DELIVERABLE 2.1.3
IMPROVED PROCEDURES FOR MEDIUM AND SEASONAL WATER LEVEL FORECAST

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1. Introduction / Motivation

The objective of this task is to investigate the current state-of-the-art in research related to forecasting of water levels on the medium to seasonal time scale. An improved ability to predict both high water events and long periods of low water may aid the shipping industry by making it possible to reduce the effects of suspended navigation. In a changing climate, this information is especially valuable since flooding events associated with heavy rainfall and snowmelt, as well as long periods of drought, may become more frequent in the future (see ECCONET Deliverable 1.1). In particular, extended periods of low water levels like that experienced during summer 2003, which amounted to a loss of € 91 million for the River Rhine alone, could occur more frequently. The impacts due to high water levels have smaller consequences for the economy (Jonkeren et al., 2007).

The application of a long-term forecast system, which is able to estimate a following drought like the event in 2003 would prevent such losses when stock keeping is able to prevent empty stocks of pre products or the overfilling of stocks of products which cannot be delivered due to obstructions of shipping transport.

Seasonal forecasting is a fast developing scientific field with considerable effort devoted to developing comprehensive coupled general circulation models (Balmaseda, 2009). So the available forecasting systems can be described, but there is not a final product which is applicable as a management and decision advice.

In general, water level forecasts are produced using hydrological models that are driven by forecasted or observed meteorological data. This impies that a correct water level forecast depends on a correct meteorological forecast. Moreover it is well known that the prognostic value of the long-term meteorological forecasts is low over the European region. Thus, possible improvements in prediction for medium to seasonal water level forecasts could stem from improvements of meteorological forecasting on the same time scale (provided there is no long time lag in the system which is deemed plausible for the studied river basins in ECCONET). Nevertheless, in spite of all the developments of the meteorological forecasts, the instantaneous states of the atmosphere have a limited predictability while the mean states of the atmosphere have a greater predictability (Céron et al., 2010).

From a practical perspective, there is only one reason for undertaking research and development to advance seasonal to interannual predictions and for investing in the infrastructure to produce and deliver them. That reason is to assist whatever decision processes are of concern to those who might make use of them. To be of real and measurable value, prediction information must be readily assimilable into the decision processes of recipients. In practice this goal may represent the ideal more than the complex reality, but it implies nevertheless that coordination between supplier and recipient is essential for the derivation of optimal benefit from the prediction information.

Such optimal benefit is difficult to achieve in seasonal prediction (Troccoli, 2007, p 19):

- when the provider does not have a clear view of the needs of the recipient,
- when the recipient does not have a clear view of the uncertainties inherent in the information, and
- without adequate and ongoing coordination and dialogue between provider and recipient.

Therefore, a description of meteorological and hydrological approaches and methods is structured in chapter 2 and 3 and also an assessment of economic needs will be done in this report. Chapter 4 is a description of anthropogenic activities which influence the predictability of water levels. Chapter 5 points out the possibilities in fusion of meteorological and hydrological approaches and the economic needs. The final chapter is dedicated to conclusions in application of long-term forecast systems today and further work which can improve this forecasting.

2. Meteorological Approaches

The state of research in the subject of meteorological forecasting on the medium to seasonal time scale will be discussed here. Following that an overview was given about the current approaches to meteorological seasonal forecasting in Section 2.3. Section 2.4 discusses the current research related to sources of predictability and the fifth and final section concludes the literature review.

2.1 Methods of seasonal forecasting

2.1.1 Empirical (statistical)

In the field of weather and climate, the empirical method of forecasting involves using past observations and statistical methods to create forecasts (Goddard and Hoerling 2006). The basic idea behind empirical forecasting entails statistically fitting observational data to known distributions, i.e., the historical observations and the accompanying circulation and surface impacts are analyzed and the same relationship is “projected” for the future. Certain advantage of this method is that it relies on real observations rather than error-prone numerical model simulations (however, it has to be mentioned that observations are also hampered by errors) (Section 2.1.2). There are also disadvantages due to a limited number of past cases with which to compare, as well as problems associated with the assumption that the climate is non-stationary. This assumption implies that relationships derived from past data remain valid in the future which may not necessarily be the case in the changing system including complex feedbacks and interactions. In spite of this, empirical models can just be used as a benchmark or a point of reference for the evaluation of model performance.

2.1.2 Dynamical

Dynamical models, on the other hand, effectively predict the weather or climate signal using dynamical general circulation models (GCMs) (Goddard and Hoerling 2006). However, the numerical *weather* predictions and *climate* projections have to be separately discussed, because of the essential differences in these simulations and in the interpretation of predictability.

The predictability of atmospheric processes is lost after few weeks (but rather 14 days in practice), which is due to the chaotic nature of the system. Taking into account the processes of the slowly varying (like ocean or ice) components of the Earth system, the atmospheric predictability can be extended in a certain sense, nevertheless, this kind of predictability does not guarantee the predictability for the successive instantaneous, but the mean states of the atmosphere. The ***weather*** prediction method , which considers the slowly changing components of the system as external forcings (for instance sea surface temperature (SST) anomalies, soil moisture and sea ice), is called a two-tiered forecast system and its predictability arises from the influence of specified slowly varying lower boundary conditions for the atmosphere. The disadvantages of the two-tier system lie in the (sometimes difficult) predictability of the external forcings and in systematic model errors that may appear in the GCMs.

One can overcome some of the disadvantages of the two-tiered system by utilizing a fully coupled Earth system model, or a coupled general circulation model (CGCM). This single-tier forecasting system is advantageous over an atmospheric circulation model (AGCM) because it predicts the evolution of the ocean and atmosphere as they interact with each other, while in an AGCM, the ocean does not respond to the atmosphere and this may lead to unrealistic conditions.

The predictability of a fully coupled Earth system model affected by the Earth system initial conditions. (It is emphasized again, that this is valid only for the weather prediction, since in climate time scale we cannot speak about the predictability in classical sense.) The advantage of such a system is that it includes a comprehensive description of physical processes, however, there are substantial systematic errors in the present-day generation of CGCMs (Gleckler et al., 2008). Thus, the uncertainty in the single-tier system lies in the imperfect knowledge of the initial conditions and the systematic errors of the models.

It must also be noted that for medium to seasonal prediction, long-term processes in the climate system, such as increasing greenhouse gases, may be assumed as constant (fixed to the observations in 90s) over the predicted time frame. However, there is mounting evidence, such as the strength of the increasing temperature trend in Europe (Oldenborgh, van et al., 2009), that suggests year-to-year changes in long-term processes are becoming increasingly important and should be included in the dynamical models. Although the inter-annual temperature variability is not significantly affected by the annually updated greenhouse gas concentrations according to the investigations of Doblas-Reyes et al. (2006), the long-term trends at the regional scale become more realistic.

In order to describe the behaviour and future evolution of the Earth system in ***climate*** time scale, global climate models are applied. These models are coupled atmosphere–ocean general circulation models (AOGCMs), which are capable of describing the physical processes of each climate system component (atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere) and properly characterizing the long-term non-linear interactions and feedbacks between them. Since these global models represent the Earth in its entire complexity, they provide the *long-term* global response of the climate system for a hypothetical forcing, but these projections are not able to reflect individual weather events. In the climate model simulations, there are three main sources of uncertainty: the internal variability, which is a natural characteristic of the climate system; the greenhouse gas concentration increasing due to the anthropogenic activity; the imperfect knowledge of the physical processes.

It should not be thought, though, that one method of seasonal forecasting (statistical or dynamical) is better than the other. While it is possible to use a purely statistical approach, it has its serious limitations, and a purely dynamical forecast needs careful calibration and interpretation. Thus, the current trend in seasonal forecasting is to combine the better aspects of both approaches in order to produce more accurate and reliable forecasts than either approach alone (e.g., Doblas-Reyes et al., 2009). Both the weather forecasts and the climate projections require the quantification of the uncertainties, and this information is produced with the help of probabilistic (ensemble) forecasts in every time scale. In the seasonal forecasting the combined multi-model–multi-analysis ensemble approach serves as a way to quantify uncertainty due to imperfect knowledge of physical processes (including physical processes of the slowly varying components of the Earth system) and due to imperfect initial conditions. This approach is discussed below.

2.1.3 Ensemble prediction: quantifying uncertainty

There are two key sources of uncertainty in atmospheric weather prediction models: uncertainty in initial conditions and uncertainty due to imperfect knowledge of the climate system, i.e., error due to the approximation of physical processes that are included in the models themselves.
The uncertainty in initial conditions arises on the one hand, from the observations: besides the instrumental inaccuracy, also the resolution of the observational network is not sufficient to prepare the initial condition (IC) on a high-resolution grid. Consequently, in order to create ICs for the model simulations, short-range numerical predictions and data assimilation techniques

are also needed. But even small errors in the shorter time scales will be amplified and propagated to the longer time scales through non-linear interactions as a consequence of the chaotic nature of the Earth system, thus affecting forecast accuracy. The other source of error arises from the inability of numerical models to resolve every physical process present in the Earth system. Many of these physical processes operate at smaller scales than the model grid size and some of them (e.g., radiation processes) are too complex to being explicitly described so they must be approximated. The approximation of unresolved processes using model-resolved variables is termed parameterization. Studies have shown that in the short time scale initial uncertainties are the most significant, however especially after the first 72 hours, model uncertainties have also important role (e.g., Harrison et al., 1999; Doblas-Reyes et al., 2009).

The result of these two sources of error is that the prognostic value of the forecasts degrades with increasing lead time. In order to make predictions on medium to seasonal time scale, the slowly varying components of the Earth system have to be coupled into the atmospheric system, which brings further uncertainties coming from the specifying the lower boundary conditions and description of the interactions between the atmosphere and other components. Thus, in order to make accurate and reliable predictions on the medium to seasonal time scale, the numerical models must attempt to cope with these issues. An ensemble approach to prediction can address all of these error sources by creating an ensemble of model members with different initial conditions and different parameterization schemes. The ensemble of forecasts can then be used to estimate the probability of a certain outcome. An even larger ensemble can be formed by combining the ensemble forecasts of different models. Indeed, recent studies have shown that an ensemble forecast generated across different models is more accurate and reliable than an ensemble generated from one model alone (e.g., Hurrell et al., 2009; Goddard and Hoerling 2006; Hou et al., 2005).

2.1.4 Scale interactions and climate system predictions

Day-to-day weather forecasting is typically carried out using an atmospheric general circulation model (AGCM) that has traditionally been forced using observed sea-surface temperature (SST) anomalies. Essentially, a weather forecast is an initial value problem of atmospheric components; the effects of longer-term processes, such as ocean circulation, are much smaller in comparison. Weather forecasts are usually produced on the time scale of 1-14 days. After roughly 45 days, all information contained in the initial conditions becomes unimportant (Kleeman 2006).

On the seasonal time scale and beyond, long-term effects are more significant meaning ocean circulation plays a greater role in the quality of the forecasts. Thus, a numerical weather prediction with an AGCM is typically coupled with an ocean general circulation model (OGCM) in order to perform forecasts past day 14. The AGCM-OGCM coupled models are limited to a relatively coarse resolution compared to the weather prediction models (which typically have 10-20 km horizontal resolution), which negatively impacts the accuracy of forecasts. Current research is examining the benefits of using AOGCMs at resolutions at or near typical weather prediction models (e.g., Hazeleger et al., 2010). Another model approach that attempts to bridge the gap between time scales is called “seamless prediction” and will be discussed in the next section.

2.2 Current approaches to seasonal forecasting

2.2.1 Seamless prediction

Both weather and climate models have evolved from similar beginnings, are built on the same principles, and face similar challenges that need to be handled (see above). Despite this, however, climate research and weather prediction are commonly thought of as different disciplines. In climate modelling, the goal is to represent the Earth system using global coupled ocean-atmosphere models, or Earth system models, in order to make predictions on the long-term from decades to centuries. Numerical weather prediction models, on the other hand, are designed to be used on the short-term from daily to seasonal time scales. In an aim to construct a single, unified framework out of both weather and climate models across all time scales, the concept of “seamless prediction” has been developed (e.g., Hurrell et al., 2009). The central idea behind seamless modelling is that all climate system predictions share common mechanisms and physical processes across all time and space scales.

The combination of numerical weather prediction models and Earth system models can prove beneficial to both communities. In general, atmospheric model development is more advanced in the field of weather prediction meaning new developments could be applied to the Earth system models. Similarly, Earth system components such as atmospheric composition and the land surface are increasingly being included in weather prediction models. Thus, the seamless model is designed to bridge the gap between numerical weather prediction and Earth system modelling by combining the knowledge gained in each respective field.

In order to take into account the limitation of computing resources as well as the fact that different physical processes operate on different times scales, model configurations are designed based on the time scale of interest. For example, in long-term climate modelling, the use of a coupled ocean-atmosphere model is essential, yet in short-range weather forecasting, the ocean plays less of a role and running a high resolution atmospheric model may suffice (see: User Guide to ECMWF Forecast Products).

