Evidences for Climate Change in Germany over the 20th Century from the Stochastic Analysis of Hydro-Meteorological Time-Series

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EXTENDED ABSTRACT

It is now commonly accepted that, owing to the increased anthropogenic CO_2 production over the last century, the earth's climate will be affected in the foreseeable future globally as well as regionally. As for Germany, recent regional climate models have predicted significant seasonal changes of temperatures and precipitation for the coming century that will require regional adjustments of water resources management, particularly, for agriculture. While the average citizen in Germany may have the feeling that a warming trend with summer extremes has affected the country several times during the last decade - also supported by meteorological measurements - it is still not clear whether such variations are just outliers in the observed hydro-meteorological time-series with it's well-known stochastic nature, or whether they are just part of a long-term trend pattern that has already been ongoing over most of the 20th century.

To study the variability of stochastic hydro-meteorological time-series several analysis methods, such as the Continuous Wavelet Transform (CWT) and Detrended Fluctuation Analysis (DFA) are applied to various hydro-meteorological data recorded over most of the 20th century, namely (1) climatic data of monthly extremal precipitation at stations throughout Germany and, (2) long-term monthly discharge series of the Elbe river. As it is now recognized that the observed variability of climatic records can be characterized by a nonstationary stochastic process with a few periodic or nearly periodic components, acting on time-scales that range from annual, over decadal, centennial to millennial periods, the goal is to understand the exact nature of the stochastic process, i.e. whether the various observed periodicities are an inherent property of the time-series or if they are triggered by external events that act on more or less regular time-scales.

Given the maximum record length of ~100 years in the present study, we are able to retrieve periodicities and the degree of persistence - as indicated by the calculation of the Hurst parameter with the DFA method - operating up to the decadal scale. Cross-correlations of the observed hydro-climatic time-series with the North Atlantic Oscillation (NAO) - whose tele-connective effect on the European weather pattern on the inter-decadal scale has been surmised for some time, indicate a strong influence of the NAO on the long-term precipitation, though with somewhat different local effects throughout Germany.

Extending the named analysis tools to various Elbe river discharge series provides further evidence of such structural breaks in the time-series variability over Germany between the first and second half of the 20th century. The scaling properties of the hydro-climatic time-series, as determined by the Hurst parameter *H*, reveal important aspects of the long-term persistence of the precipitation across the country and of the Elbe river discharge. As a general observation, the estimated Hurst parameters for the precipitation are consistently lower than those of the discharge, this being a consequence of the groundwater aquifer acting as a low-pass filter for the precipitation before discharging it as baseflow. For the precipitation, their estimated H fluctuate around H~0.5 (indicating no- or only short-term memory) for most of the stations without inter-decadal low-frequency components and H ~0.6 (indicating some persistence) for those stations where such long-period oscillations are present. Such long-range correlations of the precipitation at these locations can only be understood as being the consequence of the impact of other long-term external weather pattern, namely, the NAO.

While these results can somewhat be taken as indicators of some climate change that has been taking place in this country recently, the abnormal weather conditions experienced here in the last decade may then also be explained more as an inter-decadal intermittency phenomenon than as a hint of a long-term climatic trend.

1. INTRODUCTION

1.1 Observational indicators of possible climate change in Germany over the last century

The 20th century has seen an unprecedented rate and degree of climate change on the global as well the regional scale. Regarding the whole globe its mean temperature has risen by about 0.7 °C in the last century, with tremendous impacts on the hydrological cycle, especially precipitation, which has increased by more than 0.5 % per decade in the 20th century over the middle and high latitudes of the northern hemisphere, while it decreased over the subtropical latitudes. This has led to severe climate extremes in recent decades, as witnessed, for example, by the 1993 Mississippi flood or the present 2007 summer drought in the European Mediterranean region causing more and more disastrous wildfires like those in Greece at the time of this writing (August, 2007). The southern hemisphere has not escaped catastrophic weather events neither in the last decade, as manifested, for example, by the wrecking (and still ongoing) drought in Australia over the last few years. In any case, there has been a pronounced increase in the damage provoked by natural disasters and floods over the last 50 years (e.g. Koch, 2000) which, last but not least, is indicated by the steeply rising insurance losses over this time period.

