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Using the Köppen classification to quantify climate variation and change: An example for 1901–2010

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ABSTRACT

The Köppen climate classification was developed based on the empirical relationship between climate and vegetation. This type of climate classification scheme provides an efficient way to describe climatic conditions defined by multiple variables and their seasonalities with a single metric. Compared with a single variable approach, the Köppen classification can add a new dimension to the description of climate variation. Further, it is generally accepted that the climatic combinations identified with the Köppen classification are ecologically relevant. The classification has therefore been widely used to map geographic distribution of long term mean climate and associated ecosystem conditions. Over the recent years, there has also been an increasing interest in using the classification to identify changes in climate and potential changes in vegetation over time. These successful applications point to the potential of using the Köppen classification as a diagnostic tool to monitor changes in the climatic condition over various time scales. This work used a global temperature and precipitation observation dataset to reveal variations and changes of climate over the period 1901–2010, demonstrating the power of the Köppen classification in describing not only climate change, but also climate variability on various temporal scales. It is concluded that the most significant change over 1901–2010 is a distinct areal increase of the dry climate (B) accompanied by a significant areal decrease of the polar climate (E) since the 1980s. The areas of spatially stable climate regions for interannual and interdecadal variations are also identified, which have practical and theoretical implications.

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1. Introduction

Due to various factors limiting the distribution and abundance of organisms on Earth, each species and ecological community have a limited distribution. One of the most critical and variable determinants of the distribution of Earth's major ecosystem types is climate, which provides a source of energy and water (Zhou and Wang, 2000). Box (1981) suggests that general macroclimatic conditions influencing plant energy and water budgets are much more important than any other factors in determining the general ecological structure.

Climate is often defined as a comprehensive statistical description of weather over a sufficiently long period of time (usually 30 years) and varies at a wide range of temporal scales. Climate is determined by external forcings (e.g. solar radiation) and internal dynamics in the climate system (e.g. atmospheric and oceanic circulations and earth surface–atmosphere interactions).

In terms of the internal dynamics, there are atmospheric modes of circulation that have time scales of up to about two years (e.g. the quasi-biennial oscillation). We also have coupled ocean-atmospheric modes that have time scales from weeks to several decades (e.g. the El-Niño phenomenon which has a time-scale of about four years). These modes altogether can produce climate variations at various time scales, in addition to the long term changes which are often associated with different long term forcings.

For vegetation and ecosystems, climate can be considered general patterns of temperature, precipitation, humidity, wind, and radiation that characterize a region. But most climate classification schemes only use near-surface air temperature and precipitation as the two major variables in describing energy and water balance (e.g. Thorthwaite, 1948), mainly due to the limited accessibility of climate data.

Based on empirical observations, Köppen (1900) established a climate classification system which uses monthly temperature and precipitation to define boundaries of different climate types around the world. Since its inception, this system has been further developed (e.g. Köppen and Geiger, 1930; Stern et al., 2000) and widely used by geographers and climatologists around the world. The popularity of the system lies in its power in linking climate and natural vegetation (Bailey, 2009), and in its simplicity (Wilcock, 1968). Although there have been many efforts from German scientists to find alternative ways to classify the climate, the Köppen system remains one of the most widely used climate classification systems (e.g. Domroes, 2003).

Most applications of the Köppen system are concerned with mapping the geographic distribution of the world's climate or vegetation with the help of a long term climate dataset. Depending on the data used, the mappings may have different details and qualities for such a stationary description of the world's climate. Recently, Kottek et al. (2006) provided a well documented and easily accessible update of the world climate classification map using gridded climate data during 1951–2000. Taking a station-based approach in terms of the input climate data, Peel et al. (2007) presented another update of the Köppen climate classification scheme by using long-term station records of monthly precipitation and temperature from the Global Historical Climatology Network version 2 (GHCN2) dataset (Peterson and Vose, 1997). This update only gives long term averaged climate distributions over the whole period covered by the GHCN2 dataset.

Although most stations in the GHCN2 dataset have data that cover a period much longer than 30 years, some stations have data much shorter than 30 years. Peel et al. (2007) used all stations with at least 30 years data in their analysis, which means that the climate types in different parts of the world may represent different climates over different time periods. This is especially true for transitional zones between two different climate types.

Climate change can cause changes in the spatial extent of a climate type and plant community (e.g. Elmendorf, 2012). This kind of changes may also be reflected by changes in the areas occupied by the Köppen climate types (Wang and Overland, 2004). As an example, Diaz and Eischeid (2007) compared areas of the climate type “alpine tundra” over the 1901–1930 period with that of 1987–2006 for the mountainous western United States. They found that this type has a dramatic decline (~73%), indicating the regional warming and its possible effect on the ecosystem.

