for the hydro-meteorological variables such as precipitation and high river flow, are described more in detail. Section 6.1 focuses on risks of multiple natural hazards. An attempt to identify regions prone to multiple hazards at national level is made.

In the following, we generally drop the subscripts in the end of the single- and multi-hazard metrics listed in section 4 and refer to them just as NumDD, NumDays, NumDistricts and AvgDistricts.

5.1 Warnings and advisories for single hazards

5.1.1 Inter-annual variation

Table 5 and Table 6 summarize the number of total occurrences of issued WAs for single natural hazards, NumDD, during the period of 2011-2020. shows the same data in the form of bar charts. The other single-hazard metrics, i.e., NumDays, NumDistricts and AvgDistricts of specific WA can be found in Appendix B.

High river flow is found to be the natural hazard associated with the highest number of warnings in a Swedish context, followed by heavy snowfall and strong wind gust (Table 5, Figure 4a and Figure 4b). The advisories of water scarcity, grassland fire and forest fire

Table 5. Total number of occurrences of issued warnings covering all days and districts ($NumDD_{tc}$) for 2011-2020.

	High river flow			**Heavy rainfall**		**Heavy snowfall**		**Strong wind gust**		
	Class I	Class II	Class III	Class I	Class II	Class I	Class II	Class I	Class II	Class III
2011	190	26	6	147	0	405	22	328	72	4
2012	241	37	11	85	0	749	31	162	18	0
2013	266	29	0	75	0	228	20	180	78	14
2014	539	72	3	170	0	389	6	122	21	0
2015	506	49	14	91	0	275	6	312	117	0
2016	210	10	0	55	0	462	12	161	15	0
2017	243	16	0	45	2	551	33	149	8	0
2018	926	198	37	26	0	458	10	168	22	0
2019	423	6	0	27	0	414	14	180	35	0
2020	1084	365	14	47	0	271	6	325	35	0
Avg.	463	80.8	8.5	76.8	0.2	420	16	209	42.1	1.8

Table 5. (continued). Total number of occurrences of issued warnings covering all days and districts ($NumDD_{tc}$) for 2011-2020.

	High lake level	**High ocean level**		**Thunder**		**High temp.**	
	Class I	Class I	Class II	Class I	Class II	Class I	Class II
2011	0	305	39	163	0	*	*
2012	33	207	0	32	0	*	*
2013	0	115	24	48	0	*	*
2014	14	60	3	100	4	69	53
2015	0	340	22	0	0	19	0
2016	0	58	9	4	2	0	0
2017	0	197	13	0	0	0	0
2018	16	109	0	30	0	155	116
2019	40	107	0	45	1	39	0
2020	0	357	33	17	0	65	0
Avg.	10.3	185	14.3	43.9	0.7	49.6	24.1

*no data

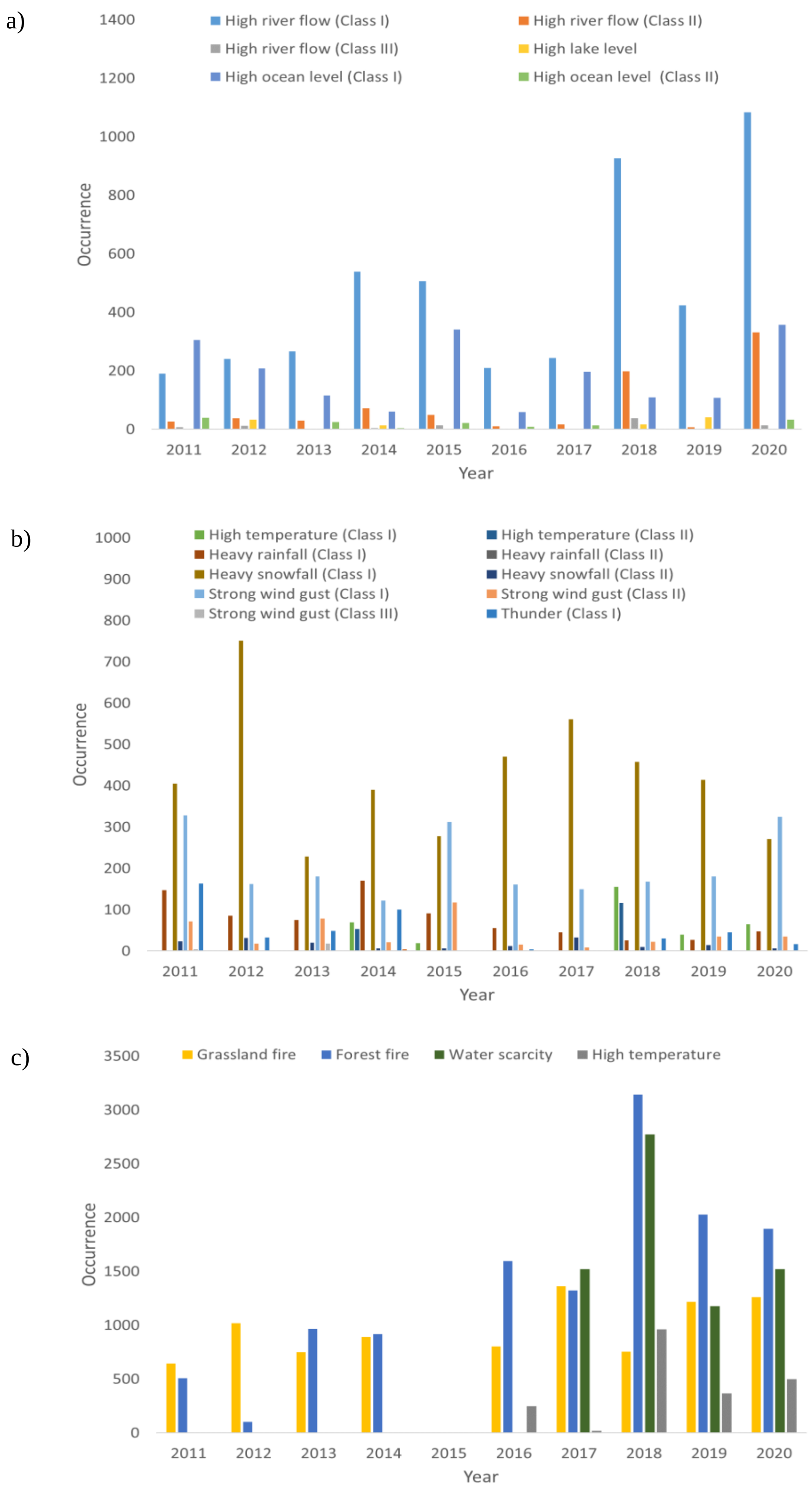


Figure 4. Total number of occurrences of issued hydrological and oceanographic warnings (a), meteorological warnings (b) and advisories (c) covering all days and districts ($NumDD_{tc}$) for 2011-2020.

are more frequently issued in comparison with all other types of warnings and advisories. Forest fire is the one with the highest number of issued advisories (Figure 4c).

Concerning high river flow, 2018 and 2020 are the two years with higher number of issued warnings at all classes compared to the other years (Table 5, Figure 4a). The number of Class-I warnings is around two times the 10-year average number of warnings; the numbers of Class-II and Class-III warnings are around 2-4 times the 10-year average warnings.

Class-I rainfall warnings were issued every year with relatively high frequency in the period 2011-2015. The year 2011 and 2014 are the years with relatively higher number of Class-I warnings when comparing to the other years (Table 5, Figure 4b). The Class-II rainfall warnings were very seldom issued; only twice during the 10-year period, both in 2017.

The Class-I snowfall warnings were issued on average around 400 times per year, with the highest number in the year 2012 (751) when the number of issued warnings for all classes reached the maximum number in the period (Table 5, Figure 4b). The second highest year is 2017, for which the issued Class II warnings are in the same magnitude as in 2012, but with fewer number of Class-I warnings (561).

The Class-I strong wind gusts warnings (Table 5, Figure 4b) were issued on average around 200 times per year. In years 2011, 2015 and 2020, the number of issued Class-I warnings are around 2-3 times the number of issued number in other years. 2011 is the year with the highest number of Class-I warnings (328) and 2015 is the one with the highest number of Class-II warnings (117). Concerning Class-III warnings, these were only issued in 2011 (4) and 2013 (18).

The Class-I warnings for high lake level was issued for four years with on average 10.3 times between 2011 and 2020. The areas endangered by high lake level experienced a high risk in 2019 with 40 warnings, followed by 2012 (33), 2018 (16) and 2014 (14) (Table 5, Figure 4a).

The inter-annual variation of high ocean level warnings was found highly correlated with the strong wind gusts warnings. The warnings were issued on average 185 times per year. 2011, 2015 and 2020 are the years with relatively high number of issued warnings (>300) compared to other years, whereas 2014 and 2016 are the years with relatively low numbers of issued warnings (~ 60). Class-II warnings were issued almost every year except 2012, 2018, 2019. The highest occurrence of issued Class-II warnings appeared in 2011 (Table 5, Figure 4a).

Class-I thunder warnings were issued around 43.9 times per year with quite large variations from year to year. The highest number of warnings were issued in 2011 (163) followed by 2014 (100) (Table 5, Figure 4b).

The high temperature warnings were introduced in 2014. Its criterion with a threshold of 30°C makes it seldom issued in Sweden (49.6 times per year on average). However, in 2018 Class-I and Class-II warnings were issued more than 100 times over the country (Table 5, Figure 4b). The issued warnings reached its maximum number since the warning was introduced, with twice as many warnings as in the year with the second highest number of advisories (2014) for both Class I and II.

Forest and grassland fire advisories were issued every year since 2011. In the second 5-year period (2016-2020) the number of issued advisories has increased dramatically for both types of fire. This is likely partly due to the new strategy for issuing the advisories (see section 3.2.2). Compared to the grassland fire advisory, forest fire is found to have a larger inter-annual variability with the lowest number in 2012 (100) and the highest number in 2018 (3144) (Table 6, Figure 4c).

The advisory of water scarcity, introduced in 2017, is the WA with the highest average number of issued occasions. As seen from Table 6 and Figure 4c, its inter-annual variation largely correlates to that of forest fire. 2018 is the year with the highest number of water scarcity advisories.

The high temperature advisories were also introduced in 2014. Compared to the high temperature warnings, the advisories were often issued with 299 times per year on average. Again, the year 2018 was the year with the highest number of issued advisories with more than three times the average number in 2014-2020 (Table 6, Figure 4c).

Table 6. Total number of occurrences of issued advisories covering all days and districts ($NumDD_{tc}$) for 2011-2020.

	Grassland fire	**Forest fire**	**Water scarcity**	**High temp.**
2011	643	506	*	*
2012	1020	100	*	*
2013	749	967	*	*
2014	890	917	*	0
2015	*	*	*	0
2016	800	1595	*	245
2017	1362	1323	1519	20
2018	755	3144	2772	963
2019	1216	2025	1176	368
2020	1262	1894	1519	497
Avg.	966	1386	1746	299

*no data

5.1.2 Spatio-temporal analysis of single hazards

Generally, the WAs show different patterns with respect to their spatial and temporal distributions. The annual number of days with warnings at district level (Figure 5a) is ~35 on average with the lowest number in Jämtland (11) and the highest number in the coastal parts in Västerbotten and Norrbotten of (>60). The inner parts of Norrbotten, Västernorrland, Värmland and Bohuslän and Göteborg are the districts with relatively high number of issued warnings with >50 days per year. December and January are the months in which the whole country is more affected by warnings, especially along the south-western and north-eastern coastlines. During May and June northern Sweden experiences a higher frequency of warnings.

Advisories (Figure 5b) were mopst frequently issued in southern Sweden, especially in April, June, July and August, with the highest number of days (18) in July in Södermanland, where is also the most affected district at annual level with 118 days per year. In May, the affected districts are mainly distributed in middle and northern Sweden, in particular in the coastal areas of Västerbotten and Norrbotten. Very few advisories were issued in winter and none at all in January.

The most affected district issued with any kind of WA (Figure 5c) is Södermanland, with almost 150 days per year and 19 days in July. The coastal area of Västerbotten is also found to be with high risk with 19.3 days but in May.

