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Research Article

Analysis and Discussion of Atmospheric Precursor of European Heat Summers

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The prediction of summers with notable droughts and heatwaves on the seasonal scale is challenging, especially in extratropical regions, since their development is not yet fully understood. Thus, monitoring and analysis of such summers are important tasks to close this knowledge gap. In a previous paper, the authors presented hints that extreme summers are connected with specific conditions during the winter-spring transition season. Here, these findings are further discussed and analysed in the context of the Earth's circulation systems. No evidence for a connection between the North Atlantic Oscillation or the Arctic Oscillation during the winter-spring transition and extremely hot and dry summers is found. However, inspection of the geopotential at 850 hPa shows that a Greenland-North Sea-Dipole is connected with extreme summers in Central Europe. This motivated the introduction of the novel Greenland-North Sea-Dipole-Index, GNDI. However, using this index as predictor would lead to one false alarm and one missed event in the time series analysed (1958–2011). Hints are found that the disturbance of the "dipole-summer" connection is due to El Niño/Southern Oscillation (ENSO). To consider the ENSO effect, the novel Central European Drought Index (CEDI) has been developed, which is composed of the GNDI and the Bivariate ENSO Time Series Index. The CEDI enables a correct indication of all extremely hot and dry summers between 1958 and 2011 without any false alarm.

1. Introduction

Extreme summers with droughts and heat waves significantly affect human wellbeing. During the heat summer 2003, for instance, several thousand of mainly elderly people were diseased in Central Europe [1], probably due to perilous dehydration [2] and/or cardiovascular problems [3]. Beside the effect on human wellbeing heat summers have adverse economic effects, for example, on agriculture [4] and forestry [5]. In some regions severe problems with water supply occurred. The financial loss due to crop failure induced by the 2003 heat wave is estimated at 12.3 US $ [6]. Moreover, extremely hot and dry summers increase the risk of forest fires (e.g., [7]) and are likely to increase rock-fall in the Alpine region due to intensified thawing of permafrost [8].

It is evident that the impact of extremely hot and dry summers on human wellbeing and the environment is eminently essential. Extreme weather cannot be avoided, but adaptation and precautionary measures could be installed. Yet, this requires sufficient handling time. Hence, early and reliable meteorological predictions of extreme heat and drought events could significantly contribute to the mitigation of the adverse effects described above and could minimize their negative impact.

For purposes like this seasonal prediction systems are developed. The goal of seasonal prediction is not to forecast the weather at a certain place and time months ahead but to estimate the dominant circulation regimes over a larger region in the upcoming months. This type of prediction is based on low frequence oscillations in the Earth-Atmosphere-System, such as ENSO, acting on hemispherical to global scales [9]. For the tropics seasonal prediction systems perform better than for extratropical regions (e.g., [9]). This is due to the dominance of low frequence oscillations in the tropics, whereas in the extratropics internal variabilities dominate. That is, in the extratropics the chaotic nature of the

Earth-Atmosphere-System has a larger influence on weather regimes than low frequence oscillations, whereas the former are more difficult to capture in seasonal prediction than the latter.

Especially the prediction of extreme summers in extratropical regions, like the one in 2003 in Europe, remains challenging [10].

To enhance the skill of the prediction of the summer season in extratropical regions is the goal of various research approaches. For example, Dutra et al. [11] developed the extreme forecast index (EFI) for the seasonal scale. By scaling the ensemble forecast of the ECMWF seasonal forecast system S4 of 2-m temperature and precipitation with respect to the model climate, the EFI measures the departure of the mean model climate and the actual forecast. However, an evaluation of the performance of EFI is currently not available.

Pavan and Doblas-Reyes [12] suggest a method to calibrate model outputs with observational climate indices using principal component analysis to enhance the prediction of summer maximum temperature over Italy. The method is based on the finding that persistent extreme temperature events during summer develop due to a linkage between large-scale circulation anomalies and local climate anomalies. Pavan and Doblas-Reyes [12] conclude that whenever dynamical forecast systems capture large-scale patterns with relevance to local climate anomalies, their proposed calibration method "leads to more skilful and reliable predictions." This finding supports the fact that seasonal prediction is possible because low frequency oscillations, that is, large scale patterns, influence regional climate on the seasonal scale, as mentioned above.

However, the origin of the issue to reliably forecast extremely hot summers on the seasonal scale is the knowledge gap of the processes behind the development leading to these extremes [13]. To close this gap it is essential to analyse extremely hot summers and the meteorological situation in their preceding time frame. The severe impact of the heat summer 2003 in Europe might be one reason why heat waves attracted wide interest, both in the public and the scientific community, and this event has been analyzed in detail from various disciplines (see [14] and references therein).

Several authors have analysed and discussed the development and origin of heat waves within the scope of meteorology. Long lasting anticyclonic circulation anomalies have been discussed by several authors as a key factor for mid latitudinal summer heat waves [15–18]. The European 2003 heat wave [14] as well as the 1995 and 1999 heat wave over the U.S. [19, 20] was characterised by 500 hPa geopotential anomaly patterns. The anticyclonic anomalies are associated with clear skies and subsequent heating of the Earth by solar surface irradiation. This in turn generates stable atmospheric stratification, which suppresses local convection.

Furthermore, circulation anomalies as blocking storm tracks and frontal systems (e.g., [21]) are often associated with a large scale stationary Rossby wave pattern Fischer (see [14] and references therein). In stable anticyclones trajectories of air parcels are bounded to the core of the cyclone in a manner that the area covered by the trajectories is much smaller than in typical summer years [22]. Air parcels are "trapped" in the anticyclone. This behavior indicates a Lyapunov stable equilibrium state of the atmospheric circulation in this region. Extreme heat summers are characterised by long lasting stable situations, which also indicates that the atmospheric circulation is in a regional equilibrium. For such extraordinary stable atmospheric states it could be expected that a specific atmospheric precursor (initial state) might indicate the occurrence of extremely hot and dry summers. Such an indicator could be used to issue early warnings.