The concept of seamless prediction has the main benefit that only one system is developed to make predictions across all time scales. Thus, it is possible to learn about climate model performance by examining such things as error growth in the shorter-range forecasts. Also, confidence is increased since using the same model at different resolutions can confirm whether or not the driving mechanisms within the models are consistent. There is also the above mentioned advantage in that cooperation between the weather and climate communities will bring mutually beneficial improvements to both longer and shorter term forecasts. At the time of writing, there are three seamless prediction models being developed, two of which (The Unified Model from the Met Office in the UK and the ARPEGE system at Météo-France) are used operationally and the other of which (EC-Earth) is currently being developed. A brief description of each of these models is found below.

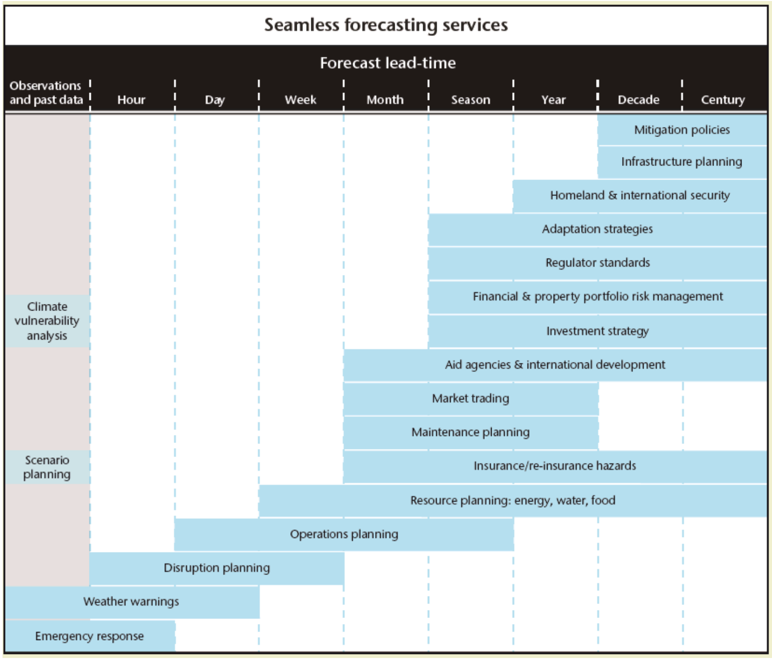

Figure 2.1: Illustration of the seamless forecasting scheme and its available services and applications which allow for the management of climate risks and impacts during all time scales. The links between medium-range to seasonal to decadal to centennial forecasting are clearly seen in the figure. Courtesy of: Met Office Science Strategy 2010-2015: Unified science and modelling for unified prediction.

<u>The Unified Model - Met Office, UK</u>

The Met Office Unified Model, abbreviated MetUM, has been in use since 1990 and is continually being developed in accordance with improved knowledge of atmospheric processes as well as steadily increasing computing power. Operationally, the model is used for both day-to-day weather forecasting as well as for seasonal, decadal and centennial climate predictions. The models that are not used for daily weather forecasting are typically of lower resolution and include additional Earth system components in order to describe the fully coupled ocean-atmospheric climate system (see: Unified Model User Guide).

The current operational version of the MetUM used for seasonal prediction is called GloSea4 which stands for Global Seasonal forecasting system version 4, and it became operational in September 2009. It is an ensemble prediction system that uses the highest resolution simulations of the global atmosphere-ocean coupled climate model HadGEM3. In addition to the high resolution forecasts made by HadGEM3, GloSea4 has the additional component of an associated set of hindcasts, i.e., historical re-forecasts, which are used for calibration and skill assessment. The same ensemble prediction system is used for both forecasts and hindcasts but with different initial conditions to reflect uncertainty. For the forecasts, simulations are initialized weekly using 14 ensemble members, and for the hindcasts, three ensemble members are initialized on fixed calendar dates. To represent model uncertainty, different parameterizations are used as well. All climate forcings, including greenhouse concentrations, are fixed and set to observed values for the period 1960-2000 and follow the SRES A1B emissions scenario afterwards (Nakicenovic et al., 2000). Each month, an ensemble seasonal forecast is made for the coming six months by combining and bias correcting all available forecast members from the previous three weeks.

The Météo-France coupled model

The Météo-France seamless ensemble prediction system is composed of the Météo-France operational weather forecasting model ARPEGE in addition to the climate model ARPEGE as the atmospheric general circulation model (AGCM) and the ORCA model as the oceanic general circulation model (OGCM) (Déqué et al., 1994). Like the MetUM, different formulations of the model are used in the ensemble according to the time frame of interest while taking into account computational costs.

The original ARPEGE-Climat model was developed in the 1990s and since the year 2000, Météo-France has been generating seasonal forecasts consisting of ten ensemble members of the coupled atmosphere-ocean general circulation model (AOGCM). Different initial conditions are used in the different ensemble members and a forecast is made for the coming three months using the ensemble forecast for the month previous.

EC-Earth

The EC-Earth project began in 2008 and continues today. The aim of the project is to develop the current seasonal forecasting system at the European Centre for Medium-Range Weather Forecasts (discussed below) into a seamless prediction Earth system model for all time scales. A consortium of representatives from 11 ECMWF member states has been formed in order to contribute various Earth system modules to the comprehensive EC-Earth model. Ultimately, the project aims toward developing a global Earth system model that consists of a modern AGCM, OGCM, a sea-ice model, a land surface model and an atmospheric composition model (Hazeleger et al., 2010). The intention is that the EC-Earth model will be used by meteorological services across the world to generate seasonal to decadal to centennial climate predictions at high resolution.

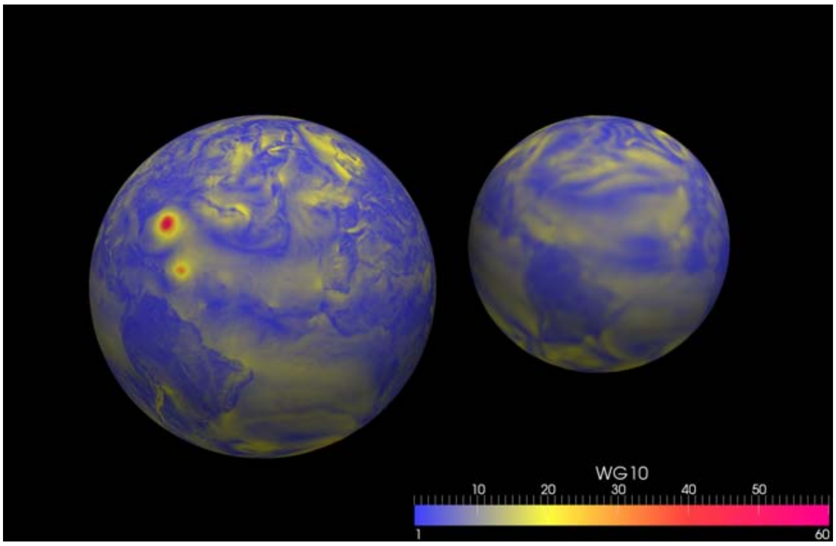

Figure 2.2: Illustration of the high-resolution EC-Earth model compared to that of a typical global climate model (GCM). The inability of multi-decadal climate-projection models to accurately resolve regional high-impact weather events such as the storms shown above (red blotches) is clearly demonstrated in the figure. Courtesy of: EC-Earth (Hazeleger et al., 2010).

2.2.2 Medium to seasonal forecasting: ECMWF (See: User Guide to ECMWF Forecast Products)

The European Centre for Medium-Range Weather Forecasts (ECMWF) is an independent intergovernmental organization supported by 34 member (and cooperating) states. Real-time medium-range forecasts have been made at the centre since June 1979. The first operational medium-range forecasts began 1 August 1979.

Medium-range

Medium-range forecasts are performed up to ten days ahead at the ECMWF. High resolution forecasts are performed for 51 ensemble members by the so-called Ensemble Prediction System (EPS). One member is used as a control and the other 50 members have slightly different initial conditions in order to take into account initial uncertainties. For each ensemble member, the initial conditions are perturbed within the limits of uncertainty compared to the control member, and as a result an ensemble of alternative forecasts is produced. A recent study compared the four best ensemble systems from Canada, the US, the UK and ECMWF, respectively, and found that the ECMWF EPS performed as the best single model (Hagedorn et al., 2010). An ensemble of the four models improved performance, but the main contribution to this improved performance is by the ECMWF EPS. The study also found that when compared to the four best-member ensemble, a recalibrated version of the ECMWF EPS based on hindcasts was of comparable or superior quality.

Monthly

Monthly forecasting addresses the time range of 10 to 30 days, meaning it is the time scale between medium-range forecasting and seasonal forecasting. As stated earlier, this time scale is short enough that initial conditions still remain important; a study on the statistical predictability of the atmosphere found a cut off time of roughly 45 days, after which initial condition information is unimportant (Kleeman 2006). Additionally, this time scale is long enough that ocean variations may have significant impact on the atmospheric circulation. Therefore, at the ECMWF, monthly forecasting is performed as an extension of the medium-range EPS, and after day 10, the medium-range atmospheric EPS is coupled with an ocean circulation model.

Seasonal

At the seasonal time scale, the influence of atmospheric initial conditions is small and the main source of variability is due to the circulation of the ocean (Balsmeda and Anderson 2009). Compared to atmospheric circulation, oceanic circulation has a long predictability, on the order of months. This means that much of the information related to the initial value problem on the seasonal scale is contained in the ocean. At ECMWF, seasonal forecasts are generated for seven months using a coupled ocean-atmosphere general circulation model (AOGCM) with a separate ocean analysis system to prepare the initial conditions of the ocean.

The real-time seasonal forecasts at ECMWF are initiated on the first day of every month and consist of a 41 member ensemble that is combined with a five member ocean analysis ensemble (see: User Guide to ECMWF Forecast Products). Perturbations in the atmosphere and sea-surface temperature (SST) are added to the control member, creating the ensemble. In addition to the forecasts, an ensemble of 11 re-forecasts, or hindcasts which are used for calibration and skill assessment, are made on the first of every month for the years 1981-2005. These hindcasts are useful because they allow users of the real-time forecast data to calibrate their models on the fly.

In addition to the seasonal forecast, ECMWF also performs an annual forecast which is made four times per year beginning on 1 February, 1 May, 1 August and 1 November. The forecast is made for 13 months except for the November date which is for 14 months. The real-time forecasts are made using a smaller ensemble with 11 members while the re-forecasts have an ensemble size of 5.

2.2.3 EUROSIP

EUROSIP is a multi-model seasonal forecasting system that has produced forecasting products since 2005 (see: EUROSIP User Guide). It consists of three independent coupled systems integrated into a common framework. The three members are: the ECMWF model, the Met Office Unified Model (MetUM) and the ARPEGE system at Météo-France. Operationally, only one version of each model is functional at a given time, and as component models are updated, the composition of the multi-model ensemble changes as well.

As discussed above, the use of multiple models in an ensemble is a method of combating uncertainty due to imperfect knowledge of the climate system. Many studies have shown that the multi-model approach produces more reliable seasonal and climate forecasts compared to using a single model alone. The most recent and comprehensive example is the ENSEMBLES project which builds upon the work from earlier multi-model projects such as PRUDENCE, STARDEX, MICE and DEMETER which may be considered precursors to ENSEMBLES. The importance of the multi-model approach is especially important to seasonal forecasting because the predicted signals are much smaller compared to the medium-range, and any errors in the models have had more time to accumulate. Thus, model error is a critical problem which the multi-model approach helps to address by averaging over an ensemble of different models. In this way, a significant portion of the error is reduced, resulting in better forecasts (e.g., Linden, van der and Mitchell (eds.) 2009 (ENSEMBLES); Hurrell et al., 2009). It must be noted, though, that some errors are common between models so averaging may not always be effective (Goddard and Hoering 2006).

The seasonal forecasts produced by EUROSIP are created from the combined output of the three component models. Each month, the 41-member multi-model ensemble generates 7-month forecasts including a 20-year hindcast period. These multi-model forecasts can be accessed just like any other ECMWF product on their website (http://www.ecmwf.int/products/forecasts/d/charts).

2.2.4 Seasonal forecasting in ENSEMBLES

The ENSEMBLES climate change project (van der Linden, and Mitchell (eds.) 2009) was initiated by the European Commission in order to help inform researchers, policy makers, businesses and the public by providing them with the most recent climate change information obtained by the latest climate modelling and analysis tools. In ENSEMBLES, the multi-model approach is utilized and the first global, high-resolution, ensemble-based modelling system for the prediction of future climate was developed. The focus of the project's first Research Theme (RT1) centred around the development of this system for use in predictions on the seasonal, decadal and centennial time scale.

A large source of uncertainty in seasonal forecasts is due to model error (see above). In ENSEMBLES, model uncertainty was addressed in three ways. The first method is the use of the multi-model approach. Past studies have shown that the multi-model approach alone improves the accuracy and reliability of forecasts (e.g., Doblas-Reyes et al., 2009). The second and third methods attempt to address the uncertainty due to processes occurring on the unresolved scale. As mentioned above, many physical processes operate at smaller scales than the model can resolve so they must be approximated. In the second approach, the unresolved processes are 'parameterized' and using a single model, an ensemble is created consisting of slight variations to these parameters. This is called the perturbed parameter approach. The third approach attempts to represent unresolvable processes by considering them "stochastic" in nature, meaning the evolution of these processes in time is considered probabilistic. This approach considers the stochastic process of energy transfer between the unresolved scales and the resolved scales and is called the stochastic physics approach. The aim of the seasonal and decadal prediction section of the ENSEMBLES project is to compare the merits of these three approaches: multi-model, perturbed parameters and stochastic physics.

