PALAEOCLIMATE WITHIN THE RIVER RHINE CATCHMENT DURING HOLOCENE AND HISTORIC TIMES

With 5 figures

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Zusammenfassung: Klimaentwicklung im Rheineinzugsgebiet auf holozäner und historischer Zeitskala

Der vorliegende Beitrag fasst den derzeitigen Wissensstand zur Klimaentwicklung im Rheineinzugsgebiet auf verschiedenen Zeit- und Raumskalen zusammen. Im ersten Teil beziehen sich die Aussagen vor allem auf das Gebiet des Alpen- und Hochrheins, das wegen der Höhenerstreckung und seiner spezifischen geoökologischen Ausstattung als besonders klimasensitiv angesehen werden kann. Grundlage bildet ein breites Spektrum an paläoklimatischen Befunden, über die die spätglaziale und holozäne Klimaentwicklung entschlüsselt wird. Ergänzend werden Aussagen aus dem Mittelrheinabschnitt, die sich u.a. aus den Eifelmaaren ableiten lassen und durch eine jährliche Auflösung besondere Aussagekraft besitzen, angeführt. Im zweiten Teil bilden chronikalische Aufzeichnungen das Rückgrat der Analysen. Über diese lassen sich die letzten 1.000 Jahre soweit auflösen, dass neben Aussagen zur allgemeinen Temperatur- und Niederschlagsentwicklung auch Klimaextreme, v.a. Hochwässer bewertet werden können. Diese zeigen sowohl in einigen Nebenflüssen wie dem Main, vor allem aber auch im Gebiet des Niederrheins signifikante Schwankungen auf. Darüber hinaus war es möglich, aus den europaweit gewonnenen Datensätze Druckdatenfelder zu rekonstruieren, die jahreszeitliche und monatliche Zirkulationsanalysen ermöglichen.

Summary: The present article summarizes the state of the art knowledge concerning climatic fluctuations in the Rhine catchment area on different time scales and spatial resolution. The first part deals with the results focussed on the alpine and Hochrhein area, which can due to its elevation and specific geoecological setting regarded as especially sensitive to climatic fluctuations. The basis is a broad variety of palaeoclimatic indicators, by which the climate development during the postglacial and Holocene period can be analysed. In addition, results for the middle Rhine area, derived from Eifel maar varves are discussed. These data exhibit a yearly resolution. The second part is based on chronological readings, giving evidence about the climate since AD 1000 in detail. Beside the overall temperature and precipitation development, these data also include information about climatic extremes, likewise flood events. For some tributaries likewise the Main River and the lower Rhine area there significant changes and fluctuations through time. In addition it was possible to derive out of European wide historical data sets pressure grid sets, enabling the derivatio of circulation patterns.

Preface

With respect to the Late Glacial and Holocene periods, there is a lot of palaeoclimatic information available on the catchment of the River Rhine. But the quality and quantity of this information differs considerably, depending on the region as well as on the archives studied and the periods under investigation. To give an overview of the state of the art, this section, entitled 'palaeoclimate', is divided in two parts, each of them dealing with different time resolutions and different palaeoclimatic archives. In the first sub-section, Late Glacial and Holocene climate fluctuations are discussed; the second sub-section focuses on the last 500 years. The importance of a closer look to climatic fluctuations before any agriculture, i.e. before the oldest Linearband Ceramics in Central Europe (before 7500 a BP), lies in their function as a baseline of natural climatic variability that needs to be distinguished from prehistoric and historic human impact. Spatially we put the emphasis of the Holocene section on the alpine area for two reasons: Firstly, the large priority programme "Changes of the Geo-Biosphere" covered with a great number of new studies most of the Rhine catchment (e.g. KALIS et al. 2003; ZOLITSCHKA et al. 2003) and we offer here just a complementary review from the headwaters. Secondly, some of the natural archives of a mountain chain are different from the lowlands and again complementary.

Regarding the last 10,000–12,000 years, the most complete palaeoclimatic information is available from the Alps. The Younger Dryas cold period and the shift to a warmer Holocene is well documented. For the Holocene, several glacier advances and timberline fluctuations indicate century scale variations of the summer temperature in the order of up to ± 1°C. Aquatic multi-proxy studies follow more or less the same pattern. The sensitive alpine altitudinal belt reacted with alternating periods of solifluction, erosion and soil development, strongly influencing fluvial dynamics downvalley (GAMPER 1987; VEIT 1993; VEIT a. HÖFNER 1993). An Early to Mid Holocene Climatic Optimum seems to be present, probably ending at about 3300 ^{14}C a BP. It might have been caused by pronounced seasonality with increased summer and reduced winter insolation. Along with solar variations, in Central Europe in general the North Atlantic thermohaline circulation might also play a role as a driving force for these more or less cyclic climatic variations. Additionally, postglacial sea-level rise and flooding of the southern North Sea probably lead to increased maritimity. In contrast to the Alps, lowland ecosystems along the middle and lower course of the Rhine were only sensitive to relatively high-amplitude climatic fluctuations. However, archives with an annual time resolution are available, such as, for example, the varved Eifel maars.

Palaeoclimatic information since 1000, as well as for the Holocene period, is drawn from isotopes, sediments, pollen, tree rings and glaciers. Additionally however, historical documents can be used as the main palaeoclimatic archive for this period (GLASER 2001). After 1500 there are almost continuous descriptions of monthly, partly even daily weather data available. From the end of the 17th Century data from individual instrumental measurements can be used, and since 1860 international meteorological networks have been in function. Temperature trends show a clear seasonality for the last 500 years. During the Little Ice Age, especially winters were relatively cold, with no great variations in summer temperatures. The latter were only depressed during certain periods, such as 1580–1600 and 1820–1860, leading to glacier advances in the Alps.

Frequency and intensity of natural hazards, such as floods, varied through time. Floods have been reconstructed for the last 1,000 years in several subcatchments using historical methods (GLASER a. STANGL 2003; WANNER et al. 2004; GLASER et al. 2004). Obviously, there was an increase of these events during the Little Ice Age. However, floods are singular events and might not be synchronous in different subcatchments. Moreover, a separation of climate and human influence is very difficult. As a conclusion one can state that regarding temperature and precipitation development, a high natural variability exists and natural disasters always happened. Information about older fluvial processes during the Holocene is relatively scarce. Results are available from subcatchments, e.g. from parts of the Rhine (DAMBECK a. THIEMEYER 2002) the Main (SCHIRMER 1983), and others (e.g. BECKER 1982; BROWN 2003; SCHELLMANN 1991, 1994; STARKEL 2003). In the Alps very few studies on past fluvial dynamics have been realized (e.g. BURGA et al. 1997; GEITNER 1999; HINDERER 2001; PATZELT 1994; VEIT 2002; VEIT a. HÖFNER 1993). Today, up to more than 50% of the water discharge in the Lower Rhine has its origin in alpine catchments.

In spite of the relatively well-established general pattern of palaeoclimatic fluctuations in Central Europe and the whole Rhine catchment, many aspects remain unclear, and there are still a lot of methodological problems. One of the main problems seems to be the absolute dating control. This holds true especially for the long records (Holocene). Data from archives with annual resolution, such as tree rings and varved lake sediments, are not available everywhere. ^{14}C data provide only a relatively broad time resolution. Events or periods yielding more or less the same ^{14}C age may differ for decades or centuries, making a comparison and interpretation of causal links difficult, if not impossible.

In an area as large as the Rhine basin, available palaeoecological archives differ greatly from region to region. For example, data coming from glacier variations, ice cores and timberline fluctuations in the Alps cannot be gained in the downstream lowlands. Since both time resolution and palaeoclimatic information from different palaeo-ecological archives are not identical, as many archives as possible should be used and compared (multi-proxy approach). Glaciers and timberline may both indicate summer temperature, but glaciers additionally react to humidity changes. Permafrost variations indicate annual temperatures, but snow plays an important role, too. Holocene temperature depressions might be indicated by moraines and inactive or fossil rock glaciers, but warm periods are difficult to detect by means of glaciers and permafrost. Reconstructions of precipitations are even more problematic than temperature. Generally, only the effective moisture (precipitation minus evaporation) can be determined. Moreover, precipitation changes may develop differently from region to region, leading to distinct dynamics in subcatchments. Lake level fluctuations might be caused by precipitation changes alone, or by temperature/evaporation changes as well.

Another problem is the fact that palaeoclimatic archives are frequently influenced not by the palaeoclimate alone. For example, it sometimes takes centuries or even more for plants to spread over long distances, which causes a time lag between climate and vegetation change. In historical times human influence on river dynamics is important due to river engineering, vegetation changes, soil erosion in the catchment, etc. Soil erosion may have already been initialised by the first colonisation during the Neolithic period, some 8,000 years ago (e.g. ZOLITSCHKA et al. 2003), pointing to the urgent need to differentiate between climatic and human influence.

There are clear needs for further investigation regarding the palaeoclimate in the River Rhine catchment. The main problems and recommendations are:

1. obtaining a better dating control (quality and temporal scale)
2. better identification and characterization of warm periods
3. improvement of transfer functions and models
4. reconstruction of Holocene fluvial processes.
5. reconstruction of precipitation or effective moisture in more subcatchments, to test the spatial variability
6. separation of climatic and human impacts on Holocene proxies
7. using as many palaeoecological archives as possible (multi-proxy approach). This will allow for control and more detailed palaeoclimatic interpretation (e.g. summer temperature, winter temperature, annual temperature).

1 *Holocene climate fluctuations in key areas of the River Rhine catchment*

1.1 Introduction

Climatic variations on many temporal, spatial, and functional scales affect various catchment processes, including water budgets and erosional and depositional regimes (e.g. Vandenberghe a. Maddy 2001). Therefore climatic reconstructions are crucial to understand not only correlations between climatic changes and catchment processes but also possible causal links. Through quantification of such processes by combining data and models, sensitivity analyses become possible.

