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Global warming and temperature changes for Saudi Arabia

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Key words: EdGCM, Downscaling, QuickSurf Modeling, Isohyets, GHG (Greenhouse Gases).

Abstract

This study aims at forecasting changes in temperature of the Saudi Arabia for the next hundred years. Temperature data of 38 years for thirteen stations in Saudi Arabia have been used as basis for this study. A Global Climate Model (GCM) has been applied to simulate temperatures by the end of the year 2100 for two scenarios namely a double carbon dioxide ($2CO_2$) and a Modern_Predicted Sea Surface Temperature (MPSST) scenario. Temperature isotherms models, for twelve grids surrounding Saudi Arabia, have been prepared for annual and seasonal averages of each of the two scenarios by using the software "AutoCAD2000i". Seasonal and annual averages have been extracted from these cited climate statistics and changes found by calculating the difference of the $2CO_2$ and MPSST values. It is found that the order (hottest remain the hottest and vice versa) of severity of the station temperatures will remain the same as being experienced for the present time. The overall change in land surface temperature for Saudi Arabia is a 4.72°C increase.

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Introduction

The impact study of climate change on water resources is today's hot topic (Hua Chen *et al.*, 2012). Climate change and Global warming are becoming threat for many parts of the world and affect the water resources by increasing the rates of evaporation and decreasing run-off - a function of precipitation (Roudier *et al.,* 2014; Abdul *et al.,* 2013; Huisjes 2006). The variables like temperature and precipitation are the most important measures which indicate the signs of climate change (Mahdi *et al.*, 2015, Muhammad *et al.*, 2015). Global warming is basically attributed to the increases of mixing ratio of Green House Gases (GHGs) like CO_2, CH_4 and N_2O (Ishtiaq *et al.,* 2010; Ogunlade 2008). The heating effects of GHGs are counteracted, to some extent, by the cooling effects of sulphate aerosols. These aerosols reflect sunlight. It is observed that land surface temperature (LST) increase, in response to increasing GHGs, is stronger over the land than that over oceans, which is termed as Sea Surface Temperature (SST), because land surfaces have a less efficient evaporative cooling and smaller heat absorption capacity than large water bodies (Sutton *et. al*, 2007). The increase in LST gives rise to precipitation and other components of hydrologic cycle especially precipitation that also increase with increase in temperature. Hence, a rule of thumb is that wet-gets-wetter (Abdul *et al.,* 2013; Ishiaq *et al.*, 2010) because of increased moisture gradients, in both vertical and horizontal directions, and a resultant dry advection regime (Chou and Neelin, 2004; Held and Soden, 2006; Chou *et. al*, 2009) moving away from a rainband (Xie *et al.,* 2010). Studies of climate change probably indicate increases in variables affecting the hydrological cycle.

There are basically two types of climate data to develop hydrologic models:

- One is based on local meteorological station data; and;
- The second one is based on gridded data obtained from Global Circulation Models (GCMs) and Regional Circulation Models (RCMs) (Kazi *et al.*, 2014).

An increase in temperature does not only affect the agriculture but also has impacts on the livestock in terms of their reproduction, vulnerability to pests, pathogens and, ultimately, morbidity and mortality (Winsemius *et al.,* 2014). The Earth's temperature differs geographically, elevation-wise, and over time – seasonally and then over decades. The spatial variation and temporal changes for different parameters associated to climate are determined by performing trend analysis (Sabyasachi *et al.*, 2015). But, a major challenge for researchers studying climate change is how to model climate change impacts since there are many uncertainties involved. These uncertainties range from the definition of greenhouse gases (GHGs) scenario's to the calculation of hydrologic projection (Seiller and Anctil 2014). There are four levels of uncertainties related to climate change impact modeling. Out of these four, three levels are comrade with climate calculations (gas emission scenarios, global climate modeling and downscaling). The Fourth level is linked with hydrologic modeling (Seiller and Anctil, 2014). There are many studies which address the four levels e.g. by Vicuna *et al.,* 2007; Minville *et al.*, 2008; Kay *et al.,* 2009; Boyer *et al.,* 2010; Görgen *et al.*, 2010; Teng *et al.,* 2012; Jung *et al.*, 2012 while others focus only on a specific level e.g. Ludwig *et al.,* 2009; Gardner 2009; Poulin *et al.*, 2011; Bae *et al.*, 2011; Teng *et al.*, 2012; Velázquez *et al.,* 2013.

This study aims to investigate variation in temperatures in major cities of Saudi Arabia where the World's largest gatherings take place during the Hajj season in addition to a continuous in and out flux of people from over the world. Being a rapidly developing country, it is interesting to simulate temperature patterns of the country since temperature change also affects the precipitation frequency (Ishtiaq *et al.*, 2010). This is very important for Saudi Arabia since the country has neither perennial rivers nor small streams. The climate of Saudi Arabia is marked by high temperatures during the day and low temperatures at night. Most of the country follows the pattern of a desert climate, with the exception of the southwest. Saudi Arabia has no perennial rivers or permanent streams. Mostly, flash rains occur in Saudi Arabia causing flooding in valleys. This rainwater is of less to no use because of its rapid evaporation and high infiltration rates due to mostly sandy soil (Ishtiaq *et al*, 2011). Climate change assessment and its impacts on climate and hydrology needs reliable information about the average values and climate fluctuations of the past and present which are simulated to establish future trends (Olsson *et al*., 2015).

