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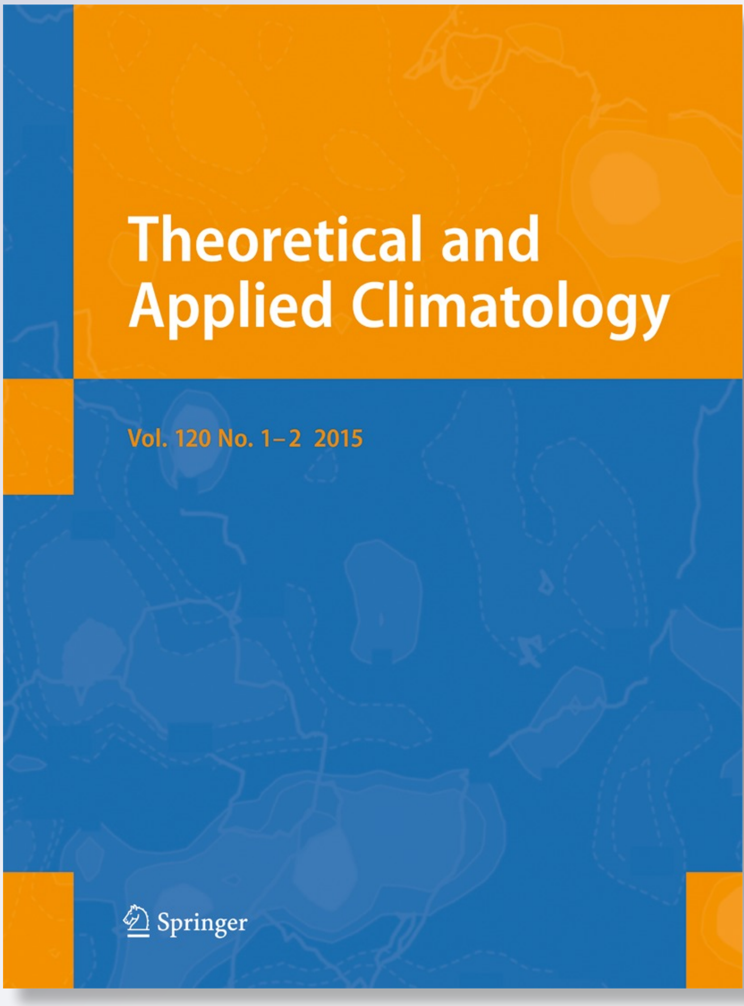

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ORIGINAL PAPER

Statistical downscaling and future scenario generation of temperatures for Pakistan Region

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Abstract Finer climate change information on spatial scale is required for impact studies than that presently provided by global or regional climate models. It is especially true for regions like South Asia with complex topography, coastal or island locations, and the areas of highly heterogeneous land-cover. To deal with the situation, an inexpensive method (statistical downscaling) has been adopted. Statistical DownScaling Model (SDSM) employed for downscaling of daily minimum and maximum temperature data of 44 national stations for base time (1961–1990) and then the future scenarios generated up to 2099. Observed as well as Predictors (product of National Oceanic and Atmospheric Administration) data were calibrated and tested on individual/multiple basis through linear regression. Future scenario was generated based on HadCM3 daily data for A2 and B2 story lines. The downscaled data has been tested, and it has shown a relatively strong relationship with the observed in comparison to ECHAM5 data. Generally, the southern half of the country is considered vulnerable in terms of increasing temperatures, but the results of this study projects that in future, the northern belt in particular would have a possible threat of increasing tendency in air temperature. Especially, the northern areas (hosting the third largest ice reserves after the Polar Regions), an important feeding source for Indus River, are projected to be vulnerable in terms of increasing temperatures. Consequently, not only the hydro-agricultural sector but also the environmental conditions in the area may be at risk, in future.

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1 Introduction

Pakistan is located in South Asia at 24–37ºN latitude and 60–76ºE longitude. It has a variety in terms of geography like the coastal belt, the eastern plains, and sub-mountainous to mountainous regions in the west and north like Himalaya-Karakorum-Hindukush (see Fig. 1a). According to Pakistan's agroclimatic classification (Chaudhry and Rasul 2004), two-third of Pakistan lies in the semiarid to arid zones. Accordingly, the majority of the people depend on arid and semiarid areas to support their livelihood through agropastoral activities. The northern parts of the country (Himalaya-Karakorum-Hindukush) cover the third largest ice reserves after the Polar Regions. They block northerly winds in winter associated with cold surges from north (Siberian winds). This mountainous region is prone to the monsoon precipitation which is the main resource of water. In addition, its glacier melt provide waters during the hot seasons, which remained available in the rivers catchments in needy times (Rasul et al. 2008).