The goal of the present review is first to summarize the existing climatic reconstructions over the entire Holocene (primarily in the River Rhine catchment) and second to address open questions that need to be answered in future studies in order to improve our understanding of climatic effects on river processes. We provide a short introduction first to the climate archives, then to the climatic parameters that can be reconstructed. Discussions of methodology are kept to a minimum but up-dated reviews are presented in Birks (2003), Brooks (2003) and Lotter (2003). Holocene climatic reconstructions are then reviewed for the different regions in the River Rhine catchment from the Alps to the North Sea.

The Holocene (i.e. the past 11,500 years) offers two advantages for an integrated understanding of climatic and environmental changes: it has a duration long enough to allow the distinction to be made between fluctuations and trends; but, in contrast to the Late-Glacial with its very rapid changes of large amplitude, it is also similar enough to the present to provide a baseline for the assessment of climatic and anthropogenic forcing (e.g. Kalis 2003; Zolitschka 2003).

Weaknesses in dating should not be overlooked. Any review of Holocene climatic fluctuations on the spatial scale of the River Rhine catchment must try to correlate results from various sites and natural archives. In many case studies, however, the time control is rather weak, and correlations among sites as well as among methods may thus suffer from a "self-reinforcing syndrome". If synchroneity actually exists, we may still be mesmerized by the basic question, just as were early researchers in the Alps (e.g. Zoller 1977 or Patzelt 1977; Patzelt a. Bortenschlager 1973): Why should recording systems as different as glaciers, lake levels, and subalpine forests respond synchronously to various types of climatic fluctuation?

1.2 The types of natural archives

Every type of archive has its strengths and weaknesses in its sensitivity to various parameters of past climate as well as with respect to the archive-inherent temporal resolution.

Traditionally, climatic fluctuations in the Alps and in Central Europe have been reconstructed from geomorphic and glaciologic features as well as from palaeobotanical data from lakes and mires. More recently, oxygen isotopes measured either on bulk-sediment carbonates (e.g. Eicher 1991; Siegenthaler a. Eicher 1986) or on ostracodes have also been used to reconstruct climatic change in Central Europe.

1.2.1 Glaciers and glacial geomorphology

Glaciers and their fore fields are among the most spectacular glaciological and geomorphic features of high alpine environments and river catchments. The history of glacier variations can be traced by mapping moraines and dating imbedded wood and soils (e.g. Hormes et al. 2001) as well as by interpreting historical documents and early paintings of glaciers (Zumbühl a. Holzhauser 1988).

Glaciers respond to the climatic system and its long-term variations, but the interactions between climatic parameters (e.g. summer temperature, annual or seasonal precipitation) and glacier mass-balance are complex and not completely understood. A change in the mass-balance of an individual glacier interacts with a number of local factors such as the bedrock topography before it results in an advance or retreat of the glacier tongue. For the recession of the last decades observed on the majority of the glaciers in the Alps and elsewhere in the world see Haeberli et al. (1999) and Glaser et al. (2005), this issue.

1.2.2 Biostratigraphies in lake sediments and peat

Traditionally, pollen has provided the best-known biostratigraphy because of its ubiquity, good preservation in lake and mire deposits, and rich morphology, making identifications possible on various taxonomic levels. Vegetation in and around lakes and mires may also be reconstructed from plant macrofossils (e.g. Birks a. Birks 2000, 2003). Other groups of organisms, such as terrestrial insects, small aquatic invertebrates (Cladocera, Ostracoda, chironomid larvae), algae (diatoms and other), and testate amoebae (Rhizopoda) may hold climatic information (Barber 2003), see also section 3. But for all biostratigraphic changes the non-climatic factors (such as nutrient status of lakes or soils) as well as historical processes (including migration of species) overlap with the climatic information and need to be separated. The temporal resolution can often be refined to about 10 years, or in the rare cases of varves (annual laminations in lake sediments) even to single years (e.g. LOTTER 1999). Examples for the high potential of varved sediments are presented in section 6 for the Eifel maar lakes.

A special opportunity in studies of biostratigraphies in alpine and subalpine landscapes is the reconstruction of past timberline fluctuations as a climatic proxy. Tree species at timberline are at their physiological limits. A change to cooler climate can exceed the tolerance of the species concerned, causing high mortality by frost or drought. Such tree diebacks can depress timberline to a new elevation. If temperature increases again, tree species may be able to re-colonise the lost territories but in theory such a vegetation response may be delayed for decades or centuries because of processes such as slow rates of spread, unfavourable competitional conditions, or slow growth due to the harsh alpine climatic conditions. On the other hand, tree species forming the timberline may survive vegetatively during an unfavourable period and then respond with higher productivity (of pollen or fruits or wood) amazingly fast (e.g. at the transition from the Late Glacial to the Holocene, see WICK (2000) and TOBOLSKI a. AMMANN (2000)). The present-day relationship between air or soil temperature and tree-limit is rather close (e.g. KÖRNER 1998), but see also sections 3.1 and 4.2.

1.2.3 Stable isotopes in sediments

The stable isotope composition of precipitation is strongly linked to the temperature in moisture bearing air masses (GRAFENSTEIN et al. 1999a, b). In lakes the isotopic composition of the water will affect the isotopic signal in autogenic and biogenic carbonates formed in the water column. Therefore, stable isotopes of oxygen measured in carbonate sediments (if detrital input can be ruled out) or in ostracod valves have proven to be useful proxies for past air temperatures (e.g. EICHER a. SIEGENTHALER 1976; GRAFENSTEIN et al. 2000; GRAFENSTEIN et al. 1999b). However, two additional factors may also influence the ratio of the oxygen isotopes: i.e. the origin of the moisture (e.g. Mediterranean vs. Atlantic), and the residence time of the water in the lake (depending inter alia on the evaporation from the lake surface).

1.2.4 Past changes in lake levels

The reconstruction of past changes in lake-levels provides proxy data relevant to the Holocene palaeohydrological history (WOHLFARTH a. SCHNEIDER 1991; HARRISON a. DIGERFELDT 1993; YU a. HARRISON 1995; MAGNY 1998). But lake-level changes can be induced by various local non-climatic factors such as damming of the lake outflow by a tributary, disturbance in the catchment area by fire (WOHLFARTH a. AMMANN 1991). However, regionally synchronous changes in lake levels can be assumed to be climatically driven (HARRISON a. DIGERFELDT 1993). Moreover, comparison of lake-level records with other palaeoclimatic records based on other proxy data from the same region (HAAS et al. 1998) or from geomorphic, ice-sheet, and marine records (MAGNY a. SCHOELLAMMER 1999) can give evidence for their climatic significance.

Some difficulties have to be taken into account in comparing regional lake-level records (MAGNY 1992). For instance, lakes cover a range of sensitivities to climatic events, depending on their hydrological regimes (e.g. pluvial vs. proglacial), the ratio of catchment/lake areas, and their type (closed or out-flowing basins). Anthropogenic forest clearance in the catchment area can reinforce the impact of changes in water supply (e.g. KALIS et al. 2003; ZOLITSCHKA et al. 2003). Furthermore, the reconstruction of lake-level changes is also affected by the exposure and erosion of the studied site. Near-shore areas in lakes are often characterized by sediment hiatuses (MAGNY a. RICHOZ 2000; MAGNY 2001) that are generally absent in cores taken from deeper parts of lacustrine basins .

1.3 What climatic parameters may be reconstructed?

Even if STOKSTAD (2001) summarizes "Myriad ways to reconstruct Past Climate" we still are confronted with the problem that not only climatic parameters are auto-correlated but all proxy data (continental or marine) are influenced by many factors, only some of which are directly related to climate.

1.3.1 Summer temperatures

Traditional interpretations of changes in biostratigraphies were rather based on expert knowledge about ecological requirements of taxa and their biogeographic distributions than on numerical relationships between species and their abiotic environment. Recently, however, several quantitative inference models have been elaborated for different regions of the world. These so-called transfer functions are based on linear or unimodal empirical relationships between biota and their physical or chemical environment and represent a multi-indicator species (assemblage) approach to environmental reconstruction (for details see e.g. BIRKS 1995). As biota are most active and reproduce during the warm season, these transfer functions commonly model their relationship to summer or July temperatures. This is valid not only for pollen (e.g. GUIOT 1991;

LOTTER et al. 2000a) but also for organisms living in aquatic environments, such as chironomids ostracods, diatoms and Cladocera. Most of these transfer functions were developed for arctic and boreal regions, but a few allow quantitative summer-temperature inferences for the Alps and their foreland (e.g. WUNSAM et al. 1995; LOTTER et al. 1997a), with an accuracy of between 1.2 and 1.8°C that is inherent in the method.

A yet unresolved problem is the discrepancy often observed between beetle-inferred summer temperatures and temperature reconstructions based on chironomids or stable isotopes (e.g. AMMANN a. OLDFIELD 2000). The mutual-climatic-range method (MCR) applied to beetles (ATKINSON et al. 1987; COOPE a. LEMDAHL 1996; LEMDAHL 2000) usually results in much higher estimations of mean July temperatures than all other methods.

In dendro-climatology the density of the late wood is usually considered to show the strongest correlation to the sums of June to September temperatures (SCHWEINGRUBER et al. 1979). Efforts to use the more readily available data on tree-ring width with a large spatial coverage are presented (e.g. by WILSON et al. 2003).

For past changes in timberline elevation, the question remains which temperature thresholds are effective for which part of the year, even if the relationship between (air or soil) temperature and tree-limit is rather close. ELLENBERG (1966) suggested that in the Alps the timberline is positioned where air temperature reaches more than 5°C for 100 days. Other suggested relationships are for example the air temperature of the warmest month, e.g. 7.5°C for *Pinus cembra* (LANDOLT 1992) or of the growing season. It seems likely that timberline is related to temperature during the growing season, considering that low temperatures impede a sufficient biomass production for trees (concept of minimum temperature for tree growth; see KÖRNER 1998). An additional problem can be caused by the spatial band (i.e. the ecocline) between the timberline (i.e. upper limit of more or less dense forest) and tree-line (i.e. the upper elevation of single trees in favourable microhabitats) as discussed by TINNER and THEURILLAT (2003).