Materials and methods

Study Area

For this study, Saudi Arabia has been selected as the Region of Interest (ROI). In this paper, a 38 years (1970-2007) temperature record (Table 1) recorded at thirteen major cities has been used as a reference data to parameterize and validate simulated changes in temperature using EdGCM. As per standard practice, this temperature data has been averaged for the four standard (Wilks, 1999) climatological seasons i.e. the winter (DJF), the spring (MAM), the summer (JJA), and the autumn (SON) and an annual value as well. Figure 1 shows the stations locations.

Simulation using Global Climate Model (GCM)

The simulation of climate is a very complex exercise and requires the solution of a large number of sometimes complex numerical equations involving a number of factors and parameters/uncertainties which may affect simulated climate quite differently. This complexity has been rationalized by the development of Global Climate Models (GCMs). Adequate spatial and temporal resolution of GCM's is needed for the evaluation of impacts, vulnerability and adaptation to Climate Change (Ramos *et al*., 2013). The most popular GCM's used globally include: the CSIRO (Australia), the DKRZ (Germany), the CCCma (Canada), the GFDL (USA), the NCAR (USA), the CCSR and NIES (Japan), the HadCM3 (UK), and the EdGCM - an educational GCM developed at the Columbia University (USA). The above GCMs, except EdGCM, are run either at their centers of development or in research institutes/universities because some require super-computers and some work on clusters of workstations as well. Results are in raster format but with different spatial resolutions. All GCMs produce results in the raster format. The spacing between raster elements (called pixel) is termed as resolution of the GCM and is expressed in degrees of "the latitudes multiplied by the longitudes".

Features of EdGCM

EdGCM, an integrated software suite, is designed by Columbia University (USA) to simplify the process of setting up, running, analyzing and reporting on global climate model simulations, essentially for educational purposes. The software package includes a full copy of 4th Dimension® database software (4D, Inc.) and the NASA/Goddard Institute for Space Studies' Global Climate Model II (i.e., GISS GCM II). The GISS GCM II is currently used for climate research at NASA labs and several universities. For a complete description of the GISS GCM II, see Hansen *et al*., 1983. EdGCM is a GUI-based (GUI: Graphical Users Interface) model and requires an uninterrupted time of approximately 36 hours to simulate climate from the year 1958 to the end of the year 2100 depending on platform computing power. In this study, the model simulation has been started from the year 1958 because that was the first year when proper measurements of GHG's started (Hansen *et al.,* 1983; The Basic Guide to EdGCM 2003-2009). EdGCM simulations are based on four fundamental equations (Ishtiaq *et al.,* 2010; Ishtiaq *et al*., 2011; Hansen *et al*., 1983). A resolution of 8 degree latitude x 10 degree longitude x 10mbar vertical layers is used in this study. The model has been run for two A2 SRES (Special Report on Emissions Scenarios) scenarios in this study (out of several other ones) i.e. the double CO_2 ($2CO_2$) concentration scenario and the Modern_Predicted Sea Surface Temperature (MPSST), (Ishtiaq *et al*., 2010, Ishtiaq *et al.,* 2011). The model has built-in files which are basis to perform the simulations required for subsequent validation. "The model creates global maps, zonal averages, time series plots, and diagnostic tables for 80 climate variables" (Ishtiaq *et al.*, 2010; Ishtiaq *et al.*, 2011; J. Hansen *et al.*, 1983). The EdGCM produces results in tabular as well as in graphical format globally. Saudi Arabia has been put in focus within this global context simulated by EdGCM. The graphical outcome of EdGCM (not shown in this paper) has a limited set of isotherms passing through the country (Hassan and Ghumman, 2015).

Downscaling GCM results

The results of GCMs are too coarse to be transformed directly at the station of interest. It means that the pixel size of a GCM is too large to be validated with the point measured data of a meteorological station. Dynamical and statistical downscaling techniques are often applied to overcome the scale difference between the coarse resolution pixels of a GCM and a meteorological station (Suchul *et al.*, 2014; Kang *et al.*, 2009; Vasiliades *et al.*, 2009; Ahn *et al.*, 2012) e.g. results of Climate Generator (CLIGEN, Nicks and Lane, 1989) show that it can be used to simulate rainfall and storm pattern variables (Mustafa *et al.*, 2014). The pixel size of GCMs is not small enough to compare its value of a hydrologic quantity (say temperature here) with that of a station of interest. As that station falls away from the grid-point and it is very important to consider the effects of the four raster point values which surround the station of interest. The researchers have developed various techniques to perform the validation with station-values. This technique is known as downscaling. The basic scheme of all downscaling techniques is interpolation and modeling of a surface. The majority of researchers apply statistical methods for this purpose. Random Cascade, k-NN and stochastic weather generators are the most commonly used statistical techniques. In this paper, in order to have closely spaced isothermal map for Saudi Arabia, the authors apply AutoCAD2000i software to downscale the twelve EdGCM raster point values surrounding the study area.

Summary of methodology

The various steps involved in this study are explained below:

- The EdGCM model has been run separately for the $2CO_2$ and MPSST scenarios. The MPSST scenario forms basis of determination of change compared with the $2CO_2$ scenario. EdGCM runs have been carried out till the end of the year 2100.
- The "Analyze output" feature of EdGCM is used to calculate average temperature values for the last five (5) years of the simulation horizon (2096-2100). It is a built-in option of EdGCM (see The Basic Guide to EdGCM, 2003-2009).
- The "Analyze output" feature of the EdGCM creates the global maps for the four standard seasonal temperatures and the annual average temperatures. Raster-pixel values, are listed in Table 2, for each seasonal and annual average temperature. They have been noted from the EdGCM "map - window – show data" function and tabulated in the "text document" as latitude (x) in the first column, longitude (y) in the second column and the temperature value (z) in the third column.
- The modeling of temperature spatial patterns has been carried out using AutoCAD2000i. Ten (10) models have been produced for this study i.e. five (05) for the $2CO_2$. EdGCM scenario results and five (05) for MPSST EdGCM scenario results, shown in Figures 2 and 3, respectively.
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Below is the explanation showing how modeling has been carried out using AutoCAD2000i (Hassan *et al.*, 2015).