According to the IPCC Fourth Assessment Report (IPCC 2007), warming of the climate system has been detected in terms of changes in atmospheric and surface temperatures. Attribution studies have identified anthropogenic causes to these changes. (Farooqi et al. 2005). The 2002–2011 ten-year average of 0.46 °C above the 1961–1990 mean matched 2001–2010 as the world's warmest ten-year period on record. This was 0.21 °C warmer than the warmest ten-year period of the twentieth century, 1991–2000. In turn, 1991–2000 was

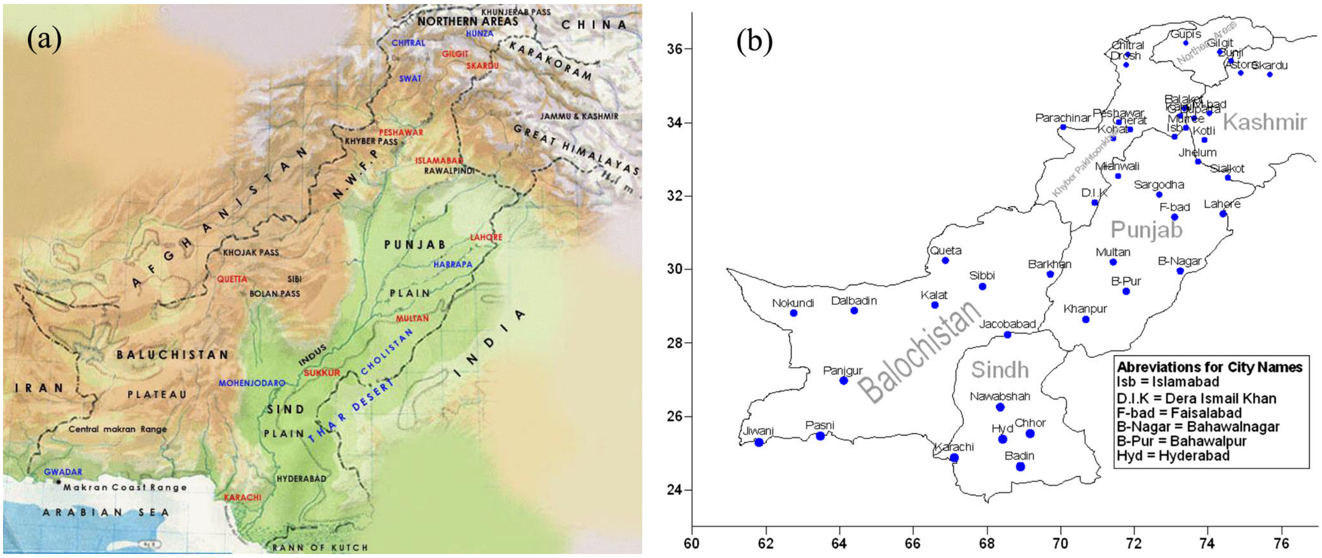

Fig. 1 **a** Topographic map of Pakistan (Source: www.virtualtourist.com). **b** Meteorological stations in different provinces of Pakistan used for data acquisition

clearly warmer than previous decades, consistent with a long-term warming trend (WMO 2011). The impact of climate change in terms of global warming is a bitter reality especially for an agrarian country (Rasul and Kazmi 2011). Mean annual temperature of Pakistan has been increased by 0.57 °C from 1901 to 2000, and it has been raised by 0.47 °C in the period from 1960 to 2007. Maximum and minimum temperatures have increased by 0.78 and 0.48 °C, respectively, during the period 1960–2007. Global temperature is likely to increase by 1.8–4.0 °C by the end of this century (Chaudhry et al. 2009). Observed extreme temperatures fall as low as −26 °C in the northern mountainous parts of Pakistan and go as high as 52 °C over central arid plains (Srinivas and Kumar 2006).

There exists a strong confidence that the recent regional rising tendency in temperature has discernable impacts on precipitation, evaporation, stream flow, runoff, and other elements of the hydrological cycle (Elshamy et al. 2006). In the global warming scenario, thermal regime of the Indus Deltaic plains has also been enhancing. Also, crop water requirement is a function of temperature, radiation intensity, cloud cover, air humidity, and wind speed, among them temperature is the major player (Rasul and Kazmi 2013). The lengthening of the growing season and simultaneous shortening of the time of plant growth to maturity due to rising temperatures could be beneficial in the mountainous areas. This is because the winter crops would mature in the optimal period of time, which impose positive impacts on crops yield (Hussain and Mudasser 2007). Not only rainfall but air temperature is also proved to be significant for healthy growth of agricultural crops especially in rainfed areas (Kazmi and Rasul 2012).

Pakistan's climatic constraints along with inadequate supply of water for agriculture use, remains a hostile reality. Reliable information in terms of atmospheric and hydrological parameters is required for a more realistic and comprehensive agrometeorological research throughout Pakistan. Therefore, we cannot rely on GCM outputs only, but have produce point to point data information in order to obtain local climate projections. To ensure a better environmental planning strategy, future scenario data in terms of temperature and precipitation are significant.

To assess the long-term impacts of climate change, Global Climate Models (GCMs) are developed having course resolution of about 300 km. However, for Pakistan's topography, this resolution may not be suited. Although it can be employed for a number of impact-assessment studies related to the risk managements of drought or flooding in large catchments, but for the research like crop modeling, we need point to point inputs in high resolution (Murphy 1999). Difficulties remained in reliably simulating and attributing observed temperature changes at smaller scales. On these local scales, natural climate variability is relatively large, making it difficult to distinguish changes which are expected due to external forcing (IPCC 2007). Particularly, it may be hard to investigate the expected variation for smaller regions or specific locations if the variables are simulated at a course resolution of 100–200 km (Guo, et al. 2012).