Indeed, empirical hints have been found that a precursor [23] of extreme summers in Central Europe exists and that an early prediction of heat summers might thus be possible.

Träger-Chatterjee et al. [23] showed that extremely sunny and dry summer seasons (June-July-August, JJA) in Central Europe are preceded by winter-spring transition seasons (February-March-April, FMA) with large positive (negative) anomalies of solar irradiation (precipitation), if the El Niño Southern Oscillation (ENSO) is not notably extreme.

In this study the summers (June-July-August, JJA) with the highest (lowest) values of solar irradiance (precipitation) have been defined as extremely sunny and dry, leading to severe heat waves. Within this scope the summers of the years 1976, 1983, and 2003 have been identified as notably extreme. Notably extreme means that the regional means of the seasonal sums of solar irradiation are within the upper 10% and the regional means of the seasonal sums of precipitation are within the lower 10% of the time-series analysed. Träger-Chatterjee et al. [23] investigated also the winter-spring transition February-March-April (FMA) prior to the abovementioned summer (June-July-August, JJA) seasons in Central Europe. They found that FMA in 1976 and 2003 were characterised by positive anomalies of geopotential in 850 hPa and solar irradiance and by negative anomalies in precipitation. Träger-Chatterjee et al. [23] conclude that a clear connection between the sunny and dry FMA seasons and the following extreme summers in 1976 and 2003 exists. In 1983 a strong ENSO event is observed instead of a "regional" FMA-JJA connection. Figures 1 and 2 show the anomalies of solar surface irradiance and precipitation for the respective period.

Based on the findings described above the authors claim that the stable state during extreme summer heat waves in Central Europe is associated with specific and unique initial atmospheric conditions (precursor) in the preceding winter-spring period. Consequently, it is hypothesised that winter-spring indicators of atmospheric circulations can be used for seasonal predictions of extreme summer heat waves.

In this paper a newly identified large-scale circulation anomaly responsible for the development of extreme summers in terms of solar irradiation excess and precipitation deficit in Germany and adjacent regions is described. The paper thus contributes to a better understanding of the development of extreme summers in Europe. In general the results support the findings of other authors (e.g., [12, 14, 24]) that the occurrence of persistent extreme temperatures is favored by certain large-scale circulation anomalies in connection with local/regional climate anomalies. However, in the present paper the Central European Drought Index (CEDI) is introduced which can be calculated with

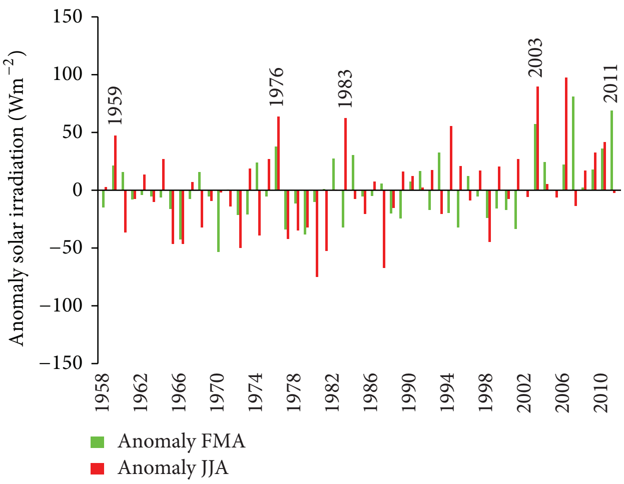

Figure 1: Anomalies of the seasons regional mean (SRM, for definition please refer to Träger-Chatterjee et al. [23]) of solar irradiation [Wm^{-2}] during winter-spring transition season FMA (green) and summer season JJA (red) in all years of the time series 1958–2011. Years marked with their number had (highly) extreme anomalies in FMA and/or JJA. Figure taken from Träger-Chatterjee et al. [23].

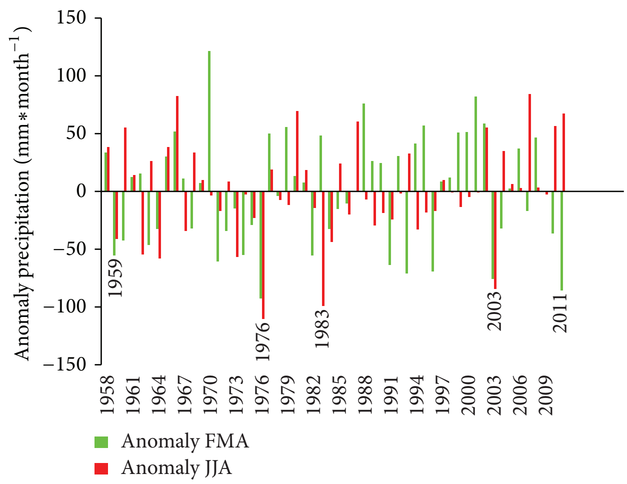

Figure 2: Anomalies of the seasons regional mean (SRM, for definition please refer to Träger-Chatterjee et al. [23]) of precipitation [mm/month] during winter-spring transition season FMA (green) and summer season JJA (red) in all years of the time series 1958–2011. Years marked with their number had (highly) extreme anomalies in FMA and/or JJA. Figure taken from Träger-Chatterjee et al. [23].

one-month lead time prior to the onset of the event using analysis data of geopotential and the Bivariate ENSO Index Time series (BEST), representing the status of the ENSO. Consequently no model forecasts would be necessary to issue early warnings of extremely hot and dry summers in Central Europe. Furthermore, compared to other seasonal prediction methods (e.g., see above), the index is easy to apply.