(i). Data Import: Click on "QuickSurf" and scroll down to "Import data" and "Read ASCII points". A new window opens where the "respective text document" file can be browsed and imported by pressing OK. Again click on "QuickSurf" and scroll down to "Points". At the command bar press "enter" and then write "draw" and press "enter". Click on "View" and "Zoom – Extents" to view the raster points which have been imported in the AutoCAD with their x, y and z values. These points are now ready to develope a lap with respect to the temperature values (isotherms).

(ii). Preparation of the model of temperature isotherms in terms of a surface model: Click on "QuickSurf" and scroll down to "contour interval". Open it and at the command bar, enter the desired value of interval, say 0.5°C and press enter. Now the spacing between the. temperature isotherms is 0.5°C. Click on "QuickSurf" again and scroll down to "contour". Open it and at the command bar, write "draw" and "No" each separated by the "enter" click. AutoCAD generates the map in terms of temperature isotherms based on the raster point data obtained from the simulations of EdGCM.

(iii). The above two steps are repeated separately ten times to develop Figures 2 and 3.

- Each seasonal model is superimposed on the location plan of Saudi Arab (Figure 1). The station values for each seasonal period have been extracted by reading the temperature isotherms of the respective period.
- Changes in temperatures by the end of the 21st century are determined by calculating the difference of the two emission scenarios experiments. Finally, comparison of temperature values at the end of 21st century and the available temperature records (1971-1997-2007) has been carried out to know differences with respect to the available temperature records.
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Results

Table 3 shows station temperature values for the two ($2CO_2$ and MPSST) emission scenarios. These values have been obtained from Figures 2 and 3. Changes in temperature for the projected period i.e. for the average of the last five years have been determined as the difference of the respective station values for the two scenarios. The summary of the results is listed in Table 3.

Table 1. Data for 13 stations (cities) of Saudi Arabia.

Time period	Station	Location NAME	Abrevation	Latitude (°N)	Longitude (°W)	Average Temperature (°C) DJF	MAM	JJA	SON	ANNUAL
1970-2007	1	Al-Riadh	AR	24.64	46.73	16.64	26.59	34.94	27.13	26.33
1970-1997	2	Al-Ahsa	AA	25.24	48.45	15.88	25.79	36.52	26.18	26.09
1970-1997	3	Al-Dawadmi	AD	24.49	44.43	14.75	23.13	33.43	25.40	24.18
1970-2007	4	Dhahran	DH	26.3	50.13	16.01	25.11	34.95	28.48	26.14
1970-2007	5	Gassim	GM	26.3	43.77	15.73	23.55	33.84	26.08	24.80
1970-2007	6	Madina	MA	24.94	39.44	19.89	28.34	35.41	29.07	28.18
1970-2007	7	Makkah	MH	21.44	39.81	23.48	29.86	35.72	31.45	30.13
1970-1997	8	Gizan	GN	16.89	42.55	21.04	28.61	33.35	27.29	27.57
1970-2007	9	Hail	HL	27.49	41.71	12.13	20.93	30.32	22.47	21.46
1970-2007	10	Tabuk	TK	28.39	36.58	12.70	21.27	30.15	22.08	21.55
1970-2007	11	Taif	TF	21.48	40.55	14.17	21.72	28.34	20.36	21.15
1970-1997	12	Jeddah	JH	21.46	39.19	19.64	27.48	33.95	26.20	26.82
1970-2007	13	Yanbo	YO	24.09	38.05	18.52	25.91	33.30	27.10	26.21

(a) An average (for the 13 stations) change of 4.41°C in the temperatures of DJF with a maximum change of +5.10°C for GN and JH and a minimum change of +3.45°C at HL; (b) An average (for the 13 stations) change of 5.57°C in the temperatures of MAM with a maximum change of +5.80°C for AR and TF and a minimum change of +5.35°C at DH and JH;

(c) An average (for the 13 stations) change of 4.53°C in the temperatures of JJA with a maximum change of +5.40°C for YO and a minimum change of +3.20°C at GN;

(d) An average (for the 13 stations) change of 4.40°C in the temperatures of SON with a maximum change of +5.00°C for HL and a minimum change of +3.70°C at GN; and

(e) An average (for the 13 stations) change of 4.72°C in the annual temperatures with a maximum change of +4.95°C for YO and a minimum change of +4.37°C at HL.

Table 2. EdGCM raster values for $2CO_2$ & MPSST emission scenarios.

