CLIMATE SHIFTS DURING THE LAST CENTURY

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Abstract. Fluctuations of the land surface areas covered by Koeppen climates are analysed for the 1901 to 1995 period using trends and outliers as indicators of climate shift. Only the extreme climate zones of the global Tropics and of the Tundra (with the highly correlated northern hemisphere temperature) realise statistically significant shifts *and* outliers. There are no significant trends and outliers in the fluctuating ocean-atmosphere patterns (Pacific Decadal and North Atlantic Oscillations) and the highly correlated intermediate climate zones (dry, subtropical and boreal) of the surrounding continents.

1. Introduction

Observed climate shifts are commonly associated with the changing patterns of the general circulation. These patterns are projections of the global circulation onto surface variables, such as the sea surface and the near surface air temperature, surface pressure, and precipitation, from which suitable measures or indices are derived to quantify a climate state in terms of teleconnections between remote locations. There are but a few such patterns, which characterise predominantly the coupled ocean-atmosphere system. For example, the North Atlantic (NAO) and Pacific Decadal Oscillation (PDO), reveal several distinct climate shifts during the last century (Corti et al., 1999; Graham, 1994; Trenberth and Hurrell, 1994; Hurrell, 1995; Hurrell and van Loon, 1997).

On the other hand, changes of the coupled land-atmosphere system, which are associated with patterns characterising the states of both vegetation and atmosphere, need to be included in climate shift analyses. In this note the Koeppen (1936) climate classification is suggested to provide such patterns (Section 2) and the areas occupied by the Koeppen climate types are used as a set of suitable measures (or indices), which span the phase space of the continental climate. In this sense, continental climate change (Section 3) is determined from trends and outliers of these index time series and compared with those indices of the coupled ocean-atmosphere system.

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2. Koeppen Climate Classification

The Koeppen climate classification links the climates of the continents with the qualitative features of the Earth's vegetation. It is based on the annual march of temperature and precipitation after being subjected to a sufficiently large time or ensemble average. Here a modified version is used (Trewartha, 1980; Rudloff, 1981; see also Guetter and Kutzbach, 1990) improving the regional representation of the vegetation. The main six climate zones are tropical (A), dry (B), subtropical (C), temperate (D), boreal (E), and snow climates (F). The A- and C-zones are further subdivided into permanent wet, summer-dry, winter-dry and monsoonal types (r, s, w, m); the B-zone consists of the types steppe (*BS*) and desert (*BW*); the D- and E-zones are both associated with a maritime (o) or continental (c) influence; the F-zone consists of Tundra (*FT*) and ice climate (*FI*). Thus the modified Koeppen classification provides 15 climate types (see Table I).

Data: The climate data set of the Climate Research Unit (University of East Anglia, New and Hulme, 1997) is most useful for analysing the climate of the continents and their shifts in the last century. The data of monthly mean surface air temperature and sums of precipitation are available on a $0.5° \times 0.5°$-grid resolution (excluding Antarctica). The spatial distribution of the Koeppen climates of the complete 95-year period is shown in Figure 1; the changes of the last 15 years are in black and discussed in Section 3.

Analysing climate change requires time series of quantitative climate indicators. Utilising the Koeppen climate classification (for earlier applications see, for example, Bailey, 1962; Fletcher, 1969) such time series are constructed as follows:

(i) *Climate zones and index time series:* Koeppen climate indices are defined by the (relative) area which an individual climate zone or type occupies (on a continent). Time series of these indices are obtained by sliding an optimal averaging window (of, say 15 years) over the temperature and precipitation records. This yields sequences (or samples) of, say 81, consecutive ensemble means or Koeppen climate zones and types, whose areas (or indices) are, for presentation, attributed to the first window year.

(ii) *Optimal averaging intervall (window):* The optimal number of consecutive years entering the ensemble average for the Koeppen classification, is deduced by employing averaging intervals increasing from five to thirty years to the temperature and precipitation fields to provide a set of index time series for all Koeppen climates. One observes that, with increasing length of the averaging intervals, these time series show variances whose magnitude

Figure 1 (facing page). Koeppen climate classification (1901 to 1995, coloured) and its recent change (1981 to 1995, black): The main six climate zones are tropical (*Ar*, *Am*, *Aw*, *As*), dry (*BS*, *BW*), subtropical (*Cr*, *Cs*, *Cw*), temperate (*Do*, *Dc*), boreal (*Eo*, *Ec*), and snow climates, which include Tundra and perpetual frost (*FT* and *FI*).

