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Dynamics of River Flow Regimes Viewed through Attractors

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> *Analysing complicated systems we must never forget that the extraordinary increase in the rate of progress in our understanding can tell us nothing about the state of our knowledge.*
> *H.Metzger (1994)*

The hydrological system is extremely complex. To get insight into its behaviour and possible future states it is important to assess not only its individual components but also consider their interaction. Studying the hydrological system in its context allows focusing on the inherent patterns of its behaviour and search for external rules of its functioning. Changing climate can alter the seasonality of river flow, increasing the frequency of some patterns and decreasing that of the other, which can be adequately described in probabilistic terms. Dimensionality reduction facilitates to discern the patterns present in high dimensional systems. The approach suggested herein allows studying the dynamics of river flow seasonality patterns in the context of the present hydrological system in terms of the probability density functions of the weight coefficients in the reduced phase space, using Principal Components for dimensionality reduction. The approach is presented on the example of a large sample of monthly runoff series for Scandinavia and France, which gives a possibility to identify some common features in the dynamics of seasonality of river flow across a vast region of Europe.

Introduction

Climate induced seasonality of river flow largely influences physical and chemical characteristics of river water and thus also the aquatic life, as well as operational schemes for different water uses. River flow regimes describe this seasonality. Being dependent on the climate the seasonality of river flow can be expected to change with changing climate. The IPCC Third Assessment Report, (TAR) (Climate Change 2001) presenting the results of model studies of the impact of climate change, as represented by different scenarios, on river flow, emphasises the expected changes in the timing of especially peak flows.

The majority of assessment studies in connection to river flow focus on modelling of its possible response to a changing climatic signal. Assessing different impacts of changing climate, however, involves also evaluation and synthesis of available information to advance understanding of climate change impacts (Climate Change 2001). Giving full tribute to the investigations based on the use of hydrological models, which at present is the only way "to look into the runoff future", we argue that the assessment of potential effects of climate change on the hydrological system cannot be achieved by only running hydrological models on scenario ensembles, as the environment adjusts continuously to the new conditions. Investigating runoff in the context of a changing environment may contribute to our understanding of the possible impacts. The observed data offer a possibility to study runoff in the corresponding environmental context. This context restricts the range of a possible future behaviour. Assessment of impacts on human and natural systems that already have occurred, as a result of recent climate change is an important complement to model projections of future impacts (Climate Change 2001, Ch.2 2001). Indeed, many of the changes in the behaviour of the river flow demonstrated by hydrological models run for different climate change scenarios have also been shown analysing the observed series during similar climatic conditions. For Scandinavia, for example, shifts in the timing of peak flows and increased frequency of extremes shown by the modelling approach (*e.g.* Krasovskaia and Sælthun 1997; Sælthun et al. 1998; Xu 1998), was demonstrated earlier using the observed flow records (*e.g.* Krasovskaia and Gottschalk 1992; Krasovskaia 1996).

The results of the model studies of climate change impact on the environment contain many uncertainties caused by problems with data, problems with models and other (for a full review see *e.g.* TAR, Climate Change 2001, Ch.2 2001). Climate change scenarios used as an input in hydrological models in impact studies still contain a great deal of uncertainties, especially what concerns regional scenarios, though much effort has been put to handle these problems. Uncertainties stem not only from the scenarios, however, but also from the lack of sufficient understanding of the processes accounting for interaction of climate and hydrological systems. All these uncertainties are propagated further and added to the uncertainties inherent to hydrological models, while consideration of the total uncertainties in the results is often unsatisfactory. Under such circumstances, methods based on the direct analyses of the observation records, like the one suggested in this paper, offer an indispensable complement to model studies.

