Extended Guidance: Document on the Natural System and Drought (D.1.2). Part of Work Package 1: Natural System XEROCHORE FP7 Project

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XEROCHORE

An exercise to assess research needs
and policy choices in areas of drought

Extended Guidance Document on the Natural System & Drought (D.1.2)

part of
Work Package 1: Natural System

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Preface

The EU-FP7 XEROCHORE project is a Support Action (SA) that for the first time brings together three interrelated drought aspects at the European scale, namely (1) the natural system (climate and hydrological systems), (2) impacts (socio-economic and environmental), and (3) drought management and policy. It compiles a roadmap that includes the state-of-the-art and identifies research gaps in these three aspects. Moreover, it provides guidance on appropriate responses for stakeholders. XEROCHORE's outcome contributes toward a future European Drought Policy, in accordance with the EU-Water Framework Directive (WFD) and other related EU legislation and actions.

A comprehensive extended network of drought experts (over 80 organizations) gathers inputs to cover the three drought aspects through two focused workshops and a concluding conference. The network includes research institutes, universities, ministries, water management organizations, stakeholders, consultants, international organizations and programs. It includes key members of the European Drought Centre (EDC) and the WFD-CIS Working Group on Water Scarcity and Drought and representatives from overseas and neighboring countries, in particular around the Mediterranean Basin. The large number of organizations covering different aspects and geographic regions guarantees that all of the above-mentioned drought aspects are well covered. The network of drought experts is embedded in the European Drought Centre to enlarge its expert's community and expertise to provide research advice and policy support to the European Commission beyond the lifetime of the XEROCHORE project. XEROCHORE's outcome will contribute towards a future European Drought Policy, in accordance with the EU-Water Framework Directive (WFD) and other related EU legislations and actions.

This Extended Guidance Document deals with the first drought aspect, i.e. the Natural System and Drought (Hydrology and Climate). It is based upon a draft document[1] that provided input to the first XEROCHORE workshop, Noordwijkerhout, the Netherlands, 15-17 June 2009. About 60 workshop participants[2] commented on the draft document. Extensive discussions in several breakout groups and a following plenary meeting eventually led to this Extended Guidance Document on the Natural System and Drought. This document subsequently feeds into the second workshop on drought impacts (Venice, 5-7 October 2009) and later at the final conference on drought management and policy (Brussels, February 2010).

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[1] Wipfler *et al.*, Draft Guidance Document on Natural System (XEROCHORE Deliverable D.1.1), June 2009.

[2] Annex 3 provides the list of persons who contributed to this Extended Guidance Document on the Natural System and Drought.

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1. Introduction

Key challenge

There is a need for a comprehensive, interdisciplinary pan-European study on the Natural System and Drought that covers both past and future conditions. Such a study should address in a joint effort, key challenges reported in the following chapters, e.g. building a concise reference database, influence of climate drivers and feedback processes on drought development, drought propagation (meteorological to hydrological droughts), detection of historic droughts, attribution to causes (incl. human influences), improved modeling of the climate-hydrological systems, quantifications of uncertainty, and development of a European early warning system (incl. seasonal forecasting system). Preferably, a few major, recent droughts in Europe (e.g. 2003 drought or other droughts with sufficient data) should be the binding factor for the study.

Background

Drought is a recurrent phenomenon that occurs in all European hydroclimatic regions. It is caused by a rather long-lasting deficiency in precipitation over an extended region. Drought has a transnational nature. Europe was hit by several severe droughts in recent years. Data for 2000-06 show that each year on average 15% of the EU total area and 17% of the EU total population have suffered from the impact of droughts. From 1976-1990 to 1991-2006 the total area and population affected by droughts have doubled (from 6 to 13 %) and the total cost of droughts over the past 30 years amounts to 100 billion Euros (CEC, 2007). In addition, climate change projections for Europe indicate that drought is likely to become more frequent and more severe due to the increased likelihood of warmer Northern winters and hotter Mediterranean summers that will lead to significant socio-economic and environmental impacts (Bates *et al.*, 2008). There is thus an urgent need to mitigate, and to adapt to droughts, and hence reduce the risks they pose in Europe, in particular in the future.

Droughts are defined in a relative way as "a sustained and regionally extensive occurrence of below average natural water availability" (e.g. Tallaksen & van Lanen, 2004)[3]. This leads to deviations from average normal conditions, such as dry periods longer than a normal dry season or periods drier than common to a region. Climate variability causes the deviations, i.e. the drought. Different types of drought are distinguished dependent on the hydrometeorological variable (e.g. *meteorological drought*, *soil moisture drought*, *hydrological drought*). Drought should not be confused with *aridity* (when potential evaporation is permanently larger than precipitation) or *water scarcity* (when people cause an imbalance between water use and availability).

Drought covers a wide range of interrelated aspects, i.e. (1) natural system (hydrology and climate), (2) impacts (socio-economic and environmental), and (3) drought management and policy (Fig. 1). The EU-FP7 XEROCHORE project brings together these three aspects at the European scale for the first time. As a first step the state-of-the-art of the natural system is described and research gaps are identified. In the next step the same is done for drought impacts, which are added to and integrated into the outcome of the Natural System. As a last step the

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[3] A list of Acronyms and a Glossary are provided in Annex 1 and 2.

state-of-the-art is presented for water management and drought policy-making and research gaps are identified. Eventually, this leads to a document that provides an integrated state-of-the-art and research gaps for the three interrelated drought aspects.

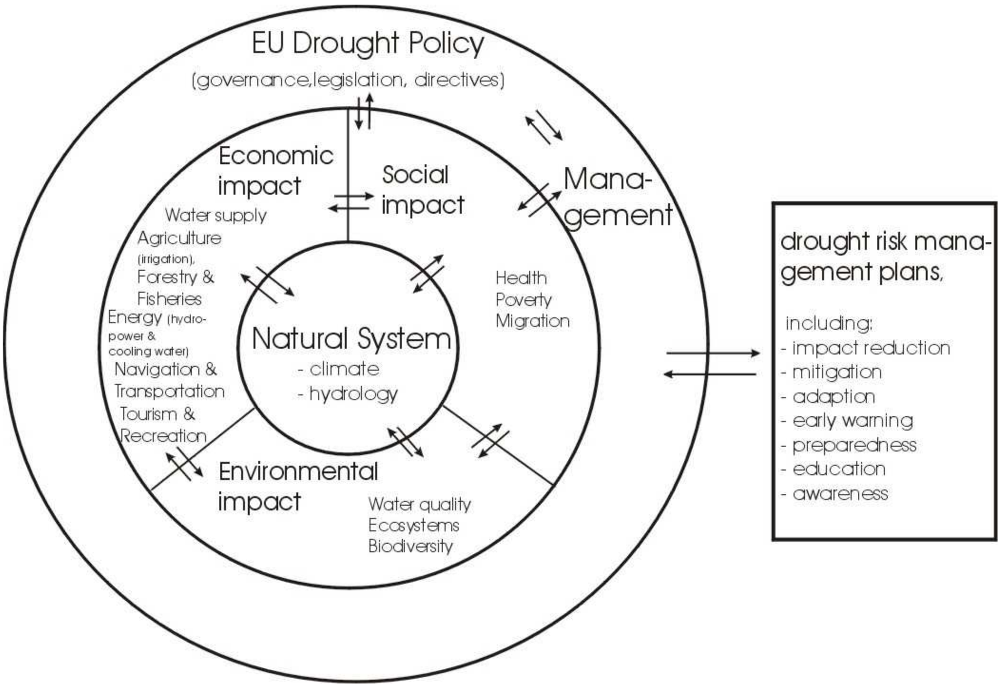

Figure 1. Integration of relevant drought aspects that attribute towards a future EU Drought Policy.

This document[4] aims: (1) to describe the state-of-the-art of the Natural System and Drought, and (2) to identify research gaps (key challenges). The *natural system* is defined as the physical system (hydrological system along with the climatological system) under natural conditions. A pure natural system does not exist, therefore the focus in this document is on drought under conditions without substantial human influences. In addition, for some topics human influences are included because otherwise these cannot be adequately dealt with (e.g. Chapters 5 and 6).

This Extended Guidance Document on the Natural System and Drought synthesizes knowledge on past, current and future drought events with focus on the hydrological and climatological systems and contributes to the roadmap that by providing a vision on research needs that contribute toward a future EU Drought Policy and related EU legislation and measures. It starts with data requirements for research and water management (Chapter 2). Data deficiency is a major issue and it hampers developments and crosscuts through all subsequent chapters. The atmospheric aspects of drought are addressed in Chapter 3. It presents the main climate drivers of drought in different hydro-climatological regions and for different spatial and temporal scales and it describes major historical droughts and their climatological causes. This is followed by a description of the response of the land, incl. the hydrological system (Chapter 4). The response includes: (i) the propagation of the meteorological drought through the subsurface leading to

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[4] XEROCHORE Deliverable D.1.2.

hydrological drought (groundwater and surface water), incl. its space-time development (generation and recovery), and (ii) the land-atmosphere feedbacks through soil moisture, shallow groundwater and snow/glaciers. The drought assessment framework (atmosphere and land) is then addressed in Chapter 5, which comprises: (i) approaches to detect different types of droughts, (ii) drought modeling through coupling of climate and hydrological models (e.g. downscaling, bias correction, feedbacks), (iii) attribution to causes (natural and human influences), (iii), and (iv) the uncertainty quantification in the chain of climate-hydrological models. The document concludes with drought monitoring (incl. early warning) and monthly and seasonal forecasting (Chapter 6).). Each chapter starts with key challenges that precede the description of the state-of-the-art. The last chapter is an important bridge between the Natural System and the other drought aspects (Impacts, Management and Policy

2. Data required for drought research and management

This chapter addresses the need for a EU database containing easy accessible and easy to share data (long time series of hydrometeorological data and thematic data with an adequate temporal resolution and spatial coverage) for drought assessment. The chapter provides information on the wide variety of data required. Research on, and management of drought would substantially benefit from the development of such a database.

2.1. Key challenges

There is a need for:

- a consistent, quality-controlled, extended and EU-harmonized database in a central location that is easy-to-share and easy-to-access. Research should focus on new solutions for archiving and continuously updating databases, for defining standards on data, and for efficient IT implementation (including links to existing databases from target-specific projects) and maintenance. Databases reporting tests on real-case studies should be promoted to encourage data use for drought-indices development and intercomparison studies, performed for different climates, scales, catchment types and modeling approaches;
- collecting and archiving long time-series of good-quality observed hydrological data over Europe, spatially continuous data (cross boundary), together with data on land-use changes and uses that highly impact water quantity and quality. The understanding of drought generating processes, the detection of changes in drought frequency and severity, the predictions of global change impacts on drought, and the validation of large-scale modeling results would, for example, highly benefit from this;
- ground-based measurements of soil moisture and evapotranspiration, which are still scarce. Actions are needed to increase data collection on these variables and to promote research on their integration to satellite-based soil moisture and evapotranspiration maps, with a focus on their usefulness for drought forecasting and monitoring.

In Europe, there is a special need for:

- having access to hydrolological data across national boundaries to study drought, which by definition is a transnational phenomenon. In general data from Eastern and Southern Europe are lacking. Unless such data become available, research in Europe will continue to be hampered, which makes Europe lagging behind regions like the US or Australia The overall key challenge stated in Chapter 1 could be a way forward to increase accessibility.

2.2. Data

A non-exhaustive list of key variables to study and manage drought includes:

- meteorological data, which should include variables describing synoptic and meteorological situations (weather and circulation types) to variables involved in the water budget at

different scales (surface and air temperature, precipitation, global and net radiation, wind speed, humidity, reference evapotranspiration);
- hydrological data, including discharge or water level in rivers, surface water storages (lakes, dams), snow accumulation, piezometric levels, soil moisture, actual evapotranspiration, catchment and aquifer characteristics;
- data on other factors influencing droughts: land use and cover, vegetation, water quantities used by agriculture, households and industry (water abstraction, water releases, storage in reservoirs);
- metadata, including detailed observation station descriptors (e.g. location, maintenance, quality of data, frequency of collection, changes in monitoring procedures), detailed description of users (e.g. presence of regulation or flow diversion, user contact-points).

A complete drought database, harmonized in space and consistent in time, is indispensable to scientists, as well as to assist local planners in assessing the severity of past events and the likelihood of future droughts to occur. As a first step a meta-database can be established that provides links to data providers. Several research projects involve field-campaigns and management of databases (measurements or model simulations) for a variety of types of data that are potentially useful for drought studies: atmospheric flux measurements, satellite or ground-based data from global observation programs (GRACE, SMOS, GCOS), meteorological data from reanalysis (ERA-40, NCEP). International cooperation to link data providers and share available data is essential to supply research with useful datasets. Some important initiatives at global and European levels have emerged:

- the Global Earth Observation System of Systems, for improving water resource management at large scale;
- the European Water Archive (EWA, UNESCO-FRIEND), daily streamflow data and associated metadata for hundreds of rather small, largely undisturbed European catchments';
- the European Climate Assessment & Dataset (ECA&D) project, containing data needed to calculate indices for monitoring and analyzing changes in climate extremes;
- the Global Runoff Data Centre, an international repository for daily or monthly river discharge data and associated metadata, usually for larger river basins;
- the Shared Environmental Information Systems, initiative for an integrated and shared EU-wide environmental information system;
- the European Drought Observatory, for drought forecasting, assessment and monitoring.

The nature and the space-time resolution at which data should be collected depend greatly on the local and regional hydrometeorological characteristics (local drought dynamics), as well as on the purposes of the study being conducted and its modeling framework (forcing variables needed as areal averages or gridded data). For example:

- long time series of high-quality records of meteorological and hydrological data (preferably > 30-40 years) are recommended for trend analysis and global change impact assessment. Special attention should be paid to the sampling of events, as sufficient independent events are needed for the statistical analyses, and for the homogeneity of the individual at-site records in regional studies. Uncertainties coming from data-collection techniques should also be reported (Sections 5.2 and 5.6);

- time series of hydrological data from usually less-affected headwater catchments also need to be collated to study drought under natural conditions, which are also relevant for detection and attribution studies (Sections 5.2 and 5.4)
- continuous databases of past drought events and spatially-harmonized descriptions contribute to understand the occurrence of droughts and to assess their severity (Sections 3.2, 3.3 and 4.2);
- real time quality-controlled data and meteorological forecast data are necessary for drought monitoring and forecasting (Sections 6.3 and 6.4);
- remote-sensed information on vegetation, evapotranspiration, soil moisture and snow cover can be employed to monitor the spatial extent, severity and persistence of drought episodes, in particular when considering land-surface feedbacks (Section 4.4).

3. Atmosphere: climatic drivers of drought

Extreme hydrological droughts and heat waves are likely to be caused by a combination of climate anomalies and already low antecedent catchment storage (e.g. soil moisture, groundwater and lake storage; Chapter 4). Dry winters can, for instance, be the cause of significant water resources stress in the following summer season even when followed by above average summer rainfall. The wetness status of the land surface is also an important memory component of the climate system through land-atmosphere interactions. This chapter presents the main climate drivers of drought in different hydro-climatological regions and for different spatial scales. Drought occurrence is also viewed in light of long-term (decadal to multi-centennial) climatic variability and fluctuations. The chapter closes with an overview of major historical droughts (in precipitation, soil moisture and streamflow) and their climatological causes. The main focus is Europe, but examples from other regions around the world are also given.

3.1. Key challenges

There is a need to better understand:

- the complex mechanisms involved in the formation and development of large- and regional scale droughts and associated heat waves (climatological causes and land surface response) in Europe, including the influence of atmosphere-ocean patterns varying on different temporal scales;
- the role of regional scale soil-moisture patterns on shorter than a monthly time step to establish links between droughts and circulation patters (land-atmosphere interactions) using statistical methods as well as targeted modeling studies (based on GCMs or RCMs);
- whether regional droughts share a common global influence, i.e. are external forcings causing drought simultaneously across the world (synchronicity);
- the variability in drought occurrence on decadal and millennial time scale using a combination of different data sources, including proxy data.

Overall, there is a need for:

- improved methodology for regional drought analysis to allow comparison across different variables and indices; and a comprehensive assessment should be undertaken for each major large-scale drought in Europe accounting for regional differences in drought characteristics, including seasonality;
- caution as to what degree we can use instrumental records and reconstructed time series to predict drought occurrence in a changing climate.

3.2 Drought hydro-climatology

As stated in Chapter 1, droughts are defined in a relative way as deviation from average normal conditions. These deviations or anomalies are part of the natural variability present in the climatic system on various spatial and temporal scales. Accordingly, droughts can occur in any hydroclimatological region and at any time of the year, and their characteristics vary considerably between the regions, in accordance with the normal, regional climate conditions. In a region with a naturally dry season (e.g. semi-arid) a drought may have to last several months or even years to be considered as a severe drought event, whereas in humid regions like western Europe, already a few weeks or months with low rainfall may constitute a severe drought. In this section the main large-scale (global) and regional- or meso-scale (continental scale) climatological causes for meteorological drought (i.e. a deficit in precipitation) are addressed. First a background on normal climate conditions are given, followed by an overview of more specific drought causing processes within Europe.

The main large-scale characteristics of the world's climate zones are determined by the solar energy and the general global atmospheric circulation, which consists of four main features: (i) the Inter Tropical Convergence Zone (ITCZ; a belt of low pressure systems going around the equator), (ii) a region with dominating easterly winds pole ward of the ITCZ (at around 30° latitude), (iii) the Subtropical High Pressure Belt (a zone of large stationary high pressure systems at around 20°-40° latitude) and (iv) a region with dominating westerly winds and eastward moving meso-scale (synoptic-scale) low and high pressure systems in the mid-latitudes (at around 60°-80°). The locations of these features vary between the seasons according to the declination of the sun. In general, high pressure systems (anticyclones) are related to clear skies and dry conditions, whereas low pressure systems (cyclones) are related to wet conditions. The climate in the middle and north of Europe is influenced by the westerlies of the mid-latitudes during the whole year, whereas the Mediterranean lies in a transitional climate zone, influenced by the Subtropical High Pressure Belt during summer and the mid-latitude westerly's during winter. Hence, three main climate regions within Europe result: a temperate climate with a dry summer season in the Mediterranean, and a temperate and a cold climate without any dry season in the middle and north of Europe, respectively (Stahl & Hisdal, 2004). These major climatic differences are further modified by numerous other permanent or temporally variable, global, regional or local factors, such as the global land-water distribution, oceanic currents and topography.