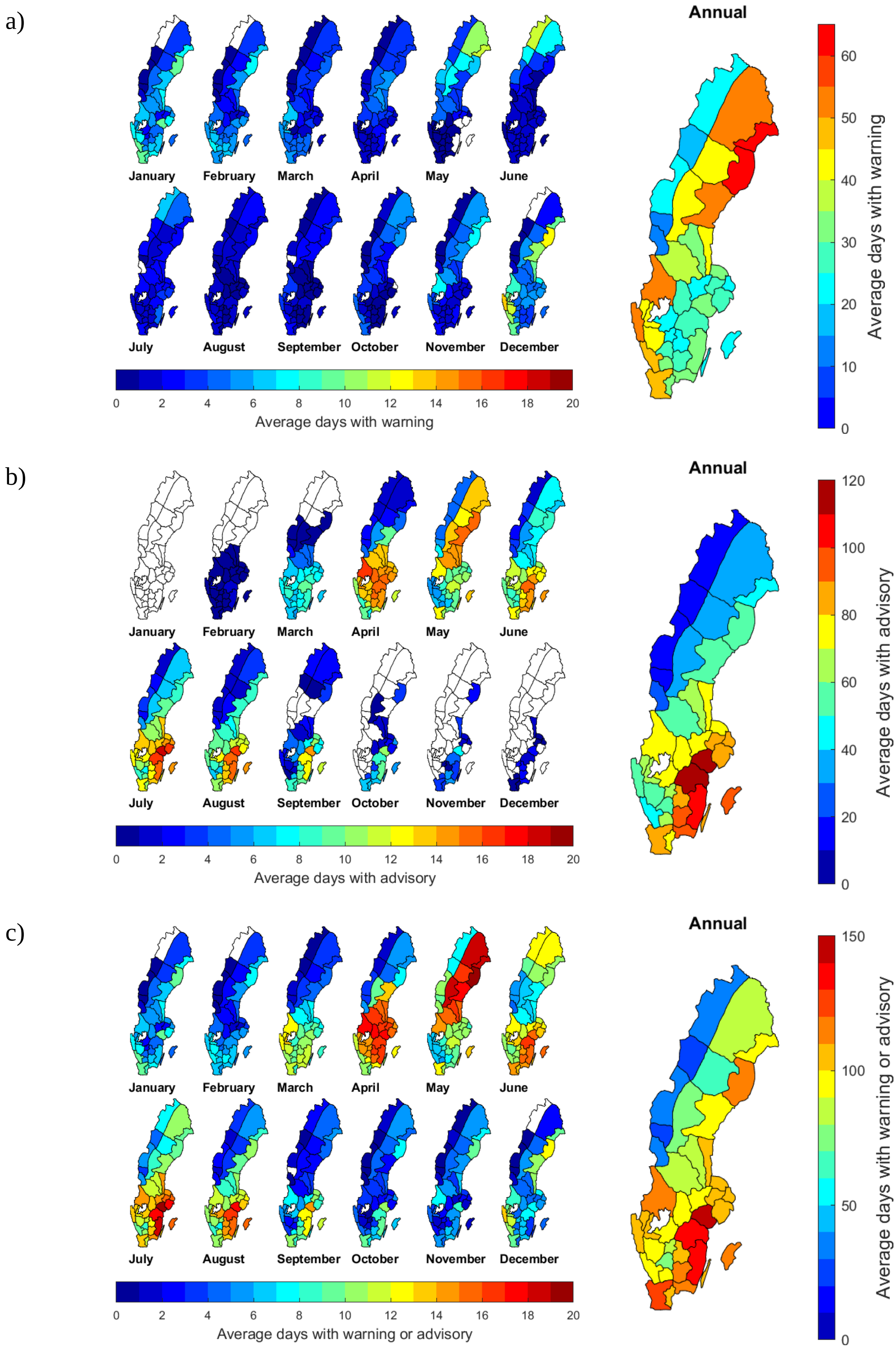


Figure 5. The spatial distribution of the monthly (left) and the annual (right) average number of days with any kind of warning (a), advisory (b) and warning or advisory (c) in the period 2011-2020. Note the different scales of the colour bars in the annual maps.

Figures 6 and 7 illustrate the average number of warnings and advisories issued for single natural hazards (of all classes) in every calendar month, i.e., NumDays per calendar months. Different types of WAs have shown different intra-annual variability.

The heavy rainfall warnings (Figure 6a) mainly occur from May to October (from 0.1 up to 1.4 warning days per month). July-October is the period in which the majority of the country is threatened by heavy rainfall, out of which higher-than-normal number of warnings are found in August, in particular for districts (1) along the east coast in northern Sweden and (2) along the west coast.

Compared to the heavy rainfall, the heavy snowfall warnings (Figure 6b) have been more often issued with on average 1-2 days in at least one district per month from November to March, particulary in December (e.g., Västernorrland and the coastal area in Västerbotten with >5 warning days on average) and January (e.g., central part of Sweden with >4 warning days on average). There are relatively fewer snow warnings in the mountain region as those that actually affect the mountain are in the excluded mountain weather category (section 2) and only those east of the mountains are included. For Norra Lapplandsfjällen there are then no snow warnings at all.

As shown in Figure 6c, high river flow warnings were issued every month of the year but with differences in frequency and spatial distribution. From December to March the warnings were issued for districts in southern Sweden, with a relatively high number along the south and west coasts. From June on, the risk of high river flow spreads towards the north, where the high river flow warnings occurred much more often in comparison with the rest of country, in particular from May to July. For the rest of the year high flow warnings were issued but with fewer numbers in general.

The warnings of strong wind gust (Figure 6d) were issued for the majority of the country except the Scandinavian mountainous regions (the five mountain districts marked grey in the figure). In the latter regions, wind gust warnings were included in the mountain weather warnings that were not included in this study (section 2). The monthly average value varied from almost 0 up to 1.3 days. From December to February relatively frequent strong wind gusts warnings were issued with the highest number in December with 3.7 days in Halland, Bohuslän and Göteborg. Gotland, Halland, Skåne and Österlen are the districts often at risk for strong wind gusts with more than 10 warning days per year.

Throughout the year, the warnings of thunder (Figure 6e) generally start in western and central Sweden in May and then spread to northern and eastern Sweden during the summer months. The average monthly frequency varied between 0.1 and 0.9 times/month. Skåne län utom Österlen, Halland and Sjuhäradsbygden in Västra Götaland are the districts with a higher frequency of thunder warnings (>2.4 times per year) in comparison to the rest of the country.

Warnings of high lake level (Figure 6f) were seldom issued with the maximum monthly frequency of 1.4 times in Dalarna in May. The warning of high ocean level (Figure 6g) is a frequently issued warning, in addition to the warnings of high river flow and heavy snowfall. Its maximum monthly frequency reached 9.1 times in the coastal districts of Västerbotten in December, followed by the coastal districts of Norrbotten with 8.1 times in the same month. The warnings often appeared during winter from November to February.

The high temperature warnings (Figure 6h) were not surprisingly only issued during summer (i.e., June-August). July is the month when the whole country except the mountainous regions has been affected by high temperatures. In general, the eastern part of Sweden, in particular Södermanland (> 5 times/year), is more endangered in comparison with the rest of Sweden.

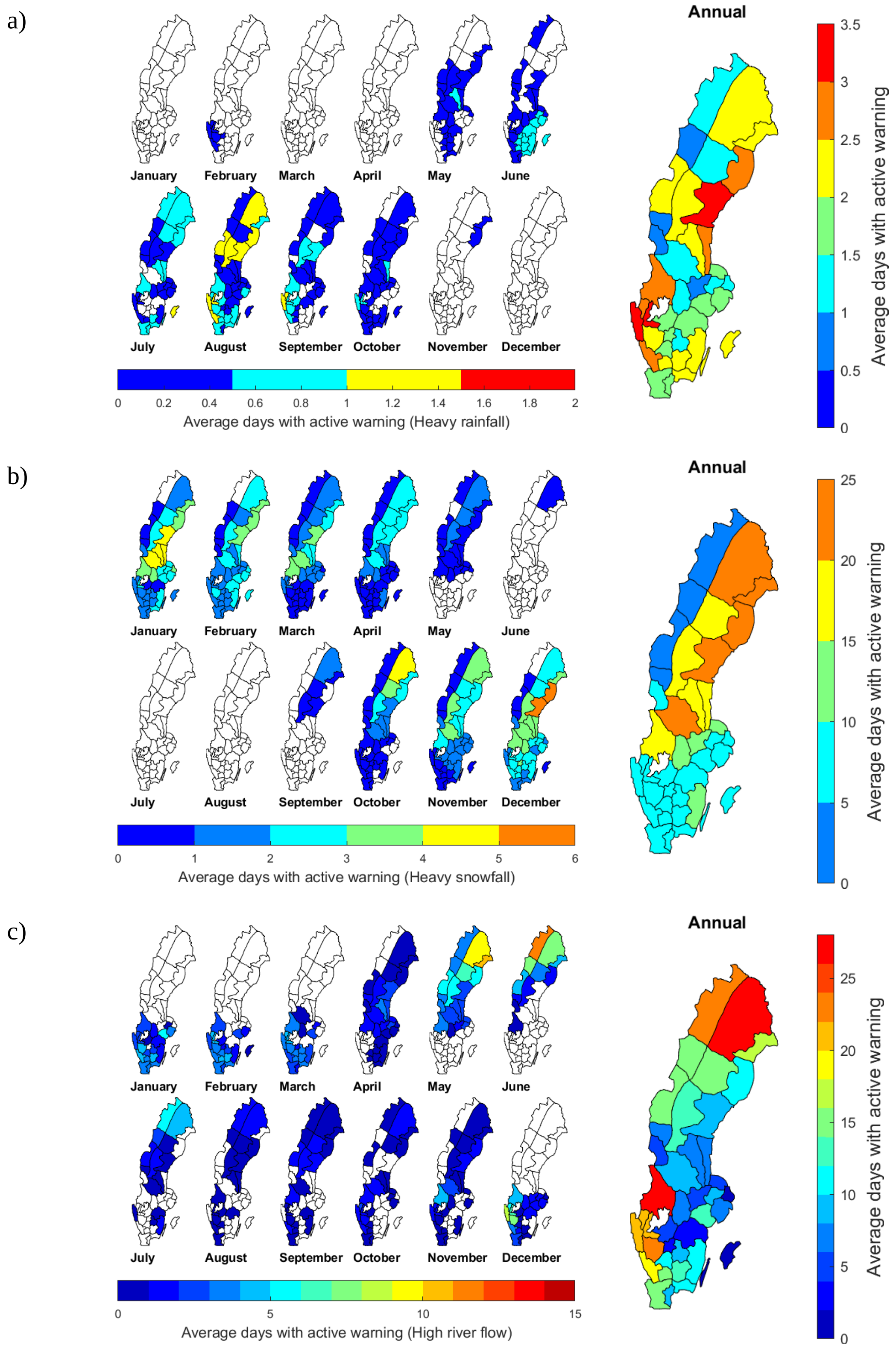
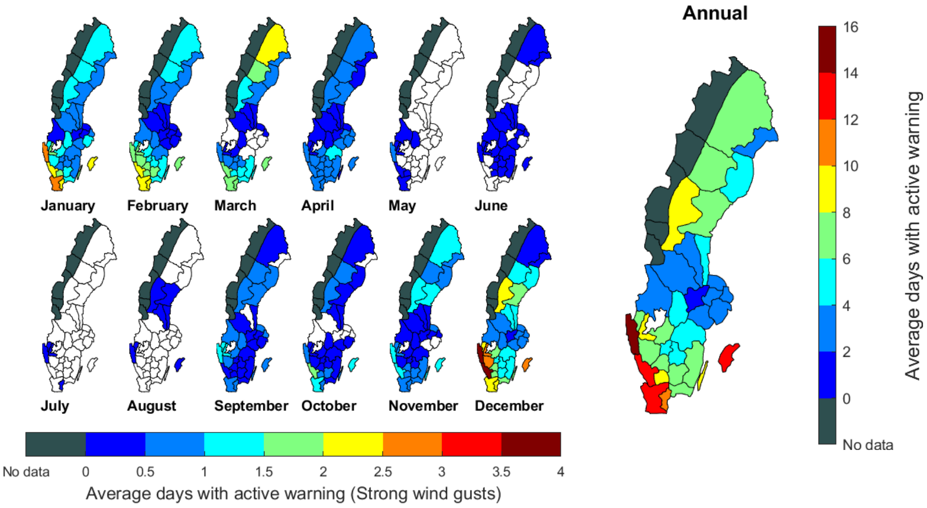
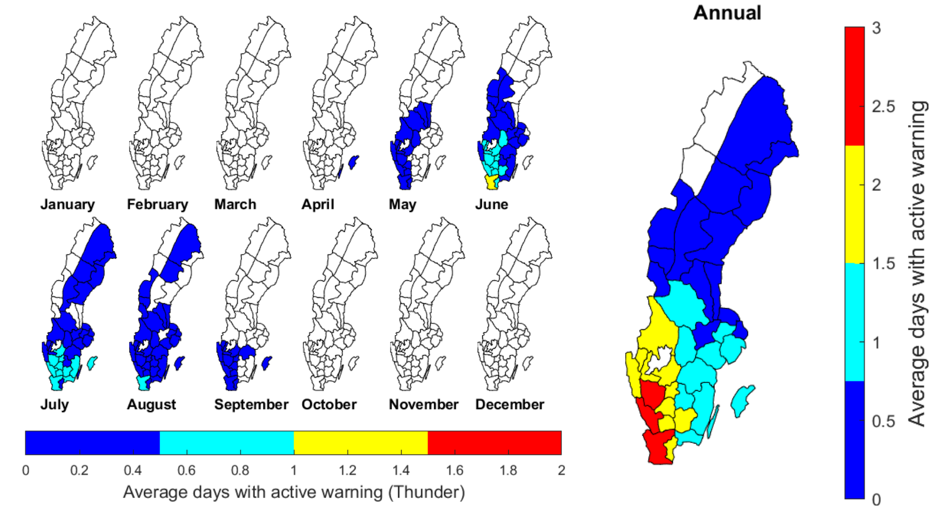


Figure 6. The spatial distribution of the monthly (left) and the annual (right) average number of days with warnings issued for heavy rainfall (a), heavy snowfall (b) and high river flow (c) in the period 2011-2020. Note the different scales of the colour bars.

d)



e)



f)

