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Climate classification revisited: from Köppen to Trewartha

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ABSTRACT: The analysis of climate patterns can be performed separately for each climatic variable or the data can be aggregated, for example, by using a climate classification. These classifications usually correspond to vegetation distribution, in the sense that each climate type is dominated by one vegetation zone or eco-region. Thus, climatic classifications also represent a convenient tool for the validation of climate models and for the analysis of simulated future climate changes. Basic concepts are presented by applying climate classification to the global Climate Research Unit (CRU) TS 3.1 global dataset. We focus on definitions of climate types according to the Köppen-Trewartha climate classification (KTC) with special attention given to the distinction between wet and dry climates. The distribution of KTC types is compared with the original Köppen classification (KCC) for the period 1961–1990. In addition, we provide an analysis of the time development of the distribution of KTC types throughout the 20th century. There are observable changes identified in some subtypes, especially semi-arid, savanna and tundra.

KEY WORDS: Köppen-Trewartha · Köppen · Climate classification · Observed climate change · CRU TS 3.10.01 dataset · Patton's dryness criteria

1. INTRODUCTION

Climate monitoring is mostly based either directly on station measurements of climate characteristics (surface air temperature, precipitation, cloud cover, etc.), or on some post-processed form of those measurements, such as gridded datasets. The analysis of climate patterns can be performed for each individual climate variable separately, or the data can be aggregated, for example, by using some kind of climate classification that integrates several climate characteristics. These classifications usually correspond to vegetation distribution in the sense that each climate type is dominated by one vegetation zone or eco-region (Köppen, 1936, Trewartha & Horn 1980, Bailey 2009, Baker et al. 2010). Thus, climate classifications can also represent a convenient, i.e. integrated, but still quite simple tool for the validation of climate models and for the analysis of simulated future climate changes.

The first quantitative classification of Earth's climate was developed by Wladimir Köppen in 1900 (Kottek et al. 2006). Even though various different classifications have been developed since then, those based on Köppen's original approach (Köppen 1923, 1931, 1936) and its modifications are still among the most frequently used systems. For application to climate model outputs the Köppen-Geiger system (Köppen 1936, Geiger 1954) or Köppen-Trewartha modification (e.g. Trewartha & Horn 1980) are usually utilized.

The first digital Köppen-Geiger world map for the second half of 20th century was published by Kottek et al. (2006). This study used the Climatic Research Unit (CRU) TS2.1 dataset (Mitchell & Jones 2005) and the VASClim0v1.1 precipitation data (gpcc.dwd.de) for the period of 1951–2000. Prior to this, many textbooks reproduced a copy of one of the historical hand-drawn maps from Köppen (1923, 1931 or 1936) or Geiger (1961). Following up on the work of Kottek

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et al. (2006), Rubel & Kottek (2010) produced a series of digital world maps covering the extended period 1901–2100. These maps are based on CRU TS2.1 and on GPCC Version 4 data, and Global Climate Model (GCM) outputs for the period 2003–2100 were taken from the TYN SC 2.0 dataset (Mitchell et al. 2004). A new high-resolution global map of the Köppen-Geiger classification was produced by Peel et al. (2007). Climatic variables used for the determination of climate types were calculated using data from 4279 stations of the Global Historical Climatology Network (Peterson & Vose 1997) and interpolated onto a 0.1° × 0.1° grid.

One of the first attempts to use the Köppen climate classification (KCC) to validate GCM outputs was presented by Lohmann et al. (1993). The observed climate conditions were represented by temperature data from Jones et al. (1991) and precipitation data from Legates & Willmott (1990). In Kalvová et al. (2003), the KCC was applied to CRU gridded climatology (New et al. 1999) for the periods 1961–1990 and 1901–1921. The latter period was used for comparison with the original results described by Köppen (1931).

The modifications of KCC proposed by G. T. Trewartha (Trewartha 1968, Trewartha & Horn 1980) adjust both the original temperature criteria and the thresholds separating wet and dry climates (for details see Section 3). The resulting classification is usually denoted the Köppen-Trewartha classification (KTC). Fraedrich et al. (2001) applied KTC to CRU data (New & Hulme 1998) with 0.5° × 0.5° resolution (excluding Antarctica). They analyzed the shifts of climate types during the 20th century in relation to changes in circulation indices (Pacific Decadal Oscillation and North Atlantic Oscillation). KTC types were also used by Guetter & Kutzbach (1990), who studied atmospheric general circulation model simulations of the last interglacial and glacial climates (126 and 18 thousand yr before present). Furthermore, Baker et al. (2010) compared KTC types over China for historical (1961–1990) and projected future climates (2041–2070) simulated using the HadCM3 model under the SRES A1F1 scenario (Nakicenovic & Swart 2000). The KTC types were obtained by applying classification criteria for each grid box of the 30 yr PRISM climatology (Daly et al. 2002) and to eco-regions defined through the Multivariate Spatio-Temporal Clustering algorithm. Feng et al. (2012) used the KTC to evaluate climate changes and their impact on vegetation for the area north of 50° N and the period 1900–2099, focusing on the Arctic region. In addition to the observed data, the outputs of 16 AR4 GCMs (Meehl et al. 2007) under SRES scenarios B1, A1B, and A2 were used. De Castro et al. (2007) used the KTC for validation of 9 regional climate models (RCMs) from project PRUDENCE (http://prudence.dmi.dk) over Europe for the period 1961–1990 and for the analysis of simulated climate change for 2071–2100 under scenario SRES A2. They used the CRU climatology as the observed dataset (New et al. 1999). Wang & Overland (2004) quantified historical changes in vegetation cover in the Arctic (1900–2000) by applying the KTC to NCEP/NCAR reanalysis (Kalnay et al. 1996) and CRU TS2.0 (New et al. 1999, 2000), and compared the results with satellite NDVI (Normalized Difference Vegetation Index, providing an areal average measure of the amount of vegetation and its photosynthetic activity). Gerstengarbe & Werner (2009) studied how global warming in the period 1901–2003 influenced Europe by using the KTC types. Their results are based on the data with spatial resolution of 0.5° × 0.5° produced at the Potsdam Institute for Climate Impact Research.

The above examples of studies employing climate classifications show how different authors use various datasets with diverse spatial resolution for time periods of different lengths (e.g. 15, 30, or 50 yr) and over various geographical areas and spatial scales. However, it is not always clearly described how the climate types are defined and which modification of the respective climate classification is used. Therefore, it is appropriate to describe KTC in detail, its differences from KCC, and to create new maps of the KTC types based on the latest version of the CRU dataset; these are the goals of the present study. These results will provide background for further validation of the new generation of CMIP5 GCMs (Taylor et al. 2012), analysis of recent climate change, and for the evaluation of simulated future climate change. These topics will be addressed in studies we are currently preparing for publication.

