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Analysis of long term meteorological trends in the middle and lower Indus Basin of Pakistan—A non-parametric statistical approach

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ABSTRACT

The Indus basin of Pakistan is vulnerable to climate change which would directly affect the livelihoods of poor people engaged in irrigated agriculture. The situation could be worse in middle and lower part of this basin which occupies 90% of the irrigated area. The objective of this research is to analyze the long term meteorological trends in the middle and lower parts of Indus basin of Pakistan. We used monthly data from 1971 to 2010 and applied non-parametric seasonal Kendal test for trend detection in combination with seasonal Kendall slope estimator to quantify the magnitude of trends. The meteorological parameters considered were mean maximum and mean minimum air temperature, and rainfall from 12 meteorological stations located in the study region. We examined the reliability and spatial integrity of data by mass-curve analysis and spatial correlation matrices, respectively. Analysis was performed for four seasons (spring—March to May, summer—June to August, fall—September to November and winter—December to February). The results show that max. temperature has an average increasing trend of magnitude +0.16, +0.03, 0.0 and +0.04 °C/decade during all the four seasons, respectively. The average trend of min. temperature during the four seasons also increases with magnitude of +0.29, +0.12, +0.36 and +0.36 °C/decade, respectively. Persistence of the increasing trend is more pronounced in the min. temperature as compared to the max. temperature on annual basis. Analysis of rainfall data has not shown any noteworthy trend during winter, fall and on annual basis. However during spring and summer season, the rainfall trends vary from −1.15 to +0.93 and −3.86 to +2.46 mm/decade, respectively. It is further revealed that rainfall trends during all seasons are statistically non-significant. Overall the study area is under a significant warming trend with no changes in rainfall.

1. Introduction

The climate of any region is defined as a temporal mean and variability of temperature, rainfall and other meteorological parameters over a typical period of 30 years (IPCC, 2007). The evolution of climate systems in time is influenced by the internal dynamics of climate and some external factors. The external factors can be natural phenomena like solar variation, volcanic eruption, and anthropogenic forcing such as change in the composition of atmosphere (IPCC, 2007). This is now a widely accepted fact that climate change is taking place globally due to these external factors. Large scale consumption of fossil fuels in developed world is believed to contribute 75% of the total greenhouse gas emission (Farooqi et al., 2005). Scientists have found that besides carbon dioxide other radiatively active gases are also responsible for climate change (Gammon et al., 1985; Bolin, 1986). According to Venton (2007), the cost of climate change would mostly be borne by poor nations as most affected regions fall in developing world. Moreover communities in these developing countries are mostly engaged in farming, a highly vulnerable sector to climate change, and have limited resources to adapt to climate change.

There is a growing consensus that long term changes in temperature and rainfall may alter the hydrological and ecological processes (Gleick, 1987, 1989). Over the past years, many studies have been conducted worldwide to assess the changing trends in temperature and rainfall e.g., USA and Africa (Nemec and Schaake, 1982; Karl et al., 1989); India (Rao, 1993; Arora et al., 2005; Singh et al., 2008), Norwegian Arctic (Hanssen-Bauer and Forland, 1998), Bangladesh (Ahmad and Warrick, 1996), Nepal (Shrestha et al., 1999), Iran (Tabari and Talaee, 2011), Northwestern Himalaya (Bhutiyani et al., 2007, 2009) and in Pakistan (Archer and Fowler, 2004; Farooqi et al., 2005; Fowler and Archer, 2005; Khattak et al., 2011).

The detection of trend in meteorological data is a common process when assessing the state of climate of a region. It provides an overall estimate of time variation of the data. The emphasis of trend analysis is not on the details of internal dynamics of climate i.e. how the climate changes over time but more in the general direction and magnitude of change. Trend in meteorological data and its quantification is complex

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due to the characteristics of skewness, persistence or auto-correlation and seasonality in data. The complexity added by these factors make it more difficult to detect long term trends (Gilbert, 1987). The problem of auto-correlation and seasonality can be solved by either trend free pre-whitening approach (TFPW) (Yue et al., 2002; Yue and Pilon, 2003) i.e. removing the seasonal cycles before applying any test for trend detection or resampling methods (Kundzewicz, 2004). Another practical way of handling cyclic and auto-correlated data is to use tests which are unaffected by cycles (Gilbert, 1987). Different researchers (Archer and Fowler, 2004; Bhutiyani et al., 2007; Khattak et al., 2011; Tabari and Talaee, 2011) have mainly used two type of tests for trend detection and quantification in meteorological time series. These tests are parametric (linear regression) and non-parametric Mann–Kendall (Mann, 1945; Kendall, 1975) and Sen's (Sen, 1968) slope estimator. Several investigators prefer the use of parametric tests for their simplicity. Parametric tests are applicable when the scatter plot of the data suggests a linear increasing or decreasing trend over time with minimum outliers. Hence a regression line can be fitted using ordinary least square. A *t*-test can then be used to test the significance of slope of the regression line. The result of this test may be misleading if there are seasonal cycles present i.e. the data is serially correlated or the data is not normally distributed. It has been further reported that the *t*-test may indicate a statistically significant slope when the true slope is zero (Hirsch et al., 1982). In contrast the non-parametric Mann–Kendall test can be used when the data is not normally distributed. The use of this method still requires the removal of seasonality or auto-correlation in the data and hence is computational intensive. On the other hand the use of seasonal Kendall test provides the best alternative when the observed data is either positively or negatively skewed, cyclic or serially correlated (Hirsch et al., 1982). In this research we used the non parametric seasonal Kendall test in combination with seasonal Kendall slope estimator in middle and lower Indus basin to estimate trends in max. temperature, min. temperature and rainfall.