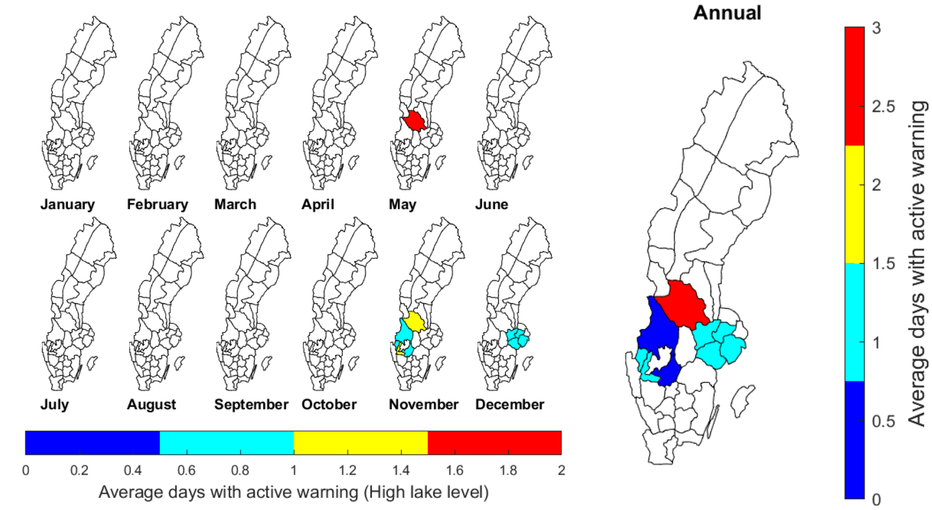
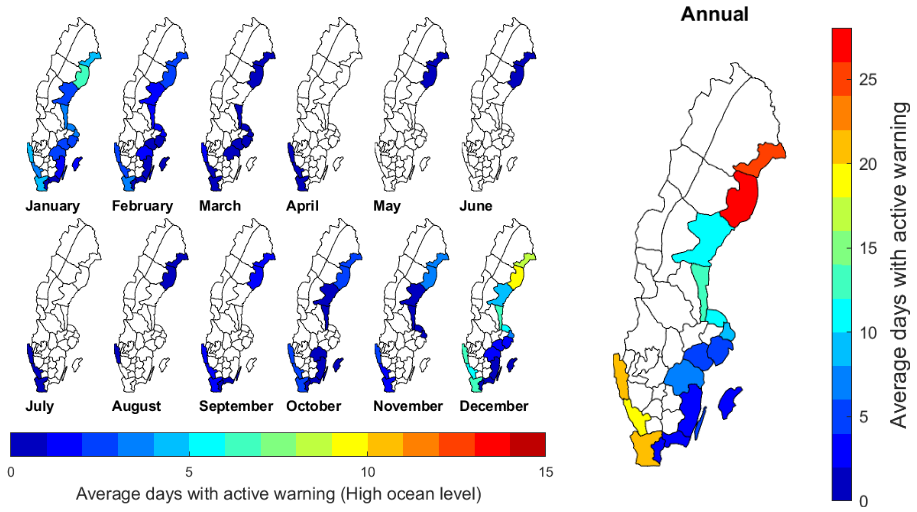


Figure 6. (continued) The spatial distribution of the monthly (left) and the annual (right) average number of days with warnings issued for strong wind gust (d), thunder (e) and high lake level (f) in the period 2011-2020. Note the different scales of the colour bars.

g)



h)

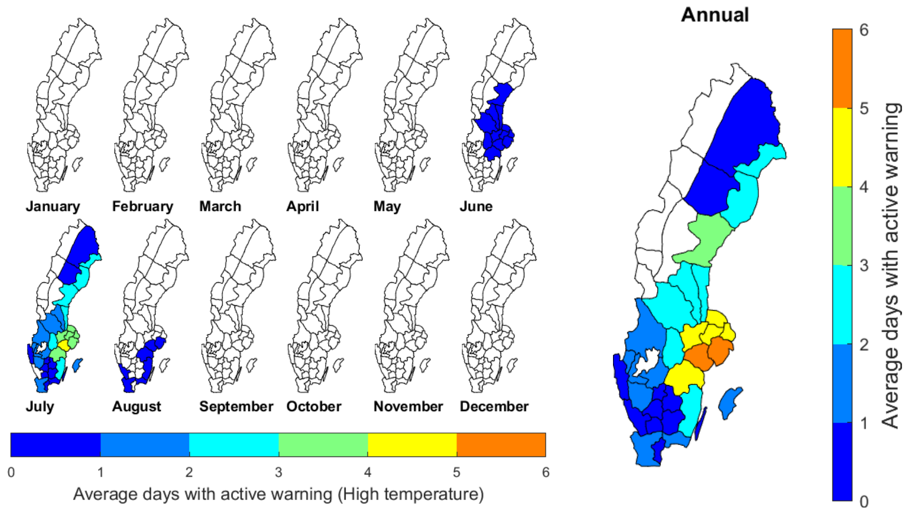


Figure 6. (continued) The spatial distribution of the monthly (left) and the annual (right) average number of days with warnings issued for high ocean level (g) and high temperature (h) in the period 2011-2020. Note the different scales of the colour bars.

The grassland fire season (Figure 7a) starts from southern and central Sweden in February and gradually spreads to the whole country during the spring. The high-risk months are April (central Sweden) and May (central and northern Sweden), with the highest number of around 17 advisory days per month. Gävleborg, Dalarna except mountainous area and Värmland exhibit high-than-normal risks (>34 days per year).

The forest fire season extends from April to October (Figure 7b). Due to different physical mechanisms its starting month is later than that of the grassland fire. Geographically, it starts from southern Sweden and then spreads towards north in May and finally influences the whole country. Its frequency reached maximum during the summer months (June-August) with a maximum value of >13 days per month. In contrast to the grassland fire, southern Sweden and especially south-eastern Sweden are the regions prone to forest fire, areas that may be affected by high temperatures during the same time. Södermanland, Östergötland, Kalmar and Gotland had more than 60 days of high temperature advisories per year.

Compared to the warnings of high temperature (Figure 6h), high temperature advisories (Figure 7c) were issued for a longer period from May to September. July is the month when the whole country (except part of the mountainous region) is likely to experience

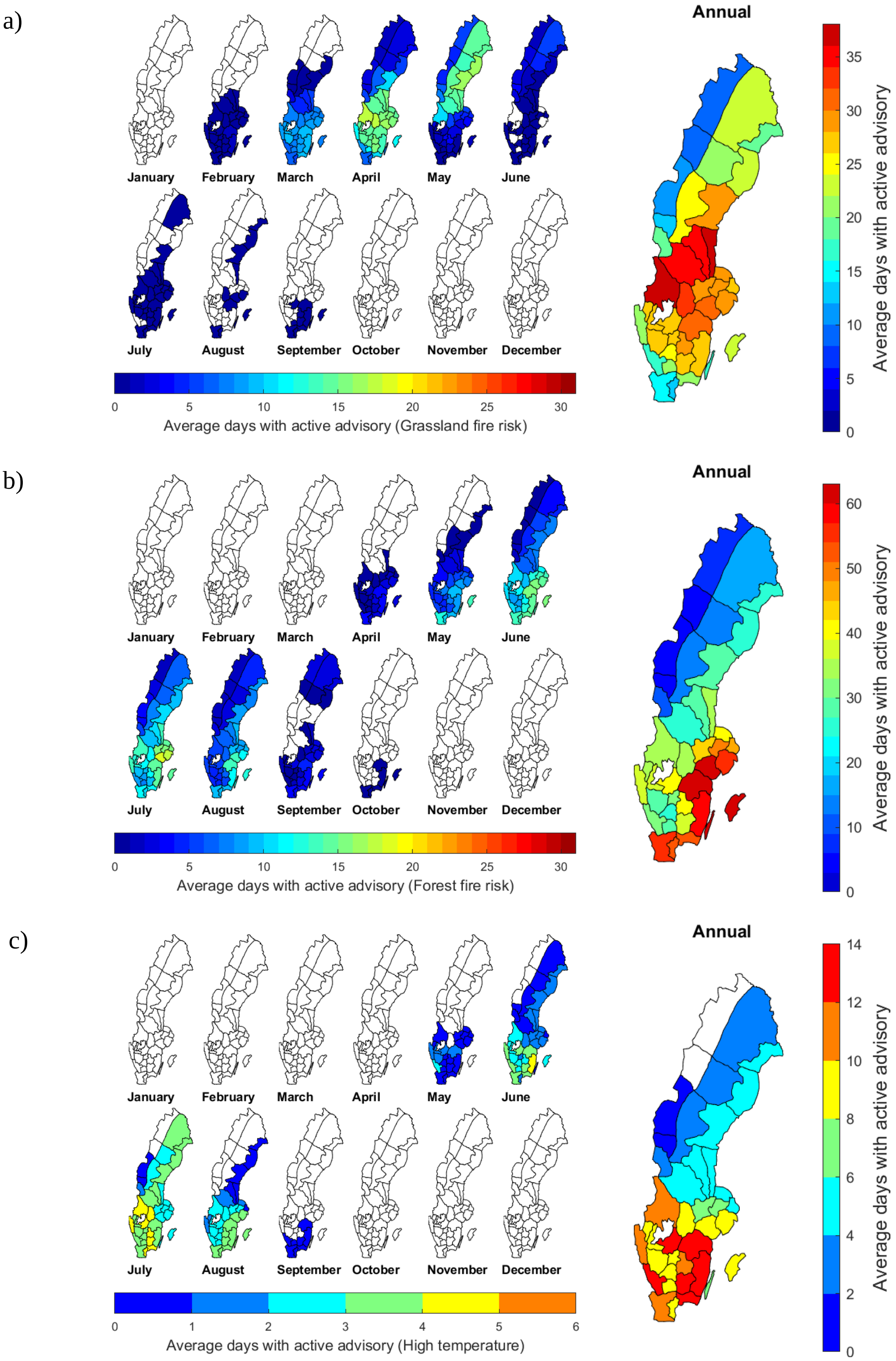


Figure 7. The spatial distribution of the monthly (left) and the annual (right) average number of days with advisories issued for grassland fire (a), forest fire (b) and high temperature (c) in the period 2011-2020. Note the different scales of the colour bars.

high temperatures. Similar to the warnings, the eastern part of Sweden is more endangered in comparison with the rest of Sweden. The high temperature advisories often d)

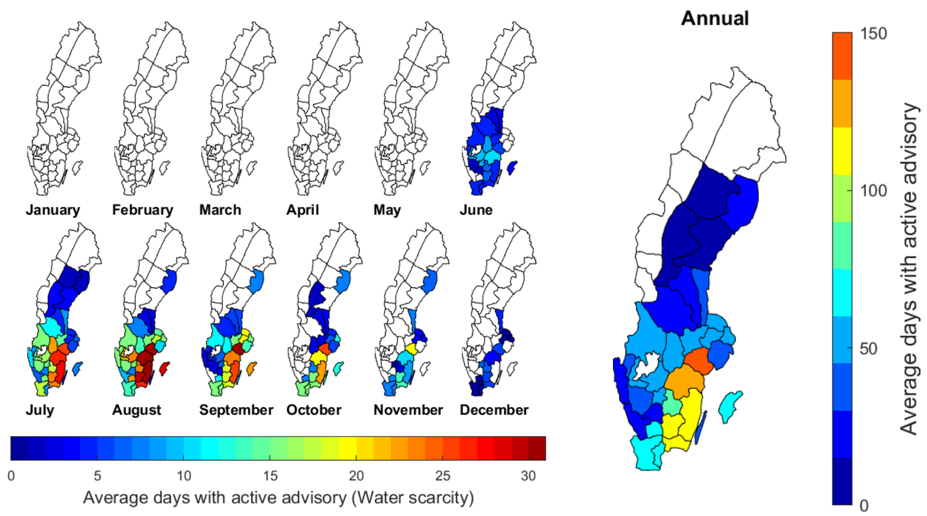


Figure 7. (continued) The spatial distribution of the monthly (left) and the annual (right) average number of days with advisories issued for water scarcity (d) in the period 2011-2020. Note the different scales of the colour bars.

appear in Kalmar in June and then spread towards the inland parts of southern Sweden, Värmland, Göteborg and Bohuslän in July.

The risk of water scarcity in watercourses (groundwater is excluded in this report, see section 2) mainly appeared in central and southern Sweden (Figure 7d) from June to December. Compared to northern Sweden, central and southern Sweden are more likely to experience low flows, in particular, the south-eastern districts. Södermanland, Östergötland and Kalmar appear as especially risk-prone regions where the number of days with issued advisories exceeded 25 days per month during July and August and above 119 days per year.

5.2 Warnings and advisories for multiple hazards

5.2.1 Multi-hazard metrics for double WA combinations

A case when either two warnings, two advisories or one warning and one advisory have been issued on the same day in the same district will hereafter be generally denoted a “double WA”. In this section, the multi-hazard metrics defined in section 0, i.e. $NumDD_{t12}$, $NumDays_{t12}$, $NumDistrics_{t12}$, $AvgDistricts_{t12}$ (in the following used without the subscript), are summarized in Tablkes 7 and 8 for all double WA combinations.

The values of the metric, NumDD, reflecting how common the different WA combinations are overall, are shown above the diagonal in Table 7. If first looking only at combinations of two warnings (i.e. inside the highlighted box in the top left part of Table 7), the most common combinations include high ocean level, together with strong wind gusts (390 occasions), heavy snowfall (249) or high river flow (158). Also, high river flow in combination with strong wind gusts (177) and heavy snowfall (155) are common combinations, followed by heavy snowfall and strong wind gusts (100) and heavy rainfall and high river flow (93).

When including also advisories in the analysis, the numbers increase substantially and the most common combinations include forest fire, together with either water scarcity (2463 occasions) or high temperature advisory (1825). Also, the combination of forest and grassland fire is worth mentioning, with 375 occasions. The most common combinations of one warning and one advisory are high river flow and grassland fire (761) and high temperature (W) and water scarcity (251).

Next, we look at metric NumDays, that indicates how many days in total the WA combination happened anywhere in Sweden. The values are given below the diagonal in Table 7. When considering only warnings, the same combinations as for NumDD stand out, i.e. high ocean level together with strong wind gusts (165 days, i.e. on average ~2 weeks per year during the 10-year study period), heavy snowfall (108) or high river flow (80). The combination of warning and advisory issued on most days was high temperature (W) together with forest fire (42), followed by high river flow and grassland fire (178). For two advisories, the combination of forest fire and water scarcity had the highest number (283).

The metric NumDistricts, presented above the diagonal in Table 8, shows how many out of the 40 districts that experienced the WA combination sometime during 2011-2020. When considering only warnings (i.e. the values inside the highlighted box in the top left part of Table 8), the highest number of districts (31) is found for the combination of heavy snowfall and strong wind gusts. More than half of all districts have also experienced high river flow in combination with either heavy snowfall (26 districts), strong wind gusts (24) or heavy rainfall (23).