This study includes only a part of the graphical materials used for our analysis. Additional maps and graphs can be found on a supplementary website at http://kmop.mff.cuni.cz/projects/trewartha.

2. DATA

As an observational data source we use the CRU TS 3.10.01 dataset (Harris et al. in press). CRU TS3.10 provides a monthly time-series of global gridded data based on observations from more than 4000 stations. Among other variables, it includes the mean surface air temperature and precipitation, on which the climate classifications used in this work are based. CRU TS3.10 is available over land areas excluding Antarctica at a high spatial resolution of 0.5° × 0.5° and covers the period 1901–2009. We concentrate on the period 1901–2005, which is also used in further studies for the validation of GCMs. The version 3.10.01 was the most recent update of the dataset at the time of undertaking this analysis. This update includes corrections to precipitation data, as well as to the data files of wet days and frost frequency.

3. KOPPEN-TREWARTHA CLIMATE CLASSIFICATION SCHEME

In the present paper, we adopt the KTC defined in Trewartha & Horn (1980) with Patton's boundaries of arid climates (Patton 1962). This scheme builds upon the original Köppen system and introduces various adjustments to make the climate types better correspond with the observed boundaries of natural landscapes (de Castro et al. 2007). Some of the modifications introduced by the KTC also deal with a certain vagueness of the KCC formulations. This section will describe the KTC and compare the definitions with the KCC, as described by Köppen (1936). See Table 1 and Table 3 for respective summaries of the KTC and KCC classifications.

The KTC defines 6 main climatic groups. Five of them (denoted as *A*, *C*, *D*, *E*, and *F*) are basic thermal zones. The sixth group *B* is the dry climatic zone that cuts across the other climate types, except for the polar climate *F*. The main climate types are, similarly to those of the KCC, determined according to the long-term annual and monthly means of surface air temperature and amounts of precipitation. The main modifications in the KTC in comparison with the KCC are the different definitions of groups *C* and *D*, a newly defined *E* type, and different thresholds for distinguishing between wet and dry climates. In the following text, the individual climate types will be discussed in detail.

3.1. Group *A*: tropical humid climates

Trewartha & Horn (1980) call this type 'killing frost absent'. The mean air temperature of the coldest month must be over 18°C (i.e all months must be warmer than 18°C). The subtypes of this group are defined according to the annual cycle of precipitation (number of dry months) Table 1. Two main subtypes are *Ar* (tropical wet, sometimes called tropical rainforest climate) and *Aw* (tropical wet and dry, called savanna climate). Subtype *As* is quite rare.

Regarding the definition of 'dry month', Trewartha & Horn (1980, p. 235) state the following: 'In equatorial lowlands where the average annual temperature is about 25 to 27°C, to be dry, a month may not have more than about 5.5 cm of average precipitation totals.' Köppen (1931, 1936) and de Castro et al. (2007) use the precipitation limit of 6 cm to distinguish between a dry and a wet month. In the present study, we also use the 6 cm threshold.

3.2. Group *C*: subtropical climates

In the *C* climate type there must be 8 to 12 months with a monthly mean air temperature of over 10°C and the temperature of the coolest month must be lower than 18°C. The subtypes are again based on the annual cycle of precipitation. Letters *s*, *w* and *f* have similar meaning as they do in the KCC. However, in the KCC, the conditions are not based on precipitation totals during the winter (summer) half-year, but on the amount of precipitation in the wettest (driest) month of the season. Another difference is in the condition for subtype *s*, which is defined by an average annual precipitation of less than 89 cm, in addition to the driest summer month having less than 3 cm precipitation.

The 2 main subtypes of group *C* in the KTC are *Cs* (subtropical dry-summer climate, sometimes also called Mediterranean) and *Cf* (subtropical humid climate). The subtype *Cw* (subtropical dry-winter) is relatively rare (Table 2).

3.3. Group *D*: temperate climates

The *D* climate type is defined by the condition that 4 to 7 months must have a monthly mean air temperature of over 10°C. The main subtypes are oceanic *Do* and continental *Dc*. Their definitions are based on the mean air temperature of the coldest month. In this study, we use the 0°C threshold to divide these subtypes.

3.4. Group *E*: boreal climates

For the *E* climate type, it is necessary to have one to 3 months inclusive with a monthly mean air temperature of over 10°C. Originally, there were no subtypes of this group, but some authors differentiate

Table 1. Climate types and subtypes defined by the Köppen-Trewartha climate classification (Trewartha & Horn 1980). T: mean annual temperature (°C); T_{mo}: mean monthly temperature (°C); P_{mean}: mean annual rainfall (cm); P_{dry}: monthly rainfall of the driest summer month; R: Patton's precipitation threshold, defined as $R = 2.3T - 0.64\ Pw + 41$, where Pw is the percentage of annual precipitation occurring in winter (Patton 1962); T_{cold} (T_{warm}): monthly mean air temperature of the coldest (warmest) month

Type / subtype	Criteria Rainfall/temperature regime
A	$T_{cold} > 18$°C; $P_{mean} \geq R$
Ar	10 to 12 mo wet; 0 to 2 mo dry
Aw	Winter (low-sun period) dry; >2 months dry
As	Summer (high-sun period) dry; rare in type *A* climates
B	$P_{mean} < R$
BS	$R/2 < P_{mean} < R$
BW	$P_{mean} < R/2$
C	$T_{cold} < 18$ °C; 8 to 12 months with $T_{mo} > 10$°C
Cs	Summer dry; at least 3 times as much rain in winter half year as in summer half-year; $P_{dry} < 3$ cm; total annual precipitation < 89 cm
Cw	Winter dry; at least 10 times as much rain in summer half-year as in winter half-year
Cf	No dry season; difference between driest and wettest month less than required for *Cs* and *Cw*; $P_{dry} > 3$ cm
D	4 to 7 months with $T_{mo} > 10$°C
Do	$T_{cold} > 0$°C (or >2°C in some locations inland)[a]
Dc	$T_{cold} < 0$°C (or <2°C)[a]
E	1 to 3 months with $T_{mo} > 10$°C
F	$T_{warm} < 10$°C
Ft	$T_{warm} > 0$°C
Fi	$T_{warm} < 0$°C

[a]In the present study the boundary between subtypes *Do* and *Dc* is $T_{cold} = 0$°C

oceanic and continental subtypes in the same way as in type *D* (e.g. de Castro et al. 2007). This distinction can prove useful especially when dealing with specific regional features. For the purposes of global evaluation we use the original definition that does not divide the *E* type. The KCC does not have an analogous climate group.