Another aspect that calls for great caution and use of different approaches when assessing the impacts of climate change on the environmental systems is the presence of complex, chaotic, non-linear dynamics in the climate system (Climate Change 2001, Ch.14 2001). When chaos is present, "negligible" differences in initial conditions are no longer negligible and can totally change model predictions. As noted by Cohen and Stuart (1994), in this situation it is no longer appropriate to start with today's data as initial conditions and then predict tomorrow's. Understanding of at least some aspects of the mechanism itself and not just its input-output characteristics is necessary. At present hydrological models used in assessment studies are not well adapted to cope with non-linear dynamics in runoff induced by that of climate.

Natural systems rarely remain for long in equilibrium, adjusting continuously to new conditions. Sudden, catastrophic changes are commonly difficult to miss, but the cumulative impact of continual small-scale change, may be of even greater significance. As noted in the TAR, an important component of the detection process is the search for systematic patterns of change across many studies that are consistent with expectations, based on observed or predicted changes of climate (Climate Change 2001, Ch.2 2001). Working directly with the observation series may allow detecting such patterns of changes long before their impact can be noted, which facilitates the possibilities of the society to adapt.

Traditionally, trend analysis has been widely used to detect gradual changes in the observation series of climate and runoff characteristics (Kundzewicz and Robson (2000) provide a valuable review). The reliability of the results of such studies, however, is strongly affected by relatively short record periods available. This is especially true in case trend analysis is used to describe the behavioural patterns of runoff in "a region" on the basis of individual observation series of various lengths. Here we will look for systematic patterns of change in the seasonality of river flow (river flow regimes) trying to identify the presence of attractors in the monthly runoff series and their development in time. An attractor, in general, is a region of a phase space that "attracts" all nearby points as time passes (Cohen and Stewart 1994). Attractors capture long-term dynamic behaviour. Following the trajectory of the attractor in time may give an early indication of the gradual changes that take place in the timing of river flow and eventually indicate their range, direction and velocity. The approach presented herein facilitates a search of systematic patterns of change across large areas.

The hydrological system, as all complex systems, has a rich structure, an order of which is rather intrinsic than imposed from the outside. In the observation records not one but a variety of seasonal flow patterns during individual years is present in each series, their number being dependent on the dimensionality of the flow regime of a particular series (Krasovskaia 1995; Krasovskaia *et al.* 1999). The intrinsic order of a hydrological system is dynamic rather than static and it changes subject to external forcing. With varying climate some of the seasonal patterns may appear more and more often (an attractor emerges), while other may become more rare and practically disappear. The attractors move and can split up, merge, disappear and reappear (*i.e.* a catastrophe or a bifurcation occurs) under the influence of a continuos change in "control" climate variables (*e.g.* temperature and rainfall). Even small changes in circumstances can produce big changes in behaviour leading sometimes to the emergence of the new attractor. The earth's climate is a huge dynamical system, and it seems to have at least two attractors: the mild kind of climate we are currently experiencing and ice ages (Cohen and Stewart 1994). Though the global warming just moves the "mild" attractor a little, it can be so that even tiny disturbances can bring the system to a threshold and switch it to another attractor. As noted in TAR, thresholds are present in the climate system and transition has occurred in the past and it is important to extract early signs of changes from model simulation and observations (Climate Change 2001, Ch.14 2001). The approach presented in this paper might be useful to identify early signs of changes in the timing of river flow across large regions.

Defining a single climate future is insufficient and unsatisfactory (Climate Change 2001, Ch.13 2001). This is certainly true also for a hydrologic future and it is obviously more appropriate to handle the "hydrologic future" in terms of probabilities. While such approach is gaining acknowledgement among climatologists studying climate change (*e.g.* Paeth *et al.* 1999; Corti *et al.* 1999; Palmer and Räisänen 2002), it is still a rarity among hydrologists involved in climate change impact studies. Running a hydrological model on manifold different climatic scenarios (*e.g.* Arnell 2000) may certainly help to handle to some extent the uncertainty induced by the scenarios in terms of probabilities but hardly those originating from insufficient knowledge about the interaction of processes involved. The dynamics of the seasonal behaviour of river flow may be with advantage studied in terms of the probability density functions. This allows identifying and following the dynamics in time and space of not just one but an ensemble of different seasonal patterns thus giving full account of many facets of a flow regime contained in each observation series. This approach applied to the observed data is a direct parallel to the one suggested by Palmer and Räisänen (2002) with respect to future extreme climatic events. They suggested to represent such events as frequency distributions based on the outcomes of different GCM's models instead of "the best guess" provided by the consensus that averages the results of different models.