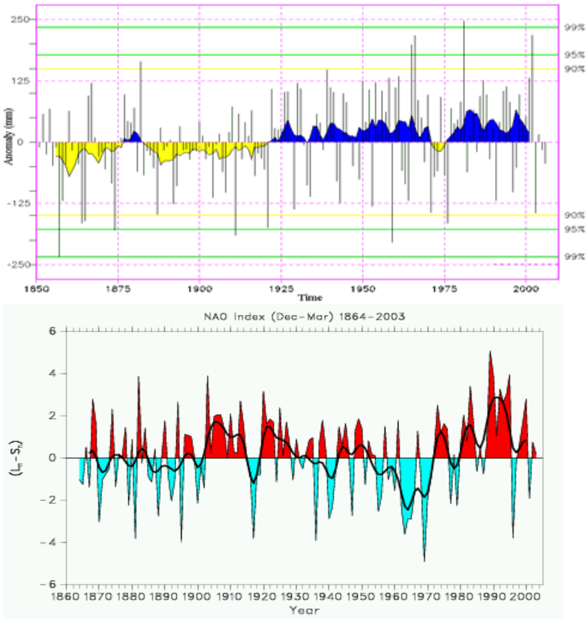

Figure 1: Changes in annual precipitation, 1850-2003 (top panel) (Baur curves) and of the winter month NAO-index (seal level pressure difference between the Azores-anticyclone and the Island-depression), 1860-2005 (bottom panel) (Hurrel, 1995). The precipitation and the NAO index are smoothed with a 11-year and 5-year window, respectively.

For Germany, the long-term weather records show that this country has also been affected by climate change, experiencing an increase of the average annual temperature up to 1ºC during the last century, although, this warming did not occur linearly. For example, a rather unsteady period up to the 1940s was followed by a warm period up to the 1970s, when a cooling trend for more than a decade was observed until the 1990s, after which one notes a continuous and strong temperature increase again that still continues today (as witnessed by the record heat wave of the summer 2003). Moreover, despite the small size of Germany, the measured temperature changes are not homogenous across the country.

Regarding variations and trends of the precipitation in Germany over the last century (whose analysis is one focus of the present paper) the situation is still dubious (e.g. Marković and Koch, 2005), at least with regard to the average annual precipitation (Fig. 1). However, there is some tendency of more positive extreme events, especially in the winter months; with an ensuing increasing number of floods – a testimony of which has been the notorious (summer) 2002 Elbe flood- and negative events (droughts) during the summer months. However, with the present summer 2007 being unusually wet again, the picture of the possible effects of climate change on the precipitation in Germany is far from clear.

1.2 Variability of hydro-meteorological time-series in Germany and their tele-connective correlation with large scale circulation pattern

The visual inspection of the precipitation series of Fig. 1 shows a rather erratic variability, though with some semi-periodical fluctuations. Such a behavior is typical for a stochastic time-series which, in general, can be characterized by a nonstationary stochastic (random) process, with a few periodic components which may act, for climate records, on time-scales that range from annual, over decadal, centennial to millennial and even longer time periods. It is then of interest to understand the exact nature of the stochastic process and whether the various observed periodicities are an inherent property of the former or if they are triggered by external events operating on these time-scales. In the present study, with hydro-meteorological time-series of a length of ~100 years, events with time-scales much less than that are to be considered, e.g. the Wolf sun spot activities on the decadal scale, and the inter-annual large-scale ocean-atmosphere circulation pattern, such as the El Nino Southern Oscillation (ENSO) or the North Atlantic Oscillation (NAO) (Hurrell, 1995). Although it is now commonly accepted that ENSO, with typical periods of 2-4 years, has a significant tele-connective impact on the global weather pattern in the circumference of the Pacific basin, its effect on European weather pattern is still at debate. More established, though still not well understood, are tele-connective impacts of the North Atlantic Oscillation (NAO) with periods of 7-11 years on the seasonal temperature and precipitation anomalies over eastern North America, Europe and Germany, in particular (Marcović and Koch, 2005b). Fig. 1 illustrates the variations of the NAO-index over the last 150 years and one may indeed recognize some cyclicity with strong positive anomalies between 1910 and 1930 and, namely in the 1990s. Overall, the variance of the NAO appears to have increased during the last half century.