3.5. Group *F*: polar climates

Within the *F* type, all months must have a monthly mean air temperature of below 10°C. The subtypes are *Ft* (tundra) with the warmest month's air temperature above 0°C and *Fi* (ice cap) where the air temperature in all months remains below 0°C.

3.6. Group *B*: dry climates

One of the main differences between the KCC and the KTC is the definition of dry climates *B*, or more precisely, the formula for the calculation of the dryness threshold used in these definitions. In the KCC, the boundary distinguishing between wet and dry climates is defined according to Eq. (1), which differs according to the annual precipitation pattern:

$$R = 2T + 14 \quad \text{for evenly distributed rainfall} \tag{1}$$
$$R = 2T \quad \text{for rainfall concentrated in winter}$$
$$R = 2T + 28 \quad \text{for rainfall concentrated in summer}$$

where R denotes the mean annual precipitation threshold in centimeters, and T is the annual mean temperature in degrees Celsius. The subtype *BS* (semi-arid or steppe climate) is found where the mean annual precipitation amount is lower than R, but higher than $0.5R$. If it is lower than $0.5R$, the KCC defines it as an arid (also desert) climate *BW*. Even though Köppen (1936) considered these criteria as convenient approximations, Trewartha & Horn (1980, p. 348) highlighted that when they are simply converted to imperial units, they 'tend to give a false impression of the degree of accuracy'. These authors preferred a modification by Patton (1962), who simplified Eq. (1) as follows:

$$R^* = 0.5T^* - 12 \quad \text{for rainfall evenly distributed} \tag{2}$$
$$R^* = 0.5T^* - 17 \quad \text{for rainfall concentrated in winter}$$
$$R^* = 0.5T^* - 6 \quad \text{for rainfall concentrated in summer}$$

where the mean annual precipitation threshold R^* is in inches, and the mean annual air temperature T^* is in degrees Fahrenheit. The differences resulting from Patton's modification are illustrated in Fig. 1. It is obvious that the boundary between wet and dry climates is similar in areas with lower mean air temperature.

In Köppen (1923, 1931, 1936), the meaning of 'rainfall concentrated in summer/winter' is not explained explicitly, but it is clear that there must be a marked seasonal contrast both in rainfall and in air temperature. Some authors have used the condition that 70 % of the annual precipitation amount must be con-

Table 2. Percentage of continental area (without Antarctica) covered by climate types according to the Köppen-Trewartha climate classification (KTC) and the Köppen climate classification (KCC, types are described in Table 3), calculated from the Climate Research Unit TS 3.10 dataset for the period 1961–1990

KCC	KTC: *Ar*	*Aw*	*BW*	*BS*	*Cs*	*Cw*	*Cf*	*Do*	*Dc*	*E*	*Ft*	*Fi*	Sum
Af	5.10												**5.10**
Aw	0.38	11.17		2.09									**13.63**
Am	1.92	1.74											**3.66**
BW		0.01	16.76	1.08	0.50			0.01			0.11		**18.47**
BS		0.01	2.52	6.36	0.27		0.23	0.22	0.39	0.02	0.13		**10.15**
Cs					0.40		0.46	0.76	0.40	0.05			**2.07**
Cw				1.46		0.77	2.71	0.38	0.26	0.02			**5.59**
Cf				0.57			4.72	1.74	1.48	0.17			**8.69**
Ds									0.48	0.14			**0.62**
Dw			0.03	1.06					1.14	2.16			**4.39**
Df				0.42					7.51	12.43			**20.36**
ET											6.10		**6.10**
EF												1.16	**1.16**
Sum	**7.40**	**12.93**	**19.31**	**13.04**	**1.17**	**0.77**	**8.12**	**3.11**	**11.65**	**14.99**	**6.34**	**1.16**	

centrated in the 6 high-sun months (April through September in the Northern Hemisphere, and October through March in the Southern) in order for it to be classified as rainfall concentrated in the summer. An analogous condition is then applied for rainfall concentrated in the winter. Others have used the same definition for summer (winter) rainfall as Köppen used in his *C* climate group (Table 3).

A further simplification of the wet/dry climate threshold was proposed by Patton (1962) who suggested replacing the original 3 criteria (Eq. 2) with one equation for the mean annual precipitation threshold R^* (in inches):

$$R^* = 0.5T^* - 0.25Pw \quad (3)$$

where T^* is the annual mean air temperature in°F, and Pw is the percentage of annual precipitation occurring in winter (meaning the 6 coldest months). If we transform Eq. (3) into centimeters and degrees Celsius, we get Eq. 4, as used, for example, in de Castro et al. (2007):

$$R = 2.3T - 0.64Pw + 41 \quad (4)$$

where R denotes the mean annual precipitation threshold in cm, T is the mean annual air temperature in °C, and Pw is the percentage of annual precipitation concentrated in winter. Instead of the 6 coldest months, the 6 low-sun months are used (October to March in the Northern Hemisphere, and April to September in the Southern Hemisphere).

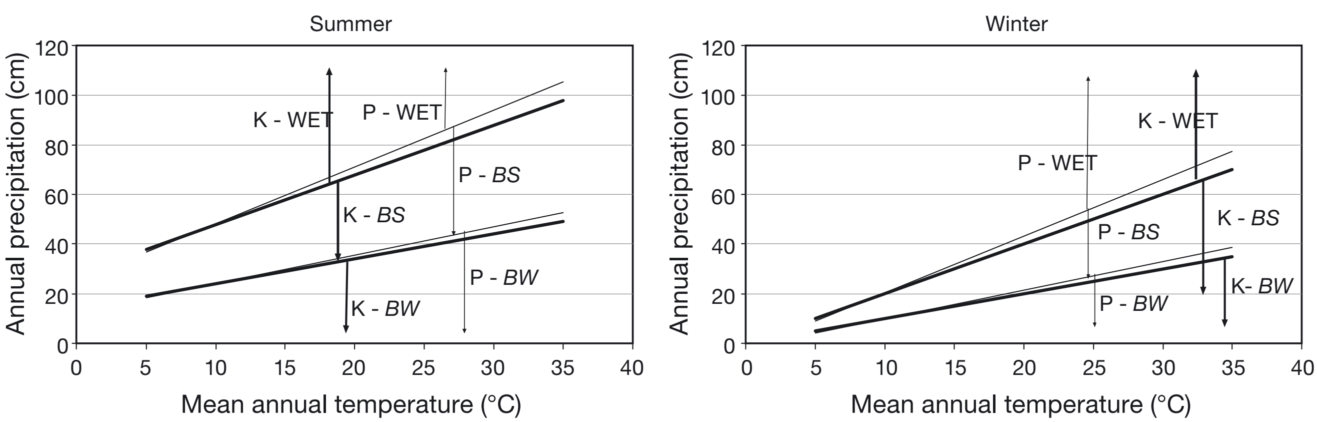

Fig. 1. Boundaries between wet climates and dry climate types *BS* and *BW* (defined in Table 1) based on Eqs. (1) & (2) for areas with rainfall concentrated in summer and winter. **Bold** lines: Köppen's boundary (K) based on Eq. (1); thin lines: Patton's modification (P) according to Eq. (2). Arrows: areas in graphs corresponding to wet climates and types *BS* and *BW*