2. Materials and Methods

This study follows the definition and selection of extremely sunny and dry summers of Träger-Chatterjee et al. [23], according to extremes in solar radiation and precipitation. Those summers showing the highest amounts of solar irradiation and (at the same time) the lowest amounts of precipitation in the time series investigated are defined as extreme. Please refer to Träger-Chatterjee et al. [23] for further details about the data sources and methods. The same time period (1958–2011) as in Träger-Chatterjee et al. [23] is investigated here in order to discuss potential precursor of extremely sunny and dry summers by analysis of the atmospheric circulation.

The atmospheric circulation of the Earth is characterized by a complex nonlinear system of coupled differential equations, which is not closed and hence not solvable without approximations and simplifications. Frequently used analysis methods in the atmospheric sciences, such as Empirical Orthogonal Functions (EOF)/Principal Component Analysis (PCA), are linked with an implicit linearisation of the system, which might cover significant processes within the scope of extremes. However, according to the understanding of the authors, it is necessary to consider the nonlinearity of the global circulation system to improve the understanding of its processes. Based on these considerations an extensive empirical analysis of the system is presented in this paper together with a discussion and investigation of established indices describing the conditions of well-known large scale climate oscillations such as the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), and the El Niño/Southern Oscillation (ENSO). The results of these investigations lead to the definition of two novel indices using nonlinear relations.

For the definition of these novel indices the geopotential at 850 hPa provided by the European Center for Medium Range Weather Forecast (ECMWF) is analysed. The 40-year reanalysis dataset ERA-40 [25] for the period 1958–1988 and the ERA-Interim dataset [26] for 1989–2011 are used.

The North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) (Arctic Oscillation (AO) is described by Thompson and Wallace [27] as a seesaw of see level pressure (atmospheric mass) "between the Arctic basin and parts of the surrounding ring") are very important for the weather and climate in Central Europe and the North Atlantic. Hence, the well-established NAO and AO indices according to Hurrell et al. [28, 29] are discussed in Section 3.1. Further, a new indicator, a distinct pressure difference index, is introduced in Section 3.2. This index results from analysis of geopotential fields at 850 hPa and aims at describing a potential precursor of extremely sunny and dry summers in Central Europe. This index covers circulations on the synoptic scale only. However, extreme summers might also be affected by global scale circulations.

Several authors discussed the effect of the El Niño Southern Oscillation (ENSO) on the seasonal climate in Europe (see [30] and references therein). Therefore, ENSO's potential role on the development of European heat summers is discussed and analysed in Section 3.3, using the BEST index according to Smith and Sardeshmukh [31]. The analysis of the BEST index leads to the postulation of a further novel index, which aims at coupling the synoptic scale and the global scale. This is discussed in Section 3.4.

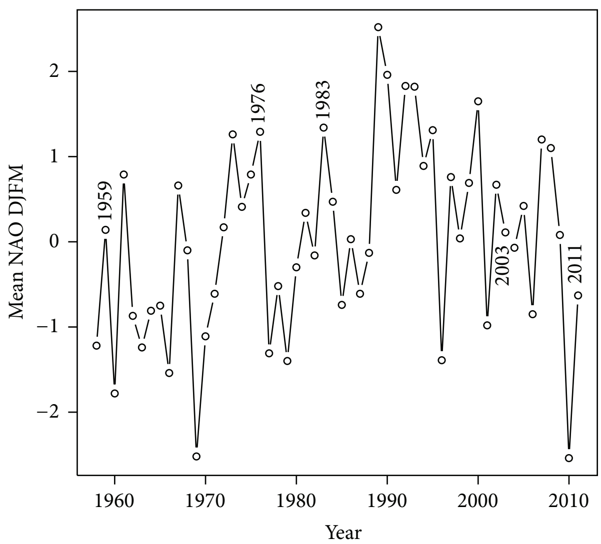

Figure 3: Time series of Hurrell's North Atlantic Oscillation index for December-January-February-March based on Principal Component Analysis [28].

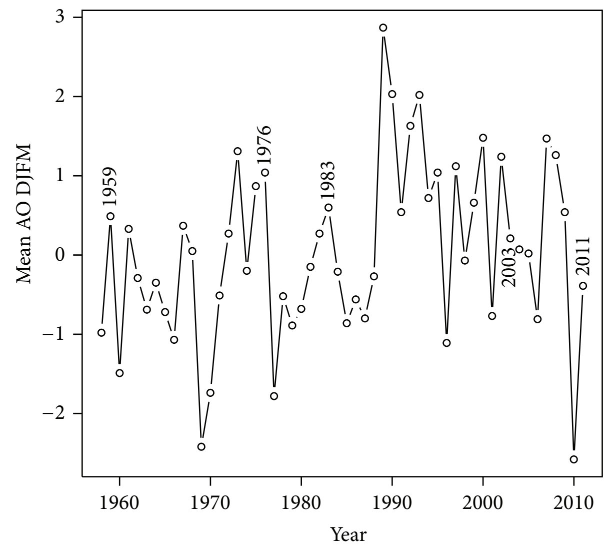

Figure 4: Time series of Hurrell's Arctic Oscillation index for December-January-February-March based on Principal Component Analysis [29].

3. Results and Discussions

3.1. North Atlantic Oscillation and Arctic Oscillation. The North Atlantic Oscillation is widely accepted as the most important circulation pattern in the northern hemisphere (e.g., [32–35]). According to several authors the NAO is closely associated with the Atlantic storm track in terms of its strength and direction (see [35] and references therein). During summer the NAO is not as pronounced as during winter. Consequently its dominance on European weather during winter is stronger than during summer (e.g., [24, 33, 34]).

