Pakistan Geographical Review, Vol. 69, No.2, December 2014, PP 111-132

REGIONALIZING THE CLIMATE OF PAKISTAN USING KÖPPEN CLASSIFICATION SYSTEM

SARDAR SARFARAZ*, MUDASAR HASAN ARSALAN* AND HIRA FATIMA**
*Institute of Space and Planetary Astrophysics, University of Karachi,
**Pakistan Meteorological Department

ABSTRACT

Pakistan is the only country in the world to have a unique range of altitudes from sea level to the second highest mountain peak of the world. This distinct characteristic gives it large variation in climate across its different areas, like huge temperature difference and large spatial rainfall distribution. These largely contrasting variations in temperature and precipitation can best be depicted by making some well-defined classifications of climate parameters and their spatial distribution across Pakistan. In this paper, we produced climate maps of Pakistan by using the 30-year monthly normal area-weighted precipitation and temperature data set of 59 meteorological sites well spread across Pakistan using the Geographic Information System (GIS). We calculated the climate variables used in Köppen-Geiger system at each of 59 meteorological stations. The result shows three principal climates classes i.e. B, C and D with their further subclasses across Pakistan. We regionalized the climate of Pakistan based on spatial proximity principals and developed a sub-regional map of climate zones of Pakistan.

KEY WORDS: Climate classification, Pakistan, rainfall, annual temperature, Climate parameters interpolation, GIS.

INTRODUCTION

World meteorological Organization (WMO) defines the climate as the statistical description in terms of the mean and variability of relevant quantities over a period of time. These average weather conditions span over years and decades, typically over a 30-year period. It is the classification, which helps distinguish similar pattern of climate from the dissimilar ones, Walterscheid (2009). The world climate has been classified into different classes by many climatologists and geographers like Supan (1896), Köppen (1936), Thornthwaite (1948), Blair (1942), Gieger (1953), Miller (1969) and Griffith (1978). According to Griffiths (1978) the climatic classification is simply a method of arranging various climatic parameters either singly or grouped into ranks to simplify the mass of data and to identify analogies. The most commonly used climate indices of the world are those given by Köppen who had divided the world climate on the basis of temperatures. He describes that it is the vegetation type that actually provides identification about climate prevailing in the regions taking into account the temperature and precipitation (Köppen, 1936). Thornthwaite, (1948) classifies the climate on the basis of two main indices, the moisture content and annual potential evapotranspiration. Based on these two climate indices he gave a famous map (Thornthwaite map) which clearly divides the wetter and drier regions. Trewartha, (1968) said that climate classification is a process basic to all sciences, recognizing individuals with some unique characteristics in common and grouping them into a few classes or types. He considers Thornthwaite classification as a more refined method, especially for agriculture applications because of containing an account of evapotranspiration than that of Köppen, which proves more helpful. Similarly Doerr (1962) comparison of maps generated by the Köppen and Thronthwaite methods signifies the latter more accurate and helpful to describe the climate of a place. But it is still the Köppen system, which is widely and popularly used around the globe by academia and researchers (Peel et al., 2007; and Kottek et al., 2006).

Some tremendous efforts have already been made on climate classification of Pakistan by Kazi (1951), Shamshad (1956) and Nasarullah (1968). Zahid and Rasul, (2011) did the Thermal classification of Pakistan. Kazi's (1951) work on climate classification of Pakistan first dates us back to the climate classification done by climatologists including Trewartha (1946), Köppen (1936), Thornthwaite (1948), Blair (1942), Kendrew (1941) and Miller (1949). For instance Trewartha had presented three types of classification, namely, Tropical and sub-tropical steppe, Tropical and sub-tropical desert and Undifferentiated highlands; Köppen gave his five famous classifications; Thornthwaite came up with six classes; Blair with four; Kendrew with four and Miller demonstrated three classes for Pakistan region. Kazi (1951) argues that being an arid continental country like Pakistan the climate elements are subject to greater fluctuations and variations, because the mean annual values of temperature and rainfall as well as mean seasonal and mean monthly values do not seem appropriate and helpful for describing a class of climate. He then suggests the construction of Tri-Liner Graphs by considering the eleven-year cycle or larger period (say 20 years) and suggests that the maxima and minima of temperature should be shown by three curves:

The first showing the actual lowest maximum temperature for each month, occurred at the station during the cycle,

The second showing the actual highest maximum for each month recorded during the cycle and

The third showing the mean monthly maximum temperature for the period.

Similarly, three curves may be drawn for minima, the highest minimum, lowest minimum and mean minimum. Shamshad, (1956),by taking into account the characteristics of seasons, suggested that Pakistan climate classifications might put under seasons classification as:

Quadruple season of extra-tropical type (Summer, Autumn, Winter and Spring),

Triple season of temperature-moisture type (Hot, rainy and cold season) and

Double season of temperature type (Hot and Cold season).

Shamshad, (1956) associated the above seasons with two main types of climate, extra-tropical and subtropical: the first group of seasons goes with extra-tropical, the second and third with the subtropical types. Khan (1993) worked out the climate classification at 32 individual meteorological stations of Pakistan by using the 1931-60 normal climatic data maintained by the Pakistan Meteorological Department by taking into account the Köppen, Trewartha and Thornthwaite climate classification systems. Chaudhry and Rasul, 2004 did the Agro-climatic classification of Pakistan by applying a modified Thornthwaite approach adopted by Reddy and Reddy (1973) using reference crop evapotranspiration and concluded that 2/3 of the total area of Pakistan lies under the arid climate.

Pakistan, stretching from 24 °N to 36 °N and 61 °E to 76.5 °E, possesses a much diversified climate with experiencing a hot and dry climate in the south, temperate in northwest and arctic in the north. Summer temperature in the south rise over 50°C and winter temperature in the north fall as low as -20°C to -22°C (Pakistan Climatic Normals, 1961-90). Similarly, the precipitation variability is also distinctively large across north and south Pakistan, ranging 1500-2000 mm and 100-200 mm, respectively, (Pakistan Climatic Normals, 1981-2010). The eastern belt of the country receives more summer (monsoon), rains whereas western belt is more influenced by the winter rains from western disturbances (Khan, 1993). Such a large gradient, therefore necessitates defining its climate into some sub-regions or classes.

All previous efforts are found based on historical data at least 50 years back, except Zahid and Rasul, (2011). Most of these efforts are to categorize the meteorological stations and contouring for climate parameter distribution across Pakistan. However, sub-regionalization for dividing the whole region into distinct climate zones is missing in the literature.

In recent years, Geographical Information System (GIS) has provided many tools and techniques to support researchers for cartographic aggregation, generalization and clustering (ArcGIS Resources, 2014a, 2015a,b).There are several geo-statistical techniques developed for interpolating the stations data in GIS environment. Sluiter (2008) classified these methods in three primary categories i.e. deterministic, probabilistic and others. Deterministic methods such as nearest neighborhood and triangulation, Inverse Distance Weighting, polynomial functions (Splines), Linear regression and artificial neural network, use geometric properties of points sampled to generate a continuous surface. While probabilistic methods such as optimum interpolation and different type of Krigging, includes the concept of randomness, linear regression and geostatistics. Other methods are the combination of deterministic and probabilistic methods, specially designed for meteorological studies. (Sluiter et. al. 2008)

Literature search shows that there is no single suggested method of interpolation. Hence, it is usually selected based on desired accuracy, available data and resources. However a study of spatial variability of climatological parameters -in which different interpolation techniques i.e. Inverse distance weighted (IDW), Spline and Kriging were used- shows that there is considerable difference in predicting the spatial variability in climate normal using different interpolation techniques. (Irmak, Ranade, Marx, Irmak, Hubbard, Meyer, and Martin, 2010).

