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Assessing the ability of the Köppen system to delineate the general world pattern of climates

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Abstract. The Köppen climate classification system [Köppen, 1923] is a scheme that provides an objective numerical basis for defining regional climatic types based on temperature and precipitation. Through the years it has been used as a scientific and teaching tool for prescribing the general world pattern of climates. Here for the first time an evaluation of the system is performed by employing coextensive temperature and precipitation data over the N. Hemisphere for the last 140 years. First the global pattern of climate type sensitivity is obtained. From this pattern it is discovered that several climate types exhibit a rather strong variability. Since all climate types depend on temperature we then tested whether or not the above variability is due to the fact that over the last 140 years the global climate system exhibits a well documented positive temperature trend known as global warming. We found that the Köppen system is rather insensitive to the observed global warming and concluded that overall the system performs rather poorly over Europe and Asia whereas it appears adequate over N.America and N.Africa.

Introduction

The Köppen system with its subsequent refinements includes five major climate types designated by capital letters as follows: **A** (tropical moist), **B** (dry), **C** (moist with mild winters), **D** (moist with cold winters), and **E** (polar) climates. The distinction of these types is based on two climatic variables, namely temperature and precipitation [Oliver and Wilson, 1987]. An additional type, the Highland climate (**H**) is assigned to places at high altitudes. The five major types are subdivided into a large number of sub-types that reflect the finer details in temperature and precipitation of the major types. Because of its applicability, the Köppen system is the most widely used system. It has, however, been criticized for not considering other climatic parameters such as sunshine and wind, and for relying on mean values, thus excluding the effect of the natural variability [Oliver and Wilson, 1987]. This is particularly important since it is well known that climate (global and/or regional) does not remain the same and even in stationary state it fluctuates significantly above the mean. The question then arises as to how robust, or alternatively, sensitive is a given Köppen type. This question has never been addressed mainly because of the lack of long temperature and precipitation data over the globe. Lately, however, a major effort has been dedicated to develop global or hemispheric temperature [Hansen and Lebedeff, 1987, Jones et al., 1986a, Jones et al., 1986b, Vinnikov et al., 1987, Folland et al., 1990] and precipitation data [Bradley et al., 1987, Diaz et al., 1989] sets. The availability of these data sets over the last 140 years or so provides a unique opportunity to objectively evaluate the Köppen system and its types. The temperature and precipitation data do not necessarily contain the same stations. The temperature data include stations for which no precipitation record is available and vice versa. From the two data sets we developed a new set by keeping only those stations for which values of temperature and precipitation are available over the same period. The number of stations retained varies unevenly with time from about 100 in the 1860's increasing steadily to about 1400 in the 1960's and declining to about 500 in the 1980's. The total number of stations considered in this study period (1851–1988) was 1,451.

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Data analysis and results

We chose to approach our problem as follows: knowing the monthly **T** and **P** values for any station for a year allows us to assign a climate type to that station. All stations with an altitude greater or equal to 1000 m were considered as Highland. In order to minimize statistical uncertainties subclassifications within a major type were not considered (the more the subdivisions the less the corresponding stations in each subdivision). By monitoring these maps in all available years we can infer long term temporal tendencies and spatial variability of all stations and climate types over the globe or over each one of the hemispheres. Due to geographical limitations of the available data and in order to maximize the statistical significance of our results (i.e utilize as maximum sample size as possible) we decided to concentrate on the continental regions of Northern Hemisphere.

An effective way to represent the massiveness of our results is Plate 1. For each station we produced a sequence of climate type as a function of time (year). We then found how many times the climate changed from one type to another. For example, assume that for some station the climate type as a function of time is **AABAABBBBA**. In this sequence the climate changes from **A** to **B** or from **B** to **A** four times. Normalizing this number by the length of the sequence or sample size, N, (ten in this case) provides a measure, m, of how stable (or how variable) the climate

type is for a given station. Plate 1 shows this measure for all available stations. Black corresponds to stations that show no change and red to stations that exhibit strong climate variability. We observe four areas of strong variability: one over the central United States, one over Central-Eastern Europe, one in India and one over North-Eastern China. A moderate variability region may also be identified across the Sahel of N. Africa. Regions of no change include England, Japan, South-Eastern Asia, the Arctic, parts of Canada and the grasslands of N. Africa.