Owing to the fixed and objective set of predefined rules, the Köppen system can be easily applied in places where the necessary climate information is available. Because of the objectivity, the system has been increasingly used to compare climate model simulations with observations (Guetter and Kutzbach, 1990), to examine climate changes in observations (Fraedrich et al., 2001) and in model simulations (Guetter and Kutzbach, 1990; De Castro et al., 2007), and to visualize the projected future climatic changes (e.g. Gnanadesikan and Stouffer, 2006; Gao and Giorgi, 2008; Rubel and Kottek, 2010).

In describing climate change, a single variable (e.g. temperature) approach is often used. A good example is the well-known global mean temperature over the period covered by the instrumental records or by past climate reconstructions. The Köppen climate classification scheme provides a framework in which climate is characterized by a number of distinct seasonal temperature and precipitation regimes depending on the combination of seasonal temperature and precipitation. As such, it offers an effective way to provide an easily-assimilated depiction of climate. Therefore, the system provides us with an integrated way to monitor climate variations on a variety of temporal scales including short term variations.

As climate changes, it is expected that climate types around the boundary between two different types may shift from one regime to another. By examining historic changes using instrumental data and future changes using climate model simulations, a number of studies have confirmed that climate changes are indeed associated with shifts between climate types.

Kim et al. (2008) detected a climatic shift toward a warmer and dryer condition in the arid climate in North China from the decades 1951–1970 to the recent decades 1981–2000. Diaz and Eischeid (2007) discovered a reduction in the areal extent of the Köppen “alpine tundra” type for the mountainous western United States. Kalvova et al. (2003) examined changes in climate types in observations and simulations on the global level. They found that under a number of global warming scenarios, all global climate model projections of future climate around 2050 show that the areas occupied by groups A and B would be larger than the current climate, and the areas for other major climate groups would become smaller. These results are in line with those from Lohmann et al. (1993). It should be kept in mind that all mentioned studies look at changes in the Köppen climate types on the typical climate time scale, which on average is about 30 years.

Although the Köppen scheme was designed to reveal averaged climate (typically over 30 years) in relation to corresponding vegetation types on Earth, it may also be useful in describing shorter climate variability if the link between climate and vegetation is not a primary concern. Vegetation change would involve a long term adaptation process and short term variation in climate may be irrelevant for vegetation change. However, a recent study of Wang and Overland (2004) shows that the variation of the climate types on the interannual scale corresponds well with the changes of the vegetation status in the Arctic observed by satellite. This confirms the impact of short term climate variation on vegetation and indicates usefulness of using the short term variation of the Köppen types for describing climate variability and its impact on vegetation in a given region.

While the usefulness of the Köppen classification in describing mean climate conditions (around 30 years and longer) has been widely recognized, the possibility to use the method to characterize climate variability on shorter time scales needs to be explored. This study attempts to demonstrate the use of the Köppen classification in describing climate change (30 years) and variability (year-to-year and decade-to-decade). As an example, a global long-term instrumental dataset is used to reveal changes and variations of the Köppen climate types on the global scale.

We will describe the data and methods in Section 2. The results are shown and discussed in Section 3, which will be followed by Section 4 with some conclusions.

2. Data and methods

2.1. Temperature and precipitation data

This study used a global gridded dataset with monthly mean temperature and precipitation, covering 1901–2010, which was produced and documented by Kenji Matsuura and Cort J. Willmott from Department of Geography, University of Delaware. The data and associated documentations can be found at http://climate.geog.udel.edu/~climate/html_pages/Global2011/. Station data were compiled from different sources, including Global Historical Climatology Network version 2 (GHCN2) (Peterson and Vose, 1997) and the Global Surface Summary of Day (GSOD), and interpolated onto a $0.5 \times 0.5^{\circ}$ latitude/longitude grid system as described in Willmott and Matsuura (1995).

Peel et al. (2007) show the geographic locations of the stations in GHCN2 (their Figs. 1–3), revealing that the geographic coverage of the stations vary with time and that there are many more temperature stations than precipitation stations. In terms of the percentage of precipitation and temperature stations with a value for a given month, 1900–1970 saw a strong increasing trend (30–90% for both temperature and precipitation stations), while there is a sizable decreasing trend

