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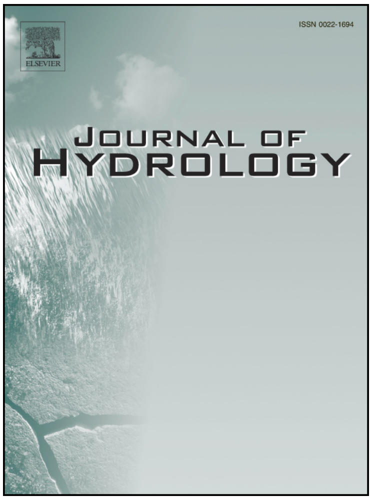

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Assessment of global aridity change

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SUMMARY

The growing demand for water and the anticipated impacts of climate change necessitate a more reliable assessment of water availability for proper planning and management. Adequate understanding of the past changes in water resources availability can offer crucial information about potential changes in the future. Aridity is a reliable representation of potential water availability, especially at large scales. The present study investigates the changes in global aridity since 1960. The study considers the UNESCO aridity index, with aridity being represented as a function of its two key drivers: precipitation (P) and potential evapotranspiration (PET). First, published literature on changes in trends of P, PET, and aridity across the world is surveyed. This is followed by the analysis of trends in the aridity observations over the period 1960–2009. The nonparametric Mann-Kendall test is performed for trend analysis and outcomes investigated for the presence of clusters of trend across different grid cells the analysis is conducted over. The results suggest that arid zones are becoming slightly more humid and vice versa. They also indicate that the trend in aridity changed, or even reversed, around 1980 in most parts of the world. We speculate that the reason for this is the dramatic change (rise) in global temperature around 1980 as per both published literature and the present analysis, which, in turn, caused similar trends for global PET. We also call for additional research to verify, and possibly confirm, the present results.

Key words: Aridity, Climate change, Precipitation, Potential evapotranspiration, Trend, Clustering

1. Introduction

In recent years, numerous studies have reported compelling evidence on the occurrence of climate change and its impacts on our water resources, environment, health, and society (e.g. Tett et al., 1999; Karl and Trenberth, 2003; IPCC, 2007; Keller, 2008; Kundzewicz et al., 2007; Raghavan et al., 2012). For instance, noticeable changes in temperatures, snowmelt, frequency and magnitude of extreme hydroclimatic events (e.g. floods, droughts), and mean sea levels have been observed in different regions around the world (IPCC, 2007). Projections based on Global Climate Models (GCMs) also indicate further rising of temperatures and negative effects on our water resources and environment over the next century than over any time during the last 10,000 years, thus giving rise to enormous challenges in their planning and management (e.g. Kundzewicz et al., 2008; Sivakumar, 2011a). The effects of climate change have and continue to put additional pressure on our water resources, which have already been significantly exploited to meet our growing water demands due to a combination of factors, including population growth, urbanization, industrialization, improved living standards, and changes in land cover and land use (e.g. Chen et al., 2011; Sivakumar, 2011b; Murray et al., 2012; Singh et al., 2014). In recent decades, development of irrigated agriculture for production of food to support the population growth has also raised the demand for water and created a condition of water stress (e.g. Postel, 1998).

On one hand, based on numerous anthropogenic and biodiversity indicators, nearly 80% of the global population in 2000 resided in high water stress regions (Vörösmarty et al., 2010). On the other hand, shortage of water availability is one of the most important problems constraining vegetation productivity in both direct and indirect ways (Mu et al., 2011). Thus, there is a need to monitor the potential water availability in order to identify and focus management efforts towards regions at risk, especially in the face of climate change and its impacts. Aridity classes are reliable representations of potential water availability at various scales, especially at large scales. They are largely defined by the climatic zones.

Study of the effects of climate variability and change on natural resources is crucial for their planning and management at local, regional, national, and global scales. To this end, there is a need to classify various climatic zones to assess possible shifts that have occurred in the past. Such a classification helps to identify aridity levels for assessment of potential water availability and, hence, for water resources planning and management in various sectors. To this end, a number of studies have attempted to find the aridity trends around the world and, as a result, different aridity indexes have also been proposed and used. The following studies serve as examples of the indexes used in aridity investigations thus far. Oguntunde et al. (2006) have used the Budyko's aridity index to study the aridity trends in the Volta River Basin in West Africa. Costa and Soares (2009) have used the Aridity Intensity Index to identify the aridity trends in the south of Portugal. Zhang et al. (2009) have used the De Martonne aridity index to study the aridity trends in the Pearl River basin in South China, while Huo et al. (2013) have used the Thornthwaite aridity index to identify the aridity trends in northwest China.. Croitoru et al. (2013) have used the De Martonne and the Pinna combinative index to study the aridity trends over Romania.(Tabari and Aghajanloo (2013) have employed the UNESCO aridity index for an aridity trend analysis in the north and northwest of Iran. Despite these studies and advances, a comprehensive global study to find, compare, and interpret probable aridity trends in each of the aridity zones separately continues to be elusive.

As of now, to assess aridity, the UNESCO aridity index (UNESCO, 1979) is most widely used. The UNESCO aridity index (AI) is based on the ratio of annual precipitation (P) to potential evapotranspiration (PET). Precipitation and PET are two important components of the hydrologic cycle. Precipitation is a very difficult process both to observe and to simulate. Precipitation is generated through complex interactions of dynamic atmospheric convergence, advection, and lifting mechanisms, as well as surface conditions that relate to moisture availability and thermal stability, and, therefore, shows a high degree of variability. Evapotranspiration (ET) is one of the most important climatic parameters and has an important role in energy control and mass exchange between the atmosphere and terrestrial ecosystems. Potential evapotranspiration, a key input to hydrologic models, is generally considered to be the maximum rate of evaporation from vegetation-covered land surfaces when water is freely available and evaporation rate is primarily determined by meteorologic controls (Zhou et al., 2008). Since evapotranspiration is affected by different climatic factors (see Yang and Yang, 2012 for some details), such as temperature (T), sunshine, atmospheric humidity, wind, surface albedo, and soil moisture, assessment of PET is a complicated and challenging task, although its variability is significantly lower than that of precipitation.

Generally, since the UNESCO aridity index can provide a reliable assessment of water balance by considering aridity as a balance between precipitation (as input) and PET (as output), it can be argued that use of this index is better for assessment of the available humidity than an index that is based only on precipitation. Therefore, in present study, aridity is described as a function of two parameters: precipitation and potential evapotranspiration. To validate this approach, a systematic two-step procedure is followed: (1) analysis of P, PET, and aridity trends based on a review of published literature; and (2) analysis of P, PET, and aridity trends based on global data observed during 1960–2009. The nonparametric Mann-Kendall test (Kendall, 1975) is used for analysis, and both spatial and temporal aspects of aridity time series are addressed. Following this, the agglomerative hierarchical clustering approach is employed to assess whether the trends that are observed can be classified into different groups or are they homogeneously dispersed across the world and over time. Finally, to interpret the aridity trends, a correlation analysis between aridity and major climatic parameters is also carried out.

The rest of this paper is organized as follows. In Section 2, particular emphasis is placed on the contribution of precipitation and potential evapotranspiration to aridity trends based on published literature. Section 3 describes the data and methods used in this study. Section 4 presents the results, with particular attention laid on aridity trends using actual observations and their temporal variability by cluster analysis. A detailed discussion of these results is presented in Section 5, and a set of conclusions is drawn in Section 6.

2. Background

2.1. Aridity indexes

Aridity has been defined by various indicators. In 1900, the first quantitative climate classification system, which included two important climatic parameters, temperature and precipitation, was introduced by Köppen (Köppen, 1900; Larson and Lohrengel, 2011). This climate classification system, called the 'Köppen's classification' was based on the principle that plants integrate several climatic elements (Sparovek et al., 2007). This classification utilizes near-surface temperature and precipitation to represent climatic regimes, thus detecting climatic shifts associated with the primary climatic components (Köppen, 1931). The Köppen climate classification is often used to assess changes over climatologically consistent spatial zones (Diaz and Eischeid, 2007; Roderfeld et al., 2008) and defines arid and semi-arid zones as two of its prominent classes. In the 1920s, the De Martonne aridity index (I ar-DM) was developed (De Martonne, 1926).. This index is calculated based on the mean annual values of precipitation (P) and temperature (T). Unlike the Köppen classification, the De Martonne aridity index expresses the aridity as a function of time, thus allowing assessment of change.

Since then, many other, and more complex, aridity indexes have been introduced, especially based on reference evapotranspiration (ET_o). There are also several formulae, as appropriate, to calculate aridity indexes, such as those adopted by UNESCO (UNESCO, 1979) and UNEP (UNEP, 1992): aridity index = precipitation (mm) / potential evapotranspiration (mm). However, when these new indexes were first introduced, there was no suitable standard method to calculate ET_o. The Penman method (Penman, 1948) was internationally recognized as a basis for this in the late 20th century. The Penman-Monteith method is a variant of the Penman method, and is recommended by FAO (Allen et al., 1998).

The methods introduced by UNESCO (1979) and UNEP (1992) are widely used for classification of different types of climate. These numerical methods use quantitative values for classifying the climatic zone boundaries. In the current study, to map the climate at the global scale, UNESCO’s climate classification is used. Based on this classification, there are five main climatic classes: hyper-arid, arid, semi-arid, sub-humid, and humid. The UNESCO aridity index assesses potential water availability by considering five climatic parameters: temperature, precipitation, wind speed, sunshine hours, and relative humidity. Temperature, radiation, and water availability are the main abiotic controls of ecosystem primary production in various regions of the world (Boisvenue and Running, 2006). Therefore, by applying this index, not only aridity is characterized by various climatic factors, but also all the three main abiotic controls of ecosystem are included in this climate classification system. It should be mentioned that, based on the UNESCO method, the potential evapotranspiration (PET) was previously assessed with the Penman formula, but this required more data. This led to the proposal by UNEP (1992) of a similar classification, but based on a simpler method for calculation of potential evapotranspiration proposed by Thornthwaite (1948). Table 1 shows the ranges of aridity values for the five climatic classes adopted by UNESCO (1979) and UNEP (1992).