As rainfall is the input source of water within the continental part of the hydrological cycle and so controlling surface water and streamflow, the question is how the above mentioned changes in the climatic variables have also impacted streamflow in Germany over the last century. Streamflow results from the passage of infiltrated rain water through the subsurface which operates as a low pass filter for the rain input (e.g. Koch and Marcović, 2007). This is concomitant to say that streamflow is an integrator of precipitation, thus making it an ideal indicator of long-term impact of climate change on water resources in general.

1.3 Objectives and outline of the paper

To look for evidence of possible climate change in Germany over the 20th century with respect of alterations in the hydrological cycle, namely precipitation and streamflow, a comprehensive long-term stochastic time-series analysis of these hydro-meteorological variables over the German territory, with emphasis on the Elbe river basin, is carried out. At the heart of the study is the analysis of the various variability modes that dominate these hydrological variables in the long term, i.e. from the inter-annual to the inter-decadal scale and an attempt to relate these with the remote pattern of large scale atmospheric and oceanic circulation, such as the North Atlantic Oscillation (NAO). As the time-series involved in such a study are usually stochastic in nature, modern methods of stochastic time-series analysis will be applied for that purpose. The ultimate goal of such a stochastic approach is to determine the autocorrelation properties of the time-series in the time domain or, equivalently, its power spectrum in the reciprocal spectral domain. This allows to infer whether the time-series is completely random or whether it has a self-similar, scaling or fractal structure (e.g. Mandelbrot, 1982), i.e. has long-term memory or persistence. These crucial properties of a stochastic time-series are nowadays ubiquitously characterized by the infamous Hurst-parameter *H,* so that its determination is an indispensable task for the understanding of the scaling properties of a time-series (Beran, 1994). Although numerous methods for the estimation of the Hurst parameter have been proposed during the last decades, practically in all branches of fundamental and empirical science, the jury is still out on which performs best (cf. Marković and Koch, 2005a, for a review). In the present application the Detrended Fluctuation Analysis (DFA) method (Peng et al., 1994) as well as the continuous wavelet tool (CTW) (Torrence and Compo, 1998) will be employed.

2. VARIABILITY ANALYSIS OF 20th CENTURY PRECIPITATION OVER GERMANY

2.1 Study area and data

Precipitation records from various gauging stations across Germany obtained from the German National Meteorological Service are used in this part of the study (Fig. 2). The monthly precipitation extremes defined as the maximum daily precipitation amounts in each month were extracted from the daily time-series and taken as input in the various stochastic analysis methods.