This paper is an attempt to spatially map the climate parameters and work out the Köppen climate classification system for Pakistan using the GIS with latest available normal climatic values of temperature and precipitation (monthly, seasonal and annual). We used the monthly climatic normal (1981-2010) data at 59 meteorological stations of Pakistan.

MATERIAL AND METHODS

The monthly climatic normal data on rainfall and temperatures for a 30-year (1981-2010) at 59 data sites was obtained from the Pakistan Meteorological Department, PMD (Fig. 1). It was a quality controlled data as PMD has published it in their publication "The 30-year (1981-2010) Climatic Normals of Pakistan". The monthly data values were aggregated over 12 months to work out the annual values. Since Pakistan normally exhibits four weather seasons based on rainfall, the summer monsoon (July through September, JAS), winter (December to March, DJFM), pre-monsoon season (April-June, AMJ) and autumn or post-monsoon (October-November, ON), (Shamshad, 1985 and Khan, 1993). So the seasonal rainfall indices for the summer monsoon (July-September), winter (DJFM), pre-monsoon (AMJ) and post-monsoon (ON) were worked out by aggregating the three, four, three and two months values respectively. Based on temperature we may define the seasonal temperature indices as, winter (or cold) temperature season consisting of December to February (DJF), spring (mild temperature) the aggregate of March-April (MA), hot/pre-monsoon of May-June (MJ), monsoon of July-September (JAS) and post-monsoon/autumn consisting of October-November (ON), (Zahid and Rasool, 2011, Khan 1993). Which means a year is sub-divided into five temperature seasons, because the March temperatures at most of the data stations rank closer to that of April than in February. Similarly May and June being the hottest (and dry) months are aggregated into a separate season as their temperatures stand higher than that of monsoon (JAS) season.

We utilized the data management capabilities of ArcGIS to store, edit and manage data. Further, the visualization and mapping capabilities of ArcGIS were used to present the data clearly and effectively. The stations data layer was created in ArcGIS from the geographical coordinates of stations (Fig. 1) and then every station was linked to its climatic data, such as Annual normal rain, DJFM-rain, JAS-rain, AMJ-rain, ON-rain and Annual and seasonal normal temperatures by a unique identifier.

As ArcGIS is fully loaded with spatial analysis tools that can be used for analyzing geographic patterns as well as advanced predictive modelling, we performed interpolation of climate parameters. The inverse distance weighted (IDW) method in ArcGIS is used for interpolation of each annual and seasonal rainfall and temperature indices for mapping the values over the area not covered by the data points. IDW interpolation is based on the assumption that the influence of variable that is being mapped decreases with distance from its sampled location i.e. weight is the function of inverse distance. IDW interpolation uses a linear weighted combination of sampled points to calculate the cell values. These cell values are limited to the range of values used for interpolation.

In a GIS environment, raster datasets can be displayed or rendered in several ways. Display colors can be changed, or the dataset values can be stretched to enhance the visual contrast or the classification renderer can be used. In rendered classification the data values of single band thematic raster -which is based on a continuous phenomenon like slope, temperature, distance, etc. - are grouped into a small number of classes. Different classification methods are used like manual, equal interval, quantile, natural breaks, standard deviation etc. (ArcGIS Resources, 2014b). To better understand the spatial variation of annual and seasonal normal rainfall and temperature by comparing (using the same legend), we grouped the range of annual and seasonal normal temperature values (i.e. -1-37) into six classes of equal intervals. This classification renderer was used to classify all the IDW interpolated annual and seasonal normal temperatures. As the range of annual rain (37-1775) was much greater than the range of seasonal rains (0-771), we created two different classification renderers of six equal interval classes: one with the range of seasonal rains to classify the IDW interpolated seasonal rains and other with the range of annual normal rain to classify IDW interpolated annual normal rain.

The climate type or class in accordance with the Köppen climate classification system (Table 1) at each data station was determined by calculating the mean annual temperature (MAT) and mean annual precipitation (MAP) from the mean monthly data values. The two seasons, summer and winter, rainfall were realized by aggregating the monthly rainfall of April through September (AMJJAS) and of October through March (ONDJFM) respectively. Then for determining the precipitation threshold (Pthresh), another parameter of Köppen classification criteria, percentage contribution to the annual total of the summer and winter precipitation was realized, (Peel et al., 2007 and Kottek et al., 2006).

In Köppen-Geiger climate scheme (1936) the climate classification type A represents the Tropical climate. Class type B represents the arid with further sub-division into the desert and steppe types. The type C represents the temperate climate type with further sub-division into the temperate with dry winter (or dry summer). The type D represents the cold climate with further sub-division into cold with dry winter (or dry summer) and E represents the Polar climate with further sub-division into Tundra and Frost climates. Further, the second letter represents the precipitation and the third is meant for temperature, e.g. the climate classification BWhw means the Desert hot with dry winter climate, Csa stands for the Temperate with dry and hot summer and so on (Peel et al., 2007). The detailed criteria and key to calculate the Köppen climate classes is given in Table 1.

One of the most commonly used aggregating technique for qualitative data (for which other interpolation techniques are not applicable) is Thiessen polygon. In this technique, data points are taken as centers for drawing polygons or boundaries around them based on the distribution of sampled data points (Beurs, 1999). For sub regionalization, we used Thiessen polygon technique to aggregate the climate classes of stations. From the individual meteorological station in the form of point geometry, we produced a consolidated map of Pakistan climate regions.

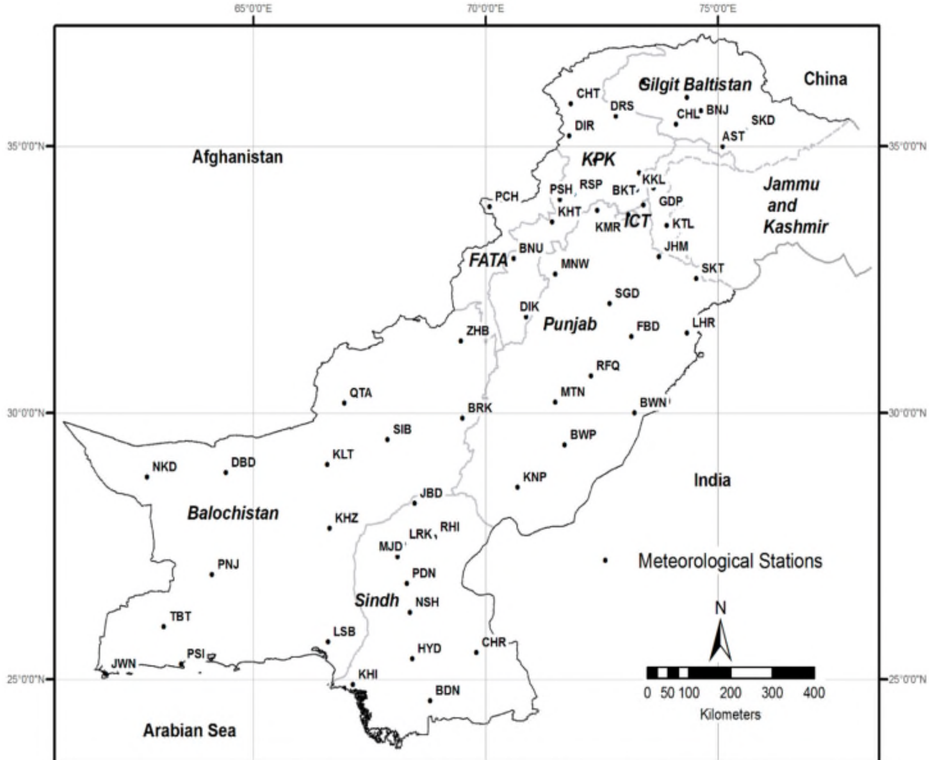
Table 1. Description of Köppen climate symbols and defining criteria with a detail on key to calculate the climate classes