Since the climate classification record sample size, N, for each station varies from as little as 10 to as much as 134 the next step is to identify biases due to sample size and to assess the significance of these results. Thus, we estimated the relative frequency distribution of N only for stations that show no change (minus the highland stations), $F1$, and the relative frequency distribution of N only for stations that show changes, $F2$. The idea behind this procedure is to see whether or not a zero measure m is more likely to be the result of a small sample size. The results are shown in Figure 1. There are obvious differences between the two distributions. The mean and standard deviations of $F1$ are $\overline{x}_1 = 45.0$ and $s_1 = 29.4$ (based on 588 stations). For $F2$ the corresponding values are $\overline{x}_2 = 62.0$ and $s_2 = 32.5$ (based on 755 stations). Accordingly, the null hypothesis that the data in $F1$ came from $F2$ using the Kolmogorov-Smirnov test is rejected at a confidence level of $a = 0.05$. That means that regions that show no change may have been classified as such because of the limited number of years in which both temperature and precipitation are reported. That brings up the question of what is the appropriate (minimum) sample size, N_{min}, that a climate classification record must have before its measure m is accepted as statistically significant. We resolved this issue by considering $F1(N)$ and $F2(N)$ only when stations for which N is greater or equal to some prescribed value are included. We found that the $F1(N)$ and $F2(N)$ become statistically equivalent at $a = 0.05$ (i.e., the null hypothesis that the data in $F1$ come from $F2$ is not rejected) when $N \geq 30$.

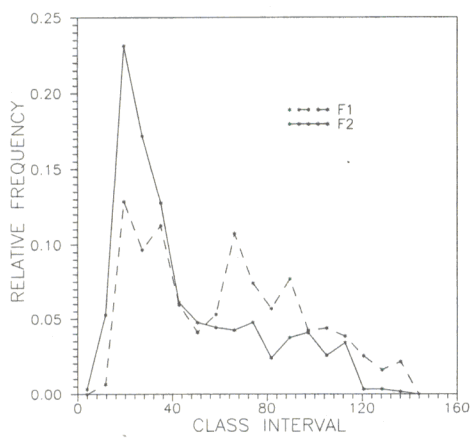

Figure 1. Relative frequency distribution of the sample size N (or number of available years) for only those stations reporting no change ($m = 0$), $F1$, and for those stations that report changes, $F2$ ($m > 0$). Each class interval is eight years wide and each asterisk corresponds to the mid-point of each interval.

We, thus, adopted $N_{min} = 30$ and produced Plate 2 which is similar to Plate 1 but does not include stations from which $N < 30$. The total number of stations is now 1,033. A comparison between Plates 1 and 2 show that they both exhibit similar characteristics and thus, the conclusions drawn from Plate 1 stand when stations with very short records are removed from the analysis.

A straight forward comparison of Plate 2 with the accepted distribution of major Köppen climatic regions indicates that only two major types can be associated with low variability. More specifically we find that a Köppen region assigned a type **A** has a less than 5% chance to deviate from that type. This number was found by averaging m for all stations which according to the accepted distribution are classified as **A** type climates. A region assigned a type **B** has a chance of close to 50% to deviate. This number becomes even greater if one considers those **B** climates not corresponding to deserts. The chance of a type **C** climate varies with the region. Humid subtropical regions (South-Eastern US, South-Eastern China and Southern Japan) are quite stable with a chance less than 5% to deviate. This chance is higher for dry summer regions such as Southern Europe ($\leq 20\%$) and much higher for more continental regions such as Central Europe (Germany, Poland, Austria) where the chance is close to 40%. A region assigned a type **D** has a chance close to 50% to deviate if it is not a subpolar (Northern Canada and Siberia) region where the chance is less than 15%. Finally a region designated the type **E** is quite stable with a chance of about 8% to deviate.

High variability does not correspond only to **B** types whose designation depends on precipitation (a more complex and fluctuating variable) but to types (such as **D** and **C**) which are delineated by temperature only. This brings up an interesting point. During the time of the available data a marked positive trend in the global (and hemispheric) mean annual temperature records (known as global warming). Is it possible that the global warming scenario is responsible for the observed variability patern and if yes to what extend? In order to address this question we proceeded with as follows. A careful examination of the global warming as depicted by the IPCC record [Folland et al., 1990] reveals that the overall trend is not gradual but rather exhibits the following features: 1) fluctuations about a constant mean temperature anomaly level of ≈ -0.25 in the segment 1870–1925, 2) a transition period during the years 1925–1930 that settles to, 3) fluctuations about a constant mean of about 0.0 in the segment 1930–1980, and 4) a transition period from 1981–1988 whose settling is at this time unknown.

The two segments have been chosen to have the same length in order to keep the sample size the same. Standard statistical tests (such as the t-test) support the above by indicating that at a significance level $a = 0.05$ the intervals corresponding to the segment 1870–1925 and to the segment 1930–1980 have means that are significantly different from each other but exhibit trends that are not significantly different than zero. Based on these observations we considered the period 1875–1980 and found from the 1,033 available stations all the stations that operated continuously in that interval ("frozen" grid). The number of those stations is 331.