Recurring and persistent, large-scale patterns of pressure and circulation anomalies that span vast geographical areas are referred to as "*teleconnection patterns*" (CPC-NOAA, 2008). Teleconnection patterns may be due to internal atmospheric dynamics or related to ocean-atmosphere interaction. The most well-known phenomena is the El Niño/La Niña cycle of sea surface temperatures (SSTs) in the Western Tropical Pacific and its effect on the Southern Oscillation of the atmosphere, constituting the El Niño-Southern Oscillation (ENSO). ENSO is linked to seasonal temperature and wetness anomalies in many parts of the globe, in particular regions around the Pacific, but has also some influence on more remote regions such as southern Africa. In Europe, the most important large-scale pattern is the atmospheric North Atlantic Oscillation (NAO; Osborne, 2000), describing the anomalies of a north-south pressure dipole over the North Atlantic, with a low pressure centered over Greenland (the Icelandic Low) and a high pressure system centered over the south-eastern North Atlantic between 35°N and 40°N (the Azores High). The NAO index indicates the strength of the westerlies.

The influence of large-scale patterns and variations on European climate is typically occurring through their influence on regional atmospheric phenomena, i.e. the eastward moving meso-scale pressure systems. Teleconnection patterns may affect their pathways ("storm tracks") and hence the resulting positions of pressure systems over Europe. The current atmospheric situation over a particular region, i.e. the location of pressure systems is referred to as "*Weather Type*" (WT), or "circulation pattern", when defined on pressure data only. For example, during a positive NAO phase in winter, the storm tracks from the Atlantic Ocean into Europe are shifted northwards and spare the south (Greatbach, 2000) thus creating a *dipole* of wet and dry anomalies within Europe, with dry conditions in central and southern Europe and wet conditions in northern Europe. The NAO is strongest during the winter and its influence on European climate is mainly restricted to the winter season. Kingston *et al.* (2009) show that the occurrence of high and low flow across northern Europe is associated with large-scale patterns of temperature and precipitation variation. Especially in winter, these patterns are linked to changes in large-scale geopotential height and wind fields. This suggests a link between the North Atlantic Oscillation (NAO) and river flow, but is too complex to be described solely in terms of the NAO. Only recently, a similar pattern for the summer NAO has been identified, which is able to explain the principal variations of the European summer climate, in particular over northern Europe (Folland *et al.*, 2009). However, the type and effect a given teleconnection pattern has on WT-frequencies over Europe may vary between the seasons (e.g. Lorenzo *et al.*, 2008). Furthermore, the relative importance on European climate may vary between different teleconnection patterns. In general, this chain of relations from large-scale (e.g. teleconnection patterns) via regional scale (WTs) to regional and local climate, is in particular important for central and northern Europe. In the Mediterranean large-scale influences may also be more direct.

Overall, droughts are caused by regional- or large-scale spatial and temporal anomalies in the climatic system. Regional drought-causing atmospheric situations are characterized by: i) an anomalous timing of a seasonal phenomenon; ii) an anomalous location of pressure centers and the track of cyclones; and iii) an anomalous persistence or persistent recurrence of dry weather patterns (Stahl & Hisdal, 2004). In the Mediterranean region, with its seasonal climate, severe droughts can for instance be caused by longer than usual influence of the subtropical high-pressure belt. Droughts can accordingly last several weeks or even months. In the mid-latitudes of western and northern Europe, "*blocking action* is the major atmospheric anomaly to cause extended dry weather periods" (Stahl & Hisdal, 2004; see below).

Blocking situations are interruptions of the usual eastward movement of the mid-latitudes pressure systems by the development of a large, persistent and quasi-stationary high-pressure system, which itself moves eastward only very slowly, if at all. The blocking high-pressure system diverts the moisture bringing pressure systems of the westerlies away from the affected region to either lower or higher latitudes thus causing an extended dry period. Even though blocking situations are the most important regional causes for severe droughts in Europe, droughts can be caused by a number of different atmospheric situations. In general, the nature of each drought event seems more unique here (and in the mid-latitudes in general) than in other climate zones, and drought-causing factors can vary already on a relatively small spatial scale. Thus, the dominating drought causing WTs (i.e. the locations of high and low pressure systems) vary between regions, and a single regional drought may be related to a (unusual) sequence of several different situations or WTs. For example, McGregor & Phillips (2004) found for major meteorological droughts in south-west England that they could be caused by a blocking situation in different locations, namely either to the north and east of the UK or to the south and west of the country. Stahl & Demuth (1999) found several WTs to be associated with drought in southern Germany, and Beck (2009) further identified the most important drought causing WTs the north and south of Germany. In general, WTs which cause dry conditions over a region are those representing a high-pressure system centered over the region as well as other anticyclonic WTs with flow directions that bring dry (and during summer also warm) air masses to the region in question. Such air masses usually come from land areas and in central Europe this implies frequently easterly or northerly flow directions, rather than the otherwise dominating westerly flows.

Furthermore, SSTs anomalies may favor anticyclonic circulation, and hence land-surface heating and limiting moisture influx, rather than supplying humidity to the continent (Black *et al.*, 2004). For example, SST anomalies in the tropical Atlantic have been shown to favor anticyclonic circulation in Europe (Cassou *et al.*, 2005), and Feudale & Shukla (2007) suggested that also warmer SSTs in the Mediterranean Sea could reinforce anticyclonic circulation over central Europe.

Previously, it had been suggested that ENSO, which in many regions is important for drought development, has only very limited effect on the climate in Europe. However, recent studies have identified the existence of links also to Europe, notably, to European precipitation (Brönnimann, 2007) and between the cold La Niña episode of the ENSO cycle and extreme droughts (Sordo *et al.*, 2008; Herweijer & Seager, 2008). Most studies on relations between ENSO and European climate are based on statistical investigations. However, Ineson & Scaife (2009) recently showed that by extending a Global Circulation Model (GCM) into the upper atmospheric layers, i.e. the stratosphere, the statistically identified links between ENSO and European climate can also be remodeled. Hence, it is suggested that in addition to the lower atmosphere (troposphere) and the oceans, also the stratosphere plays an important role in the transfer of global climatic teleconnections. This points out the importance of studying potential links between different ocean-atmospheric features over longer distances and different time periods by both statistical and numerical modeling, as also stated by Kumar & Hoerling (2008) for general climate research. Recent studies have further shown that there may also exist a "global footprint" of large-scale droughts. For instance, Herweijer & Seager (2008) found drought in western North America to coincide with the occurrence of prolonged dry spells in parts of Europe, southern South America and Western Australia. It is suggested that the global pattern is a low-frequency version of interannual ENSO-forced variability. Similar, the 1998-2002 drought events in the United States, southern Europe and south-west Asia were found to be linked through a common oceanic influence represented by sea surface temperatures (Hoerling & Kumar, 2003).

Due to their most obvious variability on the monthly to seasonal and annual scale, relations to teleconnection patterns have traditionally been analyzed mostly on those scales. However, links may exist on various time scales from daily to multi-decadal and centennial (Section 3.2). Association have been found on the shorter time scales, e.g. between the daily NAO index and the Madden-Julian Oscillation (MJO) in the tropics (Cassou, 2008), and on the longer time scales e.g. between the Atlantic Multidecadal Oscillation (AMO) and the summer NAO (Folland *et al.*, 2009) and European summer climate (Sutton & Hodson, 2005). Furthermore, the importance of teleconnection patterns for regional climate can vary throughout the year. For example, the WTs causing the severe drought of the winter 2004-05 on the Iberian Peninsula were related to the NAO between November 2004 and January 2005, to the East Atlantic pattern during February and to an anomalous blocking situation during March (García-Herrera *et al.*, 2007).

The recent advances in identifying regional- and large-scale climatic drivers for European drought, suggest this to be a promising area for further research. In particular, the role of teleconnection patterns should be further investigated. The low-frequency variability of teleconnection patterns with persistency of several weeks, months and in some cases even years, is of potential great interest for monthly and seasonal drought forecasting (Section 6.3). Further studies should consider the chain from teleconnection patterns via WT frequencies to regional (and local) drought occurrences. Both atmospheric and oceanic teleconnection patterns should be considered, including those not commonly used as well as remote patterns. Potential linkages should be investigated on various temporal scales and time lags and the varying influence of teleconnection patterns on WT frequencies during different seasons and in the interactions with other patterns should be accounted for. Studies should preferable be done on the pan-European scale to consistently address the spatial and temporal characteristics of droughts and drought causing processes across Europe. For example, López-Moreno *et al.* (2007), identified homogenous regions within Europe based on monthly precipitation series and studied the links between wintertime NAO and drought occurrence in these regions. On the regional scale, also the importance of the sequences of WTs should be investigated, in addition to the identification of drought-causing WTs.

3.3 Natural variability of current climate

The climatic conditions in all parts of the world are naturally varying due to the variability in the atmospheric circulation, the oceans and their interactions as well as in response to external climate forcing, such as volcanoes or the sun. Climatic variations can be cyclic or abrupt and occur on different time scales from a few days (e.g. the eastward-moving pressure systems of the mid-latitudes) to months (e.g. atmospheric teleconnection patterns), years and decades (e.g. due to annual and multi-decadal oscillations in the oceans) and millennia (e.g. the Earth's orbit around the sun). As droughts are caused by anomalies in normal climate conditions, they are a natural result of its variability. Accordingly, also the anomalies causing dry periods and droughts in Europe can be of varying duration and severity. Among the internal variability in the climatic system, monthly variations are frequently related to large-scale atmospheric teleconnection patterns, whereas variations on longer time scales are typically related to ocean-atmosphere interactions as the oceans have a much longer memory than the atmosphere.

To assess the natural climate variability long data records are needed, and in particular the variability on lower frequencies (decadal to multi-centennial) is still associated with uncertainty. To improve the understanding of natural variability, annually resolved climatic records over one or two centuries are needed. However, only very few instrumental climatic records cover up to a few hundred years, and reconstructions of longer climatic series based on proxy data are necessary (Robertson *et al.*, 2009). Proxy data used include documentary records as well as "the measurement of physical and chemical properties of natural archives such as tree rings, corals, ice cores, terrestrial sedimentary sequences and marine records" (Robertson *et al.*, 2009). However, up to now also the use of proxy-based data encounters several limitations as only few independent records span the entire last 1000 years and as limited data are available, the variability may easily be underestimated. Some proxies give information on either the warm or the cold season, and often both spatial coverage and temporal resolution are insufficient.

Currently, some potential for improving both extent and resolution of proxy based records is seen in the combination of different proxies (Robertson *et al.*, 2009). However, additional and extended records as well as the exploitation of so far unused proxies are still needed, particular to explore and understand the cause of extreme events. Based on proxy data, e.g. Pfister *et al.* (2006) found winter droughts in the Upper Rhine basin to be more frequent in the first half of the last 450 years period as compared to the 20th century, and often the events were connected to persistent anticyclones (i.e. blocking) over Western Europe. Linderholm *et al.* (2009) found the summer NAO (SNAO) to be related to drought in northern Europe, using a regional summer drought series from Sweden dating back to 1700. For the Mediterranean, however, they could assess SNAO-drought relations over the last 550 years and found them to be clearest at centennial scales and for the eastern Mediterranean. An improved understanding of natural variability is necessary to capture the likely severity of a regional event and historical droughts as identified from reconstructed time series, are further elaborated in Section 3.4.

The characteristics and relations of atmospheric and ocean-atmospheric teleconnection patterns have been found to change over longer time-scales or in connection with abrupt climatic shifts. For example, reconstructions based on proxy-data have shown "a general tendency for more negative NAO indices during the 17th and 18th centuries than in the 20th century", and "changes in the linkage between ENSO and moisture balance in the USA over the last 150 years" (Jansen *et al.*, 2007). More research is thus needed not only on the teleconnections of large-scale patterns over different time scale and distances, but also on the interactions between different patterns. Recently, a study by Tsonis & Swanson (2009) suggested that a synchronization of several large-scale patterns, i.e. NAO, ENSO, Pacific Decadal Oscillation (PDO) and North Pacific Index (NPI) can cause climatic shifts, which for example may be "associated with significant changes in global temperature trend and in ENSO variability."

3.4. Drought and heat waves

Europe has in the 21st century experienced several dry and hot summers, notable the record breaking 2003 event covering a large part of central Europe, but also the summers of 2005 and 2006 (western Europe; with a particular dry spring in 2006) and 2007 (southeast Europe), recorded record high air temperatures and severe drought conditions. These events were a strong reminder of Europe's vulnerability to drought with serious impacts on society, environment and various economic sectors. The heat wave that accompanied the 2003 drought contributed to the deaths of more than 30.000 people (Kosatsky, 2005; Black *et al.*, 2004). France was the country most affected with an estimated excess mortality of 54% (Grize *et al.*, 2005); for more details see MEDD (2003). The 2003 event rank the warmest amongst the ten hottest summers in Europe in the period 1948-2004 (i.e. 1950, 1952, 1959, 1964, 1976, 1983, 1992, 1994, 1995 and 2003; Vautard *et al.*, 2007) based upon average June-July-August mean daily maximum temperature.

During a dry and hot summer, interactions between soil, ocean and atmosphere may amplified the drought intensity and extent.The drying of the land surface during a drought is in mid-latitude and transitional climate zones, closely related to air temperature and the development of a heat wave. As the soil dries out, less energy is used for evaporation and the allocation of incident solar energy at the surface between *sensible* and *latent heat fluxes* (the Bowen ratio) changes as more energy is used for heating the air. Heat waves thus frequently accompany major droughts, and changes in soil moisture combined with a strong land-atmosphere coupling appears to be a dominant factor explaining the observed increases in the summer temperature variability over central Europe (Schär *et al.*, 2004; Seneviratne *et al.*, 2006). Soil moisture may in addition to interactions with air temperature, also impact the formation of precipitation and thus the dynamic of the climate system. For example, a dryer soil favors the development of anticyclonic circulation anomalies by increasing the thickness of the lower layer of the troposphere (Ferranti & Viterbo, 2006). These feedbacks reinforce the drought in return, and were in the recent four hottest European summers, found to explain most of the heat anomaly (Fischer *et al.*, 2007). Climate forcing by synoptic scale conditions (Section 3.2) is thus not the only cause of drought, also various regional land surface feedbacks concur to amplify dry weather and high summer temperatures (e.g. Della-Marta *et al.*, 2007).

In Europe, modeling studies have shown a high sensitivity of summer climate to soil moisture, whereas neighbouring SSTs have a more limited influence on continental temperatures (Vautart *et al.*, 2007). Soil moisture at the beginning of summer is for instance identified as a key factor controlling the summer mean temperature (D'Andrea *et al.*, 2006), and Zampiere *et al.* (2009) investigated the mechanisms that link summer droughts and heat waves in central Europe to their preceding winter and spring rainfall deficits in the Mediterranean region. A dry spring and early summer were found to precede anomalous hot summers through important feedback mechanisms. Drier soils in southern Europe were found to accelerate the northward propagation of heat and drying, increasing the probability of strong heat wave episodes in the middle or the end of the summer (Zampiere *et al.*, 2009; Vautard *et al.,* 2007). These and other recent studies addressing the climatological causes of major European drought and heat waves, have brought forward interesting new knowledge. Particularly emphasizing the importance of soil moisture feedbacks, which can be significant at a range of temporal (seasonal to centennial) and spatial scales (local to continental). The characteristics and origin of heat waves have been studied also for other regions and continents, most noticeable in the United States due to their severity in south-central US (e.g. Chang and Wallace, 1987); and several research studies have tried to provide a better understanding of their causes (Huang *et al.*, 1996). Land-atmosphere feedbacks are further elaborated in Section 4.4.

3.5. Major historical events and climatological causes

Dry weather and heat waves are associated with anticyclonic circulation patterns. In 2003, a high-pressure system developed over Western Europe and led to the blocking of moist air masses from the west and allowed warm, dry air masses from northern Africa to move northwards. The result was a large precipitation deficit that extended across most of central and southern Europe with extreme temperatures and drought conditions lasting from March to September. Low water levels in streamflow and groundwater and record high river temperatures were reported for several European rivers. Deficit in water resources results from a complex relationship between governing climatological causes and hydrological response. The origin of a drought as a deficit in the climatic water balance (precipitation less evapotranspiration) and its propagation in the hydrological system is elaborated in Section 4.2. In this brief overview, focus is on climatological causes for extended dry and hot periods in Europe, potentially leading to severe deficits in available water resources. It reviews recent studies on deficits in precipitation, soil moisture (as represented by the Palmer Drought Severity Index, PDSI) and streamflow.

Analysis of monthly Standardized Precipitation Indices (SPIs) calculated for the 20th century on a 0.5° grid over Europe, did not reveal any decadal trends in drought extent within Europe. However, greater pan-European drought incidence based on simulated soil moisture (PDSI) were found in the 1940s, early 1950s and the 1990s and lesser incidence in the 1910s, 1930s and 1980s (Lloyd-Hughes & Saunders, 2002). Weekly PDSI and the Palmer Z-index (measure of surface moisture without consideration of antecedent conditions) covering the period 1881-2005 similar showed significantly drying trends in central Europe (seven stations), notably after 1940 (Trnka *et al.*, 2009). The largest drying trend was found in the growing season and was related to a change in the frequency of drought-conducive circulation patterns, particular in early spring. Briffa *et al.* (2009) analysed moisture availability using the PDSI (derived from a monthly soil moisture model using observed precipitation and temperature) across the somewhat larger region of western and central Europe covering the period 1750 until 2003. They found wetter summer conditions from the end of the 17th century up until the beginning of the 19th century and conclude, in agreement with the above studies, that recent widespread drying is apparent in the latter part of the 20th century. The three driest summers (using average summer PDSI over 22 locations) were 1976, 1990 and 1921 (in order of severity). The 2003 drought does not stand out as particularly dry in this simple average, which may be due to the inclusion of stations from north Western Europe that was not so severely hit by the 2003 event. The area extent was analysed using a gridded PDSI dataset and also here, the 1976 drought stands out with about 42% of the area experiencing moderate to severe drought. A clustering of dry years was further observed in the 1990s (1990, 1992, 1998); in these years more than 30% of the area were affected (slightly dry or worse). An analysis of PDSI records based on observed precipitation only (plus climatological mean temperature), showed that anomalously high temperatures constitute a major contribution to the severity and large areal extent of recent summer droughts, particularly in central Europe. In an earlier study covering the period 1901-2002 (van der Schrier *et al.*, 2006), such a trend in summer drying since 1950 could not be distinguished from strong (multi-) decadal variability. However, the study by Briffa *et al.* (2009) based on longer records as described above, provide a different viewpoint.