On the other hand, [36] found that NAO/AO conditions in winter are highly correlated with pressure anomalies over the British Isles in summer.

A reason for this correlation might be that strong wintertime NAO "can interact with the slower components of the climate system (the ocean...) to leave persistent surface anomalies into the ensuing parts of the year that may significantly influence the evolution of the climate..." ([37, 38], both in [33]).

Thus, to investigate whether NAO/AO indices might be useful for the prediction of summer heat waves we analysed the behavior of the NAO and the AO in the time series 1958–2011.

For the NAO the PCA based seasonal NAO index (December-January-February-March, DJFM) according to Hurrell et al. [28] is used (see Figure 3). This index is available from the NCAR (National Center for Atmospheric Research)/UCAR (University Corporation for Atmospheric Research) climate data guide homepage (see http link in [28]). In contrast to station based NAO indices, the PCA based index accounts for the movement of the NAO pressure centers Azores High and Atlantic Low [28]. This is regarded as an advantage compared to the station based indices since the PCA based index covers most of the Atlantic (20–80°N and 90°W to 40°E) and thus captures the action centers regardless of their actual position.

Figure 3 reveals that the years of the summer seasons identified as being extremely sunny and dry do not show characteristic NAO index values, indicating that the NAO is not suited as an indicator of extreme summer heat waves ahead.

The same holds for the AO. To analyse the Arctic Oscillation as a possible predictor of extremely sunny and dry summers in Central Europe, the wintertime (DJFM) Arctic Oscillation index (also referred to as "Northern Annular Mode") according to Hurrell at al. [29], published at NCAR/UCAR climate data guide homepage (please see http link in [29]), is used. This index refers not only to the North Atlantic (as the NAO) but to the entire northern hemisphere sea level pressure and is defined as the first EOF of the latter [29]. Also in the time series of the AO index, no threshold value can be identified for the years with highly extreme sunny and dry summer seasons; see Figure 4.

The analysis of NAO and AO provides no hints that they might be appropriate indicators for extremely sunny and dry summers in Central Europe.

3.2. Greenland-North Sea-Dipole-Index (GNDI). Since no explicit connection between the NAO/AO and the occurrence of extremely sunny and dry FMA seasons and the following extreme JJA seasons in Central Europe could be found in the data, the atmospheric circulation over the North Atlantic has been analysed using the geopotential at 850 hPa. In the years with notably extreme sunny and dry FMA seasons a conspicuous dipole structure of anomalies between southern Greenland (negative pressure anomaly) and the North Sea/Fennoscandia (positive pressure anomaly) has been found. Figure 5 shows an example of this dipole in

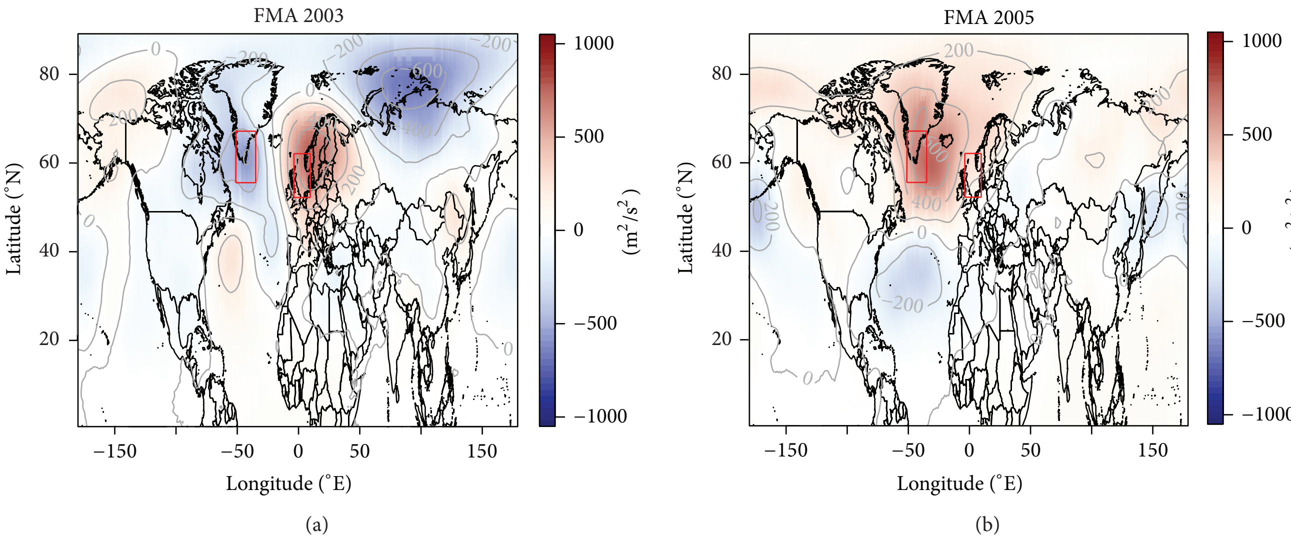

Figure 5: Example of the dipole: geopotential anomaly at 850 hPa of FMA for 2003 and 2005. In FMA prior to the European hot summer of 2003 the dipole is clearly apparent (left map) while in the relatively normal year 2005 it is not apparent (right map). The red boxes indicate the regions that are always captured by anomalies of the same direction prior to the extreme summers in Central Europe.

comparison to a year with normal winter/spring and summer conditions.