1st	2nd	3rd	Description	Criteria*
A			Tropical	T_{cold} >=18 °C
	f		Rainforest	P_{dry}>=60 mm
	m		Monsoon	Not (Af) and P_{dry} >=100-MAP/25
	W		Savannah	Not (Af) and P_{dry} <100-MAP/25
B			Arid	MAP<10*P_{thresh}
	W		Desert	MAP<5*P_{thresh}
	S		Steppe	MAP>=5*P_{thresh}
		h	Hot	MAT>=18°C
		K	Cold	MAT<18°C
C			Temperate	T_{hot}>10 and 0<T_{cold}<18
	s		Dry summer	P_{sdry}<40 and P_{sdry}<P_{wwet}/3
	w		Dry winter	P_{wdry}<P_{swet}/10
	f		Without dry season	Not (Cs) or Cw
		a	Hot summer	T_{hot}>=22
		b	Warm summer	Not (a) and T_{mon10}>=4°C
		c	Cold summer	Not (a or b) and 1<= T_{mon10}<4
D			Cold	T_{hot}>10 and T_{cold}<=0
	s		Dry summer	P_{sdry}<40 and P_{sdry}<P_{wwet}/3
	w		Dry winter	P_{wdry}<P_{swet}/10
	f		Without dry season	Not (Ds) or (Dw)
		a	Hot summer	T_{hot}>=22°C
		b	Warm summer	Not (a) and T_{mon10}>=4°C
		c	Cold summer	Not (a, b or d)
		d	Very cold winter	Not (a or b) and T_{cold}<-38 °C
E			Polar	T_{hot}<10
	T		Tundra	T_{hot}>0
	F		Frost	T_{hot}<=0

*MAP = mean annual precipitation, MAT = mean annual temperature, T_{hot} = temperature of the hottest month, T_{cold} = temperature of the coldest month, T_{mon10} = number of months where temperature is above 10, P_{dry} = precipitation of the driest month, P_{sdry} = precipitation of the driest month in summer, P_{wdry} = precipitation of the driest month in winter, P_{swet} = precipitation of the wettest month in summer, P_{wwet} = precipitation of the wettest month in winter, P_{thesh} = varies according to the following rules (if 70% of the MAP occurs in winter then P_{thesh} = 2*MAT, if 70% of the MAP occurs in summer then P_{thesh} = 2*MAT+28, otherwise P_{thesh} = 2*MAT+14). Summer and winter are defined as the warmer six months AMJJAS (April – September) and cooler six months ONDJFM (October – March) respectively, (Reproduced from Peel et al., 2007).

RESULTS AND DISCUSSION

Fig. 1 depicts the geographical location of the meteorological stations used in this study with their respective codes. It is noteworthy that some areas in the center, extreme south and southwest of the country give a scant or a sparse view despite of the fact that the spread of stations nearly cover the whole landscape of Pakistan.Fig. 2 to13 show the spatial distribution of annual normal and DJF, MA, MJ, JAS, and ON temperatures; and



Astor	AST	Drosh	DRS	Khuzdar	KHZ	Parachinar	PCH
Badin	BDN	Faisalabad	FBD	Kohat	KHT	Pasni	PSI
Balakot	BKT	Garhi Dupatta	GDP	Kotli	KTL	Peshawar	PSH
Bannu	BNU	Giglit	GLT	Lahore	LHR	Quetta	QTA
Barkhan	BRK	Gupis	GPS	Larkana	LRK	Rafiqui	RFQ
Bhawalnagar	BWN	Hyderabad	HYD	Lasbella	LSB	Risalpur	RSP
Bhawalpur	BWP	Islamabad	ISL	Mianwali	MNW	Rohri	RHI
Bunji	BNJ	Jacobabad	JBD	Moenjo daro	MJD	Saidu Sharif	SHF
Cherat	CHT	Jehlum	JHM	Multan	MTN	Sargodha	SGD
Chhor	CHR	Jiwani	JWN	Murree	MUR	Sialkot	SKT
Chilas	CHL	Kakul	KKL	Muzzafabad	MBD	Sibbi	SIB
Chitral	CHT	Kalat	KLT	Nawabshah	NSH	Skardu	SKD
Dalbandin	DBD	Kamra	KMR	Nokkundi	NKD	Turbat	TBT
DI Khan	DIK	Karachi	KHI	Padidan	PDN	Zhob	ZHB
Dir	DIR	Khanpur	KNP	Panjgur	PNJ		

Fig.1: Geographicallocationsof meteorological stations across Pakistan used in the study

JAS, DJFM, AMJ and ON rainfalls and climate classification of each meteorological stations across Pakistan.

ANNUAL AND SEASONAL NORMAL TEMPERATURE SPATIAL DISTRIBUTION

Fig. 2 shows the spatial distribution of annual normal temperature across Pakistan. It evidently shows that the annual normal temperature ranges from 24 °C to 30 °C in south Pakistan (Sindh province and south Balochistan), it decreases as we proceed along north and ranges 11-18 °C in the extreme north/ northeast of the country and in north Balochistan. Obviously the south Pakistan experiences over 26 °C more than what north Pakistan records in annual temperature which is distinctively large temperature gradient. The historical climate records reveal that the extreme temperatures (ever maximum of 53.5°C recorded at Moenjodaro, Sindh and ever minimum of -21 °C recorded at Skardu) difference is 74.5°Cin populated areas of Pakistan (Source: Climatic Normals of Pakistan 1961-90 and 1981-2010; CDPC, PMD).

Fig. 3 depicts the spatial distribution of 30-year winter (DJF) normal temperatures across Pakistan. The northern areas evidently experience -01 °C to 5 °C temperature (with at least 3 stations in Gilgit-Baltistan (GB) and one in northern Balochistan showing the frosty conditions, beryl green shaded). Then moving down the latitudes we find a gradual increase in temperature (ref. Fig. 3) culminating at 18-24 °C in southern Sindh and southwest coast of Balochistan. Hence, overall the winter temperature range across Pakistan comes out to be below zero to 24 °C which is again quite a large range like that of annual temperatures. In defining winter temperature season we slightly deviate from the norm of winter rainfall season composition because the month of March is not as much cold as December, January and February, but for winter rainfall season March is taken into account for being wet enough.

Fig. 4 shows how the spring season (March-April, MA) normal temperatures are spatially distributed. Again the temperature maxima (24-30°C, orange shade) we find over entire Sindh, southeast Punjab and extreme south and southwest Balochistan. The minimum range of 5-11 °C (dark green shade) is observed over the northeast (Gilgit-Baltistan, GB) of the country. The overall range of about 25 °C from north to south of the country persists during the spring season.

The spatial distribution of the summer or pre-monsoon temperatures is shown in Fig. 5 where the highest temperature range of 30-37 °C persists over Sindh, most of Balochistan and Punjab (except northeast part) followed by 24-30 °C over north-northeast Balochistan (except a hilly station Kalat whose range matches with that of the northern area, orange color) and northeast Punjab. Then gradual decrease is observed while moving northeastwards of the country inclusive of some isolated places in north Balochistan where the least range of 18-24 °C is noticeable. We therefore can conclude that the summer/pre-monsoon (May-June, MJ) season turns out to be the hottest of all five seasons with an overall range in excess of 25 °C between north and south of the country.