Concerning combinations of one warning and one advisory, more than 30 districts (i.e. >75% of all districts) have experienced grassland fire together with either heavy snowfall (34 districts) or high river flow (33), and forest fire together with either thunder (32) or high temperature (W) (34) (Table 8). Looking at only advisories, 38 districts, i.e. virtually all of Sweden, have experienced the combination of high temperature (W) and forest fire. Other notable combinations are forest fire and grassland fire (36 districts) and water scarcity together with either high temperature (W) (33) or forest fire (33) (Table 8).

Finally, the metric AvgDistricts, shows the number of districts affected when this WA combination is active, i.e. it can be seen as a measure of the spatial extension of the multiple hazard (Table 8, below diagonal). When only warnings are involved, more than three districts are generally affected for the combination of high river flow and strong wind gusts (3.8 districts) and the combination of thunder and high temperature (3.5) (the latter is however an unusual combination that only occurred seven times during the study period; table 8). Several combinations generally affect more than two regions (Table 8).

When including also advisories, the combination of forest fire and high temperature (A) stands out with 13 districts (i.e. almost 1/3 of Sweden) typically affected on days when this combination is active. High values are also found for the combinations of water scarcity together with either high temperature (A) (9.9) or forest fire (8.7). High temperature (W) in combination with water scarcity (8.1) and high temperature (A) (5.5) are the most notable combinations of one warning and one advisory, and also the combination of high river flow and grassland fire generally affect more than four districts (4.3).

5.2.2 Spatio-temporal analysis of multiple hazards

To identify the districts or regions that are most prone to the risk of multiple hazards, we counted the co-occurrence of different warnings and advisories issued on the same day in the same district. By far, the most common situation is to have two overlapping WAs on the same day in the same district, i.e. a double WA. However, several cases of three overlapping WAs (“triple WA”) was found and even a few cases of four overlapping WAs (“quadruple WA”). The total number of days with triple WA reaches >20 in the southwestern districts, with the most common combination being high river flow, high ocean level and strong wind gusts. These rare triple and quadruple WAs are further described in Appendix C.

Table 7. A summary of the overlap between all “double WAs” during 2011-2020. Above diagonal: NumDD, i.e. the total number of occurrences of this combination. Below diagonal: NumDays, i.e. the total number of days when this combination occurs in at least one district. Bold text = warnings; normal text = advisories.

	High lake level	**High river flow**	**High ocean level**	**Strong wind gust**	**Heavy snowfall**	**Heavy rainfall**	**Thunder**	**High temp. (W)**	Grassland fire	Forest fire	Water scarcity	High temp. (A)	
High lake level		**72**	**0**	**0**	**0**	**0**	**0**	**0**	13	4	0	0	NumDD: total no. of overlaps in all days and districts.
High river flow	**46**		**158**	**177**	**155**	**93**	**1**	**0**	761	42	4	10	
High ocean level	**0**	**80**		**390**	**249**	**8**	**0**	**0**	13	9	51	0	
Strong wind gust	**0**	**47**	**165**		**100**	**17**	**0**	**0**	64	20	66	0	
Heavy snowfall	**0**	**65**	**108**	**47**		**0**	**0**	**0**	120	0	15	0	
Heavy rainfall	**0**	**39**	**4**	**7**	**0**		**5**	**0**	5	41	27	1	
Thunder	**0**	**1**	**0**	**0**	**0**	**2**		**7**	1	115	38	25	
High temp. (W)	**0**	**0**	**0**	**0**	**0**	**0**	**2**		0	423	251	116	
Grassland fire	13	178	5	17	35	3	1	0		375	55	19	
Forest fire	4	26	6	7	0	22	39	42	93		2463	1825	
Water scarcity	0	2	34	20	9	11	13	31	15	283		793	
High temp. (A)	0	5	0	0	0	1	10	21	8	140	80		
	NumDay: total no. of days when overlap occurs in at least one district.												

Table 8. A summary of the overlap between all “double WAs” during 2011-2020. Above diagonal: NumDistricts, i.e. the total no. of districts when overlap occurs on at least one day. Below diagonal: AvgDistricts, i.e. the average no. of districts when overlap occurs in at least one district. Bold text = warnings; normal text = advisories.

	High lake level	**High river flow**	**High ocean level**	**Strong wind gust**	**Heavy snowfall**	**Heavy rainfall**	**Thunder**	**High temp. (W)**	Grassland fire	Forest fire	Water scarcity	High temp. (A)	
High lake level		**8**	**0**	**0**	**0**	**0**	**0**	**0**	1	1	0	0	NumDistricts: total no. of districts when overlap occurs on at least one day.
High river flow	**1.6**		**9**	**24**	**26**	**23**	**1**	**0**	33	10	2	4	
High ocean level	**0**	**2**		**16**	**16**	**4**	**0**	**0**	8	5	7	0	
Strong wind gust	**0**	**3.8**	**2.4**		**31**	**9**	**0**	**0**	25	11	22	0	
Heavy snowfall	**0**	**2.4**	**2.3**	**2.1**		**0**	**0**	**0**	34	0	7	0	
Heavy rainfall	**0**	**2.4**	**2**	**2.4**	**0**		**5**	**0**	4	16	10	1	
Thunder	**0**	**1**	**0**	**0**	**0**	**2.5**		**7**	1	32	22	20	
High temp. (W)	**0**	**0**	**0**	**0**	**0**	**0**	**3.5**		0	34	27	31	
Grassland fire	1	4.3	2.6	3.8	3.4	1.7	1	0		36	15	13	
Forest fire	1	1.6	1.5	2.9	0	1.9	2.9	10.1	4		33	38	
Water scarcity	0	2	1.5	3.3	1.7	2.5	2.9	8.1	3.7	8.7		33	
High temp. (A)	0	2	0	0	0	1	2.5	5.5	2.4	13	9.9		
	AvgDistricts: average no. of districts when overlap occurs in at least one district.												

Cases of double warnings occurred in every month but most frequently in winter (December-January) and least frequently in June (Figure 8a). For the risk-prone districts along the west coast the combination of high ocean level and wind gusts is the most common double warning, followed by the combination of high ocean level and high river flow. For the risk-prone districts along the north-east coast the most common double warning is again the high ocean level but with heavy snowfall, followed by the combination of high ocean level and strong wind gusts.

The cases of double advisories often occurred from April to October with a high frequency in summer. The hotspot regions appear to be south-eastern Sweden (Figure 8b). The most common combination is water scarcity and forest fire, followed by high temperature and forest fire. Both combinations are likely to occur during July and August.

The annual average number of days with combinations of one warning and one advisory ranged from up to 22 in southwestern Sweden (i.e., Bohuslän and Göteborg, Halland and Skåne utom Österlen) to a few single days in other districts (Figure 8c). Cases are found in every month but with a high frequency in southern Sweden in summer (June-August) and in northern Sweden in May. Districts along the north-east coast (i.e., Västerbottens kustland and Norrbottens kustland) experienced ~18 days per year. The most common combination in the north is high river flow and grassland fire, followed by high temperature (warning) and forest fire in the south.

6 Hydrology-related multiple hazards

In this section we will focus on the risk of multiple natural hazards, i.e. double WAs, from a hydrological perspective, using the multi-hazard metrics listed in section 4: NumDD, NumDays, NumDistricts and AvgDistricts. We consider both high flows and low flows from different perspectives and three combinations were selected for in-depth analysis:

- Two warnings: high river flow combined with heavy rainfall. This combination is of particular interest due to the increased likelihood of heavy rainfall under the changing climate. Rainfall might occur as an independent event coupled with extended periods of high river flow and finally cause a combination of pluvial and fluvial flooding.
- One warning and one advisory: high river flow combined with grassland fire. This was selected primarily as it is the most common combination of one warning and one advisory according to NumDD (Table 7). Furthermore, it is a somehow unexpected combination as it intuitively represents a situation with both wet and dry conditions at the same time.
- Two advisories: water scarcity combined with forest fire. This combination stands out very clearly as the most common combination when all WAs are considered, with almost 2500 occasions (i.e., NumDD) registered (Table 7). This is likely due to long period of water scarcity and large affected areas. Water scarcity has come into particular focus in recent years due to the droughts in 2016 and 2018.

6.1 High river flow and heavy rainfall

Compared to the other double WAs, the combination of high river flow and heavy rainfall shows a relatively large number of affected regions in terms of both NumDistricts (23) and AvgDistricts (2.4) (Table 8). Also, the overall occurrence was relatively high with NumDD=93 and there were 39 days (i.e. NumDays) when this double WA was active in at least one district (Table 7).

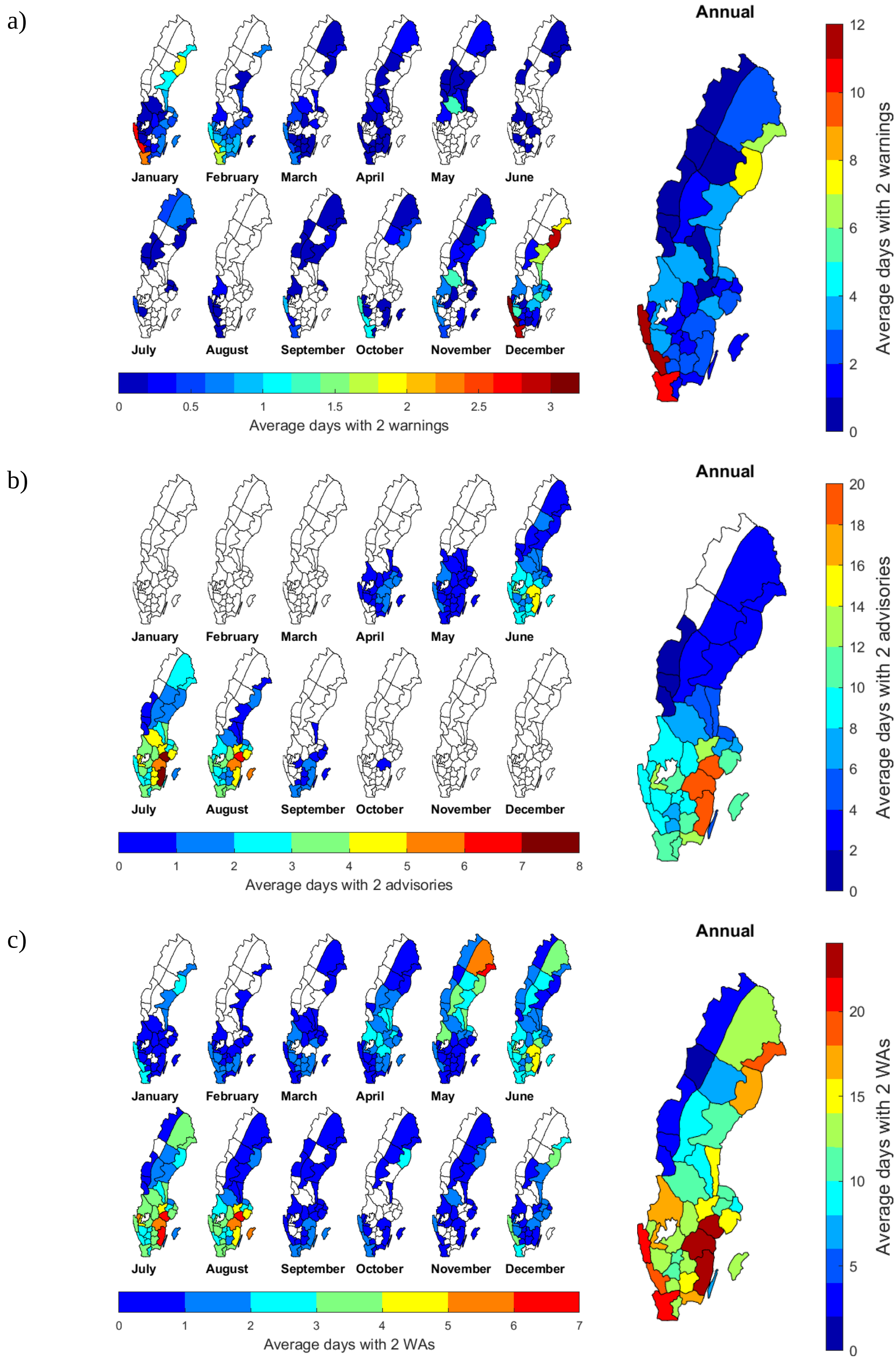


Figure 8. The spatial distribution of the monthly (left) and the annual (right) average number of days with different types of double WA in the period 2011-2020: two warnings (a), two advisories (b) and one warning and one advisory (c). Note the different scales of the colour bars.

May to October is the main period when this double WA occurred from 2011 to 2020. As seen from Figure 9, the frequency of this combination is very limited, <1 day per month. The occurrences appeared in different districts and in different months, except in January, March, April, June and December when no any occurrence was found. Overall, the districts with relatively high risk are mainly located (1) along the west coast in October, (2) in central Sweden in May and (3) in northern Sweden in July.

A period with the combination of high river flow warning and heavy rainfall warning in 2014 is given as an example in Appendix D (see Figure D1).

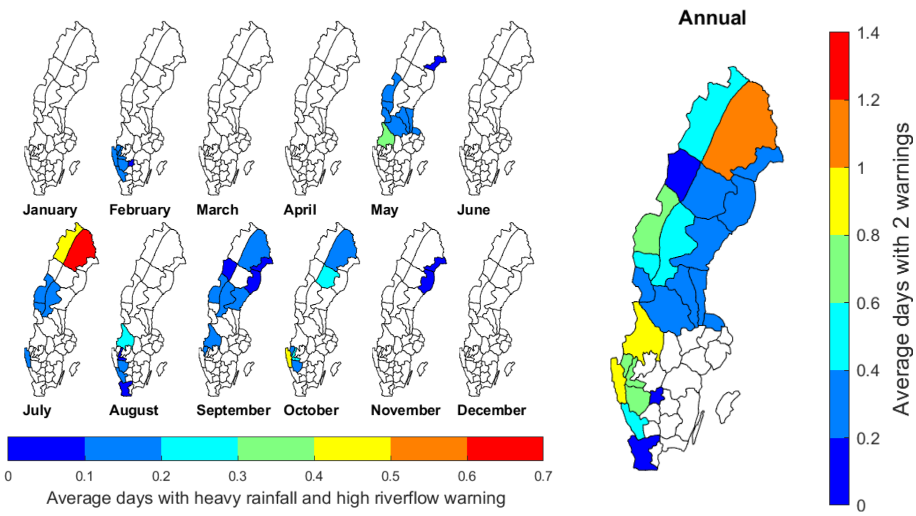


Figure 9. The spatial distribution of the monthly (left) and the annual (right) average number of days with the combination of high river flow and heavy rainfall warning in the period 2011-2020.