Table 1

2.2. A brief review of aridity changes based on P and PET

With regard to the importance of precipitation (P) and potential evarpotranspiration (PET) on aridity, we survey numerous past studies that have considered the trend analysis of these variables observed during the past several decades. Table 2 identifies these studies (black – P; red – PET), including the regions studied. Figure 1 shows the increasing (+) and decreasing (–) trend observed in P and PET (P – black; PET – red) changes for these regions, as reported by such studies. Based on Figure 1, the following interpretations may be made. The eastern parts of Asia (including Japan, South Korea, and eastern China), the Middle East, the Mediterranean countries, and West and South Africa, and the southern parts of Australia have experienced a decreasing trend in P, while increasing P, which is expected to drive decreases in water stress, causing greater water availability due to an acceleration of the global hydrologic cycle (Murray et al., 2012), has been reported for North America, central and northern Europe, and north Asia. As for PET, some eastern parts of Asia (including Japan and northern China), the Middle East, the Mediterranean countries, some parts of Europe (such as southern France, England, and Ireland), West Africa, western Brazil, Canada, and Alaska have experienced an increasing trend, while Australia, South Asia, Southern Africa, USA, and Mexico have witnessed a decreasing trend.

Table 2

Figure 1

3. Data and Methods

3.1. Data

The data used in this study are obtained from CRU TS 3.1 (Climatic Research Unit, a part of the University of East Anglia), a gridded climate dataset with a spatial resolution of 0.5° × 0.5° and constructed from monthly observations at meteorological stations across the world's land areas (Jones and Harris, 2013). It is generally believed that such grids may be inappropriate for small study regions, but for larger areas they may be more useful than a set of individual stations (Mitchell and Jones, 2005). The dataset covers all land areas of the Earth (continental areas and some large islands) with the exception of the Antarctic region (Philandras et al., 2011). CRU TS 3.1 incorporates mean temperature (TMP), diurnal temperature range (DTR) and so maximum and minimum temperatures (TMX and TMN), precipitation total (PRE), vapour pressure (VAP), cloud cover (CLD), rainday counts (WET), and potential evapotranspiration (PET). The method used for calculation of PET is a variant of the Penman–Monteith formula using the gridded TMP, TMX, TMN, VAP, and CLD (see Harris et al., 2013). The data covers the period 1960–2009.

3.2. Trend analysis

Trends indicated by time series data for P, PET, and aridity are evaluated using the nonparametric Mann-Kendall (MK) test (Kendall, 1975). Nonparametric trend detection methods are less sensitive to outliers compared to parametric ones (Wang, 2006). The MK test, which is a rank-based hypothesis test, provides information regarding the direction and significance of trends and tests the null hypothesis of ‘randomness’ or ‘no trend’. The test uses only the relative magnitudes of the data rather than the numeric values. The MK test is a helpful exploratory method for identifying monotonic changes during a specific time interval (Gao et al., 2013) and takes care of seasonality, missing data, and measurements below detection limit and, additionally, need not require prior knowledge of the distribution (Conover, 2006).

3.3. Clustering and cluster mapping

In this study, we use cluster analysis to find similar aridity time series. Clustering (Everitt, 1980) is an unsupervised learning technique that aims at decomposing a given set of elements into clusters based on similarity. The basic goal is to divide the dataset in such a way that elements are homogeneous within groups and are different between groups. Therefore, the purpose of the cluster analysis is to classify data of previously unknown structure into meaningful groupings (Fraley and Raftery, 2002). In the present study, for removing the shorter-term fluctuations from the aridity time series to observe and detect the presence of longer-term variations, the normalized and filtered aridity time series are used as input for clustering. In this study, there is an aridity time series for eachgrid over the land, which includes 50 annual aridity values (AI) for the 50 years of data considered (1960–2009). Each of these aridity time series is normalized by calculating its arithmetic mean ($\overline{AI}$) and standard deviation σ and applying $(AI-\overline{AI})/\sigma$ on any annual aridity value (AI). Then, a 10-year moving average low-pass filter (Kiely, 1999) is applied.

Many different clustering methods are available in the literature, including hierarchical clustering, k-means clustering, and model-based clustering (Fraley and Raftery, 2002). In the present study, agglomerative hierarchical clustering is employed. In agglomerative hierarchical clustering, objects are initially regarded as individual clusters and then pairs of sub-clusters are repeatedly merged until the whole hierarchy is formed (Wua et al., 2009).

Ideally, clusters should be internally cohesive structures that are isolated from each other. To assess this, adequacy criteria that encapsulate the concepts of cluster homogeneity (cohesion) and separation (isolation) are needed (Landau and Ster, 2010). Such measures can be derived from a proximities matrix of object distances or (dis)similarities, which provides distances between every pair of objects in the dataset. There is a host of methods for assessing similarity of objects or groups with cluster analysis, with often different approaches highlighting different aspects of a dataset (Mckenna, 2003; Johnston, 1976). In this study, the Euclidean distance method is used. The implementation of this is done with MathWorks (2001). The key component in agglomerative algorithms is the similarity metric used to determine the pair of sub-clusters to be merged (Wua et al., 2009). The similarity between objects can be calculated by linkage methods, which are the most common and cheap computational methods to divide dataset into clusters, such as single linkage, complete linkage, and average linkage (Nasıbov and Kandemır-Cavas, 2011). In the present study, complete linking is adopted. Complete linkage defines the similarity of clusters to be the maximum distance between elements of each cluster.

In this study, for determination of an optimal number of clusters, considering the number of observed trends for global aridity data using MK test, three clusters for normalized and filtered aridity time series are presented (the maximum number of clusters is set to three for each case). The three clusters used are: (1) Cluster 1 – no trend; (2) Cluster 2 – decreasing trend; and (3) Cluster 3 – increasing trend. The distribution of the different clusters is shown through mapping.

4. Results

4.1. Assessment of P and PET trends using actual observations

To show the spatial distribution of P and PET trends, the Z values derived from the application of the Mann-Kendall test to these variables are mapped. Figure 2(a) and 2(b) shows the results of the MK test for P and PET, respectively. For $\alpha < 0.05$, a Z parameter value of more than 1.96 shows a significant upward trend, while a value of less than –1.96 indicates a significant downward trend, and no significant trends exist if the value is between –1.96 and 1.96. The Z parameter values obtained for P and PET, shown in Figure 2(a) and 2(b), show both downward and upward trends. Figure 2(a) shows that, although some regions (e.g., eastern and western Australia, north India, northern and north-western China, some parts of Mongolia, some regions in the north of the Mediterranean Sea) had experienced a decreasing trend and some other regions an increasing trend for P, from the perspective of areal extent, many parts of the world had no significant trends. Conversely, Figure 2(b) shows that PET had a tendency to increase over a large part of the world.

Figure 2

Figure 2(c) and 2(d) indicates the area percentage of Z parameters of MK test for P and PET, respectively, at the global scale. For precipitation, about 86% of Z factors show non-significant trends, while around 3 and 11% have significant decreasing and increasing trends, respectively. For PET, on the other hand, the analysis of the data reveals that about 52, 4, and

44% of Z factors show non-significant, downward, and upward trends, respectively. Generally, it can be observed that the frequencies of non-significant trends are considerably more than upward and downward ones for both P and PET. However, it is interesting to note that, while the percentage of areas with decreasing trends is approximately the same, the number of significantly increasing trends for PET is clearly considerably more than the same trend for precipitation.

4.2. Assessment of the aridity changes due to climate change based on global aridity time series

Figure 3 shows the global spatial distribution of Z parameter values from the Mann–Kendall test for the annual aridity index time series for each of the five climatic zones mentioned above. The red parts on the map ($Z > 1.96$) show significant increasing trends, which indicate a tendency to become more humid, while the blue parts ($Z < -1.96$) show significant decreasing trends and tend to become drier. The figure shows that there exist both significant increasing and decreasing trends in all the five climatic zones. However, the area of each climatic zone as well as extension of different types of trend (downward, upward, and non-significant) in each climatic zone are different, as presented in Table 3.

The statistics in Table 3 indicate that more than half of the world has a humid climate, while a hyper-arid zone covers just 4.5%, with the remaining area divided, roughly equally (in the 13–15% range), between sub-humid, semi-arid, and arid zones. Most parts in each of the climatic zones show a non-significant trend in aridity during the period studied. The highest area percentage for non-significant trend is in the arid zone (around 89%) and the lowest in the humid zone (with 83%), while the other zones have values between 85% and 87%. It is interesting to note that just about 2% of the hyper-arid and arid zones exhibit significant downward aridity trends, while a significant positive trend is found over around

10% of these two zones. The higher percentage of dropping trend when compared to the rising one in semi-arid, sub-humid, and humid zones indicates that they are becoming more arid, while hyper-arid and arid zones, with a higher percentage of increasing than of decreasing, are becoming more humid.

Figure 3

Table 3

4.3. Clustering

Figure 4 presents the results of the clustering analysis of annual aridity time series, based on Euclidean distance and Complete linkage method (Wua et al., 2009). Although there exist some fluctuations in all the time series during the period studied, the clusters generally show clear trends with no significant fluctuations, possibly due to the application of a low-pass filter on the aridity time series. Therefore, this type of data allows trend analysis and investigation of more long-term changes. Out of the 6000 randomly-selected aridity time series, 2460 are in Cluster 2 (decreasing trend) and 1980 are in Cluster 3 (increasing trend), with just 1560 in Cluster 1 (no trend).