Two experiments, or streams, were carried out in the ENSEMBLES project for the purposes of seasonal to decadal prediction. The first stream, Stream 1, consisted of hindcasts for the years 1991-2001. A seven-month hindcast was started every May and November, and also beginning in November, a 14-month hindcast was performed in order to cover a full calendar year. In total, seven different models were used, and for each model a nine-member ensemble was generated. In addition, two further nine member ensembles of a single model were used in order to assess both the perturbed parameter approach and the stochastic physics approach respectively.

The second stream, Stream 2, consisted of seasonal (seven months), annual (14 months) and decadal projections for the hindcast period 1961-2005 with start dates every four months in February, May, August and November. The seasonal and annual hindcasts again consisted of a six separate models with nine ensemble members per model.

The results of the first experiment, Stream 1, indicate that in general, the multi-model approach provides better results overall compared to the perturbed parameter and stochastic physics approaches (Doblas-Reyes et al., 2009). The second experiment, Stream 2, contains the primary information about seasonal forecast quality in ENSEMBLES. For each region of the globe during summer (June, July and August) and winter (December, January, February), the quality of both two-metre temperature and precipitation forecasts is assessed. In Northern Europe, Stream 2 showed little skill in predicting temperature during both summer and winter. For precipitation, there is some skill, though small, in predicting summer lower limits and winter upper limits.

2.3 Potential sources of predictability

On medium to seasonal time-scales, there are some important sources of seasonal predictability. This section will include a discussion of some of these sources including initialization strategies, ocean characteristics, and land surface conditions. Additional comments will be made on other potential sources of predictability including the stratosphere, atmospheric blocking, climate change and volcanic eruptions.

2.3.1 Initialization strategies

An important consideration in seasonal forecasting is the initialization of the coupled atmosphere-ocean general circulation models (AOGCMs). As discussed above, the initial value problem on the seasonal scale is not so much contained in the atmosphere as it is in the ocean. Indeed, it has been found that after approximately 45 days, atmospheric initial conditions are no longer important for statistical prediction (Kleeman 2006). A study by Balsmeda and Anderson (2009) examined the importance of initialization strategy to seasonal forecast skill. They examined three different strategies and found that forecast skill strongly depends on the method used. The strategy that was most effective was that which utilized as many atmospheric and oceanic observations as possible by assimilating all available meteorological and oceanic observations separately. The disadvantage of this method is that the coupled state may contain initial imbalances between the coupled model climate and the observed climate. However, approximations used in the other two methods in order to ensure this balance do not produce better forecasts. According to the study, of particular importance are observations of the upper ocean density structure, such as the temperature, salinity (salt content) and sea level anomalies, which contributed to the improvement of seasonal forecast skill almost everywhere. This most effective initialization strategy is commonly used at operational centres such as ECMWF.

2.3.2 Large-scale circulation

Another source of forecast predictability considered here is long-term circulation. The impact of the El Niño/La Niña Southern Oscillation (ENSO) phenomenon, an ocean circulation pattern, will be discussed as well as the North Atlantic Oscillation (NAO) which is primarily an atmospheric phenomenon.

<u>El Niño/La Niña Southern Oscillation (ENSO)</u>

The El Niño/La Niña Southern Oscillation (ENSO) is a quasi-periodic circulation pattern across the tropical Pacific Ocean (Barry and Chorley 1989, pg. 22; 321-3). Although the pattern resides in the Pacific, its effects are felt world-wide. The circulation is characterized by variations in sea-surface temperature and air surface pressure. Warming of the sea-surface temperatures is termed El Niño and the cooling of the sea-surface temperatures is termed La Niña. El Niño is accompanied by high surface pressure in the Western Pacific while La Niña is accompanied low surface pressure (Trenberth 1997).

In some regions of the world, such as East Indonesia, Northern South America and, in particular, the Equatorial Pacific, the ENSO contributes significantly to positive forecast skill (Oldenborgh, van et al., 2005). In Europe, however, the effects of the ENSO on the climate are not entirely clear. Some studies reveal virtually no predictability in the North Atlantic European region during winter (Oldenborgh, van 2005) while other studies come to different conclusions. A study by Brönnimann et al., (2002) examined ENSO data from the past 500 years. They found a significant relationship between ENSO and late winter/spring climate in Europe over the past 300 years, and corroborated studies based on only 20th century data that El Niño events in late winter tend to bring low temperatures to Northeastern Europe and changes in precipitation patterns that differ in autumn compared to late winter. They also found that El Niño events in late winter are accompanied by increasing surface pressures in the Arctic leading to a negative North

Atlantic Oscillation (NAO) (discussed in the following section), a conclusion which was also reached by Toniazzo and Scaife (2006).

ENSO impacts on Europe's Greater Alpine Region (GAR) have also been examined in recent work (Efthymiadis et al., 2007). They found that for temperature, the impact is greatest in late autumn and early winter, and for precipitation, the largest impact was in late winter. During these time periods, there is a significant correlation between the ENSO during the preceding early autumn and late summer. In general, though, the impact of the ENSO on the GAR climate is weak. Further investigation is merited, though, since the GAR of Europe contains the mouths of both the Rhine and Danube rivers.

In Spain, the ENSO (in particular La Niña) has proven to be useful for the seasonal prediction of dry periods of winter precipitation related to drought episodes, providing another window of opportunity for improving seasonal forecasts in mid-latitudes (Sordo et al., 2008).

The fact that the impacts of the ENSO on the climate of Europe are unclear means that further investigation into this source of predictability is necessary. Should the ENSO prove important, the ability to predict the phenomenon itself will aid in improving seasonal forecasting as well. A recent multi-model study on this topic revealed that the ENSO prediction six months in advance relies heavily on the phase of the ENSO, its intensity and the season of prediction (Jin et al, 2008). The study results revealed that: strong phases of the ENSO are better predicted than the neutral phases (the best being a strong El Niño); the growth of both warm and cool phases was better predicted than the corresponding decay phases; and that the skill of forecasts that start in February or May were less skilful than those that began in August or November. (It is speculated that the reason for this is because the February and May forecasts contain more decaying ENSO events.)

North Atlantic Oscillation (NAO)

Like the ENSO, the North Atlantic Oscillation (NAO) is a large-scale circulation, but unlike the ENSO, the NAO is primarily at atmospheric circulation rather than an oceanic one (Barry and Chorley 1989, pg. 155-8). The phenomenon is centred on the North Atlantic Ocean where there is typically a large north-south contrast in surface pressure with low pressure on the northern edge near Iceland and high pressure on the southern edge near the Azores. Thus, it is measured by examining the fluctuations of atmospheric sea-level pressure between the Icelandic Low and the Azores High. This pressure difference drives the mean surface wind in this area and controls the trajectory of mid-latitude storms from west-to-east across the North Atlantic in the direction of Europe.

There are two main phases of the NAO: positive and negative. In winter, the positive phase is characterized by more northern storm tracks, bringing mild, wet and windy weather to northern Europe, and dry, calm weather to the south. In contrast, the negative phase is characterized by cold, calm and dry conditions in the north, and wet, windy conditions in the south. The positive phase of the NAO has been associated with El Niño in early winter but changes to La Niña in late winter (Keeley et al., 2009). Past work has shown that it is possible to predict the NAO phase correctly roughly two out of three times, meaning it is a powerful source of prediction for European winters (e.g., Rodwell and Folland 2002; Sauders and Qian 2002). Changes in European extreme winter weather (cold temperatures less than the 10^{th} percentile and high precipitation over the 90^{th} percentile) have been linked to changes in the NAO (Scaife et al., 2008).

In summer, the NAO is of smaller amplitude and is situated more northerly and covers a smaller area, but it is still correlated with the storm tracks, i.e., the surface pressure, and has a strong influence on rainfall, temperature and cloudiness in Northern Europe (Felstein 2007). A positive (negative) SNAO corresponds to dry (wet) conditions over much of Northern Europe and wet (dry) conditions in Southern Europe. Thus, the summer NAO has proven to be important to the prediction of summer climate extremes, such as flooding, drought and heat waves (Linderholm et al., 2009; Folland et al., 2009).

2.3.3 Land surface

In addition to the major source of predictability attributed to ocean characteristics, studies have found that there are certain locations where land surface conditions, in particular soil moisture, can contribute to the skill of a seasonal forecast. In general, these locations are in the transition zones between wet and dry climates, where the coupling is strong (Hurk, van den et al., 2010; Dirmeyer et al., 2009).

GLACE2

The Second Global Land Atmosphere Coupling Experiment (GLACE2) is aimed at determining the contribution of realistic land surface initialization to improvements in forecasts of summertime temperature and precipitation (Koster et al., 2006). It is a multi-model ensemble experiment consisting of 10 different atmospheric global climate models (AGCMs) in Europe and North America. The subseasonal forecasts (up to 60 days) cover the period 1985-1995. Two sets of 60 day forecasts were produced using a realistic (Series 1) and an unrealistic (Series 2) soil moisture initialization. The graphical scope of the project included both Europe and North America (not discussed here).

For Europe, the results show that using a realistic soil initialization can improve forecasts for temperature in the spring and summer seasons over lead times from approximately 16 to 30 days. Over longer lead times, the quality of the forecast degrades. For precipitation forecasts, the realistic soil initialization does not improve the forecast skill (Hurk, van der et al., 2010). It is speculated that the reason for this is because most of Europe is dominated by the advection of moist air from the Atlantic, meaning soil moisture has little to no impact on precipitation (Dirmeyer et al., 2009).

Revised land hydrology in ECMWF

Recent revisions have been made to the ECMWF land surface including its soil and snow hydrological components. As stated above, proper treatment of soil conditions can contribute to improved forecasts, as can consideration of snow cover, especially for spring temperatures in Central and Eastern Europe (Shongwe et al., 2007). A discussion of the ECMWF revisions and the results of implementing them appear in Balsamo et al. (2011). One aspect of the study uses sets of 10-day forecasts to assess the atmospheric impact of the revisions on near-surface temperature and it was found that the revised land surface scheme produces global scale improvements on the daily time scale. In an earlier study before the recent revisions, an examination of the ECMWF model to predict the summer heat wave in 2003 showed skillful prediction of European temperatures throughout the first month (Rodwell and Doblas-Reyes 2006). Thus, the revised land surface scheme may provide further skill in predicting such events.

Drought

Another source of predictability for forecasts is drought. Extensive past research has shown linkages between the joint occurrence of dry and warm conditions (e.g., Koster et al., 2009; Haarsma et al., 2009). However, the strength of correlation between the two events varies geographically. In a recent study, the concurrence of drought and warm periods in the Northern

Hemisphere was examined with concentration on the evaporative regime (Koster et al., 2009). Two distinct regimes are considered: a dry regime where variation in soil moisture strongly controls evaporation, i.e., locations where drought-induced warming occurs, and a wet regime where evaporation is insensitive to soil moisture. Using an AGCM and observations, a valuable map of evaporative regime for the Northern Hemisphere was produced which revealed locations where soil moisture information is particularly critical for the determination of soil moisture effects on atmospheric conditions. The results of the study for Europe showed that in the northern locations, i.e., Scandinavia, there was little impact of soil-moisture variations on atmospheric variability. For the rest of Europe, in particular the regions of interest for ECCONET, there are indications that soil-moisture variations play a part in contributing to atmospheric effects such as drought-induced warming, corroborating the Balsamo et al., (2011) study which proved that proper treatment of the soil moisture regime can contribute to improvements in forecasts.

With this knowledge, the ability to predict drought events would prove useful. One past study focussed on drought forecasting using the Standard Precipitation Index (SPI) which is based only on precipitation and is designed to give a spatially invariant indication of drought (Cancelliere et al., 2006). The study showed fairly good agreement between observations and forecasts, but the region of interest was rather small (Sicily). However, the study suggests that the SPI may prove valuable in forecasting periods of drought.

Another, more recent approach to drought forecasting is using a Regional Drought Area Index (RDAI) based on weather types rather than precipitation (Fleig et al., 2011). This study focussed on six regions of Northwestern Europe (two in Denmark and four in Great Britain) and analyzed the occurrence of weather types most frequently associated with drought conditions. The dominant drought-producing weather types varied by region, but generally, drought occurred when a high-pressure system was in control. This highly depended on the hydrological response time, however, which also varied distinctly between the regions (between 45 and 210 days). A key advantage of using weather types is that general circulation models have an easier time representing pressure patterns compared to precipitation. An extension of this study over the entirety of Western Europe may prove fruitful in improving forecasts of drought.

2.3.4 Other sources of predictability

<u>Stratosphere</u>

Accurate seasonal forecasts depend on correctly representing the longer term processes that exist in the climate system such as ocean and atmospheric circulations. As discussed above, the impacts on Northern European climate of circulations such as the El Niño/La Niña Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO) have not yet proved satisfactorily skillful for the purposes of seasonal forecasting. Recent research has attempted to increase the skill of winter seasonal forecasts by examining the strong coupling that exists between circulations in the troposphere and the stratosphere. One study (Christiansen 2006) found that for mid-latitudes in northern hemisphere winter, the use of stratospheric information in the forecast leads to significantly better results than using surface-based information alone for lead times from 3 to 40 days. A more recent study by Maycock et al., (2009) found that increasing the resolution of the stratosphere has a further positive impact on seasonal forecast skill. The study performed simulations using an ensemble of five models and found that all of them incorrectly describe the stratospheric circulation. Despite this, results indicate that anomalies in the stratospheric circulation may cause detectable responses in tropospheric circulation, meaning further improvements to the stratospheric circulation may prove valuable to the seasonal forecasting of atmospheric processes such as the NAO.