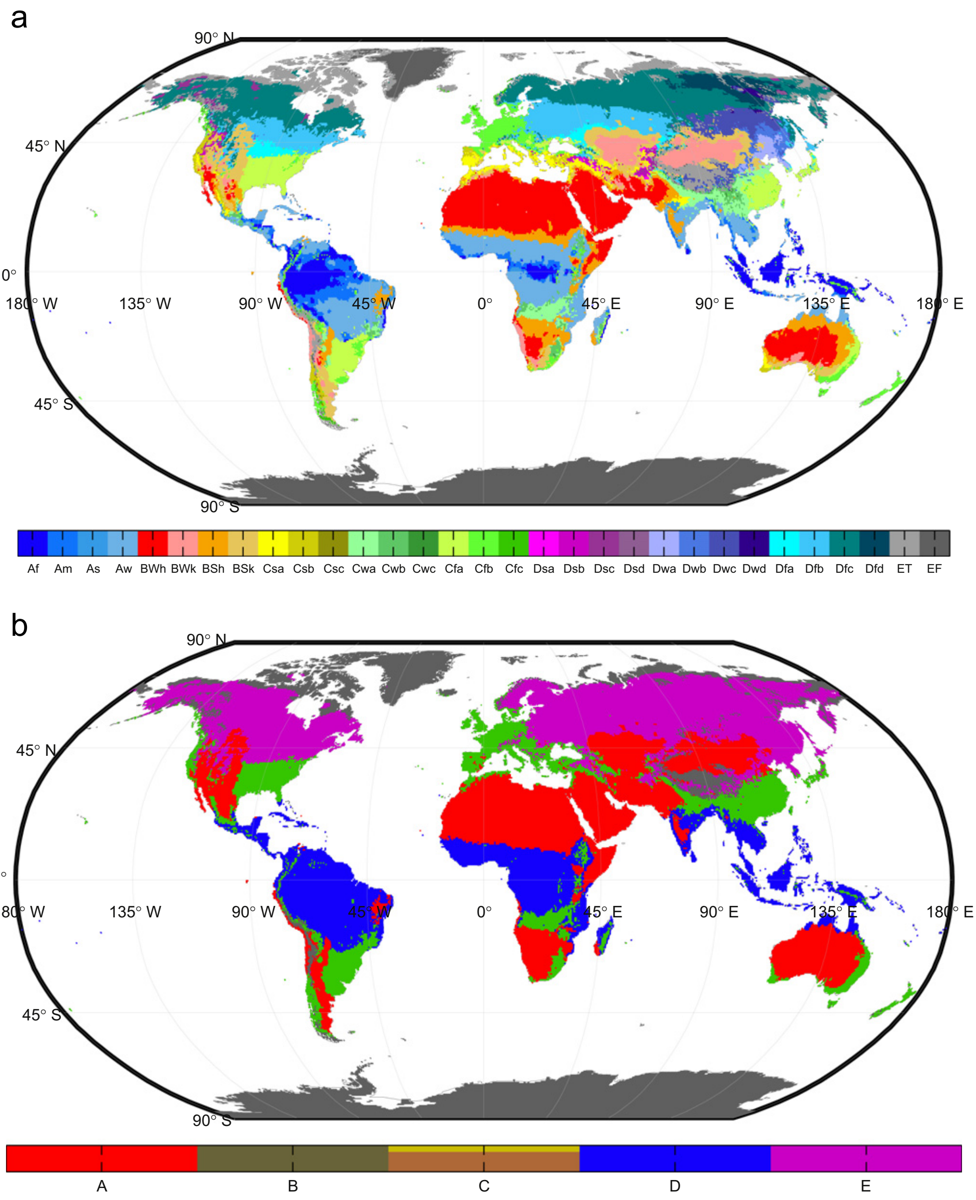

Fig. 1. Spatial distribution of the Köppen climate types for the period between 1901 and 2010: (a) with all sub-types included, (b) only the five major groups. The main characteristics of the climate types are described in Table 1.