Fig. 6 depicts the spatial distribution of monsoon season (JAS) temperatures across Pakistan. The high temperature range of 30-37 °C (red colored) is yet again seen over Sindh (excluding isolated places in the extreme south and southwest parts), east, southeast and northwest Balochistan, south and central Punjab and south Khyber Pakhtunkhwa (KP). The lowest temperature range of 18-24 °C in monsoon season is seen persisting over north, northeast of the country and isolated place in north Balochistan. Comparing the JAS season (Fig. 6) with MJ (Fig. 5) we notice that MJ temperature maxima cover more area of Balochistan and KP. The lowest and highest temperature ranges differ by about 17 °C which of course is lower than that seen in other seasons' temperatures.
Fig. 7 shows the temperature spatial distribution of autumn/post-monsoon (ON) season with maximum range of about 24-30 °C persisting over south Pakistan (Sindh) and the coast of Balochistan. The next lower temperature range of 18-24 °C is observed over entire Punjab, KP and Balochistan except a few places in its north where a lesser range of 11-18 °C is seen. The lowest range of 5-11 °C yet again features over the northeast areas of the country and isolated place over northern Balochistan. Here the difference in lowest and highest temperature ranges turns out to be of 19 °C which of course is second lowest as compared to other seasons. The autumn (ON) season thus appears to fall third behind MJ and JAS in warming and in cool stands above than MA and DJF.
From the results depicted in Fig. 2 we may understand that Pakistan experiences annual average temperature in a marked range of 11-30 °C from north to south with southern areas experiencing the maximum range 24-30 °C and northern parts observing 11-18 °C. This of course is a well marked temperature gradient and that is why the southern Pakistan is termed to have an arid to semi-arid climate, while in the north the climate is termed as temperate.
On seasonal scale the results show that Pakistan, northern areas and north Balochistan experience very cold/ frosty conditions (temperature ranging below -1°C to 5 °C), whereas south and southwest coast experience a mild-cooling winter (11-18 °C) (see Figs. 3). The spring season temperatures distribution ranges are 5 – 11 °C in the northern areas and 24-30 °C in the south (Fig. 4) with an overall range of over 21 °C between south and north. The summer (May-June, MJ) season being hottest of all records the temperature maximum range 30-37 °C in south/southeast of the country (Fig. 5) and minimum range of 11-20 °C yet again over northern region with overall range being over 25 °C between north and south of Pakistan. The JAS though, is a summer (monsoon) season, but proves a less hot (by 3 °C) than the dry summer (MJ) primarily due to being wettest of all four seasons. Its maximum range is 30-37°C and lowest one being 11-18 °C. The autumn season (ON) temperatures are found to drop to 5-11 °C in the north and 24-30°C in south and southwest. Thus the 30-year normal temperature analysis reveals that throughout a year northern areas of Pakistan experience as low as below 0 °C winter temperature and on the other hand southern areas batter the hot conditions in excess of 37 °C during summer.

The variation in temperature is due to the influence of various factors, including the latitudinal extent of Pakistan, high mountain terrain in the north and northwest, vegetation cover, solar angle and insolation, continentality and an elevation difference of as low as zero meter at mean sea level in the south to over 2300 m in the north. These highly contrasting temperatures then dictate the climatic conditions of the different sub-regions of Pakistan. The southern desert regions of Pakistan receive intense solar heating in April - June and September - October with maximum global radiation (direct or diffuse sky) per day is 700-800 cal/cm^2 in May and a minimum of 400 cal/cm^2 in January with annual average of 560 cal/cm^2 (Sikka, 1997). The typical geographical features of Pakistan result in extreme thermal contrast (Arif et al., 2013). It is the hot summer (MJ) temperature, which plays a crucial role in setting up of the heat low, a seasonal (heat) low pressure area forming over south Pakistan during May-September, which in turn plays a pivotal role in dragging in the moist currents from the North Indian Ocean during monsoon season, (Arif et al, 2013 and Sarfaraz, 2007). Hence, in southern Pakistan the lack of sufficient rain compounded with high temperatures leads to high evapotranspiration and water scarcity and as a result the area is mainly categorized as the arid to semi-arid climate.

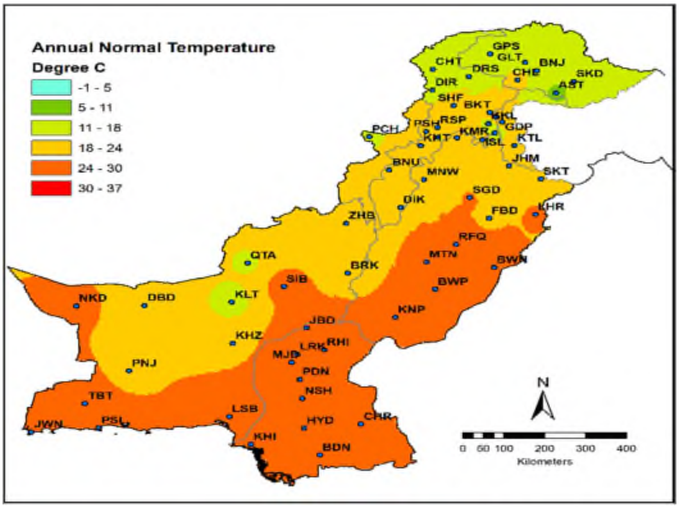


Fig.2: Pakistan 30-year (1981-2010) annual temperature (°C)spatial distribution.

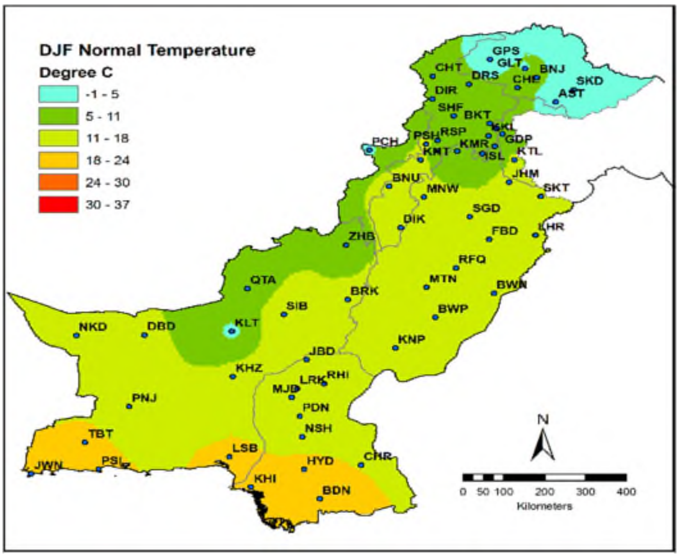


Fig.3:Pakistan 30-year DJF Normal Temperature (°C) spatial distribution.