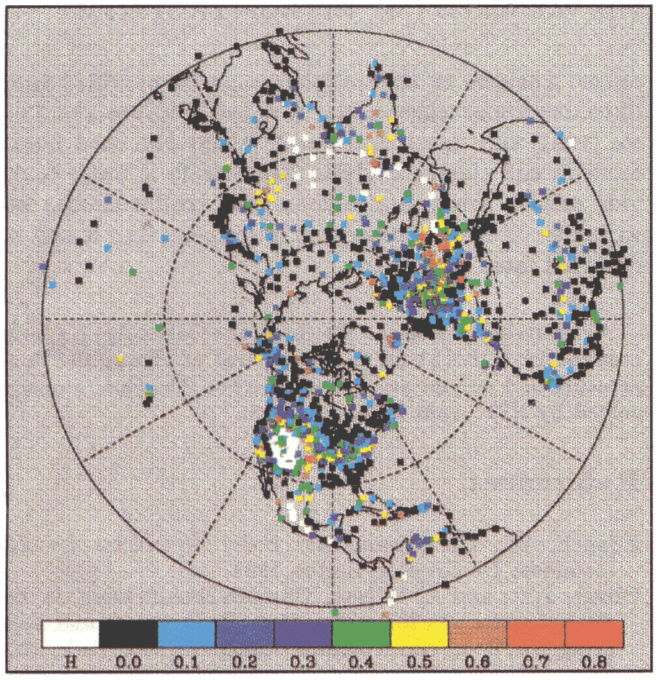

Plate 1. The map shows the measure m (see text for definition) for all 1,451 stations in the N. Hemisphere that have coextensive precipitation and temperature monthly data in the period 1951–1988. White corresponds to highland climates, black to stations that show no climate type change through their history, blue to stations with $0 < m \leq 0.1$, yellow to stations with $0.4 < m \leq 0.5$ e.t.c.

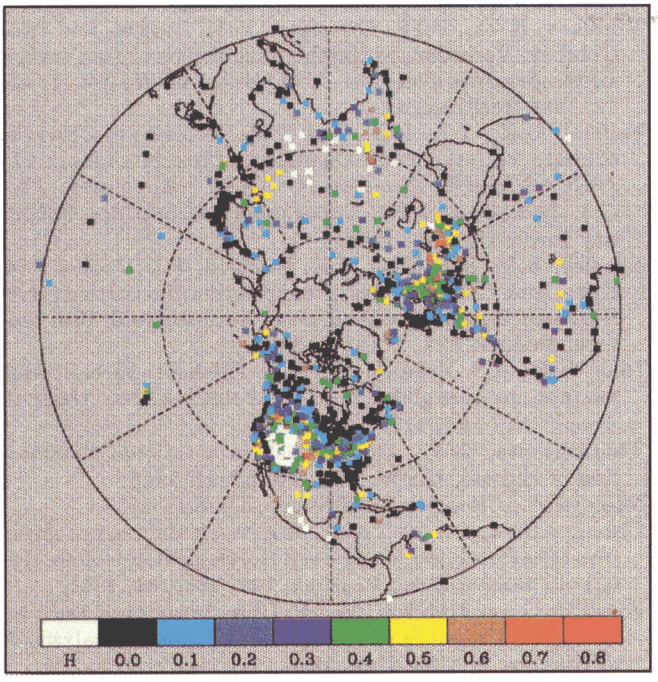

Plate 2. Same as Plate 1 but including only those stations for which available data exist for at least 30 years (total number of stations 1,033). See text for discussion.

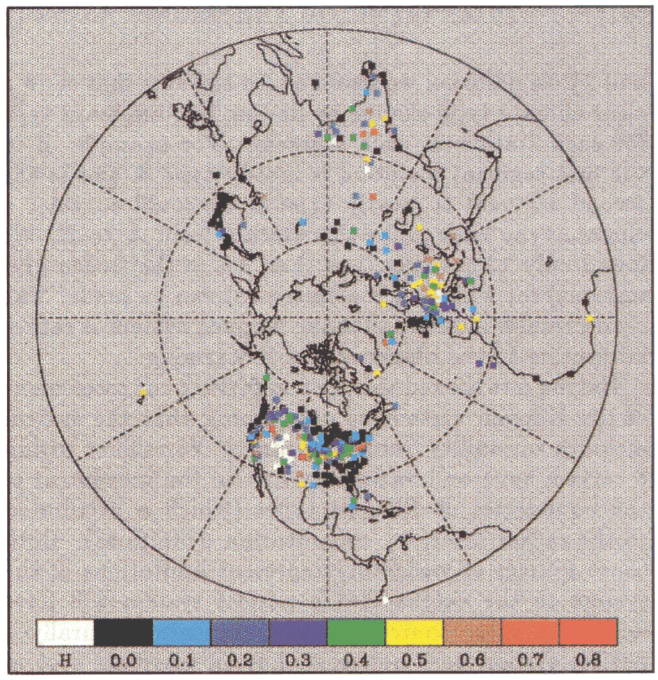

Plate 3. Same as Plate 2 but for the segment 1875–1925 and for those stations only that report monthly temperature and precipitation continuously in the 1875–1980 ("frozen" grid, 331 stations).