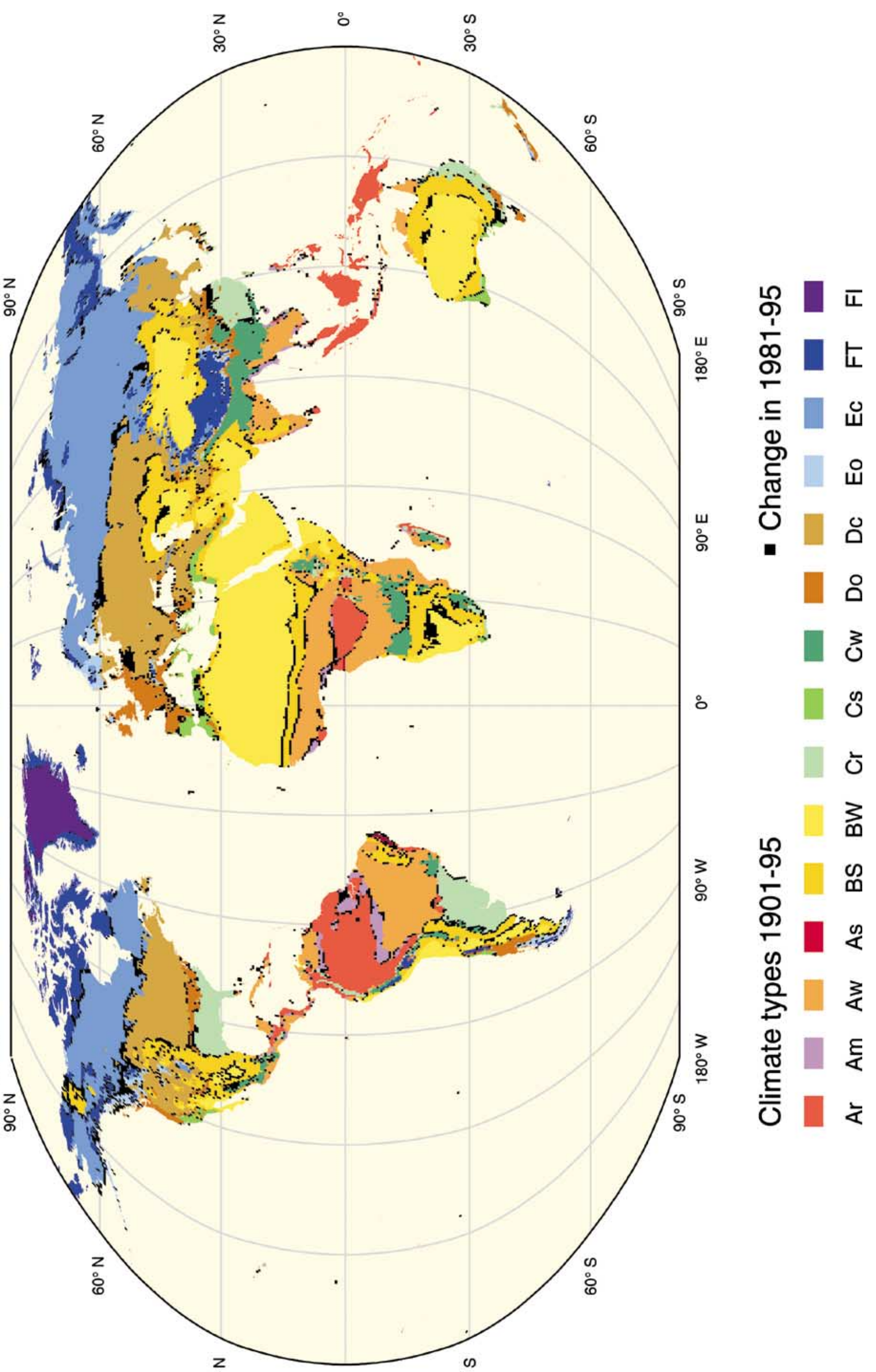
30° N
0°
30° S
60° N
60° S
90° N
180° E
90° E
0°
90° W
180° W
90° S
Climate types 1901-95
■ Change in 1981-95
Ar
Am
Aw
As
BS
BW
Cr
Cs
Cw
Do
Dc
Eo
Ec
FT
FI