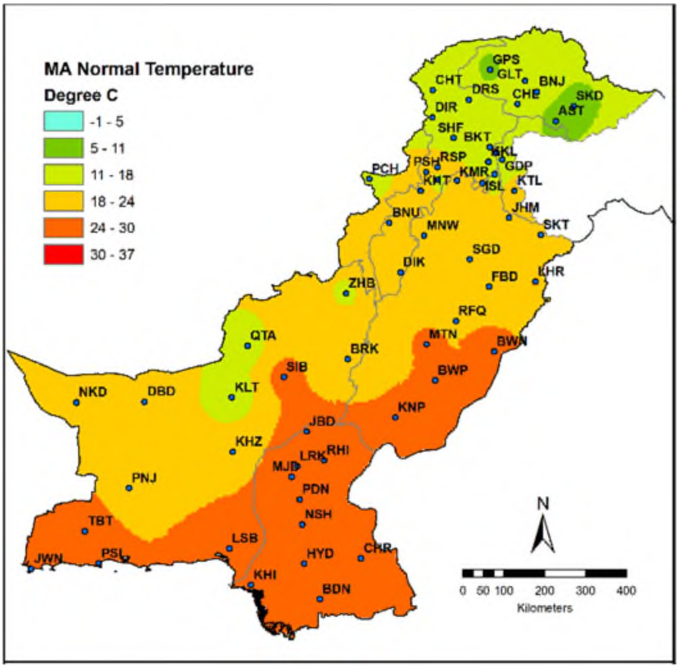


Fig. 4: Pakistan 30-year Mar-Apr (MA) Normal Temperature (°C) distribution.

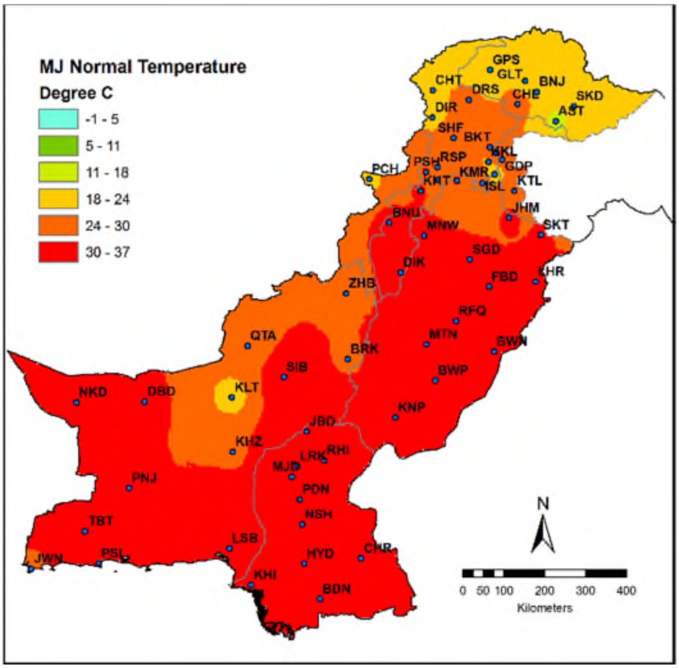


Fig.5: Pakistan 30-year (1981-2010) MJ Normal Temperature (°C) distribution.

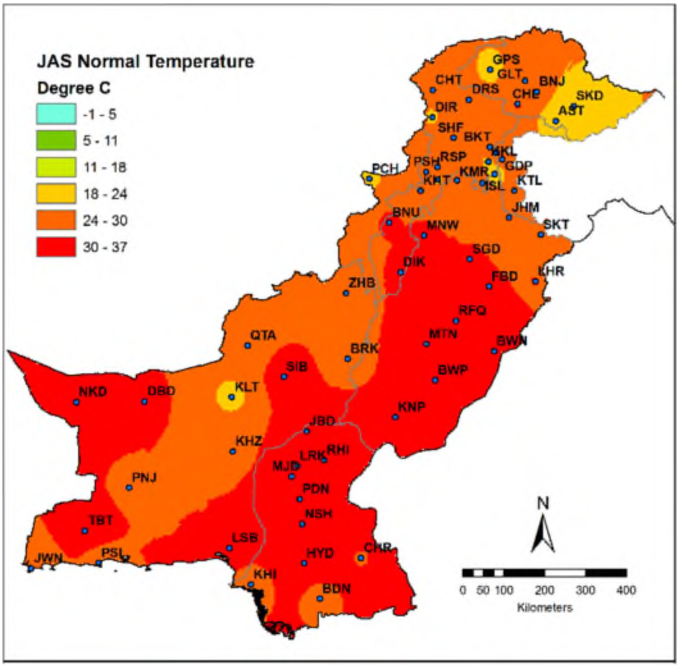


Fig. 6: Pakistan 30-year (1981-2010) JAS Normal Temperature (°C) distribution.

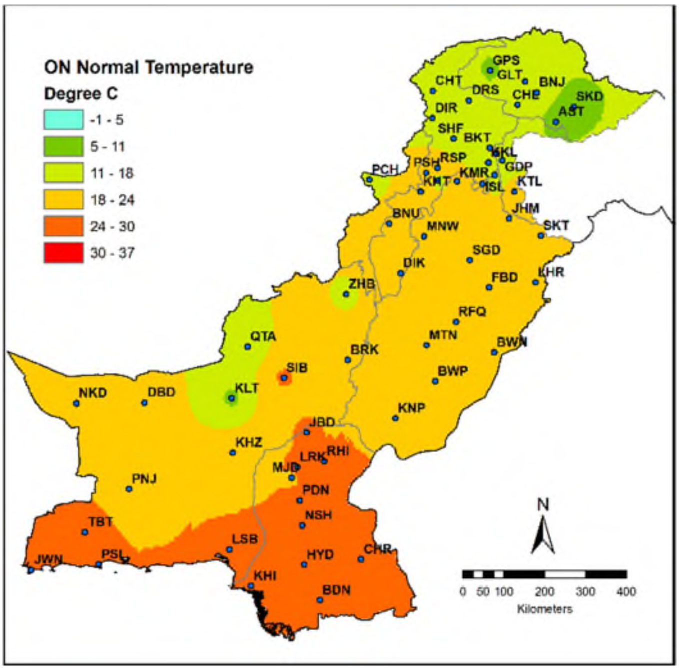


Fig. 7: Pakistan 30-year (1981-2010) ON Normal Temperature (°C) distribution.

THE SPATIAL DISTRIBUTION OF ANNUAL AND SEASONAL NORMAL RAINFALL

The Fig. 8 to 12 exhibit how annual and seasonal normal rainfalls are spatially distributed across Pakistan. Showing a distinctively large variation from north to south, Fig. 8 manifests that the sub-northern area of Pakistan receives the maximum of annual rainfall i.e.1485-1775 mm (ginger pink shade). It reduces with southward movement and reaches its minimum range of about 37 to 327 mm (medium yellow color) in Balochistan, Sindh and south Punjab. So evidently the intra-region rainfall variability (1738 mm) in annual normal rainfall spatial distribution signifies the marked climatic gradient across Pakistan.
Fig. 9 depicts the summer monsoon (JAS) rainfall distribution over different sub-regions of Pakistan. It is observed that again the most of rainfall concentration is over sub-northern areas of Pakistan i.e. ginger pink shaded spots (642-771 mm) surrounding Islamabad, Sialkot, Kakul, Balakot and suburbs. Next higher range of 514-642 mm spreads over the rest of the northeast area covering the stations, Jhelum, Kotli, Garhi Dupatta and Kamra. The third higher range of 386-514 mm engulfs the area stretching from Lahore towards northwest followed by a decrease in rainfall towards the south and southwest until comes almost entire Balochistan (with exception of a few sites in the northeast), southwest Punjab and central and upper Sindh where a minimum range of just a few to 129 mm is noticeable. Hence, we can conclude that the bulk of the monsoon rains fell over sub-northern areas of Pakistan. Pattern wise it is by and large similar to what we found in the annual rainfall spatial distribution.
Fig. 10 manifests the 30-year normal winter (DJFM) rainfall spatial distribution across Pakistan. DJFM rainfall is the second largest contributor with 30% share to the annual total rainfall of Pakistan. It is evident that largest rainfall range 514-642 mm is found only around Dir in the northwest followed by next higher range 386-514 mm persisting over the area around Murree, Kakul, Balakot, Saidu Sharif and Garhi Dupatta. It is noticeable that maximum DJFM-rainfall occur over the same geographical location as that in JAS case, but covered area getting thinned out than that observed in the latter case (Figs. 8 and 9). Here the minimum range falling below 129 mm is observed covering more than three-fourth of Pakistan stretches from southwest to northeastwards and culminating around Mianwali and suburbs and then reemerging over an eastern GB in the northeast. This is in a contrast to the range-minima we observed in annual and JAS rainfall spatial distribution (Figs. 8-9). It is because the country's west and southwest areas receive their bulk of rains during the winter season due to the eastward propagating mid-latitude cyclones called the western disturbances, WDs (Martyn, 1992).
Apart from JAS and DJFM rains, respectively 57% and 30%, the rest 13% is contributed by the local convective thunderstorm development occurring in transition periods, pre-monsoon and post-monsoon. To see how exactly the rainfall during these two transition periods is spatially distributed we further sub-divide these into spring or pre-monsoon season (April to June, AMJ) and autumn/post-monsoon season (October – November, ON). Fig. 11 depicts the spatial rainfall distribution during pre-monsoon or spring period