The role of the stratosphere in the Northern European winter surface response to the ENSO has also been studied recently. When using a well resolved stratospheric circulation scheme, the modelled tropospheric and stratospheric circulation changes under El Niño conditions have been found to agree well with the observed responses, being a negative NAO in late winter (Bell et al, 2009). This conclusion has also been reached during years when sudden stratospheric warmings occur and it has been determined that the response in European surface climate to El Niño is strong enough to be considered useful for seasonal forecasting (Ineson and Scaife 2008). Another study also concluded that sudden stratospheric warming plays a role in persistent NAO features at the surface (Cagnazzo and Manzini 2009), confirming the results of the other studies.

Another type of stratospheric circulation that has been studied recently is the quasi-biennial oscillation (QBO) (Baldwin et al., 2001). It is a quasi-periodical oscillation on the order of 25 to 29 months that is comprised of the equatorial winds in the tropical stratosphere. These winds propagate downward to the surface at approximately one kilometre per month. Typically the downward motion of the easterlies is more irregular than the westerlies and the amplitude of the easterly phase is about twice as strong. This easterly phase has been linked to sudden episodes of stratospheric warming which have been shown to play a role in the persistence of the NAO (see above). In a recent study by Marshall and Scaife (2009), the role of stratospheric resolution of the QBO was examined and it was suggested that better representations of the QBO will lead to improved forecasts on the seasonal scale.

Atmospheric blocking

In meteorology, an atmospheric block is a large scale pattern in atmospheric pressure that is nearly stationary, leading to stagnation of weather patterns, meaning a similar weather pattern may persist for several days or even weeks (Barry and Chorley 1989, pg. 128; 236-8). In Europe, blocking of high pressure systems can bring extreme heat and drought conditions in summer and extremely cold conditions in winter. In the summer of 2003, a long and intense heat wave was caused by a blocked high pressure area that sat firmly anchored over Western Europe and persisted for weeks. The blocking of low pressure systems, on the other hand, can bring periods of severe flooding as storm systems can remain over the same geographical region for extended periods of time, which was the case in Poland and Hungary in Spring 2010. Thus, the ability to forecast atmospheric blocking may aid in the forecasting of extreme events in any season.

Recent research of blocking climatology reveals that during the past 44 years, blocking frequency has been more prevalent in the east Atlantic, through Europe to Central Asia, particularly in winter, spring and fall, versus the Pacific region. For all seasons, the blocks are more persistent in the Atlantic-European region compared to the Pacific (Tyrlis and Hoskins 2007; Diao et al., 2006). Differences in blocking characteristics have also been found to be a function of distance from the storm tracks (Weijenborg 2011). Generally, north of the storm tracks, blocking tends to be cyclonic and south of the storm tracks, anti-cyclonic. However, there are regional differences particularly in Europe where the blocking of high pressure systems is more frequent and intense than over Asia where the blocking lasts longer.

The predictability of blocking events in the North Atlantic region is on the order of five to seven days. One study using the high-resolution ensemble prediction system at ECMWF (Mauritesen et al., 2004) found that the model can capture the onset of blocked flow nearly perfectly three to five days in advance, but there is a limit, at approximately the middle of the medium-range, after which the model is incapable of prediction. Another, more recent, study reached a similar conclusion and found that there are significant precursor signals for atmospheric blocking up to 5 days prior to the onset of the event (Altenhoff et al., 2008).

Climate change

The current research on the subject of climate change is fully discussed in the first deliverable of the ECCONET project, D 1.1. This section contains a brief discussion on how climate change may impact some of the sources of predictability discussed above.

During both winter and summer in Europe, climate change is increasingly causing warming temperatures. This trend is seen in both observations and models, although there is evidence that even state-of-the-art climate models underestimate this trend (Oldenborgh, van et al., 2009). The strength of the trend suggests that the inclusion of climate change in medium-to-seasonal range forecast models is becoming all the more important. For seasonal forecasting with coupled atmospheric-oceanic general circulation models, the inclusion of climate changes on both the atmospheric North Atlantic Oscillation (NAO) and the oceanic El Niño/La Niña Southern Oscillation (ENSO) may prove crucial to improving the quality of forecasts.

Thus far, there has been no clear indication as to what effect climate change will have on the ENSO in the future. During the last several decades, observations of the ENSO have revealed an increase in the number of El Niño events and a decrease in the number of La Niña events, though it is unclear as to whether or not this increase is due to normal variation or global climate changes toward increasing temperatures (Zhang et al., 2008). Coupled-model simulations for the future of the ENSO are also inconsistent. One possibility is that the observed increase in frequency and intensity of El Niño is only in the initial phase of global warming, and once the warming spreads to lower layers of the ocean, El Niño will actually become weaker (Meehl et al., 2006). It has earlier been mentioned that the ENSO has an important impact on Northern European surface conditions, therefore further research into the effects of climate change on the ENSO could provide some useful information for seasonal forecasting.

For the Northern Atlantic Oscillation (NAO), research has revealed that tropospheric warming or stratospheric cooling produces more positive NAO situations, and tropospheric cooling or stratospheric warming produces a more negative NAO response (Rind et al., 2005). In line with the earlier discussion, this could mean a future increase in northern storm tracks during winter, bringing more mild and wet weather to Northern Europe, and drier, calmer weather to the southern regions. In summer, it is likely that the NAO will increase with climate change, meaning drier conditions in the north and wetter conditions in the south, the implications of this being increased risk of drought for Northwestern Europe (Folland et al., 2009).

Volcanoes

Another potential source of predictability on the seasonal scale is the impact of volcanic eruptions on the atmospheric circulation. A recent study explored this phenomenon by comparing two versions of the Met Office's atmospheric climate model, one with lower stratospheric resolution than the other (Marshall et al., 2009). The eruption was simulated by forcing volcanic particles into the atmosphere. The response of this forcing was anomalous warming over Northern Europe with little difference between the low and high resolution models. However, the study reveals that the impact of volcanic particles may not actually have this effect since conducting a similar set of experiments without volcanic forcing produced a similar response, thus suggesting that the model cannot properly capture the effect. Despite this, the study corroborates earlier results about the value of stratospheric information to improve the quality of seasonal winter forecasts.

3. Hydrological approaches

This chapter examines low-flow forecasting and the types of situations in which forecasting is provided to improve decisions on water management operations. Of special interest in our case is the industry related operation in navigation which is dependant on the level of the nearby waters (WMO, Hydrological report No. 50, 2008).

Usually seasonal hydrological forecasts are generated by coupling meteorological forecast products and hydrological models. Due to the coarser (usually 10-25 km) spatial resolution of meteorological input data and an increasing uncertainty with larger lead times the temporal and spatial high resolution of a forecasted value cannot be provided by any seasonal forecast product directly. The current skill of seasonal hydrological forecasts is still limited and far from meeting the society's need (Luo et al, 2007). But this belongs primary to forecasted extreme precipitation and the resulting flood events. A drought event is characterised as an event which develops during a longer period and has a large spatial expansion. The lead time for performing low-flow forecasting is generally much longer than for flood forecasting, varying from a few weeks to a few months and even years.

Given that there is great uncertainty concerning future meteorological conditions, both deterministic and probabilistic forecasts are used, depending on the time frame of forecasts. A probabilistic forecast can be made using estimates of rainfall that can be generated from global climate models combined with local teleconnection relationships (WMO, Hydrological report No. 50, 2008).

Like in meteorology the idea of a seamless prediction (Palmer et. al, 2008) takes place in hydrology. There are several model systems which can be combined to forecast different lead times and to learn from the different methods in focus on forecast skill an performance. Seamless prediction is supposed to find the connection between short-term prediction (1-7 days), medium-term prediction (7 days - 1 month), seasonal prediction (1- 6 months) and long-term and decadal prediction.
Within the framework of the hydrological Ensemble Experiment (HEPEX) short, medium and seasonal forecast are tackled currently (Thielen et al., 2008).

Short-term prediction is not the target of this deliverable therefore the scientific approaches for medium-term up to decadal forecast are presented here.

The HEPEX project gives an example of a seamless prediction project. The aim of applied research in the field of seasonal forecast is to assimilate such forecasts into the decision processes of potential users. The HEPEX mission is to demonstrate how to produce reliable hydrological ensemble predictions that can be used with confidence by emergency management and water resources sectors to make decisions that have important consequences for the economy, environment, public health and safety (Schaake at al., 2006).

The key science issue for HEPEX is the adequate quantification of hydrologic forecast uncertainty. HEPEX plans to address the following key questions (Schaake at al., 2006):

- What are the required adaptations for meteorological ensemble systems to be coupled with hydrological ensemble systems?

- How should the existing hydrological prediction systems be modified to account for all sources of uncertainty within a forecast?
- What is the best way for the user community to take advantage of ensemble forecasts?

3.1 Medium-term forecast

Medium-term forecast has to be distinguished obviously from a short-term forecast before giving some examples. In Germany the short-term forecast is provided as a deterministic forecast at the River Rhine for 4 days, at the River Elbe a deterministic forecast is provided which has a lead time of one up to 4 days and at the River Danube in Germany for two days ahead. The lead time increases up to 6 days at the River Danube in Hungary.

Every forecast, which exceeds the deterministic lead time has to be regarded as a probabilistic medium-range forecast. The uncertainties in medium-term forecasts in hydrology derive from the initial conditions of the hydrological system and the meteorological input which has a decreasing forecast precision with increasing lead times, like it is shown in Palmer (2007). The Brier Skill Score (BSS) is a criteria for model quality. An optimal modelling result has a BSS of 1. For less similarity the BSS becomes zero or negative values.

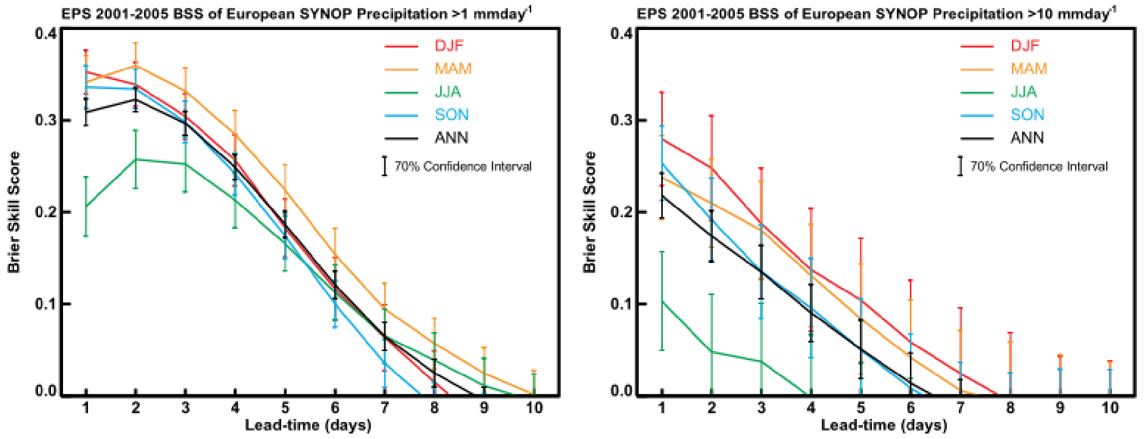

Figure 3.1 Brier Skill scores of a medium-range forecast in meteorology. The seasonal and annual mean of the daily BSS for the event that 24-hour accumulated precipitation is (a) greater than 1 mm and (b) greater than 10 mm. Bars indicate the 70% confidence interval for the estimated mean values taking autocorrelation into account. Palmer (2007)

3.1.1 Using weather predictions to forecast flows

“In a drought situation where extreme low flows already exist, it is possible to use a number of techniques, including long-term weather predictions to forecast streamflow. There are also forecasts using ensemble analysis of likely future, or past, events to predict low flows. Forecasts of climate variables, of which rainfall is the most important in water resources applications, can be obtained from NWP (Numerical Weather Prediction) models, which are routinely run by weather services. Although NWP models can provide reasonable large scale forecasts out of one week or longer, because of their coarse spatial resolution they have limited skill in forecasting point or drainage basin-scale rainfall” (Hydrological report No. 50, 2008).

The post processing of meteorological numerical models is described in Thirel et al 2010. They figured out that the spatial distribution of hydrological relevant parameters are well reproduced at day 1. Within the following days of forecast the skill is decreasing. In combination with the hydrological model suite SIM the stream flows could be simulated. The results show positive Brier Skill scores for the medium quantiles (Q20 – Q80) and bad scores for the extreme quantiles.

In Roulin an Vannitsem (2005) the forecast at two Belgian catchments were prospected, which results seems transferable to other European catchments.