Downscaling has proved to be a better option to utilize the atmospheric circulation arrays to the surface-based weather elements (air temperature, precipitation, etc.) in climate impact studies as well as for prediction of regional climate.

Downscaling has mainly two modes; dynamical and statistical (Christensen et al. 2007). In practice, the choice of downscaling technique is also governed by the availability of archived observational and GCM data because both are needed to produce future climate scenarios (Wilby and Dawson 2007). The method of statistical downscaling can be preferred to dynamical downscaling approaches for several practical advantages. Especially in the studies when low-cost, rapid assessments of localized climate change impacts are required; statistical downscaling represents the more promising picture (Wilby and Dawson 2007). Also, in comparison to other downscaling methods, the statistical method is friendlier to use and has the ability to provide local or station information (Wilby et al. 2002). Statistical downscaling is based on the view that the regional climate is conditioned by two factors: the large scale climatic state, and regional/local physiographic features (e.g., topography, land-sea distribution and land use).

Recently, many research works have been conducted incorporating statistical downscaling methodologies with application of different schemes like multiple linear regression (Ramırez et al. 2006; Fan and Wang 2009; Lang and Wang 2010; Liu et al. 2011) and singular value decomposition (SVD) (Bretherton et al. 1992; Widmann and Bretherton 2003).In this study of downscaling, past and future temperature data in Pakistan is generated by incorporating single as well as multiple linear regressions. The reliability of the model SDSM has already been tested in many climate impact studies in different parts of the world, such as Canada and China, etc. (Gachon and Dibike 2007; Zhao and Xu 2008).

SDSM provides future *scenario generation* for two story lines, A2 and B2. Considering the fact that the A2 scenario is more realistic (according to the present global conditions) than the B2 scenario, this study mainly take into account the A2 scenario. According to SRES (IPCC, 4AR), "The primary purpose of developing multiple scenario families was to explore the uncertainties behind potential trends in global development and GHG emissions, as well as the key drivers that influence these". A brief description of both story lines is given here.

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological changes more fragmented and slower than other storylines.

Table 1 Detail of stations take into account for temperatures data (north to south)

Sr. #	Station name	Latitude	Longitude	Sr. #	Station name	Latitude	Longitude
1	Gupis	36.17	73.40	23	Dera Ismail Khan	31.82	70.92
2	Gilgit	35.92	74.33	24	Lahore	31.50	74.40
3	Chitral	35.85	71.83	25	Faisalabad	31.43	73.10
4	Bunji	35.67	74.63	26	Quetta	30.25	66.88
5	Drosh	35.57	71.78	27	Multan	30.20	71.43
6	Astore	35.37	74.90	28	Bahawalnagar	29.95	73.25
7	Skardu	35.30	75.68	29	Barkhan	29.88	69.72
8	Balakot	34.38	73.35	30	Sibbi	29.55	67.88
9	Muzaffarabad	34.37	73.48	31	Bahawalpur	29.40	71.78
10	Garhi Dupatta	34.22	73.62	32	Kalat	29.03	66.58
11	Kakul	34.18	73.25	33	Dalbandin	28.88	64.40
12	Peshawar	34.02	71.58	34	Nokkundi	28.82	62.75
13	Murree	33.92	73.38	35	Khanpur	28.65	70.68
14	Parachinar	33.87	70.08	36	Jacobabad	28.25	68.47
15	Cherat	33.82	71.88	37	Panjgur	26.97	64.10
16	Islamabad	33.62	73.10	38	Nawabshah	26.25	68.37
17	Kohat	33.57	71.43	39	Chhor	25.52	69.78
18	Kotli	33.52	73.90	40	Hyderabad	25.38	68.42
19	Jhelum	32.93	73.72	41	Jiwani	25.37	61.80
20	Mianwali	32.55	71.55	42	Pasni	25.37	63.48
21	Sialkot	32.50	74.53	43	Karachi	24.90	67.13
22	Sargodha	32.05	72.67	44	Badin	24.63	68.90

Table 2 Daily variables held in the UKSDSM data archive (denoted by ×)

Daily variable	Code	NCEP 1961–2000	HadCM3 SRES 1961–2099
[a]Precipitation (mm)	prec		×
[a]Maximum temperature (ºK)	tmax		×
[a]Minimum temperature (ºK)	tmin		×
Mean temperature	temp	×	×
Mean sea level pressure	mslp	×	×
500 hPa geopotential height	p500	×	×
850 hPa geopotential height	p850	×	×
Near surface relative humidity	rhum	×	×
Relative humidity at 500 hPa height	r500	×	×
Relative humidity at 850 hPa height	r850	×	×
Near surface specific humidity	shum	×	×
[b]Geostrophic airflow velocity	**_f	×	×
[b]Vorticity	**_z	×	×
[b]Zonal velocity component	**_u	×	×
[b]Meridional velocity component	**_v	×	×
[a, b]Wind direction	**th	×	×
[b]Divergence	**zh	×	×

[a] Variables that have not been normalized and are provided for comparative purposes

[b] Secondary (airflow) variables derived from pressure fields (surface, 500 and 850 hPa)

The B2 storyline and scenario family describes a world in which the attention is toward the local solutions for economic, social, and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2 along with intermediate level of economic development. This scenario line is also oriented toward environmental protection and social equity.