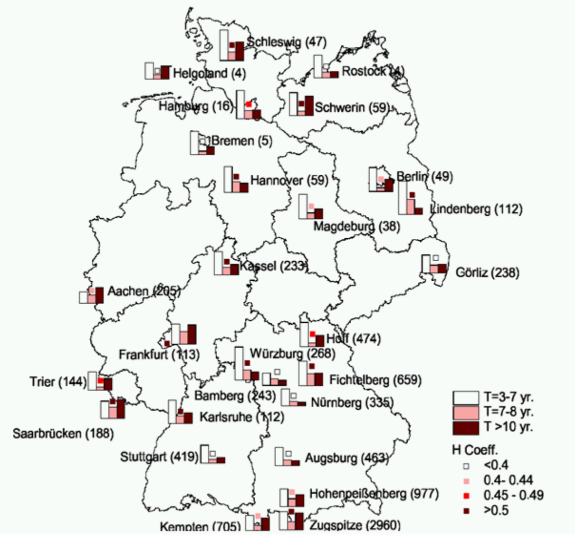

Figure 2. German precipitation stations used in the study, with station heights indicated. Also shown are the dominant periods obtained with the wavelet analysis and the Hurst parameters computed with the DFA. Vertical bars denote the portion of the variance explained by the dominant oscillations in the time-series with periods *T*= 3-7 yr, *T*=7-8 yr and *T*> 10 yr. The colour of the squares denotes the range of the DFA-estimated *H*.

2.2 Wavelet analysis of precipitation pattern

Using the continuous wavelet transform (CWT) (Torrence and Compo, 1998), we attempt to localize in time and frequency dominant oscillations in the precipitation records. The time-series span used is decisive for the quantification of the results. Thus, for comparison of the frequency content and to look for changes of the precipitation patterns in the second part of the 20th century, some of the time-series were split into 30-50 years long continuous non-overlapping subsets and the CWT applied to each of them separately.

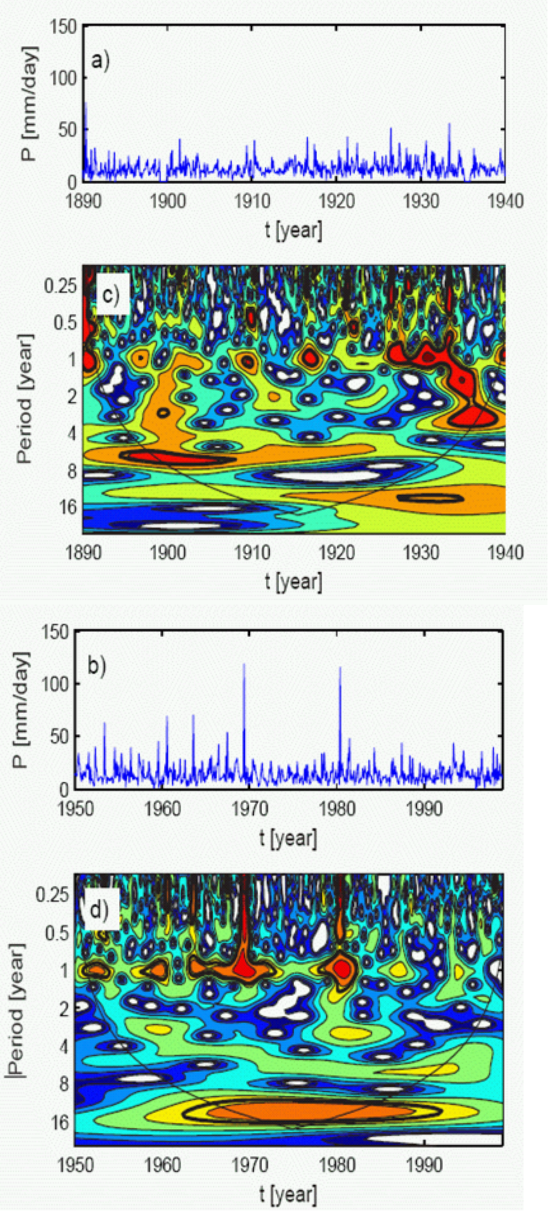

Figure 3. Precipitation series and wavelet scalograms for station Schwerin, split into two time spans 1890-1940 (upper two panels) and 1950-2000 (lower two panels). The thick black-line contours in the scalograms delineate the 95% -levels of statistical significance with respect to the red-noise hypothesis.

Figs. 3 to 5 show the most salient results of the wavelet analysis for some of the precipitation records of interest. The raw time-series of the precipitation and the wavelet scalogram are illustrated in Figs. 3 and 4, and the global wavelet spectra (GWS) (the time-averaged wavelet coefficients) in Fig. 5. The following conclusions can be drawn from these figures. In the early 20th century the monthly precipitation in Hamburg can be characterized by high-frequency oscillations, with periods of 1, 2 and 4 years, while from the mid 20th century on, only the 1-year oscillation remains significant, and a smaller 21-year oscillation peak is recognizable (Fig. 4).

