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The benefit of seamless forecasts for hydrological predictions over Europe

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Abstract. Two different systems provide long range forecasts at ECMWF. On the sub-seasonal time scale, ECMWF issues an extended-range ensemble prediction system (ENS-ER) which runs a 46-day forecast integration issued twice weekly. On longer time scales the current seasonal forecasting system (SYS4) produces a 7-month outlook starting from the first of each month. SYS4 uses an older model version and has lower spatial and temporal resolution than ENS-ER. Given the substantial differences between the ENS-ER and the SYS4 configurations and the difficulties of creating a seamless integration, applications that rely on weather forcing as input such as the European Flood Awareness System (EFAS) often follow the route of the creation of two separate systems for different forecast horizons. This study evaluates the benefit of a seamless integration of the two systems for hydrological applications and shows that the benefit of the new seamless system when compared to the seasonal forecast can be attributed to (1) the use of a more recent model version in the sub-seasonal range (first 46 days) and (2) the much more frequent updates of the meteorological forecast.

1 Introduction

ECMWF produces a range of forecasts, among them a 10 day deterministic high resolution forecast (HRES), a lower resolution 15-day 51 member ensemble prediction system (ENS) that is extended to 46 days twice weekly (Mondays and Thursdays at 00UTC; Vitart et al. 2008), and an ensemble seasonal forecast system System-4 (SYS4), operational since November 2011. SYS4 issues a 7-month (extended to 13 months four times a year) prediction once every month (Molteni et al., 2011). The ENS-ER forecast system benefits from frequent updates of the model physics and data assimilation system (Vitart et al., 2008). ECMWF releases official model updates on average 2-3 times a year which typically include new improved schemes for physical processes, better use of observations and their assimilation and sometimes increase in model resolution. The seasonal forecast has a lower resolution and is an older model version than ENS-ER. TSYS4 is also updated much less frequently. This implies that the skill of SYS4 is lower relative to ENS-ER in the overlapping first six weeks (Di Giuseppe et al., 2013).

Applications that use numerical weather predictions as forcing, such as the operational European Flood Awareness System (EFAS (Thielen et al., 2009; Bartholmes et al., 2009; Smith et al., 2016)), are often designed for a specific purpose. EFAS has since the start focused on early warning of floods in the medium-range forecast horizon, 3-15 days. Recently a seasonal hydrological outlook forced by SYS4 was implemented operationally. This extension to the monthly and seasonal scales is potentially very useful in order to; (i) produce products which extend the previous forecast horizon; (ii) benefit from hindcasts for pre- and post-processing to produce output of higher quality (e.g. model based return periods); and (iii) design completely new early warning frameworks complementing the existing ones. The extended lead time provided by running EFAS forced by weather prediction across different time scales could potentially provide added benefit in terms of very early planning, for example for agriculture, energy and transport sectors as well as water resources management. Such a forecast system would be a first step to close the identified gap between hydrological forecasts on the medium (up to 15 days) and seasonal range (White et al., 2017). These extended range systems may not be able to capture extremes of short-lived events like floods, but they are able to detect anomalous conditions on longer lead times, such as low flows (Meißner et al., 2017) and droughts (Dutra et al., 2014).

The concept of seamless forecast was first introduced by Palmer and Webster (1993). Palmer et al. (2008) formally expanded the idea showing how short-lived phenomena under certain conditions may persist and increase predictability at longer time scales. Since then the concept of a unified or seamless framework for weather and climate prediction has been vastly debated (Hurrell et al., 2009; Brunet et al., 2010). However as noticed by Hoskins (2013) in his seminal paper, while "the atmosphere knows no barriers in time-scales", often model implementation is segmented for practical reasons. Still major efforts have been made to create unified systems. Indeed, the ENS-ER was the first attempt to create a seamless extension to the ECMWF medium-range forecast (Vitart et al., 2008). Similarly, the UK Met Office has in the past twenty-five years worked to create a unified model that could work across all scales (Brown et al., 2012). Also the climate community has moved in the same direction. For example, the EC-Earth project shows that a bridge can be made between weather, seasonal forecasting and beyond (Hazeleger et al., 2010, 2012).

