Streamflow drought: implication of drought definitions and its application for drought forecasting

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Executive Summary of author's response to reviewer 1 and 2

In this file, we provide a summary of author's response to reviewer 1 and reviewer 2. In general, both reviewers are concerned about the methodology used in our manuscript and the unbalance in results between historic analyses and forecast. Here, we will provide detailed author's response only for some important remarks that were raised during the review process, including some new results. We already provide some concrete results that we promised in the reply to reviewers. Please consult previous author's response addressed to individual reviewer for detailed information on the reply. We summarize the main reviewer's concerns as follow:

1. The use of non-identical thresholds to identify drought in our paper, which are P90 for the variable and fixed threshold methods, and SSI<0 for the standardized approach. The use of the SSI threshold of zero to identify drought is not equal with P90 used in the threshold approaches, meaning that we compare droughts that occurs in 50% of the time (SSI) with the ones in 90% of the time (threshold method).
2. The use of SSI-6 instead of SSI-1 in the main text. The reviewers argued that river flow already encompasses the accumulation and delay of the meteorological signal caused by catchment properties, such as groundwater flow.
3. The use of different temporal resolution, namely daily data for the threshold approaches and monthly data for the SSI. The reviewers suggest to also use monthly streamflow data for the threshold methods to increase the comparability with the SSI, which uses monthly resolution.
4. The unbalance in results between historic analysis and forecasts. The reviewers suggest to include an evaluation and discussion of the spread in streamflow drought forecasts and to elaborate the forecast section (3.2) more.
5. Adding more drought characteristics, such as drought duration and severity (deficit volume). Moreover, the reviewers suggest to derive the drought deficit volume from the standardized time series.
6. The reviewers suggest to summarize the drought characteristic results for each climate regions.

We would like to thank both reviewers for the comments and the valuable suggestions to improve our manuscript. We do agree with the reviewer's main suggestions and therefore we will revise our paper as follow:

1. Our paper uses the drought thresholds based on common practice in the drought community. Using a threshold method either a Fixed Threshold (FT) or Variable Threshold (VT), drought is identified if the streamflow falls below the threshold, which is commonly in the range of 10-30th percentile of the flow duration curve (P70-90) (Hisdal et al. 2004; Van Loon, 2015). On the other hand, the standardized indices, e.g., the Standardized Streamflow Index (SSI) identifies drought if the SSI value falls below 0, which is the 50th percentile (Vicente-Serrano et al., 2012). Our reason to use different thresholds (50th percentile for SSI and 10th percentile for the FT and VT) is that we would like to align with common practice for the different approaches. However, the reviewer has a point that the comparison between the threshold methods (VT, FT) and SSI is not equal, because of the use of different percentiles. Thus in the revised manuscript, we will change the thresholds from P90 into P80 for VT and FT, and SSI≤-0.84 (~P80) to have a fair comparison between different drought indices (Tijdeman et al., 2020). Figure 1 shows drought occurrences (frequency) in European rivers identified using different approaches and derived using the new threshold levels, which are P80 for threshold methods and SSI<-0.84 for SSI.
2. We aware that streamflow, as included SSI 1, comprises some catchment memory aspects (delayed flow from groundwater). Hence, in the revised manuscript, we will replace SSI-6 with SSI-1 in the main text (See Fig. 1e for example). However, we need to realize that anomalies in the accumulated flow over a longer period (e.g. SSI-6) have relevance for some purposes, such as the management of surface water reservoirs.
3. We do agree with the reviewer that our study used different temporal resolution to analyze drought, which are daily for the threshold methods and monthly for SSI. Again, we followed common practice (see item 1, above) to identify drought using these methods. Many studies used daily streamflow data to analyze drought using the threshold methods and monthly streamflow data to analyze drought using the standardized indices. To the author's knowledge, only Tallaksen et al. (2009) used monthly data to derive drought using the threshold method and only for a scientific purpose. In the revised manuscript, however, we will add to the common practice approach (daily resolution), an analysis of drought characteristics using monthly streamflow data in both FT and VT drought approaches. This allows an analysis of the VT and FT threshold approach and the SSI-1 using the same temporal resolution, i.e. monthly time scale. This implies that we will have two VT and FT threshold applications: daily resolution (VTD and FTD, Fig. 1a and b, respectively), as frequently used, and monthly resolution (VTM and FTM, Fig. 1c and d, respectively) to allow comparison with SSI 1 (Fig. 1e).

Fig. 1. Drought occurrences in European rivers from October 1990 to September 2018 (28 years) identified using: a) the variable threshold method with daily streamflow data (VTD drought), b) using the fixed threshold method with daily streamflow data (FTD drought), c) using the variable threshold method with monthly streamflow data (VTM drought), d) using the fixed threshold method with monthly streamflow data (FTM drought), and e) using the Standardized Streamflow Index with accumulation time 1 month (SSI-1 drought).