1.1 Motive and objectives

Pakistan, like most of the developing world, is facing the challenges of land degradation and desertification, which are causing hydro-environmental problems, including soil erosion, loss of soil fertility, flash flooding, salinity, and deforestation as well as the consequent losses of biodiversity and carbon sequestration (Economic Survey 2008). Climate change has been imposed another serious threat to the environmental conditions in the area, as most likely the land degradation and desertification may enhance besides the ecological problems.

Pakistan's climatic constraints along with inadequate supply of water for agriculture use throughout the cropping season remain a threatening reality. Reliable information in terms of atmospheric and hydrological parameters is needed for more realistic and comprehensive agrometeorological research in the region especially in future perspective. Therefore, we cannot rely on GCM outputs only, but have to incorporate the best available options such as statistical downscaling to obtain local climate projections. To ensure a better environmental planning strategy, future scenario data in terms of temperature and precipitation is essential.

2 Data and methodology

2.1 Data

- In SDSM, to downscale any parameter daily data is required for the particular locality for the period 1961–1990. To meet the criteria, the data for daily maximum and minimum air temperature for 44 meteorological stations (shown in Fig. 1 b and Table 1) of Pakistan is utilized (as provided by Pakistan Meteorological Department).
- The predictors data for different parameters was taken from National Centre for Environmental Prediction (NCEP) for the period 1961–2000, detailed below in Table 2 (Wilby and Dawson 2007).
- For scenario generation, output data of the GCM; HadCM3 was employed for the period 1961–2099, detailed below in Table 2 (Wilby and Dawson 2007).
- The data of NCEP and HadCM3 is available online on the following address; http://www.cics.uvic.ca/scenarios/index.cgi?Scenarios

2.2 Methodology

Statistical downscaling involves developing quantitative relationships between large-scale atmospheric variables (predictors) and local surface variables (predictands). The most common form has the predictand as a function of the predictor(s), but other types of relationships, such as between predictors and the statistical distribution parameters of the predictands or between predictors and frequencies of extremes of the predictand have also been used. Shortly, the large-scale output of a GCM simulation is fed into a statistical model (as SDSM) to estimate the corresponding local and regional climate characteristics.

The SDSM software performs the task of statistical downscaling of daily weather series through seven discrete processes;

1) quality control and data transformation
2) screening of predictor variables
3) model calibration
4) weather generation (observed predictors)
5) statistical analyses
6) graphing model output
7) scenario generation (climate model predictors)

In this study, daily observed minimum and maximum temperature data for the period 1961–1990 for 44 meteorological stations of Pakistan was taken as a predictand. Observed as well as Predictors (NCEP product) were calibrated and tested on individual/multiple basis through linear regression. The model produced the past data for the specified period, parameter, and location. Then, a comparison was made between the observed and modeled data through linear regression. Muhammad (2000) stated that in scientific studies a correlation of 0.50 and above may be considered reliable. But in this study for more reliable projection of air temperature, the model had been further employed for scenario generation after getting a correlation coefficient above ±0.70, for past time series. Scenarios for A2 and B2 storylines are generated for the specified locations and for the period 1961–2099. Wilby et al. 2002 stated that advantage of the stochastic technique in generating future climate scenario is that it can exactly reproduce observed climate statistics as well as supports in producing reliable ensembles. For that reason, the same technique is applied in the present study and as per default setting of the model; the scenario data for 20 ensembles was generated.

This daily temperature data for A2 and B2 scenario was converted to yearly basis primarily and then the data for base line (1971–2000) was taken as standard or normal for comparison purpose. The reason behind this approach was that the climatic normal for the real time data and the modeled data need not be similar. Although some extensive analysis is required to be initiated for the outcome products, but presently, the decadal anomaly was extracted and it has been discussed in the following sections. The motive behind was that initially at decadal level, deviation patterns in air temperature may be explored.

3 Results and discussion

3.1 Downscaling results

The model was operated for all available stations (44) of Pakistan. But to be brief, individual results (downscaled output for minimum and maximum temperatures) for Dera Ismail Khan (D.I.K), Karachi, Multan, and Faisalabad only are being discussed whereas graphics for first three locations are shown. The mentioned stations have entirely different geographical features as well as have importance in the perspective of agricultural products, industry, etc., for the country.