2. Study area

The Indus basin is one of the world's largest basins located in Afghanistan (7%), China (11%), India (27%) and Pakistan (55%). It hosts the world's largest contiguous network of irrigation system. Based on climate and geography of the region, this basin can be divided into three distinct parts i.e. the upper, middle and lower Indus basins (Critchfield, 1987). The upper Indus basin consists of northern areas of Pakistan, Azad Jamu and Kashmir and Potohar plateau. It receives a mean annual rainfall of more than 1000 mm and falls in humid climatic zone (Khan et al., 2010). The middle Indus basin covers the upper and central parts of Punjab and spans from the districts of Jhelum and Sialkot down to Bahawalpur. The mean annual rainfall in middle Indus basin ranges from 300 mm in the southern parts to 800 mm in the central districts and hence exhibits a semi-arid to sub-humid climate (Khan et al., 2010). In this part of the study area, the annual mean air temperature varies between 23 and 26 °C with 29 to 33 °C mean maxima and 16 to 19 °C mean minima. The lower Indus basin consists of Khanpur in lower Punjab, Jacobabad, Nawab shah, Hyderabad and Badin districts in Sindh province. The annual mean rainfall in the lower Indus basin is less than 200 mm and is therefore characterized by arid climate. The designated hot climate of the lower Indus basin is due to an annual mean of 25 to 28 °C maxima and 17 to 21 °C minima air temperatures. The potential evapotranspiration in the study area ranges from 2 mm/day in winter up to 6 mm/day in summer. There is a significant difference in climatic patterns in upper, middle and lower parts of Indus Basin. The greater Himalayan region above 35°N latitude, receives winter rainfall mostly in the form of snow. The north is dominated by a mountain climate ranging from humid to arid. In the middle and lower Indus basin, the climate is broadly of a tropical continental nature. The rainfall pattern is irregular and markedly variable in magnitude, time of occurrence and in its aerial distribution. There are two major sources of rainfall in the study area i.e. the *monsoon* and the *western depression*. The former takes place from July to September and the later take place from December to March. The climate of the Indus basin can be characterized by four distinct seasons i.e. spring (March–May), summer (June–Aug), fall (Sep–Nov) and winter (Dec–Feb). Although the weather station network in Indus basin is sparse (Cheema and Bastiaanssen, 2012), but the study area is equipped with a synoptic weather stations operated by the Pakistan Meteorological Department (PMD). These weather stations record daily data of common meterological parameters including maximum and minimum air temperature and rainfall. Seven weather stations namely Jhelum, Sialkot, Lahore, Faisalabad, Multan, Bahawalpur and Bahawalnagar fall in middle Indus basin. Similarly the lower Indus basin is covered by Khanpur, Jacobabad, Nawabshah, Hyderabad and Badin stations. The selected stations in the study area lie in a north–south orientation with an east–west spread. The detail of stations name, latitude/longitude and elevation above mean sea level (a.m.s.l) are presented in Table 1 and graphically shown in Fig. 1.

3. Data and methodology

Historical (1971–2010) monthly data for mean maximum and mean minimum air temperature and rainfall was collected from Pakistan Meteorological Department (PMD) for a total of 12 metrological stations spread across the middle and lower Indus basin. The accuracy of any analysis lies in the fact that the data used should be reliable and consistent. In a long term study of climatic variables, the change in location of observation station or measurement procedure may shift the mean or variance of recorded data. If interpreted incorrectly, these inconsistencies may attribute to misleading changes in the natural processes underlied (WMO, 2011). For this purpose the consistency check of data was performed by comparing the significance of change in slope of double-mass curve of max. temperature, min. temperature and rainfall as suggested by Kohler (1949), Searcy and Hardison (1960), and Fowler and Archer (2005). To assess the representativeness of data on a regional scale Archer and Fowler (2004) proposed spatial correlation matrix drawn between stations to acertain that individual stations or group of stations are representative of the region in which they are located. Thus we draw correlation matrices of max. temperature, min. temperature and rainfall between the stations under consideration.

3.1. Seasonal Kendall test for trend detection

The seasonal Kendall test (Hirsch et al., 1982) is used in this research. This test is a generalized form of Mann–Kendall (MK) test (Mann, 1945; Kendall, 1975) and it does not require any pre-whitening treatment of

Table 1
Details of weather stations used in the study.

Location	Met. Station	Latitude °N	Longitude °E	Elevation above mean sea level (Meters)
Middle Indus Basin	Bahawalpur	29°20′	71°47′	110
	Bahawalnagar	29°20′	73°51′	161
	Multan	30°12′	71°26′	121
	Faisalabad	31°26′	73°08′	185
	Lahore	31°35′	74°24′	216
	Sialkot	32°31′	74°32′	255
	Jhelum	32°56′	73°44′	287
Lower Indus Basin	Badin	24°38′	68°54′	9
	Hyderabad	25°23′	68°25′	28
	Nawabshah	26°15′	68°22′	37
	Jacobabad	28°18′	68°28′	55
	Khanpur	28°39′	70°41′	88