Table I

Zones and types of the modified Koeppen climate classification

Climate zone		Climate type	
A	Tropical	*Ar*	Permanent wet
		As	Summer dry
		Aw	Winter dry
		Am	Monsoonal
B	Dry	*BS*	Steppe
		BW	Desert
C	Subtropical	*Cr*	Permanent wet
		Cs	Summer dry
		Cw	Winter dry
D	Temperate	*Do*	Maritime
		Dc	Continental
E	Boreal	*Eo*	Maritime
		Ec	Continental
F	Ice	*FT*	Tundra
		FI	Ice

depends on the interval length. After ordering these variances with respect to the interval length, the optimal ensemble size is determined by that averaging interval where the beginning of a variance trend is realised. This optimal size (or beginning of a variance trend) is determined by the Pettitt-test (Pettitt, 1979; Appendix D) which, supported by the shifted version of the Mann–Kendall test (Sneyers, 1975; Appendix B), lies just above 15 years. Thus, as longer averaging intervals do not lead to a significant change of the trend (but reduce the number of elements entering the time series) we use 15 years as the optimal window length (averaging interval) for the subsequent climate change analysis.

3. Climate Change Analysis

The magnitude of the continental area occupied by a particular climate zone during a 15-year time interval is denoted as a Koeppen climate index. The associated 15 index time series' characterise the land-atmosphere climate regimes which, not unlike the ocean-atmosphere patterns (Pacific Decadal Oscillation or PDO and the North Atlantic Oscillation or NAO), can be used to describe the long term or decadal variability of the Earth's climate. In this sense, the following analysis of continental climate change proceeds in two steps: (a) First, climate fluctuations realised by the land-atmosphere indices are compared by the fourfold test with the ocean-atmosphere indices of the Pacific Decadal and North Atlantic Oscillation PDO and NAO (Taubenheim 1969; Appendix C), before (b) continental climate shifts are determined by significant trends and outliers of the Koeppen climate index time series (with details being described in the Appendices A and B). Finally, (c) the last 15 years deserve special attention realising the earth's global mean temperature rising by about 0.6 K (Hougthon, 1994) in the last century.

(a) Pacific Decadal and North Atlantic Oscillation

The index of the Pacific Decadal Oscillation (PDO) is defined as the leading principal component of the North Pacific monthly sea surface temperature variability poleward of 20° N (Hare, 2000); a positive PDO corresponds to warmer sea surface temperature anomalies in the North-Pacific basin ($>$20° N). The annual index of the North Atlantic Oscillation (NAO) is based on the sea level pressure (SLP, 1865–1995) difference between Ponta Delgada, Azores, and Stykkisholmor-Reykjavik, Iceland, normalised by the long-term (1865–1984) standard deviations (Hurrell, 1999). A positive (negative) NAO corresponds to stronger (weaker) zonal flow across the North-Atlantic associated with a northward (southward) shift of the storm track.

Analysis of the indices characterising the ocean-atmosphere and land-atmosphere pattern in the 1901 to 1995 period yields the following results:

1. Both the Pacific Decadal and North Atlantic Oscillation do not show significant trends and outliers.
2. Not unexpected, the PDO and NAO show strongest correlations ($>$0.8 with 99% significance) with the intermediate Koeppen climate zones of the *adjacent* continents. For PDO these are the dry B-climates of Continental Asia (upstream, Figure 2a) and the subtropical C-climates of N-America (downstream, Figure 2b), while NAO is linked with the maritime influenced boreal *Eo*-climate in Europe (Figure 2c). Some additional points are noteworthy.
3. The area reduction of the dry continental Asian B-climates lags the PDO decline, while its area expansion (from 1910 to 1930, and since the end of the 50s) leads the PDO growth (Figure 2a).
4. Downstream, both the area reduction of the subtropical N-American C-climate and the PDO decline are in phase, but the C-area expansion (from 1910 to 1930, and since the end of the 50s) lags the PDO growth (Figure 2b).
5. The area reduction of the boreal European *Eo*-climate appears to lag the NAO decline but, since the 50s, NAO and *Eo*-areas run almost parallel (Figure 2c).