For DIK (Fig. 2a, b), simulated data shows an outstanding correlation with the observed data (Fig. 2a, b). The coefficient (R^2) for both cases is over 0.8 for the mean ensembles which indicates a strong correlation. The comparative testing for some individual ensembles has also been made and the correlation found good. Although it requires some more comprehensive analytic studies, but initially, it can be concluded that if the data projected

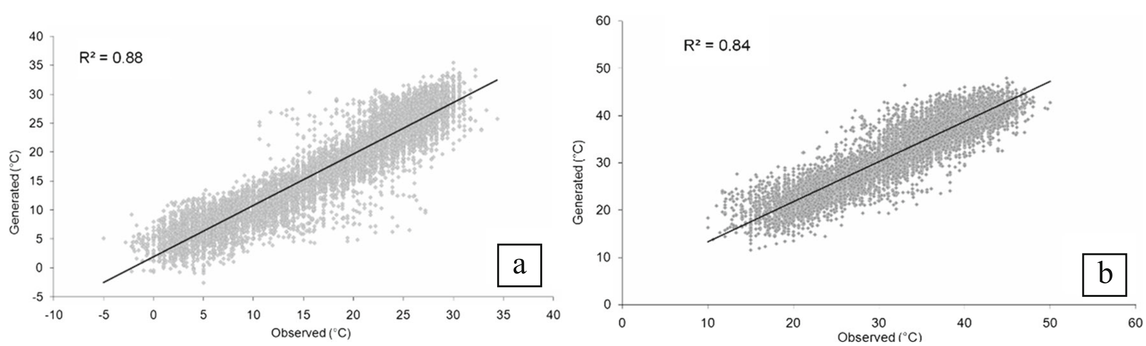

Fig. 2 Scatter plot for correlation between observed and generated data for daily minimum (**a**) and maximum temperature (**b**) for D.I.K (1961–1990)

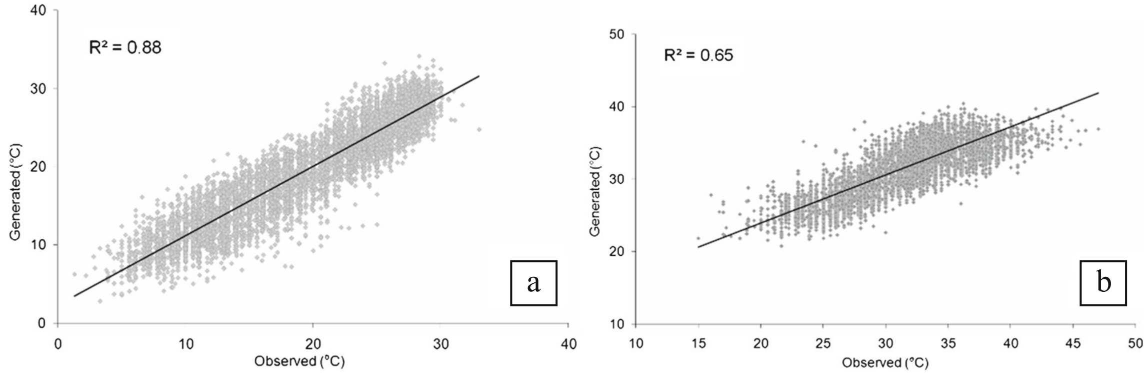

Fig. 3 Scatter plot for correlation between observed and generated data for daily minimum (**a**) and maximum temperature (**b**) for Karachi (1961–1990)

for the base period (i.e., 1961–1990) is very close to the observed data then future projections by the model may also be considered reliable.

For Karachi (Fig. 3a, b), it is observed that for maximum temperature, the correlation between observed and generated data (0.65) is not as good as for DIK. Whereas for minimum temperature, it remains above optimum level, that is 0.88. As SDSM utilizes the predictors data based on grid boxes each measuring 2.5° latitude by 3.75° longitude, corresponding to the grid coordinate system of the Hadley Centre's coupled ocean–atmosphere GCMs (Wilby and Dawson 2007). Karachi is a coastal city for which some of the area of its relevant grid box comprises on Arabian Sea and rest on land. Besides, generally sea breeze (southwesterly) blows here throughout the year except for about 40–50 days during winter season when northerly wind prevails. These are the possible reasons for failure of SDSM in producing the optimum results in terms of maximum temperature for this particular location.

For Multan (Fig. 4a, b), the observed and generated data showed a very strong correlation with coefficient value around 0.90, an indicator of promising result. In case of Faisalabad (figures not included), the correlation coefficient for minimum as well as the maximum temperature is 0.85, depicting a strong relationship. These results show that the relevant predictors have strong influence on the local climate and that the generated scenarios can be considered as reliable.

It is important to note that any single model cannot portray the very true and reliable picture of the future climate, especially for such a huge time period and for a country like Pakistan with diversified geography. But the results were required to be compared with the output of some other recommended models as well. Kazmi et al. 2014 stated that if statistical downscaling model like SDSM may produce some improved results for past time temperature against a recommended source (like ECHAM5), then it may be considered reliable for future data as well. Therefore, for comparison, the daily downscaled data for individual locations has been tested against ECHAM5 to investigate the relevance with the observed data. It is explored that for the whole country, a relatively strong relationship exists between the downscaled and observed data in comparison to ECHAM5 product versus observed. Finally, the model was applied for future scenario generation.