Table 3. Climate types and subtypes defined by the Köppen climate classification (KCC) (Köppen 1936). P_{max}: maximum annual precipitation rainfall; P_{mo}: monthly precipitation; Other abbreviations as in Table 1

Type/Subtype	Criteria Rainfall/temperature regime
A	T_{cold} > 18°C; P_{mean} above value given for *B*
Af	$P_{mo} \geq 60$ mm for all months
Aw	P_{mo} < 60 mm for several months; dry season in low-sun period or winter half-year; annual rainfall insufficient to compensate this enough to allow forest
As	P_{mo} < 60 mm for several months; dry season in high-sun period or summer half-year; annual rainfall insufficient to compensate this enough to allow forest (occurs rarely)
Am	P_{dry} < 60 mm, rainfall in the rainy season compensates this enough to allow forest[a]
B	P_{max} in summer: $P_{mean} < 2T + 28$; P_{max} in winter: $P_{mean} < 2T$; annual rainfall evenly distributed: $P_{mean} < 2T + 14$
BS	P_{max} in summer: $(2T + 28)/2 < P_{mean} < 2T + 28$ P_{max} in winter: $(2T)/2 < P_{mean} < 2T$ Annual rainfall evenly distributed: $(2T + 14)/2 < P_{mean} < 2T + 14$
BW	P_{max} in summer: $P_{mean} < (2T + 28)/2$ P_{max} in winter: $P_{mean} < (2T)/2$ Annual rainfall evenly distributed: $P_{mean} < (2T + 14)/2$
C	T_{cold} from 18 to –3°C; T_{warm} > 10°C; P_{mean} above value given in *B*
Cs	Summer dry; wettest (winter) month must have more than 3 times the average rainfall of the driest (summer) month; P_{dry} < 40 mm
Cw	Winter dry; wettest (summer) month has ≥10 times the rainfall of the driest (winter) month
Cf	No dry season
D	T_{cold} < –3°C; T_{warm} > 10°C; P_{mean} above value given in *B*
Ds	Summer dry (the same condition as in *Cs*) (occurs rarely)
Dw	Winter dry (the same condition as in *Cw*)
Df	No dry season
E	T_{warm} < 10°C
ET	0°C < T_{warm} < 10°C
EF	Mean air temperature of all months < 0°C

[a]Köppen (1936) describes the relationship between necessary annual rainfall *P* (cm) and monthly rainfall of the driest month P_{dry} (cm) in the form of graph; it can be expressed as $P_{dry} = -0.04P + 10$

In the present study, we use Patton's modification as expressed by Eq. (4). The *BS* subtype is defined by a mean annual precipitation amount P_{mean} lower than *R* and higher than 0.5*R*, and the *BW* subtype by a mean annual precipitation lower than 0.5*R*. The resulting boundaries between wet and dry *B* climate types are illustrated in Fig. 2. Köppen's original boundaries (Eq. 1), in the case of rainfall concentrated in summer and winter (bold lines 1 and 2, respectively, in Fig. 2), correspond approximately to Patton's thresholds for *Pw* equal to 30 and 75%, respectively.

4. COMPARISON OF KOPPEN-TREWARTHA AND KOPPEN CLIMATE CLASSIFICATIONS IN THE PERIOD 1961–1990

In this section, we apply both the KCC and the KTC to CRU TS3.10 and discuss their differences. The maps for both classifications are presented in Fig. 3. The percentage of continental area (except for Antarctica) classified according to the KCC and the KTC is compared in Table 2. It is important to acknowledge that, even though the designations in both classifications are mostly the same, the definitions of the types might be different in many respects. It is worth noting that in the KTC as described in Trewartha & Horn (1980), the subtype *Cw* is barely mentioned, and similarly, in the KCC (Köppen 1936), the subtypes *As* and *Ds* are considered as rarely occurring. Therefore, we did not incorporate *As* in our analysis. The *Ds* subtype was also considered in this study; however, it was confirmed that, in the CRU data for the period 1961–1990, it is present in only a very small number of grid points (Table 2).

From Fig. 3, the benefit of the KTC in comparison with the KCC is evident. An example is the extent of dry climate types in the interior United States. Trewartha & Horn (1980) discuss that the boundary is placed some 300 to 400 km west according to original Köppen's formulas due to underestimation of the dryness threshold. KTC is much more realistic in placing this boundary. In Europe, we see a clear division of the western and eastern parts between types *Dc* and *Do* in the KTC. In other words, the KTC provides a more detailed description of climate types than the KCC.

From Table 2, it can be seen that the definition of climate type *A* is practically the same in both the KCC and the KTC. The *Ar* subtype in the KTC is very similar to *Af* in the KCC; therefore, most of the continental area classified as *Ar* corresponds to *Af* in the KCC (69% of continents without Antarctica). The remainder is divided between *Am* (25.9%) and *Aw* (5.1%) in the KCC. Interestingly,

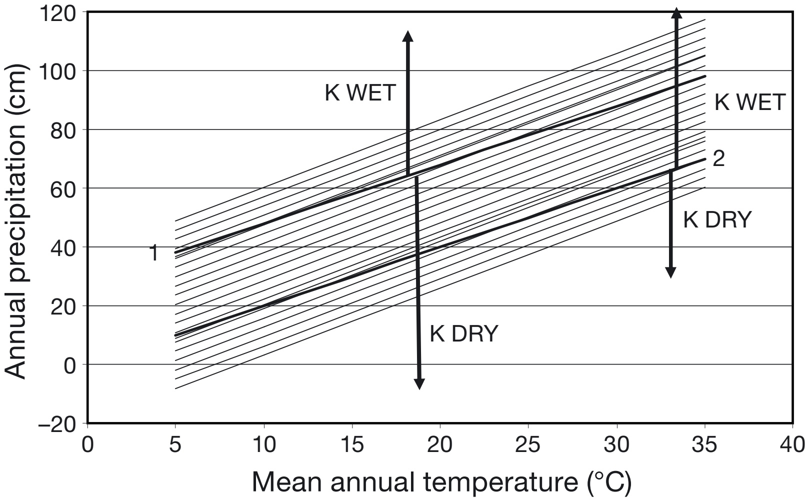

Fig. 2. Boundaries between wet and arid (type *B*) climates. Bold lines conform to Köppen's dryness criteria (Eq. 1) for climates where rainfall is concentrated in (1) summer and (2) winter. Thin lines represent Patton's dryness thresholds (*R*), based on the percentage of precipitation in the winter half-year (Eq. 4), at 5% intervals from (top line) 5% to (bottom line) 95%. Arrows: areas in graphs corresponding to wet climates and types *BS* and *BW*