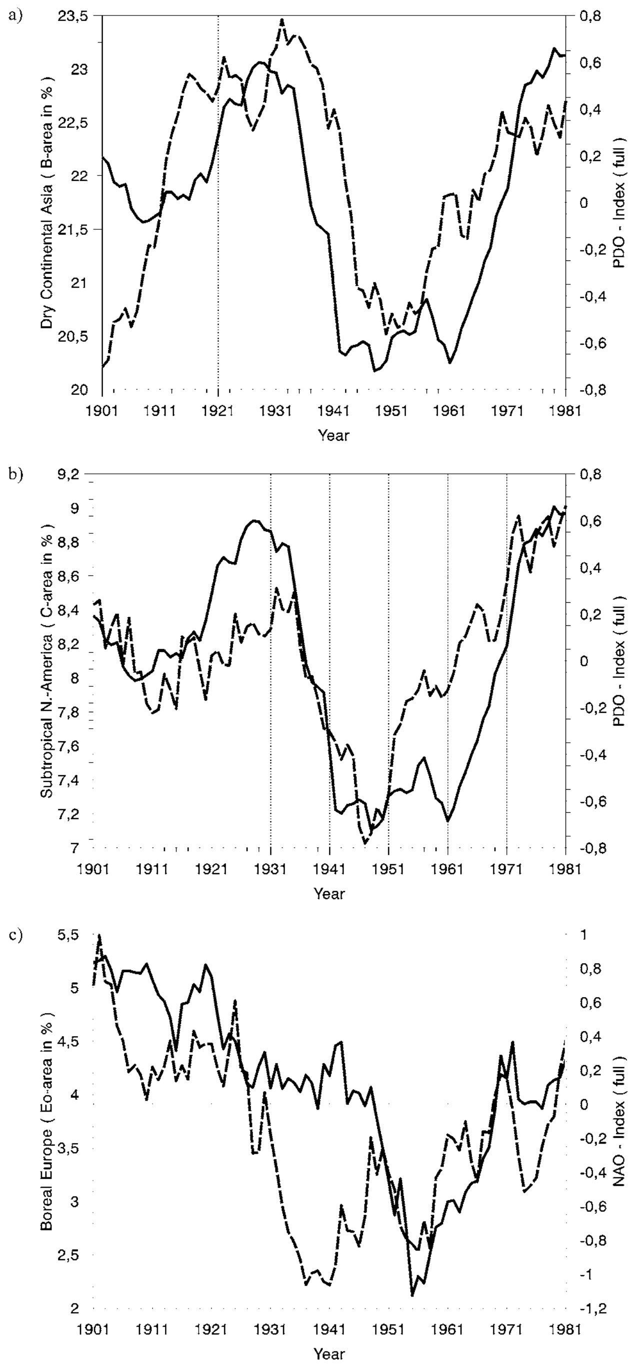

Figure 2. The 1901–1995 time series of the Pacific Decadal Oscillation and North Atlantic Oscillation (PDO- and NAO) index and associated Koeppen climate zones (relative areas occupied by the climate types): (a) PDO-index (full line) with dry continental Asian B-climate (dashed), (b) PDO-index (full line) with the subtropical North American C-climate (dashed), and (c) NAO-index (full line) with boreal European Eo-climate (dashed).

(b) Continental Climate Shift in the Last Century (1901–95)
Subjected to climate change analysis, the continental climate indices show significant trends *and* outliers during the last century only in the tropical zones (A) and in the Tundra (*FT*) where they are notable on a global scale (Figure 3a,b).

Tropics (A): The global *A*-trend is positive with 95% significance (Appendix B) and describes an expanding tropical zone. This expansion is accompanied by outliers (90% significant, Appendix A) near the beginning of the record (1901/15 to 1908/22) and in the sixties (Figure 3a) followed by a recent area reduction near the end of the time series. Some other points are noteworthy: There is an almost continuous A-area growth until the beginning of the sixties. More details emerge from the individual continents (not shown): The tropical zones in both Austral-Asia and South America realise their largest extent in the sixties and seventies with 90% significant outliers. While the associated positive trend in the Austral–Asian region is notable throughout the century, the South American positive A-trend commences in the 50s. There is no *A*-trend in Africa where the only significant outliers are found in the early years of the data set.