- The skill of ensemble stream flows forecasts is greater than the skill of precipitation forecasts.
- Precipitation is more predictable during winter than in summer.
- The skill of forecasted stream flows is greater in winter than in summer for two Belgian catchments.
- During winter, skill remains significantly positive for the whole streamflow forecast period and is similar for both catchments.
- The probabilistic skill of this hydrological prediction system is much better than the one based on historical precipitation inputs and extends 9 days.

Pappenberger and Buizza (2009) analyse the skill of a medium-term forecast is effected by the size of the catchment. The results are, that the pattern of meteorological input data (precipitation and temperature) is satisfying for hydrological modelling of large catchments. In small catchments, the requirement of a precise spatial pattern is higher. Therefore, the variance of the hydrological forecast results are higher than in large catchments. The aggregation of the forecast results over a longer time frame show largely more skill, than an aggregation over short time periods. They found again like Rodrigues-Iturbe and Mejia (1974) and Segond (2006) that the sensitivity of the river flow hydrograph (catchment response) towards the uncertainty in precipitation decreases with catchment scale.

3.1.2 Low flow frequency analysis

Due to uncertainties in forecasted hydrological input data there are methods to estimate the medium-term water levels with statistical analysis of historical datasets. Low flow frequency analysis provides an alternative mean of determining simple probabilistic stream flow forecasts when climate forecasts are either not available or not accurate. In accordance to statistical meteorological analysis (Section 2.1.1) this method assumes a stationary situation of the system, which does not exist.

Statistics are concerned with methods for making conclusions about the properties of the “true value” based on the properties of a sample drawn from measured data. A given characteristic, for example, the mean value, computed by an estimator is called a sample estimate. The probabilistic forecast provides the risk of an annual non-exceedence of water levels. For more risk-averse forecasts, more rare non-exceedence quantiles can be chosen (Hydrological report No. 50, 2008).

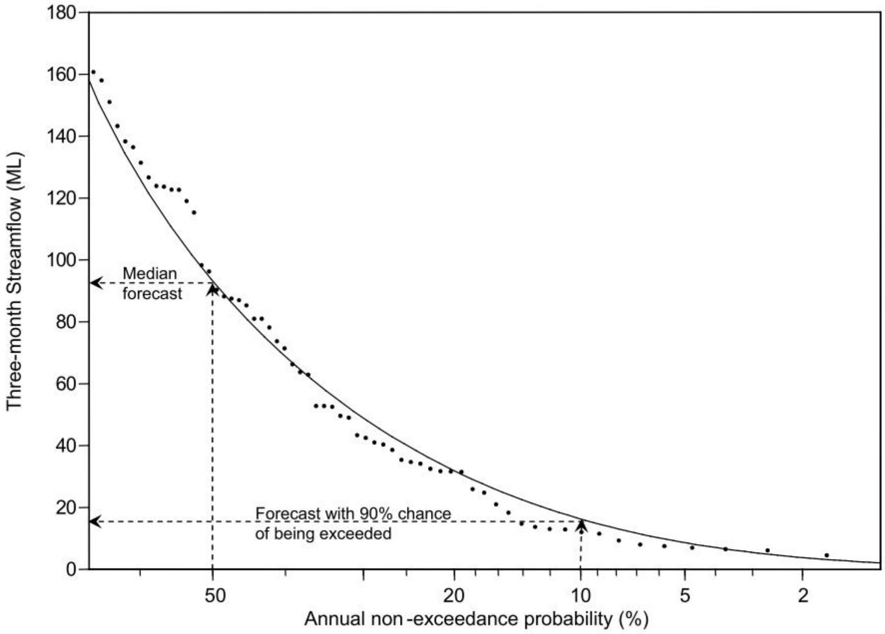

Fig. 3.2: Probabilistic forecast based on low-flow frequency analysis (WMO, Hydrological report No. 50, 2008)

Figure 3.2 shows that there is only a 10 per cent chance that stream flows over the next three months will be less than 16ML (unit of monthly discharge). In essence, such forecasts are merely a statement of likelihood based on historical precedent; however, the annual minima used to fit the distribution can be selected from a censored period that reflects the antecedent conditions of interest.

3.1.3 One month forecast of water levels / discharges for the section of the Danube Nagymaros-Mohács

This section describes the scientific derivation of an applied approach of operational low flow forecastr at Hungarian Danube sections. Most of the rivers have a well expressed seasonal regime. The main factors determining the flow rates are rainfall, snowmelt and groundwater. The periods of floods caused by extensive rainfall or by melting of accumulated snow are followed by dry or cold periods of low flow. (WMO, 1974; VITUKI, 1959) and (Szöllősi-Nagy, 1978).

The possibilities for the long-term forecasting of river flow are the best under climatic conditions where precipitation falling during the low flow period does not effect significantly flow conditions i.e. only factors within the basin govern the flow.

The seasonal regime of flow can be followed in the Danube Basin as well, though the great variability of precipitation and temperature within each season causes certain limitations for the long-term hydrological forecasting. Long-term meteorological forecasts are very uncertain, so two approaches are possible an show the elements of the hydrological system:

- rely on the meteorological weather forecasts for a limited lead time (in our case one month ahead) or our forecast may be based on values of precipitation of a certain probability.
- an assumption can be made about the absence of surface flow during the forecast period.

The first case is suitable to predict mean or minimal (water level) flow for a given station with certain limitations. Problems of snowmelt forecasts are not tackled. The result in the second case is a retention curve.

Regression of precipitation and discharges

Forecasting of monthly mean and minimum water levels (H) and discharges (Q) for the Danube-station Budapest using expected values for precipitation is done by a regression method.

Hydrological elements and the monthly sums of precipitation for the drainage area of Danube-Bratislava were used as independent variables. Monthly data for the period 1951-1983 were considered. Applying the method of principle components, only those variables were taken into consideration which had a significant effect on the result of forecasting. The following equations were received for the Danube, Station Budapest to forecast monthly mean ($\overline{H}_i$) and minimum ($H_{i(min)}$) levels.

$$\overline{H}_i = A_{1(i)} / P_i + B_{1(i)} \cdot H_{i-1(u)} + C_{1(i)} \cdot \overline{Q}_{i-1} + D_{1(i)} \cdot H_{i-1(min)} + E_{1(i)} \quad (1)$$

$$H_{i(min)} = A_{2(i)} \cdot P_i + B_{2(i)} \cdot H_{i-1(u)} + C_{2(i)} \cdot \overline{Q}_{i-1} + D_{1(i)} \cdot H_{i-1(min)} + E_{1(i)} \quad (2)$$

where P_i: monthly sum of precipitation for the drainage basin Danube-Bratislava (mm)

Q: flow rate m^3s^{-1}

i: number of month

(u): subscript noting the last day of the month

(min): subscript noting minimum value of the month A,B,C,D regression coefficients and E constant.

Equations of similar structure were received for flow rate values Q_i and $\overline{Q}_{i(min)}$. These types of relationships for H and Q were elaborated for a number of gauges in the section Nagymaros-Mohács, however results only for station Budapest are given here.

A validation of the method took place on a dataset of 2008. Results for the 12 months of 2008 are given in Table 3.1. (observed sums of precipitation were taken in computations).

Table 3.1: Predicted monthly water levels (Danube - Budapest, 2008)

Month	Monthly mean $\overline{H}_i$ (cm)			Monthly minimum $H_{i(min)}$ (cm)		
	Predicted	Observed	Error	Predicted	Observed	Error
1	213	211	2	130	144	-14
2	260	188	72	180	142	38
3	294	309	-15	175	171	4
4	327	310	17	232	265	-33
5	350	320	30	278	242	-14
6	363	307	56	355	226	29
7	280	302	-22	126	213	-87
8	246	270	-24	182	184	-2
9	179	167	12	139	144	-6
10	201	140	61	122	109	13
11	140	131	9	82	96	-14
12	152	196	-44	85	128	-43

<u>Retention curve for the Danube-Budapest section</u>

An assumption was taken into consideration, namely, the falling limb of a wave hydrographs can be divided into two characteristic phases:

- phase of surface and interflow (including period of concentration on the surface of the catchment and channel routing)
- phase of groundwater supply

The phase, where groundwater supply is predominant, is characterised by an exponential curve fitted to the logarithm of the hydrograph (WMO, 1974) and the two phases can be separated with the help of the turning point on this (logarithmical) hydrograph (Bódy, Böröcz and Hirling, 1971).

Logarithms of daily flow rates and daily sums of precipitation for the corresponding drainage basin were analyzed. Points were selected in the second phase of the falling limb using the position of turning points or assumed concentration and routing times if there were no well expressed points. Characteristic retention lines were marked and inclination ($\ln' Q$) was calculated for $\ln Q$, t=1.

The correlation between $\ln' Q$ values was established on the plot of the values. A regression line was estimated and a retention curve for Danube at Budapest can be drawn as below:

$$\ln Q = 6.363 + B \cdot e^{-0.736t} \quad (3)$$

where $B = \ln Q_{max} - \ln Q_{min)} = 2.742$.

Equation (3) can be utilized as a forecast relation after the appearance of the turning point on the falling limb of the logarithmic hydrograph or in the period when no surface water supply is assumed. The observed hydrograph is extrapolated through equation (3) using the current value of $\ln Q$.

This technique enables the forecasting of flow and stages for the whole period of falling stages, assuming that no additional rainfall or snowmelt induced floods will disturb the falling limb during the period of the lead time. After a flood period a new extrapolation can be issued if the turning point is reached. The accuracy of forecasts is around ±10% in terms of discharges (not shown here).

Certain conditions are to be met to use equation (3) in the specific situation at Budapest, which can be transferred to other gauges:

- extrapolation can be made only in the second phase of the falling limb;
- the magnitude of the falling limb should reach 2/3 of the heigh of the peak of the event and the amount of precipitation or snowmelt must remain below 5 mm;
- the falling limb is parallel with the calculated retention curve (at Budapest this stage starts 7-10 days after passing of the peak of the flood wave;
- this technique is mostly applicable between July and December and during winter if long period of cold weather is expected and no fast component is active due to snow fall and temperature prevented snow melt.

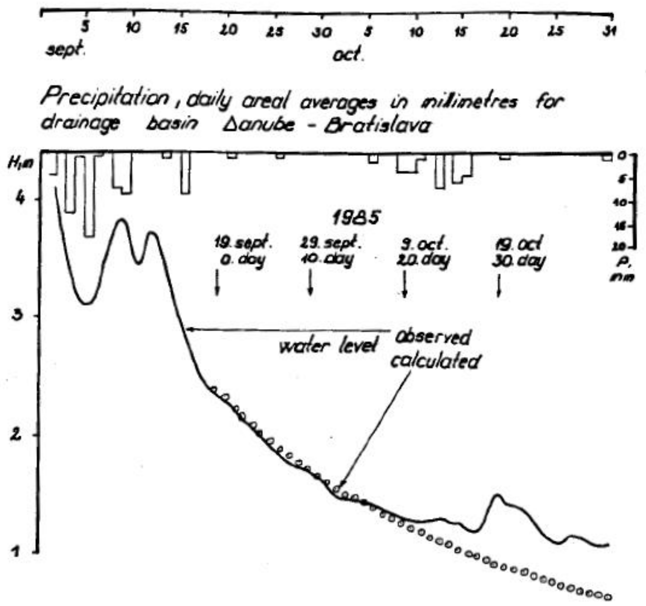

Fig. 3.3 Low water forecast, Danube-Budapest

<u>Conclusion</u>

Two methods of medium-term low flow forecast are presented:

I. A regression technique with assuming forecasted precipitation values of different probability as input to calculate monthly mean and minimum flow/stages.

II. The intensity of the depletion of ground water supply is determined and the retention curve is used to forecast flow/stages for the whole length of the falling limb assuming no rain or snowmelt during the period of lead time.

Good results can be obtained for the whole Nagymaros-Mohacs reach with the retention curve of Budapest if rating curves for different cross sections are used. See Fig. 3.3. Though more precise water level values can be calculated using the following values of exponent: Nagymaros 0.530; Dunaújváros 0.507 and Mohács 0.764.

3.2 Long-term forecast

Long-term forecast can be divided into two different lead times of interest. The seasonal forecast considers mainly a lead time of one to 6 months but it might be possible to enlarge the seasonal forecast up to four seasons. The idea of a seamless prediction suggested a gradation from seasonal forecast to the decadal forecast which is a long-term forecast, as well. Nevertheless, the methods for a decadal forecast must be significantly different from the seasonal forecast, because there is obviously a lack of knowledge of meteorological input data for such great lead times.

3.2.1 Combination of meteorological numerical modelling and hydrological models

Like in medium-range forecast the coupling of numerical meteorological models with hydrological models is possible. In climate time-scale, downscaling of climate change signals from GCMs to hydrometeorological input variables is successful (Wood et al, 2002). However, we have different expectation against the seasonal weather forecasts and the shorter-term forecasts. (I.e., in shorter term high precision is expected both spatially and in time, while in climate case “only” the realistic description of the mean climate is required.)

This kind of model coupling is still helpful for seasonal forecasts as done e.g. by Céron et al. (2010). The author evaluate a hydrological forecasting suite at seasonal time scales over France. Looking at an example about the quality of the seasonal meteorological forecasts, it can be seen that the precipitation predictions has no synoptic skill almost over whole Europe (Fig. 3.4; level ACC=60% corresponds to the limit where the forecast does not exhibit any significant synoptic skill) neither for shorter nor longer lead times. The temperature results have slightly better performance: there are some regions in Europe, where the predictions outperform the climatological statement (level ACC=50% corresponds to a categorical forecast for which the RMSE score is equal to a climatological statement) even for 2-month lead time (not shown).