3.2 Projected minimum temperatures

The scenario outcome has shown that for both the minimum and maximum temperature, increasing trends are expected.

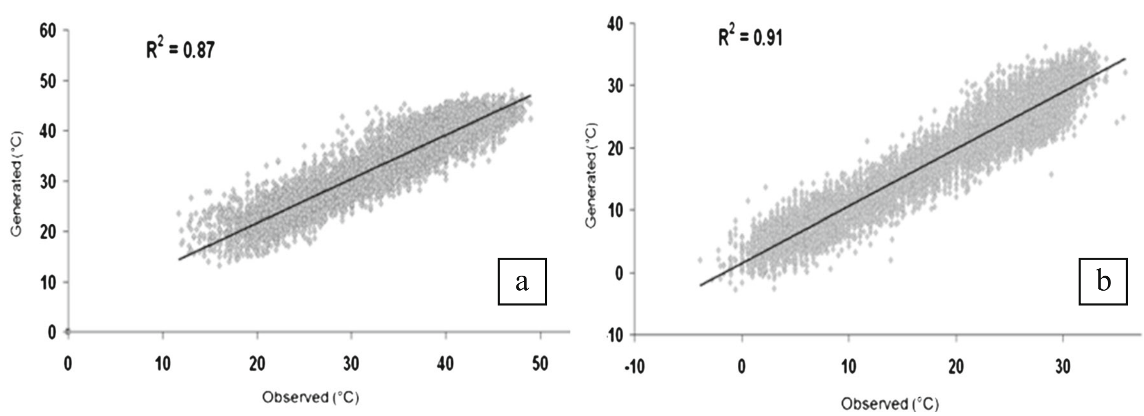

Fig. 4 Scatter plot for correlation between observed and generated data for daily minimum (**a**) and maximum temperature (**b**) for Multan (1961–1990)

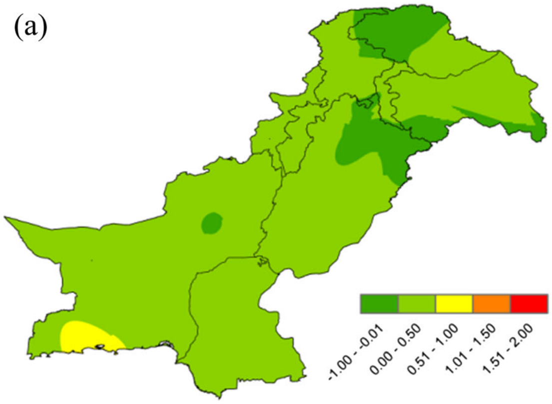

Fig. 5 Decadal anomaly for minimum temperature in A2 (**a**) and B2 scenario (**b**), 2001–2010

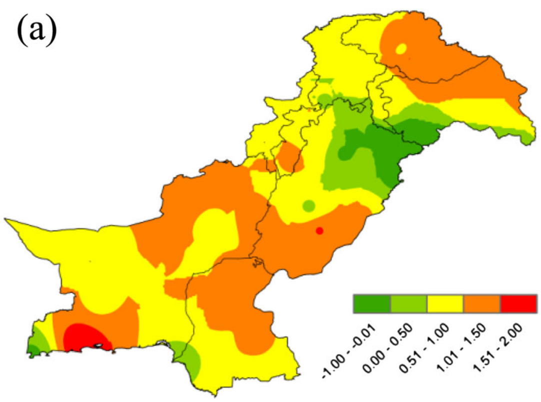

Fig. 6 Decadal anomaly for minimum temperature in A2 (**a**) and B2 scenario (**b**), 2011–20

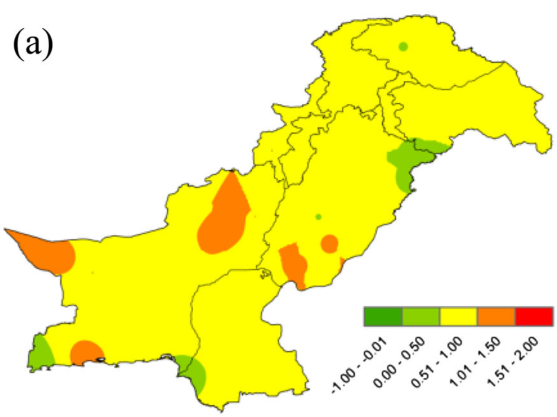

Fig. 7 Decadal anomaly for minimum temperature in A2 (**a**) and B2 scenario (**b**), 2021–30

The areas, mainly located in lower Sindh and lower Balochistan provinces show decreasing trends in few decades like 2031–2040 and 2051–2060. While in the upper half of the country, a decreasing trend in the decade 1941–1950 is projected. Results for first three decades of twenty-first century are being discussed here with five classes based legend to show the projected minimum and maximum temperatures.