Great uncertainty in the regional projections of scenarios of climate change was noted earlier. The hydrological system may develop towards some local optimum states that are different from the global ones. In this context it is important to investigate the hydrological response in a range of existing climatic conditions, trying to identify similarities and differences in the response. Different flow regime patterns can be seen as some "preferred states" of the runoff system. In our earlier study (Krasovskaia and Gottschalk 2002) we have introduced a method for studying the dynamics of river flow regimes in terms of the probability density functions represented in a reduced phase space and demonstrated its use on the example of Scandinavian river flow regimes. Later also the French river flow regimes, though for a much shorter record period, have been investigated using the same method (Krasovskaia *et al.* 2002). Here we will develop this approach further and exemplify it applying it to an extensive data for these two contrasting climatic areas of Europe studied as one sample for a common observation period, which permits identifying similarities and differences.

Data Used

An extensive sample of monthly runoff data for 48 stations all over Scandinavia and 57 stations across France has been analysed. The joint observations cover a period 1950-1995, which yields 2,200 individual observation years analysed for Scandinavia and 2,700 for France and the total of 4,900 observation years in the joint sample. These data were normalised with respect to the annual means. It is admitted that the joint time period that could be identified for such a vast area is still rather limited but here it is used to develop and present the approach rather than make some definite conclusions about the dynamics of the seasonal patterns in the area of study. Although the data for Scandinavia and France have been analysed also separately, the study focused on the analysis of the joint sample, which allowed direct comparisons, based on a larger data sample. The vast region of study offers a great variety of European seasonal river flow patterns from purely pluvial oceanic with high water in winter and low water in summer to nival with high water in spring/early summer due to snowmelt and winter minima caused by freezing. The sample contains also many transition regime types with, for example, secondary high water period in autumn due to rainfall events.

Representation of Runoff in a Reduced Phase Space

It is difficult to interpret high-dimensional patterns of river flow looking for systematic behavioural patterns, as redundant information and noise often camouflage them. Reducing the dimension first allows to get rid these latter and focus on the essential behavioural features. Such a reduction implies a representation of the original data in a form of either a moderate sized set (<1000) of points (the points can be viewed as vectors in some metric space), or as a matrix of proximities. The components of the vectors characterise the points that constitute the pattern. Then a new vector, which still possesses the main characteristics of the initial one but has a lower dimension, is looked for. This new dimension reveals the intrinsic dimension of the pattern and identifies the minimum number of components required to describe it adequately.

In this study we will use the well-established method for dimensionality reduction, namely Principal Components (PC), also called Empirical Orthogonal Functions (EOF). The formal theoretical concepts behind EOF in a continuous space have been introduced independently in works by Kosambi (1943), Loeve (1945), Karhunen (1946), Pougachev (1953) and Obukhov (1954) and are usually called Karhunen-Loeve expansions. Lorenz (1956) suggested (working on discrete data) the name "Empirical Orthogonal Functions" noting the parallel between EOF and the Factor Analysis (Principal Component Analysis, PCA) used by psychologists (*e.g.* Hotelling 1933) to interpret psychological tests into behavioural patterns. The following distinction is made between them: while the EOF refers to unit length eigenvectors, the PC model weights the eigenvectors by the square root of the corresponding eigenvalue. The weights thus represent the covariance between each variable (here seasonal regime pattern) and each principal component (amplitude function) in case of PC. The difference is rather a matter of mathematical elegance (Richman 1986) than a real influence on the results. In our experience they are identical. We anyway prefer here to apply PC rather than EOF, as in this case the weights more straightforwardly show the importance of the respective principal component.