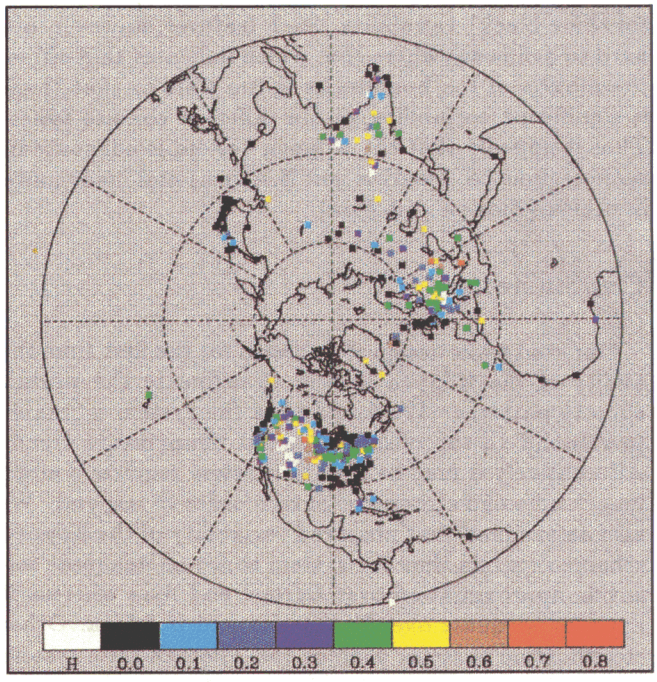

Plate 4. Same as Plate 3 but for the segment 1925–1980. The similarity between Plates 3 and 4 indicates that that the Köppen system is insensitive to the global warming scenario observed in the last century or so.

Then we reproduced maps similar to Plate 2 for the segment 1875–1925 (Plate 3) and for the segment 1930–1980 (Plate 4). Thus, each map is based on fifty years of data and represents a period during which no significant trend is observed. The map, however, in Plate 4 corresponds to a warmer global climate. If a significant part of the variability of the Köppen system was due to the global warming scenario over the 140 years or so, then one should be able to observe significant differences between Plates 3 and 4. This is obviously not the case since the same major features are clearly observed in both Plates 3 and 4 (as well as in the earlier Plates 1

and 2). In addition we searched for stations that show a clear climate type change by finding the dominant type for each station in each segment. For example, if in the first segment a station is mostly type **A** and in the second segment is mostly type **B** we could consider a climate type change for this station from **A** to **B**. We found only 12 stations (less than 4% of the frozen grid stations) for which such a statement can be made. The above results indicate that the Köppen system is rather insensitive to the observed global warming.

Having established this we can further our assessment of the Köppen system by considering that the system includes variability from two sources. Variability within a certain type and variability due to the movement of the boundaries of different types (which is attributed to the rather arbitrary classification definitions). Both those sources of variability represent limitations of the system to the extent that a perfect system will have neither of these sources of error present. Naturally a perfect system does not exist, but an adequate system should exhibit little variability within a certain type and narrow bands of high variability indicating rather small boundary movements. Such patterns are evident in Plate 2 over the United States and over the N.Africa where high variability (green-yellow-brown) is observed along rather narrow zones separating regions of different climate types which within them exhibit little temporal (blue-black) variability. Such features, however, are hard to define anywhere else, which indicates that either the motion of the boundaries is too wide or that there is significant variability within different climate types. Thus it appears that the Köppen system is adequate in some regions (N.America and N.Africa) and inadequate in others (Europe and Asia).

Conclusions

Our study was designed to assess for the first time the ability of the Köppen system to delineate the world's climate patterns. We found that the system is unable to respond to the observed global temperature trends Alternatively it may be that the system requires a much longer time and stronger events in order to respond. We also determined that observed variability of the Köppen scheme suggests that the system is not an adequate scientific approximation over Europe and Asia whereas it appears adequate over N.America and N.Africa. Other classification systems such as the Thornthwaite system [Thornthwaite, 1948], the Miller system [Miller, 1953] etc. are based on the same variables as the Köppen system and/or include other variables such as potential evapotranspiration which are extremely impractical to determine. Accordingly, we believe that these systems will also suffer from the same or additional problems. Thus, the question as to what is a robust scheme for representing the world's climate patterns remains wide open. Answers to this problem may be provided from objective approaches similar to those of Elsner and Tsonis [1991] and Fovell and Fovell [1993] who used factor analysis and cluster analysis respectively in order to divide certain areas into regions that exhibit similar covariance. Work in this area is in progress and it will be reported later elsewhere.

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