(AMJ) with telling fact of the range-maxima (about 257-386 mm) in this case found yet again over the same sub-northern area surrounding Murree, Kakul, Gari Dupatta and Muzaffarabad and Balakot. Next to this range is 129-257 mm observable in its all-around vicinity, a trend with great similarity to what observed in Fig. 8 to10. Obviously the minimum rainfall range 0-129 mm is spatially distributed over most of the GB, KP and Punjab, entire Sindh and Balochistan.

The Fig. 12 shows the rainfall spatial distribution during the autumn season (October - November, ON) which we also call the post-monsoon season. It is climatically the least rainfall yielding or most dry season of the year. Contrary to all three seasons discussed earlier here it is observable that almost the whole of the country is under the lowest minima of less than 129 mm rainfall. ON or post-monsoon thus figures out to be a season when Pakistan experiences markedly insignificant amount of rain.

The annual normal rainfall spatial distribution (Fig. 8), ranging from 1485-1775 mm in sub-northern areas of the country and 37-327 mm in southwest and south of Pakistan, shows a huge intra-region rainfall variability. Similarly the spatial distribution of four seasonal rainfalls, JAS (Fig. 9), DJFM (Fig. 10), AMJ (Fig. 11) and ON (Fig. 12), reveals that more significant rains are experienced by the sub-northern country and very little rains fell over south/southwest of the country. Thus the spatial rainfall distribution, either annual or seasonal, exposes an interestingly common feature of being significantly large in north/sub-northern areas of the country and insignificantly low over the south / southwest.

Precipitation, the second important parameter of the climate, is greatly influenced by the altitude, mountain barriers and topography, Walterschied (2009). Pakistan is geographically surrounded by the high mountain ranges, Himalaya-Karakoram-Hindukush (HKH), which have great bearing on the climate of the area by not only modifying the rainfall and temperature of Pakistan, but also greatly influence the general atmospheric circulation in the Sub-continent, Pakistan Geographical Review, (1962). Generally the windward side of the mountainous region receives enhanced rainfall while the leeward side being devoid of this advantage exposes a barren look, Chaudhry and Rasul, (2004). Hence, the great rainfall variability observed in annual and seasonal spatial distribution across Pakistan (Figs. 8 – 12) can certainly be attributed to have resulted mainly due to varying altitude peculiar topography and mountain barriers in the north of Pakistan. It is therefore this huge rainfall and temperature contrast between south and north Pakistan, which proves to be a critical factor for defining different climate types within the Pakistan mainland.

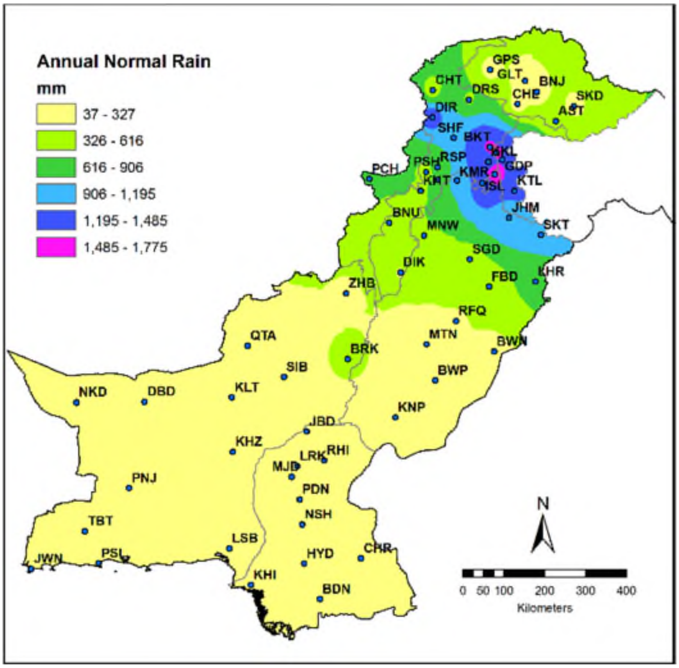


Fig.8: Pakistan 30-year (1981-2010) annual rainfall (mm) spatial distribution.

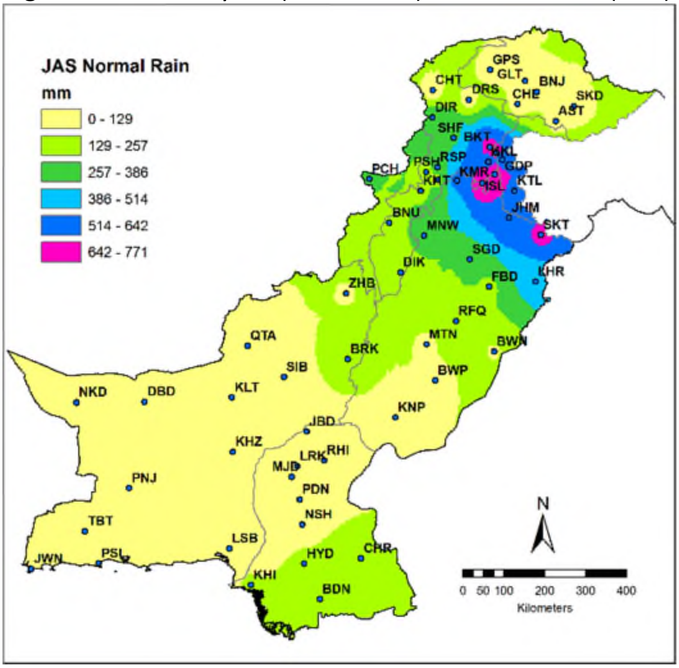


Fig. 9: Pakistan 30-year (1981-2010) summer monsoon (JAS) spatial rainfall distribution.