Regional scale studies of drought in observed streamflow are mainly limited to the second half of the 20th century due to the availability of records over a larger area. Stahl (2001) investigated the occurrence of the largest streamflow drought events in Europe from 1962-1992 based on a regional drought index derived from daily streamflow series. A clustering of dry years during three periods was found: (i) long dry spells occurred in 1962 to 1965, (ii) several large events occurred in the first half of the seventies with the most severe drought in 1976 (maximum in July), and (iii) a major European drought of considerable duration occurred in 1989-90. In addition, a single large and short dry period occurred in 1983. Generally, drought associated synoptic meteorology was characterized by high mean sea level pressure (MSLP), but the circulation pattern types (e.g. WTs) not only varied seasonally, but also per individual event (Section 3.1). Most of the severe summer droughts were associated with high-pressure systems across central Europe. During 1976, Western Europe (particularly the UK, north-western France and the Netherlands) experienced one of its most severe droughts when blocking high-pressure centres persisted over the region in the summer period (see also Zaidman *et al.*, 2001). Drought events in summer or autumn often occurred after winter periods with extreme streamflow deficiencies like in 1964, 1972-73 and 1989-90. However, it should be noted that the database used in this study, the European Water Archive (EWA), holds few stations in southern and Eastern Europe, which limited the conclusions that could be drawn at the pan-European scale. The difficulties encountered in getting access to data from these regions is a matter of concern as also addressed in a recent update of the EWA (Stahl *et al.*, 2008a). EurAqua (2004) reported in addition the following regional drought events in Europe: 1981-82 (Iberian Peninsula), 1988-91 (Mediterranean region), 1992-94 (Eastern Europe), 1992-95 (Spain) and 2000 (central Europe). During the 1992–95 drought in Spain, winter precipitation was considerably below the long-term average (Peral Garcia *et al.*, 1998), which could be related to the NAO index.

As demonstrated by these studies, large-scale droughts have been studied at the pan-European scale for different variables and indices and, in general, a good agreement is seen in the occurrence of droughts (and heat waves). Streamflow droughts in the years 1962-65, 1976, 1983, 1992-1995 and 2003 correspond for example well with years of extreme high temperatures (Section 3.3). However, there are some deviations; for instance, the streamflow drought of 1989-90 is not identified as a period with extreme high temperatures. It can further be concluded that drought likely has become more frequent in the latter part of the 20th century, partly enhanced by higher temperatures. It should be noted, however, that the comparison across variables is hampered by the different methodologies applied, records included and periods covered in each study. Further studies are thus needed to better understand the links between droughts in different hydrometeorological variables, including the development of heat waves.

The occurrence of major droughts before the 20th century is supported by studies using reconstructed time series based on proxy data (tree-rings, sediments etc.) and model simulation of SST-forced climate variations (Section 3.2). Tree-ring based reconstructed time series of drought (PDSI) for Morocco and precipitation series for Scotland dating back nearly 1000 years, found the Medieval Climate Anomaly (MCA; ~800-1300) to be the most recent pre-industrial warm period in Europe (Trouet *et al.*, 2009). Brewer *et al.* (2007) studied historical droughts in the Mediterranean using tree-ring based PDSI reconstruction dating 500 years back (1500-1999) and fount drier periods in the mid 19th century, last part of the 18th century and mid 17th century. These and other studies point to the importance of using time series dating back in time to gain a better understanding of decadal and millennial natural variability and drought causing mechanisms, particular for larger scale, multi-year events. This is further emphasised by recent studies from outside Europe. In West Africa reconstructed records of hydrological variability (from sediment records) demonstrated that severe droughts in recent decades were not anomalous in the context of the past three millennia (Shanahan *et al.*, 2009). A grid of summer PDSI reconstructions for North America revealed the occurrence of past "mega droughts" that clearly exceed any found in the instrumental records since 1850 (Cook *et al.*, 2007). Their extraordinary severity and duration was difficult to explain, but climate model simulations pointed to the importance of tropical Pacific Ocean SSTs in determining the precipitation amount over large parts of North America.

In a recent Canadian study of the extreme 2001 and 2002 drought events, it was concluded that "…the scientific understanding of the driving forces behind such massive droughts may be less solid than expected, and further complicated by climate change factors" (Wheaton *et al.*, 2005). It is further stated that additional research is needed to address the complexities of several factors influencing the climate drivers of drought development, like large-area soil moisture patterns, vegetation, albedo and atmospheric dust interactions. This is supported by recent studies showing that long-term vegetation dynamics and human induced land use changes can interact with the climate system on decadal to centennial time scales (Claussen *et al.*, 2004; Pielke, 2005). For example, Deo *et al.*, (2009) showed that clearing of native vegetation in eastern Australia may have a significant effect on climate extremes including the duration and severity of droughts.

Further, increased air pollution and dust may create global dimming (and thus reduced solar radiation) as observed since the 1950s, but also longer dry periods as dimming may disrupt the pattern of global precipitation. An important question thus remains as to what extend we can use instrumental records and reconstructed time series to predict drought occurrence in a changing climate.

4. Land: hydrological/land surface responses

Drought develops due to a larger than normal precipitation deficit over a large area and for an extensive period and may affect all components of the hydrological cycle. A precipitation deficit causes shortage of soil moisture, groundwater and surface water (this is called drought propagation) and subsequently reduces water availability for agriculture, hydropower, water supply, industry and ecosystems. Understanding how a water deficiency propagates through the hydrological system and its feedbacks to the atmosphere is crucial to support drought mitigation and adaptation plans. Moreover, it is the basis for hydrological drought early warning and forecasting. This chapter deals with the temporal and spatial aspects of drought propagation through the hydrological cycle. It closes with feedbacks in the land-atmosphere system, which may impact seasonal to interannual climate variability and thus drought development.

4.1. Key challenges

There is need for:

- a generic framework that translates meteorological drought into a hydrological drought based upon drought propagation across various spatial scales, from continental scale studies to the river basin that considers the land surface characteristics (in particular storages characteristics, e.g. soils, aquifers, lakes) and the hydro-climatic regime. It should include both drought development and recovery, incl. multi-year events. The crucial hydro(climato)logical processes and land surface should be identified resulting in a tailored drought assessment for each region. Process studies and modeling studies in usually less-affected headwater basins can increase understanding;
- better understanding and characterization of the spatial and temporal characteristics of drought at the regional and global scale for both the past and future. This should include the extent of the event, the variability within the affected area, the dynamics of the drought and possible links to large-scale climate drivers (Chapter 2);
- improving understanding of: (i) the role of feedbacks from (slowly varying) soil moisture to atmospheric variables, which is important for the development of large-scale / continental drought events, (ii) feedbacks associated with varying seasonal snow cover and snow accumulation on subsequent drought events, (iii) feedbacks from irrigation, and (iv) ecosystem/vegetation feedback (e.g. change of land cover, soil hydraulic properties, evapotranspiration) on the development of drought.

4.2. Propagation of drought

The primary climatic driver for a drought usually is a dry anomaly of precipitation that propagates through the hydrological system. The usually increased solar radiation leaves an additional signature through the soil water state, as it is controlling evapotranspiration. Due to their storage capacity, soil, groundwater and other stores (e.g. bogs, lakes) of the hydrological system serve as interconnected low-pass filters, adding memory (*lag-time*) and decreasing the frequency (*attenuation*) in the responding components as illustrated in Figurer 2 (Changnon, 1987; Eltahir & Yeh, 1999).

Lag-time and *attenuation* will vary for each catchment. They are controlled by the contribution of fast components with small storage capacity (e.g. overland flow, quick shallow saturated subsurface flow) and slow components with large storage capacity (e.g. deep groundwater systems). In catchments with a considerable contribution of fast reacting components, droughts occur more frequently and are of a shorter duration than in catchments with slow reacting components (van Lanen *et al.*, 2004). However, these catchments also recover more quickly when precipitation increase again.

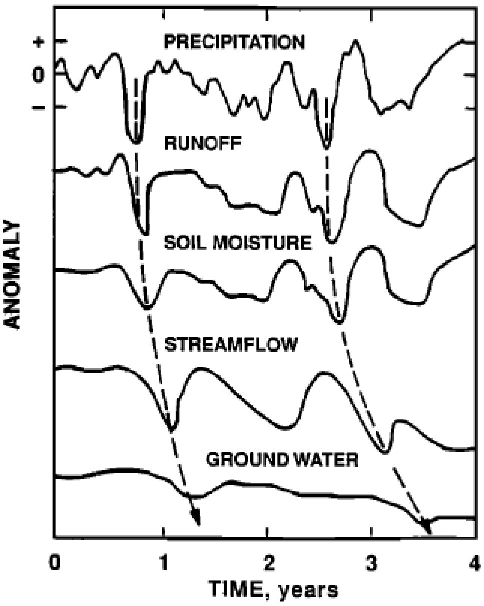

Figure 2. Illustration of drought anomaly propagation through the hydrological system (from Changnon, 1987)

Changnon (1987) and Eltahir & Yeh (1999) were the first papers that pointed at the phenomenon of drought propagation. Peters *et al.* (2003) investigated systematically the propagation of a meteorological drought through a groundwater-influenced system. They found responding decreased soil water content, decreased recharge to the groundwater, lower groundwater levels and decreased discharge. Using the *threshold level approach*[5] for drought characterization (Yevjevech, 1967), they showed that due to the combined effect of delay and attenuation, drought *deficit volume* and drought frequency decrease and drought duration increases while propagating through the groundwater system (aquifers and aquitards). Increased drought duration may lead to multiyear droughts. The effect is stronger for groundwater systems with lower transmissivity, higher storativity or longer distances between streams. Direct consequences of *groundwater drought* are decrease in groundwater flow to riparian areas, springs and streams. Groundwater drought may

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[5] Selection of the threshold should be linked to the impacts of drought, e.g. environmental flows, phenological development of vegetation / crops.

also affect the capillary rise to natural vegetation and crops. In (semi-)arid regions groundwater drought is particularly important because streams often have an ephemeral nature.

In addition to the land surface characteristics of the river basin, which includes land use / land cover and might change over time, climatologic conditions have an important effect on drought characteristics. Large differences of drought duration and drought deficit volumes are observed between regions with different hydro-climatology (van Lanen & Tallaksen, 2007; 2008). Also, the timing of a meteorological drought affects hydrological drought development. For example, reduced precipitation in a dry season influences soil moisture depletion but not recharge (which is assumed to be zero during a dry season). The low soil moisture content might be replenished in the subsequent wet season, whereas reduced precipitation in a wet season may lead to a serious hydrological drought in the subsequent dry season.

Next to soil and groundwater, lakes and wetlands play an important role for *hydrological drought* propagation as they reduce streamflow runoff variation and maintain base flow (Smakhtin, 2001; van Lanen *et al.*, 2004). In addition, glaciers and snow serve as water storages. The dynamics of their melting water releases, driven by temperature differences and the seasonal cycle in solar radiance results in modified runoff variation (Smakhtin, 2001; Jansson *et al.* 2006). Inter-annual temperature variation, however, may cause shifts in snowmelt period and/or snow depth increasing or decreasing the probability of hydrological droughts.

Process studies and associated hydrological modeling in generally less-affected river basins may contribute to knowledge about drought propagation in different hydro-climatic regions. For example, remote sensing, high-resolution geo-sensors and hydrochemistry, incl. tracers are applied to investigate fast and slow components. Knowledge from natural systems can be transferred to catchments with human influences to study development and recovery of drought in these systems.

4.3. Temporal and spatial patterns of drought

Meteorological droughts usually cover large areas of land and last for a considerable time. The duration of a major meteorological drought depends on the hydroclimatic region. In humid regions, a major meteorological drought may last a few months, whereas in climate types with a higher variability it may last almost a whole season or even more than a year (Section 3.2). However, both the timescale and the spatial scale change while a meteorological drought propagates through the hydrological system (Tallaksen *et al.*, 2009). At a regional scale, for example, the different response times of catchments are an important reason for spatial variability of drought. At a smaller (catchment) scale, spatially variable soil hydrologic processes and land-use cause spatial variability of evapotranspiration and subsequently, of soil moisture content and of groundwater recharge. Additional spatial variation is introduced due to groundwater flow processes as droughts are more attenuated the farther they are from the stream (Peters *et al.*, 2006).

The space-time development and recovery of drought addresses the whole range of spatial and temporal scales (catchment to globe and month to multi-year). The space-time characteristics of a drought can be analyzed in several ways depending on the purpose of the study and data available. Often a distinction is made between (i) the analysis of spatial patterns of at-site drought indices by displaying results on maps as point values or isolines, and (ii) the derivation of regional and catchment scale drought characteristics where the area covered is incorporated in the characterization of the event, e.g. the total deficit over the region. In both cases, the results can be derived for a given time (e.g. at the time of maximum extent) or as a development over time. The importance of including the area covered as an important characteristic of major drought events has recently been highlighted by several authors (Sheffield & Wood, 2007; Osti *et al.*, 2008; Tallaksen *et al.*, 2009).

Hisdal & Tallaksen (2003) estimated regional meteorological and hydrological drought characteristics based on interpolated, gridded values of precipitation and streamflow for Denmark. A comparison of the drought characteristics showed that streamflow droughts are less homogeneous over the region, less frequent and last for longer time periods than precipitation droughts. Similar results have been found for catchment scale studies that are based on data derived from physically based distributed models. The use of model output allows estimating drought characteristics in different variables across the hydrological cycle, e.g. recharge, groundwater levels and discharge (Peters *et al.*, 2003; Tallaksen *et al.*, 2009). Based on simulated data for a small catchment in the UK, Tallaksen *et al.* (2009) found that a drought in rainfall frequently covers the whole catchment and lasts for a short time (1-2 months), whereas droughts in recharge and hydraulic head typically cover a smaller area and last longer (4-5 months). The results originate from a case study in the Pang catchment, which is of a scale smaller than the region influenced by a meteorological drought. The authors recommended not using the area covered by a drought alone as a measure of drought severity at the catchment scale, but rather in combination with other drought characteristics like duration and deficit volume. Regional drought characteristics are important for catchment management plans (i.e. Water Framework Directive). These also need to include a possible lateral propagation of droughts from upstream to downstream.

As the drought recovers, a spatially extensive hydrological drought may collapse into smaller patches of drought (Andreadis *et al.*, 2005). Some of these drought patches can be very persistent and may sustain for multiple years, whereas other patches may recover much more quickly.

Large scale droughts at the land surface are commonly investigated using a gridded land surface hydrological model or global hydrological model that simulates soil moisture and runoff continuously in space and time. Andreadis *et al.* (2005) identified major drought events (1920-2003) in the US based on their severity, areal extent and duration using the macroscopic hydrological model VIC forced by gridded precipitation and temperature data. Sheffield & Wood (2007) similarly used the VIC model to derive a monthly soil moisture drought index at the global scale (1950-2000) and found in general a good agreement with the PDSI for major events at the global scale. However, deviations were found in cooler regions and seasons (Wang *et al.*, 2009).

In all modeling studies, drought characteristics (e.g. severity and extent) are calculated using simulated data and are thus limited by uncertainties inherent in the model structure and parameters as well as in the input data. Irrespective of scale, it is thus important to validate model simulations for historical events using a wide range of variables and data sources.

4.4. Land surface feedbacks

The role of land-surface-atmosphere interactions (incl. terrestrial hydrological processes, vegetation and seasonal snow cover feedbacks) in controlling weather and climate is increasingly recognized (Seneviratne & Stockli, 2008). Similar to ocean-atmosphere interactions, land surfaces provide the lower boundary of the atmosphere, with which energy and water are exchanged. In addition, the storages of water on land provide a memory component within the climate system.

Several positive regional land surface feedbacks may amplify dry weather and summer high temperatures (Zampieri *et al.*, 2009) especially in transitional regions between wet and dry climates, where evapotranspiration is limited by (temporally variable) soil moisture availability. As drier soils are established they may strengthened the warming through two main feedback mechanisms: higher sensible heat emissions and favored upper-air anticyclonic circulation. A dry soil induces fewer clouds, which in turn increases the amount of incident solar energy at the surface, and further enhances heat fluxes and the ratio of sensible over latent heat fluxes (Bowen ratio). This causes a positive feedback to soil drying as introduced in Section 3.4. This positive feedback to soil drying may lead to a decrease in precipitation recycling and evapotranspiration as a mechanism for drought development and persistence. In (semi-)arid areas the (change of) the ratio bare soil / vegetated surfaces affects the feedback to the atmosphere. Under future climate conditions the regions that are strongly controlled by soil moisture variability (and thus land surface feedbacks) are expected to shift northwards from the Mediterranean region to Central and Eastern Europe.

Groundwater storage exerts additional controls on climate; through capillary rise, shallow groundwater is observed to be an important component that controls the susceptibility of regions to changes in precipitation or temperature. Understanding the effect of groundwater and associated soil moisture on the energy partitioning over sensible and latent heat fluxes may be a key step towards improved understanding of the development of droughts (Maxwell & Kollet, 2008).

Another important terrestrial feedback is the positive feedback of snow cover towards climate variability. I.e. a retreat of snow cover in spring reduces the surface albedo and subsequently increases the net incoming short wave radiation. This in turn rises near surface temperature and increases the snowmelt. Although in Europe a correlation is observed between snow cover and land surface temperatures (Shongwe *et al.*, 2007), it is still not well understood how this interacts with the spatial and temporal development of drought.