Tundra (FT): The global *FT*-trend is negative describing a decreasing area of the Tundra (Figure 3b, full line). Note the rapid decline rates at the beginning and the end of the century where they are associated with 90% significant outliers. In between lies a relatively quiet period with small fluctuations. The *FT*-decline (the trend is 99% significant) is well correlated ($r \sim -0.7$ with 99% significance) with the rising mean surface air temperature of the northern hemisphere (Figure 3b, dashed line).

(c) Last 15 Years (1981–95)
An overview of the climate shifts during the last 15 years is presented in Figure 1, which covers, in actual fact, a period of thirty years considering a climate state comprising an ensemble mean of 15-years. The details with changes larger than $100 \cdot 10^3$ km^2 are given in Table II; note that all area losses and gains (last line) comprise the total climate shift.

With more than 8% of its area being affected, Europe realises the largest total climate shift compared to the smallest with 3% in Austral-Asia. Integrated over all continents (that is $146, 181.3 \cdot 10^3$ km^2), 4.4% of the area has been changed, which corresponds to twice the Indian subcontinent. The largest changes (of a single climate type) during the last 15 years are observed in the polar regions, where the global Tundra (*FT*) loses $707 \cdot 10^3$ km^2 and in Africa, where deserts (*BW*) gain $585 \cdot 10^3$ km^2. That is about 130 km^2 per day for the global Tundra and 100 km^2 per day for the African desert. More details follow.

Europe realises the largest climate change with a significant increase of the area covered by the maritime temperate climate (*Do*) replacing mainly the continental temperate climate (*Dc*). The 5.6%-change in North America is based on a retrogression of the Tundra (*FT*) which is replaced by the boreal climate (*Eo*) compensating the losses to the *D*- and *C*-climates. The 4.8%-change in South America