Grids		Double CO_2 Scenario					Modern_Predictedsst Scenario				
Longitude	Latitude	Average temperature (°C)					Average Temperature (°C)				
(Degrees)	(Degrees)	DJF	MAM	JJA	SON	ANNUAL	DJF	MAM	JJA	SON	ANNUAL
35	12	23.16	28.05	30.94	25.40	26.89	17.89	23.69	26.68	21.84	22.53
45	12	23.65	27.13	28.86	25.85	26.37	19.17	23.93	26.79	22.52	23.10
55	12	28.27	30.12	28.85	28.75	29.00	23.59	26.47	25.52	25.11	25.17
35	20	24.92	30.63	37.45	30.25	30.81	19.51	25.69	31.61	26.26	25.77
45	20	22.94	29.92	35.09	27.60	28.89	17.48	24.24	31.76	23.83	24.33
55	20	26.10	31.91	34.14	28.90	30.26	20.57	26.75	32.01	25.43	26.19
35	28	16.44	26.22	36.56	26.53	26.44	12.28	20.64	31.73	22.16	21.70
45	28	15.00	26.02	36.56	27.51	26.27	11.60	20.44	31.88	22.40	21.58
55	28	15.85	22.75	32.30	24.66	23.89	11.96	17.85	28.94	20.59	19.84
35	36	12.02	18.26	29.51	22.16	20.49	8.44	14.13	24.23	17.62	16.11
45	36	6.32	15.96	30.29	19.07	17.91	3.41	11.36	27.17	14.55	14.12
55	36	5.93	15.35	28.80	19.61	17.42	2.35	11.01	22.28	13.35	12.25

Table 3. Station values for $2CO_2$ and MPSST emission scenarios and their change for the last 5 years' (2096-2100) average.

STATION	DJF			MAM			JJA		
(city)	MPSST	$2CO_2$	CHANGE	MPSST	$2CO_2$	CHANGE	MPSST	$2CO_2$	CHANGE
AR	14.80	19.25	4.45	22.50	28.30	5.80	32.40	36.50	4.10
AA	14.30	18.80	4.50	21.75	27.50	5.75	31.75	35.65	3.90
AD	14.90	19.25	4.35	23.00	28.75	5.75	32.50	37.15	4.65
DH	12.75	16.75	4.00	20.15	25.50	5.35	30.75	34.60	3.85
GM	13.00	16.70	3.70	21.70	27.40	5.70	32.50	37.10	4.60
MA	14.80	19.00	4.20	23.05	28.50	5.45	32.55	37.75	5.20
MH	17.25	22.25	5.00	24.25	29.75	5.50	32.00	36.80	4.80
GN	18.60	23.70	5.10	24.50	30.00	5.50	30.50	33.70	3.20
HL	11.90	15.35	3.45	20.75	26.25	5.50	32.25	37.00	4.75
TK	11.55	15.50	3.95	20.10	25.50	5.40	31.55	36.15	4.60
TF	17.00	22.00	5.00	24.20	30.00	5.80	32.00	36.75	4.75
JH	17.50	22.60	5.10	24.50	29.85	5.35	32.00	37.10	5.10
YO	16.00	20.50	4.50	23.75	29.25	5.50	32.50	37.90	5.40
Average	*14.95*	*19.36*	*4.41*	*22.63*	*28.20*	*5.57*	*31.94*	*36.47*	*4.53*
STATION	SON			ANNUAL					
	MPSST	$2CO_2$	CHANGE	MPSST	$2CO_2$	CHANGE			
AR	23.70	28.15	4.45	23.35	28.05	4.70			
AA	23.10	27.50	4.40	22.73	27.36	4.63			
AD	24.10	28.65	4.55	23.63	28.45	4.82			
DH	22.00	26.45	4.45	21.41	25.83	4.42			
GM	23.35	28.25	4.90	22.64	27.36	4.72			
MA	24.40	28.80	4.40	23.70	28.51	4.81			
MH	24.80	29.00	4.20	24.58	29.45	4.87			
GN	23.50	27.20	3.70	24.28	28.65	4.37			
HL	22.50	27.50	5.00	21.85	26.53	4.68			
TK	21.65	26.05	4.40	21.21	25.80	4.59			
TF	24.60	28.75	4.15	24.45	29.38	4.93			
JH	25.10	29.30	4.20	24.78	29.71	4.93			
YO	24.90	29.30	4.40	24.29	29.24	4.95			
Average	*23.67*	*28.07*	*4.40*	*23.30*	*28.02*	*4.72*			

Table 4. Average Temperatures of Stations for the Base Period (1970-2007) and the Projected Period (2096-2100).

STATION	DJF		MAM		JJA		SON		ANNUAL	
	1970-2007	2096-2100	1970-2007	2096-2100	1970-2007	2096-2100	1970-2007	2096-2100	1970-2007	2096-2100
AR	16.64	21.09	26.59	32.39	34.94	39.04	27.13	31.58	26.33	31.03
AA	15.88	20.38	25.79	31.54	36.52	40.42	26.18	30.58	26.09	30.72
AD	14.75	19.10	23.13	28.88	33.43	38.08	25.40	29.95	24.18	29.00
DH	16.01	20.01	25.11	30.46	34.95	38.80	28.48	32.93	26.14	30.56
GM	15.73	19.43	23.55	29.25	33.84	38.44	26.08	30.98	24.80	29.52
MA	19.89	24.09	28.34	33.79	35.41	40.61	29.07	33.47	28.18	32.99
MH	23.48	28.48	29.86	35.36	35.72	40.52	31.45	35.65	30.13	35.00
GN	21.04	26.14	28.61	34.11	33.35	36.55	27.29	30.99	27.57	31.94
HL	12.13	15.58	20.93	26.43	30.32	35.07	22.47	27.47	21.46	26.14
TK	12.70	16.65	21.27	26.67	30.15	34.75	22.08	26.48	21.55	26.14
TF	14.17	19.17	21.72	27.52	28.34	33.09	20.36	24.51	21.15	26.08
JH	19.64	24.74	27.48	32.83	33.95	39.05	26.20	30.40	26.82	31.75
YO	18.52	23.02	25.91	31.41	33.30	38.70	27.10	31.50	26.21	31.16
Average	16.97	21.38	25.25	30.82	33.40	37.93	26.10	30.50	25.43	30.16