Climate models (Sections 5.3 and 5.5) acknowledge the role of the land surface –atmosphere interaction by using so-called Land Surface Schemes (LSS) that simulate the partitioning of precipitation over evapotranspiration, storage and runoff and the partitioning of the radiant energy over sensible and latent heat fluxes. Although the representation of land surface hydrology has improved by further developing the LSS, especially the large size of the grid prohibits the proper simulation of land atmosphere interactions and feedbacks. In addition, LSSs appear to be simplified as compared to hydrological models (e.g. Gedney & Cox, 2003). They only allow for vertical transport processes and do not include physically based lateral surface and subsurface flow (Maxwell & Kollet, 2008; Wipfler *et al.*, in prep.).

5. Drought assessment framework: interactions and global change

A framework, which combines observed and simulated data from both the climate system and hydrological system, is required to assess the (future) impact of natural and human influences on drought frequency and severity (meteorological and hydrological drought). The approach includes the following main lines: (i) detection of changes (e.g. trends) in time series of observed hydrometeorological data (e.g. precipitation, streamflow) or, in time series of simulated data, in case the variable is difficult to measure or under sampled (e.g. soil moisture, evapotranspiration), (ii) drought modeling: new model developments and evaluation, (iii) attribution of changes in historical drought frequency and severity, i.e. the investigation of the dominant mechanisms (natural and/or human influences) responsible for the detected changes, (iv) assessment of future changes, which require linking and coupling of climate and hydrological models, and (v) analysis of uncertainty in detection, attribution and projections.

The main lines are highly interconnected. The detection of changes in hydrometeorological data and identifying their possible main causes help to improve climatic and hydrological models and are necessary steps to assess the impact of global change on drought and to quantitatively evaluate uncertainty. The drought assessment framework should be applicable at different scales to investigate meteorological and hydrological drought over a wide range of catchments, covering large areas that represent different climate conditions, land surface characteristics, level and type of human intervention (from natural to heavily exploited catchments). This might likely also helps to explain the apparently contradicting results that are regularly reported in the literature on the positive (frequent and/or less severe) and negative (more frequent and/or more severe) impacts of human and natural influences on droughts (van Lanen *et al.*, 2004).

5.1. Key challenges

There is a need for a:

- combined at-site and regional analyses for consistency in trend detection (i.e. consensus fails for one standard technique of investigating stationarity and detecting trends in time series of hydrometeorological data). It should also take in groundwater rather than only streamflow The combined analysis must account for temporal and spatial correlations of the natural phenomenon, which is expected to give more consistency to the highly variable, and in certain cases apparently contradictory, results obtained from individual at-site analyses;
- more consistent approach to attribute most likely causes for the detected change in drought. Increase of understanding of drought-generating mechanism is prerequisite and it should include the analyses of time series of both observed and simulated hydrometeorological variables using a suite of statistical methods and physically-based climate and hydrological models;
- development of global, high resolution, integrated climate-hydrological models (Earth System models) with a fully two-way coupling that support the drought assessment approach. Land Surface Schemes (LSSs) used by these models need to be improved: (i) to better reflect local

scale land characteristics (e.g. soil, land use / vegetation cover, snow, shallow groundwater) and the spatially varying interaction between hydrological processes (including soil water storage, groundwater dynamics and snow cover dynamics) and atmospheric processes, (ii) to better address the link between the energy and the water balance ensuring that heat waves associated to large-scale drought can be better predicted, and (iii) to better simulate low streamflow through hydrological modules. In the long run, Earth System models should replace the coarse- scale online approaches (e.g. GCMs and RCMs) or the offline approaches (e.g. LSHMs, GHMs, RBHMs forced by the outcome from climate models);

- joint effort by the climate and hydrological communities at short term to improve the offline approach for drought assessment through the development of methodologies to downscale and correct the bias from the large-scale climate models to obtain time series of climate forcing data that are useful for prediction of dry extremes and include all relevant uncertainties. Non-stationarity of downscaling relationships and cross-correlations (e.g. precipitation, temperature, humidity) need to be considered in the bias correction;
- a consistent approach that quantifies the propagation of uncertainties in the chain climate models, hydrological models and subsequent drought analysis tools needs to be further developed based upon sound process knowledge. This should consider: (i) observed data, model structure and parameter uncertainties, (ii) drought identification and characterization tools, (iii) identification of restricted sets of ensemble members that still adequately addresses climate variability and keep the number of ensemble members manageable for drought prediction and forecasting, while using a-priori expert knowledge and likelihoods, (iv) further development of the Hydrological Ensemble Prediction Experiment (HEPEX) with a wider focus on changes in climate and hydrological variability also focusing on low flows and droughts, and (v) objectification and quantification of uncertainty in the proposed combined at-site and regional analyses for trend detection in time series of hydrometeorological data.

5.2. Detection of changes in historical drought frequency and severity

A variety of data analysis methods (temporal and spatial) have been used to study changes in drought as a result of climate variability (incl. intra-year, inter-year, long-term oscillations) and global change. Methods and approaches for detecting changes (trends) in time series of hydrometeorological data can be found in the literature (e.g. Kundzewicz & Robson, 2000; 2004). Changes and their probability to occur are evaluated on the basis of long-term data The data include time series of observed hydrometeorological data (Section 2.2) and simulated data which may come from a suite of models (e.g. GCMs, RCMs, GHMs and river basin hydrological models, see also Section 5.5). The magnitude and direction of changes are usually drawn from frequency analyses and statistical tests developed to evaluate non-stationarity at local and regional levels. The choice of one specific test and its parameters depends on the properties of the studied series: its expected distribution, sample size, autocorrelation, and the expected type of change to be detected, i.e., a statistical trend, jumps or sudden changes (e.g. Lang *et al.*, 2006). Long periods of record are necessary to avoid misinterpreting a signal of decadal climate variability as a long-term trend (natural variability and fluctuations of the physical phenomena are high). The great sensitivity of low streamflow to measurement errors, the short length of time series available for a robust statistical trend assessment, the lack of consistent regional data for the *detection* of spatial patterns and trends, the strong autocorrelation, all of them pose challenges towards trend detection in climate and hydrological data records. In the particular case of droughts, which usually are characterized by mixed populations of minor droughts and long lasting events, high time-dependency in records and time series affected by seasonal effects, attention must be paid to the sampling of enough independent events for the statistical analyses (e.g. Tallaksen *et al.*, 1997; Engeland *et al.*, 2004). In addition, one must also check for homogeneity in the individual at-site records. Changes in monitoring procedures, conversion of records or relocation of the observation site create artificial changes. These effects are even more striking when considering extreme events as droughts. A reliable assessment of changes in drought across Europe can only be done if data can be retrieved from a high-quality EU database (Chapter 2). It requires long, temporally consistent and spatially-continuous records Hydrological models (physically- or conceptually-based rainfall-runoff models) may help to improve trend analysis as they allow for the performance of resampling techniques and distribution-free tests to detect gradual changes in the hydrological behavior of catchments (Andreassian *et al.*, 2003).

State-of-the art studies on the detection of changes in historic climatic variables indicate a clear global warming and point out that recent climate change is very likely attributed to human activity (see also Section 5.4). As stated in the IPCC-AR4, “warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average see level" (Trenberth *et al.*, 2007). Observed changes indicate increased soil moisture stress during hotter and drier summers in Northern Europe and a decrease in seasonal snow cover (at lower elevations) in the Alps (Bates *et al.*, 2008). Global observation-driven simulations of soil moisture have indeed shown a switch since the 1970s to a drying trend, especially in high northern latitudes (Sheffield & Wood, 2008a). They also analyzed drought occurrence at the global scale for the 1950-2000 period using simulated soil moisture data from a land-surface model driven by an observation-based meteorological dataset (Sheffield & Wood, 2007). They showed that short-term meteorological droughts (less than 6 months) are prevalent in the tropics and mid-latitudes, while medium-term meteorological droughts (7–12 months) are more frequent in mid- to high-latitudes and long-term droughts (longer than 12 months) are generally restricted to sub-Saharan Africa and higher northern latitudes. Climate change appears to most detectable in cold season processes which may impact drought occurrence, e.g. reduced snow pack, earlier snow melt, glacier retreat eventually leading to higher probability on summer drought.

Trend studies at the catchment or national scale are seldom comparable across space and time as they use different variables, time periods and methodologies. This is partly overcome by the approach used by Hisdal *et al.* (2001) in a Pan-European study that investigated streamflow drought. In their study they showed that although there were no significant changes for most gauging stations in Europe in the period 1962-1990, distinct regional differences could be detected: trends are observed towards more severe droughts in Spain, the western part of Eastern Europe, and in large parts of the UK, whereas trends towards less severe droughts were observed in large parts of Central Europe. In a recent pan-European study Stahl *et al.* (2008a; 2008b) show that in particular the timing of low streamflow has changed in some regions. Regional analyses can thus contribute to the detection of spatial patterns of changes for improved management at regional level.

5.3. Drought modeling: new model developments and evaluation

One important line towards the prediction of meteorological drought is the use of large-scale coupled Ocean Atmosphere General Circulation Models (OA-GCMs or GCMs) (van den Hurk & Jacob, 2009). GCMs and global climate models are widely applied for weather forecasting, understanding the climate, and projecting climate change. This section is restricted to prediction at the decadal (near future) and centennial scale. The prediction at the monthly and seasonal scale at a specific future time (i.e. forecasting) is described in Section 6.3. GCMs simulate a range of different weather variables such as air pressure, temperature, precipitation and wind speed. All GCMs use basically the same physical relations but differ in parameterization, especially in the way feedback mechanisms from ocean and land surface processes are modeled. Different institutes around the globe and in Europe have developed their own GCMs. GCM predictions typically use at a spatial resolution of 100-200 km and are subject to large uncertainties. GCMs are important tools for studying the impact of higher greenhouse gas concentrations on hydrological regimes and extremes (e.g. drought) over medium-range timescales (e.g. Bates *et al.*, 2008), but suffer from some weaknesses (Section 5.5).

A global, high resolution, integrated climate-hydrological model (i.e. two-way coupling) would be the ideal tool to investigate drought, i.e. (i) influence of climate drivers on different types of droughts, (ii) response of the land surface, incl. the development and recovery of soil water and hydrological droughts, feedbacks land-atmosphere, (iii) support the detection-attribution process, and (iv) assess the impact of human influences (e.g. global change) on drought. Although, the global scientific community is working on it, such Earth System model will not exist at short term. The model needs, for instance, an integration of the dynamic atmospheric physics and chemistry, incl. aerosols, ocean physics, chemistry and biology, land and terrestrial ecosystem processes. In Europe, an important initiative is the development of EC-EARTH. EC-EARTH is the name of an Earth system model that is being developed by a number of institutes in Europe. It is based on the Integrated Forecast System of the European Centre for Medium Range Weather Forecasts (ECWMF)[6]. Scientists still have to compromise with complexity and realism.

The module that simulates the interaction of land-hydrosphere-biosphere processes at the proper temporal and spatial scales (i.e. river basin scale) is, especially, important for the assessment of drought. It needs a good representation of the land use / vegetation cover, soils, groundwater and surface water. Such a module at the right spatial scale, which is integrated in an Earth System model does not exist yet. As an alternative for the high resolution, integrated climate-hydrological model, coarse-scale integrated models and off-line approaches are being used to assess drought (Section 5.5).

New integrated models or revised models that are used for drought assessment should be evaluated on their ability to simulate time series of daily hydrometeorological fluxes and state variables (e.g. precipitation, rain, snow water equivalent, temperature, evapotranspiration, soil water storage, groundwater storage, streamflow) at a rather detailed spatial scale (e.g. 1 km grid). Models should generate reliable precipitation, for instance, number of drizzle days, consecutive dry days, timing of precipitation events for a correct onset and start of the recovery. Clearly, the models need to have a higher reliability in the low range for soil water, groundwater and surface water. When developing new or revised models people need to realize that the current generation

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[6] http://www.ecmwf.int/about/special_projects/hazeleger_EC_EARTH/index.html

of hydrological models, although they already have a long history, is still insufficiently capable to simulate low streamflow. Models need to be evaluated on their skills to capture drought propagation (conversion from meteorological into hydrological droughts, Section 4.2). Multi-model analyses are widely applied to assess a possible range of droughts, especially for future drought. These intercomparison studies are only appropriate if a particular model variable (e.g. soil moisture storage) has the same meaning amongst all models. Good descriptions of model structures, model concepts, parameters to be tuned, model variables are a prerequisite in this context.

5.4. Attribution of changes in historical drought frequency and severity

Attribution studies try to establish the most likely causes for the detected change in drought with some defined level of confidence. It has strong links with detection studies (Section 5.2). It requires understanding of the mechanism causing drought (e.g. climate processes, hydrological processes, human influences). Climate-hydrological modeling plays a crucial role in attribution studies.

The assessment of the impacts of global change warming on the hydrological regime of a specific catchment is not straightforward and high uncertainties remain. A recent study using monthly streamflow data from 1948-2004 and 925 largest ocean-reaching rivers in the world, revealed large interannual to decadal variations in most of the analyzed time series (Dai *et al.*, 2009). Statistically significant trends were found in only one third of the 200 top rivers, with 45 rivers with negative trends and 19 with positive trends. Precipitation (i.e. natural climate variability and climate change) was the major driver for the discharges trends and variations. Results also showed that the direct effects of human activities (besides through human-induced climate change) on yearly streamflow were likely to be small, comparatively to the effects of climate variations during the studied period. Especially for rivers with low streamflow, impacts of human activities are considered to prevail over changes in precipitation. Human impacts on hydrological drought are mostly studied by investigating their effect on streamflow, while studies on groundwater drought are still very limited (e.g. Lanen *et al.*, 2004).

Climate variability and human influences pose challenges to the detection of changes in hydrological time series (Section 5.2) and the need to distinguish between natural and anthropogenic causes of changes. There are many human influences that can have an impact on hydrological droughts, for example, human-induced climate change, land use change, abstractions from both groundwater and surface water, urbanization, dams, river regulation, land drainage, reclamation of peatland and riparian areas, etc. If frequency or severity of droughts has been changed, then, in almost all cases, more than one human influence might have caused it, which makes it hard to unravel the effect of individual causes based only upon observed time series of soil moisture, groundwater levels or streamflow only (e.g. van Lanen *et al.*, 2004; 2007). The attribution of changes and the detection of trends in several historical hydrometeorological variables related should be examined in the various compartments of the hydrological cycle. Changes in precipitation or evapotranspiration could occur as a result of climate change and, consequently, induce changes in runoff time series and may also feed back towards the atmospheric processes. Surface or groundwater flows can also be impacted by changes in the catchment hydrological behavior due to changes in land use (e.g. deforestation), water management (e.g. river regulation, dams) or land occupation (e.g. urbanization).

5.5. Assessment of future changes: linking and coupling of climate and hydrological models

The drought assessment approach based on observations and modeling (Sections 5.2 - 5.4) to detect changes in meteorological and hydrological droughts and to attribute these to different natural and human-influenced causes is a prerequisite to develop the approach further to assess future changes in drought. As mentioned in Section 5.3, one important line towards the prediction of meteorological drought is the use of large-scale coupled Ocean Atmosphere General Circulation Models (OA-GCMs or GCMs). These models produce projections.

GCMs are used in two ways to evaluate the effect of climate change on hydrological extremes and water resources: (i) *online approach*: the climatology, in particular, the climate variability, is directly derived from the GCM output, and (ii) *offline approach*: the effect is studied through Land Surface Hydrological Models (LSHMs) or hydrological models, which use the climate output as driver. Different types of hydrological models are applied, e.g. Global Hydrological Models (GHMs) and more detailed River Basin Hydrological Models (RBHMs). The GHMs cover the globe or a continent, whereas the RBHMs are limited to a river basin. Important to note is that these hydrological models are run in an offline mode, which implies that hydrological feedbacks (Sections 3.4 and 4.4) towards the atmosphere (two-way coupling) are not considered.

Actually, GCMs were not designed for hydrological assessment studies. The use of climate model outputs as drivers for hydrological models (offline approach)is therefore not straightforward. GCMs act on a coarser scale than hydrological models, and still have difficulties to produce reliable time series of predicted climate variables (i.e. climate forcing data) that can be used as a driver for hydrological models. Using multiple simulations (ensembles) enables the quantification of some uncertainties in climate model output (Section 5.6).

Since there exists a considerable *bias* between observed data and model prediction through GCMs, particularly for hydrological important atmospheric variables such as precipitation and temperature, future GCM projections cannot directly be used as input for hydrological models. Climate models tend to overestimate land-atmospheric coupling leading to overestimation of precipitation recycling. Some kind of bias correction of the climate data is needed. Usually, GCM output is used to derive differences in climate variables (i.e. precipitation, temperature). Based on these differences, historical dataset are adapted and time series for the future are constructed (perturbated time series of forcing data). Clearly, to assess the effect of climate change on the frequency and severity of droughts, appropriate time-series are needed that correctly reproduce the frequencies of extremes (see e.g. Wood *et al.*, 2002).

The coarse scale of GCMs prohibits a proper simulation of spatially heterogeneous local land atmosphere interactions (e.g. processes modeling through spatially variable soils and land-use) and of the feedbacks between climate and the hydrological cycle. GCM's resolution needs to be improved to discern e.g. topographic dependent processes such as snow pack and snow-albedo feedback. To overcome this deficiency, the climate and hydrological communities have put considerable effort to develop techniques to bridge this resolution gap and to downscale climate forcings with a spatial resolution of approx. 100-200 km to the smaller scales of catchments (grid size approx. 1 km). Downscaling needs to be appropriate to the region and application (e.g. downscaling of extremes as well mean quantities). Two different downscaling methods are currently widely used: statistical and dynamical downscaling techniques. For a recent overview of downscaling methods, see Fowler *et al.* (2007).