4. We will extend the novel part of paper to pass the important message that the outcome of drought forecasts depends on the drought identification method, which frequently is overlooked by academics and end-users. We will do this by describing: (i) pan-European maps showing forecasted drought timing and duration using different drought identification methods (FT and VT with daily and monthly resolution, and SSI-1, see Fig. 2, for example, of forecasted drought duration from July 2003 to January 2004 using the forecast initiated on July 2003 for 7-month LT) (other drought characteristics, such as number of drought occurrence/frequency and drought deficit volume will be provided in the Supplementary Material), (ii) summary of forecasted drought characteristics identified using different approaches for the Rhine River using forecasts initiated from 1st January 2003 to 1st December 2003 with a lead time of 7-month (see Table 1 and 2), and (iii) ensemble spread of forecasted drought for the Rhine River using forecasts initiated in April and July 2003 for different approaches (VTD, FTD, VTM, FTM, and SSI) (Fig. 3). In addition we will also provide information on the percentage of ensemble members showing drought for each identification method (Ne in Table 1 and 2).
5. We will add drought duration and deficit volume derived from the FT, VT, and SSI approaches in the revised manuscript (see Fig. 2, for example, of forecasted drought duration). However, the SSI drought deficit volume will not be added because it is impossible to derive the deficit volume using the SSI approach (major drawback of standardized approaches).
6. In the revised manuscript, we will provide a summary of drought characteristics (number of drought occurrence/frequency, timing, duration, and deficit volume) for 5 Köppen Geiger climate regions identified using different approaches (FTD, VTD, FTM, VTM, and SSI-1; see Table 3 and 4).

In conclusion, we agree to elaborate all major suggestions raised by the reviewers in our revised paper. We will revise the paper accordingly and will submit the revised version after the online discussion is ended. Given that we already have all the new version of the results, we will manage to revise our paper within the given time by the editor. Some Figures and Tables presented in this executive summary are taken from the draft of our revised paper. We look forward for submitting the revised paper and hope that the reviewers will agree to review our revised paper.