In contrast to the NAO, which is generally described as a meridional pressure gradient over the North Atlantic [33], the FMA geopotential anomaly maps prior to the extreme summers (e.g., the year 2003 shown in Figure 5) rather show a zonal pressure gradient between southern Greenland and the North Sea/Fennoscandia.

To quantitatively analyse this dipole, the mean anomaly values of the regions southern Greenland (−50.96° to −34.78° longitude, 55.27° to 66.88° latitude, red box over Greenland in Figure 5) and North Sea (−3.46° to 9.34° longitude, 51.93° to 61.82° latitude, red box over the North Sea in Figure 5) are calculated and normalised with their standard deviation for the time series 1958–2011 for each of the two dipole regions. The exponential function of the difference of these values is introduced as the novel Greenland-North Sea-Dipole-Index (GNDI). Equation (1) provides the mathematical definition of the GNDI. The use of the exponential function is motivated by the finding that only after the occurrence of notably large differences between the geopotential anomalies of the dipole centers, extremely sunny and dry summer seasons occurred. Thus, strong anomaly differences need to be stronger emphasized than weaker differences. Further, the use of this nonlinear function accounts for the nonlinear nature of the circulation system (see Section 2).

$$\mathrm{GNDI} = \exp\left(NA - GA\right), \text{ with:} \tag{1}$$

$$NA = \frac{A_y^N - \overline{A}^N}{\sigma A^N}, \tag{2}$$

$$GA = \frac{A_y^G - \overline{A}^G}{\sigma A^G}. \tag{3}$$

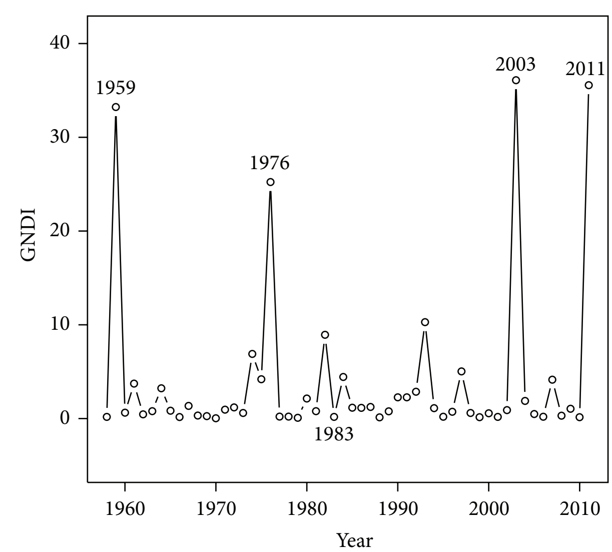

Figure 6: Time series of the Greenland-North Sea-Dipole-Index.

Here, A is the anomaly of the geopotential, $\overline{A}$ is the arithmetic mean, and σA is the standard deviation of the anomalies. G and N depict North Sea and Greenland region, respectively. The time series of the GNDI is shown in Figure 6.

The alignment of the GNDI with the heat summer years 1976 and 2003 reveals a threshold of >20. That is, in years where the GNDI during FMA exceeds 20, an extremely sunny and dry summer would be indicated for Central Europe. Years exceeding a GNDI of 20 are 1959, 1976, 2003, and 2011. The FMA season of all the four years exceeding a GNDI of 20 shows large positive anomalies of solar irradiation and large negative anomalies of precipitation in Central Europe; see Figures 1 and 2.

Two of the years, 1976 and 2003, were among the highly extreme summers regarding high solar irradiation and low precipitation in the time series, that is, among the 10% with the highest solar irradiation amounts and the lowest precipitation amounts (for the definition of highly extreme summers please refer to Träger-Chatterjee et al. [23]).

The dipole situation associated with the highly extreme summers may depict a stable solution of the dynamics associated with the atmospheric flow. This stability in the atmospheric circulation is observed in 1976 and 2003 by the predominance of the anticyclonic weather conditions over Central Europe, which largely persists from winter-spring transition throughout summer. The stable anticyclone determines the high (low) solar irradiation (precipitation) amounts. Solar irradiation and precipitation in turn determine soil moisture which is an important factor in the development of strong heat waves [14, 39] due to its importance for the development (or suppression) of convective clouds and precipitation [23, 40].

Thus the findings provide hints for a connection between conditions during winter-spring transition of the North Atlantic circulation and the following summer season in Central Europe. That is, a dipole with negative geopotential anomaly over Greenland and positive geopotential anomaly over the North Sea/Fennoscandia during FMA is a valuable indicator for extremely sunny and dry summer seasons in Central Europe.

According to the definition in Träger-Chatterjee et al. [23] the summer of 1959 is not among the highly extreme summers but among the extreme summers, that is, among the 20% with highest solar irradiation and lowest precipitation amounts, and is thus not contradicting the connection described above.

However, the evaluation of heat summers performed in Träger-Chatterjee et al. [23] reveals that the GNDI would lead to a year with "false alarm" and one year with a "missed event": the false alarm year 2011 has a GNDI value clearly above the threshold (see Figure 6), which is associated with an extremely sunny and dry FMA season, but the following summer had close to normal solar irradiation amounts and was more rainy than usual; that is, it was by no means extremely sunny and dry. 1983, the year with the missed event, has a GNDI value far below the threshold, but the cloudy and wet FMA season has been followed by an extremely sunny and dry summer. In the following the former (2011) is referred to as a false alarm and the latter (1983) as a missed event. In 1983 and 2011 the dipole shows a different behavior than in 1976 and 2003. In both years (1983, 2011) the dipole changes polarity between FMA and JJA (not shown). This might indicate that in these two years the connection of the dipole to the following summer is disturbed by another interfering large scale circulation.