6.2 High river flow and grassland fire

During 2011-2020 there were in total 761 occurrences of the combination high river flow warning and grassland fire advisory (NumDD). In terms of NumDays, 178 days experienced the WA combination in at least one district (Table 7). Concerning the corresponding influencing areas, on average 4.3 districts (i.e., AvgDistricts) experienced the WA combination (i.e. ~10% of all districts) (Table 8). It is found that in 2018, the year with record-high number of issued wildfire advisories and second record-high number of issued high river flow warnings, the number of days when high river flow warnings and fire advisories co-occurred reached the highest value of 35 days (i.e., approximately 20% of all days with this double WA in the analysis period). The corresponding affected area reached 7.9 districts which is almost double the average affected districts in the same period (not shown here).

This double WA occurs from February to June, from southern Sweden with a relatively high risk in March (~2 days on average), and then spreads northward to northern Sweden. The highest risk appeared in May with up to seven days per month for the coastal district in Norrbotten. In terms of its affected area, April stands out as the month in which almost all of Sweden has experienced this double WA, except in the southwestern regions and in the mountain chain (Figure 10).

An example showing the combination of high river flow warning and heavy rainfall warning in 2014 is given in Appendix D (see Figure D2).

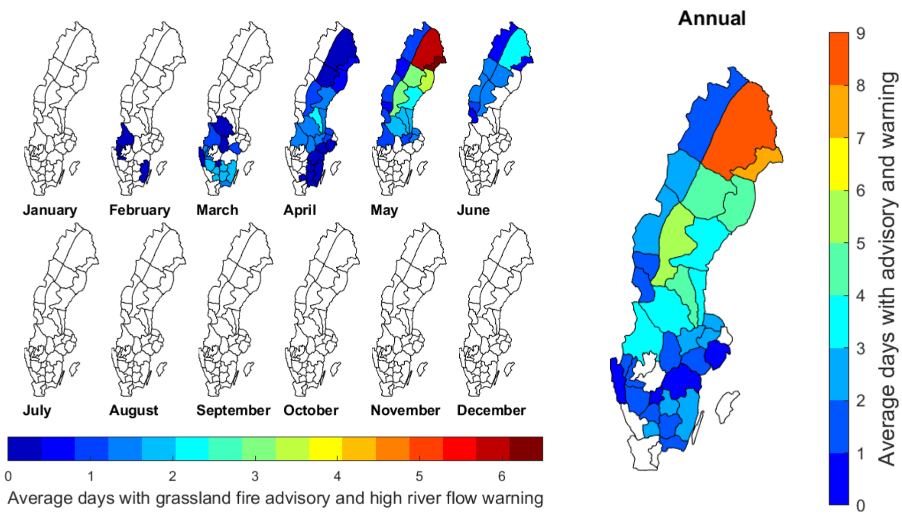


Figure 10. The spatial distribution of the monthly (left) and the annual (right) average number of days with the combination of high river flow warning and grassland fire advisory in the period 2011-2020.

6.3 Water scarcity (low river flow) and forest fire

Water scarcity is a new advisory recently added to the forecast system and only four years of data were therefore available for this study (2017-2020). Nevertheless, in combination with forest fire it represents the most common double WA according to NumDD (Table 7). Out of the 1461 days in the 4-year period, on 283 days this double WA was active in at least one district (i.e., NumDay in Table 7). This WA combination has affected 33 districts (NumDistricts, Table 8) in the study period, with on average almost nine districts being affected when the double WA is active in at least one district (AvgDistricts, Table 8), which makes this one of the most spatially extensive WA combinations.

As seen from Figure 11, the overlaps between water scarcity and forest fire normally starts from June and lasts till October, peaking during the summer months (i.e., June-August). July stands out as the month when this double WA has been active in most of Sweden, except in the mountain chain and in the very north. In particular the districts in south-eastern Sweden are a hot-spot where the frequency of occurrence exceeds half the month in July and August.

Figure D3 in Appendix D shows an event with combined water scarcity and forest fire advisories in 2018.

7 Summary and conclusions

Warnings and advisories (WA) issued by SMHI in the period 2011-2020 have been compiled and analyzed. The data preparation included digitization and various components of quality control and assurance. The analysis was simplified by converting the recorded WAs to an indicator (binary) matrix format on day and district scale. Thus, even if a WA was active for only a part of the day or in a part of the district, it was assigned to that (whole) day and that (whole) district. The investigation included both single-hazard analysis, by investigating the occurrence of single WAs, and multi-hazard analysis, by investigating mainly the occurrence of combinations of two WAs (double WA). We have focused primarily on hydrological WAs.

The main findings for single hazards with focus on hydrology include:

- Concerning the overall number of affected districts and days, NumDD, warnings of high river flow and heavy snowfall, were the most common warnings, with on

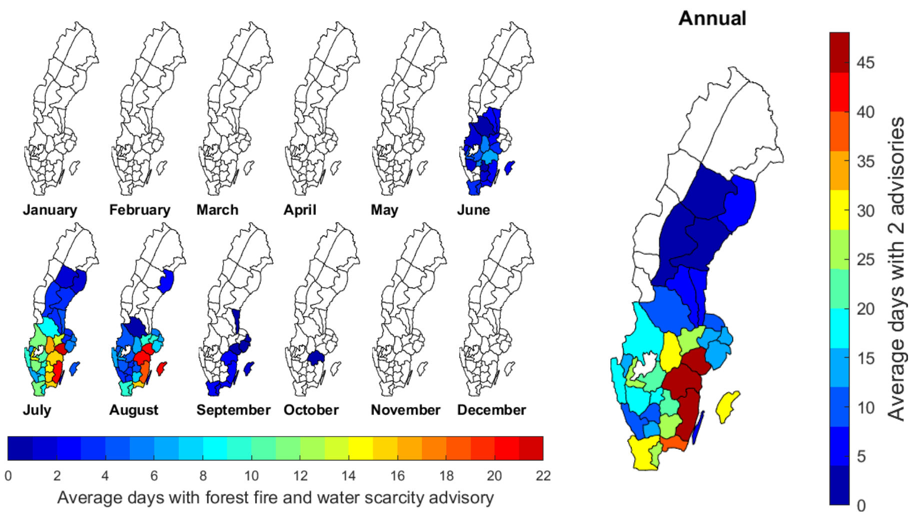


Figure 11. The spatial distribution of the monthly (left) and the annual (right) average number of days with the combination of forest fire and water scarcity advisory in the period 2011-2020.

average more than 400 warnings issued per year. Also, warnings of strong wind gusts and high ocean level were issued more than 200 times per year on average.

- Advisories, except high temperature advisories (NumDD = 299), were more frequently issued when compared with the different types of warnings, with on average ≥1000 advisories issued per year (i.e., 1746 times for water scarcity, 1386 times for forest fire and 966 times for grassland fire).
- From December to March, high river flow warnings were mainly issued for districts in southern Sweden with a relatively high number along the south and west coasts. From April on, the same type of risk spread towards the north, where high river flow warnings occurred much more often in comparison with the rest of the country and reached the annual peak from May to July in connection with the spring flood. For the rest of the year high flow warnings were issued but with fewer numbers in general.
- Heavy rainfall warnings mainly occurred from May to October. July-October is the period in which the majority of the country is affected by heavy rainfall. Higher-than-normal number of warnings were issued particularly in August and particularly for districts along the east coast in northern Sweden and the west coast in southern Sweden.
- Heavy snowfall warnings were often issued with on average 1-2 days in at least one district per month from November to March, in particular in December (e.g., Västernorrland and the coastal area of Västerbotten with >5 warning days on average) and January (e.g., central part of Sweden with >4 warning days on average).
- The risk of water scarcity in watercourses mainly appeared in the central and southern part of Sweden from June to December. In particular, the south-eastern districts Södermanland, Östergötland and Kalmar appear as more risk prone regions where the number of days with issued advisories reached high during July and August.
- Year 2018 was the year with a record-high number of issued forest fire advisories, water scarcity advisories and high temperature warning. It was also

the year with the second highest number of issued high river flow warnings, likely due to relatively heavy snowfall in winter 2017-2018.

The main findings for double (overlapping) WAs are summarized in the following, with focus on hydrology and warnings:

- Concerning two overlapping warnings, the districts along the west coast (i.e., Bohuslän and Göteborg, Halland and Skåne utom Österlen) and the north-east coast (i.e., Västerbottens kustland and Norrbottens kustland) were most affected, in particular during winter (December-February).
- The most common combination according to metrics NumDD and NumDays was high ocean level together with strong wind gusts. The two single warnings included showed fairly high inter-annual variability.
- The main warning combination including hydrology was that of high river flow and strong wind gusts, which showed up high in all metrics. The most affected districts are located along the west coast in southern Sweden, where the combination occurred up to once per month in in February and December.
- Concerning the combination of one warning and one advisory, the districts along the south-eastern coast in July and August were found most affected, followed by the districts along the north-east coast. High river flow warning combined with grassland fire advisory ia a hydrology-related multiple hazard that came up high in all metrics.
- The combination between water scarcity and forest fire stands out as the most frequent combination of two advisories.

The overlap between high river flow and heavy rainfall warnings came up high in terms of affected districts (NumDistricts and AvgDistricts) and thus normally affected large areas. It appeared from May to October but with low frequency, less than day per month. It is especially “hydrologically problematic”, as when high river flow coincides with heavy rainfall, simultaneously or successively, the infrastructure may be damaged or corresponding preparedness is inadequate in case the combined risk is overlooked. Three regions were found associated with relatively high risk: (1) the western coastal districts in October, (2) central Sweden in May and (3) northern Sweden in July.

Also, the combination between high river flow and high ocean level deserves to be mentioned and described as a notable warning combination, as it comes up quite high in terms of both NumDD and NumDays. It is also hydrologically problematic in coastal regions, where total water levels may be influenced by both processes. The consideration of this type of double WA is important for designing flood protection infrastructure and drainage in affected regions. In Sweden, it mainly occurs in the districts along the west and south coast (October to March), the south-east coast (January and February) and the north-east coast (June, October and November). The results show that Halland, Bohuslän and Göteborg in Västra Götaland and Skåne län utom Österlen were the most influenced with a ferquency >4 times/year. Especially, in February in Skåne län utom Österlen the monthly occurrence is almost twice per month.

The double WA of high river flow warning and grassland fire advisory starts from southern Sweden with relatively high risk in March and then spreads northward to northern Sweden. The highest risk appeared in May, with up to seven days per month for the coastal district in Norrbotten. April is a hotspot month, as nearly all of Sweden has experienced this double WA in April, except in the south-western regions and in the mountain chain. This WA was found to often affect large areas and it is likely to occur due to snow melt from February to June.

As mentioned above, water scarcity shows a strong link to the forest fire hazard with frequent overlap. This combination of advisories normally starts in June and ends by

October, peaking during the summer months (June-August). July stands out as the month when this double WA were active in most of Sweden, except in the mountain chain and in the very north. In particular the districts in south-eastern Sweden are a hotspot where the frequency of occurrence exceeds half the month in July and August.

To conclude, exploring the spatio-temporal distributions of warnings and advisories is a way to identify risk-prone regions and seasons. This may help municipalities and rescue services to make up infrastructure plans and precaution strategies so as to maximize the capability and avoid potential disasters. Furthermore, the results may be used as a basis to identify topics of special interests for different purposes, e.g., acquire a deeper understanding of the involved processes, develop tailored indicators, etc.

The results show that high river flow and high ocean level are often one of the single hazards involved in overlapping combinations (double WAs) in a Swedish context. They may co-occur with other single hazards such as strong wind gusts, heavy snowfall, etc., and trigger different kinds of compound events causing a stronger-than-expected impact. Also, more attention should be given to advisories of forest fire and water scarcity, that are frequently issued.

As the climate varies naturally from one year to the next, sufficiently long time series (i.e., ≥30 years) are always required in order to capture different kinds of forcing that may have effects on climate system. The limited length of data on warnings and advisories in this study (10 years) means that we cannot draw any firm conclusions in terms of how certain parts of Sweden are affected by different kinds of natural hazards and their combinations, only find indications. Thus, the presented results, e.g. in terms of regional patterns, are to some extent affected by samling uncertainties.

Further research is needed confirm the findings in this report as well as to focus on different multiple and/or compound events in order to deepen the knowledge of the underlying physical processes and driving forces. Model data such as ensemble forecasts and climate projection can be used for assessment on different time horizons, aiming at developing early warnings and alerts as well as estimating changes in frequency, severity and seasonality of multiple hazards. We believe such efforts should be a key component in analyses for adaptation towards a climate-proof society.

Acknowledgements

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APPENDIX A

Analysis of durations of single WAs

As described in section 4.1, the WAs extracted from the KEPS system contained short-lived, “false” WAs that were just updates of an existing WA and not a new WA. To eliminate as many as possible of the false WAs, it was decided to use a lower “duration threshold” below which a WA is considered false. Figure A1 illustrate how the false WAs influence the distributions (histograms) of single natural hazards’ durations at sub-daily scale. They show the total number of entries in the KEPS outtake 2011-2020 of any class of the type of warning, for durations between 0 and 24 hours.