The latter projects went all the way to create new systems starting from existing components and were therefore costly and time demanding. In contrast, a practical and simpler approach could be taken. The seamless idea could be translated into the simple concatenation of "the best" forecast at each lead-time. The clear advantage of this off-the shelf seamless prediction conversion is that it utilizes products that are already in place, thereby avoiding the complications of new developments while generating forecast products to meet different types of users (Pappenberger et al., 2013). There is however an underlying complexity in this simplification; the substantial difference in design between the various forecasting systems makes the concatenation a task technically difficult. As systems are designed for different users they often have non-matching temporal and spatial resolutions, different hindcast span and different ensemble sizes. One important consequence of this difference in design is that, for example, the much more frequent updates to the extended range compared to the seasonal system at ECMWF, implies that the bias characteristics of the two systems diverge over time, only re-converging when the seasonal system is updated (Di Giuseppe et al., 2013). Then model outputs either need to be bias-corrected to be useful forcing to drive sectoral models such as EFAS, or that final products should be provided in terms of anomalies calculated against the model climate. In both cases the seamless system needs to account for the use of the hindcast dataset and the application of some bias correction algorithm. In return, the advantage is in the gain in skill and the extension of the lead-time.

In this work the benefit of a seamless hydro-meteorological system was tested for a span of time ranges from 1 week to 6 months for stream flow forecasts over the European domain using the EFAS system. The aim was to test whether integrating medium-range forecasts with seasonal prediction contributes to enhance hydrological predictability. Specifically, the questions addressed were: What is the gain of using a more recent model version in the first 46 days provided by the use of the ENS-ER? What is the skill gain provided by having more frequent forecast updates?

2 Method

2.1 Hydrological model system

The hydrometeorological system used in this study was the European Flood Awareness System (EFAS Thielen et al. 2009; Bartholmes et al. 2009; Smith et al. 2016). EFAS is an operational early warning system covering most of the European domain and has been run operationally since October 2012 as part of the COPERNICUS Emergency Management Service (CEMS). The hydrological component of EFAS is the distributed rainfall-runoff model LISFLOOD (De Roo et al., 2000; Van Der Knijff et al., 2010; Burek et al., 2013). LISFLOOD calculates the main hydrological processes on sub-daily and daily time-scales that generate runoff, such as soil and ground water interactions, for each grid cell. In the operational setup EFAS covers most of Europe on a 5x5 km equal-area grid. The runoff is transformed through a routing scheme to estimate the river discharge at each grid cell along the river network. The routing scheme also takes into account water retention in lakes and reservoirs. This study will concentrate on the forecast of river discharge, and more specifically on 786 reference points on the river network across the EFAS domain. These points were chosen as they are the ones that have good historical observations and has been used to calibrate the model and represent both larger and smaller rivers.

In its operational implementation the latest calibration (referred to as tuning in the NWP nomenclature) of LISFLOOD used an observational dataset of meteorological forcing data (precipitation and temperature) and observed discharge covering the model domain over the period 1990-2013. The meteorological dataset comprises more than 5000 synoptic stations that have been interpolated to a 5x5 km Lambert azimuthal equal-area projection (Ntegeka et al., 2013). The high resolution gridded observation of precipitation and temperature were used for the calibration of LISFLOOD. The observational dataset was also used to generate a reference modeled climatology of discharge (hereafter called water balance, WB) which is used as; (i) initial conditions for the operational forecast and hindcasts and (ii) reference model run to assess the performance of the forecasts. Using the WB run as proxy observation simplifies the interpretation of the skill scores as it avoids the complication of having to assess the bias against observed discharge.