Discussion

Figure 4 shows the trend of the seasonal average temperature changes for ($2CO_2$ – MPSST) values. Table 4 lists average temperatures of Stations for the Base Period (1970-2007) and the Projected Period (2096-2100). The projected (average for 2096-2100) temperature-values of the stations show a similar pattern of temperatures as found while working out average base period values. It means that the order of station-temperatures, in terms of the warmest to the warm, will remain unchanged. The trend of average seasonal temperatures of Saudi Arabia for the base period (1970-2007) and the projected period (2096-2100) are shown in Figure 5. In this figure, the maximum change is seen for MAM and the least for SON.

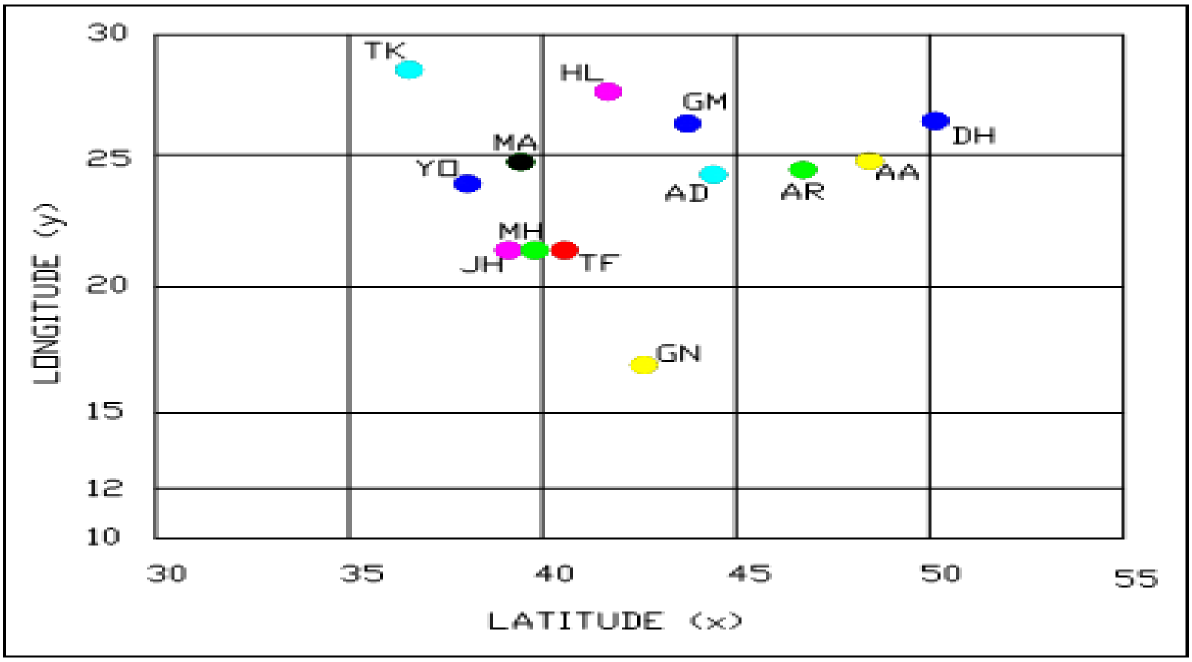

Fig. 1. (a) Meteorological stations location on a map of Saudi Arabia with latitude and longitudes.