As the data will be aggregated to a daily scale, the first step is to construct a matrix $A_{tc}^{d}(i,j)$ of all active warnings of type t and class c on day i in district j, of a duration longer than the duration threshold d. To study the impact of the threshold d, the KEPS outtake was traversed and if the duration of an entry is more than d=0, 1, 2, etc., hours, $A_{tc}^{d}(i,j)$ is increased by 1 for the districts and days where it was active. Table A1 shows the sum of $A_{tc}^{d}(i,j)$ over all days, districts and classes for d=1 to 12 hours.

The analysis then uses the indicator matrix $S_{tc}(i,j)$ (section 4.2.1), which is 1 if $A_{tc}^{d}(i,j)>0$ and 0 otherwise. Table A2 shows the sum of $S_{tc}(i,j)$ over all days, districts and classes of each WA type (this is metric NumDD summed over all classes). Some WA types have a large difference between Table A1 and A2, e.g. high river flow has a sum that is almost twice as high in Table A1. This is mainly because those warnings are extended on most days and then produce two active warnings in a day in KEPS, although it is the same warning.

The bars in figure A1 are approximately the difference between two adjacent columns in Table A1 and is more loosely related to the difference between the columns of Table A2. As can be seen in the histograms and Table A2, warnings related to slow processes like high river flow and high temperature are fairly independent of the duration threshold at a sub-daily scale from one or a few hours and up. The meteorological warnings have a much more gradual decay.

To choose a single duration threshold for all WAs means to strike a balance between two risks; on one hand including too many suspicious warnings for types associated with slow processes, and on the other hand excluding too many “true” warnings for short-lived meteorological hazards. From the sums in Table A2, a duration threshold of 2 hours appears to be appropriate as (1) the number of WAs of slow processes stabilizes for longer durations and (2) most of the numbers associated with short-lived WAs have not started to decay sharply. The 2-hour duration threshold was also discussed and agreed with the reviewers of the report, and we believe that the final indicator matrix $S_{tc}(i,j)$ well reflect the spatio-temporal characteristics of only true warnings.

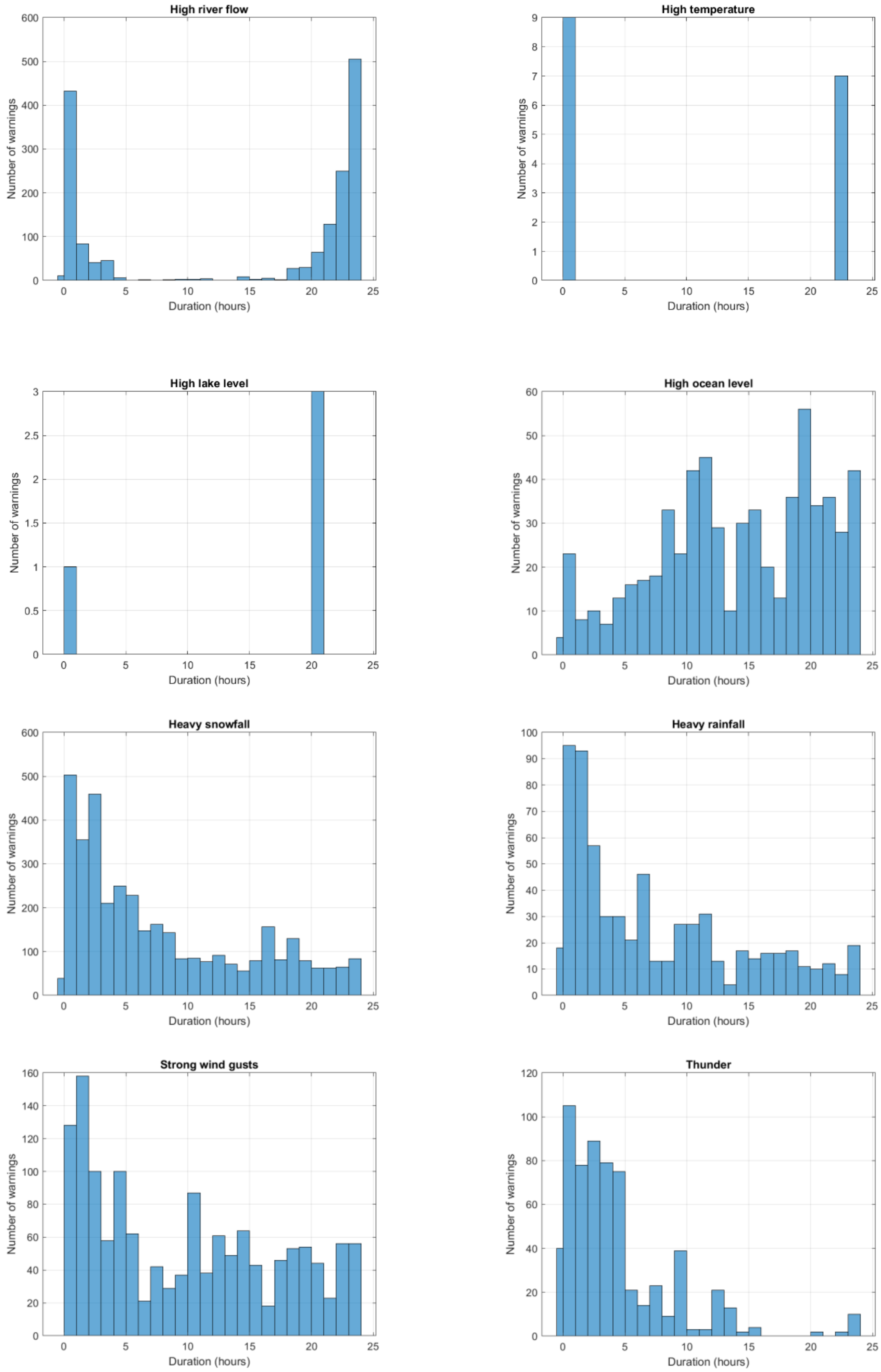


Figure A1. Histograms of durations of single warnings that were active less than 24 hours.

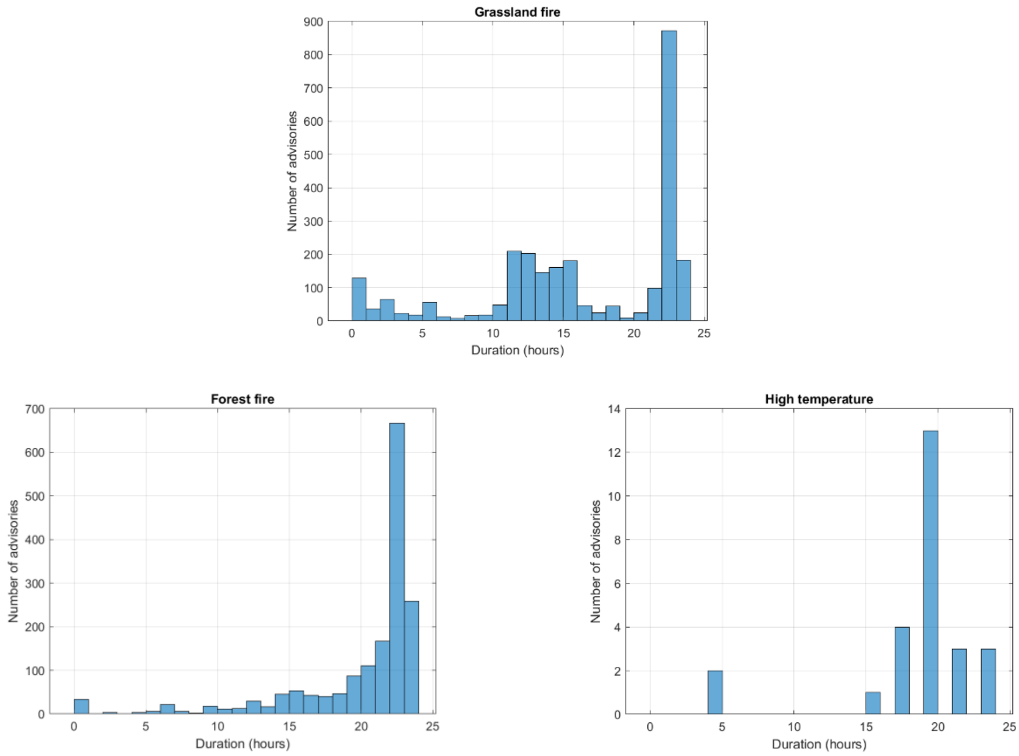


Figure A2. Histograms of durations of single advisories that were active less than 24 hours.

Table A1. Number of active WAs summed over all days, districts and classes in 2011-2020 (bold text = warnings, normal text = advisory) for different duration thresholds (0-12 hours). This is where all warnings in a district each day are summed.

	0	1	2	3	4	5	6	7	8	9	10	11	12
Grassland fire	9853	9725	9688	9623	9601	9583	9527	9504	9497	9481	9461	9407	9175
Forest fire	14 977	14 943	14 943	14 940	14 939	14 936	14 930	14 909	14 899	14 897	14 879	14 867	14 847
High temp.	2096	2096	2096	2096	2096	2094	2094	2094	2094	2094	2094	2094	2094
High temp.	**525**	**516**	**516**	**516**	**516**	**516**	**516**	**516**	**516**	**516**	**516**	**516**	**516**
High lake lev.	**124**	**123**	**123**	**123**	**123**	**123**	**123**	**123**	**123**	**123**	**123**	**123**	**123**
High river flow	**11 078**	**10 646**	**10 572**	**10 531**	**10 486**	**10 480**	**10 479**	**10 477**	**10 477**	**10 475**	**10 472**	**10 469**	**10 461**
High ocean lev.	**3063**	**3041**	**3035**	**3025**	**3018**	**3005**	**2989**	**2969**	**2951**	**2915**	**2880**	**2829**	**2746**
Wind gust	**3214**	**3078**	**2920**	**2819**	**2761**	**2655**	**2592**	**2570**	**2520**	**2488**	**2440**	**2332**	**2285**
Snowfall	**6343**	**5979**	**5682**	**5258**	**5059**	**4880**	**4683**	**4527**	**4384**	**4205**	**4122**	**4004**	**3911**
Rainfall	**1109**	**1014**	**904**	**847**	**811**	**778**	**757**	**703**	**690**	**672**	**632**	**602**	**566**
Thunder	**752**	**647**	**569**	**480**	**390**	**309**	**286**	**271**	**244**	**235**	**194**	**191**	**188**

Table A2. Number of active WAs summed over all days, districts and classes in 2011-2020 (bold text = warnings, normal text = advisory) for different duration thresholds (0-12 hours). This is where multiple warnings in a day counts as 1.

	0	1	2	3	4	5	6	7	8	9	10	11	12
Grassland fire	8855	8735	8699	8639	8624	8606	8550	8529	8522	8506	8488	8464	8284
Forest fire	12 479	12 471	12 471	12 470	12 469	12 469	12 469	12 461	12 455	12 455	12 453	12 453	12 446
High temp.	2093	2093	2093	2093	2093	2091	2091	2091	2091	2091	2091	2091	2091
High temp.	**525**	**516**	**516**	**516**	**516**	**516**	**516**	**516**	**516**	**516**	**516**	**516**	**516**
High lake lev.	**103**	**103**	**103**	**103**	**103**	**103**	**103**	**103**	**103**	**103**	**103**	**103**	**103**
High river flow	**5527**	**5525**	**5521**	**5519**	**5518**	**5518**	**5518**	**5518**	**5518**	**5516**	**5516**	**5516**	**5511**
High ocean lev.	**2002**	**1998**	**1998**	**1996**	**1993**	**1988**	**1983**	**1978**	**1970**	**1959**	**1948**	**1941**	**1904**
Wind gust	**2561**	**2553**	**2530**	**2519**	**2487**	**2451**	**2428**	**2408**	**2385**	**2356**	**2318**	**2262**	**2232**
Snowfall	**4449**	**4399**	**4388**	**4361**	**4325**	**4305**	**4251**	**4181**	**4119**	**4002**	**3942**	**3859**	**3798**
Rainfall	**796**	**782**	**770**	**765**	**735**	**723**	**716**	**683**	**674**	**661**	**630**	**600**	**564**
Thunder	**478**	**472**	**446**	**410**	**346**	**291**	**268**	**254**	**235**	**232**	**192**	**189**	**186**

APPENDIX B

Calculated statistics of single WAs during 2011-2020

Table B1. Number of days with an issued warning for at least one district, NumDays.

	High river flow			Heavy rainfall		Heavy snowfall		Strong wind gust		
	Class I	Class II	Class III	Class I	Class II	Class I	Class II	Class I	Class II	Class III
2011	64	17	3	22	0	40	6	38	17	2
2012	94	20	6	23	0	94	15	31	2	0
2013	65	13	0	18	0	49	5	30	16	5
2014	152	42	3	33	0	67	2	26	7	0
2015	163	20	4	17	0	41	3	42	17	0
2016	69	5	0	13	0	81	6	31	3	0
2017	94	10	0	19	1	97	12	41	6	0
2018	96	37	15	7	0	90	6	35	8	0
2019	99	3	0	14	0	80	6	45	12	0
2020	159	74	7	15	0	73	4	52	7	0
Avg.	105.5	24.1	3.8	18.1	0.1	71.2	6.5	37.1	9.5	0.7

Table B1. (continued) Number of days with an issued warning for at least one district, NumDays.

	High lake level	High ocean level		Thunder		High temperature	
	Class I	Class I	Class II	Class I	Class II	Class I	Class II
2011	0	57	10	18	0	*	*
2012	13	35	0	4	0	*	*
2013	0	40	8	7	0	*	*
2014	14	26	1	13	2	6	4
2015	0	71	9	0	0	5	0
2016	0	22	3	2	2	0	0
2017	0	40	4	0	0	0	0
2018	16	39	0	7	0	16	18
2019	10	35	0	15	1	6	0
2020	0	71	12	4	0	8	0
Avg.	5.3	43.6	4.7	7	0.5	5.9	3.1

Table B2. Number of days with an issued advisory for at least one district, NumDays.