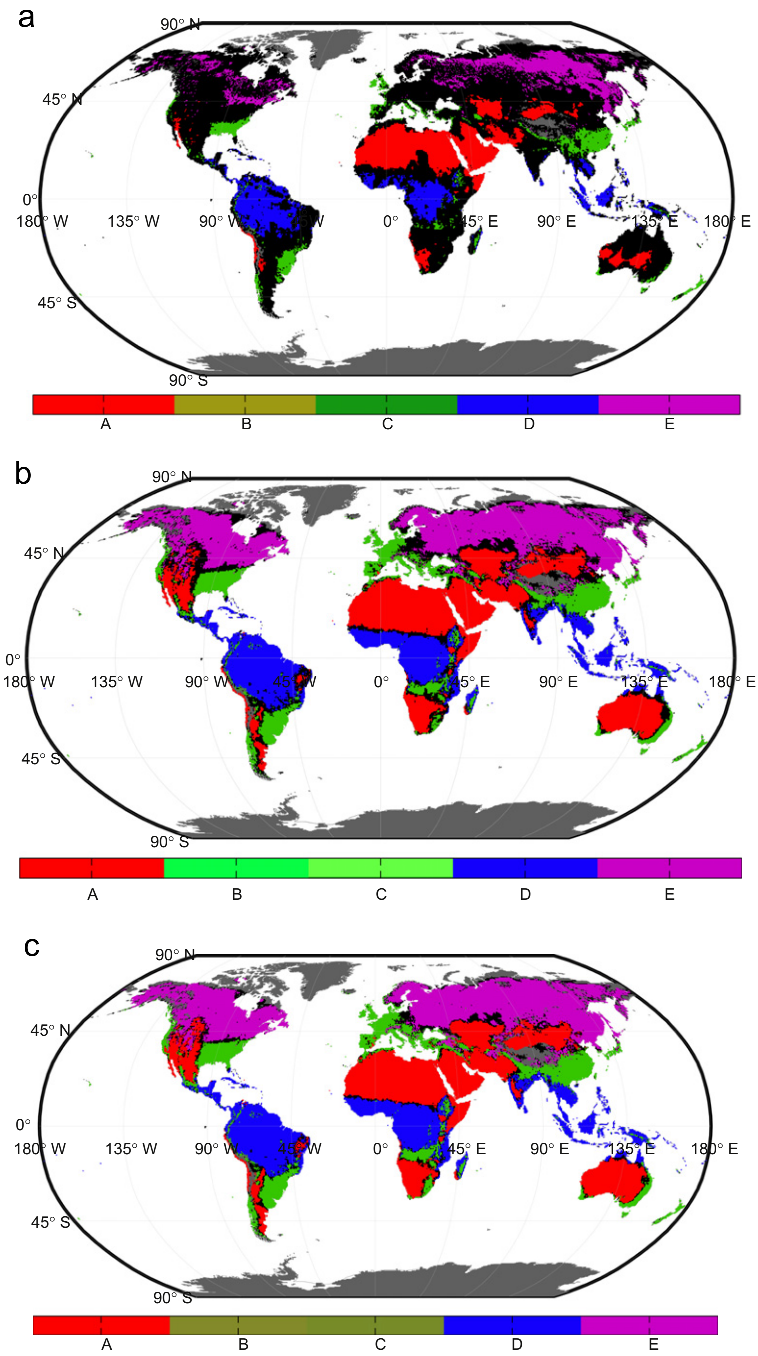

Fig. 2. Spatially instable (black) and stable major Köppen climate types on three time scales: (a) interannual, (b) interdecadal, (c) 30 year.

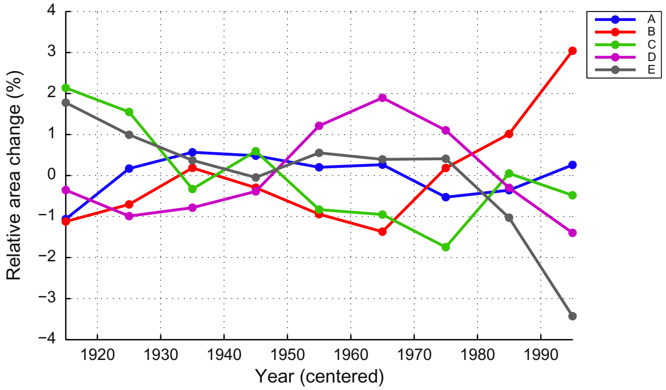

Fig. 3. Temporal changes in the relative areas (area for 30 year windows minus the long term mean during 1901–2010, divided by the long term mean) of the five major Köppen groups. The 30 year window is moved forward with an interval of 10 years and the years showing the data indicates the middle of the 30 year window, e.g. 1995 = 1981–2010.

Table 1
Main characteristic of the Köppen climate major groups and sub-types.

Major group	Sub-types
A: Tropical	Tropical rain forest: Af Tropical monsoon: Am Tropical wet and dry savanna: Aw (Sometimes As is used in place of Aw if the dry season occurs during the time of higher sun and longer days)
B: Dry	Desert (arid): BWh, BWk Steppe (semi-arid): BSh, BSk
C: Mild temperate	Mediterranean: Csa, Csb, Csc Humid subtropical: Cfa, Cwa Oceanic: Cfb, Cfc, Cwb, Cwc
D: Snow	Humid: Dfa, Dwa, Dfb, Dwb, Dsa, Dsb Subarctic: Dfc, Dwc, Dfd, Dwd, Dsc, Dsd
E: Polar	Tundra: ET Ice cap: EF

starting from around 1970. Generally speaking, Europe, North America, Japan and eastern Australia have good spatial and temporal coverage, while Africa, the polar regions and some tropical regions have sparse station density and relatively short records.

To our knowledge, this dataset is the longest instrumental records that have been subject to the Köppen climate classification on the global scale.

2.2. Köppen climate classification over different periods of time

The Köppen climate classification consists of five major groups and a number of sub-types under each major group, as listed in Table 1. While all the major groups except B are determined by temperature only, all the sub-types except the two sub-types under E are decided based on the combined criteria relating to seasonal temperature and precipitation. Therefore, the classification scheme as a whole represents different climate regimes of various temperature and precipitation combinations.