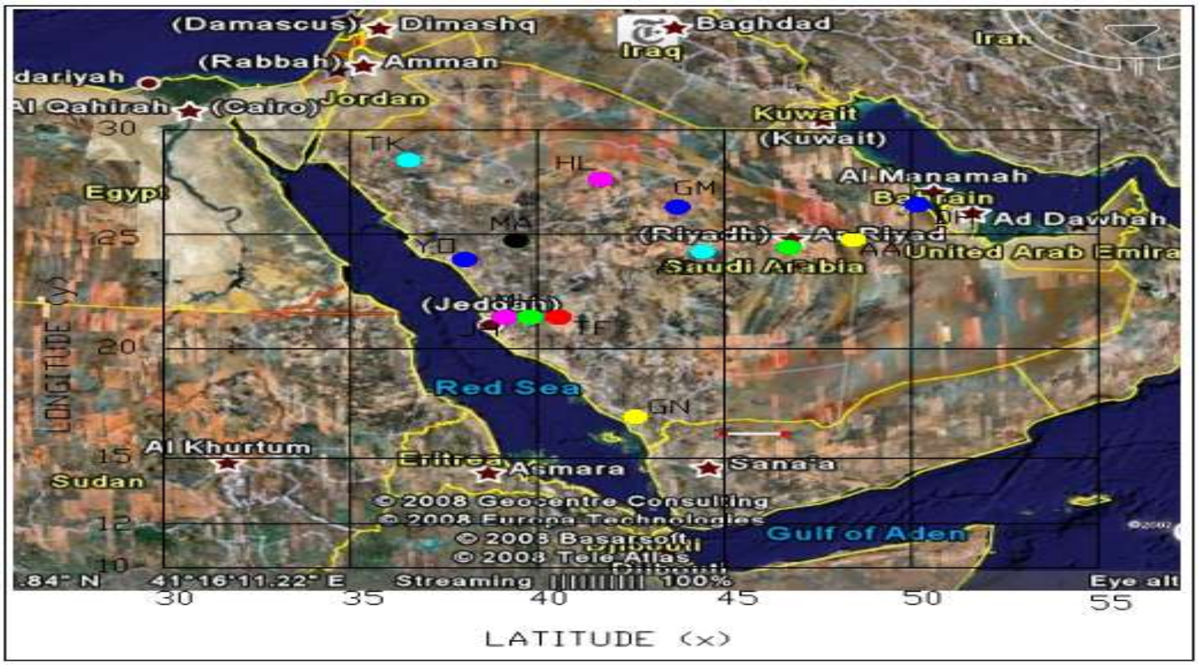

Fig. 1. (b) Meteorological stations location (figure 1a) superimposed on google map of Saudi Arabia (small deviation is due to different scales of figure 1a and google map).

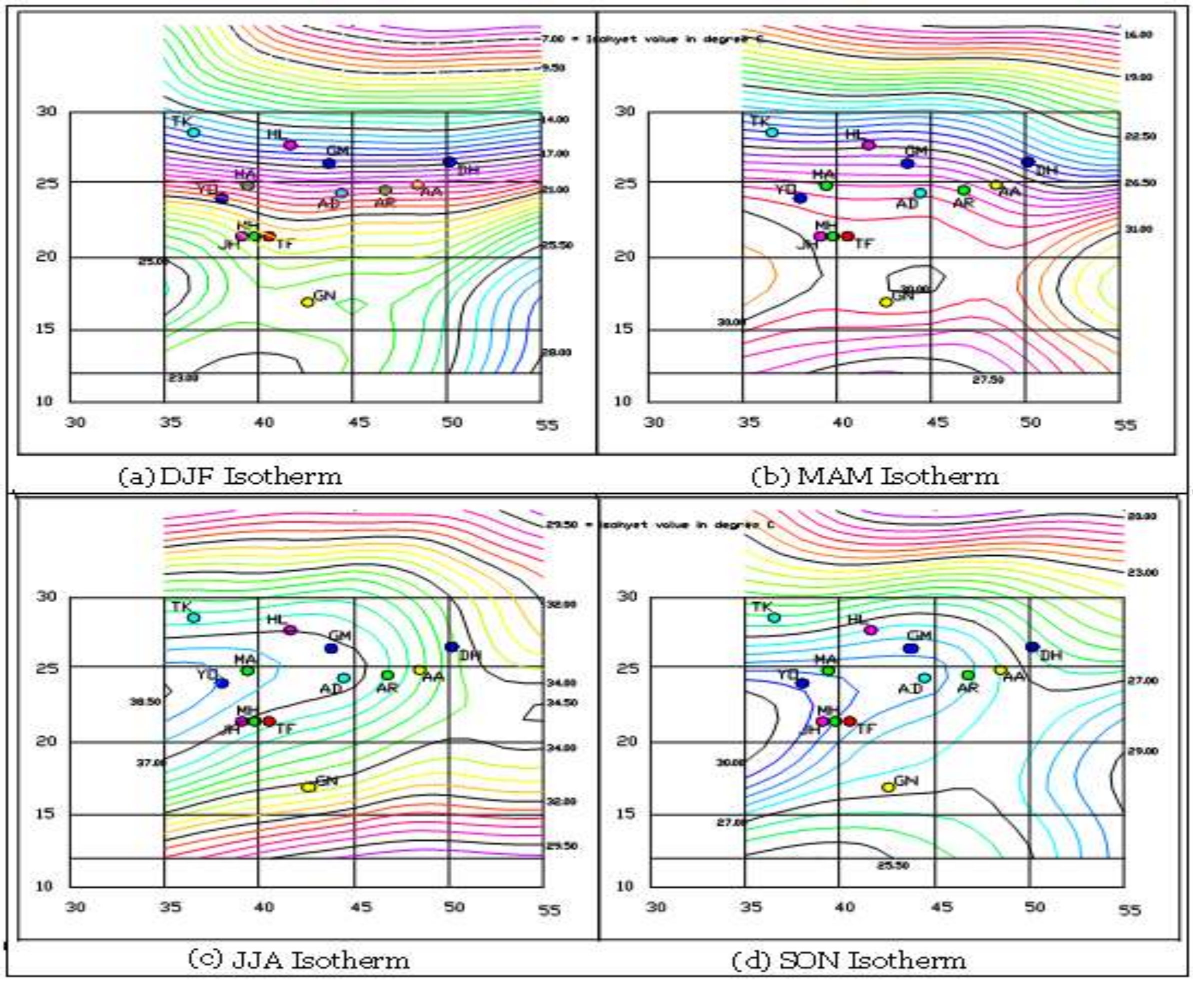

Fig. 2. (a - d): Temperature isotherms for: (a) DJF, (b) MAM, (c) JJA, and (d) SON for double CO_2 scenario.