	Grassland fire	**Forest fire**	**Water scarcity**	**High temperature**
2011	51	51	*	*
2012	71	10	*	*
2013	60	64	*	*
2014	65	85	*	0
2015	*	*	*	0
2016	91	119	*	20
2017	110	89	126	3
2018	72	126	175	65
2019	93	143	154	26
2020	99	143	196	32
Avg.	79.1	92.2	162.8	20.9

Table B3. Number of districts with an issued warning at least once, NumDistricts.

	High river flow			**Heavy rainfall**		**Heavy snowfall**		**Strong wind gust**		
	Class I	Class II	Class III	Class I	Class II	Class I	Class II	Class I	Class II	Class III
2011	24	7	2	38	0	40	9	33	16	2
2012	25	6	4	32	0	37	10	28	9	0
2013	26	11	0	26	0	37	8	31	23	9
2014	23	9	1	38	0	39	3	23	6	0
2015	23	10	5	31	0	38	3	33	25	0
2016	24	2	0	24	0	40	7	30	5	0
2017	24	3	0	19	2	40	14	24	3	0
2018	32	18	10	13	0	37	4	34	10	0
2019	30	2	0	15	0	36	7	30	12	0
2020	30	19	2	15	0	30	3	35	11	0
Avg.	26.1	8.7	2.4	25.1	0.2	37.4	6.8	30.1	12	1.1

Table B3. (continued) Number of districts with an issued warning at least once, NumDistricts.

	High lake level	High ocean level		Thunder		High temperature	
	Class I	Class I	Class II	Class I	Class II	Class I	Class II
2011	0	17	8	32	0	*	*
2012	4	17	0	14	0	*	*
2013	0	12	3	20	0	*	*
2014	1	7	3	32	2	20	14
2015	0	15	5	0	0	4	0
2016	0	5	3	4	1	0	0
2017	0	17	8	0	0	0	0
2018	1	15	0	21	0	32	13
2019	4	13	0	22	1	10	0
2020	0	17	9	10	0	14	0
Avg.	1	13.5	3.9	15.5	0.4	11.4	3.9

Table B4. Number of districts with an issued advisory at least once, NumDistricts.

	Grassland fire	Forest fire	Water scarcity	High temperature
2011	40	39	*	*
2012	40	33	*	*
2013	40	35	*	*
2014	40	37	*	0
2015	*	*	*	0
2016	40	36	*	32
2017	35	34	23	8
2018	40	40	33	38
2019	40	40	18	36
2020	39	38	20	37
Avg.	39.3	36.9	23.5	21.6

Table B5. Average number of districts with an issued warning at least once, AvgDistricts.

	High river flow			**Heavy rainfall**		**Heavy snowfall**		**Strong wind gust**		
	Class I	Class II	Class III	Class I	Class II	Class I	Class II	Class I	Class II	Class III
2011	3	1.5	2	6.7	0	10.1	3.7	8.6	4.2	2
2012	2.6	1.9	1.8	3.7	0	8	2.1	5.2	9	0
2013	4.1	2.2	0	4.2	0	4.7	4	6	4.9	2.8
2014	3.5	1.7	1	5.2	0	5.8	3	4.7	3	0
2015	3.1	2.5	3.5	5.4	0	6.7	2	7.4	6.9	0
2016	3	2	0	4.2	0	5.7	2	5.2	5	0
2017	2.6	1.6	0	2.4	2	5.7	2.8	3.6	1.3	0
2018	9.6	5.4	2.5	3.7	0	5.1	1.7	4.8	2.8	0
2019	4.3	2	0	1.9	0	5.2	2.3	4	2.9	0
2020	6.8	4.9	2	3.1	0	3.7	1.5	6.3	5	0
Avg.	4.3	2.6	1.3	4	0.2	6.1	2.5	5.6	4.5	0.5

Table B5. (continued) Avg. number of districts with an issued warning at least once, AvgDistricts.

	High lake level	**High ocean level**		**Thunder**		**High temperature**	
	Class I	Class I	Class II	Class I	Class II	Class I	Class II
2011	0	5.4	3.9	9.1	0	*	*
2012	2.5	5.9	0	8	0	*	*
2013	0	2.9	3	6.9	0	*	*
2014	1	2.3	3	7.7	2	11.5	13.3
2015	0	4.8	2.4	0	0	3.8	0
2016	0	2.6	3	2	1	0	0
2017	0	4.9	3.3	0	0	0	0
2018	1	2.8	0	4.3	0	9.7	6.4
2019	4	3.1	0	3	1	6.5	0
2020	0	5	2.8	4.3	0	8.1	0
Avg.	0.9	4	2.1	4.5	0.4	5.7	2.8

Table B6. Average number of districts with an issued advisory at least once, AvgDistricts.

	Grassland fire	**Forest fire**	**Water scarcity**	**High temperature**
2011	12.6	9.9	*	*
2012	14.4	10	*	*
2013	12.5	15.1	*	*
2014	13.7	10.8	*	0
2015	*	*	*	0
2016	8.8	13.4	*	12.3
2017	12.4	14.9	12.1	6.7
2018	10.5	25	15.8	14.8
2019	13.1	14.2	7.6	14.2
2020	12.7	13.2	7.8	15.5
Avg.	12.3	14	10.8	9.1

APPENDIX C

Distribution of risk-prone districts with triple and quadruple WAs during 2011-2020

In terms of triple WAs. the number of affected regions is largely reduced. The districts along the west coast, east coast and Gotland are the only regions that have been affected with a maximum of >20 days along the western coast (Figure C1). The most common triple warning combinations are (1) high ocean level. high river flow and strong wind gusts (2) high ocean level, strong wind gusts and heavy snowfall.

In terms of quadruple WAs. the affected regions are limited to the coastal area in Västerbottens. Bohuslän and Göteborg and Halland (Figure C2). The corresponding frequency is reduced to be 1-3 days in the 10-year period. In total seven events have been found, where high river flow. high ocean level and strong wind gusts were overlapped either with heavy rainfall or with heavy snowfall.

a)

b)

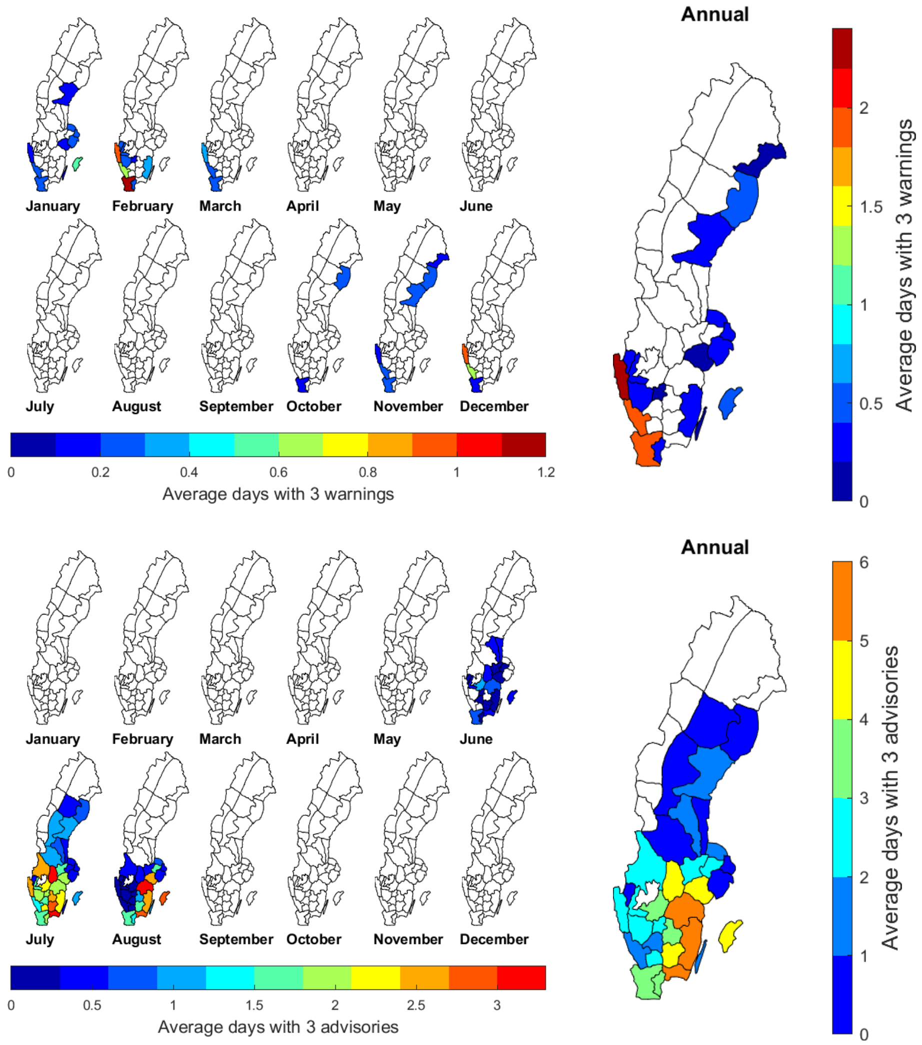


Figure C1. Distribution of risk-prone districts with triple WAs during 2011-2020: triple warnings (a), triple advisories (b) and triple warnings and advisories (c).

c)

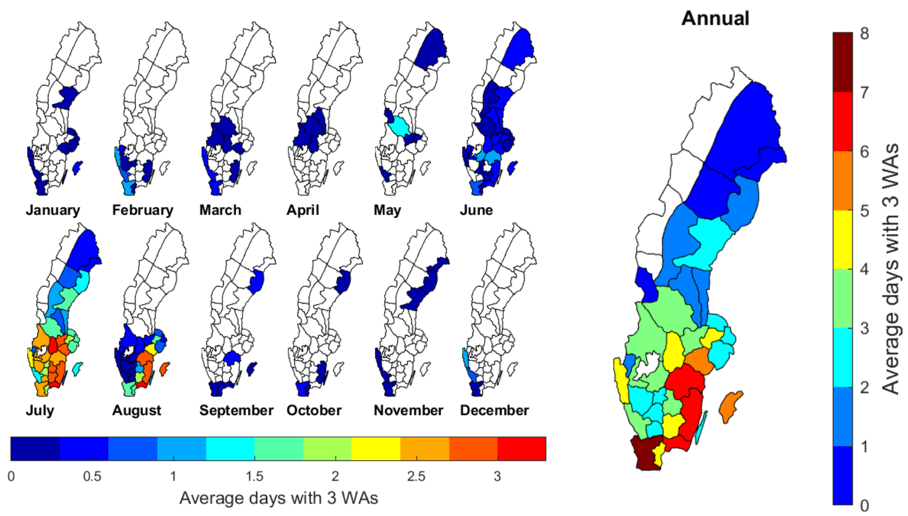
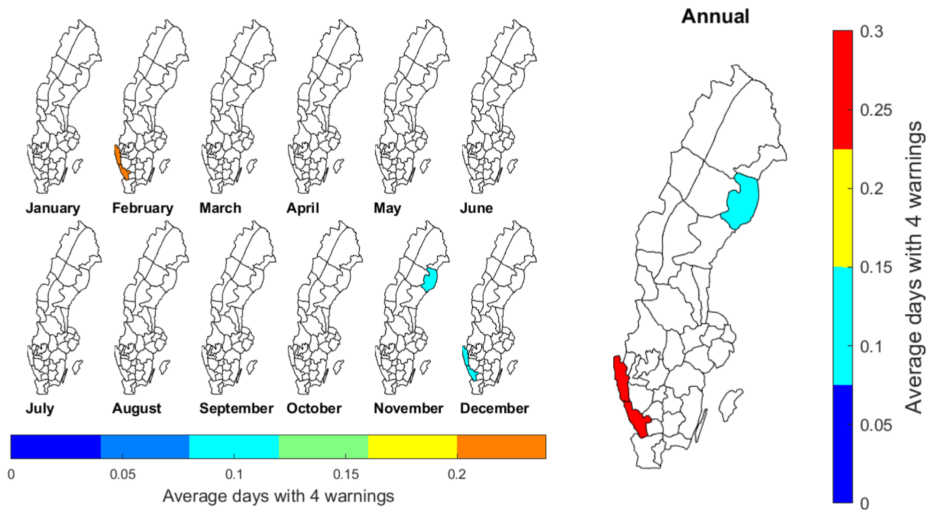


Figure C1. (continued) Distribution of risk-prone district with triple WAs during 2011-2020: triple warnings (a), triple advisories (b) and triple warnings and advisories (c).

a)



b)

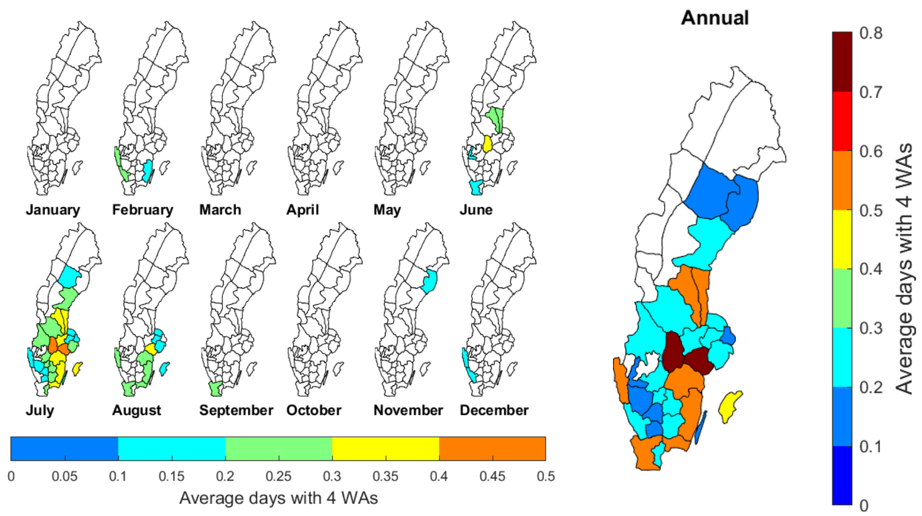


Figure C2. Distribution of risk-prone districts with quadruple WAs during 2011-2020: quadruple warnings (a) and quadruple warnings and advisories (b).