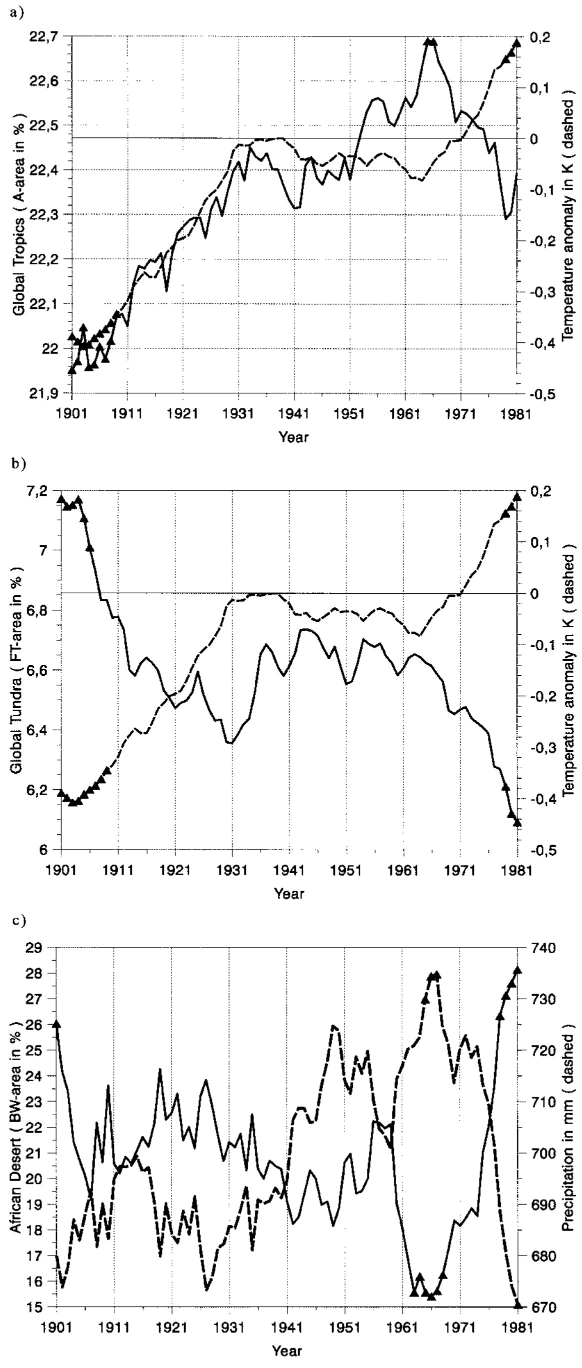

Figure 3. The 1901–1995 time series of the relative areas (in percent) occupied by (a) the global tropical zone *A* (full line) with the global mean temperature (dashed), (b) the Tundra *FT* (full line) with the Northern Hemisphere mean temperature (dashed), and (c) the African desert *BW* (full line) with the annual sum of precipitation averaged over the dry South African *B*-zone (dashed). A 15-year averaging window is employed during the 1901 to 1995 period. Triangles represent 90% significant outliers.

Table II

Area changes ($> 100 \cdot 10^3$ km^2) of the continental climate types for the period 1981/95 (compared to 1901/95) and the total shift of all climate types

Region	Europe	Africa	N-America	S-America	Cont. Asia	Austral-Asia
Ar		–142		238		
Am				–216		
Aw						111
BS	173	–105	141		194	
BW		585	–151	–102		
Cr			169		–120	
Cs						124
Cw		–138		160		
Do	289					
Dc	–222					
Eo			225			
Ec	–268				–135	
FT			–457		–250	
Total shift (%)	1179 (8.4)	1187 (3.1)	1427 (5.6)	968 (4.8)	1014 (3.7)	678 (3.0)

shows a reduction of the monsoonal type (*Am*) and an expanding permanently wet climate (*Ar*) of the Tropics. The 3.7%-change in continental Asia occurs in the permanently wet subtropics (*Cr*), the continental boreal climate type (*Ec*) and in the Tundra (*FT*), all of which decrease while the steppe (*BS*) expands at the cost of *Dc*, *Ec* and *BW*. The increase of *Aw*, *BS* and *Cs* in the Austral-Asian region is accompanied by a reduction of *Ar*, *BW* and *Cr*.

In *Africa*, about half of the total 3.1%-change is caused by a strong expansion of the desert climate (*BW*). The course of the African desert is shown (Figure 3c, full line) with its smallest area coverage in the 60s (corresponding to the largest extent of the African *A*-climate) which is followed by a rapid increase towards the end of the century (partially at the expense of the *A*-climate); both extremes show 90% significant outliers. This course is dominated by the rainfall variations of southern Africa (correlation of $r \sim -0.66$ with 99% significance). No such strong relation is found in the northern parts of the continent.

In summarising, although the end of the last century reveals considerable area change of the continental climate types, it is only the global Tundra which shows both a significant trend (associated with the global temperature rise) during the last century and outliers at its end while, for the Tropics, outliers occur in the sixties and seventies.

4. Summary and Outlook

The Koeppen climate classification has been employed to define climate indices to examine continental climate shifts. These indices describe the areas covered by the climate zones or types during a sufficiently long time interval (whose length has been estimated by a variance trend test); they characterise the land-atmosphere system and, therefore, supplement the more frequently used indices based on ocean-atmosphere circulation regimes (Pacific Decadal and North-Atlantic Oscillation). Utilizing significant trends and outliers to indicate climate change, the analysis of both land- and ocean-atmosphere indices during the last century yields the following results:

1. There are no significant trends and outliers in the fluctuating ocean-atmosphere patterns (Pacific Decadal and North Atlantic Oscillations) and the highly correlated intermediate land-atmosphere zones (dry, subtropical and boreal) of the surrounding continents.
2. Only the extreme land-atmosphere climate zones of the global Tropics and the Tundra (and the highly correlated northern hemisphere temperature) realise statistically significant shifts and outliers and, regionally, the deserts of southern Africa.
3. At the end of the last century, the analysis of the land surface climate reveals considerable change of some of the Koeppen climate zones. These results appear to correspond to what model scenarios predict for the beginning of the present century: (i) 'Desertification arises ... from adverse climatic conditions such as extended drought – which may trigger, maintain, or even accelerate the process of dryland degradation' (IPCC, 1996a). (ii) 'Maximum warming in high northern latitudes in late autumn and winter associated with reduced sea ice and snow cover' (IPCC, 1996b). That is, Africa (in particular the southern part) has gained a desert area of $585.0 \cdot 10^3$ km^2 from the neighbouring climate regimes, and the Tundra has been reduced by $706.9 \cdot 10^3$ km^2 due to climate shifts in North America and continental Asia.