Statistical downscaling techniques use a relation between large-scale phenomena, which are well represented in GCMs, and observed local quantities like daily precipitation or temperature. This relation is subsequently applied to the GCM output to obtain local and regional climate change signals. The advantage of this method is that series of climate variables can be obtained for a particular location (e.g. meteorological station). Therefore, using these statistical tools, the same analyses can be applied to future and historical droughts, implicitly assuming unchanged relationships (stationarity) under future climate conditions (Jacob & van den Hurk, 2009). Recent research also showed that precipitation and temperature should not be independently downscaled (Boberg *et al.*, 2009).

A more physically based downscaling method, also referred to as dynamical downscaling, is the use of high-resolution regional climate models (RCMs) nested into GCMs. These models add detailed information on land use, coastlines, topographical structures and better-resolved spatial gradients in physical fields. GCM large-scale boundary conditions are used to constrain the RCM simulation. The use of RCMs allows for an improved representation of local feedback processes such as snow-albedo/temperature or soil moisture/temperature feedbacks (Jacob & van den Hurk 2009). These local feedbacks may be important for drought development (see also Section 4.4). The major disadvantage of RCMs is their large demand on computer resources and the complexity of their operation (e.g. Wilby *et al.*, 2006).

In some studies, a combination of dynamical and statistical downscaling is applied. First, the GCMs outcome is used as a boundary condition for the nested RCM and then the RCM's outcome is statistically downscaled using observed hydrometeorological observations from the regions.

Impact studies using global simulation outcomes from large-scale climate models show that it is very likely that droughts become more frequent, and that more hot days and heat waves are to occur over nearly all land areas. Although climate model projections indicate an increase of the global amount of precipitation, changes will not be equal across the globe. In Europe, "the already hot and semi-arid climate of Southern Europe is expected to become still warmer and drier, threatening its waterways (…)" (Bates *et al.*, 2008). Projected changes point out the reinforcement of a north-south gradient with, in general, the mean annual precipitation increasing in northern Europe and decreasing further south. The areas to be most affected by a projected decrease in annual runoff are the Mediterranean Basin, Central and Eastern Europe. Mediterranean Europe are in fact likely to receive less precipitation, which, combined with higher temperatures, might increase the number and severity of droughts. From a study based on a GCM forced by data from different climate models, Lehner *et al.* (2006) showed that for Spain and Southeast Europe major droughts (i.e. droughts that have a return period of 100 year under the current climate) are likely to become more frequent. In association with projected higher demands of water for irrigation, these more vulnerable regions are most prone to an increase in drought risk and water scarcity problems. Under future global warming, the analysis of multimodel and multi-scenario simulations shows that the spatial extent of severe soil moisture deficits is expected to double by the end of the 21st century and that long-term droughts in soil moisture will likely become three times more common (Sheffield & Wood, 2008b).

High-resolution climate projections for 2071-2100 from a number of regional climate models were made available by the PRUDENCE project (2001-2004), a major European-scale project that aimed at addressing and reducing the deficiencies in regional climate projections in order to support EU policies for adapting and mitigating climate change impacts. Risk assessment of weather extremes showed that "the RCMs all predict earlier and longer droughts in the Mediterranean basin" (PRUDENCE, 2005). An analysis of water availability and demand during dry summers in the Alpine region, based on a climate model and a distributed hydrological model to simulate water balance, showed that although the results do not indicated serious water stress on regional level, local deficits may occur and average groundwater recharge reductions can have a large impact on water supply (Vanhan *et al.*, 2009). Another important EU-FP6 initiative is the ENSEMBLES project (2004-2009). The project develops an ensemble prediction system for climate change based on the principal state-of-the-art, high resolution, Global and Regional Earth System models developed in Europe. It produces a probabilistic estimate of uncertainty in future climate at the seasonal to decadal and longer timescales. The ongoing EU-FP6 integrated project WATCH (2007-2011) aims to quantify and predict the components of the current (20th C) and future global water cycles (21st C). An important component of WATCH is linking climate and hydrological models. Improvements on the knowledge of the effects of climate change on droughts are expected to be an important outcome of the project (van Lanen *et al.*, 2007).

Intense research efforts have been devoted to better assess changes in hydrological variables (e.g. groundwater, streamflow) (e.g. Tallaksen & Lanen, 2004; Demuth *et al.*, 2006; Lanen & Fendeková, 2008). The initiative FRIEND of the International Hydrological Program of UNESCO (Servat & Demuth, 2006) has fostered collaborative and multidisciplinary research on the impact of climate and human-induced changes on hydrology, aiming at policy supporting for improved land and water management, while providing links to other international initiatives on data collection and exchange (WMO-WHYCOS, GRDC, GEWEX).

Datasets are indispensable for the evaluation of the performance of climate models and hydrological models (see also Section 2.2). Re-Analyses of past observations (e.g. ERA40 from ECMWF or NCEP from NOAA), describing the state of the atmosphere and land and ocean-wave conditions can be useful together with the Global Runoff Dataset (GRDC), and the European Water Archive (EWA) (Stahl *et al.*, 2008b). Currently EWA contains long-term daily flow data and catchment information for more than 3700 river gauging stations in 29 countries. Data archived in the EWA have been supplied on a voluntary basis and free of charge by various data providers. However, it should be stressed that an improvement in climate modeling is dependent on ground truth data (i.e. hydrological data) to validate current GCMs and RCMs and further improve these. Availability of hydrological data is not obvious as stated in Section 2.1. Continuously updated hydrological databases are in this context vital as we want to constantly evaluate model simulations against observations.

5.6. Quantification of uncertainty

The drought assessment framework that combines observed and simulated climate and hydrological data, faces various sources of uncertainty. Not all observed hydrometeorological data are error-free (Section 2.2). For instance, it is a challenge to measure low streamflow and to quantify its uncertainties (e.g. Rees *et al.*, 2004). Time series of some variables are too short for drought analysis. Statistical tests (Section 5.2) to detect droughts handle uncertainties through evaluation of significance levels, although, for example, the choice of the test and the use of different time windows introduce uncertainties. The use of models (climate and hydrological) and drought analysis tools to assess historical and future droughts and to attribute causes (natural and human influences) are other main sources of uncertainties (Sections 5.3 – 5.5). Uncertainties in the climate – hydrological model chain are more elaborated below.

The current skills of climate models to predict droughts directly or to produce climate forcing data for hydrological models are limited (Sections 5.3 and 5.5). Hence, an important research interest for the long run is to improve understanding of the predictability of droughts and the ability of climate models to predict droughts at the medium-range and decadal timescale. Next to improving model prediction skills, however, a complementary approach at the shorter run may be to account explicitly for uncertainties associated with the projections of current climate models. Usually, this is done by creating probability distributions functions (PDFs) using multiple model simulations (ensembles) instead of e.g. scenarios or single valued projections. The ensemble approach allows additionally for the assessment of uncertainties in case of sequential; application of climate and hydrological models, hence also including the uncertainties associated with the hydrological system. Explicit uncertainty quantification using PDFs creates the opportunity to address and communicate climatological and hydrological variability and uncertainty in terms of risks. Subsequently, it enables the development of a risk-based decision-making framework to support drought management plans.

Until now, explicit uncertainty quantification is usually not considered in relation to drought and drought propagation. However, there have been various attempts to systematically quantify the cascade of uncertainties associated with climate variability and the subsequent propagation of the climate signal through the hydrological system. These attempts were related to either hydrological forecasting (e.g. Wood *et al.*, 2002; Jaun *et al.*, 2008) or climate change hydrological impacts (e.g. Mauer and Duffy, 2005; Wilby *et al.*, 2006; Wilby & Harris, 2006; New *et al.*, 2009; Murphy *et al.* 2007).

In order to quantify the known uncertainty, usually probability density distributions are constructed from an ensemble of simulations weighted by their estimated likelihoods. The chosen ensembles are constrained by selected observations and by expert-specified prior distributions (i.e. constrained ensemble). Although this is probably the best method available, the PDFs only represent the known and/or chosen range of uncertainty as incorporated in the variations in model simulations. In other words, the probabilistic outputs of ensemble climate predictions remain conditional upon the chosen emission scenarios, the climate models used in the (multi-) climate model runs and the statistical method used to compute probability distributions (Hall, 2007; New *et al.*, 2007).

Ensemble projections may account for various sources of uncertainty. Identified sources of uncertainty in climate projection are uncertainty in future greenhouse gas emissions, initial conditions (in Ocean, land and Ice masses), internal climate variability and the predictive capacity of the models. Uncertainty due to the predictive capacity of the model is probably most difficult to estimate. The approach of the IPCC (e.g. Bates *et al.*, 2008) and other studies is using a large range of different climate models (i.e. multi model ensemble). However, there are still processes and feedbacks that are not considered in any model. The multi model ensemble is strictly an ensemble of opportunities and it does not guarantee to span the full range of uncertainty. Therefore, the actual uncertainty is probably larger than the uncertainty predicted by a multi model ensemble.

At the catchment scale, additional output uncertainties of hydrological models (which are presented as a plume of hydrological ensembles with associated PDFs) are due to model structure uncertainty, uncertainties associated with initial conditions and boundary conditions, parameter uncertainty (identifiability problem), uncertainty in observed data that are used for calibration. In terms of model structure, most hydrological models tend have restricted potential in simulating low streamflow. These uncertainties add to the ones introduced by downscaling methods and bias correction (Wilby *et al.*, 2006; New *et al.*, 2007; Prudhomme & Davies, 2009; Kay *et al.*, 2009) and by not including feedbacks in a sequential climatological and hydrological modeling approach.

Drought characterization (e.g. drought duration or severity) adds supplementary uncertainty, in that drought characteristics are conditioned by the detection method (e.g. threshold approach, Sequent Peak Algorithm), the possible pooling method, the selection of threshold flux of state variables, and definitions of regional characteristics in case of space-time analysis (Sections 4.2 and 4.3).

While research dedicated to ensemble climate predictions have advanced rapidly, it remains a challenge to adapt the climate model outputs to reliable ensemble climate forcing data for hydrological models to understand and predict droughts. One of the main reasons is that ensemble climate prediction studies tend to be biased towards PDFs of average climate change (e.g. expected temperature change) whereas for droughts the focus should be on the climate variability, i.e. occurrences of extremes and multiple time series (i.e. time slices) are needed that reflect climate variability as input for hydrological models. Wang *et al.* (2009) report that multiple hydrologic models generally give the same average representation of drought (e.g. large events) but differ in the details: severity, area, duration can vary widely and so drought can develop quite differently. The Hydrological Ensemble Prediction Experiment (HEPEX) is in this respect an important and very active initiative that aims to improve hydrological probabilistic forecasting, including reliable uncertainty estimates (e.g. Schaake *et al.*, 2007). Although HEPEX appears to be especially focused to flood forecasting, also low flows and droughts are considered.

6. Methodologies for monitoring and forecasting

Adequate pro-active and re-active water management of river basins that supports the EU Water Framework Directive and management of natural hazards, need: (i) current information on the spatial and temporal development and recovery of an ongoing drought (i.e. monitoring), which usually has a transnational nature, (ii) reliable drought forecasting (monthly and (multi-)seasonal time scale). , and (iii) projections for future droughts (decadal, 2010-2030, are more important than the centennial time scale, 2070-2100). Key challenges identified in the previous chapters support management of droughts This chapter tries to apply the knowledge in early warning systems for droughts as a practical tool to proactively manage this natural hazard. Early warning comprises the two main aspects of monitoring and detection, as well as drought forecasting. The chapter begins with a brief overview of existing drought indices as the basis of and the main tool for drought monitoring, detection, prediction and forecasting. It is followed by a section on monthly and seasonal drought forecasting that is a logical extension of drought monitoring and often asked for, but difficult to achieve. The chapter concludes with a short overview of existing and evolving drought early warning systems that try to turn information on droughts from monitoring and forecasting into rapidly available and useful information for stakeholders, decision makers, and the public.

6.1. Key challenges

There is a need for:

- improved drought monitoring through: (i) establishment of science-based guidance on how to use and choose appropriate drought indices that considers existing drought indices for the application in different application domains, different spatial scales, rather than recommending single indices directly, (ii) new drought indices should have a combined and integrated nature (comprise information from different disciplines (water quantity and quality) and technologies (e.g. remote sensing) to depict drought in a more comprehensive way, (iii) identification of areal drought indices considering a range of spatial scales and hydro-climatological conditions and physical catchment structures, (iv) performance assessment of existing and newly derived drought indices against various climatic and hydrological conditions, and different scales;
- drought impact monitoring (e.g. media reports on state of aquatic ecosystems, crop yields, navigation) to verify monitoring and forecasting products;
- significantly improve probabilistic forecasting skills for seasonal droughts in Europe by: (i) taking better into account land-atmosphere feedbacks into numerical methods (see also Sections 3.4, 4.4, 5.3 and 5.5.), including the use of improved data assimilation techniques to better initialize the forecasting tools, e.g. land surface information, such as vegetation cover, soil moisture and snow, (ii) implementing ensemble-based probability information through multiple forecast models and multiple hydrologic models, (iii) benefitting from developments in neighboring disciplines, such as flood forecasting, (iv) investigating hindcasts to assess forecast skill, and (v) better understanding of the link between droughts, weather types, sea surface temperature patterns and these teleconnection patterns (e.g. NAO or ENSO, Sections 2.2 and 2.4);

- increased understanding of the possible link between seasonal forecasting of large-scale drought and heat waves (see also Section 3.4);
- improving existing and future Drought Early Warning systems through: (i) interconnection of existing and emerging early-warning systems from different regions and countries in Europe to allow for (inter-) comparison and provision of complementary neighbourhood information, and (ii) examining how to produce more user-friendly products (e.g. tailored, timely, understandable, affordable, more adequate indices, integrating information from different disciplines and sources).

6.2. Identification of drought indices

Drought indices are indispensible to detect, monitor, and evaluate drought events. Due to the multi-disciplinary character of droughts a single, unique and concise definition of a drought (Chapter 1) is hard to give. It is subject to the domain of interest of the user (e.g. Wilhite & Glantz, 1985; Tate & Gustard 2000 and Maracchi, 2000; Hisdal *et al.*, 2004). Drought indices essentially face the same problem; there is no concise accepted overall definition of a drought, there is no single and universal drought index.

Nevertheless there is a need to develop indices that can describe characteristics of drought events such as the start and end of a drought, drought length and severity. In order to compute these characteristics from drought indices, triggers and thresholds have to be defined that are necessarily specific to the nature of the index, but depend also on the subjective assessment of drought levels by the actor, e.g. water managers. Another example for a need for a drought index and applicable thresholds are formulated in Article 4.6 of the Water Framework Directive that postulates a clear definition of “severe droughts” that triggers certain legal consequences for the application of the Directive.

Besides drought indices, other observations can be and are also used as drought indicators in order to monitor components of the water balance and to detect possible drought events. Examples of these kinds of drought indicators are reservoir and lake water levels, spring flow, or groundwater levels. Opposite to drought indices, these indicators are not drought specific, but serve multiple purposes within the management of water resources.

Drought indices have been developed in the domains of meteorology, hydrology, agricultural research and application, remote sensing and water resources management. Accordingly, drought indices can be typically categorized in meteorological, hydrological, agricultural or remote sensing-based drought indices, with the Standardized Precipitation Index SPI (McKee *et al.* 1993), PDSI (Palmer, 1965), the Crop Moisture Index, CMI (Palmer, 1968), or the Vegetation Condition Index, VCI (Kogan, 1995) as respective prominent examples. In addition, two other categories have recently been described by Niemeyer (2008): (i) comprehensive drought indices that incorporate data from more than one discipline such as precipitation, soil water content and river discharge, and (ii) combined drought indices that aim to combine different drought indices and other indicators into a single figure. While the multivariate Aggregate Drought Index, ADI, proposed by Keyantash & Dracup (2004) represents the former category, the recently developed VegDRI index (Brown *et al.* 2008), which combines NDVI, SPI, and PDSI is a good example for a combined drought index.

Reviews and classifications of drought indices have been produced regularly during the last decades, among which: Heim (2000), Vogt & Somma (2000), Heim (2002) and Hayes *et al.* (2007). More than 80 drought indices have been recently described by Niemeyer (2008), who indicated that the actual total number is probably close to twice as high.

In addition to the above-mentioned indices that can be computed from at-site or gridded data, areal indices have also been proposed. These indices comprise information from different hydrometeorological variables (e.g. precipitation, groundwater recharge or levels) and take explicitly into account the space-time dependencies and structural properties of the variables involved. These indices produce information on, for instance, the proportion of gauging stations in drought (Regional Deficiency Index (RDI), Stahl & Demuth, 1999), the average area affected by a drought, the average deficit volume, or the average duration (Tallaksen *et al.*, 2006, Tallaksen *et al.*, 2009). Areal indices can also be combined to yield severity-area-frequency (SAF) curves (Hisdal & Tallaksen, 2003; Sheffield & Wood, 2007; Osti *et al.*, 2008) or similar severity-area-duration curves (Andreadis *et al.*, 2005; Andreadis & Lettemaier, 2006). SAF curves provide the probability of a drought of a given severity covering a certain fraction of the area.

The exploitation of new technologies that provide novel datasets and the application of new methodologies are important drivers to develop drought indices. Recently, besides areal indices, most progress has been made in the field of exploiting novel remote sensing information available. Some studies provide new indices on a yearly basis or even more frequently (e.g. Ghulam *et al.*, 2007). Not only the derivation of drought indices from single new sensors, but also the combination of different sensors will surely remain a wide field for research in this domain (e.g. Wang & Qu, 2007).

Drought observatories on the continental scale aim at applying drought indicators that produce a consistent image of the wetness state of the land surface over the entire area, and that use a consistent set of input data such as from remote sensing. Equally important are the local requirements of the practitioner. Both continental and local applications do not exclude each other, but will be complementary and will provide valuable insight into the phenomenon of droughts from different perspectives. Usually, the emphasis is put on reliability and robustness of the index, as well as on the availability of data to compute it. In practical applications such as operational drought monitoring systems, it is essentially a very limited handful of drought indices that is applied due to restricted data availability, as well as the fallback on and application of already proved methodologies. From the recent developments of agricultural drought indices it can be deduced that practitioners in this domain prefer to get hands-on indices that are simple to apply and as specific as possible to their crops. This tendency will probably be enforced by the increasing establishment of drought management plans in almost all parts of the world, mainly at the catchment scale. Here, specific and operational drought indices are required in order to define indicators, thresholds, and triggers for practical management of water resources in case of drought. These indices have to describe best the local and regional conditions of the hydrological cycle and comply with the already available data that are measured routinely (short term), or with more extended data (future monitoring need to be extended/adapted), if the indices improve drought characterization for the different purposes (long-term).