For the Alps it is conventionally assumed that under undisturbed (and natural) conditions the transitional zone between forest and alpine meadows would encompass only about 100 altitudinal meters (OZENDA 1988). The two vegetation types that form this clear boundary normally leave unmistakable traces in archives such as lakes and mires that can be followed back for millennia. The analyses of these macrofossils and microfossils may hence reveal the past position of the timberline and its fluctuations in response to climatic change. Assuming lapse rates of 6–7°C km^{-1} and timberline vegetation in equilibrium with climate, Holocene summer temperature variations may be reconstructed.

1.3.2 Winter temperatures

In spite of the early seminal paper by IVERSEN (1944) using "climatic space" (mean temperatures of the warmest and of the coldest month) vs. biogeographic space of three frost-sensitive plant genera (*Hedera, Ilex, Viscum*), estimations of winter temperatures remained more difficult. This "Iversen-approach" sensu lato is also applied in numerical techniques (e.g. KLIMANOV 1984; TARASOV et al. 1999), that may provide spatially coherent pictures but rather variable error ranges. Similarly, the mutual climatic range method applied to fossil Coleoptera uses an estimate of continentality similar to that of IVERSEN, but the difference between the warmest and the coldest month rather than the mean of the coldest month (e.g. COOPE a. LEMDAHL 1996).

1.3.3 Precipitation and its seasonality

Proxies for precipitation are even more problematic than the ones for temperatures. What can be estimated in the best case is the past effective moisture, i.e. the difference between precipitation and evapotranspiration (M = P – E). Studies on the hydrology of ombrotrophic raised mires using peat humification and rhizopods may give information on past precipitation regimes (e.g. BARBER 2003). Such studies have been carried out in north western Europe (e.g. AABY 1976; CHARMAN et al. 2004) but there are only very few such studies from Central Europe and the Alps (MITCHELL et al. 2001; ROOS-BARRACLOUGH et al. 2004).

The approach of reconstructing lake-level changes is based on the assumption that closed lake basins are the nearest equivalent of a "long-term rain gauge" available for palaeoclimatological studies. Closed basins are rare in temperate zones such as the catchment of the River Rhine. Most lake-level reconstructions in Europe are therefore made for lakes with inlets and outlet.

Furthermore, it is difficult to reconstruct temperature and precipitation from lake-level fluctuations alone, because a positive water balance may be due to a decrease in precipitation and/or a decrease in temperature. Moreover, other factors such as cloudiness and wind have a direct impact on lake evaporation (HOSTETLER a. BENSON 1990). However, at present pronounced low water levels of lakes without glacial water supply in the Jura Mountains and on the Swiss Plateau are often associated with dry and warm late summers. This observation suggests that Holocene lake-level lowering could reflect periods of negative summer water balance due to decreasing water supply and to lengthening summer season with stronger evaporation and evapotranspiration (MAGNY 2004).

Glacier advances and retreats also can be assumed to give (partial) information about the water balance. Glacier mass balance depends not only on summer temperatures (ablation) but also on snow accumulation in Alpine catchment areas (alimentation).

What may be the most relevant precipitation effect for river systems is the frequency and magnitude of extreme thunderstorms. The temporal distribution of turbidity currents in lake sediments may be a proxy of extreme precipitation events that remains to be exploited (GILLI et al. 2003).

1.3.4 The link between temperatures and precipitation during the vegetation period

The observation that cool summers may also be wet summers is often made in modern and historical climatology, but it is not true for all summers, for high values of precipitation may also be caused by high frequencies of thunderstorms . In the case of climate proxies, such a (simplifying) correspondence may serve as a qualitative explanation for the synchronicity between fluctuations of timberlines, glaciers, and lake levels: In summer low-temperature-sums (expressed as growing-degree-days) and high precipitation sums may result in poor and short growing seasons. At the same time little ablation and high albedo (i.e. positive water-balance) may cause glaciers to advance, and high values of P-E in catchments may cause lake levels to rise. If such conditions last over longer periods the result thus may be lower timberlines, longer glacier tongues, and higher lake levels (e.g. PAULSEN et al. 2000; MAGNY 1993a).

Additional, rather elegant methods are restricted to the period covered by historic documents such as records of frozen lakes and rivers.

1.4 The alpine area

1.4.1 Glaciers and proglacial varves

Based on glaciological data, depressions of the mean annual temperature of 3–4°C (HAEBERLI 1991) and of the mean summer temperature of 1.0–1.4°C (HERREN et al. 2000) have been deduced for the Younger Dryas period. Annual precipitation at an altitude of 2,000 m a.s.l. may have been as much as 25% lower than today at the northern border of the Alps and 30–35% lower in the inner alpine areas (HAEBERLI 1991).

With the beginning of the Holocene about 11,500 cal years ago (10,000 radiocarbon years ago) and the final melting back of the Alpine glaciers far into the upper reaches of the mountains, there appears to be evidence of an extraordinarily steady climatic and glacial evolution, with reduced or minimal fluctuations (Fig. 1 D). Compared with the preceding Late-Glacial period, a much warmer climatic level is now well documented. At least eight advancing phases can be compared with the same number of recessional phases with a glacial extent similar to that found today. The period of maximum extent in 1850/60 AD, with its pronounced moraine systems, thus represents a dimension of glacial history that is not only typical for the period of the Little Ice Age (ca. 1350–1850 AD), but also for almost all the preceding Holocene periods of maximum extent (PATZELT a. BORTENSCHLAGER 1973; PATZELT 1995; FURRER 1991; HOLZHAUSER 1995).

However, much more uncertainty exists about the minimum extents in the warm periods than about the geomorphic-stratigraphic periods of advance, for which clear proof can usually be given because of datable morainic deposits. Recent research into glacial history indicates that glaciers during the warmer or drier climatic periods of the Holocene might have been slightly smaller than today (HORMES et al. 2001). Thus for the period of about 8,850 to 5,750 cal (or 8,000 to 5,000 radiocarbon-) years ago peat profiles found near the edge of the ice at the Rutor Glacier (PORTER a. OROMBELLI 1985; BURGA 1991) and at the Gauli Glacier (WAESPI 1993) showed that the ice extent was smaller than during the 1980s. The same was found in the forefield of the Pasterze Glacier in the Austrian Alps (SLUPETZKY et al. 1998; NICOLUSSI a. PATZELT 2000). Even at the Great Aletsch Glacier (which is considered to react slowly at its terminus because of its mass), fossilized centuries-old wood debris of trees grown in situ recently emerged from under the ice edge. This means that the glacier was probably shorter approx. 3400 cal years ago, i.e. just following the final phase of the CE-7 fluctuation (“Löbben”, 3750 to 3400 cal years ago or 3500 to 3200 radiocarbon years BP) and approx. 2000 cal years ago than it was in the AD 1990s (HOLZHAUSER 1997).

The Holocene seems to be a period of glacial variations that, although numerous, were always of similar size and caused by climatic changes of comparably low amplitude (± 1°C). Within the Holocene glacial variations, the large extent of the glaciers around the year 1850/60 AD marks a characteristic extent and rapidity that was reached repeatedly but was surpassed only rarely. It is quite possible that glacier dimensions in the earlier warm phases of the post-glacial period, i.e. the time of the “pre-industrial”, mainly “natural” climate, were smaller than those of the present greenhouse time. The current glacial situation is thus within the

Holocene range of variation, while being clearly in the warm transition area of all reconstructable glacial and climatic fluctuations. This range, on the other hand, will probably be exceeded if the predicted temperature-rise scenarios really occur (IPCC 2001; Maisch et al. 2000).

Varve studies of a proglacial lake by Leemann and Niessen (1994) and Ohlendorf (1999) suggest that in the Eastern Swiss Alps no glaciers existed between about 10,750 and 3,500 cal a BP (or 9,400 and 3,300 radiocarbon a BP). Neoglaciation began around 3,500 cal a BP, and the highest glacier-induced sediment accumulation, which also points to the maximum Holocene glacier extent, occurred during the Little Ice Age. For the Little Ice Age several well-documented glacier advances are evidenced in the Alps (Wanner et al. 2000).

1.4.2 The timberline

The timberline represents the major ecotone in the Alps that is sensitive to climatic change. Tentative late-glacial and Holocene timberline reconstructions based mainly on palynological data have been presented for different parts of the Alps (Welten 1982; Schneider 1985; Burga 1987). However, two major problems make purely pollen-derived reconstructions problematic: firstly, most alpine studies have a poor time control (i.e. are based on few radiocarbon dates only), and secondly, pollen and spores are easily transported by winds for hundreds or thousands of metres. Therefore, to spatially trace past treeline positions unequivocally, macrofossils are certainly better indicators than pollen grains. In addition, stomata of conifers (pines, spruce, fir, larch, and juniper, usually counted on pollen slides) may serve as proxies for the presence of needles (Ammann a. Wick 1993). But due to the wide distribution of pollen by wind, pollen results have been successfully used to capture regional climate-induced vegetational signals, such as collapses or expansions of entire vegetation belts (e.g. subalpine *Pinus cembra* forests, Tinner et al. 1996). In this sense macrofossil and pollen analysis complement one another (local vs. regional vegetation reconstructions, see Tinner a. Theurillat 2003 and Fig. 1 A, B).

Only a small set of such combined investigations is available from higher elevations in the Alps, where a reliable estimation of past timberlines is possible (e.g. Markgraf 1969; Welten 1982; Lang a. Tobolski 1985; Lang 1993; Ponel et al. 1992; Ammann a. Wick 1993; Wick et al. 2003; Heiri 2003a; Heiri et al. 2003b). In a study of two well-dated sites in the Central Alps (Wick a. Tinner 1997) could correlate Holocene timberline fluctuations with glacier advances (Patzelt 1977), solifluction phases (Gamper 1993), and dendroclimatic data (Renner 1982; Bircher 1986; Kaiser 1991).