Appendices

The focus of this note lies on climate change occurring in samples of climate states. Each sample comprises a set of (81) elements; they represent ensemble averages (over 15 years) and describe fluctuations of the area covered by one (of 15) climate types. All samples are subjected to a set of four statistical tests (described below) to identify climate change, if (1) periods occur, for which the area covered by one (of 15) climate types deviates significantly from the sample average; (2) significant trends exist, which show an increase or a decrease of the area occupied by one (of the 15) climate types; and (3) significant links can be established between the fluctuating area-cover of climate types and the variations of meteorological parameters underlying the climate change.

Appendix A: Thompson Rule

The significance of outliers is tested by the Thompson rule (Müller et al., 1973). It supports or rejects the null-hypothesis that sample elements from the (time series of 81 values of) relative areas covered by an individual climate type do not qualify as significant outliers. This test defines outliers by

$$t_i = (X_i - \bar{X})/s^* \quad \text{for } i = 1, \ldots, n\,, \tag{A.1}$$

where $\bar{X}$ and s^* are means and standard deviations of the sample (comprising 15-year ensemble averages). Outliers are all values $x_i (i = 1, \ldots, n)$ for which $|t_i| > t_{m;\alpha}$ holds with $m = n - 2(t_{m;\alpha} =$ critical value, $m =$ degree of freedom; $s =$ statistical table). In this sense the Thompson rule is a two-sided test to examine the hypothesis *H0*: ‘The sample has no outliers for a chosen level of significance’.

Appendix B: Mann–Kendall-Test

The significance of trends is tested following the Mann–Kendall-test (Mann, 1945) with the test statistic

$$a = \sum_{i=2}^{n} R_i\,, \tag{B.1}$$

where R_i is, for each element x_i, the number of preceding elements $x_j (i > j)$ smaller than $x_i (x_i > x_j)$, with $i = 2, \ldots, n$ (length of the sample) and $j = 1, \ldots, i - 1$. The introduction of the reduced variable is necessary to use the Gaussian statistic in a simple way. The reduced variable, $u(a)$, may be calculated using the following equation

$$u(a) = \frac{a - Ea}{\sqrt{\sigma_a^2}}\,, \tag{B.2}$$

where Ea is the expected value of the sample and σ_a^2 the respective variance with

$$Ea = \frac{n(n-1)}{4} \tag{B.3}$$

and

$$\sigma_a^2 = \frac{n(n-1)(2n-5)}{72}\,. \tag{B.4}$$

For $n \to \infty$ the a are approximately of Gaussian type with $u(a)$ as its test statistic. The null hypothesis (the sample is not affected by a trend) must be rejected, if the reduced variable is greater than a chosen level of significance of the Gaussian distribution. The shifted version of this test has also been utilised to define the optimal ensemble mean (averaging interval or window).

Appendix C: Fourfold-Test

Fluctuations of the area occupied by a Koeppen climate type are linked with the variations of climate parameters if their correlations r pass the parameterfree fourfold test (Taubenheim, 1969). Employing the test statistic

$$r = \sin(q * \pi/2) \tag{C.1}$$

with $q = 1 - 4a/n$, the correlation r is significant, if the X^2-value exceeds the prescribed level β of the X^2-distribution (with $m = 1$), $X^2 = q^2 n$, with the quadrant ratio q, the number of values within the first quadrant a, and the total number of values n.

Appendix D: Pettitt-Test

The Pettitt-test can be derived from the U-test (Mann and Whitney, 1947), which is based on the rank values of the sequence. The inflection point is defined as that point for which the absolute value of the sequence d_i, has reached a maximum with

$$X_p = 2 \cdot R_p - p \cdot (n + 1)\,, \tag{D.1}$$

where p is the position within the series d_i, n is the number of values of the series, and R_p is the sum of the ranks of the series d_i of the values. Continuously increasing the number of years, the Pettitt-test finally defines that position within the series d_i which divides this series into one part with significant changes values and the other one without changes. This test has also been utilised to define the optimal ensemble mean (averaging interval or window).

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