Common to all newly developed drought indices is the issue of performance assessment. Often, the new indices are compared to already established indices with good agreement, although the initial idea was to develop an index with a better performance. Furthermore, the exercise is mostly restricted to a few test cases in specific regions and periods. While there is clearly a need for targeted drought indices as mentioned before, it is equally important that the underlying assumptions and limitations, under which a new index has been developed and tested, are explicitly described. Frequently, the criteria to evaluate the performance of the drought index, which are certainly application dependent, are omitted or marginalized. For an external user, however, it is often more important to know about these assumptions of a new drought index than the choice of the index itself.

Instead of developing more new single-discipline drought indices, the integration into more comprehensive and integrative drought monitoring, detection and forecasting tools seems to be a more promising way forward. To this end, the combination of remote sensing-derived drought indices and those derived from climatic networks such as VegDRI, preferably in combination with a comprehensive soil moisture, groundwater and low-streamflow (space-time) analysis from (measured and/or simulated) hydrological data would be the most desirable way to paint a full picture of a drought situation.

In addition to the development of further drought indices, the obvious abundance of already existing drought indices should firstly lead to the development of a comprehensive intercomparison with clear indications of strengths and weaknesses of the existing indices. Secondly, there is a need for a framework and generic methodology to choose suitable indices for given purposes. Such a methodology would have to match needs to the characteristics of various indices, hence being a second step of the proposed intercomparison. Although such a framework would need to be used and applied with care, it could give a practitioner with given requirements a tool in his hand to facilitate his choice among the large quantity of existing indices.

6.3. Monthly and (multi-)seasonal drought forecasting

Seasonal forecasting tools

Especially during the last decade, seasonal forecasting tools[7] have rapidly emerged. Seasonal forecasts are particularly powerful in regions and seasons where there is large climate variability and a strong connection between slowly varying sea surface temperatures (SST) and other climate variables such as rainfall and temperature. Accordingly, seasonal forecasts are currently particularly useful in areas with a variable climate like monsoon climates or land areas in the (sub) tropical regions. These regions are also highly vulnerable to droughts. In areas with small variations in the seasonal climate like the mid-latitudes such as Europe or arid regions, there are considerably fewer opportunities to successfully use seasonal forecasts for long-term drought forecasting. In fact, today the skill of seasonal drought forecasts in Europe is rather poor (e.g. Palmer & Anderson 2006). An improved understanding of the linkage between droughts and global teleconnection patterns, however, could eventually lead to an improved seasonal forecasting of European droughts (Section 3.2). The recently proposed methodology of spatial coherence of historical droughts has also the potential to increase the skill of drought forecasting;

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[7] Prediction of drought for longer time scales (e.g. intermediate future or centennial scale) is described in Section 4.4.

it is based on the pattern of development of past drought events and the matching of the current situation to possible initial conditions of droughts in the past (Hannaford *et al.* 2009).

Seasonal forecasting tools do not aim at forecasting a specific drought or precipitation event, but rather at specifying the probability that the seasonal mean precipitation or air temperature is higher or lower than the climatological mean (van den Hurk & Jacob, 2009). This implies that the tools predict drought at the seasonal scale rather than forecast (i.e. do not provide information on drought for specific week or month ahead). The changes in precipitation and/or air temperature probabilities can then be used to predict meteorological droughts and next hydrological drought by feeding the climate information in hydrological models.

The existing seasonal forecasting tools can be roughly divided into two classes: statistical and numerical methods (Palmer & Anderson, 1994). Statistical methods use observed historical correlations between anomalies in for instance SST and regional weather patterns to make predictions for the future. The historical correlations are used to calculate the probability of anomalously high or low precipitation and to choose historical analogue years. Climate data from these analogue years can then be used as input for e.g. hydrological models to predict hydrological droughts (Ludwig, 2009). One of the assumptions of the statistical methods is stationarity, i.e. the historical correlation between SSTs and climate does not change (van den Hurk & Jacob, 2009).

Numerical methods are based on the use of large-scale GCMs. By using a number of model simulations (ensembles), it is possible to deal with the uncertainty introduced by the chaotic nature of the climate system (van den Hurk & Jacob, 2009) (see also Section 5.6). When using GCMs for seasonal climate prediction it is important to have proper information/data on the initial status of the ocean and the land. The quality of the projections strongly depends heavily on the availability of observations on the ocean and land status (particularly ocean temperatures and soil moisture), as these are used to constrain the evolution of the model forecasts. The produced ensembles include different initial conditions.

Nearly all studies on the use of seasonal climate forecasts in water management and agriculture focus on statistical methods based on the analogue-year approach (Ludwig, 2009). Historical climate records are divided into different types of years or seasons based on prevailing ocean and/or atmospheric conditions. In most cases, the analogue years are linked to the different phases of the El Niño Southern Oscillation (ENSO) or Pacific Decadal Oscillation (PDO) (Hamlet & Lettenmaier, 2000). Numerical methods for seasonal climate forecasts are still rarely used, e.g. hydrological models coupled with Regional Climate models (RCM). RCMs still have a significant bias in precipitation fields and usually need a statistical correction of their output (Ludwig, 2009).

Recently, experimental hydrological forecasting approaches have been developed to forecast streamflow on a seasonal timescale (e.g. Wood *et al.*, 2002) using downscaled GCM atmospheric forcing in a macroscale hydrological model. Although still under developmental, these approaches are promising for further develop the predictive capacity of hydro-climatological models for low flows and droughts.

Besides the advances on the research side, the dissemination and transfer of research results to operational meteorological services need to be considered. Currently, the application of seasonal forecasts in operational services throughout Europe is exceptional rather than an established standard. This is even truer when it comes to the application of long-term forecasts to droughts.

Sources of seasonal predictability

Both the statistical and numerical methods used for seasonal forecasting of meteorological drought rely on the same source of predictability. The major source of seasonal climate variability is the surface temperature of the ocean (SST). The best-known variation of SST is linked to the El Niño Southern Oscillation (ENSO) phenomenon. Depending on the strength of the El Nino and La Nina, it changes the climate almost throughout the globe and has strong impacts on droughts especially around the Pacific (Section 3.2). Current research and operational forecasting in the U.S.A is based on seasonal outlooks of precipitation and temperature from the Climate Prediction Center (based on statistical models, e.g. canonical correlation analysis based on global SSTs and especially ENSO), dynamical forecasts (e.g. NCEP Climate Forecast System, CFS, gives 9-month lead forecasts) and climate analogues (e.g. ENSO composites). Luo & Wood (2008) propose to merge information from different sources (e.g. Bayesian merging of different forecasts dependent on their individual skill, that may be regionally and seasonally varying, and ensemble prediction). For seasonal forecasting, the index most important for Europe is the North Atlantic Oscillation (NAO).

Indices important for other parts of the world are the Pacific Decadal Oscillation (PDO) and Indian Ocean Dipole (IOD, Ummenhofer *et al.*, 2009). The PDO is an especially useful indicator for the west coast of North America. IOD is correlated with precipitation in East Africa, but also influences precipitation in West Australia.

Land surface state variables can also be used to improve the predictive skill of seasonal forecast, especially variation in snow cover and soil moisture can be used for seasonal forecasts (e.g. Li et al., . For example, in Europe, there is a correlation between snow cover and land surface temperatures (Shongwe *et al.*, 2007). In addition, the chance of a severe summer drought in Europe is higher if soil moisture contents are low during the spring. More data and observations on the status of the land surface however are needed to improve their inclusion and exploitation in numerical seasonal forecasting tools.

6.4. Drought monitoring and early warning systems

Monitoring and early-warning within disaster management

Droughts as a recurrent natural disaster require a proactive approach for management including adaptation and mitigation. Within the comprehensive cycle of disaster management, monitoring plays a key role. Monitoring of the current state serves as the basis for decision making for the future. It is thus an important prerequisite for early-warning. At the same time, monitoring provides the indispensable initial conditions for any forecasting activities (Section 6.2) that in turn enhance the early-warning capabilities by indicating future conditions. Furthermore, monitoring provides necessary information for post-disaster activities such as damage assessment.

Existing and emerging drought early-warning systems[8]

After the occurrence of severe drought events with increasing economic damage in the last decades throughout the world, but also in Europe, drought early-warning systems are being considered as part of a comprehensive strategy to manage drought events in a proactive way.

One of the first continental-scale drought monitoring systems was established at the University of Nebraska by the National Drought Mitigation Center (NDMC) (Wilhite *et al.*, 1996). The U.S. Drought Monitor (USDM) has been widely recognized as a reference system for drought monitoring and early warning (Svoboda *et al.*, 2002). The system has been extended in its spatial domain to the North American Drought Monitor (NADM), and developed from mere monitoring to early-warning and impact assessment (i.e. the Drought Impact Reporter). In the USA there is a great deal of interest in improving drought monitoring, particularly under the umbrella of the National Integrated Drought Information System (NIDIS) and the National Drought Monitor (www.drought.gov). The drought monitor is a subjective blend of multiple drought indices plus on the ground human NIDIS) (WGA, 2004) is hosted by NOAA and supported by various national agencies is under development. It will integrate many existing components such as the U.S. Drought Monitor into a comprehensive information system for droughts.

In Europe, a prototype for a European Drought Observatory is being developed at the Joint Research Centre of the European Commission (JRC). It will combine continental overview information with detailed drought information from national and regional information systems. It will benefit from increased efforts for drought monitoring at the national level such as the development of national drought observatories, e.g. the Observatorio Nacional de la Sequia in Spain (ONS/MARM).

On the sub-continental level in Europe the Drought Management Centre for South East Europe (DMCSEE) was established by UNCCD and WMO in 2007. The DMCSEE is hosted by the Environmental Agency of the Republic of Slovenia. A first monitoring component for Southeast Europe has been developed by providing monthly estimates of the Standardized Precipitation Index for the region.

A global overview on existing initiatives towards Drought Monitoring and Early Warning Systems has been given by the UN (2007).

In the frame of the Group on Earth Observations (GEO) and the implementation of the Global Earth Observation System of Systems (GEOSS) the current work plan for 2009-2011 foresees activities within the Water Theme on drought forecasting and monitoring as a contribution towards a Global Drought Early Warning System (GEO).

In many more countries around the globe, national and regional authorities provide drought relevant information to decision makers and the public. This is especially true in countries that have experienced severe drought episodes in the past decades, or those have generally scarce water resources and are thus highly vulnerable to a further reduction in water supply caused by droughts, such as Australia, the Republic of South Africa, Kenia, Mexico, or Iran. However,

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[8] Links to early-warning systems discussed can be found in the Acronym list at the end of this document

often a dedicated centre or portal to access drought-relevant information from difference sources and disciplines is missing.

Gaps and limitations in current drought early-warning systems

A WMO expert group meeting in 2000 identified shortcomings of existing drought early warning systems (WMO, 2000). The list of shortcomings was emphasized also by ISDR Ad Hoc Working Group on Droughts in 2003 (UN, 2003). In a publication of the UN (2007) the objectives for improved early warning systems for droughts were summarized as "to promote the development of systems that are timely, relevant, understandable, affordable, and people-centered." The shortcomings triggered the identification of research questions that apply to most regions in the world, including Europe.

By nature drought events can last for very long periods of time and cover more than a year. Multi-annual drought events, however, are rarely in the focus when early-warning systems are designed and established, although it is precisely this characteristic of a drought that can cause serious and irreversible impacts and damage. Clearly also coping capacities such as reservoirs and other water storages arrive at their limitations once the drought continues for years. Accordingly, drought early-warning systems should allow for multi-annual monitoring and assessment of droughts, even if the data basis for observations has a much higher temporal resolution.

Monitoring systems and data

Opposite to the monitoring of droughts from the meteorological or hydrological side, drought impact monitoring is a relatively new domain. Collecting and documenting information on drought impacts, independently from observations of the natural system, such as media reports on drought events and the consequences, opens another important perspective on droughts that can be used to compare and verify the information derived from observations and simulations of the natural system.

Chapter 2 specifies data that need to be monitored for drought assessment. It should be stresses that remote sensing has the potential to augment ground-based monitoring systems, especially in regions with sparse ground monitoring. There are issues over temporal and spatial resolution, accuracy and budget closure (e.g. Sheffield *et al.*, 2009). New missions such as SWOT, GPM, SMAP may have potential for improved drought monitoring.

References

Andreadis, K.M., Clark, E.A., Wood, A.W., Hamlet, A.F. & Lettenmaier, D.P., 2005: Twentieth-century drought in the conterminous United States. J. Hydrometeorol., 6(6), 985-1001.

Andreadis, K.M. & Lettenmaier, D.P., 2006: Trends in 20th century drought over the continental United States. Geophys. Res. Lett. 33, L10403, doi:10.1029/2006GL025711.

Andréassian, V., E. Parent, Michel, C., 2003: A distribution-free test to detect gradual changes in watershed behavior, Water Resour. Res., 39(9), 1252, doi:10.1029/2003WR002081.

Bates, B.C., Z.W. Kundzewicz, S. Wu, J.P. Palutikof, Eds., 2008: Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp. [http://www.ipcc.ch/pdf/technical-papers/climate-change-water-en.pdf]

Beck, C. 2009: Variability of summer droughts in Central Europe and relation to large-scale circulations types. Poster at the EGU General Assembly, April 2009, Vienna.

Black, E., M. Blackburn, G. Harrison, B. Hoskins, and J. Methven, 2004: Factors contributing to the summer 2003 European heatwave. Weather, 59, 217–221.

Boberg, F., P. Berg, P. Thejll, W.J. Gutowski, J.H. Christensen, 2009: Improved confidence in climate change projections of precipitation evaluated using daily statistics from the PRUDENCE ensemble, Climate Dynamics, 32, 1097-1106.

Brewer, S., A. Alleaume, J. Guiot and A. Nicault, 2007. Historical droughts in Mediterranean regions during the last 500 years: a data/model approach. Clim. Past, 3, 355-366.

Briffa, K.R., G. van der Schrier and P.D. Jones, 2009. Wet and dry summers in Europe since 1750: evidence of increasing drought. Int. J. Climatol., DOI: 10.1002/joc.1836.

Brönnimann, S. 2007: Impact of El Niño-Southern Oscillation on European Climate. Reviews of Geophysics, 45, RG3003.

Brown, J.F., Wardlow, B.D., Tadesse, T., Hayes, M.J., and Reed, B.C., 2008: The Vegetation Drought Response Index (VegDRI): A new integrated approach for monitoring drought stress in vegetation. GIScience and Remote Sensing, 45 (1): 16-46.

Cassou, Ch. 2008. Intraseasonal interaction between the Madden–Julian Oscillation and the North Atlantic Oscillation. Nature, 455, 523-5278. doi:10.1038/nature07286.

Cassou, C., Terray, L. and A. S. Phillips, 2005: Tropical Atlantic influence on European heat waves. J. Climate, 18, 2805-2811.

CEC, 2007: Communication Addressing the challenge of water scarcity and droughts in the European Union, (COM(2007) 414), Commission of the European Communities, Brussels, Belgium.

Chang, F.-C. & J. M. Wallace, 1987: Meteorological conditions during heat waves and droughts in the United States great plains. Mon. Wea. Rev. 115, 1253.

Changnon, S.A., Jr., 1987: Trends in floods and related climate conditions in Illinois, Clim. Change 5, 341-363.

Claussen, M., P.M. Cox, X. Zeng, P. Viterbro, A.C.M. Beljaars, R.A. Betts, H.-J. Bolle, T. Chase and R. Koster, 2004. The global climate. In: Vegetation, Water, Humans and the Climate: A New Perspective on an Interactive System, P. Kabat, M. Claussen, P.A. Dirmeyer, J.H.C. Cash, Guenni L. Bravo de, M. Meybeck, R. Pielke Sc, C.J. Vörösmarty, R.W.A. Hutjes, and S.Lüthemeier, eds., Springer, Berlin.

Cook, E.R., R. Seager, M.A. Cane and D.W. Stahle, 2007. North American drought: Reconstructions, causes, and consequences. Earth Science Reviews, 81, 93-134.

CPC-NOAA. 2008: Teleconnections. http://www.cpc.ncep.noaa.gov/data/teledoc/teleintro.shtml)

Dai, A., Qian, T., Trenberth, K.E., Milliman, J., 2009: Changes in Continental Freshwater Discharge from 1948 to 2004. Journal of Climate, 22 (10), 2773–2792.

D'Andrea F., Provenzale A., Vautard R., De Noblet-Decoudre N, 2006: Hot and cool summers: Multiple equilibria of the continental water cycle. Geophys. Res. Lett., 33(24).

Della-Marta P.M., J. Luterbacher, H. Von Weissenfluh, E. Xoplaki, M. Brunet and H. Wanner, 2007: Summer heat waves over Europe 1880-2003, their relationship to large scale forcing and predictability. Clim. Dyn., 29, 251-275.

Demuth, S., Gustard, A., Planos, E., Scatena, F., Servat, E. (Eds), 2006: Climate Variability and Change. Hydrological Impacts. IAHS Publication 308 (Nov. 2006) ISBN 978-1-90150278-7 708 + xii pp.

Deo, R.C., J.I. Syktus, C.A. McAlpine, P.J. Lawrence, H.A. McGowan and S.R. Phinn. 2009. Impacts of historical land cover change on daily indices of climate extremes including droughts in eastern Australia. Gephysical Res. Letters, 36, L08705.

Eltahir, E. A. B. and P.J.-F. Yeh, 1999: On the asymmetric response of aquifer water level to floods and droughts in Illinois. Water Res. Research 35(4), 1199-1217.

Engeland, K., Hisdal, H., Frigessi, A., 2004: Practical Extreme Value Modelling of Hydrological Floods and Droughts: A Case Study. Extremes 7, 5–30.

EurAqua, 2004: Towards a European Drought Policy. Discussion document prepared by the EurAqua network of Europe’s leading freshwater research organisations (http://www.euraqua.org).