all the area falling into *Af* in the KCC is classified as *Ar* in the KTC. In addition, *Aw* in the KTC corresponds well with *Aw* in the KCC. Only 13.5% of area where *Aw* is identified according to the KTC falls into *Am* in the KCC, and only a small part of it is marked as *BS* or *BW*.

Thermal definitions of *C* type in the KTC (Table 1) and in the KCC (Table 3) are different. Additionally, the subtypes *s*, *w* and *f* are defined in slightly different ways (see Section 3.2). *Cs* in the KTC represents only approximately 1% of all continental area (without Antarctica). In the KCC, this area corresponds to *BW* (42.8%), *Cs* (34.4%), and *BS* (23%). *Cw* occurs quite rarely in the KTC, accounting for only 0.8% of continental area without Antarctica; the same areas are also classified as *Cw* in the KCC. *Cf* in the KTC is more widespread than *Cs* and *Cw* (8% of continental area without Antarctica), and in the KCC, it is divided between *Cf* (58.1%), *Cw* (33.4%), *Cs* (5.7%), and *BS* (2.8%).

The definition of type *D* in the KTC with its 2 subtypes *Do* (oceanic) and *Dc* (continental) is again different from the boreal or snow-forest climate group *D* in the KCC. Continental territory with a temperate continental climate, *Dc* in the KTC, is most frequently marked as *Df* in the KCC (64.4%), and occasionally as *Cf* (12.7%), *Dw* (9.8%), and *Ds* (4%). The remainder is divided between *BS* (3.3%), *Cs* (3.5%), and *Cw* (2.2%). Temperate oceanic climate *Do* in the KTC occurs much less frequently than *Dc*. Most of the *Do* area is classified as group *C* in the KCC (93.5%), with *Cf* defined for 56% of *Do* area, *Cs* for 24.4%, and *Cw* for 12.1%; the remainder (7.5%) falls mostly into dry climates *BS*.

Type *E* in the KTC includes mainly the area that the KCC marks as boreal climate *D*, with 83% of these points falling into *Df* and 14.4% into *Dw*. Only approximately 1.5% of *E* type area in the KTC is classified as *C* in the KCC (mostly *Cf*), and a negligible part falls into *Ds* (0.9%) and dry climates *B* (0.2%).

Thermal definitions of the polar climates *F* are the same in the KTC and the KCC. Because we do not include Antarctica in our analysis, the tundra subtype *Ft* (*ET*) is more widespread (approx. 6.3% of the continental area) than ice cap climate *Fi* (*EF*) (1.2%). All areas classified as *Fi* in the KTC fall into group *EF* in the KCC. *Ft* largely corresponds to *ET* in the KCC (96.2%); approx. 3.7% of *Ft* grid points are defined as *B* in the KCC. This is because in the KCC, those areas (CRU grid points in our case) satisfying the conditions for *B* climate type are classified in the first step. In contrast, in the KTC, the first step selects the *F* areas, and *B* is evaluated subsequently; i.e. the *B* type cuts across all climate groups except for *F* (Trewartha & Horn 1980). Most of the grid points classified as *Ft* in the KTC, but as *B* in the KCC, occur in high elevations in the Andes in Peru and Chile (Fig. 3). Trewartha & Horn 1980 designate these areas as 'highland' climate type. However, the definition of the highland climate type is not clear enough to be applied unambiguously. Moreover, the orography in CRU data is smoothed and not always realistic. For these reasons the highland climate type was omitted in the present study. Most of the areas designated by Trewartha & Horn (1980) as highland fall into *Fi* or *Ft* according to our results.

As discussed in Section 3.6, the criteria for the determination of wet and dry climates are different in the KCC and the KTC, which results in differences regarding types *BS* and *BW* between the two classifications (Table 2, Fig. 3). *BW* areas in the KTC are mostly divided between *BW* (86.8%) and *BS* (13%) in the KCC. The areas marked as *BS* in the KTC are defined as various climate types in the KCC: most frequently *BS* (48.8%), with the remainder falling into types *Aw*, *Cw*, *Dw*, *BW*, *Cf*, and *Df*. *BS* occurs more often in the KTC than *BS* does in the