The EOF-method (without really making a clear distinction to PC) has been widely used in hydrology (*e.g.* Stidd 1967; Bartlein 1982; Gottschalk 1985; Obled and Creutin 1986; Braud 1990; Krasovskaia and Gottschalk 1995; Sauquet *et al.* 2000). Lorenz (1956) used EOF to reduce dimensionality, *i.e.* get rid of the large amount of redundant information contained in meteorological data. EOF has been used for dimensionality reduction in our previous pilot studies of the dynamics of the seasonal patterns in terms of attractors (Krasovskaia and Gottschalk 2002; Krasovskaia *et al.* 2002). Today both approaches are used in meteorology, climatology and hydrology and a difference can be traced in the interpretation of the empirical functions viz. whether they are only mathematical constructions or can be interpreted in some process oriented way. Here PCA will be used purely for dimensionality reduction of the normalized monthly runoff data.

Studying the intrinsic dimensions of Scandinavian river flow regimes, Krasovskaia *et al.* (1999) have shown that the two first amplitude functions in the EOF expansion of the original series contribute to 70%-90% of the total explained variance in seasonal patterns. Five amplitude functions were needed to describe the seasonal patterns with high accuracy for the majority of flow regimes, also less stable ones. Similarly, limited number principal components can be sufficient for describing the time evolution of the flow regimes with sufficient accuracy. Basing on the intrinsic dimension of the flow regimes indicated by the study referred to above, we have chosen to represent the data sample in a five-dimensional phase space, and not two as in our two previous pilot studies (Krasovskaia and Gottschalk

2002; Krasovskaia *et al.* 2002). This would allow considering adequately all types of flow regime patterns and not only the stable ones with lower intrinsic dimensions. The first five principal components represent 0.857 of the total variance in the data sample studied.

In a study of the signature of recent climate change in frequencies of natural atmospheric circulation regimes Corti *et al.* (1999) studied the climate as a nonlinear dynamic system with a chaotic attractor having a few stable climate regime patterns. In this interpretation a climate regime represents a pattern in space. The irregular fluctuations in climatic regimes were studied in terms of the changes in the probability density function (PDF) of the reduced phase space between the regime centroids of this function. It was shown that the locations of these centroids did not change but their probabilities did. A river flow regime describes a seasonal flow variation pattern in time. We can similarly treat it as a dynamic process centred around some preferred states (flow regimes). We assume that the present river flow regimes formed under the variety of climatic conditions in the global scale will persist (at least in the time perspective of the impact studies) but their frequencies might change influenced by changing climate (or more precisely by changed frequencies of the preferred climatic regime patterns). The PDF over the reduced phase space will allow identifying the probability for different seasonal flow regime patterns and follow their dynamics over time.

Dynamics of Seasonal River Flow Patterns Across France and Scandinavia

The phase state portraits of the seasonal patterns demonstrated by the monthly data during different time periods are shown in Fig.1. The regime state vector PDF in the reduced space spanned by the first five principal components is shown in two dimensions in this figure, where the first and second principal components are plotted against each other (along the x and y-axes, respectively). The intensity of the colours in the figure describe relative frequencies of different seasonal patterns, the darker the colour the higher the frequency. Examining Fig.1 we can see that the domains with high frequencies (attractors) situated mostly in the left part of the image, as well as those with lower frequencies in the right part, obviously change their position and extension in time. Some patterns become more frequent, while other ones appear more seldom during individual years.