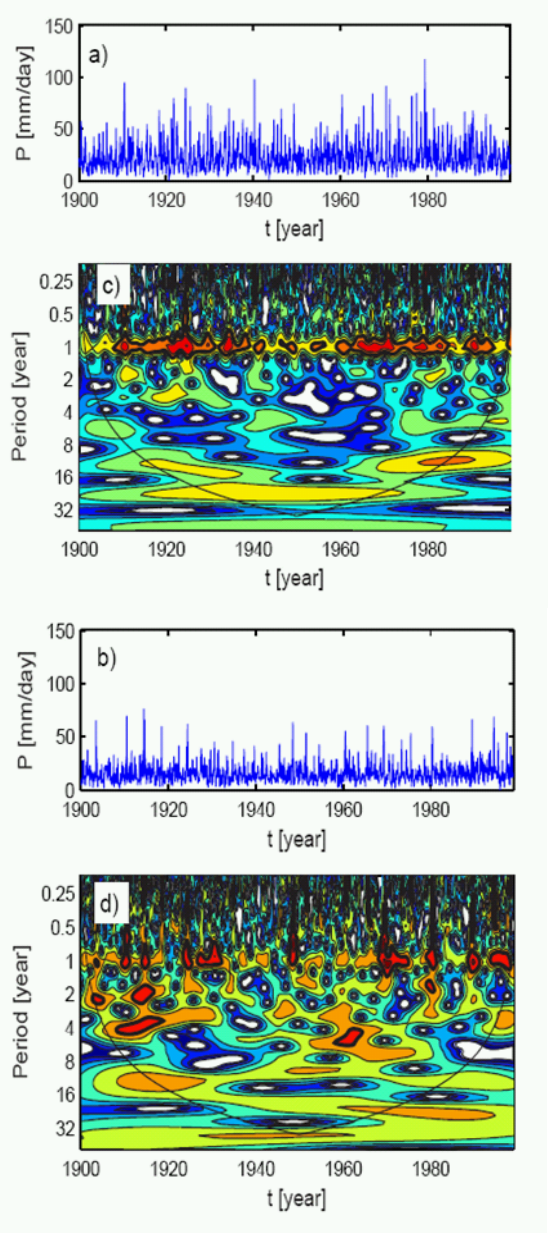

Figure 4. Similar to Fig. 4, but for Hohenpeißenberg (upper two panels) and Hamburg (lower two panels).

Similarly, a 6-year pattern is observable until the 1940's for Schwerin which almost disappears in the second half of the 20th century, when a 14-year period becomes significant. A constant spectrum is found for Hohenpeißenberg whose cause could be the high altitude of this station (977m), though there is also some evidence that the precipitation variance for this station in the 2-14 yr scale-averaged band has been increasing since the 1960s (Marković and Koch, 2005b).Generally, for most of the analyzed locations a low-frequency component with periods of either 11 or 14 yr is noticeable, namely for stations Hannover and Potsdam. Although no precipitation data prior to 1960 are available for these two stations for comparison, the general trend observed over the course of the 20th century for the precipitation regime in Germany, such as enhanced power at the inter-annual (7-8 yr.) and/or inter-decadal (11-14 yr.) low-frequency scales in the second part of the century, must be taken as a fact.

2.3 Estimation of the Hurst parameter and analysis of long-term memory with DFA

Using the Detrended Fluctuation Analysis (DFA), we look for long-term correlation pattern in the precipitation time-series through the computation of the Hurst parameter *H*. Since for the majority of the precipitation stations the records have only been available from 1960 on, and to have a better regional comparison, the DFA is applied only of these 40 year precipitation series. Details of the approach and the intricacies involved with the practical application of the DFA are presented in Marković and Koch (2005a) where also the effects of nonstationaries, oscillations and noise on the DFA estimate has been investigated. In fact, these authors clearly indicate the DFA method as the reliable one for estimating the Hurst parameter.