2.2 Seamless integration of meteorological forcing data

Twice weekly every Monday and Thursday, the ENS-Extended Range (ENS-ER) forecast at ECMWF issues a 46-days forecast integration (Figure 1). Each ENS-ER integration comes with an 11-member hindcast set produced for the same dates over the previous 20 years. This hindcast set provides identical integrations as the current operational forecast with the difference that ERA-Interim reanalysis (ERAI; Dee et al. (2011)) and ERAI land reanalysis (Balsamo et al., 2015) is used to provide the initial conditions for the hindcast. The hindcast period can together with observations be employed to calibrate the forecast in an operational setting (Di Giuseppe et al., 2013). Thus, twice every week a set of 21 years of 46-days ensemble predictions is available using the same forecast system.

The operational seasonal forecast (SYS4) issues a new forecast at the beginning of each month with a lead-time up to 7 months, four times a year extended to 13 months (Figure 1). SYS4 has a hindcast consisting of 30 years started at each month and consisting of 15 members. The new seamless forecasting system (hereafter called SEAM) was created by concatenating each ENS-ER ensemble member with a randomly selected SYS4 ensemble member at day 46, which is the last day of the ENS-ER (Figure 1). SEAM benefits from the frequents updates of the ENS-ER and has the seven months horizon of the seasonal system. As the two systems have different resolutions (table 1) the horizontal resolution was homogenized to the 5x5 km equal-area grid through a mass-conserving interpolation for precipitation and a bilinear for temperature before it was used as input to the hydrological model in EFAS. The time step was reduced to daily by averaging (accumulating for precipitation and evapotranspiration) the three hourly outputs of the ENS-ER and the six hourly outputs of SYS-4. Since the ENS-ER has a reduced hindcast (20 years) and number of members (11), SEAM has the same number of members and hindcast period. Note that in real-time mode, a full 51-member SEAM is possible. The technical details of the forecast and the hindcast used in this

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experiment are presented in table 1. For simplicity SYS4 and SEAM will from now on refer to the full hydro-meteorological integrations for the remainder of this paper.

2.3 Experimental set-up

This study focuses on the performance of SYS4 and SEAM over the hindcast period of the operational forecast with a sequence of starting dates over the period 2015-05-14 (the first available date with 11-member hindcast for ENS-ER) to 2016-06-02 producing daily output time series of discharge over the 20-year hindcast period. The output was averaged to weekly means before the skill score analysis. This provided 13 monthly starting dates for SYS4 and 111 biweekly starting dates for SEAM with corresponding hindcast set covering all seasons over the previous 20-year period, each with 11 ensemble members.

SEAM was verified against the runs with SYS4 to assess the added value of the merged forecast. Further, both model systems were compared against a climatological benchmark simulation (hereafter called CLIM). CLIM was constructed by forcing the LISFLOOD with 11 randomly selected time series of observed meteorological forcing from the period 1990-2014, excluding the modeled year. CLIM has the advantage of having the same initial conditions as the SYS4 and SEAS hindcasts, but has no expected predictive skill beyond the horizon of the initial conditions. The advantage of CLIM is that in theory it has near perfect reliability with regards to the WB runs since it is produced with the same unbiased forcing data. It should therefore score better or equal as the hindcasts as predictor on time ranges beyond their respective limits of predictability.

2.4 Score metrics

The performance of the two forecasts were quantified using the continuous ranked probability score (CRPS; Hersbach 2000) applied to the modeled discharge over the 786 reference points. CRPS is a common tool to verify probabilistic forecasts and can been seen as generalization of the mean absolute error to the probabilistic realm of ensemble forecasts. It is defined as:

$$CRPS = \frac{1}{N}\sum_{n=1}^{N}\int_{-\inf}^{+\inf}\left[F(x(n)) - H(x(n)-x_0)^2\right]dx \tag{1}$$

where x(n) is the nth forecast of the N number of forecasts and x_0 is the observed value. The CRPS is the continuous extension of RPS where $F(x)$ is the cumulative distribution function (CDF) $F(x) = p(X - x)$ and $H(x - x_0)$ is the Heaviside function, which has the value 0 when $x - x_0 < 0$ and 1 otherwise.