Indeed, in both years, the large scale El Niño Southern Oscillation (ENSO) was in an extreme state. In 2011, the year with the false alarm, a very strong La Niña event was recognized, and in 1983, the year with the missed event, a strong El Niño was recognized, which both might have influenced the large scale circulation also in the northern hemisphere and thus also the summer conditions in Europe.

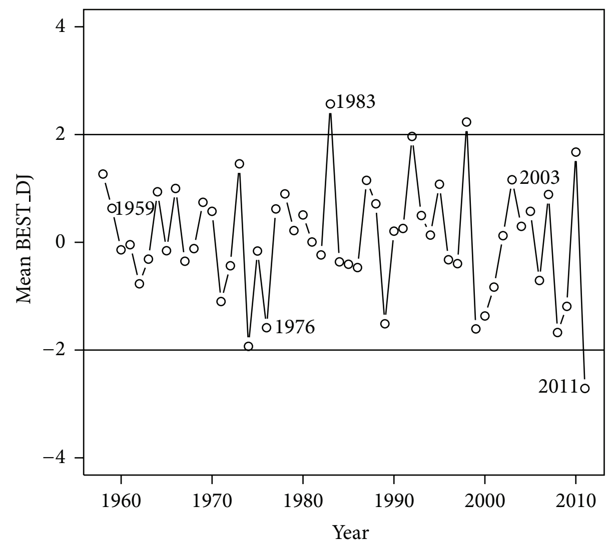

Figure 7: Time series of the December-January BEST index, according to [4]. The year dates refer to January of the year indicated and to December of the year before (e.g., 1959 refers to December 1958 and January 1959). Positive values indicate El Niño events; negative values indicate La Niña events. The BEST index is extreme for the years with false alarms or missed events according to GNDI.

3.3. The ENSO Disturbance. In the analysis presented, two summers have been found for which the GNDI is not a suitable indicator. In 1983 the GNDI indicated a normal summer, but an extremely hot and dry summer occurred after the cloudy and rainy FMA (missed event). In 2011, on the other hand, the GNDI indicated a hot and dry summer, but a summer with relatively "normal" solar radiation and high precipitation occurred (false alarm).

For 2011, the dipole between Southern Greenland and the North Sea/Fennoscandia exists in FMA, but not in JJA (not shown). This means that during that year the atmospheric equilibrium/connection is presumably disturbed (superimposed) by another effect. In 1983, the situation is vice versa: a dipole is apparent but with opposite polarity; hence the GNDI is close to 0, but the following JJA was extremely hot and dry.

As discussed in Träger-Chatterjee et al. [23], the missed event and false alarm are accompanied with strong El Niño Southern Oscillation (ENSO) events in the winter seasons 1982/83 and 2010/11 (please see Figure 7). We assume that this is not a coincidence but that ENSO is the disturbing factor, which is further discussed and analysed, hereafter.

It is widely agreed that the El Niño Southern Oscillation (ENSO) is one of the most important [30] and strongest [41] climate patterns of the globe [42]. Its impacts are not restricted to the tropical Pacific, but it affects weather and climate all over the globe [42]. A summary description of

ENSO and its impacts on European climate can be found in the review paper of [30].

Broennimann [30] concludes that ENSO effects on Europe interact with many other mechanisms (e.g., Pacific Decadal Oscillation, tropical Atlantic SSTs, and NAO), differ with the strength and position of the respective ENSO event, and are modulated by other environmental phenomena, such as volcanic eruptions. That is, ENSO induced effects on European climate are variable.

However, some common features appearing during El Niño (La Niña) winters could be identified for Europe: more cyclonic (anticyclonic) pressure systems following after El Niño (La Niña) events associated with more (less) precipitation over western and Central Europe and the contrary over northern Europe [43].

Beside others Lau and Nath [44] and Herceg Bulić and Kucharski [45] show that ENSO events could lead to SST anomalies in the Atlantic. As a possible physical explanation of the connection between ENSO events and SST anomalies in the northern Pacific and Atlantic Lau and Nath [44] describe an "atmospheric bridge": their model experiments exhibit that a chain of air-sea-interactions resulting from "heat and radiative fluxes at the air-sea interface". In their model experiments this chain of air-sea-interactions starting in the ENSO region needs 4-months lead time to affect the North Atlantic. The feedback of the SST anomalies to the weather in Central Europe needs additional time. As ENSO events usually occur around Christmas the "atmospheric bridge" serves as a possible physical explanation for the effect of ENSO on European spring and summer conditions.

In summary, several authors show clear evidence that ENSO events affect the weather in Central Europe (see [30] and references therein). Thus, it is likely that extreme ENSO events disturb/superimpose the synoptic connection between winter-spring transition and the subsequent summer. As the ENSO events in 1982/83 and 2010/11 have been notably extreme it is a self-evident assumption that La Niña has been a reason for the normally sunny and rather rainy summer 2011, despite the high GNDI value, and that EL Niño has been a reason for the extremely sunny and dry summer 1983, despite the low GNDI value. Hence, the extreme ENSO events are likely the reason for the "failure" of the GNDI.

That is, due to the extremely strong ENSO events in 1983 and 2011 the climate during summer of those two years is not a consequence of the prior North Atlantic winter-spring conditions. Instead, the anomalies in both seasons, FMA and JJA, of these years are likely a consequence of interactions of the Earth-Ocean-Atmosphere system which was strongly influenced by ENSO induced processes. Hence, in years with extreme ENSO events the GNDI alone is not suitable to indicate hot and extreme summers.