Ferranti L. and P. Viterbo, 2006: The European Summer of 2003: Sensitivity to Soil Water Initial Conditions. J. Climate. 19(15), 3659-3680.

Feudale, L. and J. Shukla,, 2007: Role of Mediterranean SST in enhancing the European heat wave of summer 2003. Geophys. Res. Lett., 34(3), doi: 10.1029/2006GL027991. issn: 0094-8276.

Fischer E. M., S. I. Seneviratne, D. Lüthi, C. Schär, 2007: Contribution of land-atmosphere coupling to recent European summer heat waves. Geophys. Res. Lett., 34, L06707.

Folland CK, Knight J, Linderholm HW, Fereday D, Ineson S, Hurrell JW. 2009: The Summer North Atlantic Oscillation: Past, Present, and Future. Journal of Climate 22: 1082–1103.

Fowler, H.J., S. Blenkinsop and C. Tebaldi, 2007: Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. Int. J. Climatol. 27, 1547-1578.

García-Herrera, R., Paredes, D., Trigo, R.M., Trigo, I.J., Hernandez, H., Barriopedro, O., Mendes, M.T., 2007: The outstanding 2004/05 drought in the Iberian Peninsula: Associated atmospheric circulation. Journal of Hydrometeorology 8, 483–498.

Gedney, N. and P.M. Cox, 2003: The Sensitivity of Global Climate Model Simulations to the Representation of Soil Moisture Heterogeneity, Journal of hydrometeorology, 4 (6), 1265 - 1275

Ghulam, A., Qin, Q., Teyip, T., and Li, Z.-L., 2007: Modified perpendicular drought index (MPDI): a real-time drought monitoring method. J. Photogramm. Remote Sens., 62: 150-164.

Greatbach, R.J., 2000: The North Atlantic Oscillation. Stoch. Env. Res. Risk A. 14, 213–242.

Grize, L., Huss, A., Thommen, O., Schindler, C. & Braun-Fahrländer, C., 2005: Heat wave 2003 and mortality in Switzerland. Swiss. Med. Wkly, 135, 200-205.

Hall, J., 2007: Probablistic climate scenarios may misrepresent uncertainty and lead to bad adaptation decisions, Hydrol. Process. 21, 1127-1129.

Hayes, M.J., Alvord, C., and Lowrey, J., 2007: Drought indices. Intermountain West Climate Summary, 3 (6): 2-6.

Heim, R.R., 2000: Drought Indices. A review. In: Drought: A Global Assessment, Hazards Disaster Series, vol I, D.A. Wilhite (ed.), Routledge, New York: 159-167.

Heim, R.R., 2002: A review of twentieth-century drought indices used in the United States. Bull. Am. Met. Soc., 84: 1149-1165.

Herwijer, C. & Seager, R., 2008: The global footprint of persistent extra-tropical drought in the instrumental era. Int. J. Climatol., 28, 1961-1774.

Hisdal, H. & Tallaksen, L. M., 2003: Estimation of regional meteorological and hydrological drought characteristics. J. Hydrol. 281(3), 230–247.

Hisdal, H., Tallaksen, L.M., Clausen, B., Peters, E. & Gustard, A., 2004: Hydrological Drought Characteristics, in Tallaksen, L.M. and Lanen, H.A.J. van, "Hydrological Drought - Processes and Estimation Methods for Streamflow and Groundwater". Developments in Water Science, 48, Elsevier Science B.V., 139-198.

Hisdal, H., Stahl, K., Tallaksen, L.M., Demuth, S., 2001: Have droughts in Europe become more severe or frequent? International Journal of Climatology, 21, 317-333.

Hoerling, M.P. & Kumar A. 2003: The perfect ocean for drought. Science 299: 691–699.

Huang J., van den Dool, H. and Georgakakos, K.P., 1996: Analysis of Model-Calculated Soil Moisture over the United States (1931-93) and Application to Long-Range Temperature Forecasts. J. Climate, 9(6), 1350–1362.

Hurk, van den, B. & D. Jacob, 2009: The Art of Predicting Climate Variability and Change in: Climate Change Adaptation in the Water Sector. Eds.: F. Ludwig, P. Kabat, H. van Schaik and M. van der Valk. Earthscan, London.

Ineson, S. & Scaife, A.A., 2009: The role of the stratosphere in the European climate response to El Niño. Nature Geoscience, 2, 32–36.

Jansen, E., J. Overpeck, K.R. Briffa, J.-C. Duplessy, F. Joos, V. Masson-Delmotte, D. Olago, B. Otto-Bliesner, W.R. Peltier, S. Rahmstorf, R. Ramesh, D. Raynaud, D. Rind, O. Solomina, R. Villalba & D. Zhang, 2007: Palaeoclimate. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor & H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jansson, P., R. Hock and T. Schneider, 2003: The concept of glacier storage: a review, J. Hydrol. 282, 116-129.

Jaun, S.,B. Ahrens, A. Walser, T. Ewen and C. Schär, 2008: A probablistic view on the August 2005 floods in the upper Rhine catchment, Nat. Hazards Earth Syst. Sci. 8, 281-291.

Jacob, D. & B. van den Hurk, 2009: Climate Change Scenarios at the Global and Local Scale in: Climate Change Adaptation in the Water Sector (Eds. F. Ludwig, Pavel Kabat, H. van Schaik and M. van der Valk). Earthscan, London

JRC, 2009: Joint Research Centre, European Commission, http://edo.jrc.ec.europa.eu

Kay, A.L., H.N. Davies, V.A. Bell and R.G. Jones, 2009: Comparison of uncertainty sources for climate change impacts: flood frequency in England, Climate Change (2009) 92, 41-63.

Keyantash, J. A. and Dracup, J. A., 2004: An Aggregate Drought Index: assessing drought severity based on fluctuations in the hydrologic cycle and surface water storage. Water Resources Res., 40: W09304.

Kingston, D.G., Hannah, D.M., Lawler, D.M. & McGregor, G.R., 2009: Hydrol. Process. 23, 985–996, DOI: 10.1002/hyp.7202.

Climate –river flow relationships across montane and lowland environments in northern Europe

Kogan, F.N., 1995: Application of vegetation index and brightness temperature for drought detection. Adv. Space Research, 11: 91-100.

Kosatsky T., 2005: The 2003 European heat waves. Euro Surveill., 10(7); available online: http://www.eurosurveillance.org/ViewArticle.aspx?ArticleId=552

Kumar A. & M.P. Hoerling, 2008: Climate diagnostics and predictions. BAMS, 89(4), 521–524.

Kundzewicz, Z.W. & A.J. Robson (Eds), 2000: Detecting trend and other changes in hydrological data. World Climate Programme - Data and Monitoring. WMO/UNESCO, Geneva, 157 pp.

Kundzewicz, Z.W., Robson, A.J., 2004. Change detection in hydrological data-a review of the methodology. Hydrological Sciences Journal, 49 (1), 7-19.

Lanen, H.A.J. van & M. Fendekova, 2008: Low Flow and drought research in Europe: achievements and future. Outcome of the Workshop on Low Flow and Drought held at the Comenius University, Bratislava, Slovakia, 10-12 November 2008, 3 pp. [available at: http://www.unesco.org/water/ihp]

Lanen, H.A.J. van, Fendeková, M., Kupczyk, E., Kasprzyk, A., Pokojski, W., 2004. Flow Generating Processes, Chapter 3. In: Tallaksen, L.M. & van Lanen, H.A.J. (Eds.), 2004: Hydrological Drought. Processes and Estimation Methods for Streamflow and Groundwater. Development in Water Science, 48, Elsevier Science B.V., 53-96.

Lanen, H.A.J. van, Tallaksen, L.M, Rees, G., 2007: Droughts and climate change. In: Commission Staff Working Document Impact Assessment (SEC(2007) 993), Accompanying document to Communication Addressing the challenge of water scarcity and droughts in the European Union (COM(2007) 414), Commission of the European Communities, Brussels, Belgium. [available at: http://www.eu-watch.org/]

Lanen, H.A.J. van & Tallaksen, L.M., 2007: Hydrological drought, climate variability and change. In: Heinonen, M. (Ed.) Climate and Water. Proc. of the third Int. Conf. on Climate and Water, Helsinki, Finland, 3-6 September 2007, 488-493.

Lanen, H.A.J. van & Tallaksen, L.M., 2008: Drought in Europe. In: Lambert, M., Daniell, T. & Leonard, M., (Eds.). Proc. Water Down Under 2008, Adelaide, Australia, 14-17 April 2008, pg. 98-108.

Lang, M., Renard, B., Sauquet, E., Bois, P., Dupeyrat, A., Laurent, C., Mestre, O., Niel, H., Neppel, L., Gailhard, J., 2006: A national study on trends and variations of French floods and droughts. Proceedings of the Fifth FRIEND World Conference, "Climate Variability and Change-Hydrological Impacts", Havana, CUBA, November 2006; IAHS Publication, N°308, 2006, 514-519.

Lehner, B., Döll, P., Alcamo, J., Henrichs, T., Kaspar, F., 2006: Estimating the impact of global change on flood and drought risks in Europe: A continental, integrated analysis. Climatic Change, 75, 273-299.

Li, H., Luo, L., Wood, E. F. & Schaake, J., 2009: The role of initial conditions and forcing uncertainties in seasonal hydrologic forecasting, J. Geophys. Res., 114, D04114, doi:10.1029/2008JD010969.

Linderholm, H.W., C.K. Folland and A. Walther, 2009. A multicentury perspective on the summer North Atlantic Oscillation (SNAO) and drought in the eastern Atlantic Region. Journal of Quaternary Science 24: 415–425.

Lloyd-Hughes, B. & M.A. Saunders, 2002: A drought climatology for Europe. Int. J. Climatol., 22, 1571-1592.

Lopez-Moreno, J.I., S. Begueria, S.M. Vicente-Serrano & J.M. Garcia-Ruiz, 2007: Influence of the North Atlantic Oscillation on water resources in central Iberia: Precipitation, streamflow anomalies, and reservoir management strategies. Wat. Res. Research 43 (9), 10.1029/2007WR005864

Lorenzo, M.N., Taboada, J.J., Gimeno, L., 2008: Links between circulation weather types and teleconnection patterns and their influence on precipitation patterns in Galicia (NW Spain). International Journal of Climatology 28, 1493–1505.

Ludwig, F., 2009: Using Seasonal Climate Forecasts for Water Management in: Climate Change Adaptation in the Water Sector (Eds. F. Ludwig, P. Kabat, H. van Schaik and M. van der Valk). Earthscan, London.

Luo L. & Wood, E. F., 2008: Use of Bayesian mering techniques in a multimodel seasonal hydrologic ensemble prediction system for the Eastern United States. Journal of Hydrometeorology 9: 866-884.

Maracchi, G., 2000: Agricultural Drought – a practical approach to definition, assessment and mitigation strategies. In: Vogt, J.V. and Somma, F. (eds.): Drought and Drought Mitigation in Europe. Advances in Natural and Technological Hazards Research, 14, Kluwer Academic Publishers, Dordrecht, NL: 63-78.

Marsh, T.J., 2004: The UK drought of 2003 – an overview. Weather, 59(8).

Matteo, Z., D'Andrea, F., Vautard, R., Ciais, P., de Noblet-Ducoudré, N., Yiou, P., 2009: Hot European Summers and the role of soil moisture in the propagation of Mediterranean drought. J. Climate, early online release, posted April 2009.

Mauer, E.P. & Duffy, P.B., 2005: Uncertainty in projections of streamflow changes due to climate change in California, Geophys. Res. Lett. 32, L03704, doi: 10.1029/2004GL021462.

Maxwell, R.M. and S.J. Kollet, 2008: Interdependence of groundwater dynamics and land-energy feedbacks under climate change. Nature Geoscience 1(10), 665-669.

McGregor G.R. & I.D. Phillips, 2004: Specification and prediction of monthly and seasonal rainfall over the south-west peninsula of England. Q. J. R. Meteorol. Soc., 130, 193–210.

McKee, T. B., Doesken, N. J., & J. Kleist, 1993: The relationship of drought frequency and duration to time scale. Preprints, Eighth Conf. on Applied Climatology, Anaheim, CA, Am. Met. Soc.: 187-190.

MEDD, Ministère de l'Ecologie et du Développement Durable, (2003) Evaluation des coûts de la canicule de l'été 2003 en France : premiers éléments de bilan. Recherche Environnement, 8, Octobre 2003, p.3-4. [available at: http://www.ecologie.gouv.fr/IMG/pdf/LRE_200310.pdf]

Murphy, J.M., B.B.B. Booth, M. Collins, G.R. Harris, D.M.H. Sexton & M.J. Webb, 2007: A methodology for probability predictions of regional climate change from perturbed physics, Phil. Trans. R. Soc. A 365, 1993-2028.

New, M., A. Lopez, Dessai, S. & R. Wilby, 2007: Challenges in using probabilistic climate change information for impact assessments: an example from the water sector, Phil. Trans. R. Soc. A (2007) 365, 2117–2131

Niemeyer, S., 2008: New drought indices. in: Drought management: Scientific and technological innovations. Proceedings of the 1st International Conference "Drought management: Scientific and technological innovations", Zaragoza, Spain, 12-14 June 2008, 267-274.

Osborne, T. 2000. North Atlantic Oscillation. [http://www.cru.uea.ac.uk/cru/info/nao/]

Osti, A.L., Lambert, M.F. & Metcalfe, A.V., 2008: On spatiotemporal drought classification in New South Wales: Development and evaluation of alternative techniques. Australian J. Water Resources, 12(1), 21-34.

Palmer, T.N. & Anderson, 1994: The prospect of seasonal forecasting-a review paper, Quarternary Journal of Geophysical Research, 120, 755-793.

Palmer, W.C., 1965: Meteorological drought. Research Paper no. 45, U.S. Weather Bureau, Washington, D.C.

Palmer, W.C., 1968: Keeping track of crop moisture conditions, nationwide: The new Crop Moisture Index. Weatherwise, 21:156-161.

Peral Garcia, C., Mestre Barceló, A. & Garcia Merayo, J.L., 1998: The drought of 1991–95 in southern Spain. Analysis, repercussions, and response measures. In: DROUGHT, A Global

Assessment, Vol I (ed. by D.A. Wilhite), Routledge Hazards and Disasters Series, Routledge, London, 267–380.

Peters, E., Torfs, P.J.J.F., Lanen, H.A.J. van & Bier, G., 2003: Propagation of drought through groundwater – a new approach using linear reservoir theory. Hydrological Processes 17(15) 3023-3040.

Peters, E., G. Bier, H. A. J. van Lanen & P. J. J. F. Torfs, 2006: Propagation and spatial distribution of drought in a groundwater catchment. J. Hydrol. 321, 257–275.

Pielke, Sr, R.A., 2005. Land use and climate change. Science, 310, 14, 1227-1242.

Pfister, Ch., R. Weingartner & J. Luterbacher, 2006. Hydrological winter droughts over the last 450 years in the Upper Rhine basin: a methodological approach. Hydrological Sciences–Journal–des Sciences Hydrologiques, 51(5), 966 – 985.

PRUDENCE, 2005: Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects, EU project EVK2-CT2001-00132. Final Report 1 November 2001 – 31 October 2004 (Section 1), 8 February 2005, 269p. [available at http://prudence.dmi.dk/]

Prudhomme, C. & Davies, H., 2009: Assessing uncertainties in climate change impact analyses on the river flow regimes in the UK. Part 1: baseline climate, Climatic Change (2009) 93, 177–195.

Rees, G., Marsh, T.J., Roald, L., Demuth, S., Lanen, H.A.J. van & Kašpárek, L, 2004: Hydrological Data, Chapter 4. In: Tallaksen, L.M. & van Lanen, H.A.J. (Eds.) (2004) Hydrological Drought. Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Science, 48, Elsevier Science B.V., 99-138.

Robertson, I., C.A. Froyd, M. Gagen, & S. Hicks, 2009. Climates of the past: evidence from natural and documentary archives. J. Quaternary Science, 24(5): 411–414. DOI: 10.1002/jqs.

Schaake, J.C., T.M. Hamill, R. Buizza and M. Clark, 2007: HEPEX, the hydrological ensemble prediction experiment, Bull. of the Am. Meteorol. Soc. 88, 1541-1547.

Schär, C., P.L. Vidale, D. Lüthi, C. Frei, C. Häberli, M.A. Liniger & C. Appenzeller, 2004. The role of increasing temperature variability in European summer heatwaves. Nature 427: 332-336.

Schrier, G. van der, K.R Briffa, P.D. Jones and T.J. Osborn, 2006. Summer moisture variability across Europe. J. Climate, 19(12), 2828-2834.

Seneviratne, S.I., D. Lüthi, M. Litschi, and C. Schär, 2006: Land-atmosphere coupling and climate change in Europe. Nature, 443, 205-209.

Seneviratne, S.I. & R. Stöckli, 2008. The role of Land-Atmosphere Interactions for Climate Variability in Europe, in Brönnimann *et al.* (eds.) Climate Variability and Extremes during the Past 100 Years. Springer, 2008.

Servat, E. & Demuth, S. (Eds), 2006: FRIEND - a global perspective 2002-2006. UNESCO, Koblenz 2006, 209 pp. [available at http://unesdoc.unesco.org].

Shanahan, T.M., J.T. Overpeck, K.J. Anchukaitis, J.W. Beck, J.E. Cole, D.L. Dettman, J.A. Peck, C.A. Scholz, and J.W. King, 2009. Atlantic Forcing of Persistent Drought in West Africa. Science 324 (5925), 377. DOI: 10.1126/science.1166352.

Sheffield, J. & Wood, E.F., 2007: Characteristics of global and regional drought, 1950-2000: Analysis of soil moisture data from off-line simulation of the terrestrial hydrologic cycle. J. Geophys. Res., 112: D17115

Sheffield, J., Wood, E.F., 2008a. Global trends and variability in soil moisture and drought characteristics, 1950-2000, from observation-driven simulations of the terrestrial hydrologic cycle. Journal of Climate, 21 (3), 432-458.

Sheffield, J., Wood, E.F., 2008b. Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations. Clim Dyn, 31, 79-105.