By Céron et al. the hydrometeorological model SAFRAN-ISBA-MODCOU (SIM) is forced by seasonal forecasts from the DEMETER project for the March–April–May period. Despite a simple downscaling method, the atmospheric (meteorological) forcing is reasonably well represented at the finest scale. The computed soil moisture and the reference spring-averaged soil wetness index (SWI) shows a correlation above 0.3 in large regions. Probabilistic scores for soil moisture and river flows for four different catchments are higher than that for atmospheric variables. The results suggest to go further for building an operational hydrological seasonal forecast system, however, a simple benchmark method by building regressions between forecasted catchment rainfall and corresponding SIM reanalysed river flow has very poor quality. Correlation lies between 0.01 and 0.24 according to Céron et al. (2010). First tests using atmospheric forecasts from the ECMWF model for including them in the DEMETER database led to similar scores (Céron et al. 2010).

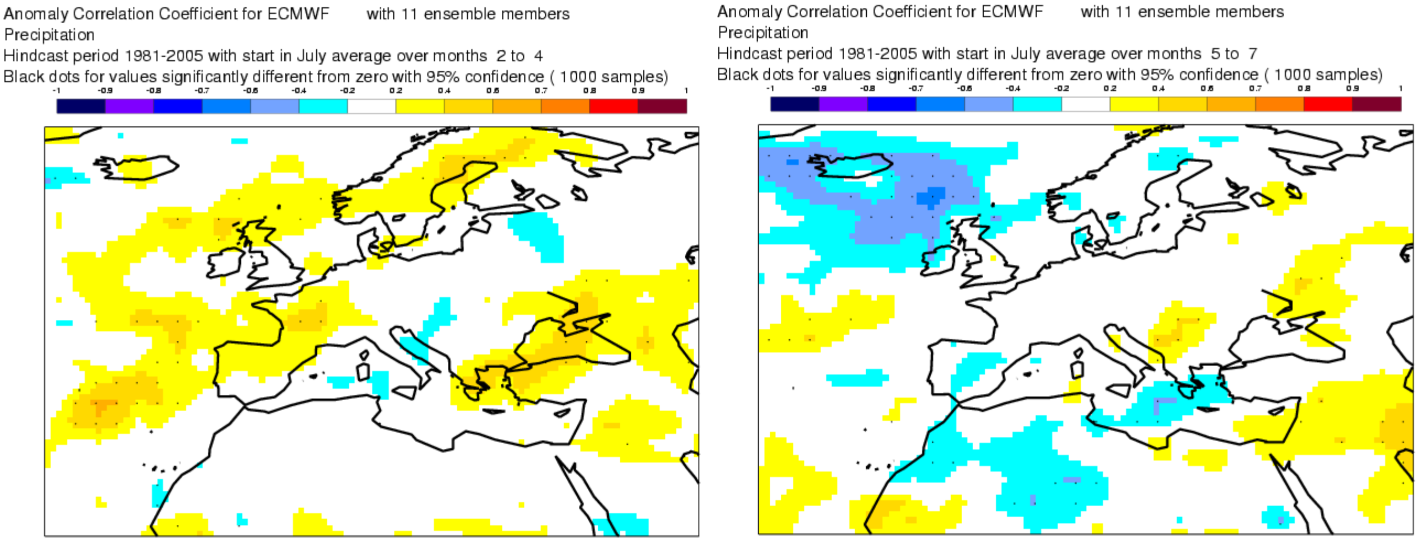

Figure 3.4 Anomaly correlation coefficient for the ECMWF seasonal precipitation forecast started in July 2010 with respect to the hindcast for 1981–2005, with one-month (top) and four-month (bottom) lead time. The higher the value of the score, the better the forecast quality is.

The difficulties are due to large uncertainties in snowmelt especially in February (Lohmann et al., 1998) but a well known snow pack is seen as a great chance in future for the predictability of snowmelt (Ceron et al., 2010). Further exploration of the approach should also include a broader range of climate and land surface conditions. Where snow pack plays a major role in the seasonal cycle it is necessary to focus on it. The second difficulty is the handling of an ensemble forecast which was analysed by Bohn et al., (2010). He suggests the simple average of meteorological weather input, which leads to a better forecast skill in hydrology compared with any individual model input (however, the physical consistency between the meteorological variables are lost with this solution).

Luo and Wood (2008) propose a post-processing for ensemble modelling. The key challenge in seasonal hydrological prediction is the accurate quantification of the uncertainties associated with precipitation and other forcing variables at spatial and temporal scales relevant to catchment hydrology. They took on this challenge by implementing a Bayesian merging approach for the atmospheric ensemble preprocessor that provides the atmospheric forcings to the hydrologic model. The Bayesian merging approach evaluates the skills of these models and combines their forecasts based on their hindcast performance, so that the strengths from each model are combined. As shown in Luo et al. (2007), the Bayesian merging of multiple climate model forecasts provides better predictions of future conditions in both the mean forecast and the associated distribution, which measures its uncertainty (Luo and Wood, 2008).

In the context of seasonal hydrological forecasting, multimodel averaging may be as effective in reducing forecast errors as applying a monthly bias correction to any single model (Bohn et al.; 2010). So it might be a later discussion on a suitable post processing of the results.

3.2.2 Statistical approaches

River catchments have a long memory and a typical response behaviour during a year. Several methods can be figured out of the literature which try to analyse the typical behaviour of a catchment for a longer time period. The principles of statistical mechanics are to be regarded as permitting us to make reasonable predictions as to the future condition of a system, which may be expected to hold on the average, starting from an incomplete knowledge of its initial state. (Blöschl and Zehe, 2005; Tolman, 1979: 1) The statistical seasonal forecasting methods are useful in data-rich environment. However, statistical methods assume that climate processes are stationary and linear, which is contrary to our knowledge of the way in which the climate system behaves (Hydrological report No. 50, 2008).

Figure 3.5 is presenting the annual distribution of daily discharges at Achleiten / Danube and Kaub / Rhine. The different coloured Areas are showing the quantiles of the daily distribution of discharges over the year. As the medians of the daily distribution also the extreme values ode the quantiles are following a certain function. These functions are different in different Rivers as it can already be seen in figure 3.5.

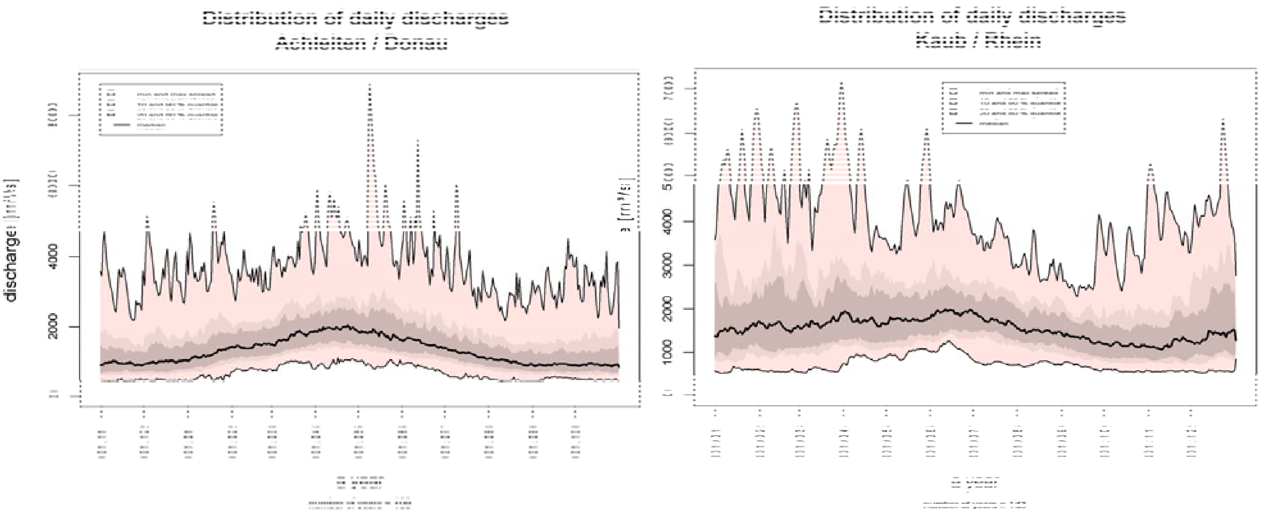

Fig. 3.5: Distribution of measured daily discharges of long records (109 and 143 years) at Achleiten/Danube and Kaub /Rhine.

Another method which could be used are complex statistical models like Montanari (2000) is describing with the aim to detect long-term memories in monthly discharges with FARIMA models. A seasonal fractional autoregressive integrated moving average (ARIMA) model with short- and long-term persistent periodic components is introduced. The estimation of the parameters is carried out by applying the Whittle's approximation to the Gaussian maximum likelihood function, which yields asymptotically consistent estimates. This method is particularly useful for hydrological time series. It is applied to the Nile River monthly flows at Aswan in order to detect whether long memory is present. The results are compared with ones obtained by applying heuristic procedures, some of which were developed recently, in order to see how these perform on seasonal data (Montanari et al., 2000). In this modelling framework the fractional ARIMA model neglects seasonal variations in the correlation structure. The development of suitable models that take this into account is the subject of ongoing work (Montanari et al. 2000).

3.2.3 Teleconnection and hydrologic variability

Teleconnection in atmospheric science refers to climate anomalies being related to each other at large distances (typically thousands of kilometers). The most emblematic teleconnection is that linking sea-level pressure at Tahiti and Darwin, Australia, which defines the Southern Oscillation (ENSO). Also in Europe there are general circulation patterns which might influence climate and its impact on hydrology. The general circulation patterns are called AO (Arctic oscillation) and NAO (north atlantic oscillation). Like described in section 2.3.2 specific NAO indices are representative for special atmospheric patterns. So there might be a potential correlation between atmospheric indices and hydrological behavior.

Usually the ENSO-streamflow teleconnection and streamflow of interannual variability is very low in Europe. This correlation is more significant in other regions of the world (Chiev and McMahon, 2002; Hydrological report No. 50, 2008). Therefore, the one- to two-month lag serial correlation in streamflow is often higher than the streamflow ENSO correlation and should therefore be used together with ENSO to forecast streamflow. However, the strength in the ENSO-streamflow relationship is maintained over a longer lead time compared with the streamflow serial correlation (Hydrological report No. 50, 2008). Strong and regionally consistent ENSO-streamflow teleconnections are identified in Australia and New Zealand, South and Central America, and weaker signals are identified in some parts of Africa and North America. The results suggest that the ENSO-streamflow relationship and the serial correlation in streamflow can be used to successfully forecast streamflow (Chiev, F.H.S. and T.A. McMahon, 2002)

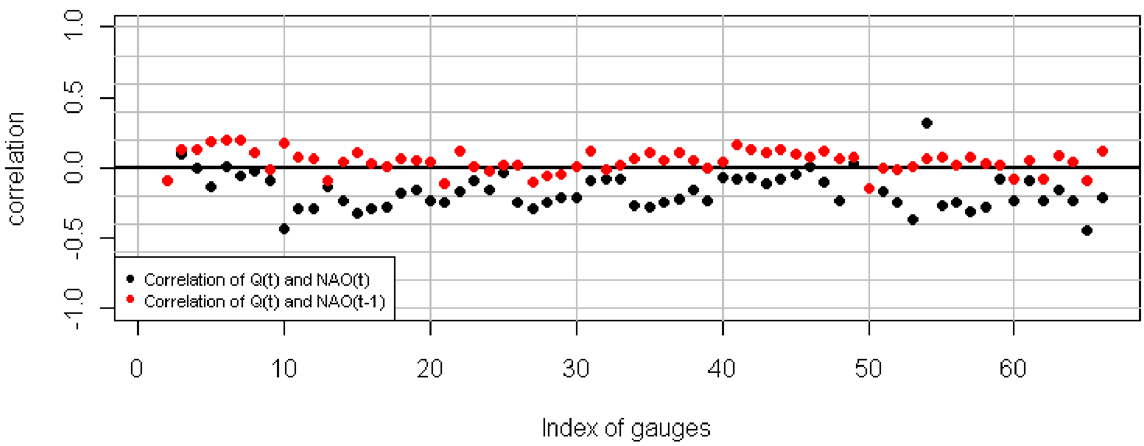

Fig 3.6: Correlation of annual mean discharges and NAO-Index at different gauges at the German Danube (own figure).

Other teleconnections deriving from AO and NAO and describing the correlation between the oscillation patterns and the hydrological anomalies have to be detected. Just as published in the Hydrological report No. 50 the correlation of oscillations and the serial correlation in streamflow can be used for an improved seasonal forecast in hydrology. Rödel (2005) describes spatial pattern in correlation of discharges and NAO-Index at the northern hemisphere. He found out, that Southern Europe shows a negative correlation between NAO and discharges in nothern Europe there is rather a positive one. But these correlations suggest a constant connection between the pressure patterns and discharge relevant meteorological variables, which is barely true. Figure 3.6 shows an example of correlations between the annual NAO index and the annual average discharge of long time series at some gauges at the German part of the River

Danube. Due to the long aggregation of the variables the correlations for the River Danube show an unstable and a barely continuous behaviour. The correlation of the annual mean discharge and the NAO-Index (black) is mostly negative on a low level. The shifted correlation (red) between these two variables shows almost no correlation, because the values are similar to zero. There might be a better correlation to illustrate, when shorter time periods are aggregated.