Figure 4

An interesting observation that can be made from the results in Figure 4 is the change in behavior of the time series around the 1980s in all the three clusters. This allows separation of the study period (1960–2009) into two sub-periods, before 1980s and after. Further, according to Figure 4, for 1965–1980 (with consideration of 10-year moving average filter for data starting from 1960), the time series in Cluster 1 show a rising trend, Cluster 2 contains time series with no clear trends, and the time series that exhibit downward trends are located in Cluster 3. For the period 1980–2004 (with consideration of 10-year moving average filter for data ending in 2009), the time series in Cluster 1 have no clear trends, while the ones in Cluster 2 and Cluster 3 show decreasing and increasing tendencies, respectively.

The clustering results are even clearer from the spatial distribution of the three clusters around the world, as presented in Figure 5. The direction of the clusters' tendency is distinguished based on their observed trends after 1980s. According to Figure 5, some regions in the northern hemisphere, north and north-west of China and some parts of Mongolia, north India, eastern and western Australia, and some regions in the north of the Mediterranean Sea are located in Cluster 2. It may, therefore, be construed that they are becoming more arid. These results are in reasonable agreement with the results obtained based on the Mann-Kendall test on the aridity time series (Figure 3). In addition to its usefulness in verifying and confirming the Mann-Kendall test results, the clustering analysis can be particularly helpful in obtaining additional information on the occurred changes in aridity amounts during specified periods.

Figure 5

The nonparametric Mann–Kendall test is applied to identify and compare the spatial patterns of aridity trends between 1960–1979 (Figure 6(a)) and 1980–2009 (Figure 6(b)). A comparison of the results shows a change in the direction of trends, or even inverse, between these two periods over a considerable part of the world, including Australia, Africa, South America and some parts of North America, Asia, and Europe. Further, a comparison of the MK map for post-1980s with Figure 5 indicates a significant fitness between the results over a considerable part of the world.

Figure 6

For an expanded assessment of the changes in global aridity trends during the above two periods, the regions with a shift in the direction of trend are classified based on the type of shift in tendency, and the results are presented in Figure 7. Generally, for the period 1980–2009, around 24% of the world experienced a different trend from that for the period 1960–1979. As can be seen in Figure 7, among the trend shifts, the 'no significant to increasing' trend is more pronounced with its occurrence in more than 7% of area around the world, while the shift in 'increasing to decreasing' trend is observed only very rarely (less than 1%).

Figure 7

4.4. Relationships between aridity and major climatic factors

The results from the cluster analysis (Figure 4) and the trend analysis (Figure 6) suggest a change in tendency of the aridity time series around 1980. Aridity changes can be partitioned into changes in precipitation (P) and potential evapotranspiration (PET), the latter being mainly influenced by temperature (T). Therefore, to be able to interpret the observed changes in aridity over the entire study period (1960–2009) as well as over the two sub-periods identified earlier (1960–1979 and 1980–2009), global average time series of aridity, P, T, and PET, and their first-order fitted line are presented in Figure 8. The first-order fitted lines generally show a positive trend for P, T, and PET over the period 1960–2009, but a decreasing trend (towards becoming more arid) with a slight negative steepness in the fitted line. The trends observed for the sub-periods (1969–1979 and 1980–2009) indicate a significantly increasing trend for global T and PET. This observation is also consistent with the results reported in the literature (see Figure 1).

Figure 8

As mentioned earlier, it is important to analyze the relation between aridity and other climatic factors. Therefore, to assess the extent of contributions of the changes in climatic factors to the variation in aridity, five climatic factors that are likely to be altered due to climate change are studied. The conventional Mann-Kendall test is used to estimate or compare probable similarities between trends of aridity and of the selected climatic variables in different climatic zones. We use the Pearson's correlation coefficient, which is a measure of the linear dependence between two random variables (real-valued vectors) (Rodgers and Nicewander, 1988), for measuring the relation (correlation) between several climatic factors and aridity to evaluate their effects on aridity.

A trend analysis is carried out for P, T, PET, cloud cover (an indicator for assessing sunshine duration), and wet days (an approximate representative of humidity conditions) using MK test for every climatic zone separately. The results are presented in Table 4, in terms of area percentage of each kind of trend (non-significant, decreasing, and increasing) for every climatic zone. Based on statistics presented in Table 4, the area percentage of non-significant trend in all climatic zones for precipitation, cloud cover, and wet days is found to be greater than 50 (for precipitation between 82 and 87). Conversely, Table 4 also shows that between 87 and 97% of area in all climatic zones experienced a significant positive trend for temperature. It is interesting to note, however, that for PET, non-significant and increasing trends are found to cover approximately 50 and 40% of all climatic zones, expect in hyper-arid zones where increasing trends are found to cover more than its 90%.

Table 4

To find the sensitivity of aridity to the meteorologic factors for a better understanding and comparison, area percentage of the regions (for each climatic parameter) that are significantly correlated with aridity is determined for all the climatic zones. The significance of the relationships is ascertained based on p-values (< 0.05). The results of this analysis are presented in Table 5. As Table 5 indicates, aridity is positively correlated to P in all the zones, and even more strongly in the arid zone, where almost all its area is significantly correlated to P. Aridity is also clearly inversely correlated to PET in all the zones, except in the hyper-arid zone that has just 17% significant correlated area. The percentage of the correlated area between aridity and cloud cover also does not show a considerable difference among all the zones, except for hyper-arid zone with just 2%. The correlation results indicate that aridity in around of 50% of humid and sub-humid zones, 60% of semi-arid and hyper-arid zones, and 83% of arid zones has significant relationship with wet days.

Table 5

5. Discussion

The observations made from the studies published in the literature together with the results obtained from the trend analysis, clustering, and analysis of relationship between aridity and five major climatic parameters in the present study lead to a few important questions, which are discussed below.

5.1. Are there different trends in different aridity zones?

Past studies (see Section 2) have reported increasing and decreasing precipitation trends for different parts of the world. However, the results from the trend analysis of precipitation in this study show that, at the global scale, the significant upward trends are more considerable than the significant downward trends. Generally, based on the trends for P and PET reported in the literature (see Figure 2), it can be concluded that some parts of the world, such as the Middle East, northwestern Africa, north of China, and the Mediterranean are becoming more arid. Therefore, the results reported in the literature and the actual data observations match well for most regions around the world. The minor differences that exist for a few regions around the world are very likely due to the period of study, accuracy of data, and the nature of trend tests, among others.

One of the most important aspects of the present study is the consideration of PET in the aridity analysis. It can indeed be claimed that one of the main components of the terrestrial water cycle at the global scale is evapotranspiration (ET), because a major part (more than 60%) of rainfall on land is returned back to the atmosphere by ET and, therefore, this factor is an important limiting parameter on land surface water availability (Mu et al., 2011). Kharel Kafle and Bruins (2009) have concluded that a wetter or drier climate in agricultural or bio-climatic terms is caused not only by the changes in rainfall (input) but also by the changes in ET (output). As calculating the (actual) evapotranspiration is enormously complicated, potential evapotranspiration, as the key parameter representing the intensity of the atmosphere to extract water from the selected system, can be adopted as output (Tsakiris and Vangelis, 2005). Undoubtedly, increasing or decreasing the rates of PET as output plays an important role in the availability of water in the system. One of the main advantages of the PET concept is that it shows a standardized value in different climatic conditions and, thus, compares different evaporative environments.

For PET, studies have pointed out both increasing and decreasing trends throughout the world. Based on Table 3, during 1960–2009, PET had an obvious rising tendency in approximately 44% of the regions around the world. Temperature is one of the most important parameters in the PET trends. Relative humidity and sunshine duration are the other important parameters. One of the possible reasons for the general increase in PET rates around the world is the observation of positive trends for temperature. The results from the present study indicate that about 88% of the world experienced significant upward trends in temperature during 1960–2009, while it was more than 98% for the hyper-arid zone, which could also be a reason for the high rate of significant rising trends in PET in this zone. Moreover, while it can be claimed that climatic changes and global warming have significantly affected PET, the results from the present study do not offer sufficient evidence to conclude that they have affected the precipitation trend.

Finally, although only small parts of each of the climatic zones experienced significant increasing or decreasing aridity trends, it is also important to point out that significant increasing trends are more prevalent than the decreasing ones in hyper-arid and arid zones. Therefore, it can be concluded that dry areas, including hyper-arid and arid zones, are becoming more humid, while semi-arid, sub-humid, and humid zones are slightly becoming drier.

5.2. Do the Mann-Kendall test results support the conclusions from the cluster analysis?

Comparing Figures 3 and 4 reveals that there exists a clear accordance between the results of the MK test and the clustering analysis in many parts of the world. However, since the nature of the MK test is different from that of the clustering analysis, complete matching between the results from these two methods cannot be expected or derived. While the purpose of the MK test herein is mainly to perform the spatial analysis of the aridity time series, the clustering analysis is a more detailed temporal analysis. It should also be mentioned that a statistical level of significance is applied in the MK test and only the significant trends are considered, while the cluster results are mostly interpreted visually and, as a consequence, for example, significant increasing trends cannot be distinguished from non-significant increasing trends.

The 10-year normalized moving average time series in all the three clusters used in this study exhibit a shift in tendency of the aridity time series after about 1980 (Figure 4). Aridity trend maps for the period before 1980 and after that (Figures 7 and 8) also confirm the shifts. The increasing trend in the global mean surface temperature is generally regarded as a strong evidence of global warming due to the increasing greenhouse gases (Misra et al., 2012). Based on our results (Figure 8) and also the literature survey (Hansen et al., 2010), it may be interpreted that significant changes in the global temperature began in about 1980. Therefore, the global aridity time series show a considerable match with the observed global warming occurrence, and temperature is very likely an important factor in reflecting this. These changes could be the result of an increase in PET as a consequence of an increase in temperature. While assessments of trends using short-term data can be misleading (such as a non-increasing trend in global temperatures if evaluated only over 1998–2008), several studies indeed point to certain periods (e.g. 1998–2008) as segments of an overall increasing temperature record (e.g. Easterling and Wehner, 2009). The high PET trends observed are also consistent with this argument (Figure 8). If this is indeed the case, then aridity (P/PET) in response to this change decreases when P is assumed constant. It is obvious, therefore, that analysis of aridity changes must also consider fluctuations in the precipitation patterns. If temperature and precipitation rise simultaneously, then aridity may not change at all.