The images in Fig.1 characterise some average PDF for the different seasonal patterns present in the record period. To investigate the character and direction of changes with respect to a particular seasonal runoff pattern it is necessary to identify the location of its centre of gravity in the phase state portraits. To do this the monthly runoff series having this particular flow regime during each individual year can be aggregated first using some grouping procedure. Then the five coordinates of the centre of gravity of the obtained group can be determined as the mean values of the weights of the five principal components used. To exemplify this procedure we have chosen to follow the development in time of four regime patterns common in the region of study. These are the regimes: a) with high water in spring-early summer and low water in winter (associated with "nival" types); b) with high water in winter and low water in summer-early autumn (associated with "oceanic" types); c) with high water in spring-early summer and autumn and low water in winter (associated with "pluvio-nival" and "nivo-pluvial" flow regimes) and d) with high water in spring and low water in summer (associated with river flow regimes in the temperate zone with more continental climatic conditions). The series with the explained variance lower than 81% were withdrawn from the analyses as obviously very unstable (about 10% in each group). The explained variance for individual series for the remaining sample was 91%-97%. A hierarchical aggregation procedure based on the Wards algorithm was used for grouping (see for example Krasovskaia 1997).

Figs. 2a-d offer an illustration of the seasonal flow regime patterns selected as the example. The centres of gravity for these patterns are shown in Fig.1 by: big circles for pattern a); big squares for pattern b); small circles for pattern c) and small squares for pattern d) (solid and transparent symbols identify the Scandinavian and French data, respectively). We can see that the centres of gravity of the Scandinavian and French series having similar seasonal patterns occupy close positions. Series with seasonal patterns a) and c) are located to the right in the phase portraits and have lower relative frequencies, while those in groups b) and d) in the left part are located in the domain with much higher frequencies (the attractor zone) during all the periods studied. Following the dynamics of the four selected seasonal patterns in time, we can note a general tendency for a small increase towards the end of the period in the relative frequencies of patterns b) and d) and for Scandinavian data also pattern c), while pattern a) tends to lower relative frequency there. We see that for this latter pattern a small attractor domain present at the beginning of the record period (in the right part of the images) weakens at the end of it.

The dynamics of the relative frequencies of seasonal patterns can be followed only in two dimensions in Fig. 1. Fig. 3 complements the identified tendencies by showing the diagrams for their respective relative frequencies during different periods basing on all five principal components. We note a rather big variability in the frequencies for some of the seasonal patterns. We see the general tendency for an increase of the relative frequencies of seasonal patterns with high water in winter and low water in summer-early autumn (b) confirmed for both Scandinavia and France, as well as the decreasing frequencies of patterns with low water in winter and high water in spring-early summer (a) in Scandinavia. While patterns with high