3.2.4 Seasonal streamflow forecast in Hungary

Being situated at mid-latitudes in an area of various relief, the Danube River catchment and its hydrological processes are strongly influenced by the amount of snow accumulated during winter season. Each year on 1st of March a special report is issued at VITUKI National Hydrological Forecasting Service of Hungary (the report in Hungarian can be found on the webpage: http://www.hydroinfo.hu/Text). Its main purpose is to give information about the runoff processes expected during the subsequent spring period.

The following meteorological and hydrological information are taken into consideration:

- The amount of precipitation in the November – February period
- Temperature conditions in the November – February period
- Actual value of snow water equivalent of the snow accumulated on the catchment during winter
- Long-term meteorological forecasts for the spring period

In the first step the amount of precipitation and temperature conditions for the first third of the actual hydrological year are analyzed and compared with the 30-year average.

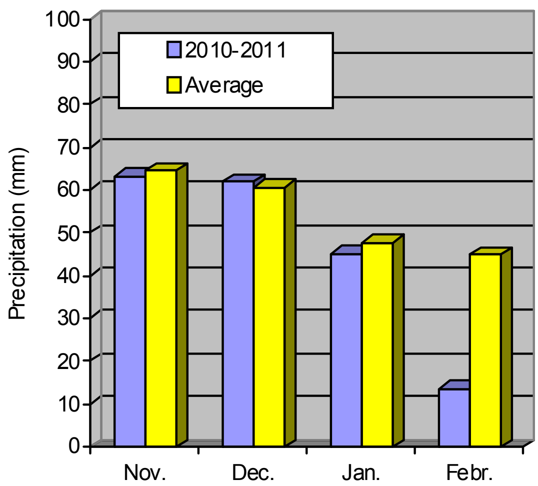

Fig. 3.7: Monthly precipitation sums above Danube - Nagymaros

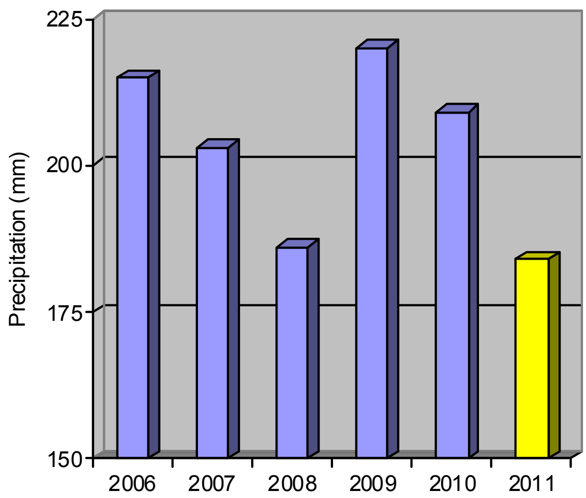

Fig. 3.8: Winter precipitation amounts above Danube - Nagymaros

The total water amount stored in the snow on the area above Nagymaros (Fig. 3.9) is calculated based on approximately 2300 snow depth and snow water equivalent data using snow related data from almost 120 meteorological stations and additional meteorological data considering the effects of the orography. Detailed calculations are showed in Table 3.2.

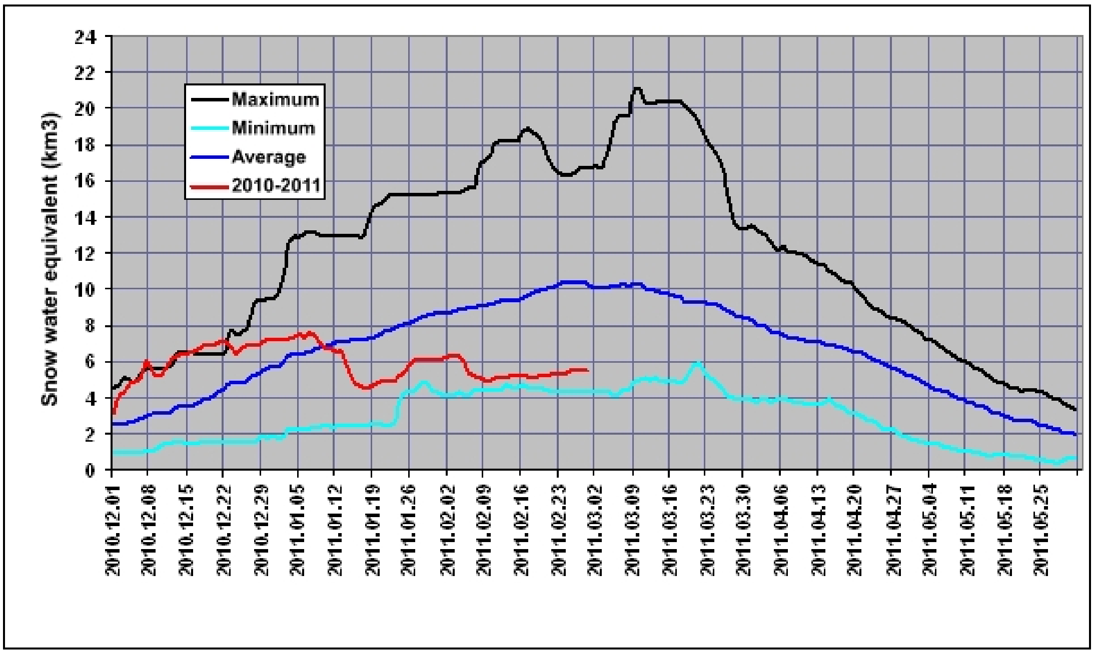

Fig. 3.9: Snow accumulation course above Danube - Nagymaros

Table. 3.2. Accumulated snow amount above Danube – Nagymaros on 1st March 2011.

Elevation [m.a.s.l.]	**Catchment size [km²]**	**Average snow depth [cm]**	**Average density [g/cm³]**	**Snow water equivalent [mm]**	**[km³]**
0 - 500	95250	0.4	0.286	1.0	0.097
500 – 1000	58000	4.2	0.244	10.2	0.591
1000 – 1500	15000	36.9	0.217	80.1	1.202
1500 – 2000	6925	81.5	0.210	171.5	1.187
2000 – 4000	8075	135.1	0.215	290.8	2.348
Total:	**183250**				**5.426**

Based on the estimated snow amount and on the long-term meteorological forecasts seasonal hydrological forecasts are produced for the subsequent spring period using regression equations (Table 3.3).

Table. 3.3. Expected average and maximum water level values for Danube - Budapest (Spring 2011)

Danube - Budapest	**March 2011**	**April 2011**	**May 2011**
Monthly mean water level [cm]	247± 56	252± 82	278±56
Monthly maximum water level [cm]	395±113	344±125	391±81

Since long-term meteorological forecasts are of limited reliability, multiannual average values can also be used in this method. The estimations give a short overview of the current snow accumulation situation in the catchment. It is suitable for large catchments with a mayor influence of snow melt processes.

4. Predictability of river basin management

Seasonal risk analysis for water management and the influence of water management on water levels is analysed here. A lot of long-term forecast is done for water-management tasks, which means a reservoir management is done to control water supply for irrigation, fresh water and low water management for navigation.

Water management for economic purpose can change the natural spatial and temporal supply of water clearly. Natural discharges at high water and low water situations are higher or lower than the influenced situations, because the water reservoirs have the purpose to moderate the annual distribution of the natural water supply (Koch et al. 2010).

Usually hydrologic modelling bases on a natural system. In cases of high water the forecasting is dependant on human influences in a catchment of interest. Also low water forecasts must be done with respect to large reservoirs which have been constructed during the last decades having a great influence on the regime of a river. These controlling of the reservoirs is usually described by rules, but in severe situations the controlling will be switched to a manual regulation manipulated by political and economic interests.

Usually the filling of a reservoir is a initial condition in hydrological modelling. During a seasonal forecast the initial condition plays a significant role. It has to be acknowledged that the influence of the basin initial conditions should be further analysed by considering other variables, such as soil moisture, to evaluate antecedent effects on hydrological forecast skill when AR (antecedent rainfall) is zero or very low (Mascaro et al. 2010).

River Rhine

Hydrological models which include reservoir behaviour can calculate the human impact at the river Rhine. For this report the antopogenic influence on the River Rhine has been estimated by modelling the river discharges with the BfG-model LARSIM_18. It is a Model with a spatial resolution of 18 x 18 km and it include the Reservoirs of the Alpine Rhine and the Bodensee. The Suisse reservoirs at the alpine Rhine has an influence up to approx. 80 m³/s at gauge Maxau in low water situations (<1000 m³/s). This means that in a low water situation where discharge is only 1000 m³/s and the water level, according to the rating curves is about 448 cm, the influence of the Suisse Rhine reservoirs raise the water level about 10 cm. In Cologne the corresponding augmentation due to the Suisse reservoirs is still approx. 8 cm.

River Elbe

The construction and management of barrages at the River Elbe influence the streamflow at the River Elbe clearly. In low water situations the fraction of discharges out of reservoirs is significant. Koch et al (2010) identified the anthropogenic influence of 40% at the river Elbe during the low water situation in 2003. Due to the construction work during the last decades the water management system at the River Elbe became more robust in times of low water (Koch et al, 2010).

River Danube

The contribution of alpine river systems to the discharge of the River Danube is very high. On the same hand the mountainous situation supports water management for energy production and fresh water supply. There are several large reservoirs which influence the regime of the rivers in the Danube catchment strongly. A study based on a hydrologic model with a temporal resolution of one month estimates the influence of the 14 largest reservoirs. The following figure gives an overview of the absolute change in discharge downstream of the reservoirs (Pöyry,Final report, 2011).

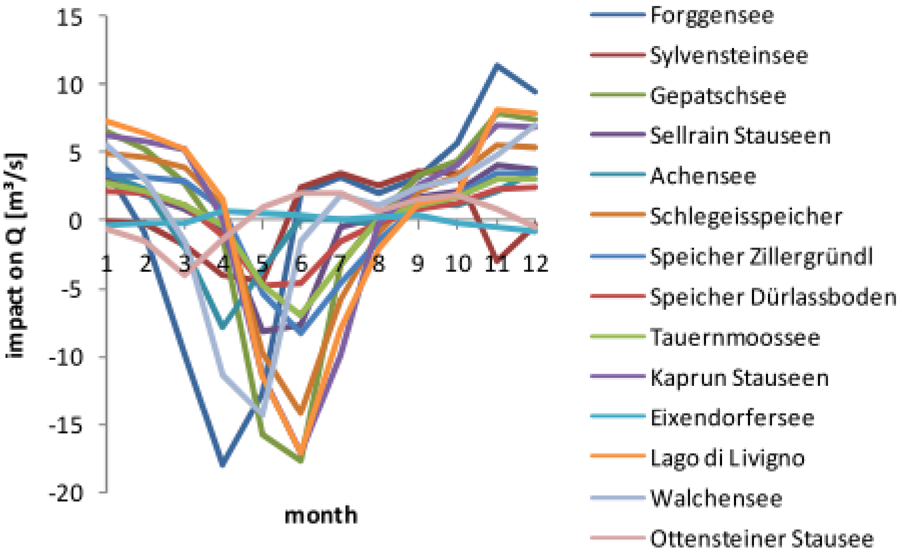

Fig. 4.1: Simulated impact of the reservoirs on discharges between 1991-2007.

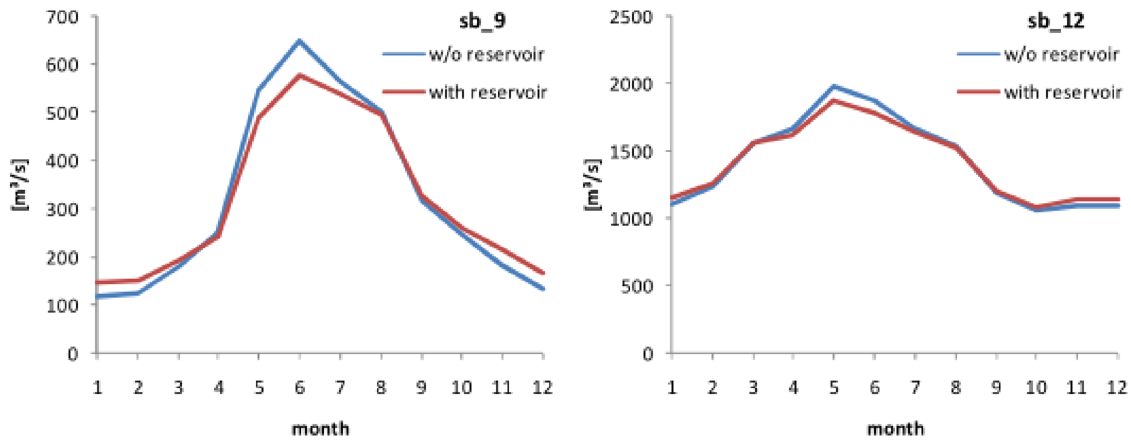

Fig. 4.2: Simulated discharge with and without influence of reservoirs within the period 1991-2007. (a) gauge Oberaudorf / Inn, (b) gauge Achleiten / Danube.