5.3. Can the observed aridity trends be partitioned to precipitation and PET changes?

Table 5 indicates that aridity is positively and significantly correlated with precipitation in all the climatic zones. Table 4 shows that in arid and semi-arid zones, the percentage of area with increasing precipitation trends is clearly more than the area with decreasing trends, but PET has an increasing trend. However, Table 4 also indicates that the correlation between aridity and PET for the hyper-arid and arid zones is clearly less than that for the other zones, especially significantly less than that for the hyper-arid zone. The combined effect of all this is an overall positive aridity trend for these two zones.

The low correlation observed between aridity and PET in the hyper-arid zone may be due to the significant fluctuation in the spatio-temporal distribution of precipitation in the arid regions, since low precipitation with a high range of variability is the main characteristic of arid climates. To this end, the results from our analysis is interesting, as the average coefficient of variation (CV) of precipitation for the hyper-arid zone is approximately four times greater than that for the humid zone. The average CV value for the hyper-arid and humid zones is 0.66 and 0.17, respectively, while it is 0.38, 0.25 and 0.21 for the arid, semi-arid and sub-humid zones, respectively. In hyper-dry regions, where PET does not show too much fluctuation year by year, aridity fluctuates only by small amounts of changes in precipitation, which are common in such regions. Therefore, while PET is not supposed to vary remarkably, aridity changes with respect to precipitation variations and also temperature and PET show a low rate of correlation with aridity in hyper-arid zone. All these suggest that precipitation plays a key role in characterizing the aridity variations in hyper-arid areas.

6. Conclusions

This study attempted to provide a more reliable assessment on the global aridity trend over the past five decades. The study considered aridity as a balance between precipitation (as input) and potential evapotranspiration (as output) by applying the UNESCO aridity index. A two-step approach was followed for a systematic investigation and verification: (1) analysis of results reported in the literature on trends in precipitation, evapotranspiration, and aridity; and (2) analysis of trends based on global data observed during 1960–2009. For real data, the nonparametric Mann-Kendall test and clustering analysis were performed for identifying trends, and an analysis of the relationship between aridity and major climatic parameters was also carried out.

At a general level, a good agreement between the results reported in the literature and those obtained from the Mann-Kendall and clustering methods is evident. The results indicate that while just one-sixth of the world exhibited a significant trends in precipitation during 1960–2009, about a half of the world exhibited significant (mostly increasing) trends for PET. The existence of a non-significant aridity trend in five-sixth of the world, together with the result from the analysis of relationship between aridity and major climatic parameters, suggest that aridity is mainly a function of P rather than PET. While significant decreasing trends were more prevalent than the increasing trends in semi-arid and sub-humid, and slightly less prevalent in humid zones, increasing trends were more dominant than the decreasing trends in hyper-arid and arid zones. Therefore, in contrast to the semi-arid and sub-humid zones, which were becoming drier, hyper-arid and arid zones were becoming more humid.

Analysis of the temporal variability within three aridity clusters, identified by the hierarchical clustering approach, revealed a dramatic change in most aridity time series around the 1980s. A comparison of the global aridity trend analysis results for before and after 1980 indicated a reversal in the trends in most parts around the world. The annual average temporal analysis of some major climatic parameters indicated a substantial increase in the rising trend of global temperature since around the 1980s. While this observation seems reasonable, especially in light of the results reported by climate change-based studies, further research is necessary to verify, and possibly confirm, the present results.

Water resources management strategies should be adjusted according to changing the trends and spatio-temporal patterns of aridity. Apparently for the major parts of the world, such changes in aridity are not overly detrimental to drinking water supply, agricultural production, and ecosystem rehabilitation. However, since PET, one of the two derivatives of the aridity index, is a key parameter in terrestrial ecosystem and crop production, its observed substantial upward trends can be an important concern. Positive PET rates are harmful for the natural vegetation and increase the need for irrigation. On the other hand, decreasing trend of aridity (becoming drier), which can be caused by decreasing precipitation or increasing PET, especially in arid zones, may accelerate desertification and increase the frequency of sandstorms. These areas require a more efficient regulation to manage water resources and meet the requirements of agricultural and drinking water supply.

While this study focused on changes in aridity over space and time, the arguments expressed here are equally important in the context of understanding the effect of drought in various parts of the world. For instance, the trends in aridity that are exhibited in the cluster analysis results presented in Figures 4 and 5 could be interpreted as a very low-frequency modulation in the precipitation signal, often attributed to long-term droughts; see, for example, Mishra and Singh (2010, 2011), Madadgar and Moradkhani (2013), and Maity et al. (2013) for recent comprehensive accounts of drought concepts, characterization, modeling, and forecasting. Furthermore, as the effect of drought is felt more in already-water stressed parts of the world, we anticipate conclusions similar to those reported here to be drawn were our analysis extended to include the frequency and severity of droughts in different parts of the world. This is the subject of ongoing research, and some preliminary results of such an investigation are reported in Asadi Zarch et al. (2014).

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Figure 1: Global observed trends in precipitation (black) and potential evapotranspiration (red) rates during recent decades

Figure 2: Z factor derived from the application of the Mann-Kendall test on global (a) precipitation and (b) PET data between 1960 and 2009. Area percentage of (c) precipitation and (d) PET in global scale. $Z > 1.96$ represents a significant increasing trend, and $Z < -1.96$ represents a significant decreasing trend for ($\alpha < 0.05$).

Figure 3: Mann–Kendall test results for annual Aridity Index time series between 1960 and 2009 for different climatic zones ($\alpha < 0.05$). $Z > 1.96$ represents a significant increasing trend, and $Z < -1.96$ show a significant decreasing trend.

Figure 4: Three clusters of aridity time series and their tendencies for the period after around 1980: Cluster 1 – no trend; Cluster 2 – decreasing trend; Cluster 3 – increasing trend

Figure 5: Global spatial distribution of the three clusters of aridity index time series. The legend is presented based on the observed trends of the clusters after around 1980. The trends are comparable and relatively similar with those observed for the aridity time series after 1980 from the application of the Mann-Kendall test (see Figure 6b).

Figure 6: Spatial distribution of Z factor of Mann-Kendall test on aridity for (a) 1960–1979 and (b) 1980–2009 ($\alpha < 0.05$). $Z > 1.96$ represents a significant increasing trend, and $Z < -1.96$ represents a significant decreasing trend.

Figure 7: Changes in the direction of aridity trend for periods 1960–1979 and 1980–2009

Figure 8: Global average (a) precipitation, (b) temperature, (c) PET, and (d) aridity time series and first-order fitted lines for the entire study period (1960–2009) and the two sub-periods (1960–1979 and 1980–2009).

Figure 1

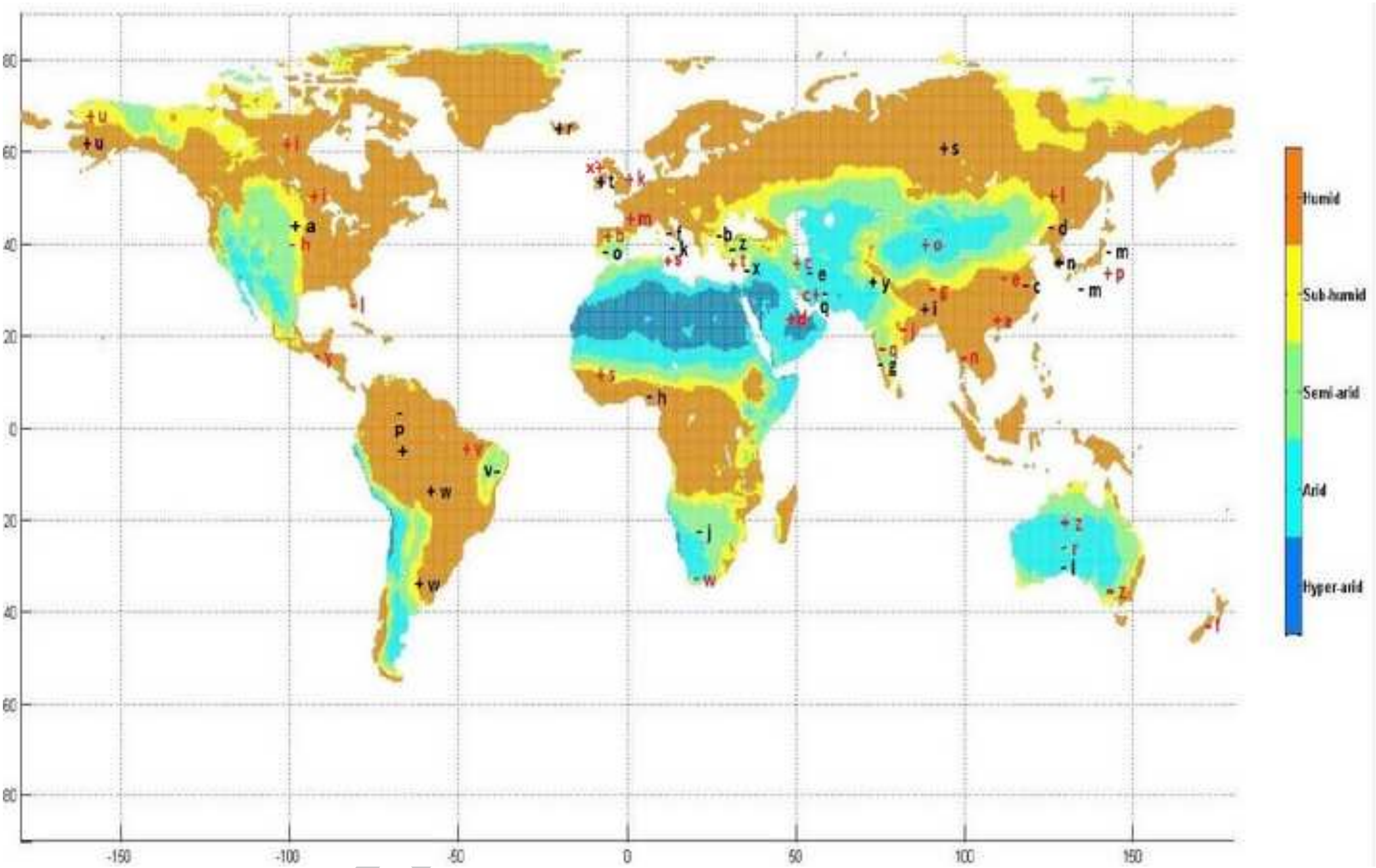

80
60
40
20
0
20
40
60
80
-150
-100
-50
0
50
100
150
Humid
Sub-humid
Semi-arid
Arid
Hyper-arid