The interpretation of palaeobotanical results from timberline is based on the assumption that forest diebacks caused by cold periods are characterised by decreasing frequencies of macrofossils and microfossils of tree species in the sediment. In contrast, warm climatic periods are mirrored by increasing frequencies of tree-species remains because of higher local abundance of trees around the site. However, in studies with very high temporal resolution, an opposite effect may be possible: during the first years of climatic cooling increasing mortality initially may lead to an increased release of tree macrofossils such as wood, bark, needles, and seeds to soils and sediments.

According to several authors (e.g. Burga a. Perret 1998) the range of Holocene climatically induced timberline fluctuations was not more than 100–150 m. Assuming modern air-temperature lapse rates for the Alps of 6–7°C km^{-1}, the Holocene climatic fluctuations during the warm season may, therefore, have had an amplitude of 0.5–1°C.

In figure 1 (A and B) oscillations of timberline are illustrated by declines in the curves (macrofossils and pollen) of *Pinus cembra* and the sum of tree pollen. After the local extinction of *Pinus cembra* at around 4000 cal BP the cold phases are recorded by tree species growing 200–300 m below the former *Pinus cembra* belt (e.g. *Picea abies*).

This approach is based on well-dated continuous profiles showing an uninterrupted development throughout the entire prehistoric Holocene and was first presented by (Wick a. Tinner 1997). It differs from previous timberline studies in the Alps, for single cold phases were conventionally identified at different name-giving sites (e.g. Misox, Piora). The new approach may help to overcome the following problematic aspects of previous studies:

(1) Synchronous climatic changes were sometimes interpreted as asynchronous because of site-related dating problems.

(2) Considering that in previous studies the Holocene overviews relied on discontinuous sources, the general Holocene trend was not directly documented. Moreover, because of site-related environmental differences (such as different altitudes, soil conditions, disturbances) the magnitudes of the timberline and climatic oscillations could not be directly compared.

(3) Single cold phases were unpublished or published separately in local or national journals. Because of the large amount of data, the synthesis publications

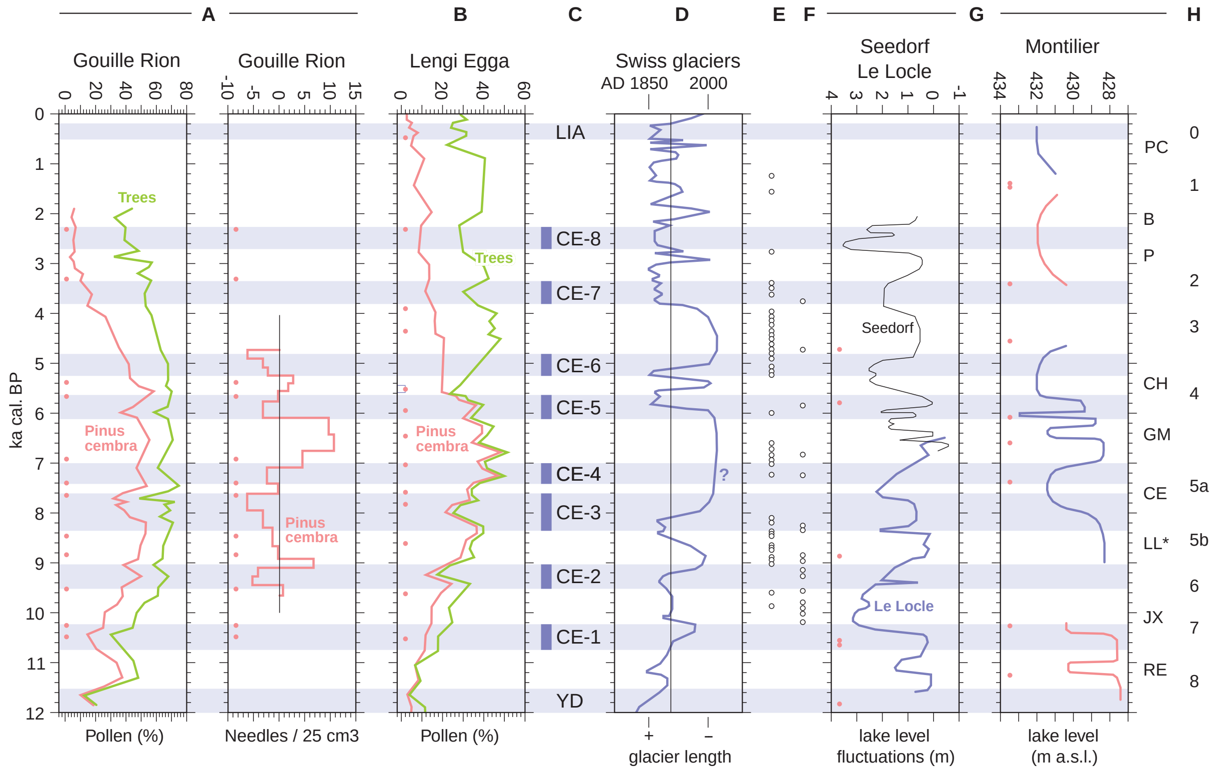

Fig. 1: Synthesis over Holocene fluctuations in the Alps based on various archives on a time-scale of calibrated years before present (BP).

A: Timberline fluctuations recorded by pollen percentages (*Pinus cembra*, sum of trees) and macrofossil concentrations (*Pinus cembra* needles) at Gouillé Rion (Swiss Alps, TINNER et al. 1996; WICK a. TINNER 1997). The pollen sum includes only subalpine and alpine taxa.

B: Timberline fluctuations recorded by pollen percentages (*Pinus cembra*, sum of trees) at Lengi Egga (Swiss Alps, TINNER a. THEURILLAT 2003). The pollen sum includes only subalpine and alpine taxa.

C: Central European cold-humid phases (HAAS et al. 1998). CE-1 approximately corresponds the Schlaten oscillation (PATZELT 1977), CE-2 to the Venediger and Bivio oscillations (PATZELT 1977; ZOLLER 1977), CE-3 to the Misox oscillation (ZOLLER 1960), CE-4 to the Frosnitz oscillation (PATZELT 1977), CE-5 to the Rotmoos I and Piora I oscillations (PATZELT 1977; ZOLLER 1977), CE-6 to the Rotmoos II and Piora II oscillations (PATZELT 1977; ZOLLER 1977), CE-7 to the Löbben and Tiefengletscher oscillations (PATZELT 1977; ZOLLER 1977) and CE-8 to the Historical First Millennium BC and Göschenen I oscillations (PATZELT 1977; ZOLLER 1977). For further details and original chronologies of cold phases in previous studies see WICK and TINNER (1997) and HAAS et al. (1998).

D: Glacier length variations: The dimension of the present-day glaciation lies at the «warm» boundary but still within the range of the Holocene variations (compiled after various sources, adapted and modified after (MAISCH et al. 1999, 2000).

E: Dated wood from Swiss Alpine glaciers representing warm phases (HORMES et al. 2001).

F: Dated wood from Austrian Alpine glaciers (SLUPETZKI et al. 1998; NICOLUSSI a. PATZELT 2000).

G: Lake-level changes combined from the three sites Le Locle (Early Holocene, MAGNY a. SCHOELLAMMER 1999), Seedorf (Late Holocene, MAGNY a. RICHOZ 1998), and Montilier (MAGNY a. RICHOZ 2000). The abbreviations on the right side (PC, B, P, CH, GM, CE, LL*, JX, RE) stand for phases of high lake levels according to MAGNY (1999).

H: Holocene climatic cold phases as evidenced by marine sediment analyses from the North Atlantic (BOND et al. 1997, 2001). The cold period 5 (BOND et al. 1997) was subdivided into 5 a and b according to BOND et al. (2001).

The dots in A, B, and G show the chronological position of radiocarbon dates used for the depth-age models.

Fig. 1: Synthese der Holozänen Schwankungen in den Alpen basierend auf verschiedenen Archiven in kalibrierten Jahren vor heute (BP).

A: Schwankungen der Baumgrenze aufgezeichnet als Pollenanteile (*Pinus cembra*, Summe der Baumpollen) und Makrofossilkonzentrationen (*Pinus cembra* Nadeln) in Gouillé Rion (Schweizer Alpen, TINNER et al. 1996; WICK a. TINNER 1997). Die Pollensumme beinhaltet nur subalpine und alpine Arten.

B: Schwankungen der Baumgrenze aufgezeichnet als Pollenanteile (*Pinus cembra*, Summe der Baumpollen) in Lengi Egga (Schweizer Alpen, TINNER a. THEURILLAT 2003). Die Pollensumme beinhaltet nur subalpine und alpine Arten.

C: Mitteleuropäische Kältephasen (HAAS et al. 1998). CE-1 entspricht ungefähr der Schlaten Schwankung (PATZELT 1977), CE-2 den Venediger und Bivio Schwankungen (PATZELT 1977; ZOLLER 1977), CE-3 der Misox Schwankung (ZOLLER 1960), CE-4 der Frosnitz Schwankung (PATZELT 1977), CE-5 den Rotmoos I und Piora I Schwankungen (PATZELT 1977; ZOLLER 1977), CE-6 den Rotmoos II und Piora II Schwankungen (PATZELT 1977; ZOLLER 1977), CE-7 den Löbben und Tiefengletscher Schwankungen (PATZELT 1977; ZOLLER 1977) und CE-8 den Schwankungen im ersten Jahrtausend v. Chr. und Göschenen I (PATZELT 1977; ZOLLER 1977). Weitere Details und Chronologien aus vorhergehenden Studien finden sich bei WICK und TINNER (1997) und HAAS et al. (1998).

D: Änderungen der Gletscherlängen: Die heutige Gletscherausdehnung liegt im Bereich der «warm» Grenze, jedoch noch innerhalb der holozänen Schwankungsbreite (zusammengestellt aus verschiedenen Quellen, verändert übernommen aus (MAISCH et al. 1999, 2000).

E: Datiertes Holz aus Schweizer Alpengletschern als Repräsentant für warme Abschnitte (HORMES et al. 2001).

F: Datiertes Holz aus Österreichischen Alpengletschern (SLUPETZKI et al. 1998; NICOLUSSI a. PATZELT 2000).