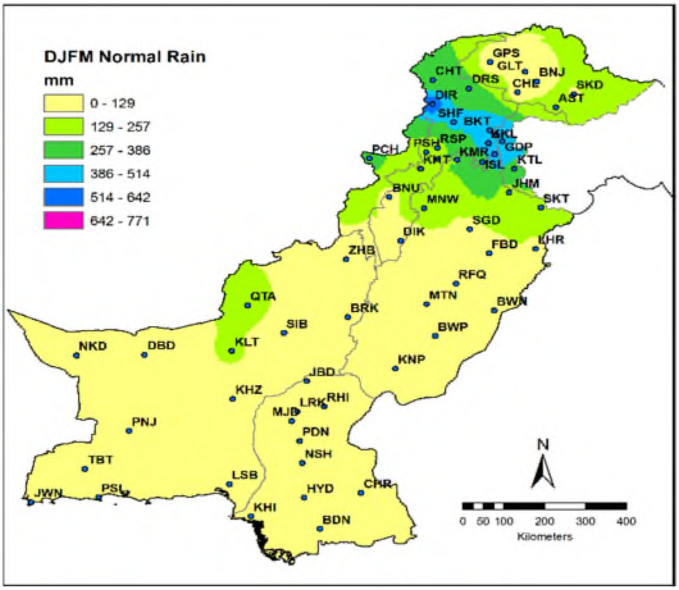


Fig. 10: Pakistan 30-year (1981-2010) winter (DJFM) spatial rainfall distribution.

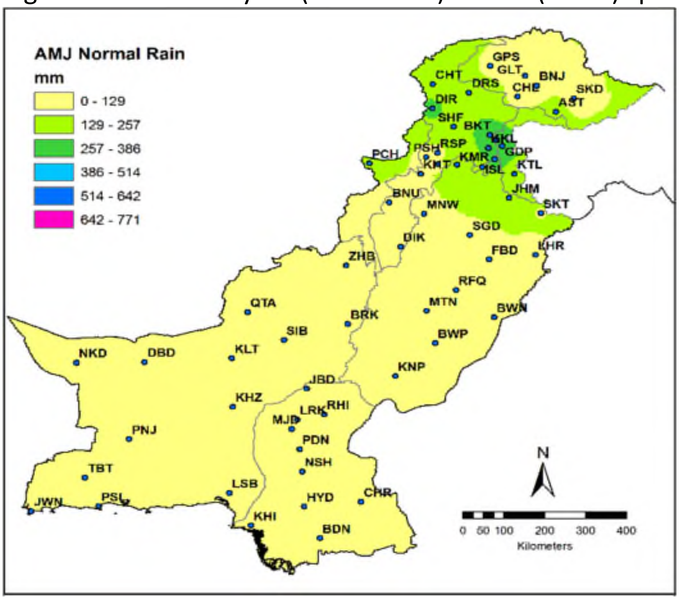


Fig.11: Pakistan 30-year (1981-2010) spring (AMJ) spatial rainfall distribution.

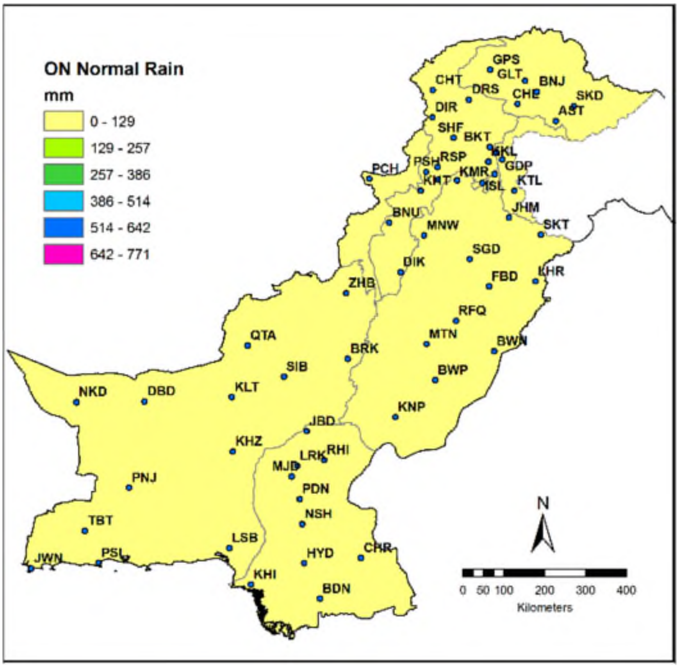


Fig.12: Pakistan 30-year (1981-2010) autumn (Oct-Nov) spatial rainfall distribution.

KÖPPEN CLIMATE CLASSIFICATIONS

The climatic variables used in Köppen-Geiger system were calculated at each of 59 meteorological stations and the resultant map is given in Fig. 13. The result clearly manifests that more than three-fourth of Pakistan climate is the arid to semi arid (middle and south Pakistan). It is characterized by high temperature and less rainfall. About 17 percent (of the meteorological stations used in the study) is under the temperate (sub-mountain areas in the north) and just over 5 percent falls under the cold type climate (in northeast Pakistan, three GB stations demonstrate the D type climate). Table 2 shows the detail of main climate classes and their further sub-classes. So we can conclude that in total the calculated Köppen climate classes across Pakistan come out to be 12 whereas there are 27 number of Köppen climate classes as per criteria given in Table 1.

Table 2: Pakistan point climate classification based on Köppen climate classification system

S. No	Köppen climate classification system	Description	Percent (%) of data sites used
1	BWhw	Desert hot with dry winter	30.5
2	BWhs	Desert hot with dry summer	11.9
3	BShw	Steppe hot with dry winter	23.7
4	BSh	Steppe hot with fully humid	10.2
5	BSks	Steppe cold with dry summer	01.7
6	Csa	Temperate cold with dry summer	05.1

7	Cfa	Temperate cold with fully humid	10.2
8	Cwb	Warm temperate without dry season/fully humid	01.7
9	Dsa	Cold snowy with dry and hot summer	01.7
10	Dsb	Cold snowy with dry and warm summer	01.7
11	Dwa	Cold snowy with dry winter and hot summer	01.7

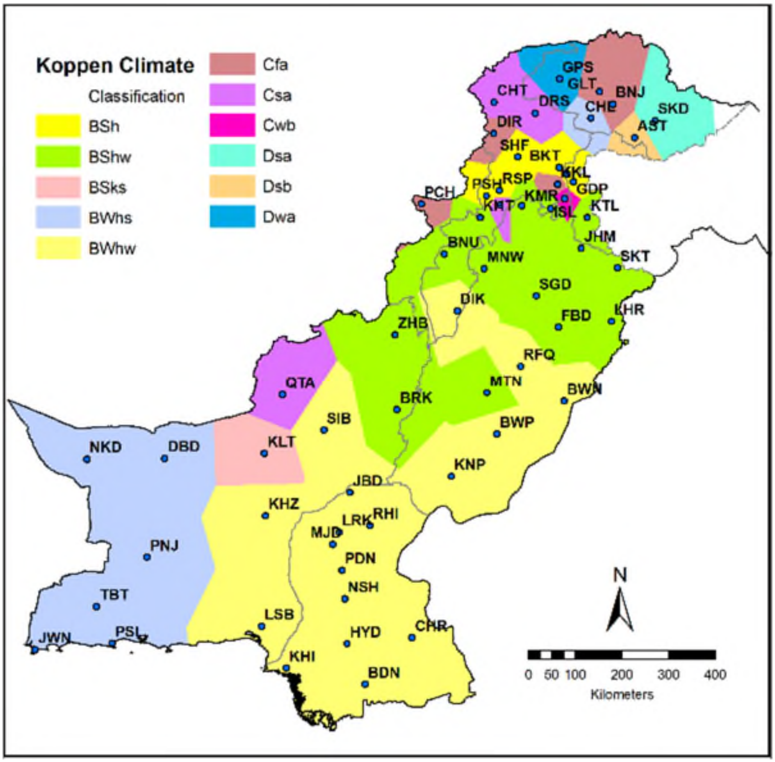


Fig. 13: Pakistan climate classification map based on Köppen climate classification system showing spatial distribution of 12 Köppen climate classes with dominant one being the BWhw followed by the rest.