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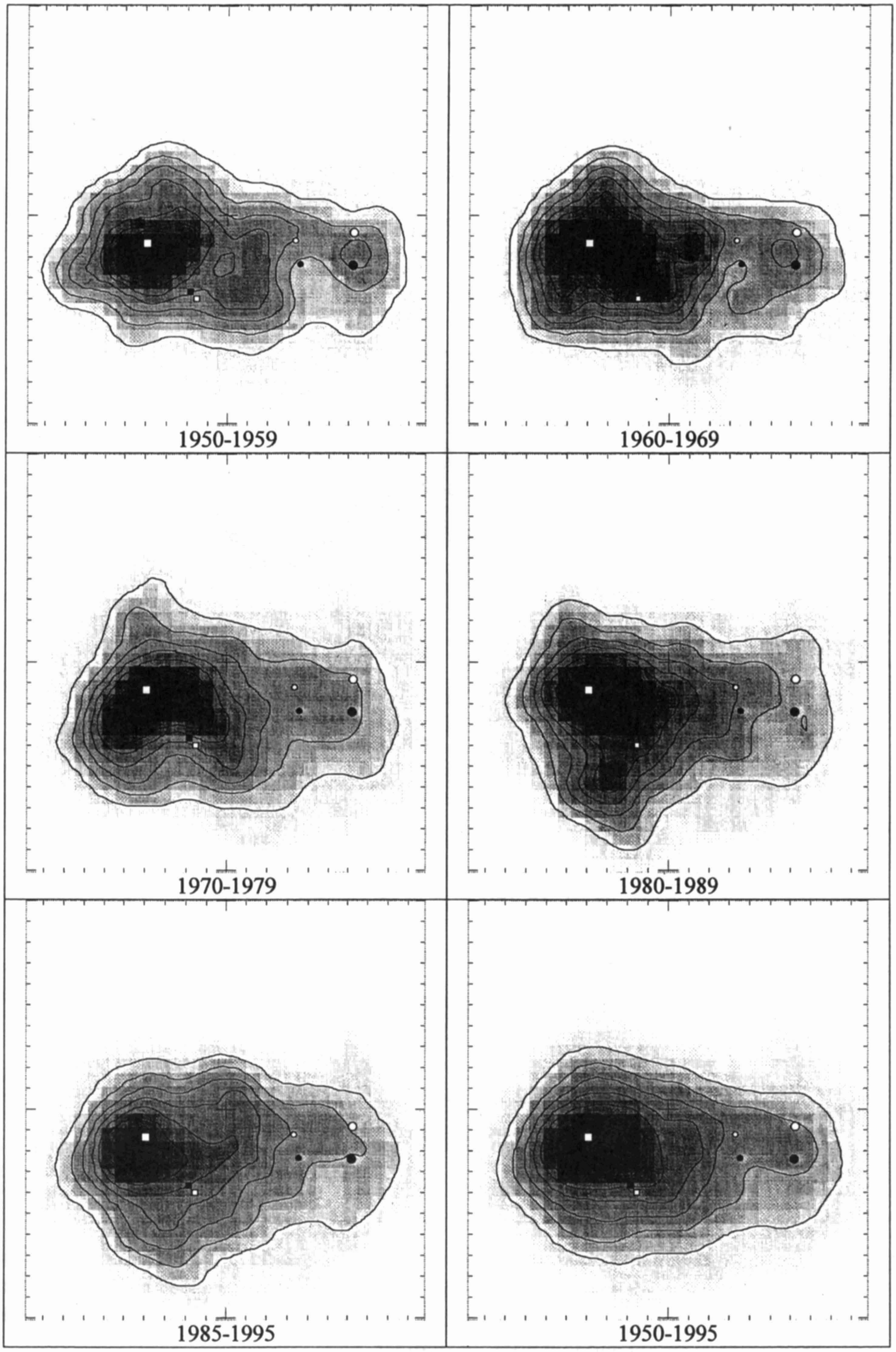
Fig. 1. Regime state vector PDF in the reduced phase space spanned by the two dominant principal components of monthly runoff. The symbols identify the location of the centres of gravity of the seasonal patterns discussed.