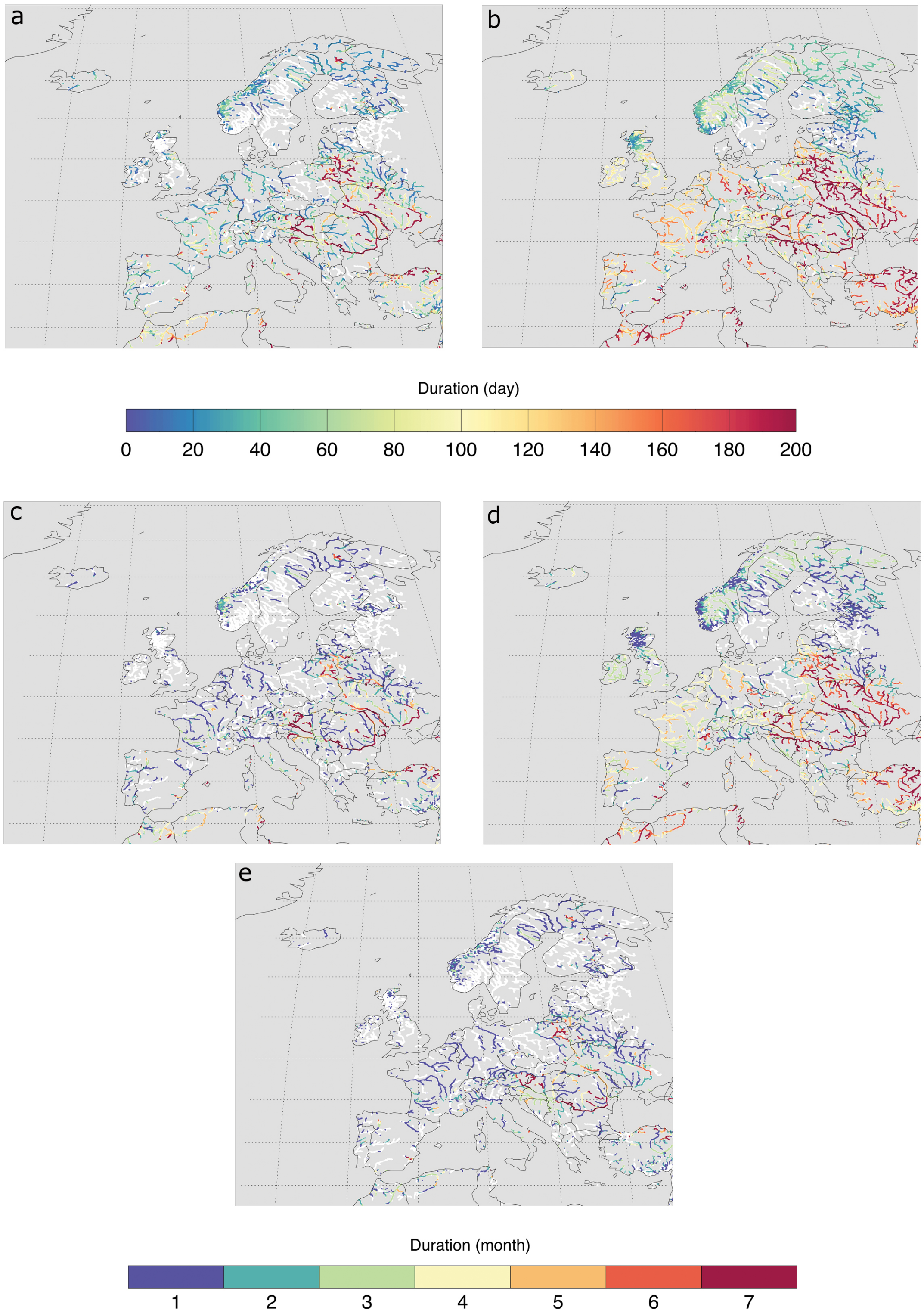

Fig. 2. Forecasted average duration of drought events in the European rivers using the forecast initiated on 1st July 2003 with a lead time 7-month for: a) the VTD drought, b) the FTD drought, c) the VTM drought, d) the FTM drought, and e) the SSI-1 drought. White river color indicates that drought was not forecasted.

Table 1. Forecasted streamflow drought characteristics derived from daily streamflow data using the VTD and FTD approaches for the Rhine River initiated from 1st January 2003 to 1st December 2003 for 7 months ahead (215 days). Drought characteristics were derived using median of the ensemble. N stands for number of occurrence, Ne stands for maximum number of ensemble members falling below drought thresholds (%), T stands for timing (month), D stands for duration (day), and DV stands for deficit volume (m^3)

Forecast initiation month	Drought characteristics									
	VTD					FTD				
	N	Ne (%)	T (m)	D (d)	DV (m^3)	N	Ne (%)	T (m)	D (d)	DV (m^3)
1	0	20	0	0	0	0	20	0	0	0
2	0	20	0	0	0	0	28	0	0	0
3	0	20	0	0	0	0	48	0	0	0
4	2	76	10	3	173	9	92	9	6.2	433
5	6	56	10	3.8	204	3	76	10	24	4244.7
6	7	64	10	5.6	534	4	80	8	28.7	5163.2
7	12	100	12	3	204	9	100	8	12.7	1467.5
8	11	100	11	12.1	1819	8	100	1	15.9	5172.7
9	6	100	12	16.3	2657	7	100	12	14.7	4478.9
10	3	100	10	23.7	4295	4	100	11	20.5	4685.2
11	6	100	1	10.2	2654	3	100	11	15.3	5295.9
12	2	100	12	22.5	10346	1	100	12	43	14803

Table 2. Forecasted streamflow drought characteristics derived from monthly streamflow data using the VTM, the FTM, and the SSI-1 approaches for the Rhine River initiated from 1st January 2003 to 1st December 2003 for 7 months ahead (215 days). See Table 5 for symbol descriptions.

Forecast initiation month	Drought characteristics													
	VTM					FTM					SSI-1			
	N	Ne (%)	T (m)	D (m)	DV (m^3)	N	Ne (%)	T (m)	D (m)	DV (m^3)	N	Ne (%)	T (m)	D (m)
1	0	8	0	0	0	0	8	0	0	0	0	8	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	8	0	0	0	0	28	0	0	0	0	16	0	0
4	0	36	0	0	0	1	52	10	1	2314.2	0	24	0	0
5	1	56	10	1	1160	1	60	9	2	10210	0	44	0	0
6	1	60	10	1	1407	1	72	9	3	12569	0	48	0	0
7	0	48	0	0	0	1	68	9	2	5689.9	1	56	7	1
8	2	100	8	2	6649	1	100	8	4	33096	2	100	8	1.5
9	1	68	9	2	9843	1	100	9	2	26095	1	92	9	2
10	2	72	12	1	3508	1	92	10	2	13212	1	72	10	1
11	1	84	11	2	5423	1	96	11	1	10246	1	80	11	1
12	1	84	12	1	14150	1	84	12	1	10785	1	64	12	1