Figure 2

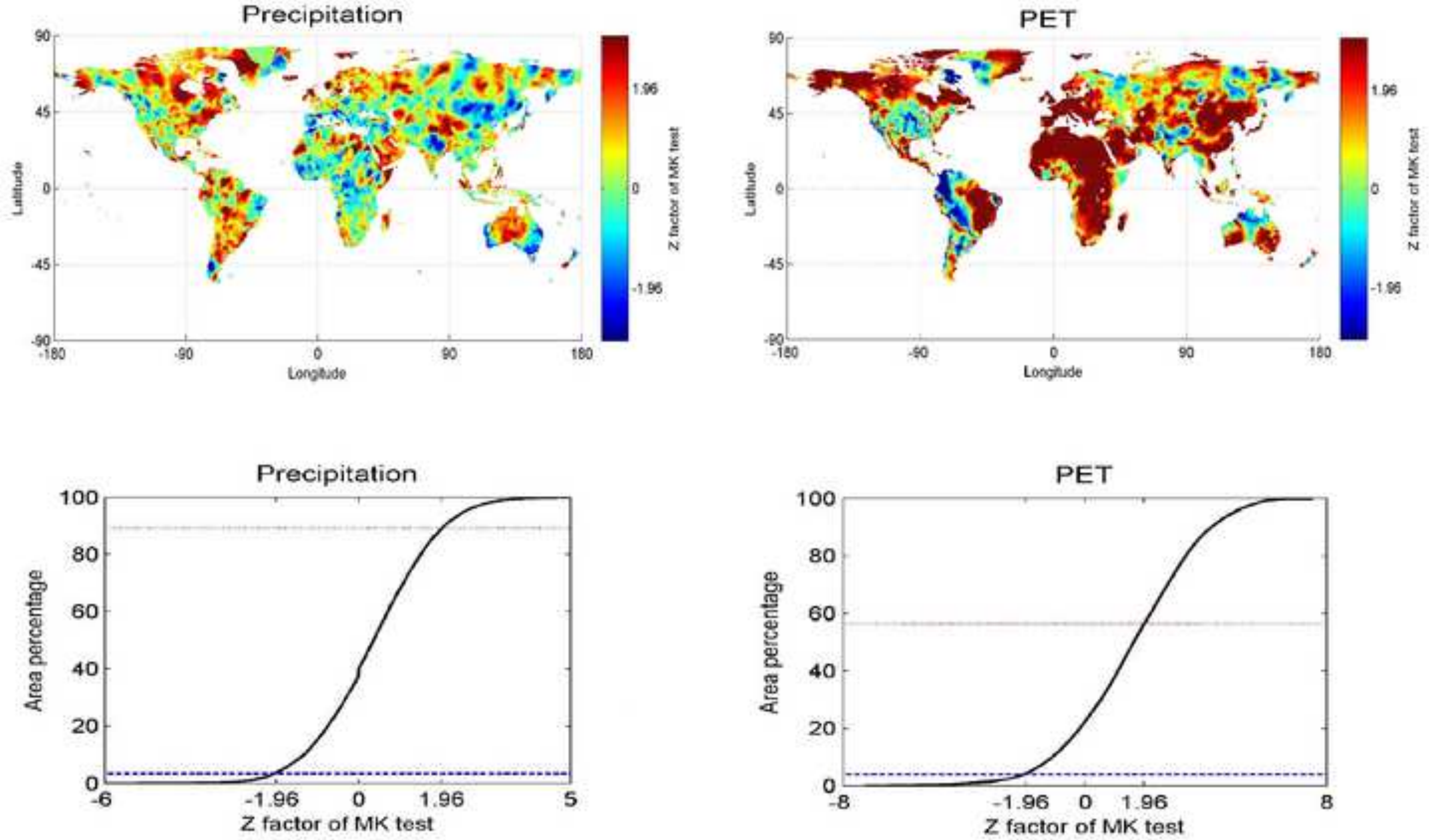

Precipitation
90
45
0
-45
-90
Latitude
-180
-90
0
90
180
Longitude
1.96
0
-1.96
Z factor of MK test
PET
90
45
0
-45
-90
Latitude
-180
-90
0
90
180
Longitude
1.96
0
-1.96
Z factor of MK test
Precipitation
100
80
60
40
20
0
Area percentage
-6
-1.96
0
1.96
5
Z factor of MK test
PET
100
80
60
40
20
0
Area percentage
-8
-1.96
0
1.96
8
Z factor of MK test

Figure 3

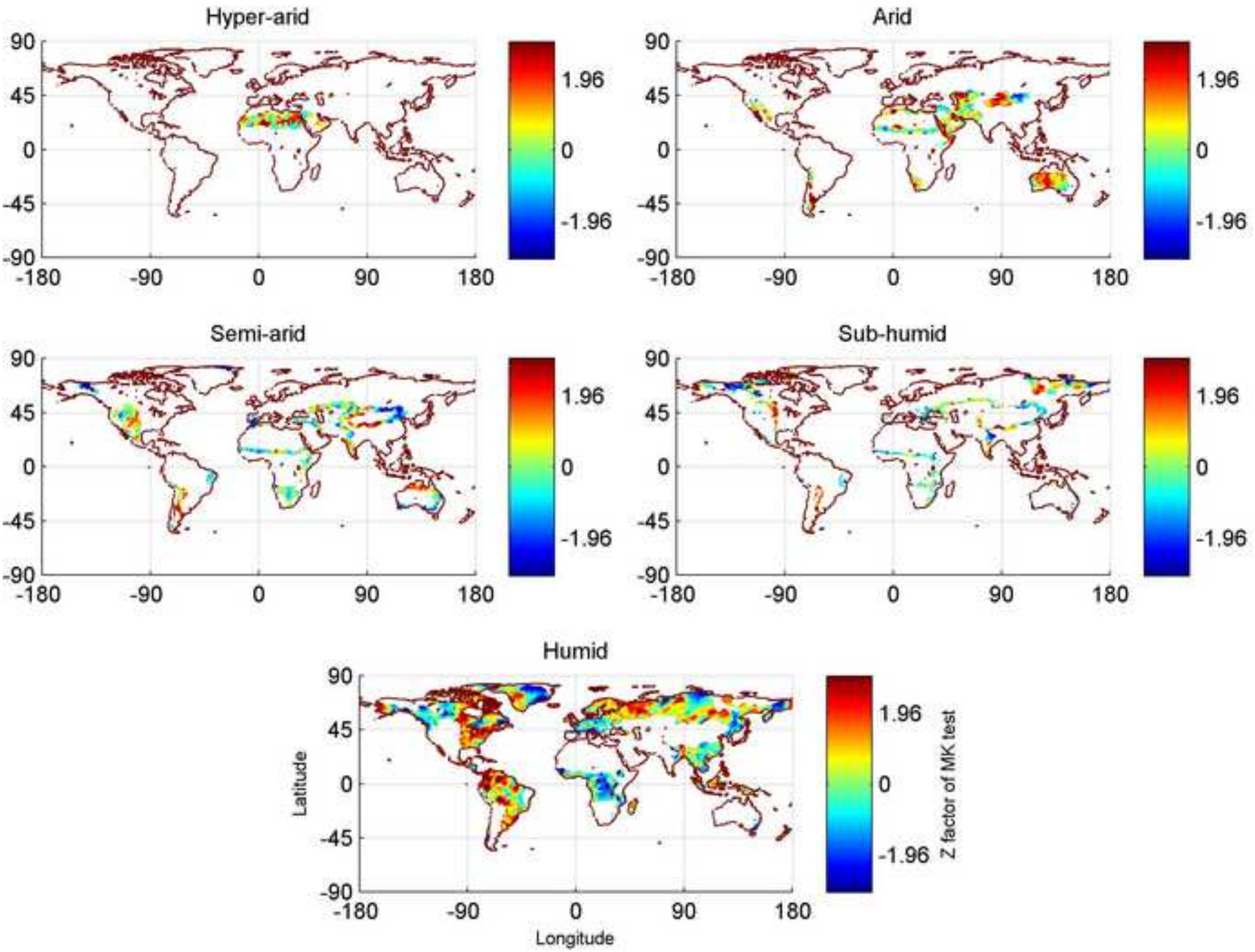
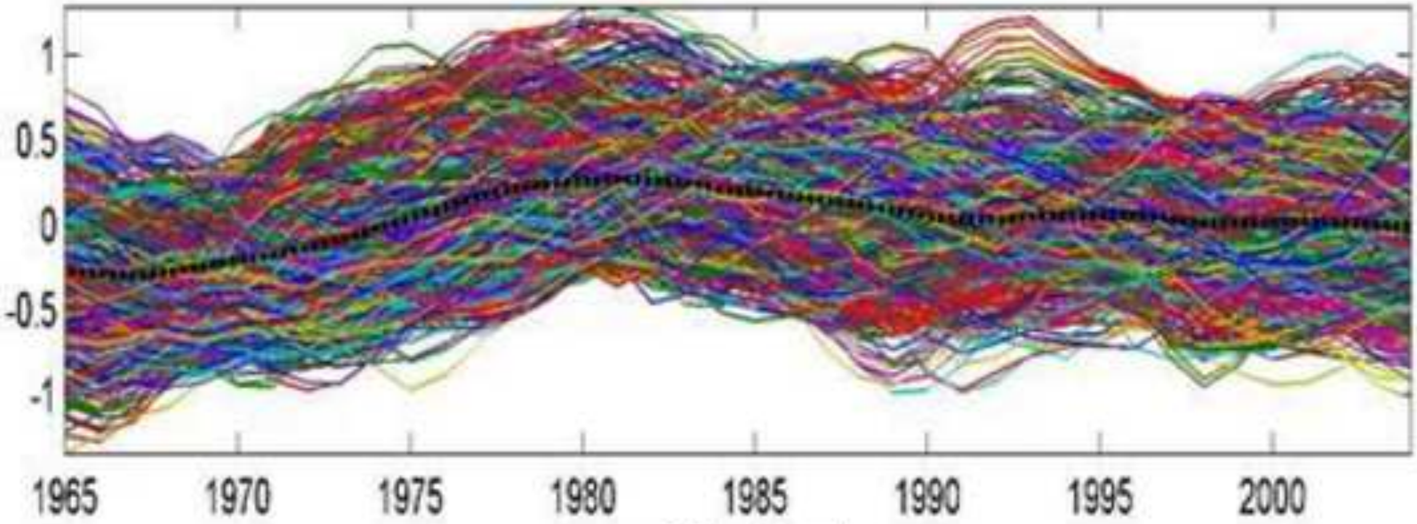
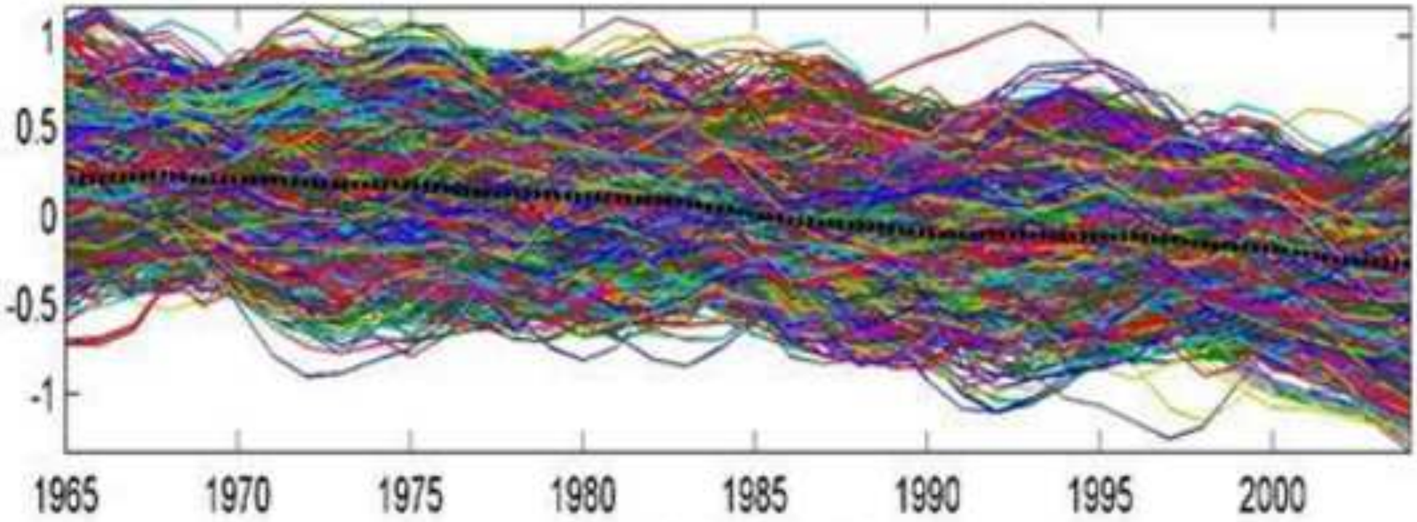