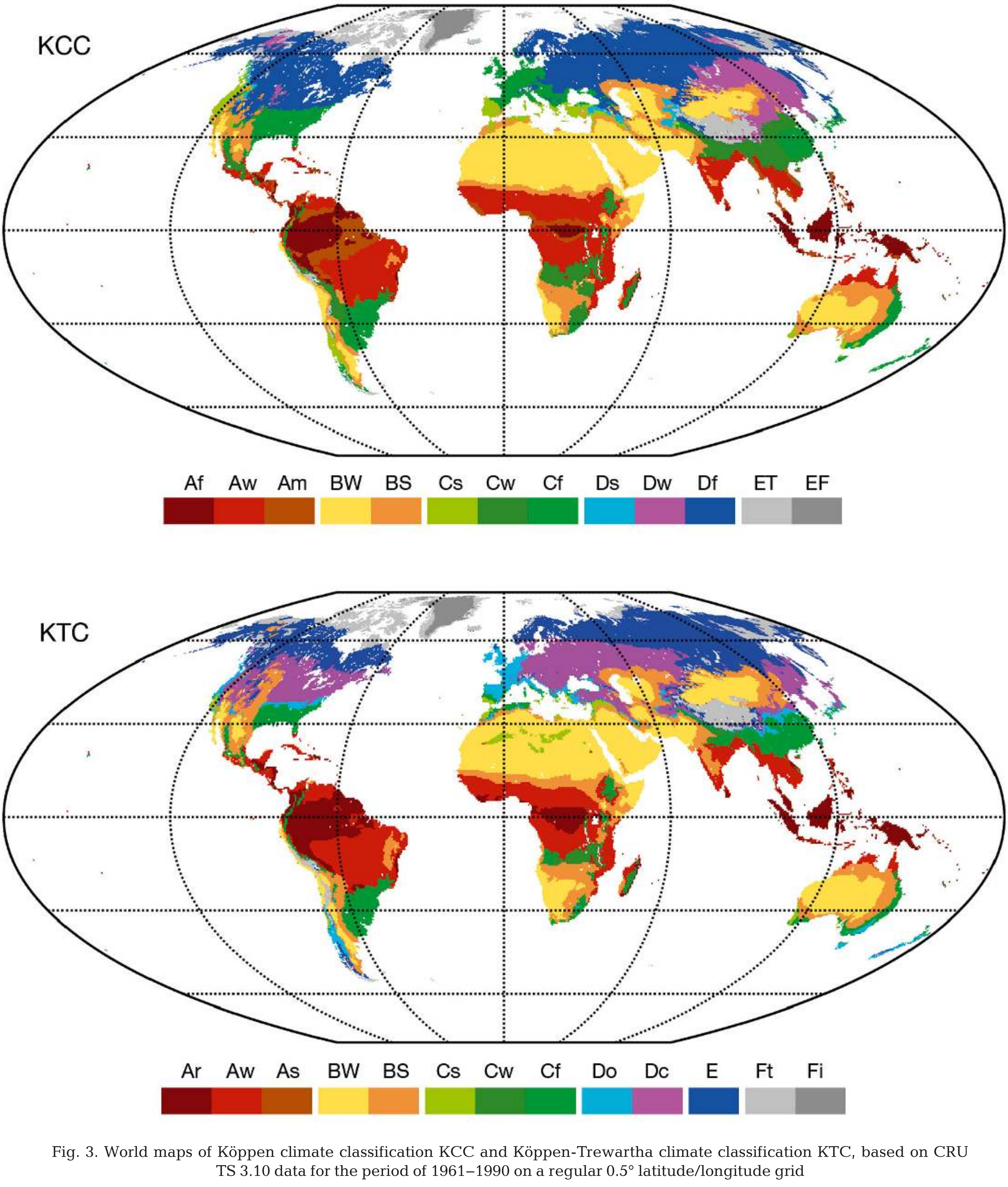

Fig. 3. World maps of Köppen climate classification KCC and Köppen-Trewartha climate classification KTC, based on CRU TS 3.10 data for the period of 1961–1990 on a regular 0.5° latitude/longitude grid

KCC. The percentage of areas classified as *BW* is very similar in both classifications (approx. 19% of continental area).

5. KOPPEN-TREWARTHA CLIMATE TYPES OVER THE PERIOD 1901–2005

We calculated the percentage of continental areas (except Antarctica) occupied by particular KTC types for moving 30-yr averages over the period 1901–2005 for the CRU TS3.10 dataset. The results for the main climate types and selected subtypes are shown in Fig. 4. Transitions of climatic types between 1901–1930 and 1976–2005 are presented in Table 4. Maps showing the KTC distribution for the beginning and the end of 20th century are presented in Fig. 5. The map for the reference period 1961–1990 is shown in Fig. 3. Maps for other periods based on both the KTC and the KCC can be found on a supplementary website at http://kmop.mff.cuni.cz/projects/trewartha.

The area of climate type *A* increased between the periods 1901–1930 and 1935–1964. In the following years, we see either a stagnation or slight decrease; however, since 1965–1994, there has again been an increase in the area of type *A* (Fig. 4). This recent increase is caused mainly by an increase in subtype *Aw*, represented particularly as a shift from types *Cf* and *Cw* (Table 4).

In Fig. 4, we also see an increase of the area occupied by type *B* (approx. 1.2%) in the second half of 20th century. This is mainly because of the extension of semi-arid climates *BS*, chiefly in areas classified as *Aw*, *Dc* and *E* in the beginning of 20th century