Sheffield, J., Ferguson, C.R., Troy, T.J. & Wood, E.F., 2009: Closing the terrestrial water budget from satellite remote sensing. Geophysical Research Letters, Vol. 36, L07403, doi:10.1029/2009GL037338, 2009.

Shongwe, M.E., C.A.T. Ferro, C.A.S. Coelho, G.H. van Oldenborgh, 2007: Predictability of cold spring seasons in Europe. Monthly Weather Rev. 135(12), 4185-4201.

Smakhtin, V.U., 2001: Low flow hydrology: a review, J Hydrol. 240, 147-186.

Sordo, C., M.D Frías, S. Herrera, A.S. Cofiño, and J.M. Gutiérrez, 2008. Interval-based statistical validation of operational seasonal forecasts in Spain conditioned to El Niño–Southern Oscillation events. Journal of Geophysical Research, 113, D17121, doi:10.1029/2007JD009536.

Stahl, K., 2001: Hydrological Drought – a Study across Europe. PhD Thesis Albert-Ludwigs-Universität Freiburg, Freiburger Schriften zur Hydrologie no. 15, Freiburg, Germany [also available at http://www.freidok.uni-freiburg.de/volltexte/202].

Stahl, K. & S. Demuth. 1999. Linking streamflow drought to the occurrence of atmospheric circulation patterns. Hydrol. Sci. J: 44(3), 467-482.

Stahl, K. & Hisdal, H., 2004: Hydroclimatology. In: Tallaksen, L. M. & Lanen, H. A. J. van (Eds) Hydrological Drought – Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Sciences 48, Elsevier Science BV, The Netherlands, pg. 19-51.

Stahl, K., Hisdal, H., Tallaksen, L.M., van Lanen, H.A.J., Hannaford, J. & Sauquet, E., 2008a: Trends in low flows and streamflow droughts across Europe. UNESCO Report, Paris, 39 pg.

Stahl, K., Hisdal, H., Tallaksen, L., Lanen, H.A.J. van, Hannaford, J., Sauquet, E., Demuth, S., 2008b: Trends in low flows and droughts in small undisturbed rivers across Europe. In: European Geosciences Union (EGU) - General Assembly, Vienna, Austria, 13 - 18 April, 2008. – Vienna. EGU, (EGU2008-A-04801)

Svoboda, M., LeComte, D., Hayes, M., Heim, R. , Gleason, K., Angel, J. , Rippey, B. , Tinker, R., Palecki, M., Stooksbury, D., Miskus, D. & Stephens, S., 2002: The Drought Monitor. Bulletin of the American Meteorological Society, 83(8):1181-1190.

Sutton, R.T. and D.L.R. Hodson, 2005. Atlantic Ocean forcing of North American and European summer climate. Science, 309, 115–118.

Tallaksen, L.M., Hisdal, H. & H.A.J. van Lanen, 2009: Space-time modelling of catchment scale drought characteristics. J. of Hydrol. 375:363-372 (doi:10.1016/j.jhydrol.2009.06.032).

Tallaksen, L.M., Hisdal, H. & van Lanen, H.A.J., 2006: Propagation of drought in a groundwater fed catchment, the Pang in UK. In: FRIEND 2006 – Water Resource Variability: Processes, Analyses and Impacts (ed. S. Demuth), IAHS Publ., 308, 128-133.

Tallaksen, L.M., Madsen, H., Clausen, B., 1997: On the definition and modelling of streamflow drought duration and deficit volume. Hydrological Sciences Journal, 42 (1), 15-33.

Tallaksen, L. & Lanen, H.A.J. van (Eds), 2004: Hydrological Drought, Processes and Estimation Methods for Streamflow and Groundwater. Developments in Water Science, 48, Elsevier BV, The Netherlands, 579 pp.

Tate, E.L. and Gustard, A., 2000: Drought Definition: A hydrological perspective. In: Vogt, J.V. and Somma, F. (eds.): Drought and Drought Mitigation in Europe. Advances in Natural and Technological Hazards Research, 14, Kluwer Academic Publishers, Dordrecht, NL: 23-48.

Trenberth, K.E., Jones, P.D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank A., Parker, D., Rahimzadeh, F., Renwick, J.A., Rusticucci, M., Soden B., Zhai, P., 2007: Observations: Surface and Atmospheric Climate Change. In: Solomon, S., D. Qin, M. Manning, Z. Chen, M.

Marquis, K.B. Averyt, M. Tignor and H.L. Miller (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA..

Trnka, M., J. Kyselý, M. Možný and M. Dubrovský, 2009. Changes in Central-European soil-moisture availablility and circulation patterns in 1881-2005. Int. J. Climatol. 29, 655-672.

Trouet, V., J. Esper, N.E. Graham, A. Baker, J.D. Scourse and D.C. Frank, 2009. Persistent Positive North Atlantic Oscillation Mode Dominated the Medieval Climate Anomaly. Science, 324, 78.

Tsonis, A.A. & Swanson, K.L., 2009: The pacemaker of major climate shifts. Presentation and abstract at the EGU General Assembly 2009, Vienna, Austria, 19 – 24 April 2009 [http://meetingorganizer.copernicus.org/EGU2009/EGU2009-3122.pdf].

Ummenhofer, C.C., England, M.H., McIntosh, P.C., Meyers, G.A., Pook, M.J., Risbey, J.S., Sen Gupta, A.. & Taschetto, A.S., 2009: What causes southeast Australia's worst droughts? Geophysical Research Letters, Vol. 36, L04706, doi:10.1029/2008GL036801.

UN, 2003: Living with Risk: An Integrated Approach to Reducing Societal Vulnerability to Drought. ISDR Ad Hoc Discussion Group on Drought. United Nations International Strategy for Disaster Reduction, Genève, Switzerland, 41 pp.

UN, 2007: Drought Risk Reduction Framework and Practises: Contributing to the Implementation of the Hyogo Framework for Action. United Nations International Strategy for Disaster Reduction, Genève, Switzerland 97 pp.

Vanham, D., Fleischhacker, E., Rauch, W., 2009: Impact of an extreme dry and hot summer on water supply security in an alpine region. Water Science and Technology, 59 (3), 469-477.

Vautard, R., P. Yiou, F. D'Andrea, N. de Noblet, N. Viovy, C. Cassou, J. Polcher, P. Ciais, M.

Kageyama & Y. Fan, 2007: Summertime European heat and drought waves induced by wintertime Mediterranean rainfall deficit, Geophys. Res. Lett., 34, L07711.

Vogt, J.V. and Somma, F. (eds.), 2000: Drought and Drought Mitigation in Europe. Advances in Natural and Technological Hazards Research, 14, Kluwer Academic Publishers, Dordrecht, NL.

Wang, A., T.J. Bohn, S.P. Mahanama, R.D. Koster, D.P. Lettenmaier., 2009: Multimodel Ensemble Reconstruction of Drought over the Continental United States. J. Climate 22, 2694-2712.

Wang, L. & Qu, J.J., 2007: NMDI: A normalized multi-band drought index for monitoring soil and vegetation moisture with satellite remote sensing. Geophys. Res. Lett., 34, L20405.

Wheaton, E. (ed.),2005: Lessons Learned from the Canadian Drought Years 2001 and 2002: Synthesis Report. SRC Publication, No. 11602-46E03, Ministry of Agriculture and Agri-Food, Canada.

WGA, 2004: Creating a Drought Early Warning System for the 21st Century: The National Integrated Drought Information System. Western Governors' Association, Denver, CO, 16 pp.

Wilby, R.L., I. Harris, 2006: A framework for assessing uncertainties in climate change impacts: lowflow scenarios for the River Thames, UK. Water Resour Res 42 : W02419.1–W02419.10

Wilby, R.L., P.G. Whitehead, A.J. Wade, D. Butterfield, R.J. Davis & G. Watts, 2006: Integrated modeling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK, J. of Hydrology, 330, 204-220.

Wilhite, D. A., Smith K. H., and Hayes, M. J., 1996: The National Drought Mitigation Center. In: Proc. of Conservation 1996, pp. 795–799, American Water Works Association, Washington, D.C.

Wilhite, D.A. and Glantz, M.H., 1985: Understanding the drought phenomenon: The role of definitions. Water International, 10: 111-120.

Wipfler, E.L., K. Metselaar, J.C. van Dam, R.A. Feddes, E. van Meijgaard, L.H. van Ulft, B. van den Hurk, S.J. Zwart & W.G.M. Bastiaanssen, -: Seasonal evaluation of the land surface scheme HTESSEL against remote sensing derived energy fluxes of the Transdanubian region in Hungary (in prep).

WMO, 2000: Proceedings of an Expert Group Meeting held September 5-7, 2000, in Lisbon, Portugal. Donald A. Wilhite, M.V.K. Sivakumar and Deborah A. Wood (eds), World Meteorological Organization, Genève, Switzerland, WMO/TD No. 1037.

Wood, A.W., E.P. Maurer, A. Kumar & D.P. Lettenmaier, 2002: Long-range experimental hydrologicforecasting for the eastern United States, J. Geophys. Res., 107 (D20), 4429, doi:10.1029.2001JD000659.

Yevjevich, V., 1967: An objective approach to definition and investigation of continental hydrologic droughts, Hydrology Papers 23, Colorado State University, Fort Collins, USA..

Zaidman, M.D., H.G. Rees and A. Young, 2001. Spatio-temporal development of streamflow droughts in north-west Europe. Hydrol. Earth Syst. Sci., 5(4), 733-751.

Zampieri, M., F. D’Andrea, R. Vautard, Ph. Ciais, N. de Noblet-Ducoudré and P. Yiou, 2009. Hot European Summers and the role of soil moisture in the propagation of Mediterranean drought. J. Climate, 22, 4747–4758.

Annex 1 Acronyms

ADI	Aggregate Drought Index
CMI	Crop Moisture Index
DMCSSEE	Drought Management Centre for the South East Europe, Environmental Agency of Slovenia, http://www.dmcsee.org/en/drought_monitor
ECMWF	European Centre for Medium-Range Weather Forecasts
EDC	European Drought Centre (http://www.geo.uio.no/edc/)
EDO	European Drought Observatory (http://edo.jrc.ec.europa.eu/php/index.php?action=view&id=2)
ENSEMBLES	http://www.ensembles-eu.org/
ENSO	El Nino Southern Oscillation
EWA	European Water Archive (http://ne-friend.bafg.de/servlet/is/7413/)
FRIEND	Flow Regimes from International Experimental and Network Data (http://typo38.unesco.org/en/about-ihp/ihp-partners/friend.html)
HEPEX	Hydrological Ensemble Prediction Experiment (http://hydis8.eng.uci.edu/hepex/)
GCM	Global Circulation Model
GEO	Group of Earth Observation http (//www.earthobservations.org/)
GEOSS	Global Earth Observation System of Systems (http://www.earthobservations.org/geoss.shtml)
GEWEX	Global Energy and Water Cycle Experiment (http://www.gewex.org/)
GHM	Global Hydrological Model
GRDC	Global Runoff Data Centre (http://www.bafg.de/GRDC/Home/homepage__node.html)
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change (http://www.ipcc.ch/)
ISDR	International Strategy for Disaster Reduction (http://www.unisdr.org/)
JRC	Joint Research Centre of the European Commission
LSHM	Land Surface Hydrological Model
LSS	Land Surface Scheme
MARM	Observatorio Nacional de la Sequia, Ministero de Medio Ambiente y Medio Rural y Marino, [available at: http://www.mma.es/portal/secciones/acm/aguas_continent_zonas_asoc/ons/index.htm]
MSLP	Mean Sea Level Pressure
MJO	Madden-Julian Oscillation
NADM	North American Drought Monitor (http://www.ncdc.noaa.gov/oa/climate/monitoring/drought/nadm/)
NCEP	National Centers for Environmental Prediction [www.**ncep**.noaa.gov/]
NDMC	National Drought Mitigation Centre (http://drought.unl.edu/)
NIDIS	National Integrated Drought Information System
NOAA	National Oceanic and Atmospheric Administration (http://www.noaa.gov/)
NOA	North Atlantic Oscillation
PDF	Probability Density Function
PDSI	Palmer Drought Severity Index
PDO	Pacific Decadal Oscillation
PRUDENCE	Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate

	change risks and effects (http://prudence.dmi.dk/)
RBHM	River Basin Hydrological Model
RCM	Regional Climate Model
RDI	Regional Deficiency Index
SAF	Severity-Area-Frequency
SEIS	Shared Environmental Information Systems (http://ec.europa.eu/environment/seis/)
SPI	Standard Precipitation Index
SST	Sea Surface Temperature
UK	United Kingdom
UNCCD	United Nations Convention to Combat Desertification (http://www.unccd.int)
USDM	US Drought Monitor http (//www.drought.unl.edu/dm/monitor.html)
VCI	Vegetation Condition Index
VegDRI	Vegetation Drought Response Index
VIC model	Variable Infiltration Capacity model (http://www.hydro.washington.edu/Lettenmaier/Models/VIC/VIChome.html)
WATCH	Water and Global Change (http://eu-watch.org/nl/25222705-Home.html)
WFD	European Water Framework Directive
WFD-CIS	Working Group on Water Scarcity and Drought
WGA	Western Governors' Association
WMO	World Meteorological Organization (http://www.wmo.ch/)
WMO-WHYCOS	World Hydrological Cycle Observing System (http://www.whycos.org/rubrique.php3?id_rubrique=2)
WT	Weather Types
XEROCHORE	An Exercise to Assess Research Needs and Policy Choices in Areas of Drought (Support Action) (http://www.feem-project.net/xerochore/index.php)

Annex 2 Glossary

Agricultural drought: short-term dryness in the surface soil layers (root-zone) at a critical time in the growing season. The start and end may lag that of a meteorological drought, depending on the preceding soil moisture status[1].

Aridity: a deficiency of moisture (especially when resulting from a permanent absence of precipitation).

Attenuation: the gradual loss in intensity or amplitude of a flux or signal.

Attribution: process of establishing the most likely causes for the detected change in drought with some defined level of confidence.

Bias: a systematic deviation of a value from a reference value. In the context of this document it is the systematic deviation of a model outcome from a observed value.

Blocking (atmospheric): large scale patterns in the atmospheric pressure field that are nearly stationary, effectively "blocking" or redirecting migratory cyclones. They are also known as blocking highs or blocking anticyclones. These blocks can remain in place for several days or even weeks, causing the areas affected by them to have the same kind of weather for an extended period of time. In the Northern Hemisphere, extended blocking occurs most frequently in the spring over the eastern Pacific and Atlantic oceans[2].

Bowen ratio: the ratio of sensible heat flux over latent heat flux, respectively.

Deficit volume: is the sum of the deficit volume of a certain variable (e.g. groundwater recharge) below the threshold level over time, for one specific drought event.

Detection is the process of demonstrating that drought has changed (e.g. due to natural and/or human influences) in some defined statistical sense, without providing a reason for that change.

Drought: a sustained and regionally extensive occurrence of below average natural water availability due to climate variability. Relative to normal conditions.

External climate forcings: refers to a forcing agent outside the climate system causing a change in the climate system. Volcanic eruptions, solar variations and anthropogenic changes in the composition of the atmosphere and land-use change are external forcings[3].

Forecasting: estimate at the monthly and seasonal scale at certain specific future times.

Groundwater drought: prolonged low groundwater levels that affect surface water supply. Due to the slow reaction of groundwater, the start and end of the groundwater drought may lag month or even years behind that of a meteorological drought.

Hydrological drought: prolonged moisture deficits that affect surface or subsurface water supply, thereby reducing streamflow, groundwater, dam and lake levels. This may persist long after a meteorological drought has ended[1].

Lag-time: time delay between incoming signal and outgoing signal

Latent heat flux: is the flux of heat from the Earth's surface to the atmosphere that is associated with evaporation or transpiration of water at the land-surface[2]

Meteorological drought: a period of months to years when atmospheric conditions result in low rainfall. This can be exacerbated by high temperatures and high evaporation, low humidity and desiccating winds[1];

Natural system is the physical system (hydrological system along with the climatological system) under natural conditions.

Offline approach refers to simulations of hydrological or land surface models that are driven by climate model output, however, instead of online or coupled models, feedback towards the climate models are not included

Online approach: refers to integrated climate model simulations. In contrast to the offline approach feedbacks from the land surface towards the atmosphere are considered.

Physical system is the combined hydrological system and climatological system that causes the different types of drought due to climate variability.

Prediction: estimation at decadal or centennial timescales. The estimates are formulated in more general terms.

Sensible heat flux: heat energy transferred between the land surface and the atmosphere due to temperature differences

Socio-economic drought: the effect of elements of the above droughts on supply and demand of economic goods and human well-being[1];

Soil moisture drought: see agricultural drought

Synoptic meteorology: meteorology primarily concerned with large-scale weather systems, such as extra-tropical cyclones and their associated fronts

Severity (drought): volume of below average precipitation, soil moisture, groundwater or streamflow during a drought

Teleconnection pattern: refers to a recurring and persistent, large-scale pattern of pressure and circulation anomalies that spans vast geographical areas. Teleconnection patterns are also referred to as preferred modes of low-frequency (or long time scale) variability[4].

Threshold level approach (drought): approach to define drought by using deficit volume, duration and intensity of a hydrological variable (e.g. streamflow or precipitation) below a predefined threshold level.

Water Scarcity: a situation where there is insufficient water to satisfy normal water requirements

Weather type: A series of generalized synoptic situations; weather types are selected to represent typical pressure patterns, devised as a method for lengthening the effective time-range of forecasts.

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[1] K. Hennessy, R. Fawcett, D. Kirono, F. Mpelasoka, D. Jonesb, J. Bathols, P. Whetton, M. Stafford Smith, M. Howden, C. Mitchella, and N. Plummer, 2008: An assessment of the impact of climate change on the nature and frequency of exceptional climatic events.

[2] Wikipedia [http://en.wikipedia.org/]

[3] Glossary published in the IPCC Fourth Assessment Report.

[4] NOAA (National Weather Serevice) [http://www.cpc.noaa.gov/data/teledoc/teleintro.shtml]

Annex 3 List of contributors

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