The tropical climate A is characterized by the lowest mean monthly air temperature being equal to or higher than 18 °C, while the four sub-types are decided based on the annual and seasonal mean precipitation. The dry climate B is determined by the annual mean precipitation and temperature, as well as the annual cycle of precipitation. Different sub-types distinguish between arid (desert) and semi-arid areas and further seasonal difference in precipitation conditions. The mild temperate C represents the climate with the lowest monthly mean temperature between −3 °C and +18 °C, while the different seasonal precipitations give rise to the four sub-types. The snow climate D has the lowest monthly mean temperature equal or lower than −3 °C, whereas the sub-types are decided based on the seasonal precipitation. Finally the polar climate E has the highest monthly mean temperature equal or lower than +10 °C, and the two sub-types further divide the major group into two temperature conditions.

Here we mainly focus on the five major groups to demonstrate the application of the Köppen classification as a tool to describe climate variation and change. The same method can be applied to all sub-types. A total of 31 sub-types are represented in the Köppen classification used in this study. See Kottek et al. (2006) for details about the various criteria for each type.

The Köppen climatic types were obtained by applying the classification rules described in Kottek et al. (2006) to each grid cell of the 1 year, 10 year, and 30 year monthly mean precipitation and temperature. For the 30 year scale, an overlapping in time is allowed. We look at changes of all the climate types, with a focus on the major five groups, with a sliding window of 30 years. Every time we move 10 years ahead, which means that the mean climate information used between two adjacent 30 year periods has a 20 year overlapping period.

3. Results and discussions

First of all, the average monthly temperature and precipitation for 1901–2010 at all grid points on the Earth are subject to the Köppen classification scheme and the results are shown in Fig. 1. Fig. 1a shows all 31 types which correspond well with the map of Rubel and Kottek (2010) who provided a welcomed update of the world climate classification map using gridded climate data during 1901–2002. The overall agreement between the two maps indicates that the dataset used in this study has a good quality, which gives us some confidence in the results to be analyzed below.

Since this study focuses on variations of the five major groups, the geographical distribution of the major groups is first given in Fig. 1b. It is estimated that the five major groups A, B, C, D, E cover 19.4%, 28.4%, 14.6%, 22.1%, and 15.5% of the total land area on Earth, respectively. This can be compared with 19.4%, 29.1%, 14.7%, 21.6%, and 15.2% of the total land area covered by respective climate types A, B, C, D, E presented by Rubel and Kottek (2010) for the mean climate over 1976–2000. This comparison again shows that the dataset used in this study is comparable with the independent dataset used by Rubel and Kottek (2010).

If the climate type or major group for a region remains the same, the region may be considered stable in terms of the climate characterized by the climate type or group. Fig. 2 shows the stable and variable climate regions on interannual, interdecadal, and climate time scales. We classified climate types for all grid points using annual, decadal, and 30 year running means of the climate data. If a grid point is always classified as a climate type under the same major group, it is shown in the same way as in Fig. 1b. Otherwise this grid point is taken as having varying climates on a given time scale since it contains more than one climate type over the time period considered. This provides a means to identify areas with stable climate types. If an experimental site to monitor environmental changes under a typical climate type is needed, these stable areas should be preferred. On the hand, the areas with shifting climate types are places where factors affecting the climate may have changed their strength, which provides indications for the dynamics behind the variation. Understanding the dynamics of these variations is one of the key tasks in climate research since the variation would have implications for the ecosystem changes.

Table 2 summarizes the fractions of the stable areas on interannual, interdecadal, and 30 year time scales. As shown by Fig. 2a, on the interannual scale there is a large variability, which results in large transition areas for the major climate groups. Obviously, there are some regional differences, and low latitudes generally have larger stability than middle and high latitudes, as expected. Type D occupies a large portion of the land area in the middle and high latitudes in the northern hemisphere and experiences the largest relative temporal change in its area. Yoshino and Kazuko (1981) examined the year-to-year variations of the Köppen types in eastern Asia and successfully linked these variations

Table 2
Portion of spatially stable major Köppen climate types on different time scales.

Major group	Time scales		
	Interannual (%)	Interdecadal (%)	30-year (%)
A	45.5	89.0	94.2
B	45.1	85.2	91.8
C	35.3	77.4	87.3
D	30.0	83.3	91.0
E	78.2	92.8	96.2

with the upper air streams such as the subtropical jet stream. He also discusses the impact of these variations on the agricultural production in the region.

The corresponding stable areas under interdecadal variations are much larger, as can be seen in Fig. 2b. Again, more instable regions occur in middle and high latitudes. Relatively speaking, group C now takes the top position in terms of the area variability. Variations at interannual and interdecadal time scales usually consider variability of climate. When we move to the 30 year time scale, the relatively small transition zones reflect changes in climate. At that time scale, the fractions of the stable climate types become large than those at other time scales. As pointed out by De Castro et al. (2007), regions with shifting climate types may impose a risk on the local ecosystem. Since certain sets of plants and animals are likely associated with environmental types such as the Köppen climate types, identification of spatially stable climates should be useful in the conservation of these associated plants and animals (Baker et al., 2010).