In terms of predictability we have to conclude that a high human impact on a river basin improves the forecast, because the river management usually follows rules improving low water situations or damp the flood situation. The rule follows thresholds which are defined by certain water management interests in navigation drinking water supply or irrigation. It can be shown that river management has improved the navigation conditions significantly and its impact on certain low water levels very high. This percentage is predictable besides the knowledge of the initial state of a river management tool. There is the need of space and available water in the reservoirs which is commonly not known in the modelling. The second part of uncertainty is due to unexpected manual regulation or a change in automatical regulation.

5. Fusion of meteorology, hydrology and economic needs

5.1 Economic interests

In combination of the information above together with economic purpose written in the WMO report No. 50 it can be figured out:

Medium-term forecast of river flows are required for a number of purposes.

- Hydropower generation
- Water-supply purposes
- Irrigation
- Cooling water

Long-term forecast has also a number of purposes

- Management of water resources systems (particularly systems with high interannual variability.
- Realistic decisions on water allocation of water for drinking and irrigation
- Estimation of risk based decisions.

The purpose for navigation optimisation is not yet introduced in literature although the high relevance is figured out in this chapter. Medium-term forecast is useful for contracts of water abstractions and their optimal distribution. It can avoid short dated allocation bottlenecks because of unforeseen events. Long-term forecast is useful for a better allocation of loads on waterways by estimating water dependant payloads. This is optimising cost in ship rental for drought periods.

In accordance with the suggestions of Troccoli (2009) the interests of recepients play a big role in performing a seasonal forecast product. The following list gives a first suggestion what the interests of stakeholders might be. In the course of the ECCONET project the need of a multilateral discussion with the stakeholder became clear. Therefore a questionnaire was invented which can initialise and improve such discussions in future.

Relevant economic interests concerning navigation might be:

- Forecast of loading relevant water depths.
- With increasing lead time the relevance of the forecast for store management increases.
- The forecast must be reliable to trust on it and to make plans on it.
- The delay of a single ship .
- The duration of navigation limitations.

Users of hydrologic predictions need reliable, quantitative forecast information, including estimates of uncertainty, for lead times ranging from less than an hour during flash fooding events to more than a year for long-term water management (Schaake at al, 2006). Especially for medium-range and seasonal forecast some detailed conclusions can be done. They can be regarded as different from conclusions of the short-term forecast although there might be some overlaps. The potential users of short-term and seasonal forecasts are different. By using medium- and seasonal-range forecasts for economic decision making the following conclusions have to be taken into account:

⇒ The threshold for the definition of a low flow event corresponds to water depth relating to drafts of economical loading of ships.
⇒ Forecasting statements should have a high significance
⇒ Guaranteed of water levels above relevant thresholds is of high interest for navigation.
⇒ The forecasted lowest water level and its date of occurrence gains relevance at water levels near the relevant thresholds.
⇒ The deficit volume is not of interest for navigation
⇒ Besides the water level navigation relevant characteristics of a drought are date of occurrence and duration.

Interview

In contact with economic decision makers, some specification could be done. There are of course decisions to make concerning store keeping and planning. Planning actions must be divided into two parts:

1.The shipping action (disposal of loading) and
2. the planning of flexibility in transport capacities for several months.

The loading is dependent on a several days up to a medium-range forecast. During the logistic workflow a certain contract has to be fulfilled in a manner of just in time production. The windows of delivery have an extend of several days wherein the transport can be optimised. The planning of transport capacities or a long timeframe lowers the price for renting this capacity. If the shipping company is aware of a drought situation three months in advance they are able to rent additional cargo capacities earlier for a lower price. The economic benefit of a seasonal forecast is obvious. Unfortunately there is no seasonal forecast product which can be used for such planning. Economic decision makers would use any product including uncertainties and wide spreads of results. A qualitative forecast would already improve their decision making.

As there is no seasonal forecast product available any product would be an improvement. A cascade of desired products can be figured out which represent an increasing precision:

1. qualitative forecast
2. tendencies in relation to a long-term mean or in relation to the start day of prediction.
3. range of water levels with uncertainties of 20-50cm
4. definition of a start date of periods with limitations.
5. number of days within the forecast period with navigation limitations

The significance of the forecast products should have a minimum ~ 0.3 to know at least the tendency. The use of such a forecast lies within the risk of the user.

5.2 Economic decision making and probabilistic forecast

Since several years, users of weather forecasts have begun to realize the benefit of quantifying the uncertainty associated with forecasts rather than relying on single value forecasts. At the same time, hydrologists and water managers have begun to explore the potential benefit of ensemble prediction systems (EPS) for hydrological applications (Thielen et al., 2008).

In medium- and longer-term the ensemble forecast outperforms the single forecast still knowing that ever ensemble member has the same probability of occurrence. Economic decision makers are maybe more familiar to calculate with risks (insurance or reinsurance). Also a forecast uncertainty can be transformed into a distribution of risk, however, beyond some limit, neither the probabilistic information helps the decision.

5.3 The seasonal forecast service

The utility of monthly to decadal forecasts for Europe may rely on careful optimization of the whole “end-to-end” forecast-to-user decision-making process. Important issues include the recognition that

1. estimates of forecasted values can affect the cost of mitigating actions and
2. that reducing volatility (not just expense) may be an important motivator for some users.

Since the interests of different users are not necessarily aligned, careful consideration may be required of which user communities to target when developing end-to-end forecasting systems (Rodwell and Doblas-Reyes, 2006).

<u>Status</u>
Within writing this report it became clear, that the information needed for adaptation measures due to climate change is in progress but it is not part of a service yet. It is still not possible to quantify the effect of such a forecast service, because neither the scientific validated product nor the service exists. This document is showing clearly that there are a lot of possibilities, but there is a lack of communication between scientists and stakeholders.

5.4 The ongoing research experiments

This information gives the background for a future seasonal forecast product, which might be offered as a service for economic stakeholders. Firstly there must be a conclusion of scientific possibilities and economic desires. Out of the broad possibilities which are figured out in this document some meteorological forecast products and also a hydrological model can be chosen to calculate discharges and water levels. Every validation of the results must be done in focus of the economic interests.

In coordination of BfG/Germany a new coupling of meteorological inputs, which are needed for a hydrological model forcing was figured out. This can be seen as a multiple interface between meteorological models and hydrological models on a daily time step and which requires a minimum of input variables.

Seasonal forecasts from ECMWF are available for the period of 1980-2006 with an 11-member ensemble of 7-month hindcasts and for 2006-2011 with a 41-member ensemble of a 7-month operational forecast. The following variables are written out in a 1,25° grid over Europe:

No.	Description	Resolution
57	2m minimum temperature	24h
58	2m maximum temperature	24h
167	2m temperature	6h
165	10m horiz. wind component	6h
166	10m vert. wind component	6h
168	dewpoint temperature	6h
169	solar radiation downwards	24h
228	total precipitation	24h

As it was shown in section 3.2.1, the prognostic skill for seasonal meteorological forecasts is diminishing with the lead time over the European region, which is especially valid for precipitation. However, there is the sound idea, that prediction of absence of precipitation can have greater skill than prediction of precipitation existence (blocking actions,…), which suggest to focus on longer dry periods among meteorological situations and on the low flow period among hydrological situations.

With this dataset several hydrological models at BfG can be forced. Analyses will take place following the stategies of Hashino et al. (2007). Within this study a hydrological model was run with a probabilistic meteorological forecast. Different hydrological bias correction were evaluated to affect the quality of a seasonal streamflow forecasting. The study focuses on an monthly bias correction. As an outlook new evaluation should evolve results of smaller timescales. The use of Brier Skill scores can support the (threshold) idea of predicting a navigation relevant low water event. The evaluation will show whether a combination of the models will give proper results of the stakeholders favourite seasonal information, which are written in section 5.1. and which can be modified slightly to a precise question of a scientific manner.

1. a tendency in water levels for the next 3 months or the next 6 months
2. probability of non-exceedence of a certain critical water levels within 1-3 months
3. the start date of a certain critical water level

These aims lie within the pyramid of desired aims of economic stakeholders which show an increase of precision. The focus will remain on the reduction of the uncertainty which is attached to statistical evaluation of the past and also to the outcomes of an ensemble forecast analysis. Might the results show intersections between different methods? Will it be possible to reduce uncertainty by focussing on a specific question, which is given by a potential user?

6. Conclusions

The purpose of this literature review is to provide a description of the current state-of-the-art in research related to meteorological forecasting on the medium to seasonal time scale and the possibilities in the future of improvements to these forecasts. This information is useful because the accuracy and reliability of most approaches of water level forecasts hinges on the accuracy and reliability of meteorological forecasts, and it is the forecasting of water levels that is ultimately of interest in the ECCONET project, especially periods of low water levels which have significant economic consequences for the shipping industry.

In the opening of this literature review, the current methods of forecasting as well as the current approaches to forecasting in Europe are discussed. Currently the ECMWF, UK Met Office and Météo France models are used to perform medium-range ensemble forecasts, and for seasonal forecasts, an ensemble of the three models called EUROSIP is used. All climate system predictions share common mechanisms and physical processes across all time and space dimensions, and this concept is exploited by the UK Met Office and Météo France seamless prediction models that perform forecasts for all time scales; the incorporation of the ECMWF medium-range forecasting model into a unified, seamless prediction model called EC-Earth is currently ongoing. At the root of the approach, very high-resolution dynamical models that are now used for numerical weather prediction are extended to longer time-scales offering the potential to improve forecasts well into the future. There is potential to improve forecasts using empirical (statistical) models and methods as well, but generally, dynamical models are considered to be of higher quality.

Other potential improvements to forecasting lie in the sources of predictability. On the shorter time scales, improvements to the land surface including the method of soil initialization have been proven valuable to improving forecasts. The successful prediction of atmospheric blocking is also promising as long periods of drought and heat are often due to high pressure systems that have stagnated and become stationary. On the longer time scales, large-scale circulations such as the North Atlantic Oscillation (an atmospheric phenomenon) and the El Niño/La Niña Southern Oscillation (an oceanic phenomenon) have proved important and it is becoming increasingly necessary to include the impacts of climate change on these phenomena. Another promising source of improvement across all time scales is the inclusion of comprehensive information about the stratosphere.
There is definitely room for improvement of meteorological forecasting in Europe, especially on the seasonal time scale, and recent developments of which some are discussed in this literature review, have increasingly made this possible.

First steps for a coupling of meteorology and hydrology have been done already by several research groups and their results are promising to reach a medium- to seasonal-range forecast. The skill of meteorological forecast in a seasonal-range is dramatically low. There might be a solution for coping with uncertainty on a seasonal scale from meteorological predictability and hydrological statistics. While the future investigation lies within the model chain of meteorological models and hydrological models the evaluation of ensemble forecasts cannot be avoided.

There are alternative approaches coming from hydrological methodologies alone. Usually the auto correlation of hydrological time series is higher than meteorological forecast skill. A seasonal forecast without an input from meteorological models is conceivable. Especially for long lead times up to six months statistical evaluations are the most favourable system to get probabilistic information. The empirical and statistical solutions described within this report assume always static conditions and these methods also have results dealing with probabilities. The potential lies within the coupling of different systems. The forecast skill of hydrological models driven with meteorological ensembles forecasts is higher than for the meteorological forecast alone.

The solution for stakeholders is to handle with probabilities. At the moment there is no concept for quantifying the gain of seasonal forecast in terms of water levels and their probability. The adjustment of forecasting services on economic needs will clarify the aim of the scientific work. First results of interviews could be published here and its outcome gives a clear direction for research in selection of variables and lead times. The aims come much closer on the scientific way.

For ECCONET the following facts and conclusions are the most relevant for the status and further work in the working chain:

- The research product got its first orientation due to the feedback of a shipping company. Other stakeholders should be included into the definition of a forecast service. For a purposeful research a certain target group must be defined which has particular ideas of implementing a forecast in their decision-making.
- Costs for running a forecast system cannot be quantified now due to high research costs. Costs for running the system operationally will be relatively low.
- The gain of this service cannot be quantified in centimetres and this might never be possible. The focus of the research aims shows, that the demand of a seasonal forecast is very high. Implicit: the cost reduction due to a better knowledge of seasonal preview of water levels might be very high.
- The steps towards a seasonal forecast service seem to be smaller than expected at the beginning. Especially due to focusing on special needs of potential users it might be easy initially to satisfy the demands they have.
- It is possible to open windows for further research in seasonal forecast. This report can be a powerful collection for recombination and new ideas.

Coupling of meteorological and hydrological model-systems can be improved. A lot of hydrological research is done for short-term forecasts especially due to high costs of flood protection near the rivers.

Medium-term and seasonal prediction has its focus more on economic activities and water management instead of flood management. The focus lies on drought prediction which is a large scale prediction. It is affecting land and economy on a national or international scale. So the responsibilities lie dominantly on national and international institutions where coordination plays an important role. The use of meteorological model input for hydrological purposes is favourable for a medium-term and seasonal-term forecast but due to poor forecast skills this method is limited and new ideas must refresh the evaluation of probabilistic results.

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