G: Seespiegelschwankungen als Kombination der Befunde in Le Locle (Frühes Holozän, MAGNY a. SCHOELLAMMER 1999), Seedorf (Spätholozän, MAGNY a. RICHOZ 1998), und Montilier (MAGNY a. RICHOZ 2000). Die Abkürzungen auf der rechten Seite (PC, B, P, CH, GM, CE, LL*, JX, RE) kennzeichnen Hochstandsphasen nach MAGNY (1999).

H: Holozäne Kältephasen nach Meeresbodenablagerung im Nordatlantik (BOND et al. 1997, 2001). Die Kältephase 5 (BOND et al. 1997) wurde unterteilt in 5 a und b gemäß BOND et al. (2001).

Die Punkte in A, B, und G markieren die Radiokohlenstoffdatierungen aus Tiefen-Alter-Modellen

were made without raw data (^{14}C-dates, pollen curves, sedimentological results). This led some authors to question the accuracy and reproducibility of such results (e.g. LANG 1993).

(4) Because of the multitude of publications and hence of named cold phases the temptation was high to selectively choose cold phases fitting one's own results. Unfortunately, such arbitrary selections are traceable in some studies from the Alps.

Recently, a systematic redefinition of the Holocene climatic fluctuations in the Alps was attempted by (HAAS et al. 1998) introducing a nomenclature (CE-1 to CE-8, see Fig. 1 C), which is based on explicitly defined raw data such as taxa curves and ^{14}C-dates of four sites. Surprisingly, this small selection of sites confirmed most cold phases of earlier works accomplished between the 1950s and the 1990s. Furthermore, some of the more severe Alpine oscillations seem synchronous with the cool climatic periods recently found in the North Atlantic and in Greenland (HEIRI et al. 2004).

1.4.3 Terrestrial and aquatic multi-proxy studies on an altitudinal gradient

In recent years several well-dated lake sediments in the Bernese Oberland were studied using a multi-proxy approach (LOTTER et al. 2000b; KORHOLA et al. 2000). These lakes are situated along an altitudinal transect spanning modern vegetational zones from the montane to the alpine belt. According to quantitative climate reconstructions using different biological proxies such as vegetation remains (WICK et al. 2003), and chironomids (HEIRI a. LOTTER 2003) that are supported by sedimentological (KOINING et al. 2003; OHLENDORF et al. 2003), and geophysical data (HIRT et al. 2003), the summer temperatures were on average higher in the early to mid-Holocene and decreased gradually towards modern values. Climatic oscillations such as the one around 8200 cal a BP that led to timberline depressions had also an impact on aquatic organisms, most likely through prolonged ice-cover leading to a shortening of the growing season and to anoxic conditions in the bottom waters of the lakes (LOTTER a. BIGLER 2000).

Comparing chironomid-inferred temperatures with the palaeobotanical data of TINNER et al. (1996), HEIRI (2001) suggested six Holocene periods of reduced summer temperature in the Alpine region (at 10500–10400 cal a BP, 9200–9100 cal a BP, 8200–7700 cal a BP, 6000–5800 cal a BP and 4000–3700 cal a BP). These coolings were tentatively correlated to ice-rafted debris events in the North Atlantic. Recent evidence suggests a different timing of ice rafting in the North Atlantic (BOND et al. 2001), making this correlation questionable. Nevertheless, the results of TINNER et al. (1996) and HEIRI et al. (2003) show that millennium- to centennial-scale Holocene climatic oscillations can be found in biotic records from the Alps. In contrast to glacier reconstructions their records suggest that cold phases at ca. 10700–10500 and 8200–7700 cal a BP were more severe than climatic fluctuations during the rest of the early to Mid-Holocene.

1.4.4 The combination of lake levels and pollen

Models using both pollen and lake-level data can be used to reconstruct changes in moisture conditions (GUIOT et al. 1993; HARRISON a. DIGERFELDT 1993). Pollen data may offer information on past changes in precipitation as well as in temperatures. But in the mid-European latitudes precipitation is rarely a main limiting factor in vegetational development. From a modelling approach combining pollen and lake-level data, various climatic parameters have been reconstructed at Le Locle, Swiss Jura, for the Younger Dryas to the Mid-Holocene period (MAGNY a. BÉGEOT 2004). This quantitative reconstruction suggests that phases of lake-level rise coincided with increasing annual precipitation, P–E (runoff), and P/PE (actual/potential evapotranspiration, i.e. available moisture), decreasing mean temperature of the warmest month, and a cooling and/or shortening of the growing season. These results are consistent with modern analogues and with the synchronicity between the rise in lake level in the Jura Mountains and cooling oscillations in the Alps (glacier advances and timberline declines) observed by MAGNY (2004) and HAAS et al. (1998). They seem largely to correlate with various palaeoclimatic records in Europe and sites around the North Atlantic (provided that time-control is good enough (MAGNY 2004).

1.4.5 Alpine foreland and Jura mountains

Lowland ecosystems are generally only sensitive to high-amplitude climatic fluctuations, such as the ones occurring during glacial-interglacial cycles. Several studies of fossil biota or stable isotopes from lowland sites in Central Europe suggest a temperature increase at the onset of the Holocene of about 2–6°C (GRAFENSTEIN et al. 1999b); (ISARIN a. BOHNCKE 1999; KORHOLA et al. 2000; LOTTER a. BIGLER 2000; LOTTER et al. 2000a). Hardly any biotic evidences exist for Holocene climatic fluctuations from lowland sites, as these are too far away in climatic space from ecotonal situations. However, using timberline fluctuations in the Alps and different climatic reconstructions from sites on the Swiss Plateau, HAAS et al. (1998) identified eight synchronous pre-Roman cold phases, i.e. at 9600–9200, 8600–8150, 7550–6900, 6600–6200, 5350–4900, 4600–4400, 3500–3200, and 2600–2350 radiocarbon years BP, which translate into 10700–10200, 9600–9050, 8300–7700, 7450–7050, 6100–5700, 5250–5050, 3750–3400, and 2650–2400 cal a BP; they suggest an approximate 1000-year cyclicity of Holocene climatic oscillations. In the Jura Mountains MAGNY (1998) found several Holocene fluctuations of lake levels. As these fluctuations coincided with fluctuations in ^{14}C and glacier fluctuations in the Alps, he suggested that changes in solar activity and in ocean circulation cannot be ruled out as forcing factors of Holocene climatic changes.

Other examples for abiotic evidences of Holocene climatic change are the detection of several short fluctuations in the oxygen isotopes of ostracode valves from a pre-Alpine lake in southern Germany amongst others the 8200 cal a BP event (GRAFENSTEIN et al. 1998), which is interpreted as caused by short weakening of the thermohaline circulation through an interval of freshwater input into the North Atlantic. TINNER and LOTTER (2001) found a striking coincidence between the 8200 cal a BP event and the onset of changes in the vegetation composition in two annually laminated Central European lakes, which was attributed to the onset of moister conditions due to changed air-mass trajectories.

LIVINGSTONE and HAJDAS (2001) presented different cyclicities in the thickness of biogenic varves that they attributed to solar forcing of the biological productivity in the water column of Soppensee, a small lowland lake on the central Swiss Plateau.

1.5 Central and north western Europe

Rapid climatic fluctuations of large amplitudes during the last glacial/interglacial transition are well documented in north western Europe in pollen and lake sediment data (e.g. ISARIN a. BOHNCKE 1999; LITT et al. 2001; BRAUER et al. 2000), whereas it is more problematic to detect the attenuated changes during the Holocene. In particular, quantitative reconstructions of specific climatic parameters are difficult to achieve. Therefore, changes in the hydrological cycle that are considered as integrated responses to both temperature and precipitation changes are key sources for tracing climatic variability. Common measures of hydrological changes are lake-level variations and bog evolution (e.g. AABY 1976; MAGNY 1993a; STARKEL et al. 1996; VAN GEEL et al. 1996). A less frequently utilized integrative signal of climatic change are annual to seasonal variations in the sedimentation pattern of varved lake sediments such as the one from the Eifel maars. Long varved records provide precise chronologies reaching back even into the last glacial maximum (ZOLITSCHKA et al. 2000). Past climatic oscillations are well reflected in varve micro-facies and thickness changes (BRAUER et al. 1999; BRAUER 2004). Time-series analyses of varve-thickness data revealed periodicities similar to those known from solar irradiation variations like the 11-year Schwabe cycle and the 88-year Gleisberg cycle (VOS et al. 1997).

Thus it can be expected that also more pronounced fluctuations and abrupt or gradual shifts leading to persisting changes are visible in varve micro-facies. In the early Holocene two periods (11350–11000 and 10450–10250 varve a BP) with marked variations in seasonal diatom blooms and detrital influx in the sediments from Holzmaar indicate short-term cold and wet climatic oscillations (Brathauer et al. 1999). These phases correlate with events of increased ice-rafted detritus in the North Atlantic (events 8 and 7 according to Bond et al. 1997). At 9700 varve a BP a longer-lasting change in diatom assemblages coupled with decreased erosion occurred within 150 varve years. These changes coincide with a phase shift in the 11-year cycle in varve-thickness data (Vos et al. 2001). Both observations suggest a re-organisation of the lake system that is not yet fully understood. The 8.2 ka-event does not show a distinct signal in the maar lakes. At Meerfelder Maar diatom abundances decreased at that time, but since the low-productivity phase lasted for about 600 years it does not reflect an event-type signal. A further gradual transition to colder climatic conditions is documented in the Holzmaar varves between 5800 and 5200 varve a BP by changes in the diatom assemblages and related formation of seasonal layers. One of the strongest climatic fluctuations during the Holocene presumably occurred at 2650 varve a BP and has been frequently observed (van Geel et al. 1996). From this time on (Iron Age) the sedimentation pattern in the Eifel maar lakes is to a high degree influenced by human activities in the catchment (Zolitschka et al. 2003).