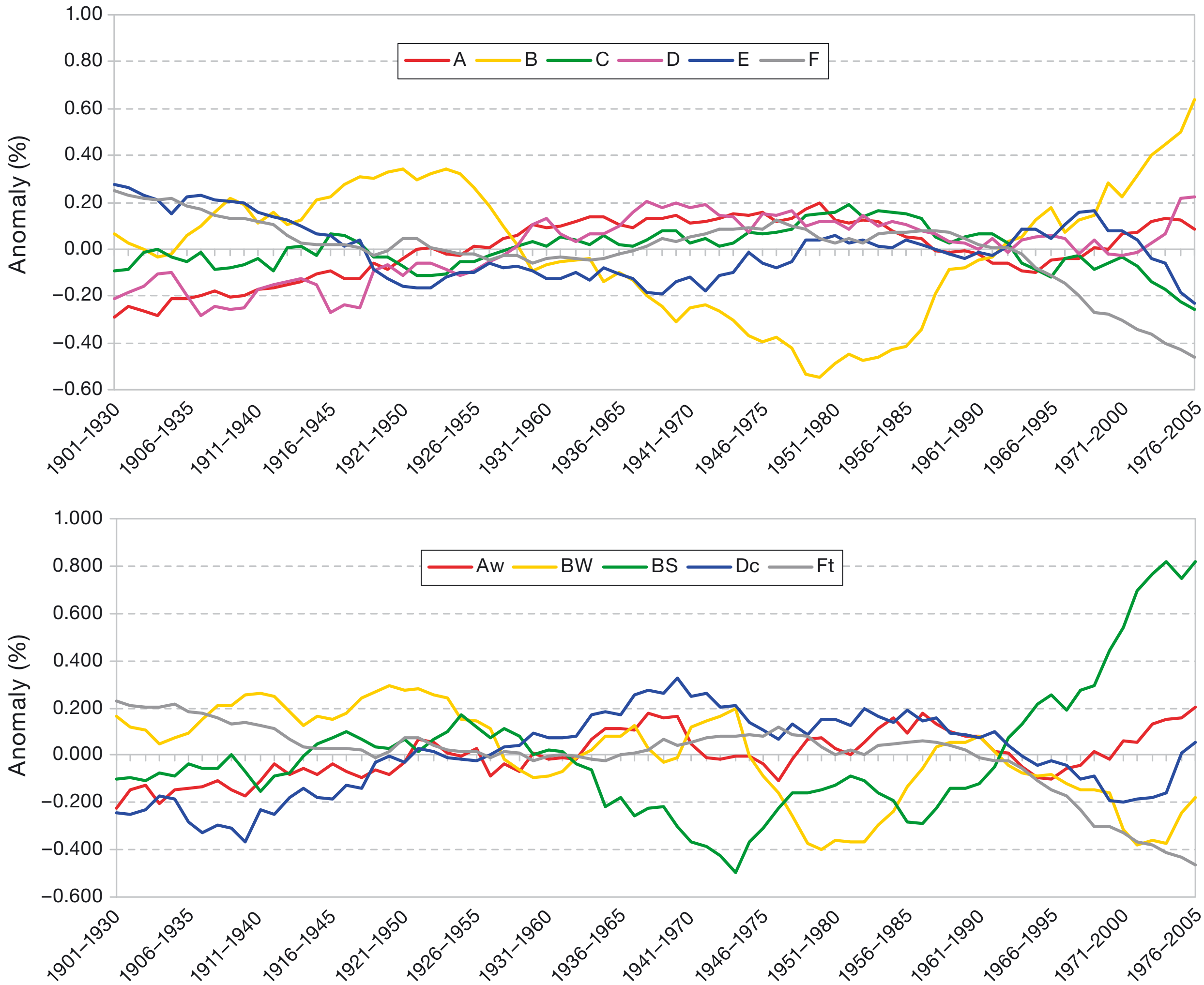

Fig. 4. Anomalies of percentage of continental area (excluding Antarctica) covered by KTC climate types (top) and selected subtypes (bottom) for moving 30 yr means with respect to the mean value for the period 1901–2005, calculated from the CRU TS 3.10 dataset

Table 4. Percentage of continental area (excluding Antarctica) covered by Köppen-Trewartha (KTC) climate types at the beginning and end of the 20th century (1901–1930 and 1976–2005, respectively), calculated from CRU TS 3.10 dataset

		1976–2005												
		Ar	*Aw*	*BW*	*BS*	*Cs*	*Cw*	*Cf*	*Do*	*Dc*	*E*	*Ft*	*Fi*	Sum
1901–1930	*Ar*	6.93	0.49					0.01						**7.43**
	Aw	0.41	11.85		0.36		0.00	0.01						**12.63**
	BW			18.51	0.88							0.00		**19.40**
	BS		0.29	0.52	11.66	0.01	0.02	0.29	0.10	0.16	0.01			**13.06**
	Cs		0.00		0.05	1.08		0.05	0.01					**1.20**
	Cw		0.13		0.05		0.52	0.10						**0.79**
	Cf	0.04	0.30		0.27	0.06	0.01	7.19	0.04					**7.91**
	Do				0.03	0.01		0.37	2.73	0.08	0.01			**3.22**
	Dc				0.52				0.43	10.36	0.03			**11.33**
	E				0.14				0.04	1.03	14.05	0.02		**15.29**
	Ft			0.02	0.03						0.68	5.85		**6.58**
	Fi											0.02	1.14	**1.16**
	Sum	**7.38**	**13.06**	**19.06**	**13.98**	**1.16**	**0.56**	**8.02**	**3.35**	**11.63**	**14.78**	**5.89**	**1.14**	

(Table 4). The increase of *BS* occurred mainly in Australia, and central Asia, but also in South and North America (Fig. 5). The area falling into the *BW* type shows relatively large fluctuations throughout the 20th century (Fig. 4). It is worth noting that during the second half of the 20th century changes in the area of the *BW* type are accompanied by opposite changes in the *BS* type. The first marked phase shift of this kind occurs after around 1936–1965 period and a second one can be identified after the period 1961–1990. As illustrated by Table 4, a large part of these shifts can be explained by mutual replacement of *BW* type with *BS* and vice versa; however, a considerable part is also caused by transitions between other types, especially *BS*-*Cf* and *BS*-*Aw*.

With respect to the *C* type, we see only small fluctuations and a slight decrease of the area in the second half of 20th century.

The area of *D* type increased by approximately 0.4 % in the first half of the century. This was caused mainly by the spread of those areas falling into type *Dc*. In the past 50 yr, relative changes to the *Dc* and *Do* areas almost compensate for each other; *Dc* has decreased slightly (except most recently since 1970), whereas *Do* has increased. The recent increase in *Dc* is mainly caused by transitions from types *E* and *BS* (Table 4).

Furthermore, we see 2 phases of decrease in the area belonging to type *E*. The first took place between the periods 1901–1930 and 1921–1950, and the second is stronger and occurred after 1969–1998. Between these 2 intervals, a slight increase in the area of type *E* occurred. A similar course can be identified in the case of *Ft*, but in this case in the central period there is no trend and in the final period the decrease is more pronounced. A decrease of both *E* and *Ft* types can be attributed to the rising surface air temperature. In the Northern Hemisphere, the northward shift of the border between *E* and *Dc* is clearly visible (Fig. 5).

6. DISCUSSION AND CONCLUSIONS

We present a description of the Köppen-Trewartha climate classification (KTC), its comparison with the Köppen classification (KCC), and their application to the most up-to-date CRU dataset version with horizontal resolution of 0.5° × 0.5° over the period 1901–2005. The KTC (Trewartha & Horn 1980), sometimes denoted 'K-T scheme', has been used as frequently as the KCC or Köppen-Geiger classification for the analysis of climate model performance and for model projections of future climate change. The advantage of the KTC is a more detailed depiction of climate types (e.g. Fig. 3). This classification has also been proven suitable for the creation of maps of global Ecological Zones (www.fao.org/docrep/006/ad652e/ad652e07.htm) for the Forest Resources Assessment Programme of The United Nations Food and Agriculture Organization (FAO). According to FAO (2001), 'there is a demonstrated good correspondence between Köppen-Trewartha subzones or climatic types and the natural climax vegetation types and soils within them'.

We originally intended to use only the KTC for our analysis of the outputs of the new generation of GCMs. However, during preparations for this task we encountered much ambiguity in publications and papers dealing with climate classifications. These