The CRPS compares the cumulative probability distribution of the discharge forecasted by the ensemble forecast system to an observation. It is sensitive to the mean forecast biases as well as the spread of the ensemble. 11 ensemble members were randomly drawn from the SEAS ensemble to

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have the same number of ensemble members as in SEAM. To account for the difference in ensemble size between SEAM From the CRPS a skill score (CRPSS) can be derived by comparing CRPS of the verified forecast against a reference forecast.

$$SS_{CRPS} = 1 - \frac{CRPS_{fc}}{CRPS_{rf}} \tag{2}$$

In this paper CRPS was calculated for SYS4, SEAM and CLIM over the hindcast period. CRPSS is used throughout the paper as a measure to calculate the added value of the different forecasts.

3 Results and discussion

3.1 Overall forecast skill

The forecast skill gain provided by SEAM with respect to SYS4 is mostly concentrated to the first six weeks (Figure 2,a) when the forcing data are from the ENS-ER. The difference in CRPSS is 0.6 at week one, which then decreases to 0.2 by week six. All river points show a gain in skill up until week three, then some points show a benefit of using the SYS4 instead of SEAM. However, in some catchments there is skill up further than eight weeks. The overall better performance of SEAM with respect to SYS4 is partly because of the use of a more recent model version and partly because of the more frequent update of the atmospheric and hydrological initial conditions. It is possible to disentangle the relative contributions between these two factors by only considering a reduced number of starting dates for the SEAM forecast; i.e dates that are the closest to the SEAS4 starting dates (figure 2,b). This reduced statistic provides a measure of the expected contribution of *only* employing a newer model cycle in the first weeks while both simulations benefits from the same hydrological initialization. In this case the skill gain in CPRS reduces to between 0 and 0.4 (median 0.2) against SYS4 for the first week, reducing to neutral around week four. Therefore the most relevant gain comes from the more frequent initializations of the hydrological model.

To put these increments into context we also look at the improvement in skill of the two system SYS4 and SEAM against the CLIM benchmark forecast (Figure 2c-d). The gain from having an improved initial conditions in SEAM is similar in comparison with CLIM (Figure 2c) as with SYS4 (Figure 2a) in the first week, but the skill deteriorates quicker and the median CRPSS is negative after 5 weeks. Without the increase in skill due to the advantage in the better initial conditions, SEAM still shows a gain against the CLIM forecast with a CRPSS of 0.4 for the first week, although the spread is quite large (Figure 2d). Also SYS4 shows an increase of skill against the CLIM forecast. Both forecasts are less skillful than CLIM for most river points after week four. It can also be noted that SEAM has a higher spread than SYS4 on longer lead times even though they are forced with the same data from day 47 and onwards. An explanation can be that the ensembles from the two meteorological forecasts are not matched in terms of their relative attributes with regards to their ensemble mean. If two extreme driving forecasts from the two meteorological forecasts are combined it can lead to members that are further away from the ensemble mean than when only one driving forecast is used.

3.2 Geographical variation of forecast skill

The geographical distribution of skill gain provided by the SEAM and SYS4 prediction reveals a coherent picture with good scores against the CLIM run over most of Europe (Figure 3 a-b). The gain in the figure is expressed as a difference in the number of weeks into the forecast needed for the CRPSS to drop below zero (i.e. there is no skill in the forecast in comparison with CLIM), which gives an indication of the expected time gain in terms of information provided by the forecast against the reference forecast. Both SYS4 and SEAM are better than CLIM, and SEAM has higher skill than SYS4 for most of Europe. There is a small negative affect over the Alps, southeastern Europe and northern Finland (Figure 3d). The performance of the operational EFAS in these regions is generally poor, which is caused by the difficulty of having good observations of precipitation in high altitude stations and the atmospheric models difficulty in resolving steep orography (Alfieri et al., 2014). Another interesting aspect to showcase is the relevance of more frequent model version updates is the overall improvement on river discharge for all stations in proximity to the western coasts. This can be attributed to recent developments of the precipitation forecasts, for example a new diagnostic closure introduced in the convection scheme (Bechtold et al., 2014) and a new parameterization of precipitation formation (Haiden et al., 2014).