It can be seen in Fig. 5a (A2 scenario) that during the first decade of the twenty-first century, minimum temperature may be expected to have no or a slight increase for most parts of the country. However, in few parts located in the NA and northeast Punjab province, it is expected to be a little lower. Besides, a small patch located in the southwest of the country near Arabian Sea may experience an increment of 0.5–1.0 °C. On the other hand, with the B2 scenario as well (Fig. 5b), most of the areas may be expected to have no or a slight increase for most parts of the country except in few areas in the north and southwest where 0.5–1.0 °C increase is expected.

Under the A2 scenario for the decade 2011–2020 (Fig. 6a), most the areas are expected to have light to moderate increase in terms of minimum temperature. Especially, few areas in NA and southern half may experience a considerable increase of 1.01–1.50 °C during this decade. Also, a small area near Arabian Sea in the southwest may have a rise of nearly 2 °C. For this decade, the results for the B2 scenario (Fig. 6b) are quite different than A2, as minimum temperature is expected to be normal or increase slightly in the northern and a bit higher in the southern half of the country. However, few small patches in the south are projected to have the same mild increasing trend as expected in the northern half.

The projections of minimum temperature for 2021–2030 under the A2 scenario show a rise of 0.50–1.00 °C in most parts of the country with a little exception in few locations in the eastern and southern Punjab and northern and southern Balochistan provinces (Fig. 7a). The exceptional areas are expected to have more increasing temperatures in this decade. Under B2 scenario, the results are quite similar to the A2, as most of the country may experience same increase in terms of minimum temperatures during the decade (Fig. 7b).

Overall, it has been observed that the whole country would face increasing trends in night temperatures especially the areas in the central-southern regions and occasionally NA. These are the areas (central-southern regions) already facing hot and dry weather conditions so the conditions may get even worse in future. Besides, NA hosts the glaciers, a major source of river Indus flowing from north to south of the country.

3.3 Projected maximum temperatures

For maximum or day temperatures, during the first decade of the century under A2 scenario (Fig. 8a), most of the country may experience no or a slightly increasing trend. However, few areas including some patches from southeastern Kashmir and northeastern Punjab are expected to have negative trend. Besides, few parts in southern Sindh and Balochistan may experience more rise in terms of minimum temperatures. Under B2 scenario, higher increasing trend (0.51–1.00 °C) is expected for night temperatures in the north most regions and no or slightly increasing trend in rest of the country (Fig. 8b).

The decadal anomaly for maximum temperature in the second decade is projecting more increasing trend particularly for NA and most parts of southwestern province Balochistan (Fig. 9a, b). In B2 scenario, some additional area may experience this increasing trend. However, an area in the northeastern Punjab and southeastern Kashmir is expected to have negative trend during the decade.

Under A2 scenario, the maximum temperatures in the third decade are projected to be even higher from the previous decades in most parts of the country except an area in the northeastern Punjab and southeastern Kashmir is expected to have negative trend (Fig. 10a). Particularly, NA and few areas located in the north and west of the country have an increase of 1–2 °C for day temperatures. On the other hand, B2

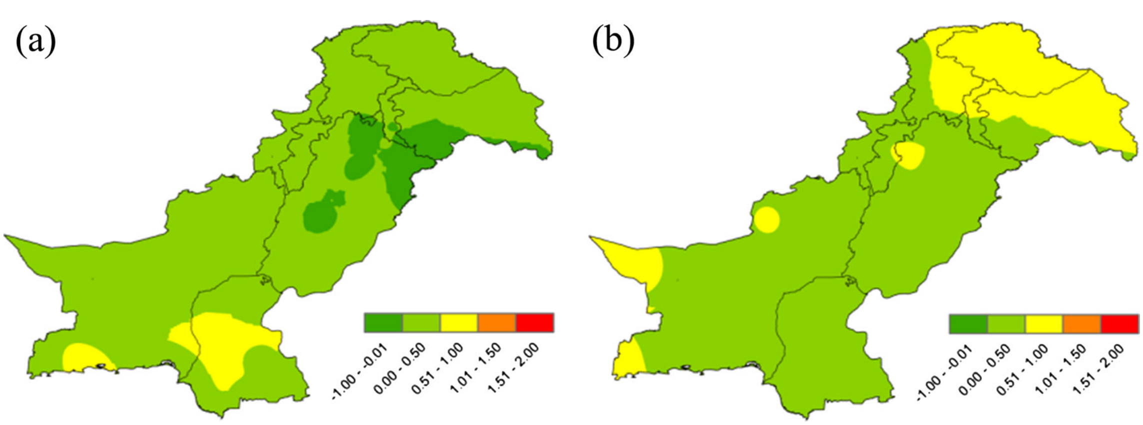

Fig. 8 Decadal anomaly for maximum temperature in A2 (**a**) and B2 scenario (**b**), 2001–10