The analysis performed so far indicates that for the definition of an indicator for extreme sunny and dry summers the Greenland-North Sea-Dipole as well as the ENSO has to be considered. Thus, the combination of the BEST index, representing ENSO, and the GNDI, representing the strength of the Greenland-North Sea-Dipole, might lead to an index which can be used to improve the predictability of hot and dry summers in Central Europe significantly. This leads to the introduction of the novel Central European Drought Index (CEDI), which is discussed and evaluated in the following section.

3.4. The Central European Drought Index (CEDI). To account for the ENSO influence on the development of Central European summer climate, as discussed in Section 3.3, the GNDI is combined with the BEST index, a measure of the state of the ENSO [31]. Negative BEST values indicate a La Niña and positive BEST values indicate El Niño events.

The combination of GNDI and BEST results in the Central European Drought Index (CEDI). Several tests were made to find an appropriate definition of the CEDI aiming at identifying as many of the highly extreme summers as possible in the time period analysed by the end of April, while keeping the number of false alarms as low as possible. In all the CEDI definitions presented below, the BEST index is considered in such a way that only very strong ENSO events have an influence on the value of the CEDI. This consideration results from the findings presented in Section 3.3 that the false alarms and the missed events resulting from the GNDI coincide with years that followed after very strong ENSO events (see Section 3.3 and Figures 6 and 7). This finding can be explained with the large distance between Europe and the South Pacific, where ENSO occurs. That is, only very strong events have the power to send their signal to Europe and are strong enough to not be (completely) masked by other disturbances, as discussed in Broennimann [30]. In the definitions of the CEDI the absolute value of the BEST index averaged over the early winter season (December-January) prior to the FMA season to which the GNDI refers is used. Using the absolute value of BEST has the advantage that the algebraic sign of CEDI provides information whether GNDI (positive) or ENSO (negative) has been a driving factor for extreme summers.

The results of the different CEDI definitions are presented in the following.

CEDI_{v1} is defined in such a way that the ENSO term is only applied if the absolute BEST value exceeds 2. In the case of weaker ENSO events, the Greenland-North Sea-Dipole dominates the development of the summer season:

$$\mathrm{CEDI}_{v1} = \begin{cases} \mathrm{GNDI} - \left|\mathrm{BEST}_{dj}\right|, & \text{if } \left|\mathrm{BEST}_{dj}\right| \geq 2 \\ \mathrm{GNDI} & \text{else,} \end{cases} \quad (4)$$

where $|\mathrm{BEST}_{dj}|$ is the absolute value of the BEST index averaged over the early winter season (December-January) prior to the FMA to which the GNDI refers.

The time series of CEDI_{v1} is shown in the top row of Figure 8. Even though a distinction between weak and strong events is made in this definition, the CEDI values hardly differ from the GNDI values (6). Thus, the missed event (1983) and the false alarm (2011) are not eliminated using this definition. This is due to the imbalance between GNDI and BEST: GNDI is defined as the exponential function of the difference between the anomalies of the dipole centers (see Section 3.2). That is, large differences in the geopotential anomaly dipole

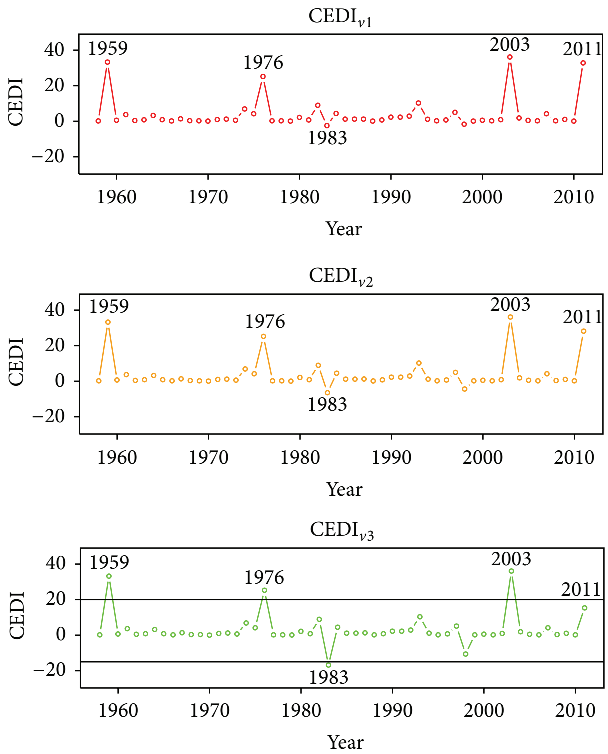

FIGURE 8: Time series of the three different CEDI definitions discussed.

result in large values and small differences result in small values. However, to use an exponential function of the BEST index as well is not an option, since it would depress large negative values of the BEST index, which indicate notable El Niño events.

In order to balance between the effect of the Greenland-North Sea-Dipole (expressed in the GNDI) and ENSO (expressed in the BEST term) the power of 2 of the BEST index is applied. Which results in definition of CEDI$_{v2}$ as follows:

$$\mathrm{CEDI}_{v2} = \begin{cases} \mathrm{GNDI} - \left|\mathrm{BEST}_{dj}\right|^2, & \text{if } \left|\mathrm{BEST}_{dj}\right| \geq 2 \\ \mathrm{GNDI} & \text{else.} \end{cases} \quad (5)$$

However, as can be seen in the time series of CEDI$_{v2}$ (Figure 8, middle row), the power of 2 is still too weak to pronounce large ENSO events appropriately.