3.3 Added value of the seamless forecast

Even though the increase in the overall skill provided by the SEAM in comparison with SYS4 is noticeable, the justification for its use in an operational context also depends on the actionable time gain in a response situation. More frequent forecast updates could potentially be useful in decision making. As an example we analyze the predicted stream flow for the Rhine river at a station just upstreams Cologne, Germany, during the European heat wave in the summer of 2003. It was an exceptional meteorological event which combined significant precipitation deficits with record-setting high temperatures (García-Herrera et al., 2010). At its peak in August, extremely low discharge levels of rivers were reported in large parts of Europe. Economic losses where huge in many primary economic sectors including transportation (Ciais et al., 2005). For several months inland navigation was heavily impaired and the major European transport routes in the Danube and Rhine basins ceased completely (Jonkeren et al., 2008). The navigations on the Rhine is not allowed if the water levels reach a certain upper limit but there is no restrictions on the lower water limit (Meißner et al., 2017).

Despite the fact that 2003 conditions were extreme from the meteorological point of view, the upcoming deficit in precipitation and the high temperatures were well predicted by the ECMWF

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seasonal systems operational at that time (System-3; Weisheimer et al. 2011). The good predictability of the event is confirmed by the low discharge prediction provided by SYS4 at the Rhein upstreams of Cologne (4). More then 30 % of the ensemble members forecast extreme low-flow conditions. In fact the observed discharge confirms that the river flow on two separate occasions, event one on August 17-27 and event two September 18-28 2003, went below the 3% percentile of its climatological value for the season (figure 4). While most of SYS4 ensemble members mark the extreme condition three to four weeks ahead, there is no information of the recovery period observed between event one and two in the forecast starting the first of August. SYS4 predicts a swift recovery back to normal conditions on the forecast issued 1 September. A more detailed picture of this intermediate recovery is instead conveyed by the seamless system. Thanks to the more frequent updates, the temporary increase in river flow is correctly picked-up giving a potential advantage of two to three weeks for planning actions.

Even if this was a good forecast for SYS4, the information it provides is more informative (anomaly condition) than "actionable" (White et al., 2017). In the above example, a decision maker would have to make a decision based on a forecast that was issued 2.5 weeks earlier, which would inherently make the decision more uncertain if you only had the seasonal forecast. With the seamless system available a decision maker would gain the same early indication of a hazardous event and also have the benefit of frequent updates. In this particular case, the SEAM forecast for the first event was more unstable for some ensemble members, but in general the event was well captured (Figure 4). The SEAM could also correctly capture the recovery with higher water levels between the extreme low flow events. The onset of the second low period was correctly modeled by the SEAM system, whereas SYS4 did not predict it in with the right timing. It should be said that using other less extreme thresholds (<90 and <95 percentiles) even further strengthened the case for using the SEAM.

4 Conclusions

This study compared a set of hydrological hindcast experiments over the European domain with two meteorological forcings; ECMWF's seasonal forecasting system (SYS4) and a merged system of ECMWF extended range forecast and seasonal forecast system (SEAM). The latter showed a better overall skill over most areas in Europe with lead times up to seven weeks. This increase in skill could be attributed to better initial conditions of the hydrological and meteorological model as well as a better atmospheric model version in SEAM. In some areas, particularly in the Alps and northern Finland, the seasonal forecast outperformed the merged forecast. However, in these areas the predictability the hydrological model is generally poor which makes these results quite uncertain. Given that the skill in the sub-seasonal range over Europe is in the range of the extended-range ensemble forecast would motivate to use the ENS-ER instead of SYS-4 for hydrometeorological

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predictions. Still there is an added benefit of using a seamless forecast over the extended range due to the extension of forecast horizon for the early detection of upcoming anomalous conditions. Indeed, as an example this study also highlighted the potential for the use of a sub-seasonal to seasonal forecast in the case of an extreme low-flow situation in the River Rhine. The higher frequency and skill of SEAM has the advantage of being a more "actionable" forecast than seasonal forecasts, given that a decision maker would be able to make use of the extra information.