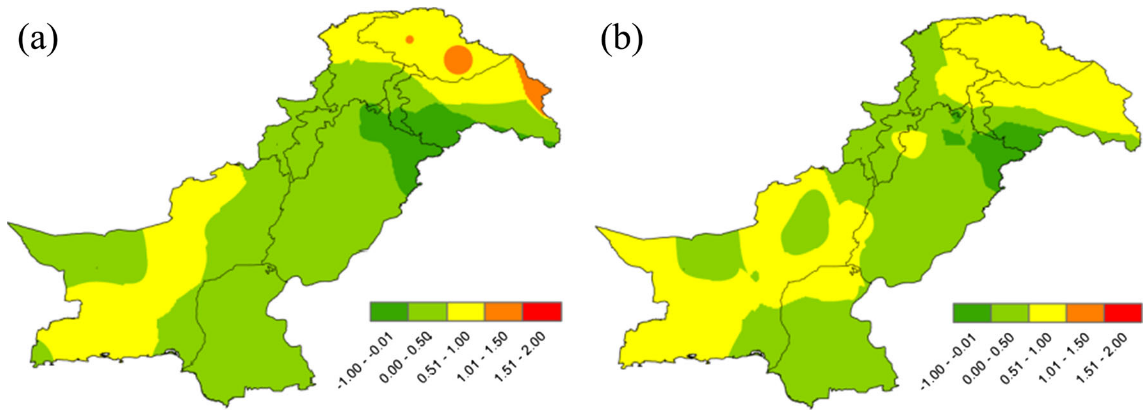

Fig. 9 Decadal anomaly for maximum temperature in A2 (**a**) and B2 scenario (**b**), 2011–20

storyline depicts somewhat mild conditions for maximum temperature during 2021–2030 as compare to A2 (Fig. 10b).

4 Conclusion and recommendations

It is important to note that a single model cannot portray reliable climate conditions, especially for long time periods and for a country like Pakistan with diverse topography. For the core reason, downscaled data produced by SDSM and output from a distinguished source ECHAM5 were tested against the observed data set. It is revealed that a relatively strong relationship exists between SDSM output verses the observed. After the comparative testing made, the SDSM employed for future scenario generation. The results show that the temperatures are increasing considerably throughout Pakistan particularly in the northern as well as in southwest of the country in the three decades (2001–2030). Although this increase in temperature may be beneficial for the local agriculture in northern areas of the country, but the associated impacts on weather pattern would threaten the sustainable development in the downstream regions.

Bhutiyani et al. (2007) conclude that the northwestern Himalayan region has "warmed" significantly during the last century at a higher rate than the global average. Chaudhry et al. (2009) have shown a non-significant increasing trend for annual mean temperature over the mountainous areas of the Upper Indus Basin in Pakistan. On the basis of long-term data sets since the late nineteenth century, analyses of the temperature data show significant increasing trends in annual temperature in the northwestern Himalayan region (Bhutiyani et al. 2009). IPCC, 4AR; the warming is likely to be well above the global mean in central Asia, the Tibetan Plateau, and northern Asia, above the global mean in east and south Asia, and similar to the global mean in Southeast Asia. The results of this research agree with the findings by the mentioned studies as well as the recent document published by WMO for global climate in 2011. The projected increase in minimum and maximum temperatures underline the general assumption that this part of Asia as well is very likely to experience warmer climate conditions in the twenty-first century.

This effort of future scenario generation for temperature conditions will provide useful information for a research platform of meteorological sciences not only in Pakistan but South Asia as a whole. The results obtained in this study make clear that future increase in temperature may not be even

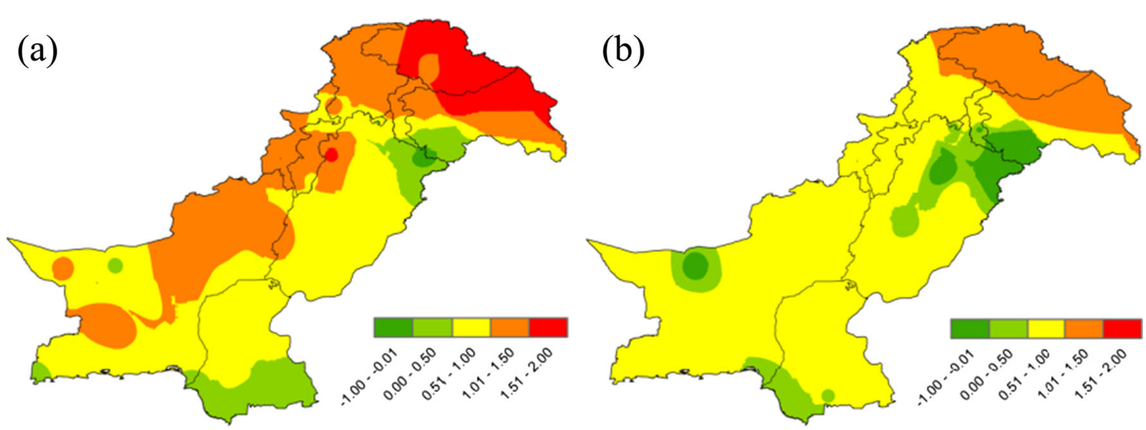

Fig. 10 Decadal anomaly for maximum temperature in A2 (**a**) and B2 scenario (**b**), for 2021–30

throughout the region. In further studies, the results need to be equated with outputs of other models for a comprehensive comparison and to achieve higher reliabilities in terms of future projections.

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