Thus, in CEDI$_{v3}$ the power of 3 of the BEST index is applied:

$$\mathrm{CEDI}_{v3} = \begin{cases} \mathrm{GNDI} - \left|\mathrm{BEST}_{dj}\right|^3, & \text{if } \left|\mathrm{BEST}_{dj}\right| \geq 2 \\ \mathrm{GNDI} & \text{else.} \end{cases} \quad (6)$$

The time series of the CEDI$_{v3}$ is shown in the bottom row of Figure 8. The highly extreme summers 1976 and 2003 are clearly visible as notable extremes and exceed the threshold of 20. Also the extreme summer 1959 exceeds a CEDI threshold of 20. The previously missed event of 1983 can also be predicted using CEDI$_{v3}$ and a threshold of −15. And finally, the false alarm in 2011 is no more occurring, since CEDI$_{v3}$ shows a very low value for this year.

Based on these results the authors propose to define the Central European Drought Index (CEDI) following (6). Large positive CEDI values are associated with an extreme dipole anomaly in the Northern Atlantic and hence associated with the synoptic scale. Large negative values indicate a strong El Niño event as the reason for the extremely hot and dry summer. Thus the algebraic sign indicates whether the Greenland-North Sea-Dipole of ENSO is the dominant driver for the development of the summer season. It is obvious that if CEDI is dominated by very strong El Niño events (negative values) a different threshold has to be applied.

Due to the low number of extreme summer events in the time series, the CEDI as well as the mentioned thresholds of 20 and −15, respectively, and the $|\mathrm{BEST}_{dj}|$ threshold of 2 cannot be finally evaluated. However, the skill of CEDI is high, which supports the discussion and hypothesis outlined. A final evaluation of the CEDI and a final definition of the threshold used require a larger database. At the time this study started the 20th century reanalysis dataset [46] was not yet available. However, this dataset may now be used to further evaluate CEDI and GNDI and their influence on the development of extremely sunny and dry summer seasons in Europe.

4. Conclusions

Long lasting anticyclonic circulation anomalies have been discussed by several authors as a key factor for mid latitudinal summer heat waves [15–18]. These circulation anomalies block storm tracks and frontal systems (e.g., [21]) and are often associated with a large scale stationary Rossby wave pattern (see [14] and references therein). Moreover, in the center of the anticyclone air parcel trajectories are “trapped” compared to normal summers [22], which is an indicator for a regional Lyapunov stable equilibrium of the atmospheric circulation.

It is likely that long lasting stable atmospheric states during summer time have indicators that are visible prior to summer season.

Indeed, in Träger-Chatterjee et al. [23] evidence has been found that extremely hot and dry summers might be connected to specific conditions during the winter-spring transitions (February-March-April, FMA), namely, sunny and dry conditions in Central Europe. This connection might be useful to improve the predictability of heat waves.

In the present study the atmospheric dynamic on the synoptic and the global scale has been analysed in order to gain a deeper knowledge of the winter-spring transition (FMA) and summer (JJA) connection described by Träger-Chatterjee et al. and its disturbance. Furthermore potential indices have been evaluated regarding their suitability to support the prediction of extremely hot and dry summers in Central Europe.

For this purpose the potential interlink of North Atlantic Oscillation (NAO) as well as Arctic Oscillation (AO) with extreme summers in Central Europe has been investigated.

No evidence for an interlink of NAO or AO with extreme summers has been found. Instead, an analysis of the geopotential anomaly as proxy for the atmospheric circulation has led to the introduction of the Greenland-North Sea-Dipole-Index (GNDI). This index is a measure for the strength of the dipole anomaly in the geopotential at 850 hPa over southern Greenland and North Sea/Fennoscandia. It has been discussed that the GNDI serves as an indicator of approaching summers with very large positive anomalies in solar irradiation and very large negative anomalies in precipitation in Central Europe. The GNDI supports the conclusions of Träger-Chatterjee et al. 2013 that solar irradiation and precipitation are an important proxy for the development of sunny and dry summers: the atmospheric pressure regimes which determine the high solar irradiation amounts and the low precipitation amounts have now been identified.

Hence, monitoring of the Greenland-North Sea-Dipole is expected to improve our knowledge of the North-Atlantic circulation system and its role for the development of extreme Central European summers in terms of heat (solar irradiation) and drought. While the GNDI indicates the heat summers in 2003 and 1976 it shows no evidence for the heat summer 1983 and erroneously indicates 2011.

It has been analysed whether these failures are due to global scale ENSO disturbances. Indeed, evidence has been found that ENSO is the second main driver for extreme summers on one hand and the disturbance of the GNDI connection on the other.

In order to account for both, synoptic scale and global scale processes, a coupled index, the Central European Drought Index (CEDI), is proposed. This index considers the coupling of the dominant processes for the development of extreme summers on synoptic and global scale. For the synoptic scale the novel GNDI and for the global scale the well-established BEST index, as a measure of ENSO, are used.

With the definition of the CEDI it is possible to indicate all extreme summers during the investigated time period (1956–2011) without any false alarm. According to the results presented, the CEDI serves as an indicator of approaching summers with highly extreme positive anomalies in solar irradiation and highly extreme negative anomalies in precipitation in Central Europe.

However, due to the nonlinear nature of the Atmosphere-Ocean system and the (by definition) low frequency of occurrence of extremes, the forecast skill of CEDI cannot yet be finally determined. Moreover further empirical adjustments of CEDI might be needed. This could for example, be done by analysing reanalysis datasets reaching further back into the past than the datasets used in this study and by monitoring CEDI in the future. Yet, for the investigated time period the skill of CEDI is close to 1 (no missed event, no false alarm). This is a strong hint that the described coupling of the northern hemisphere circulation and ENSO is a key element for the understanding and prediction of extremely hot and dry summers in Europe. To the knowledge of the authors it is the first time that the coupling of the synoptic northern hemisphere circulation and the ENSO has been expressed in a convenient coupled circulation index. Hence, although CEDI might be not finally defined, it describes an important feature in the development of extremely hot and dry summers in Central Europe.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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