CONCLUSION AND RECOMMENDATION

The climate of an area is best characterized by the temperature and precipitation. The GIS based spatial distributions of Pakistan annual and seasonal temperatures and rainfalls depict the sub-regional distribution of climate parameters across Pakistan. The work was carried out by analyzing 30-year climatic normal data (from 1981 to 2010) to classify the patterns of climate parameters across Pakistan and find out the climate classes at each data station using the Köppen climate scheme. Based on results, we conclude that there is high variability in temperature and precipitation (annually as well as seasonal). It is quite contrast in south and north of Pakistan, which is actually the sole cause of the climate differences between north and south of Pakistan. The Köppen climate classifications at 59 meteorological stations demonstrate that with total 11 number of Köppen climate classes found the three-fourth area falls under arid to semi-arid climate, a handful falling under the temperate class followed by a dry cold climate in the north observed at a few stations. The results can further be refined by using the data over longer periods of 50-year, 60, or 90years.

ACKNOWLEDGEMENT

The authors are extremely thankful to the Pakistan Meteorological Department for providing the data used in this work.

REFERENCES

ArcGIS Resources. (2014a) An overview of Generalization Toolset. In ArcGIS Help 10.1, Esri, Redlands, CA, URL: http://resources.arcgis.com/en/help/main /10.2/index.html#//009z00000033000000 Last visited 02/05/2015

ArcGIS Resources. (2014b) Renderers used to display the raster data, Esri, Redlands, CA, URL: http://resources.arcgis.com/en/help/main/10.1 /index.html#//009t0000006r000000 Last visited 02/05/2015

ArcGIS Resources. (2015a) What is Production Mapping? (Production Mapping). In ArcGIS Help 10.1, Esri, Redlands, CA, URL: http://resources.arcgis.com /en/help/main/10.2/index.html#//010300000214000000 Last visited 02/05/2015

ArcGIS Resources.(2015b) Extending your map with spatial analysis. In ArcGIS Help 10.1, Esri, Redlands, CA, URL: http://resources.arcgis.com/en/ communities/analysis/017z00000015000000.htm Last visited 02/05/2015

Arif Zubair, A. Farhan Khan and Muhammad Umer Khan, 2013: Elements of Monsoon Circulation and its Behaviour Impact over Pakistan; European Academy Research, Vol. I (5).

A. Irmak, P. K. Ranade, D. Marx, S. Irmak, K. G. Hubbard, G. E. Meyer, D. L. Martin (2010): Spatial Interpolation of Climate Variables in Nebraska, Transactions of the ASABE. 53(6): 1759-1771.

Austin Miller, 1949: Climatology, London.

Anwar, M.M. (1993): A geography of Pakistan, Book-World Islamabad andLahore, pp. 20-60.

Blair, T.A. (1942): Climatology, general and regional, Prentice-Hall, INC.,New York, pp. 484.

Burgos, J.J. (1958): Agroclimatic classifications and representations: report of the applications value of climatic and agroclimatic classification for agricultural purposes;Comission for Agricultural Meteorology, WMO, Varsovia.

B. J. Garnier, 1951: Thornthwaite's New System of Climatic Classification inIts Application to New Zealand; Trans-action of the Royal Society of New Zealand, Vol. 79, pp. 87-103.

Climate Data Processing Centre, Pakistan Meteorological Department, 2013: The Climatic Normals of Pakistan,1961-90 and 1981-2010
C. W. Thornthwaite, 1948: An Approach towards a Rational ClimateClassification, Geographical Review, Vol. 38, No. 1, pp. 55-94.
R. da Cunha, A. R., & Schöffel, E. R. (2011): The Evapotranspiration in Climate Classification; INTECH Open Access Publisher.
De Beurs, K., Stein, A., & White, J. W. (1999). Interpolation techniques for climate variables (p. 26), Mexico, DF: CIMMYT.
Doerr, A.H. (1962). Thornthwaite's original climatic classification andOklahoma's climate,
Proceedings of the Oklahoma Academy of Science Vol. 42 (1), pp. 231-235.
Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., & Jarvis, A. (2005): Very highresolution interpolated climate surfaces for global land areas; International journal of climatology, 25(15), pp.1965-1978.
J. F. Griffiths, “Applied Climatology,” 2nd Edition, Ox-ford University Press, London, 1978, p. 136.
Kazi S. Ahmad, E. T. Dean, A. Haye, Mrs. R. M. Durrani, K. U. Kureishy and
Afzal Jaffri, 1951: Pakistan Geographical Review, Vol. VI, No. 1.
Khan J. A., 1993: The Climate of Pakistan, Rehber Publisher, Karachi, Pakistan
Köppen W., 1936: “Das Geographisca System der Klimate,” In: W. Köppen and G.
C. Geiger, Eds., Handbuch derli-matologie, Gebr, Borntraeger, pp. 1-44.
Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006): World map of the Köppen-
Geiger climate classification updated; Meteorologische Zeitschrift,15(3), PP.259-263.
Maida Zahid and Ghulam Rasul, 2011: Thermal Classification of Pakistan;Atmospheric and Climate Sciences, Vol. 1, pp. 206-213.
Martyn D, 1992: Climate of the world; Elsevier first edition, pp. 436
Miller, A.A. (1959). Climatology, Mehtewn London and E.P. Dulton and Co.INC., New York, pp. 313.
Nasrullah, K. (1968). Climate of West Pakistan according to Thornthwaite system of classification of climates, PGR Vol. 23 (No. 1): 12-25.Pakistan Geographical Review, 1962, Vol.17 No. 1(1).
Peel, Murray C., Brian L. Finlayson, and Thomas A. McMahon, 2007: "Updated world map of the Köppen-Geiger climate classification." Hydrology and earth system sciences discussions 4(2). Pp. 439-473.
Q. Z. Chaudhary and G. Rasul, 2004: Agro-Climatic Classification ofPakistan, Science Vision, Vol. 9, No. 1-4, pp. 59-66.
Rodman E. Snead,1968: Weather patterns in Southern West Pakistan, Archiv für Meteorologie, Geophysik und Bioklimatologie Serie B, Vol. 16 (4), Page 316.
Shamshad K.M., (1986): The Meteorology of Pakistan:Climate and Weather of Pakistan, Royal Book Company Karachi Pakistan, pp. 313.

Sluiter, R. (2008). Interpolation methods for climate data: literature review. De Bilt, Royal Netherlands Meteorological Institute(KNMI).

Steven K. Walterscheid, 2009: Climate Classification for the Earth's Oceanic Areas using the Köppen System; Masters Dissertation, Kansas State University, Manhattan Kansas

Stern Harvey, Graham De Hoedt, and Jeneanne Ernst. 2000: "Objective classification of Australian climates." Australian Meteorological Magazine 49(2) pp.87-96.

S. U. Khan, M. Hassan, F. K. Khan and A. Bari, 2010: “Climate Classificationof Pakistan,” BALWOIS, Ohrid, pp. 1-47.

Walterscheid, Steven K., 2011: Climate classification for the earth's oceanic areas using the Köppen System. Diss. Kansas State University

WMO - World Meteorological Organization No. 100 (2009): Guide to climatological practices, 3rd ed., pp. 180, URL://www.wmo.int/pages/prog/wcp/ccl/guide/guide_climat_practices.html.