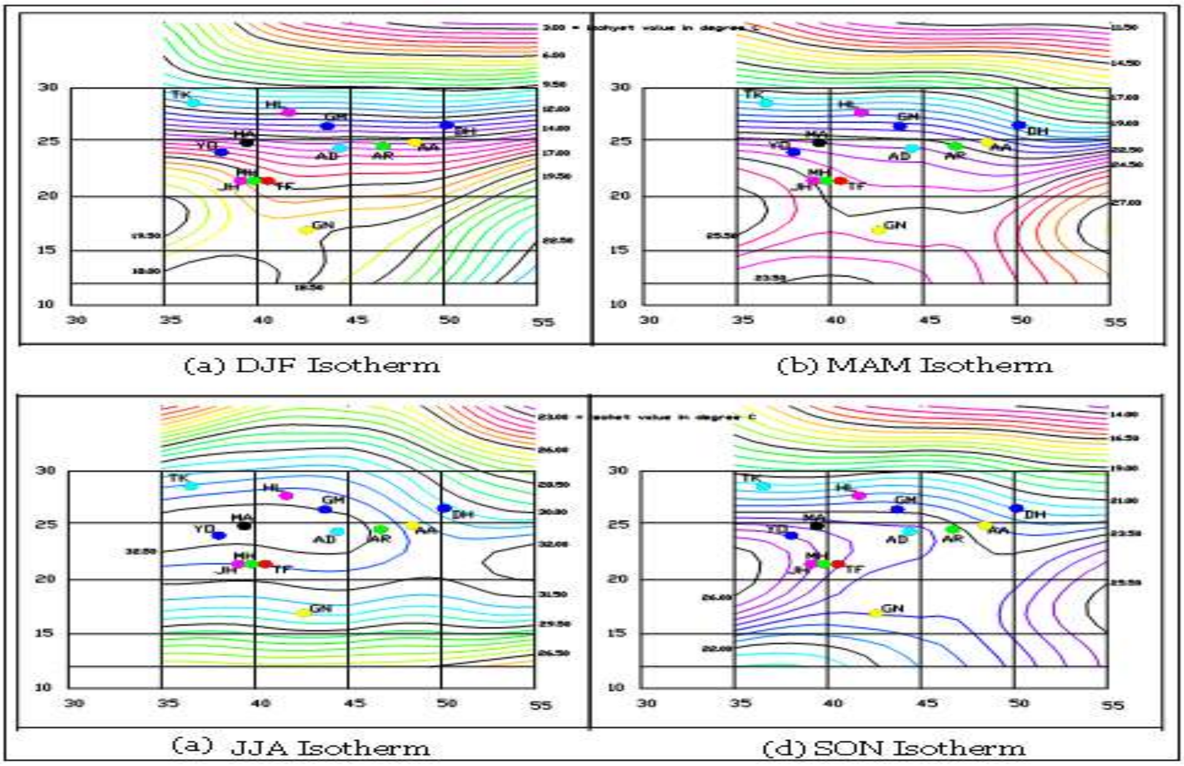

Fig. 3. (a - d) Temperature isotherms for: (a) DJF, (b) MAM, (c) JJA, and (d) SON for MPSST scenario.

In figures 2 and 3, the graphical outcome of AutoCAD2000i shows an identical pattern (not values) of variations in temperature during all seasons and annually. If we move from the center of the country to east or west, temperature increases, if we move to the north or south, temperature decreases. The same pattern of temperature variations is observed from the base period record given in table 1. This similarity of variation in temperature between base period and software-based downscaling technique by the end of 21st century gives confidence in using the graphical outcome with the downscaling technique.

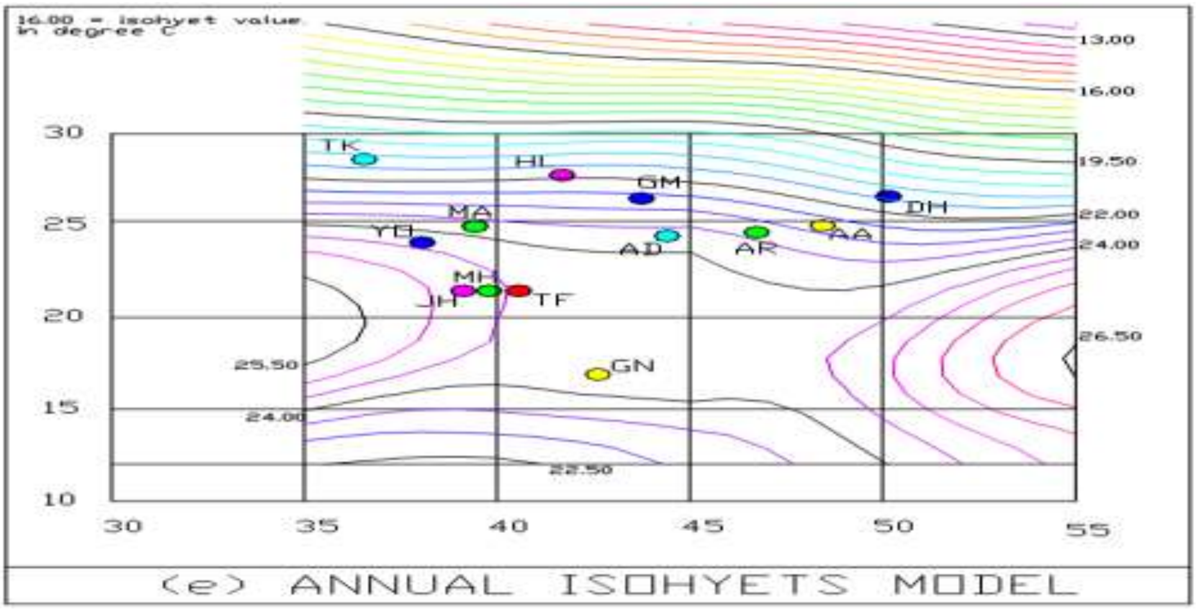

Fig. 3. continued (e): Annual Temperature isotherms for MPSST scenario.