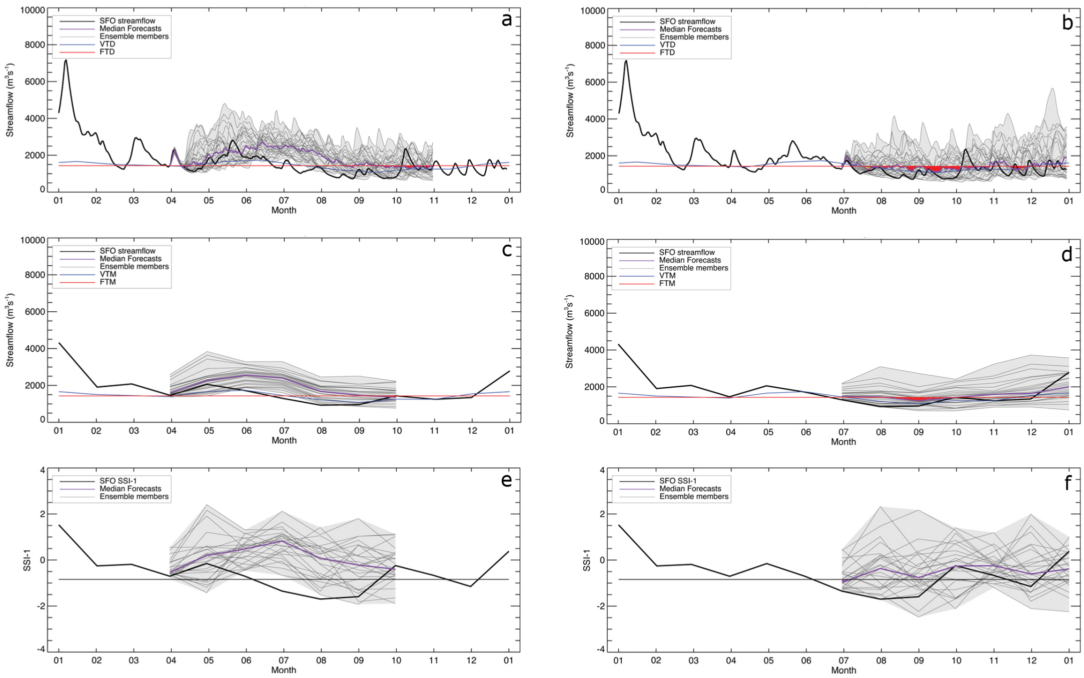

Fig. 3. Observed (SFO) and forecasted streamflow for 25 ensemble members and median streamflow in the Rhine River: a) daily streamflow drought (VTD and FTD) initiated on 1st April 2003 for 7 months ahead, c) monthly streamflow drought (VTM and FTM) initiated on 1st April 2003 for 7 months ahead, and e) forecasted SSI-1 drought initiated on 1st April 2003 for 7 months ahead. b), d), and f) same as a, c, and e but for forecasts initiated on 1st July 2003. Droughts are indicated by blue shaded area for VTD and VTM, red shaded area for FTD and FTM, and purple shaded area for SSI-1.

Table 3. Streamflow drought characteristics derived from daily streamflow data using the VTD and the FTD methods obtained from the hydrologic years 1991 to 2018 for the five climate regions. N stands for number of events, T stands for timing (month), D stands for duration (day), and DV stands for deficit volume (m^3). D, and DV are average drought characteristics and T is median drought timing for all river grid cells located in each climate region

No	River	Drought characteristics							
		VTD				FTD			
		N	T (m)	D (d)	DV (m^3)	N	T (m)	D (d)	DV (m^3)
1	ET	55.4	4	44	571	51.5	8	80	1112.9
2	DFB	48.3	3	43.8	1113	47.9	7	57.9	1606.2
3	DFC	49.2	3	46.7	823	44.4	10	91.3	2136.1
4	CFB	57.8	10	36.4	886	55.6	7	59.5	1494.7
5	Med	41	10	56.3	455	38.6	7	96.8	997.1

Table 4. Streamflow drought characteristics derived from monthly streamflow data using the VTM, the FTM, and the SSI-1 drought identification method obtained from the hydrologic years 1991 to 2018 for the five climate regions. N stands for number of events, T stands for timing (month), D stands for duration (day), and DV stands for deficit volume (m^3).D, and DV are average drought characteristics and T is median drought timing for all river grid cells located in each climate region

No	River	Drought characteristics										
		VTM				FTM				SSI-1		
		N	T (m)	D (m)	DV (m^3)	N	T (m)	D (m)	DV (m^3)	N	T (m)	D (m)
1	ET	28.9	7	2.5	1344	39.3	9	3.4	1443.1	35.2	7	2.2
2	DFB	26.5	5	2.5	1727	33.8	8	2.6	2126.6	29.5	5	2.2
3	DFC	25.6	6	2.5	955	35.9	10	3.6	2406.8	30	5	2.4
4	CFB	30.7	5	1.9	1495	38.7	7	2.7	2106.4	34.8	7	1.9
5	Med	22.6	9	2.9	690	32.2	7	3.7	1194.8	25.5	8	2.4

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