Hyper-arid
Arid
Semi-arid
Sub-humid
Humid
90
45
0
-45
-90
-180
-90
0
90
180
1.96
0
-1.96
Latitude
Longitude
Z factor of MK test

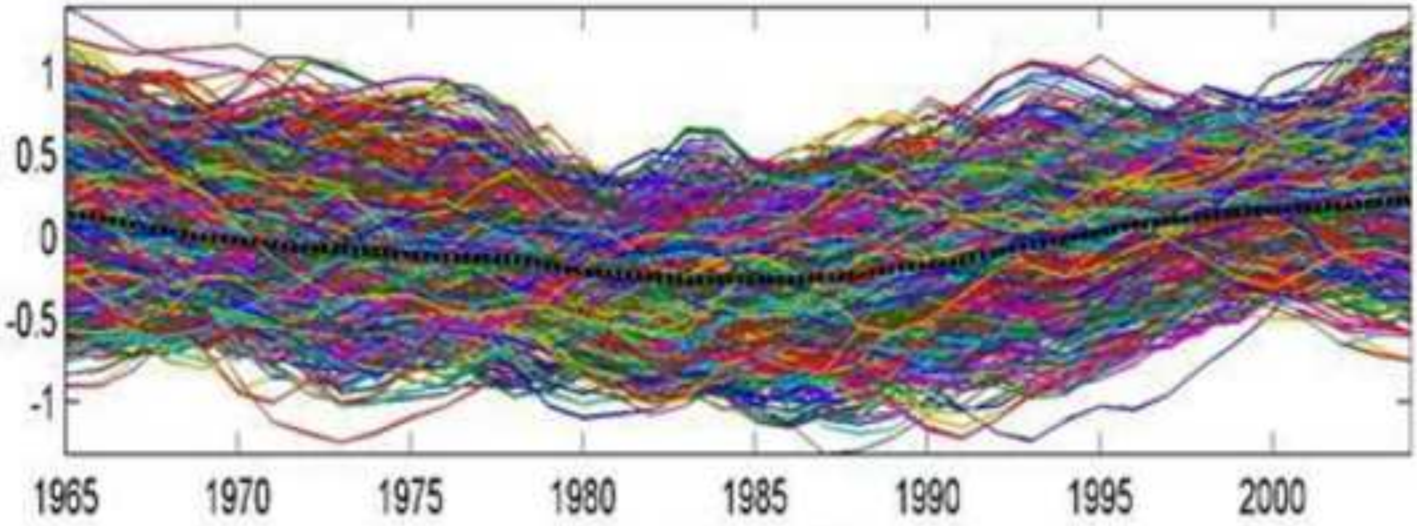
Figure 4



Cluster 1



Cluster 2



Cluster 3

Figure 5

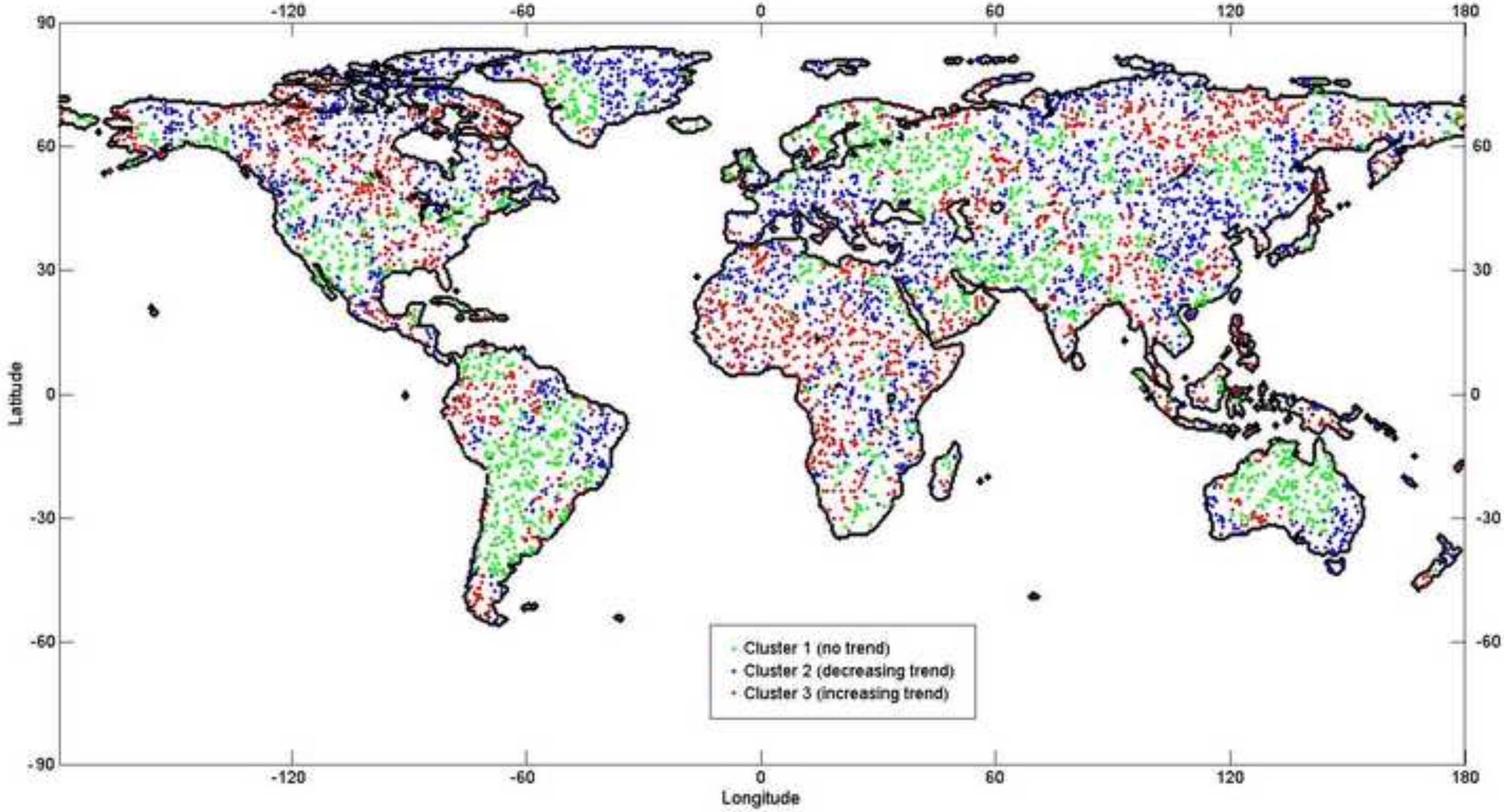

-120
-60
0
60
120
180
90
60
30
0
-30
-60
-90
Latitude
Longitude
Cluster 1 (no trend)
Cluster 2 (decreasing trend)
Cluster 3 (increasing trend)