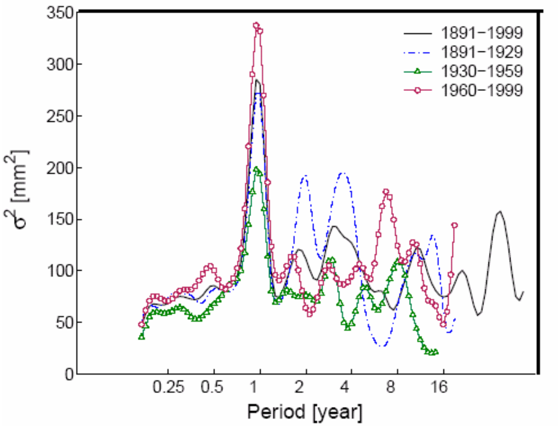

Figure 5: Global wavelet spectrum for Hamburg. The solid thick line is the overall global spectrum and the other ones represent global wavelet spectra for the specified data time windows.

In the introductory Fig. 2 of this section the ranges found for *H* for the various stations are depicted. One notes that most of the DFA estimates for *H* hover around *H*~0.5 - which would indicate white-noise (Beran, 1994) (i.e. no long-range persistence) for the precipitation – with a trend to values *H* <0.5 for stations without the observed inter-decadal low-frequency components in the wavelet spectrum (like Hamburg or Hohenpeißenberg). On the other hand, stations with these long-period oscillations (*T* > 7 yr) present (Schwerin, Hannover, Potsdam) have *H* >0.6, indicating some amount of persistence or long-term memory in the precipitation series for these stations. Such long-range correlations of the precipitation found here can only be understood as a consequence of the impact of other long-term external weather pattern, for example the NAO.

2.4 Correlation of the precipitation with NAO

In the present section we test the hypothesis that the North Atlantic Oscillation (NAO) is one determinate of Germany's long-term climate and of its inter-annual variability.

Fig. 6 (top panel) shows the wavelet scalograms of the winter NAO-index, using the full-length time-series 1860-1999 (also shown in Fig. 1). One notes strong large 7-8 yr oscillations at the end of the 19th century and in the 1910-1920 time interval, after which a 8-14 yr oscillation appears up to the 1950s. The 1960s and 1970s see the variability of the NAO index shifting again to

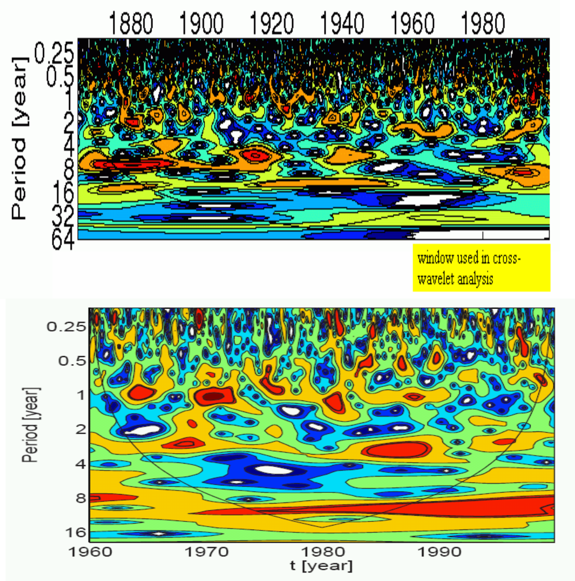

Figure 6. Left panel: Wavelet spectrum for the winter NAO index (1860-1999), right panel: Cross-wavelet spectrum for monthly extremal precipitation (Hannover) and the NAO index 1960-1999. The thick contours in each spectrum are the 95% confidence level against the red noise.

lower-scale periods of 2-4 yr. From the 1980s onward this oscillation is complemented by another one with *T*= 8-14 yr, clearly indicating that the overall spectral power of the NAO index has truly increased during the last 30 years or so (Hurrel, 1995). Analogously to the wavelet spectrum of most of the precipitation time-series, there appears to be also a trend towards higher periods *T*>8 yr of the NAO index after 1960, which hints of a significant amount of tele-connectivity between these two climatic indices.