The identified unstable regions represent transition zones which deserve some special attention. As pointed out by Stern et al. (2000), Köppen's rigid boundary criteria often leads to large discrepancies between climatic subdivisions and features of the natural landscape. In the nature, the division between two climate types can hardly be a sharp cut. Thus, the transition zone should be taken separately from the two distinct climate types. It can be considered a fuzzy division between the two.

The identified changes of the Köppen types on climatic time scale may be used as a means to display changes in the global climate. A way to do this is to look at area changes in the major climate groups at the 30 year scale. Here we calculated the changes in the areas covered by the five major groups over nine intervals of the 30 year window. Fig. 4 shows the changes in terms of the fraction of the area in relation to the 1901–2010 long term mean.

As has been pointed out earlier, all major groups except B are decided based on temperature only. Thus changes associated with A, C, D, and E reflect changes in the temperatures. Out of the five major groups, A has the smallest relative change, while B and E show the largest changes over the whole period of time. It is well known that the high latitudes, especially the polar regions, have much higher warming than lower latitudes under the influence of the global warming, and the tropical regions experience very small changes (Solomon et al., 2007), which can explain the small and big changes in A and E respectively.

The area of type B shows an overall increasing trend while for type E there is a decreasing trend which is similar to that of group C over a large portion of the whole period. Several studies have examined the changes of the Köppen types over the last decades, which revealed a poleward movement of the Köppen climate zones (e.g. Wang and Overland, 2004), in accordance with the global warming. Using a global climate model with changed vegetation types in the arctic region, Jeong et al. (2012) recently showed that the changed vegetation in the northern high latitudes can trigger a positive feedback in the climate system. This positive feedback, in addition to the well-known ice-albedo feedback, may have contributed to the observed polar amplification effect.

The expansion of type B is most remarkable, since the area covered by B is the largest and the dry climate represented by B has a significant impact on ecosystems and humans. This type of climate is characterized by the fact that precipitation is less than potential evapotranspiration. Thus, decreased precipitation in combination with increased temperature (evapotranspiration) may be the cause for

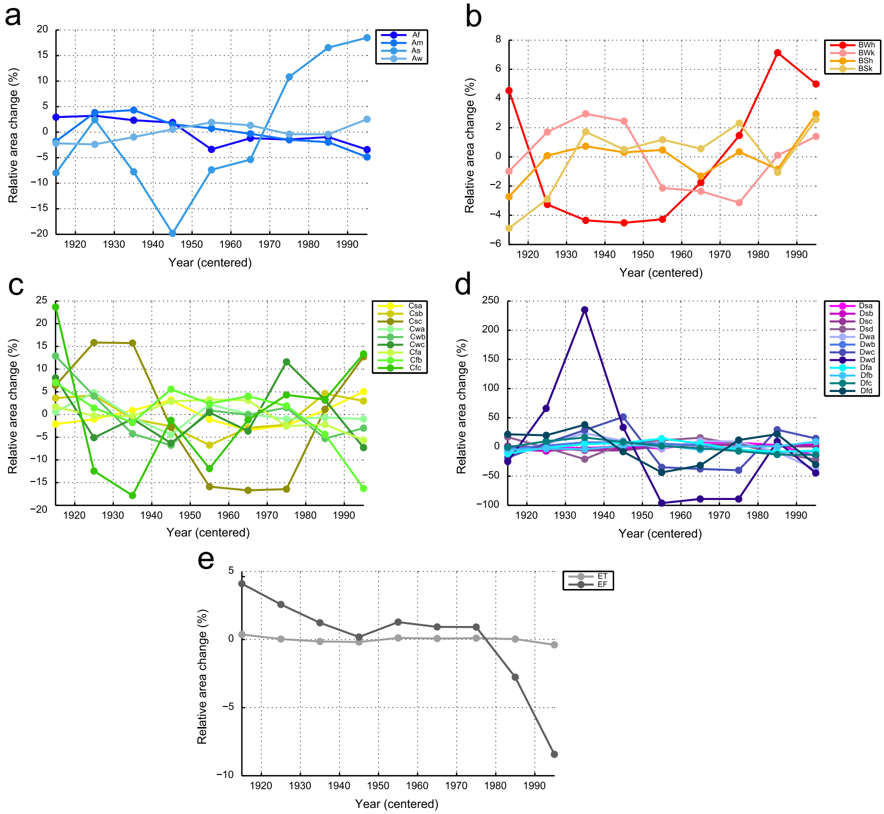

Fig. 4. Same as Fig. 3, but for all Köppen sub-types: (a) sub-types under A, (b) sub-types under B, (c) sub-types under C, (d) sub-types under D, (e) sub-types under E.

the expansion of type B whose poleward boundary is associated with the extension of the Hadley circulation in the tropics. Several previous studies show that during the past few decades (starting from 1979) the tropical belt has expanded (e.g. Seidel et al., 2008). Whether the changes in group B are associated with this expansion remains to be studied.