APPENDIX D
Exemplary compound events

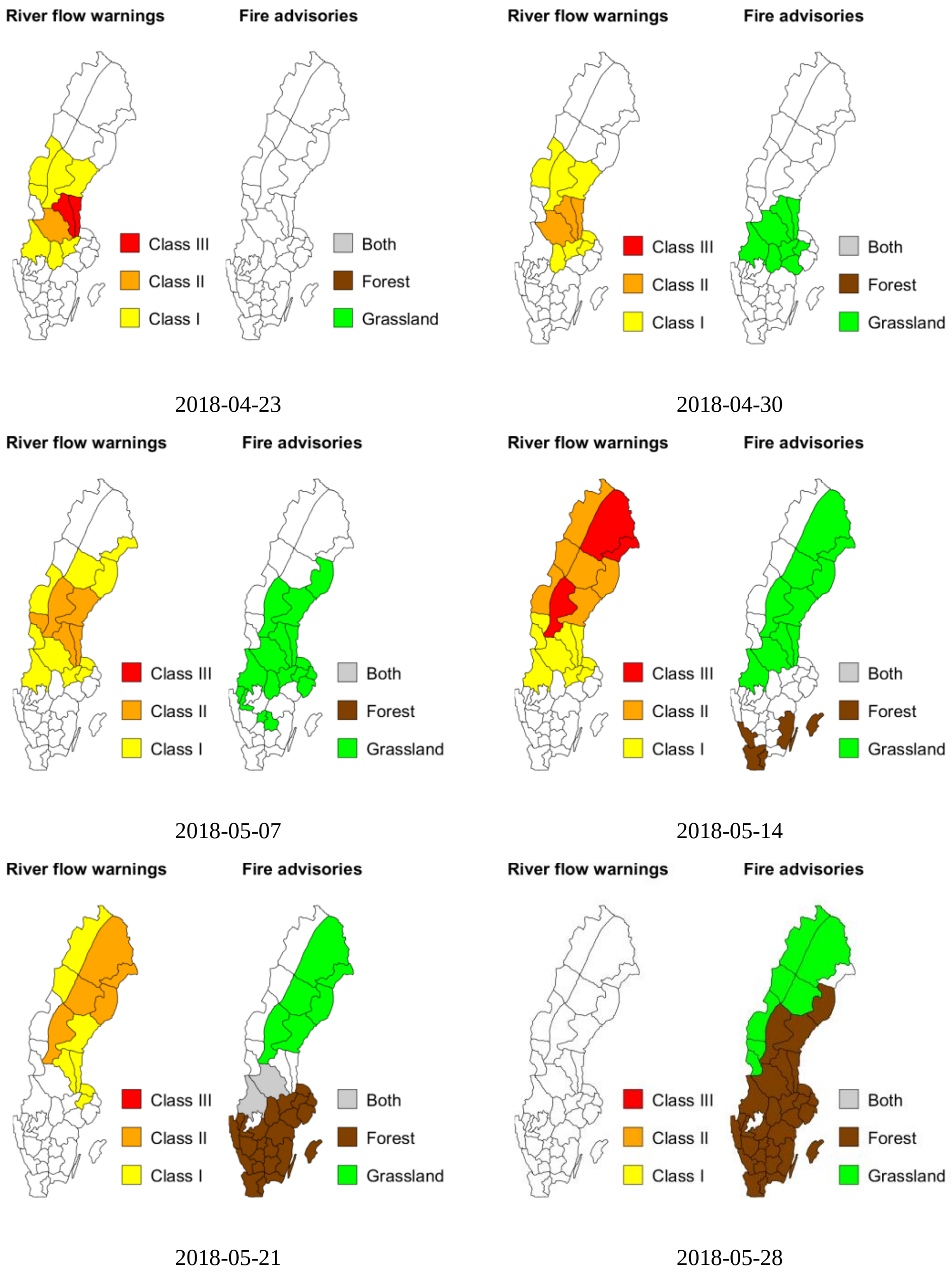


Figure D1. A period with advisories of grassland fire and forest fire and warnings of high river flow in 2018.

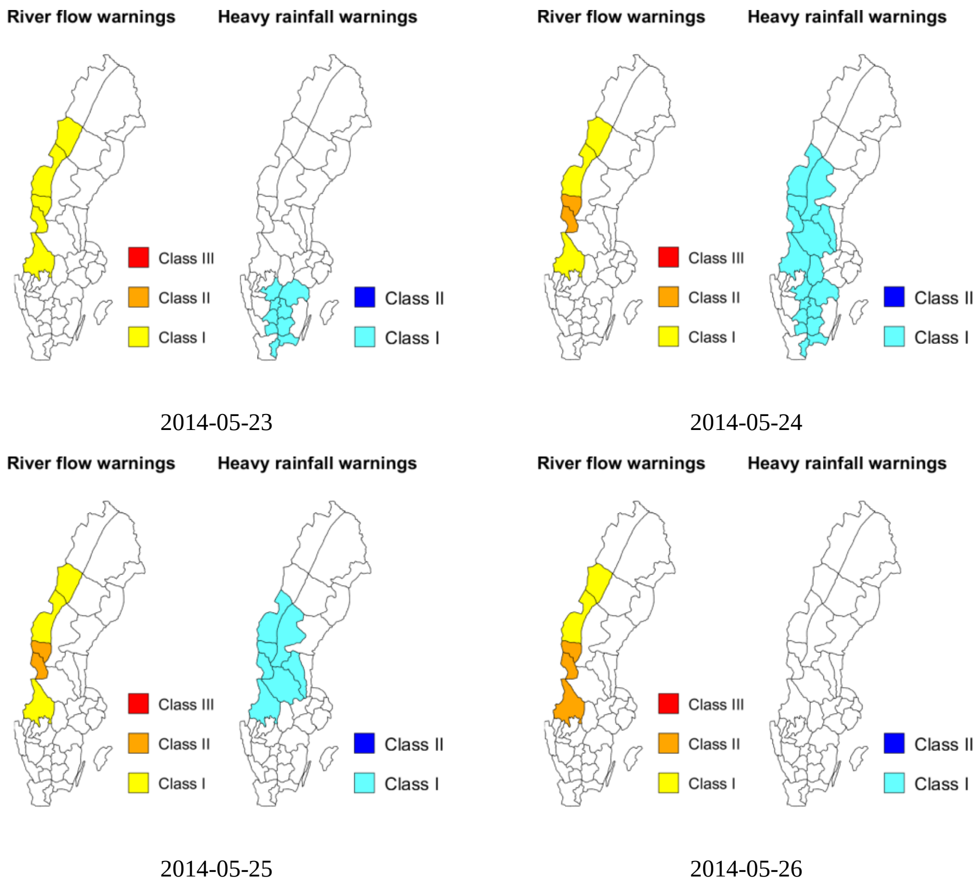


Figure D2. A period with warnings of high river flow and heavy rainfall in 2014.

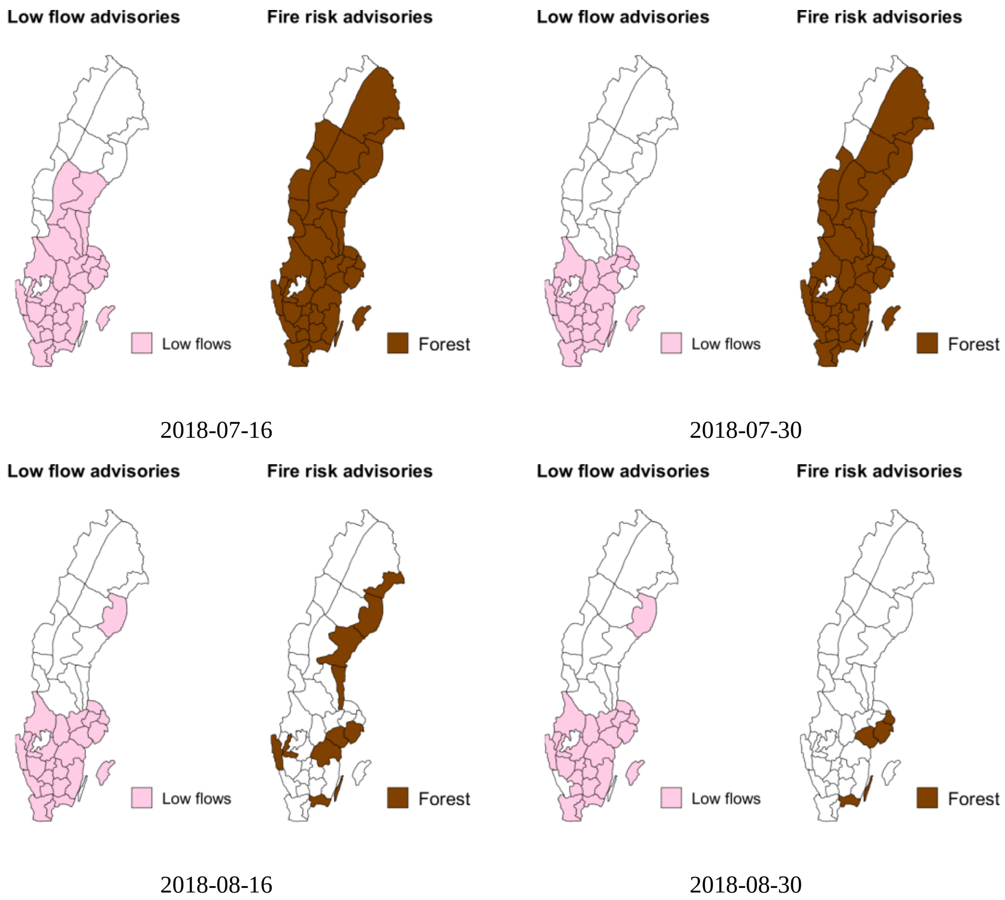
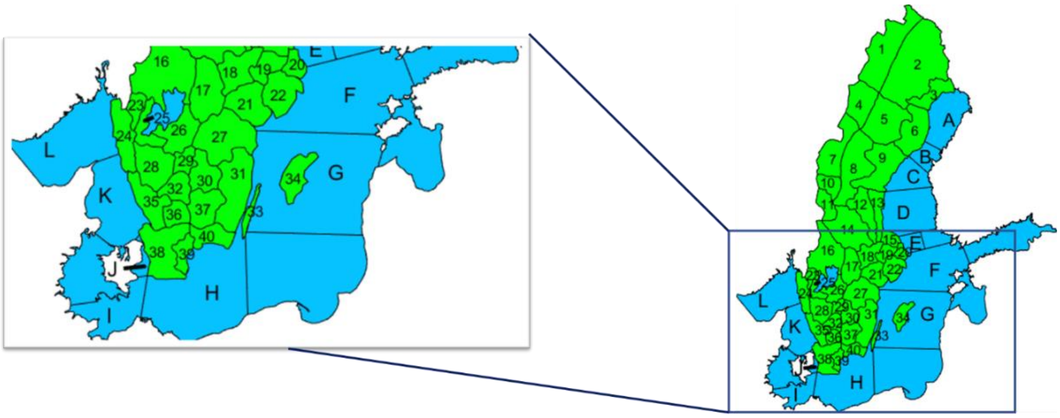


Figure D3. A period with advisories of water scarcity (low river flow) and forest fire in 2014.

APPENDIX E

Distribution of land districts and water bodies used for warnings and advisories



AL	Water bodies	Nr.	Land districts	Nr.	Land districts
A	Bottenviken	1	Norrbottens län,norra Lapplandsfjällen	21	Södermanlands län
B	Norra Kvarken	2	Norrbottens län inland	22	Stockholms län utom Roslagskusten
C	Norra Bottenhavet	3	Norrbottens län kustland	23	Västra Götalands län,inre Dalsland
D	Södra Bottenhavet	4	Västerbottens län, södra Lapplandsfjällen	24	Västra Götalands län,Bohuslän och Göteborg
E	Ålands hav	5	Västerbottens län inland	25	Västra Götalands län,sydväst Vänern
F	Norra Östersjön	6	Västerbottens län kustland	26	Västra Götalands län,norra Västergötland
G	Mellersta Östersjön	7	Jämtlands län, Jämtlandsfjällen	27	Östergötlands län
H	Södra Östersjön	8	Jämtlands län utom fjällen	28	Västra Götalands län,Sjuhäradsbygden och Göta älv
I	Sydvästra Östersjön	9	Västernorrlands län	29	Jönköpings län,syd om Vättern
J	Öresund	10	Jämtlands län, Härjedalsfjällen	30	Jönköpings län,östra delen
K	Kattegatt	11	Dalarnas län, Dalafjällen	31	Kalmar län utom Öland
L	Skagerack	12	Gävleborgs län inland	32	Jönköpings län,västra delen utom syd om Vättern
		13	Gävleborgs län kustland	33	Kalmar län,Öland
		14	Dalarnas län utom Dalafjällen	34	Gotlands län
		15	Uppsala län, Upplandskusten	35	Hallands län
		16	Värmlands län	36	Kronobergs län,västra delen
		17	Örebro län	37	Kronobergs län,östra delen
		18	Västmanlands län	38	Skåne län utom Österlen
		19	Uppsala län utom Upplandskusten	39	Skåne län,Österlen
		20	Stockholms län, Roslagskusten	40	Blekinge län

Figure E1: Details of the 40 land districts and the 11 sea districts adjacent to mainland Sweden referred to in the text

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