1950-1959

1960-1969

1970-1979

1980-1989

1985-1995

1950-1995

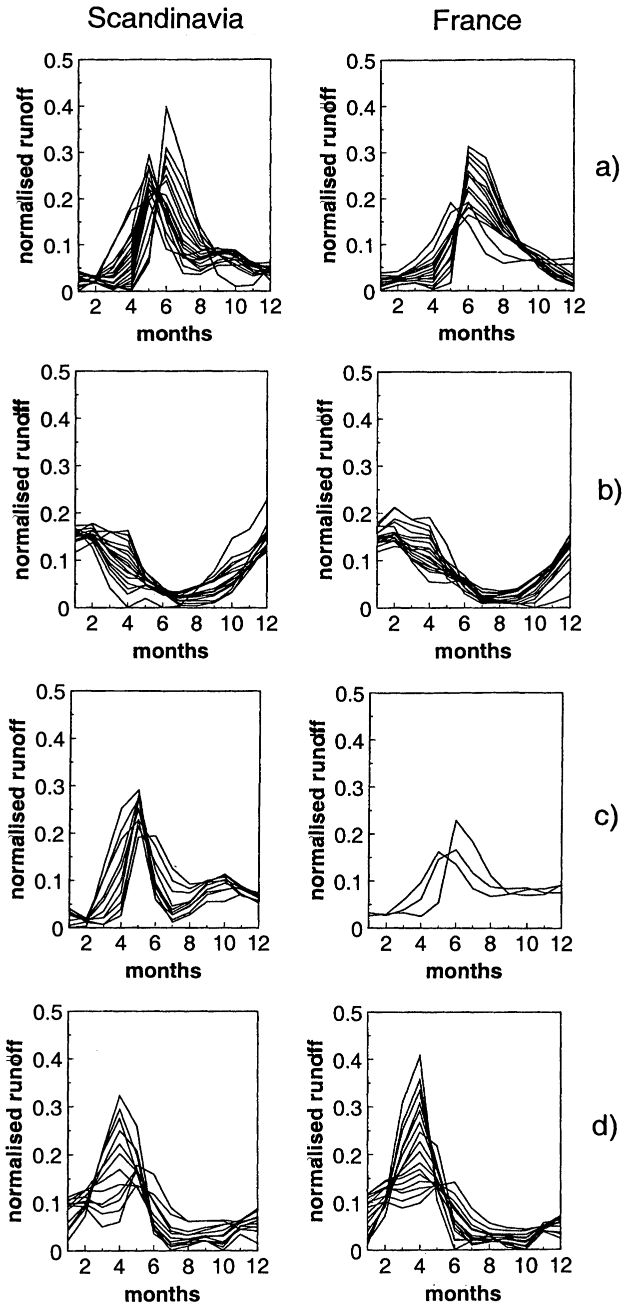
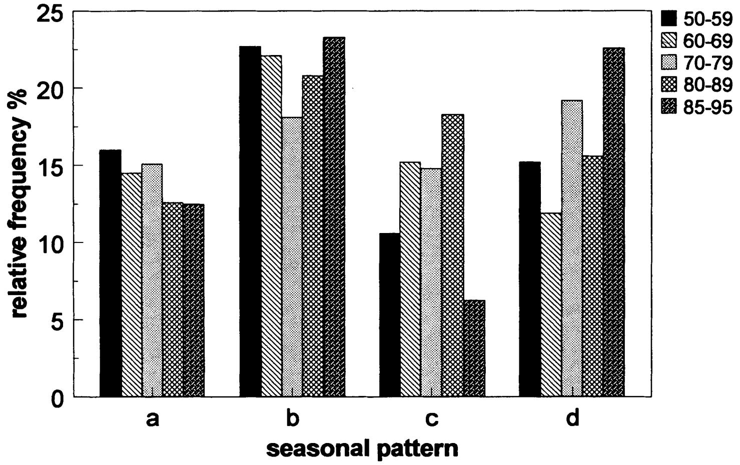


Fig. 2. Seasonal runoff patterns: a) with high water in spring-early summer and low water in winter, b) with high water in winter and low water in summer-early autumn, c) with high water in spring-early summer and autumn and low water in winter and d) with high water in spring and low water in summer.

Scandinavia



France

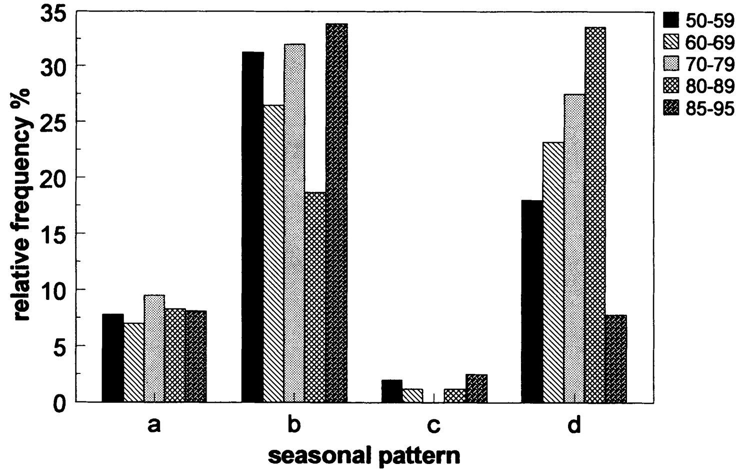


Fig. 3. Dynamics in the frequencies of seasonal patterns.