Using methods of cross-wavelet analysis between the NAO-index and the precipitation as shown, exemplarily, in Fig. 6 (bottom panel) for the station Hannover, this aspect can be quantified further. Note that, as most of the precipitation time-series at the gages across the country (Fig. 2) have been recorded only from 1960 on, solely the 1960-1999 time window could be analyzed. From the figure one can observe a significant correlation in the 6.5-14 year scale range throughout the 1970s to 1980s and the appearance of a shorter, 4-year oscillation in the late 1980’s, clearly corroborating the idea of NAO affecting inter-annual and inter-decadal precipitation pattern in parts of Germany.

3. ANALYSIS OF ELBE RIVER FLOW

3.1 Motivation and approach

Discharge at the outlet of a large river basin is particularly well suited for the evaluation of long-term changes in the hydrological cycle, namely of the incoming rainfall (the input) since short-term fluctuations of the latter are filtered out during the infiltration process which finally may lead to streamflow with long-term memory structure. Thus, discharge has usually higher Hurst parameters than precipitation (e.g. Koch and Marković, 2007). In the present section we look at some further evidence for recent climate change in Germany by analyzing monthly extremes of long-term records of streamflow at several stations within the German part of the Elbe basin (Fig.7) which covers nearly about one third of the country using the wavelet tool and DFA.

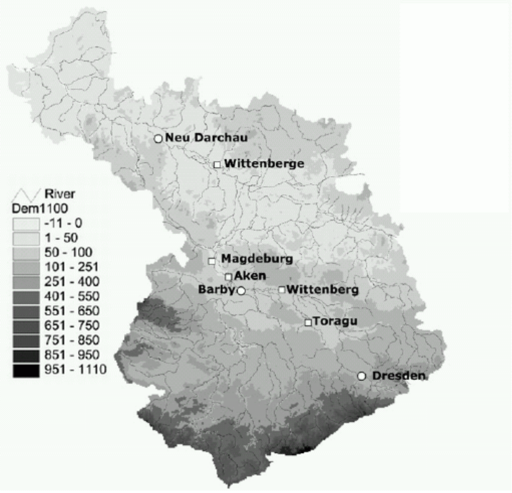

Figure 7. The German part of the Elbe river basin with river gauges used and topography as shown.

3.2 Wavelet analysis of the Elbe river discharge

Fig. 8 shows the discharge time-series and the corresponding wavelet spectra for the two Elbe river gages Dresden and Neu Darchau. The following conclusions can be drawn from these plots with regard to long-term changes of the Elbe flow characteristics. Before 1920, the seasonal (annual) cycle is the only significant periodic component of the monthly extreme discharge time-series at all gages. After that time a broad low-frequency spectrum, with peaks at T= 7−8 yr and T = 14−15 yr can be detected which, interestingly enough, has also been the time when the NAO-index started to experience a similar behavior (Fig. 7). The GWS of the various discharge series along the Elbe river are similar in shape but differ in their absolute power, due to the increased mean discharge downstream. Confirming the results from the scalogram, other than the seasonal cycle, significant low-frequency oscillations with periods of 7.1 yr and 10-14 yr are identified.