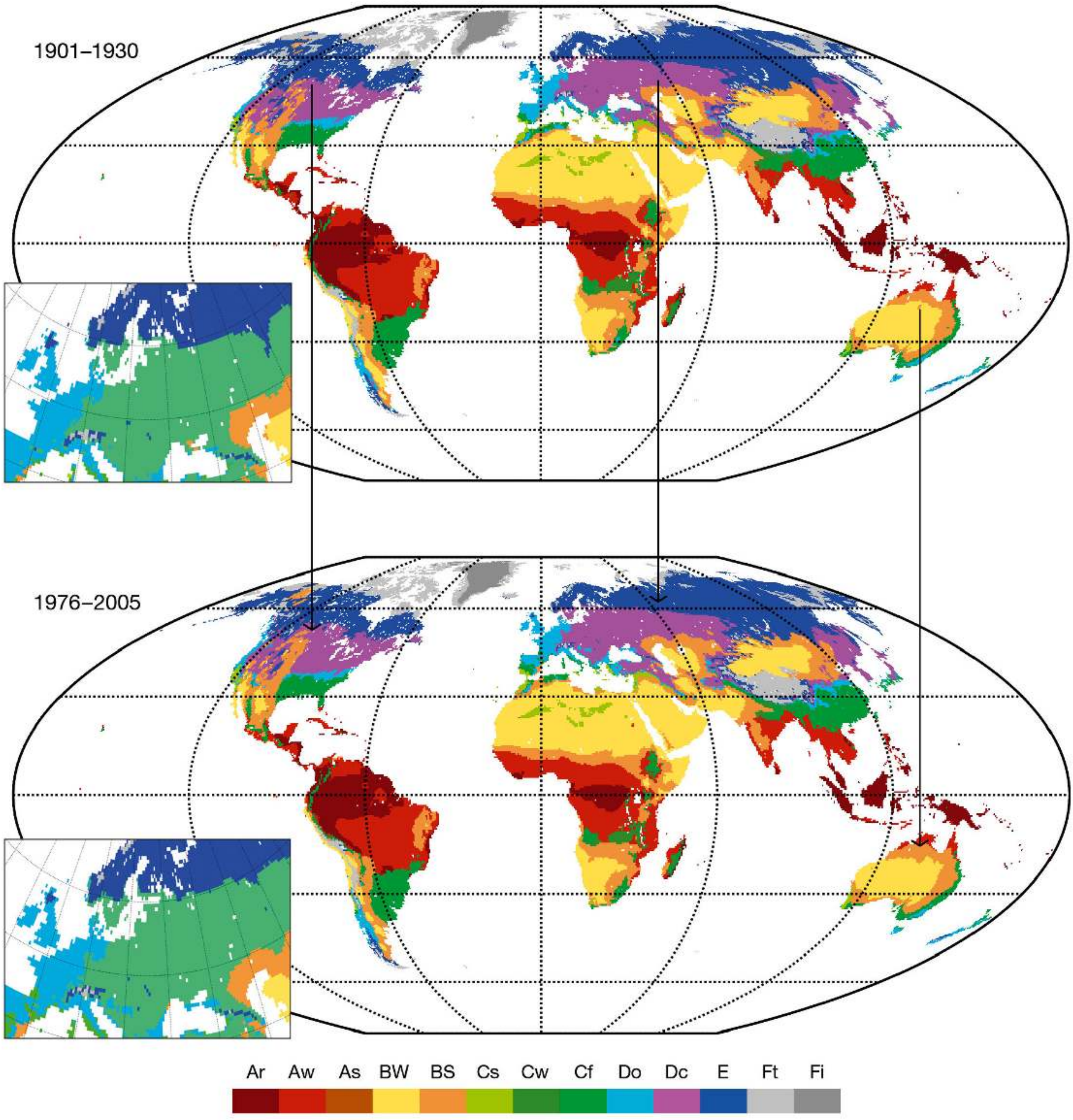

Fig. 5. World maps of Köppen-Trewartha climate classification based on CRU TS 3.10 data for the periods (top) 1901–1930 and (bottom) 1976–2005 on a regular 0.5° latitude/longitude grid. Arrows indicate areas of change

issues related to the designation of the classification (some studies by title suggest the KCC, but actually use the KTC), modified values of thresholds, and different interpretations of classification algorithms, e.g. whether to apply the dryness criteria first or to set apart polar climates. Therefore, we decided to first analyze and describe the KTC in detail, according to Trewartha & Horn (1980) using Patton's criteria of dryness, and compare it to the widely used KCC scheme (Köppen 1936). Following this preparatory study, the analysis of the validation and of future simulated climate change by using the CMIP5 GCM outputs, will follow in subsequent papers.

Another motivation for our study is that the digital maps of Köppen-Geiger climate types are already available in various versions (Kottek et al. 2006, Peel et al. 2007, Rubel & Kottek 2010). However, to our knowledge, digital maps of the KTC climate types for the up-to-date CRU data have not been presented before. We believe that making these maps accessible via the internet will be beneficial to other researchers, not just in the field of climatology, but also in the fields of hydrology and ecology, etc.

It is hardly possible to directly compare our results regarding the spatial distribution of the KTC types and areas belonging to particular climate types with other studies because of the differences in the analyzed datasets and time periods. For example, according to the present study, the order of climate types ranked by the percentage of continents (excluding Antarctica) that they cover in the period 1976–2005 is as follows: *B* (33.04 %), *A* (20.44 %), *D* (14.98 %), *E* (14.78 %), *C* (9.74 %), and *F* (7.03 %). Fraedrich et al. (2001) show that for the period 1981–1995 global tropical zone *A* covers around 22.4 % of the continental area. Rubel & Kottek (2010) rank type *B* according to KCC as the most abundant, covering total 29.14 % of the global land area (including Antarctica). The ranking derived in this study from the CRU data is different from the one mentioned by Trewartha & Horn (1980), who present type *A* as 'the most widespread of any great climatic groups', estimating the area covered by the type *A* to be around 20 % of the land surface.

Regarding the changes in the area covered by individual climate types observed during 1901–2005, we have shown that there are observable changes, especially in subtypes *BS*, *Aw* and *Ft* (Fig. 4). Comparison of our results concerning the temporal evolution of the cover of climate types with other studies is again somewhat difficult. Temporal variations of tundra *Ft* agree well with the findings of Feng et al. (2012), who found a weak trend towards reduced tundra cover from the beginning of the 20th century to the 1940s and a more abrupt decrease during the past 40 yr. This is also in accordance with trends described by Wang & Overland (2004) and Fraedrich et al. (2001). Furthermore, Feng et al. (2012) describe an expansion of continental temperate climate *Dc* in the area north of 50° N over the past few decades. In our global analysis, the *Dc* area has expanded in the 30-yr periods since 1970 (Fig. 4). Fraedrich et al. (2001) found that the global tropics (*A*) and the tundra (*Ft*) types show statistically significant shifts in the 1901–1995 period. The expansion of the *A* type was replaced by an areal reduction near the end of the period. Similar to our results concerning the *Ft* subtype, they also found a negative trend both at the beginning and at the end of the 20th century.

The analysis of the time development of climate types was, however, not the main goal of the present study; we intended primarily to prepare the background for the validation and the analysis of the CMIP5 GCMs outputs in subsequent papers, where the temporal evolution will be addressed both for simulations of the 20th century and future projections. Therefore, a more detailed examination of this issue is beyond the scope of this study. Here we were only able to show a part of the results obtained during our analysis. Additional materials, including digital maps for various time periods and animations, are accessible at http://kmop.mff.cuni.cz/projects/trewartha.

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