For a long time the cyclic climatic fluctuations in north western Europe during the Holocene have been related to changes of the North Atlantic thermohaline circulation. More recently, previously suggested links to solar variations (e.g. Magny 1993b; Vos et al. 1997; van Geel et al. 1998) appear to become more widely accepted (Bond et al. 2001), although the mechanisms influencing the climate system are still poorly understood. The overall trend from a Mid-Holocene climatic optimum towards colder and wetter conditions in the Subboreal and Subatlantic might be linked to orbital changes leading to decreasing summer and increasing winter insolation. However, this can only partly explain the more continental situation in north western Europe with a pronounced seasonality in the early Holocene. It is assumed that also the post-glacial sea-level rise with the flooding of the southern North Sea and the establishment of a link to the North Atlantic between 9500 and 9000 cal a BP (Beets a. Spek 2000) played an important role for the maritime influence on north western Europe. Flooding of the North Sea Basin and subsequent sea-level rise also affected fluvial activities through a decreasing river gradient.

2 *Climate variations and flood frequencies in the River Rhine catchment area since 1500*

2.1 *Climate trends and floods in the 20th century*

In the 1990s numerous severe floods occurred in Central Europe, for example at the River Rhine and at the Mosel in December 1993 and January 1995, at the Moldavia, at the Oder in July 1997 and at the Elbe 2002. Again, these events made it clear, that floods are amongst the most disastrous natural hazards. For this reason, flood-events regularly cause discussions about their frequencies, tendencies and the changes in their intensities (s. Mendel et al. 1997).

In recent years, questions have arisen, whether human activities are responsible for the increased greenhouse effect (e.g. Bendix 1997) and what kind of changes affect the catchment areas. Answers to these questions can be found by comparing series of temperature, precipitation and atmospheric circulation patterns with series of severe flood-events.

Since the mid 19th century, climate development in the catchment area of the Rhine can be evaluated on the basis of official and standardized measuring data. On a global as well as on a regional scale, this relatively short period of about 150 years is still the only commonly recognized scale for characterizing climate development.

In Central Europe, from 1891 to 1990 temperature increase for all seasons was proven to be up to 1°C. During winter, these values range between 0.5 and 1.0°C, during spring between 0 and 0.5°C and during summer and winter also by up to 1.0°C (Schönwiese et al. 1993). Even though, this warming is clearly recognizable in many places, it can neither be explained by changing forcing factors nor can it be brought into a simple context with large-scale circulation deviations (Schmutz et al. 2000). In the 1990s the global and regional warming trend has significantly accelerated. Within the past 500 years, this recent warming is unique in scale and structure for Central Europe (Pfister 1999; Glaser 2001). In the northern hemisphere the 1990s decade was the warmest in the past millennium (Mann et al. 1999). In western Europe the exceptional heat wave during the summer of 2003 caused many deaths and heavy economic losses – and seems to resemble the event of 1540. Further effects of global warming are the melting of Alpine glaciers (Maisch et al. 2000) and the premature disappearance

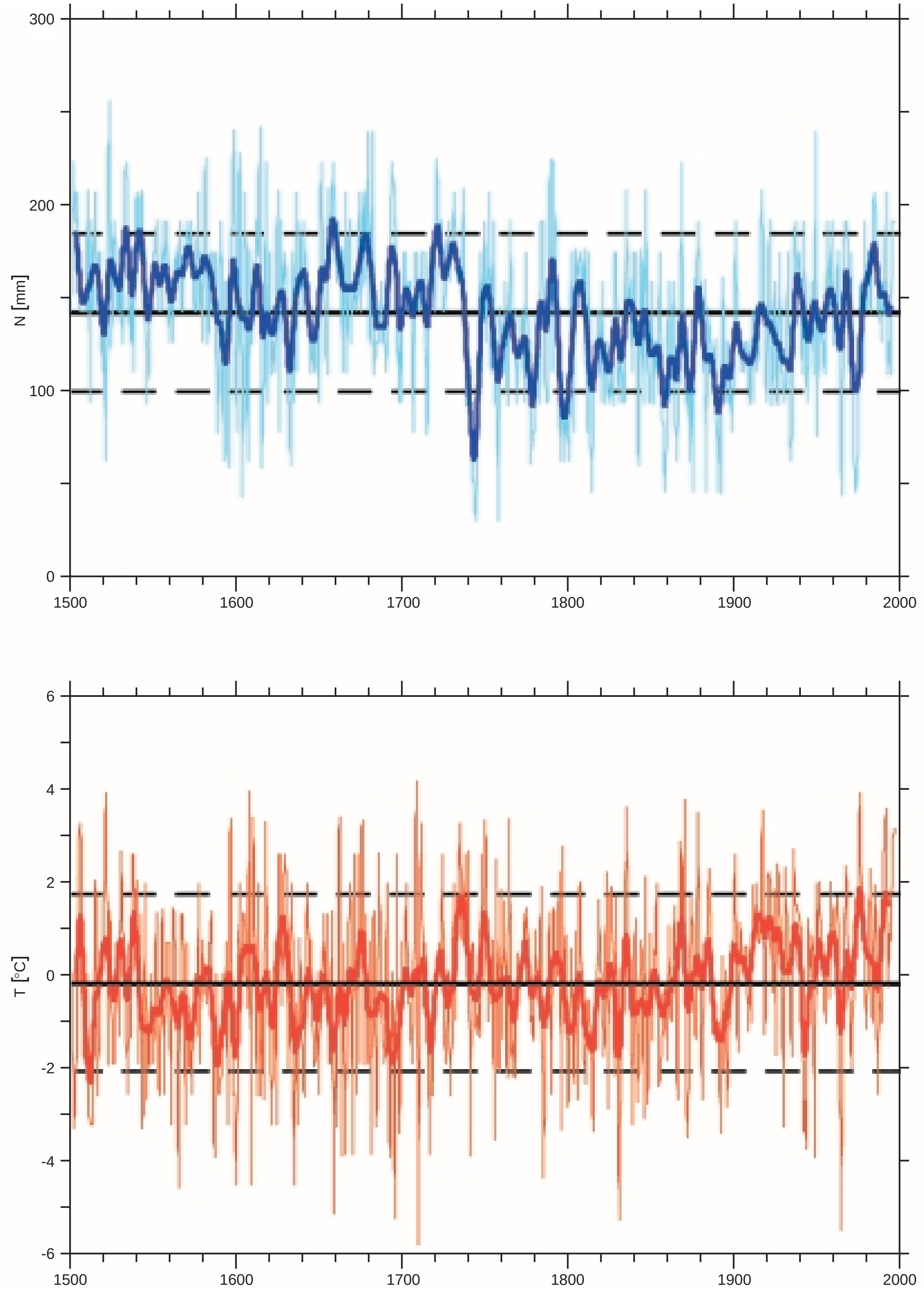

Fig. 2: Development of winter temperatures and precipitation in Central Europe since the year 1500 (Glaser 2001)
Entwicklung der Wintertemperaturen und -niederschläge in Mitteleuropa seit 1500 (Glaser 2001)

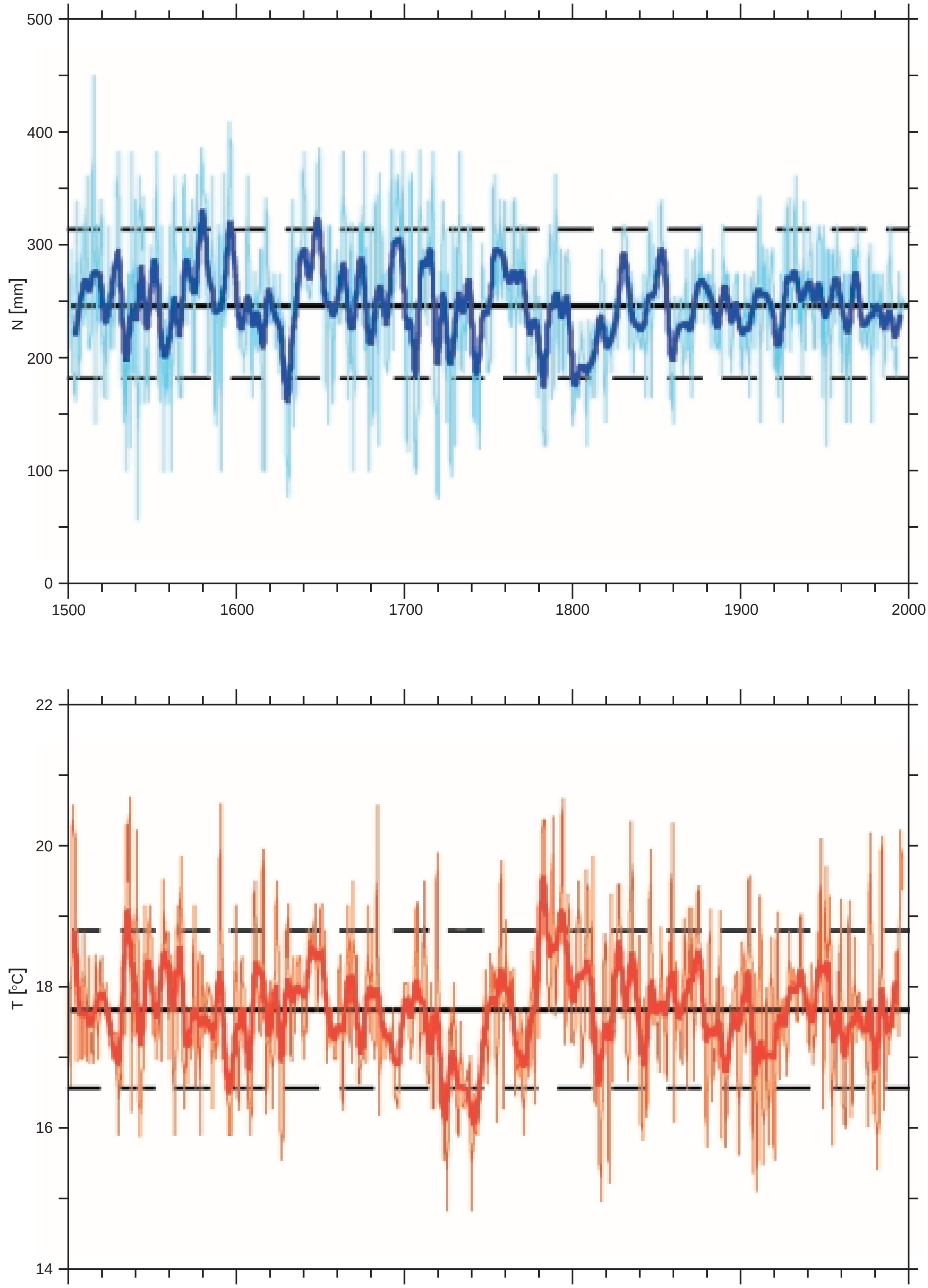

Fig 3: Development of summer temperature and precipitation conditions in Central Europe since the year 1500 (GLASER 2001)

Entwicklung der Sommertemperaturen und -niederschlagsverhältnisse in Mitteleuropa seit 1500 (GLASER 2001) of the ice cover on lakes and rivers that happens up to two weeks too early. Moreover, it is also observed that the vegetation period is up to 12 days longer.