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Table 1. technical details of the forecast and the hindcast used in this paper.

System	T Res	Spatial Res	Horizon	Ens size	Issue frequency	Hindcast set	Hindcast Ens size
ENS-ER	3h/6h	18/36 km[1]	46 days	51	Twice weekly	20 years	11 members
SYS4	6h	80 km	7/13 months	51	Monthly	30 years	15/51 members
SEAM	6h	5 km	6 months	51	Twice weekly	20 years	11 members

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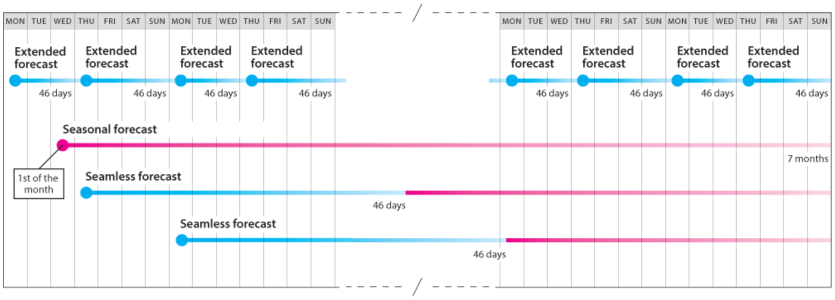

Figure 1. Schematic overview of the seasonal, extended-range forecast and merged systems. The Extended forecast is issued every Monday and Thursday and extends up until 46 days, the seasonal forecasts is issued on the first of each month and extends up until 7 months (13 months in February, May, August and November). The merged forecasts concatenates the latest extended forecast with the latest seasonal forecast.

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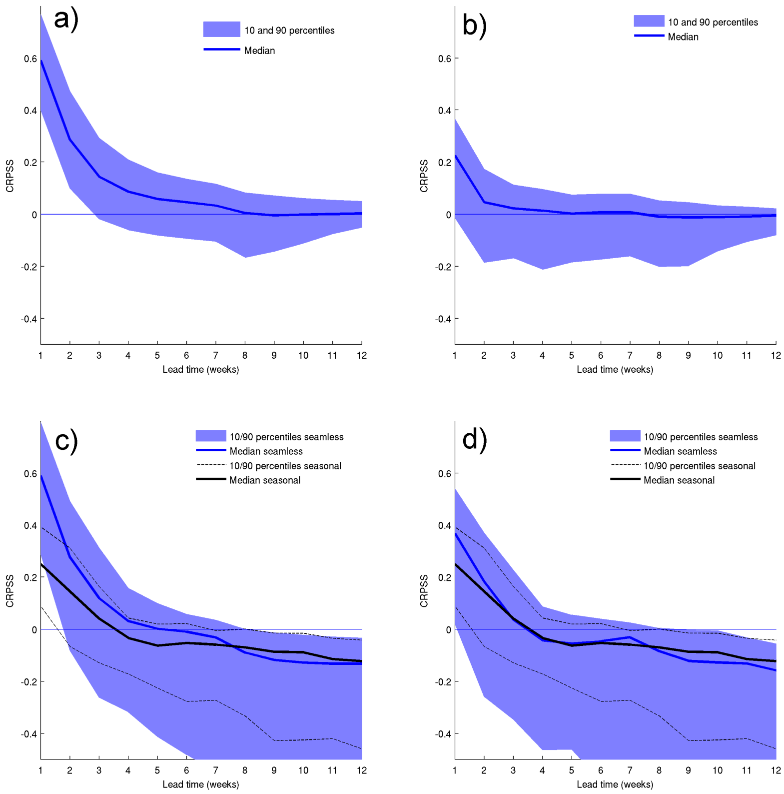

Figure 2. Continuous ranked probability skill score for a) Merged forecast against seasonal forecast for all start dates; b) as in a) but only for the first merged forecast of each month; c) merged forecast against climatology for all lead times in blue and d) as in c) but for the first merged forecast in the month. The shaded blue area denotes the 10-90 percentile of the CRPSS and the blue line the median. The black solid (dotted) lines in figure c and d denote the mean and 10-90th percentile of the CRPSS of the seasonal against the climatological forecast.