Figure 6

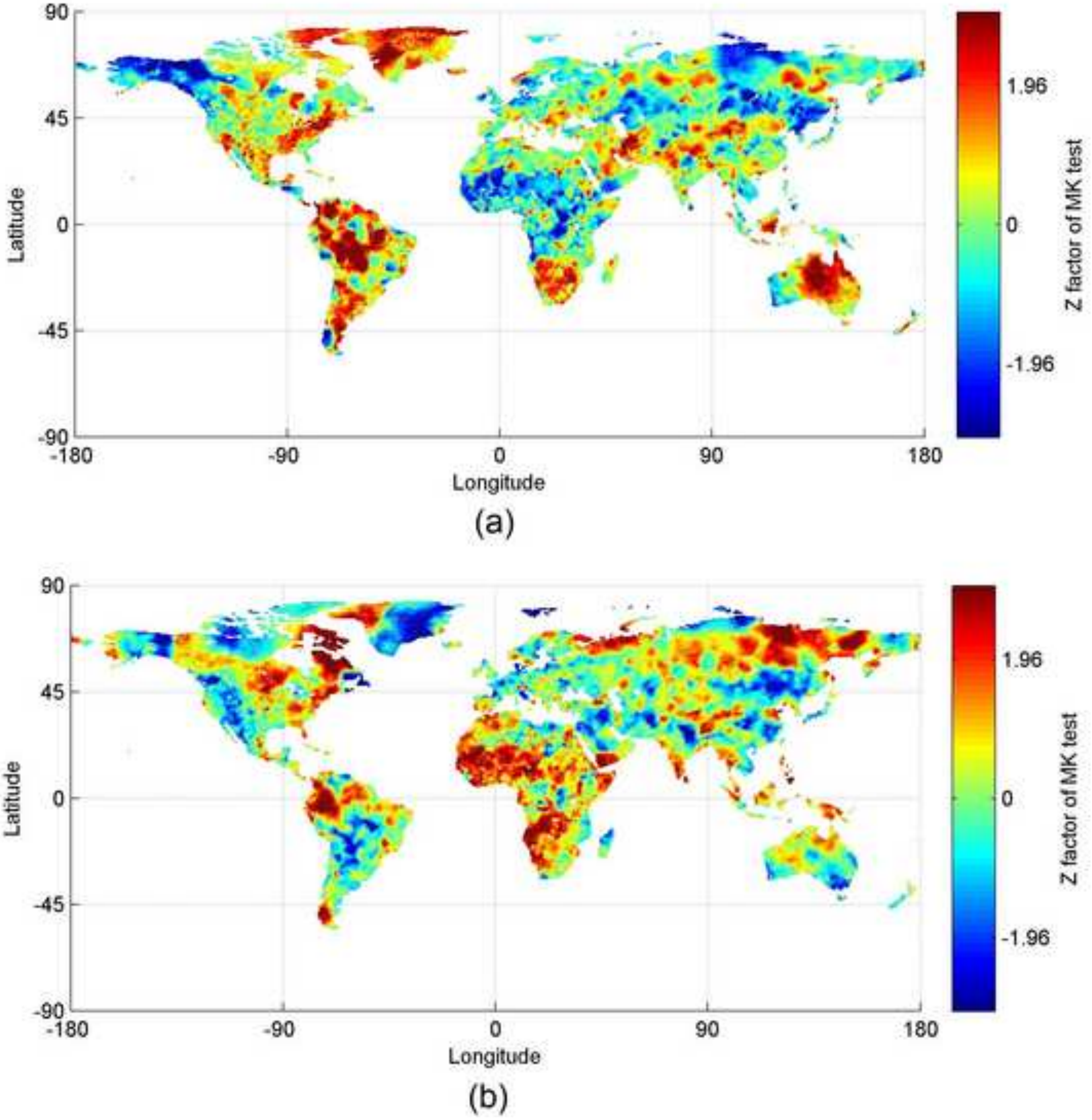

90
45
0
-45
-90
Latitude
-180
-90
0
90
180
Longitude
1.96
0
-1.96
Z factor of MK test
(a)
90
45
0
-45
-90
Latitude
-180
-90
0
90
180
Longitude
1.96
0
-1.96
Z factor of MK test
(b)

Figure 7

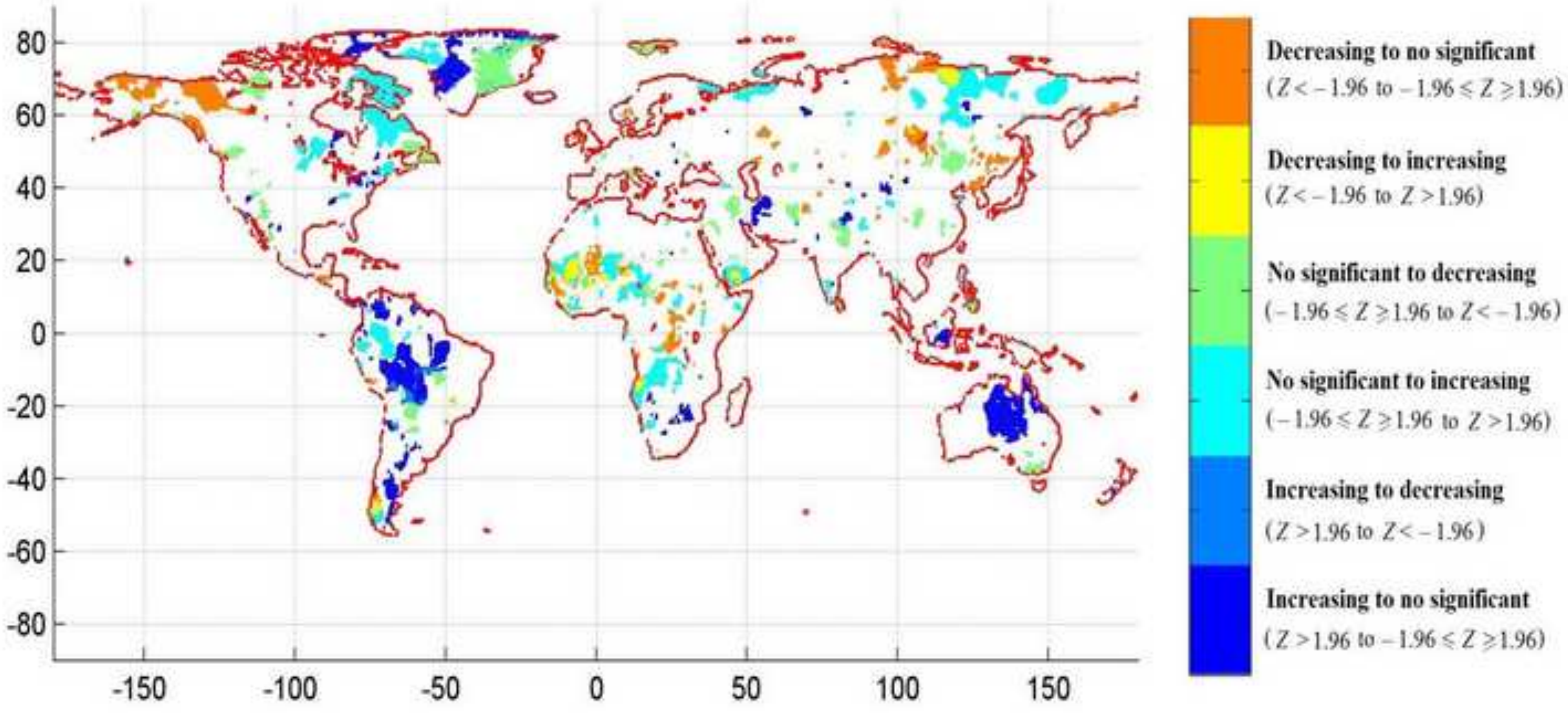

80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150
Decreasing to no significant
(Z < − 1.96 to − 1.96 ≤ Z ≥1.96)
Decreasing to increasing
(Z < − 1.96 to Z > 1.96)
No significant to decreasing
(− 1.96 ≤ Z ≥1.96 to Z < − 1.96)
No significant to increasing
(− 1.96 ≤ Z ≥1.96 to Z > 1.96)
Increasing to decreasing
(Z > 1.96 to Z < − 1.96)
Increasing to no significant
(Z > 1.96 to − 1.96 ≤ Z ≥1.96)