During this century, in Switzerland, the annual precipitation has increased significantly at numerous stations, especially during the recent warm phase and particularly in winter (PFISTER 1992; WIDMANN a. SCHÄR 1997). In their paper the two authors show that the increase in precipitation is mainly based on the activities of weather patterns (higher temperatures and wind velocities) and not on a change in their frequencies. Recent studies on historical circulation variability also confirm that internal variations of circulation modes are a major factor of atmospheric dynamics (BECK et al. 2001; JACOBEIT et al. 2001). Thus, with respect to the zonal circulation mode in winter, the transition from the Little Ice Age to modern conditions is not primarily reflected by frequency changes but rather by long-term internal changes implying increases of vorticity, intensity, temperature and precipitation across an extended period from 1800 to 1930 (JACOBEIT et al. 2002).

In their precipitation trend study for Germany, for the period from 1891–1990, RAPP and SCHÖNWIESE (1996) clearly show a highly significant increasing trend for winter precipitation in large parts of Southwest and West Germany. Especially in the west and south-west of Germany, that is to say regions important for the Rhine catchment area, winter precipitation has increased by about 30%. These findings are confirmed by a detailed study of long-term changes of precipitation in Baden-Württemberg (SÁNCHEZ PENZO a. RAPP 1997). These changes go along with a corresponding increase of annual flood discharge from 1891 on, for example at the gauging station Cologne (MENDEL et al. 1997). In the 1980s and 1990s, the zonality above the Atlantic and Europe has increased. At the same time the number of weather patterns of long duration has increased, while those of short duration have decreased (SCHMUTZ et al. 2000).

According to the latest IPCC-Report, evidence exists that the frequency of strong precipitation events generally increases with global warming. This is in agreement with the recent findings of PALMER and RÄISÄNEN (2002). Especially during winter, flood levels and frequencies should increase in many regions (IPCC II-ES4). Until 2050 most climate change scenarios predict an increase in the average annual discharge of about 10% north of the Alps (IPCC II-13.2.1.). Concerning the precipitation, it should be of special importance to know how far south the jet-axis will reach, that is to say the corridor of the low pressure systems (WANNER et al.).

2.2 The contribution of historical climate research

In this context we have to ask several questions :

– Are these developments part of a natural climatic trend or really the result of a man-made climate change?

– Which time span do we use for comparisons ?

– Since when do we have reliable data concerning weather, climate and floods ?

– Which relationships exist between natural climate variations and groups of years of increased floods or few floods?

Up to a certain point answers to these questions can be given by historic climate research. The discipline is situated at the interface between climatology and environmental history. Its goal is to reconstruct the course of the weather, climate parameters (temperature, precipitation) and large-scale weather patterns for the period before official measuring networks were installed. Furthermore, it studies the stress capacity of societies for climate variations and natural disasters and the changing social representations of climatic phenomena.

In order to do this, it primarily uses data from historical documents and secondarily natural archives like isotopes, sediments, pollen and tree rings (BUISMAN a. ENGELEN 1998; PFISTER 1999, 2001; BRÁZDIL 2000; GLASER 2001).

In Western and Central Europe climate observations in historical documents exist since Carolingian time. Looking at the amount, continuity and temporal resolution of this material we can divide the past 1250 years until the present into five periods:

1. before 1300: predominantly, descriptions of singularities and natural disasters.
2. 1300–1500: almost uninterrupted description of summer and winter, partly spring and autumn.
3. 1500–1800: almost uninterrupted description of monthly, partly daily weather.
4. 1680–1860: individual instrumental measurements, beginning of short time measuring networks.
5. Since 1860: instrumental measurements within national and international measuring networks.

This enumeration is to be understood accumulatively, i.e. older forms are overlapped but not substituted by newer ones. Within this subject, data concerning precipitation and discharge are in the foreground of discussion.

Beside contemporary written sources, systematic accounts of the daily weather are of special importance for the reconstruction of precipitation conditions. For the River Rhine area such records exist since the end of the 15th century. Daily observations can by evaluated by counting and then standardizing phenomena like rain, snow, frost, degree of cloud cover, fog and subjective remarks like "hot", "terribly cold". Then the resulting values have to be correlated with the respective mean values of the next measuring station (GLASER 2001).

Data concerning the extends of floods can be obtained by looking at contemporary records, flood marks, more than two dozens for example at a house situated in Wertheim in the confluence area of the rivers Tauber and Main, as well as historical and recent water level measurements (from the early 19th century on) (DEUTSCH a. PÖRTGE 2001; GLASER 2001).

Historical climate data is interpreted and evaluated by using a wide variety of methods, reaching from historical source criticism to the application of statistical procedures with a multitude of variables (PFISTER 1999; GLASER 2001).

A common procedure is the derivation of indices. In order to do this, levels of intensity, that are expressed in the records, are correlated with numerical values. "Very wet", for example, could have the value "+3", "wet" "+2", "above average" "+1" and finally "normal" or "average" the value "0". In this way one obtains weighted indices that already represent semi quantitative time series, which can be transformed into estimate values for precipitation and temperature values by using regression functions (PFISTER 1999; GLASER 2001). A similar procedure was developed in order to identify classes of intensity for floods deduced from historical document data (STURM et al. 2001). Working with recent water level data, one is often confronted with the problem that no official or scientifically objective definition, other then the very general paraphrase of "the river overflows its banks", exists for the term flood. In order to arrange data based on the description of flood damages and discharge data based on water level measurements into a single comparable series, the monthly maxima of the daily discharge are classified according their deviation from the average maxima of the reference period 1901–1990. As a criteria for the definition of the classes the deviation from the mean value at one-, two- and three-fold standard mean deviation was used; that is to say that the level of highest intensity was classed with the maxima that surpassed the average maxima by more than the triple standard deviation (STURM et al. 2001).

Historical climatology experienced a new dimension through the cooperation with circulation dynamics specialists (JACOBEIT et al. 1998; WANNER et al. 2000; LUTERBACHER et al. 2000, 2002a/b). Based on historical data seasonal and even monthly mean sea level pressure grids have been reconstructed (JONES et al. 1999; LUTERBACHER et al. 2002) enabling multivariate analy-

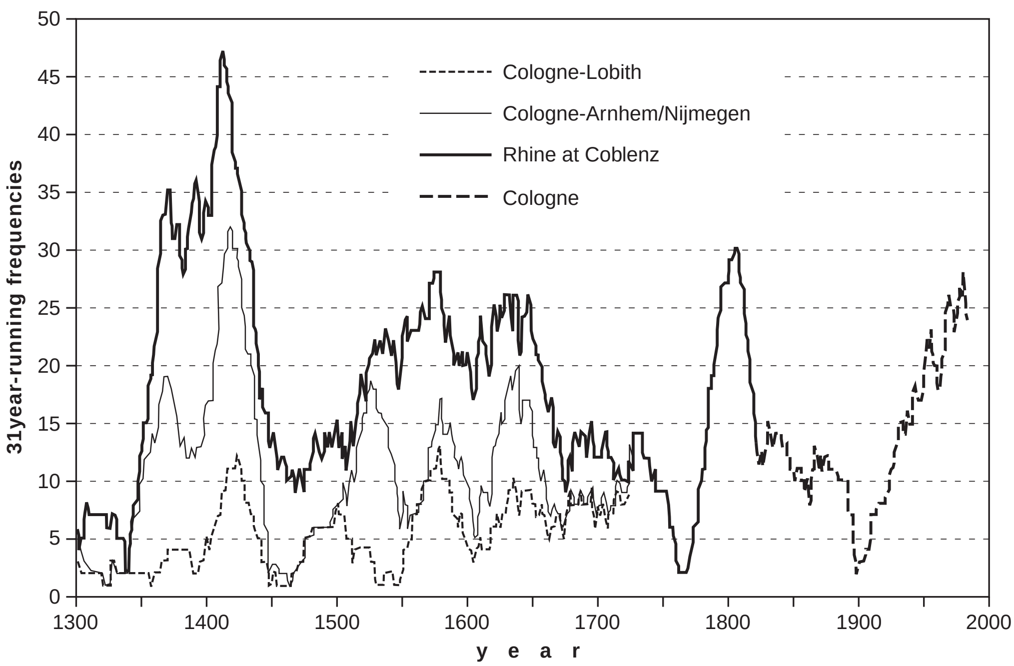

Fig. 4: Flood Lower Rhine since 1300 (GLASER et al. 2002)
Hochwasser am Niederrhein seit 1300 (GLASER et al. 2002)

ses of circulation dynamics for periods considerably extended into the historical past (e.g. JACOBEIT et al. 2001). Furthermore, historical climatology offers to "climate modellers" times series that can be used for climate simulations and calibrations.

2.3 *Climate trends and variations during the pre- and early instrumental period (1500–1860)*

In the following the most important events from the catchment areas of the Hochrhein and alpine Rhine (PFISTER 1999), of the Main and Middle Rhine (GLASER 2001) as well as for the Lower Rhine (BUISMAN a. ENGELEN 1998, 2000; GLASER a. STANGL 2003) will be summarized, in the course of which we will only differentiate according to summer and winter.