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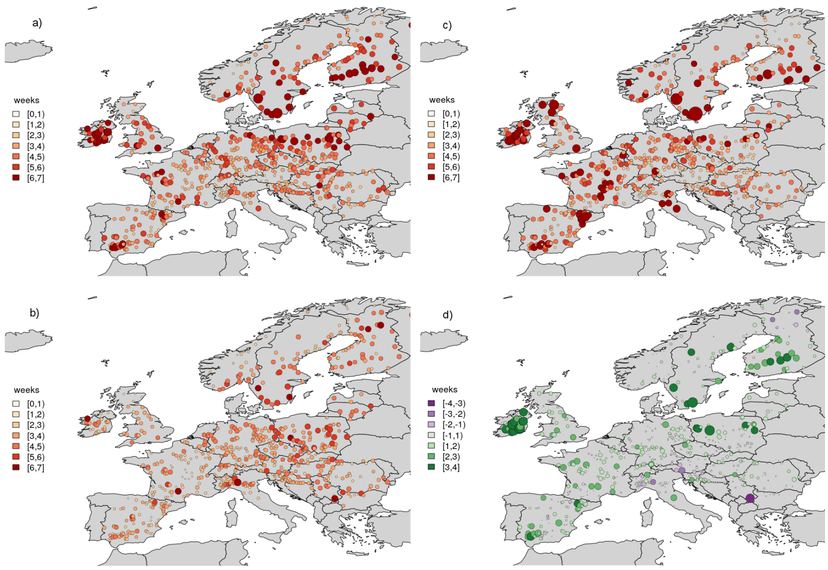

Figure 3. The number of weeks before the CRPSS goes below zero for the first forecast of the month for a) SEAM against CLIM; b) SYS4 against CLIM c) SEAM against SYS4; and d) difference between SEAM against CLIM and SYS4 against CLIM expressed in weeks. The dimension of the circles is proportional to the number of days while the color scale refers to progressive weeks.

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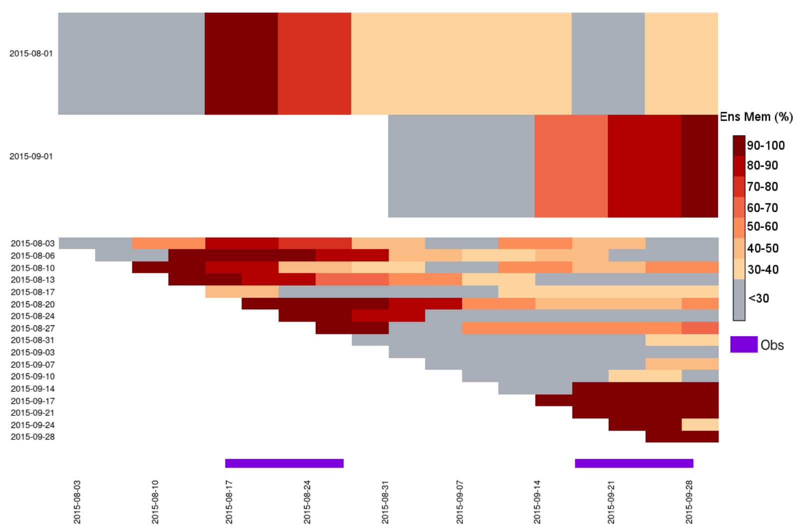

Figure 4. Percentage of ensemble members predicting low flow anomaly (< 97%) on the Rhine river north of Cologne for summer 2003. The two starting dates in August and September from SYS4 are compared to the 17 starting dates of the seamless forecasting system. In two separate events the discharge was recorded below the 97 % percentile, event 1 on 17-27 of August and event 2 on 18-28 of September 2003.