water in spring and low water in summer (d) become more frequent in Scandinavia, as seen earlier in Fig.1, their frequency decreases considerably during recent years in France, which could not be seen in two dimensions. The situation is similar for pattern with two high water periods *viz.* in spring and in autumn in Scandinavia (c), the frequency of which also seems to decrease during the recent years. It should be noted that both these patterns are in general unstable (Krasovskaia 1995) and the result must be treated with caution. Thus, studying the seasonal patterns in a reduced five-dimensional space brings forward new important information hidden earlier.

There is also an indication of a possible difference between Scandinavia and France in the dynamics of some flow regimes with similar seasonality. The observed tendencies are in a general agreement with the results of other studies of the impact of the changing climate on river flow regimes in the region (*e.g.* Krasovskaia and Gottschalk 1992; Krasovskaia 1996; Sælthun *et al.* 1998; Martin and Etchevers 2001; Leblois 2001; Etchevers *et al.* 2002). We have shown here the application of the method on the example of four different flow regime types but naturally such an analysis can be performed for any regime type of interest following the same procedure.

Conclusions and Discussion

Studying the possible impact of climate change on water resources and, in particular seasonality of river flow, in the context of the present climate is an important complement to the dominating modelling approach, as this context restricts the range of the possible changes.

This is a "top-down" approach, which, as expressed by Gell-Mann (1995), "begins with the identification of important regularities at the less fundamental level and defers until later understanding of the underlying, more fundamental mechanisms". The totality of possibilities is constrained by the rules that operate on climate and hydrological systems. The approach described here offers a possibility to study a hydrological system in its natural context looking at it from outside in search of external rules of its functioning.

Amongst the great variety of river flow regimes existing at present, some will become more frequent under the influence of changing climate, while the other will be observed more and more seldom. Studying the present regime patterns across a large region during different time periods might indicate the character of possible changes, their velocity and range. The approach presented herein allows studying a system consisting of different blocks without decomposing it into these blocks, looking for patterns rather than isolated steps of causality.

To discern the structure in seasonality of river flow hidden by the high dimensionality, we first reduced this dimensionality, applying the PC transformation, to a five dimensional space, efficiently preserving the main features of the patterns and leaving out the redundant information. The seasonal patterns were then studied in a five dimensional phase space for different periods, which allowed following their dynamics in time.

Here we studied this dynamics in terms of probability density functions preferring this approach to a more conventional way of considering dynamics of individual series and averaging the results (applied to both observed and modelled data). This not only makes the results less sensitive to eventual discrepant behaviour of individual series (cased by local scale processes, human impact, errors etc.) but also yields an answer in terms of probabilities, offering not one but a variety of seasonal patterns present more or less frequently in the sample. Seasonal patterns handled in terms of probabilities are also more suitable in risk studies, as part of an investigation of climate change impact on water systems.

The patterns of frequencies of the flow regimes present in the analysed sample proved to change with time. The range of the changes in the seasonal patterns chosen here to exemplify the method was in general moderate. Some general tendencies could be seen *viz.* increasing frequency of flow regime types with low water in summer-early autumn and high water in winter-spring, especially in Scandinavia. Also a decreasing frequency of regime patterns with winter minima was noted there, while in France the frequency of this pattern varied very little. As this paper focuses on the presentation of the method we leave deeper analyses of the revealed dynamics of seasonal patterns and reasons for such behaviour for further investigations.

"The future is not given. We face the end of certainties. There is not one future but futures." said the Nobel Prize winner Ilya Prigogine (2001). This puts forward new challenges to science and calls for approaches that allow discerning the many facets of the future in the information available, whether it is observed or modelled on the observed data with some assumptions. This study is a modest contribution to such efforts.

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