It would be interesting to determine the contribution of each of the sub-types in the total changes shown in Fig. 3. Therefore, we show in Fig. 4 the changes of all the sub-types in the same way as for the major groups. For sub-types under A, the type As stands out as the most variable type. For the dry climate, the identified increase for group B appears to be mainly caused by the increased in BWh, although other three types also have an overall increasing trend over the last few decades. For group C types Cfc and Csc turn out to be the two most variable types which often have opposite directions in their changes. As a result, the total change in group C is small. Dwd dominates the changes in group D and all other types show relatively small changes compared with those of Dwd. However, the sub-types in group D generally have larger changes than those in other groups. There is almost no change in ET (tundra), whereas EF (ice cap) shows a dramatic change with a two stage decrease that caused the overall decreasing trend for group E. Changes in EF is most likely a manifestation of the enhanced warming in the arctic region under the global warming trend.

The intention of this work is to demonstrate the use of the Köppen system to depict climate variation and changes on the global scale. Although a detailed analysis of the reasons behind the identified changes in the climate types is beyond the scope of this study, the analysis can give us useful information about regional climate variability/change and its potential impact on vegetation and should be performed in future studies. This is especially true if such an analysis is done on the regional basis.

4. Conclusions

The Köppen climate classification makes a useful link between climate and vegetation and provides a simple framework within which climate variability and climate can be described in an integrated way. Unlike the single variable approach, this description may be directly linked with consequences for the real world and provide additional information about the changes in the global climate system (e.g. the biosphere), which makes it an effective tool to monitor climate variations on various temporal scales.

By using a global gridded temperature and precipitation data over the period of 1901–2010, we reached the following conclusions:

- Over the whole period (1901–2010), the mean climate distributions have a comparable pattern and portion with previous estimates. The five major groups A, B, C, D, E take up 19.4%, 28.4%, 14.6%, 22.1%, and 15.5% of the total land area on Earth respectively. Since the relative changes of the areas covered by the five major groups are all small on the 30 year time scale, the agreement indicates that the climate dataset used overall is of comparable quality with those used in other studies.
- On the interannual, interdecadal, and 30 year time scales, the climate type for a given grid may shift from one type to another and the spatial stability decreases towards shorter time scales. While the spatially stable climate regions identified are useful for conservation and other purposes, the instable regions mark the transition zones which deserve special attention since they may have implications for ecosystems and dynamics of the climate system.
- On the 30 year time scale, the dominating changes in the climate types over the whole period are that the arid regions occupied by group B (mainly type BWh) have expanded and the regions dominated by arctic climate (EF) have shrunk along with the global warming and regional precipitation changes.

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References

Bailey, R.G., 2009. Ecosystem Geography: From Ecoregions to Sites. Springer, New York.

Baker, B., Diaz, H., Hargrove, W., Hoffman, F., 2010. Use of the Köppen–Trewartha climate classification to evaluate climatic refugia in statistically derived ecoregions for the People's Republic of China. Climatic Change 98, 113–131, http://dx.doi.org/10.1007/s10584-009-9622-2.

Box, E.O., 1981. Predicting physiognomic vegetation types with climate variables. Vegetatio 45, 27–39.

De Castro, M., Gallardo, C., Jylha, K., Tuomenvirta, H., 2007. The use of a climate-type classification for assessing climate change effects in Europe from an ensemble of nine regional climate models. Climate Change 81 (Suppl. 1), 329–341, http://dx.doi.org/10.1007/s10584-006-9224-1.

Diaz, H.F., Eischeid, J.K., 2007. Disappearing "alpine tundra" Köppen climatic type in the western United States. Geophysical Research Letters 34, L18707, http://dx.doi.org/10.1029/2007GL031253.

Domroes, M., 2003. Climatological characteristics of the tropics in China: climate classification schemes between German scientists and Huang Bingwei. Journal of Geographical Sciences 13 (3), 271–285.