Figure 8

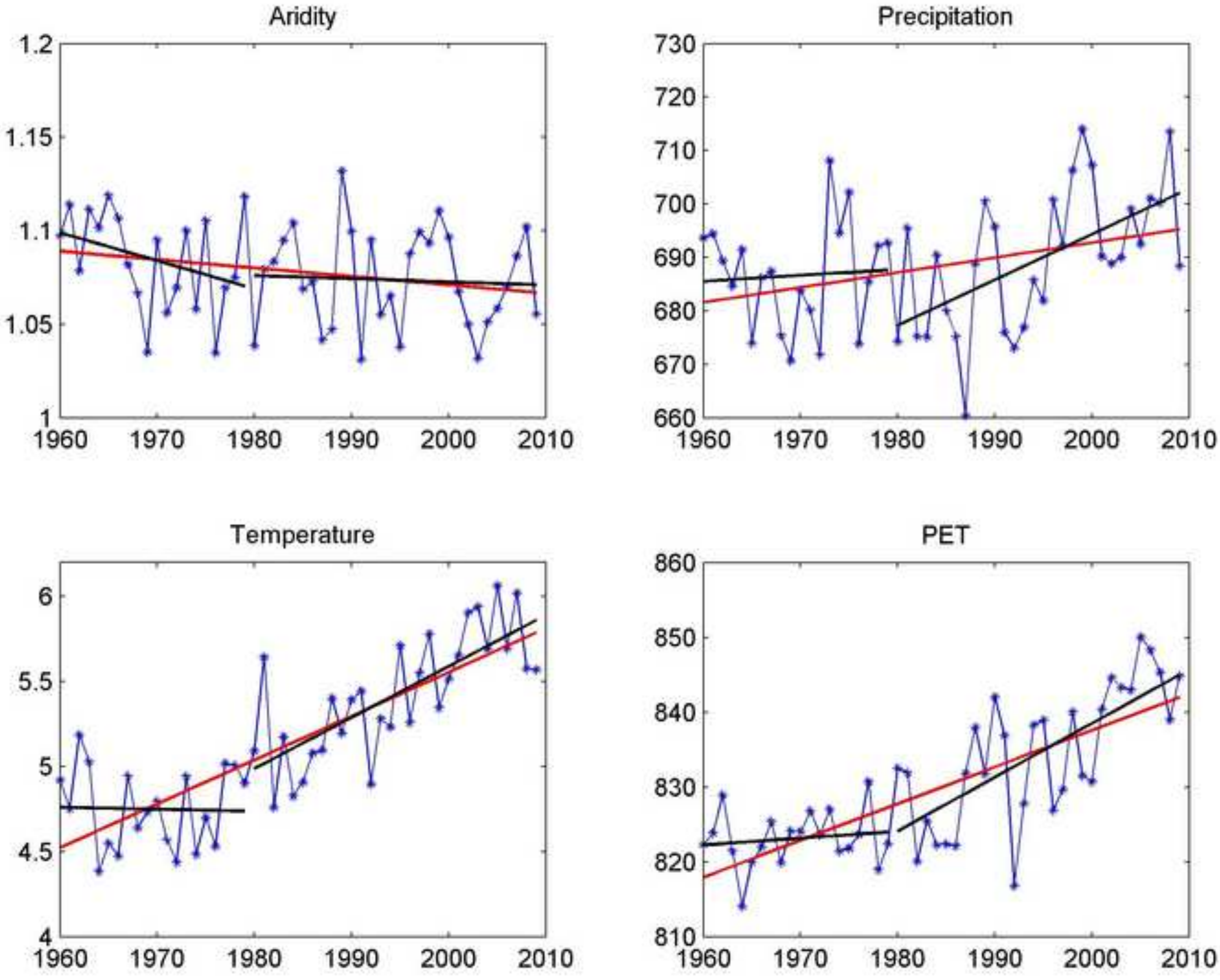

Aridity
1.2
1.15
1.1
1.05
1
1960
1970
1980
1990
2000
2010
Precipitation
730
720
710
700
690
680
670
660
1960
1970
1980
1990
2000
2010
Temperature
6
5.5
5
4.5
4
1960
1970
1980
1990
2000
2010
PET
860
850
840
830
820
810
1960
1970
1980
1990
2000
2010

Table 1: Aridity index classification system based on UNESCO (1979) and UNEP (1992) methods

Zone	UNESCO (1979) P/PET Penman method	UNEP (1992) P/PET Thornthwaite method
Hyper-arid	AI < 0.03	AI < 0.05
Arid	0.03 < AI < 0.20	0.05 < AI < 0.20
Semi-arid	0.20 < AI < 0.50	0.20 < AI < 0.50
Sub-humid	0.50 < AI < 0.75	0.50 < AI < 0.65
Humid	0.75 < AI	0.65 < AI

Table 2: Published literature on global precipitation and potential evapotranspiration changes

Precipitation				PET			
Symbol	**Author(s)**	**Year**	**Region**	**Symbol**	**Author(s)**	**Year**	**Region**
a	Irmak et al.	2012	Central Nebraska, USA	**a**	Zuo et al.	2012	Wei River basin, China
b	Alexandrov et al.	2004	Bulgaria	**b**	Espadafor et al.	2011	Southern Spain
c	Huang et al.	2009	Huanghe River basin, China	**c**	Kousari and Ahani	2011	Iran
d	Liang et al.	2011a	Northeast China	**d**	ElNesr et al.	2010	Saudi Arabia
e	Modarres and Sarhadi	2009	Iran	**e**	Liu and Yang	2010	Yellow River Basin, China
f	Longobardi and Villani	2009	Campania and the Lazio regions, southern Italy	**f**	Roderick and Farquhar	2005	New Zealand
g	Nikhil Raj and Azeez	2012	Bharathapuzha River basin, Kerala, India	**g**	Xie and Zhu	2012	Tibetan Plateau, China
h	Oguntunde	2011	Nigeria	**h**	Irmak et al.	2012	Central Nebraska, USA
i	Shahid	2010	Bangladesh	**i**	Fernandes	2007	Canada
j	Batisani and Yarnal	2010	Botswana	**j**	Jhajharia	2012	Northeast India
k	Cannarozzo et al.	2006	Sicily, Italy	**k**	Jacobs et al	2010	Wageningen, Netherlands
l	Barua et al.	2012	Yarra River catchment, Victoria, Australia	**l**	Liang et al.	2011b	West Songnen Plain, China
m	Yue and Hashino	2003	Japan	**m**	Chaouche et al.	2010	Pyrenees-Orientales and Aude departments, France
n	Jung et al.	2011	Korea	**n**	Kosa and Pongput	2007	Chao Phraya River Basin, Thailand
o	De Luis et al.	2009	Iberian Peninsula, Spain	**o**	Liu and Zhang	2012	Northwest China
p	Marengo	2004	Amazon Basin, South America	**p**	Murakami et al.	2000	Hitachi Ohta Experimental Watershed, Japan
q	Some'e et al.	2012	Iran	**q**	Bandyopadhyay	2009	India
r	Jonsdottir et al.	2008	Iceland	**r**	Donohue et al.	2010	Australia
s	Groisman and Rankova	2001	RPF, western and central parts of Russia	**s**	Palumbo et al.	2012	Southern Italy
t	Möller and Stanhill	2007	Valentia, Ireland	**t**	Kitsara et al.	2013	Greece
u	Yuan et al.	2012	Yukon River Basin, USA	**u**	Yuan et al.	2012	Yukon River Basin, USA
v	de Paulo and da Silva	2004	Northeast of Brazil	**v**	de Paulo and da Silva	2004	Northeast of Brazil
w	Doyle et al.	2012	La Plata Basin, South America	**w**	Hoffman et al.	2011	Cape Floristic Region, South

							Africa
x	Ramadan et al.	2013	Litani Basin, Lebanon	**x**	Stanhill and Möller	2008	Ireland
y	Hanif et al.	2013	Pakistan	**y**	Blanco-Macías et al.	2011	State of Zacatecas, México
z	Toros	2012	Turkey	**z**	Johnson and Sharma	2010	Australia

Table 3: Area percentage of observed trends of annual aridity index time series

Climatic zone	Area percentage	Area percentage		
		Non-significant trend	Decreasing trend	Increasing trend
Hyper-arid	4.4	88.6	1.6	9.8
Arid	13.0	87.6	2.1	10.3
Semi-arid	14.9	84.6	10.3	5.0
Sub-humid	13.5	84.7	11.1	4.3
humid	54.2	83.1	8.5	8.4

Table 4: Area percentage of each observed trend for different parameters in each climatic zone

Parameter	Climatic zone	Area percentage		
		Non-significant trend	Decreasing trend	Increasing trend
Precipitation	Hyper-arid	86.0	0.6	13.4
	Arid	85.8	1.0	13.2
	Semi-arid	87.0	6.1	6.9
	Sub-humid	85.9	6.8	7.2
	humid	82.0	3.0	15.0
Temperature	Hyper-arid	1.70	0.07	98.23
	Arid	9.62	0.27	90.11
	Semi-arid	16.10	1.43	82.47
	Sub-humid	7.87	0.72	91.41
	humid	11.90	0.98	87.11
PET	Hyper-arid	9.1	0.1	90.8
	Arid	48.5	1.3	50.3
	Semi-arid	56.6	5.0	38.4
	Sub-humid	54.1	4.3	41.6
	humid	55.2	4.8	40.0
Cloud cover (sunshine hours)	Hyper-arid	87.4	3.5	9.1
	Arid	75.6	8.7	15.7
	Semi-arid	79.9	7.9	12.2
	Sub-humid	78.3	10.3	11.4
	humid	74.5	11.7	13.8
Wet days (humidity)	Hyper-arid	84.51	2.09	13.41
	Arid	74.12	14.44	11.44
	Semi-arid	57.90	38.03	4.07
	Sub-humid	53.39	43.47	3.15
	humid	59.22	20.68	20.10

Table 5: Area percentage of significant Pearson correlation

Zone	Area precent	Precipitation	Temperature	PET	Cloud cover (sunshine hours)	Wet days (humidity)
Hyper-arid	4.4	90.8	13.4	17.0	6.4	64.10
Arid	13.0	99.5	41.7	74.1	50.5	83.06
Semi-arid	14.9	98.4	56.8	90.6	63.5	61.27
Sub-humid	13.5	99.3	38.8	92.8	57.9	46.15
Humid	54.2	97.1	30.1	88.5	59.9	49.75

Highlights

- A comprehensive study on global aridity change is presented.
- A new clustering procedure is performed to detect trends in aridity time series.
- Three distinct groups of aridity index series around the world are identified.
- The results indicate a change in aridity occurred around the 1980s.