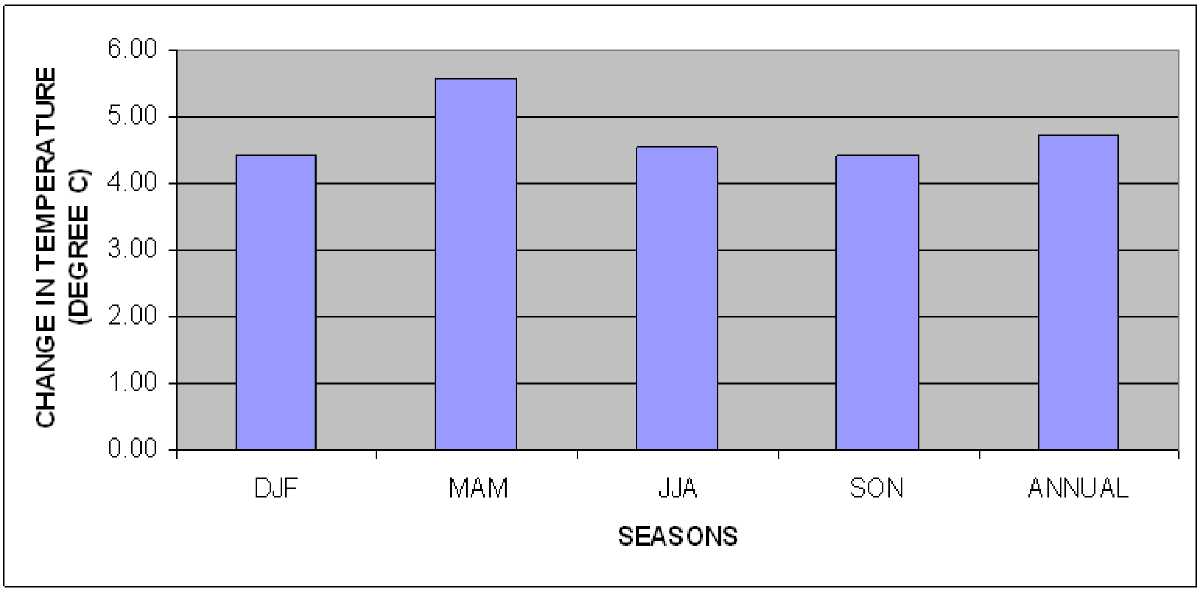

Fig. 4. Trend of seasonal temperature changes for ($2CO_2$ – MPSST) scenario.

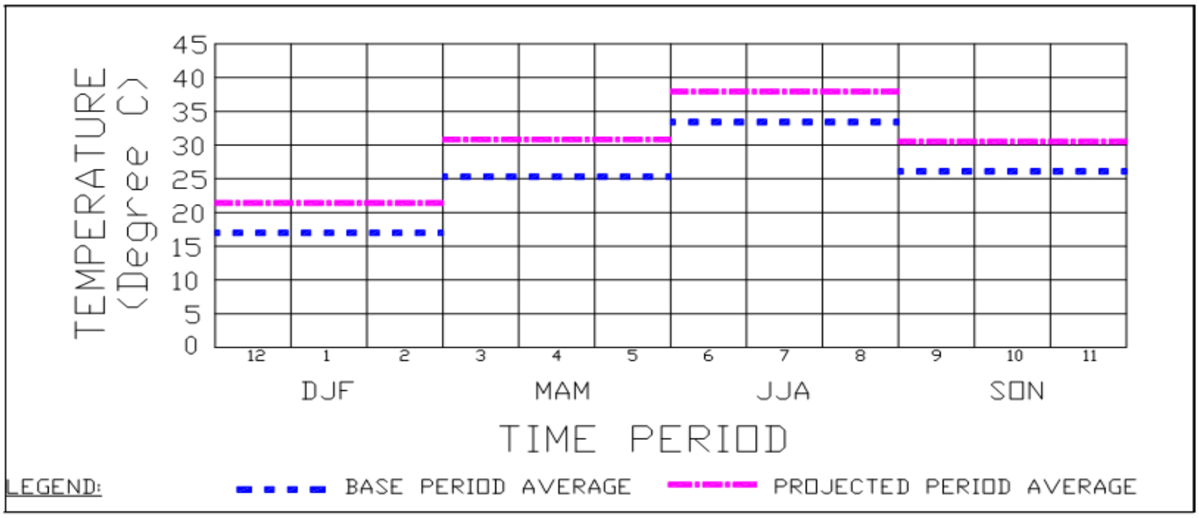

Fig. 5. Trend of average seasonal temperatures of Saudi Arabia for the base period (1970-2007) and the projected period (2096-2100).

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Conclusions and remarks

The study concludes that the country may experience an average change of +4.72°C in temperature by the end of the 21st century. However, this change of temperature will remain close to stable across the country. This means that global warming is not going to change the locations of “the warmest station to the warm station”, but global warming will probably give increased temperatures for Saudi Arabia. It is interesting to note that the overall temperature change for Saudi Arabia by 4.72°C is in line with the conclusions as reported by the IPCC Assessment

Report wherein it is stated that temperature change may vary from 1.4 degree C to 5.8 °C over the globe (Report 2001a, Carter, 2007).

The technique applied for downscaling in this study is helpful for further work by researchers working in the fields of water resources and environmental engineering. This technique involves modeling of temperature isotherms in AutoCAD2000i, as shown in Figures 2 and 3. The facilitation in the development of isotherms of desirable close interval (here 0.5 °C), is very helpful in framing the results up to their maximal accuracy.

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