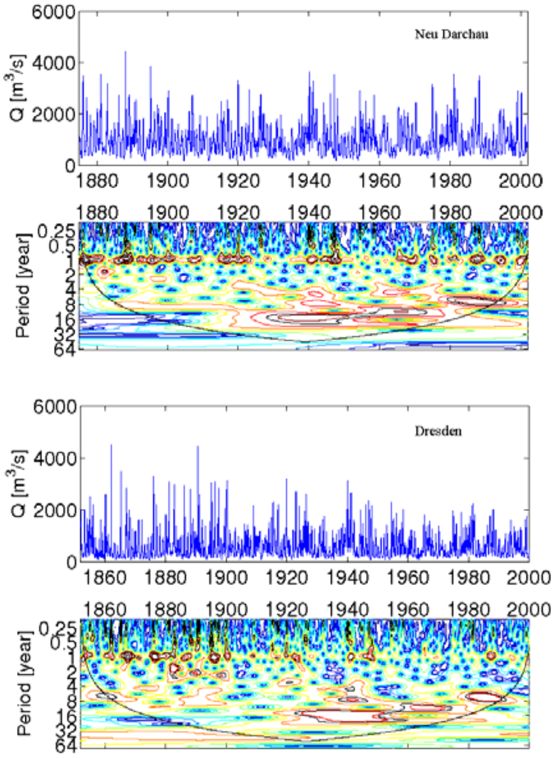

Figure 8. Monthly extremal discharge time-series and wavelet spectra for stations Dresden and Neu Darchau. Black contours around the spectral peaks the 95% confidence levels against red noise.

3.3 Temporal changes of the Hurst parameter

To test whether the estimated Hurst parameters for the Elbe discharge time-series are possibly time-dependent over the 20th century, data subsets are studied for different constant-length, non-overlapping time windows. Table 1 lists the DFA *H* parameters of the mean monthly discharge of several Elbe River gages for the total time span recorded, as well as for several non-overlapping time intervals within this recorded period.

One notices from Table 1 for all stations a continuous increase of the estimated Hurst parameter *H* over the studied time intervals, from about H~0.5 (white noise) at the beginning of the 20th century, to H> 0.80 at its end, with values for the average H for the total record somewhere in between. Whereas *H* up to the middle of the last century is $0.71<H<0.76$ for all stations, it jumps up to H >0.80 after that time, up to now. This means that the hypothesis of a sizeable change in the scaling- and long-range-dependence property of the Elbe discharge somewhere in the middle of the last century should be accepted.

Table 1. Hurst parameters *H* estimated with the DFA-method for various Elbe gages for the total record period as well as for several sub-windows.

Station	H (tot. wind. as specified)	H (pre-1900 wind. as specified)	H (1900-1960)	H (1960-2000)
Neu Darchau	0.61 (1875-2000)	0.48 (1880-1920)	0.76	0.80
Wittenberge	0.70 (1900-2000)		0.76	0.81
Barby	0.60 (1900-2000)		0.73	0.80
Dresden	0.58 (1852-2000)	0.53 (1852-1900)	0.71	0.81

4. CONCLUSIONS

To look for evidences of possible climate change in Germany over the 20th century with respect to alterations in precipitation and streamflow, a long-term stochastic time-series analysis using the wavelet tool for the frequency- time localization and the detection of dominant oscillations in these series as well as in the NAO index has been carried out. The similarity of the NAO index variability with that of the precipitation and with that of the Elbe river discharge itself, is a clear indicator that German long-term hydro-climate is affected remotely by this hemispherical index.

The scaling properties of the hydro-climatic time-series, as determined by the DFA-computed Hurst parameter *H*, reveal important aspects of the long-term persistence of the precipitation across the country and of the Elbe river discharge. In particular, *H* turns out to be time-dependent over the course of the 20th century, with a continuous increase of *H* over the studied time intervals, from about H~0.5 (white noise) at the beginning, to H> 0.80 (long-range memory) at the end of the 20th century. Thus, notwithstanding uncertainties in the exact time-localization of the appearance of these nonstationarities of *H,* the idea of a certain change of the Elbe discharge's scaling property, i.e. increased persistence and variability, occurring somewhere in the middle of the last century is to be accepted. Whether this is just an inter-decadal intermittency phenomenon or a hint of a long-term climatic trend is another story.

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