2.3.1 *Winter*

In the area of the Hochrhein and alpine Rhine, winters during the "Little Ice Age" (until 1895) on average were 0.4°C colder than during the reference period 1901–1960. Until 1650 this general tendency was overlaid by phases during which winter was often mild (1520–1545; 1602–1650), while during other years (1565–1595) they were colder. After 1650 on average the temperatures remained 1–2°C (1687–1698) below the mean values of the reference period. Correlating with the lower temperatures and as a result of frequent "Bisenlagen", during the period from 1530–1895 there was on average less precipitation than from 1901–1960 (PFISTER 1999). In between 1560 and 1860 winters in the Upper and Middle Rhine area were also significantly colder than in the 20th century. The same true for the periods 1571–1600, 1631–1660, 1681–1730 and 1751–1830. Only in the 20th century we get a longer enduring phase of mild and humid winters, which leads us into present day's greenhouse climate (GLASER 2001).

In the Lower Rhine area, winters, with exception of the years 1500–1550, 1625–1650, and 1700–1775 until 1850 remained cold. The lowest temperatures were reached during the "Late Maunder Minimum (LMM)" between 1675 and 1700 (BUISMAN 1998, 2000) (Fig. 2).

2.3.2 *Summer*

In the area of the Hochrhein and alpine Rhine the "Little Ice Age" can not be detected in the summer temperature graph. On average the summers during the period from 1530–1895 were as warm as those of the period from 1901–1960. This comes as a surprise, especially, if we consider the fact that a glacier's mass balance reacts, above all, to changes in summer weather.

The connection to glacial history can be made more obvious by looking at the two cool summer phases which caused and accompanied, the two advances of alpine glaciers in between 1580–1600 and 1820–1860 (ZUMBÜHL a. HOLZHAUSER 1988). The years 1718–1729 and 1945–1952 stick out as periods with the warmest and driest summers (PFISTER 1999).

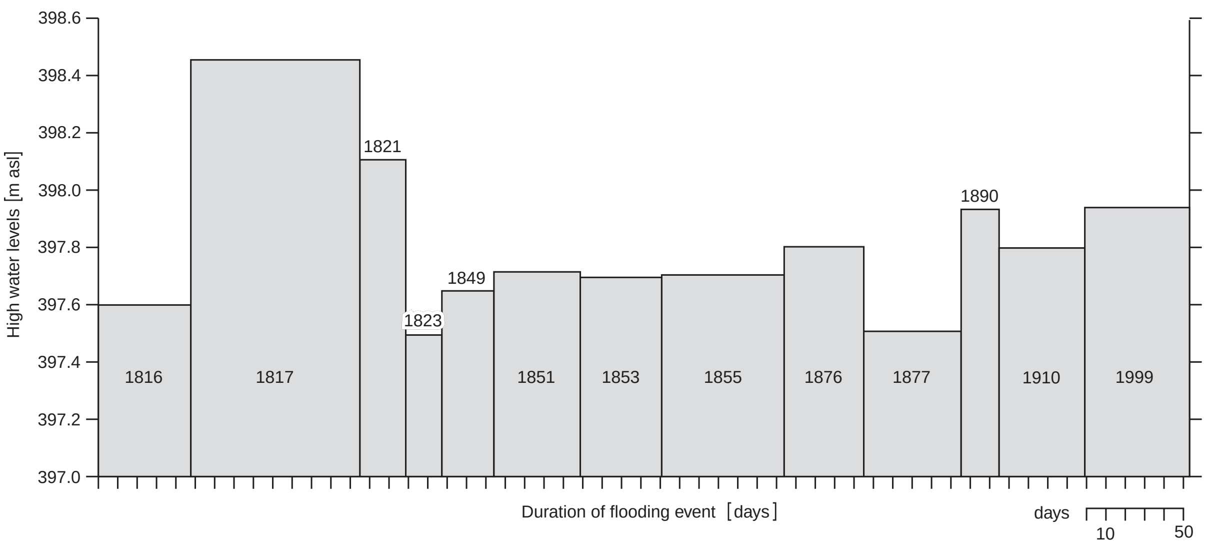

Fig 5: High water levels at Lake Constance in the period 1816–1999 (PFISTER 1999, updated)
Hohe Wasserstände im Bodensee im Zeitraum 1816–1999 (PFISTER 1999, aktualisiert)

In the Upper and Middle Rhine area the past 5 centuries were mainly characterized by cool phases with the exception of the climate development during the 20th century. This is especially true for the years 1571–1591, 1690–1700 and 171?–1730. A comparison of temperature and precipitation graphs shows, that warmer phases usually are also the drier ones, whereas cooler phases coincide with more humid periods (cf. GLASER et al. 2000). In the Lower Rhine area cooler phases dominate from 1525 until 1925, while the lowest values are reached during the last quarter of the 16th century as well as the first quarters of the 19th and 20th century. On the other hand the summer of 1775–1800 (BECK 2000) and 1850–1875 were warmer than average (BUISMAN 1998, 2000) (Fig. 3).

2.4 Influence of atmospheric circulation on floods

The frequency of flood events in Central Europe normally shows a clear interdecadal variability (WANNER et al. 2004). The crucial question is if there exists a significant relation between atmospheric circulation and these frequencies. At least, the preconditioning processes leading to heavy and devastating precipitation events are known. First of all, air masses have to incorporate moist air over the large oceans through enhanced latent heat fluxes. These air masses have to be transported to the continental surfaces along the storm tracks of the midlatitude westerlies and forced to rain out, mainly along frontal systems.

In Central Europe, two types of synoptic events lead to strong floods:

(a) Local to regional events during the warmer season: In this case, heavy rain is related to low-pressure gradients and unstable atmospheric conditions leading to strong thunderstorms.

(b) Larger scale regional to semi-continental events during the cooler season: Normally the Atlantic "storm track" is shifted south and south-westerly to north-westerly flow with excessive rain persists over days or weeks. In spring, such events are very often coupled with snowmelt.

There is some evidence that periods with higher flood frequencies in winter (e.g. during the mid 19th century) are connected with a higher frequency of the above mentioned circulation configuration with advective westerly weather types (JACOBEIT et al. 2003; WANNER et al. 2004).

2.5 Development of flood frequencies

Since the second half of the 1990s, natural disasters have become a major topic, maybe because of the overall impression that the world is haunted by such events in shorter getting intervals. Whether this is because of the greenhouse effect remains yet an open question. From the Middle Ages on anomalies and natural disaster have been recorded in chronicles. The more extreme an event, the more frequent and detailed was it described. The most extreme natural disasters of the past, which are of special interest for today's society, can be relatively reliably reconstructed by means of observations found in historical documents. Until the 19th century both catholic and protestant clerics interpreted natural disasters as of God's "practical sermons". The forces of nature were seen as God's whip, with which a wrathful God would punish his children, who had strolled away from the right path (KEMPE a. MAUELSHAGEN 2002).

The theological image of the biblical flood as a revenge was used to explain floods (KEMPE 1996). The few studies, available today, give evidence to the fact, that, during the period of "natural climate", important deviations in the medium-term frequencies of such events occurred (BRÁZDIL et al. 1999; PÖRTGE a. DEUTSCH 2000; STURM et al. 2001). Compilations of historical Rhine floods – like those of other rivers in Central Europe – allow us to identify periods with frequent floods and periods with few floods, which often occur simultaneously in Central Europe. Yet, differences become clear as well: explanations could be regional climate variations and specifics and above all different and not simultaneously conducted engineered changes during the recent period (Fig. 4).

It shows the medium-term course of 31-years running frequencies. From 1817 on, years were counted as "flood years", if water levels surpassed the mean value (1901–1990) by 7.5 times (green graph) or 10 times (red graph) standard deviation. At present, an international research project is trying to identify the relations between singular phases of frequent or few floods and the atmospheric circulation (STURM et al. 2001). In this context southward shifts of the westerlies and northwest European central lows with southwesterly flow above Central Europe are confirmed on historical time scales as major circulation patterns being important for strong flood events during the winter season. On the other hand, during particular periods of high flood frequency in the historical past other than zonal circulation regimes also contributed significantly to these extreme events thus extending the spectrum of dynamic conditions that has to be taken into account in context with increased flood frequencies.

Historical time series can be used to determine long-term developments and secular events – i.e. floods. Among the greatest flood events for the Main and the

Middle Rhine area are those of the years 1595, 1682, 1784 and 1845. These floods can also be identified at the rivers Weser and Elbe, but not in the catchment area of the Hochrhein or the alpine Rhine (Fig. 4?).

A good indicator for flood disposition are the water levels of Lake Constance (Fig. 5?). This lake is not regulated and mirrors the numerous affluent in North- and Middle Bünden as well as Vorarlberg. Early high lake levels point to a abundant snow-break and/ or a humid spring season. If, under these starting conditions, heavy rainfalls occur, floods with damages are likely. In between 1640 and 1770 no single high water level was recorded, while during the 7 years from 1849 until 1855 it overflowed its banks four times. Between 1910 and 1999 no extremely high lake levels were recorded.

2.6 Conclusions

Reconstructed temperature and precipitation conditions make it clear, that, for the largest part, the climatic development within the instrumental period since 1850 lies within the long-term natural climate variability since 1500. Yet, according to the present findings, especially winter temperature development in the 20th century features as a climatic anomaly, which in that dimension has no comparable equivalent during the previous centuries.

It became also clear, that natural disasters in Central Europe always happened. This is equally true for thunderstorms, storms and floods. Yet the appearance of these disasters drastically changed during the past 500 years. Medium-term increases and decreases within a range of 30 to 100 years were normal. By looking at these phases, it became clear, that during some periods of our historical climate development natural disasters happened more frequently than during the past two centuries. This is especially true for the severe floods that happened between 1500 and 1750. Also, many natural disasters happened during the period of the Little Ice Age from 1550–1850.

Based on these findings, we have to assume, that, regarding temperature and precipitation development, a much higher natural variability exists concerning natural disasters than could be supposed by just looking at present day figures. These findings are especially remarkable, because they concern a time, when mankind did not yet cause climatic change.

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