Elmendorf, S.C., Henry, G.H.R., Hollister, R.D., Björk, R.G., Boulanger-Lapointe, N., Cooper, E.J., Cornelissen, J.H.C., Day, T.A., Dorrepaal, E., Elumeeva, T.G., Gill, M., Gould, W.A., Harte, J., Hik, D.S., Hofgaard, A., Johnson, D.R., Johnstone, J.F., Jónsdóttir, I.S., Jorgenson, J.C., Klanderud, K., Klein, J.A., Koh, S., Kudo, G., Lara, M., Lévesque, E., Magnússon, B., May, J.L., Mercado-Dı´az, J.A., Michelsen, A., Molau, U., Myers-Smith, I.H., Oberbauer, S.F., Onipchenko, V.G., Rixen, C., Schmidt, N.M., Shaver, G.R., Spasojevic, M.J., Þórhallsdóttir, Þ.E., Tolvanen, A., Troxler, T., Tweedie, C.E., Villareal, S., Wahren, C.-H., Walker, X., Webber, P.J., Welker, J.M., Wipf, S., 2012. Plot-scale evidence of tundra vegetation change and links to recent summer warming. Nature Climate Change 2 (6), 453–457.

Fraedrich, K., Gerstengarbe, F.-W., Werner, P.C., 2001. Climate shifts during the last century. Climatic Change 50, 405–417.

Gao, X., Giorgi, F., 2008. Increased aridity in the Mediterranean region under greenhouse gas forcing estimated from high resolution simulations with a regional climate model. Global and Planetary Change 62, 195–209.

Gnanadesikan, A., Stouffer, R.J., 2006. Diagnosing atmosphere-ocean general circulation model errors relevant to the terrestrial biosphere using the Köppen climate classification. Geophysical Research Letters 33, L22701 , http://dx.doi.org/10.1029/2006GL028098.

Guetter, P.J., Kutzbach, J.E., 1990. A modified Köppen classification applied to model simulations of glacial and interglacial climates. Climatic Change 16 (2), 193–215.

Solomon, S, Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., Miller, H.L., 2007. IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jeong, J.-H., Kug, J.-S., Kim, B.-M., Min, S.-K., Linderholm, H.W., Ho, C.-H., Rayner, D., Chen, D., Jun, S.-Y., 2012. Greening in the circumpolar high-latitude may amplify warming in the growing season. Climate Dynamics 38, 1421–1431, http://dx.doi.org/10.1007/s00382-011-1142-x.

Kalvova, J., Halenka, T., Bezpalcova, K., Nemesova, I., 2003. Köppen climate types in observed and simulated climates. Studia Geophysica et Geodaetica 47, 185–202.

Kim, H.-J., Wang, B., Ding, Q., Chung, I.-U., 2008. Changes in arid climate over North China detected by the Köppen climate classification. Journal of Meteorological Society of Japan 86 (6), 981–990.

Köppen, W., 1900. Versuch einer Klassifikation der Klimate, vorzugsweise nach ihren Beziehungen zur Pflanzenwelt. Geographische Zeitschrift 6, 657–679.

Köppen, W., Geiger, R., 1930. Handbuch der Klimatologie. Gebrueder Borntraeger, Berlin.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World Map of the Köppen–Geiger climate classification updated. Meteorologische Zeitschrift 15 (3), 259–263.

Lohmann, R., Sausen, R., Bengtsson, L., Cubasch, U., Perlwitz, J., Roeckner, E., 1993. The Köppen climate classification as a diagnostic tool for general circulation models. Climate Research 3, 177–193.

Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen–Geiger climate classification. Hydrology and Earth System Sciences 11, 1633–1644, http://dx.doi.org/10.5194/hess-11-1633-2007.

Peterson, T.C., Vose, R.S., 1997. An overview of the Global Historical Climatology Network temperature database. Bulletin of the American Meteorological Society 78 (12), 2837–2849.

Rubel, F., Kottek, M., 2010. Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen–Geiger climate classification. Meteorologische Zeitschrift 19, 135–141, http://dx.doi.org/10.1127/0941-2948/2010/0430.

Seidel, D.J., Fu, Q., Randel, W.J., Reichler, T.J., 2008. Widening of the tropical belt in a changing climate. Nature Geoscience 1, 21–24.

Stern, H, de Hoedt, G., Ernst, J., 2000. Objective classification of Australian climates. Australian Meteological Magazine 49, 87–96.

Thorthwaite, C.W., 1948. An approach toward a rational classification of climate. Geographical Review 38, 55–94.

Wang, M., Overland, J.E., 2004. Detecting Arctic climate change using Köppen climate classification. Climate Change 67, 43–62.

Wilcock, A.A., 1968. Köppen after fifty years. Annals of the Association of American Geographers 58 (1), 12–28.

Willmott, C.J., Matsuura, K., 1995. Smart interpolation of annually averaged air temperature in the United States. Journal of Applied Meteorology 34 (12), 2577–2586.

Yoshino, M.M., Kazuko, U., 1981. Regionality of climatic change in East Asia. Geo Journal 5 (2), 123–132.

Zhou, G., Wang, Y., 2000. Global change and climate-vegetation classification. Chinese Science Bulletin 45 (7), 577–585.