The 3rd International Conference on Water Resources and Arid Environments (2008)
and the 1st Arab Water Forum

Impacts of Climate Change on Water Resources in Saudi Arabia

Faisal Macci Al Zawad
Presidency of Meteorology and Environment, Dammam, Saudi Arabia

Abstract

In this research, the impact of climate change over Saudi Arabia at the end of 21st century is investigated using PRECIS system. PRECIS is an abbreviation for "Providing Regional Climates for Impacts Studies", which is a regional climate model that can be run on a personal computer, and developed by the Hadley Center at UK Met office to produce high resolution climate scenarios. The Intergovernmental Panel on Climate Change (IPCC), designed several emission scenarios from which two (A2 and B2) were evaluated to determine the impacts of climate change at the end of the 21st century on water resources in Saudi Arabia. Four experiments were carried out to generate high resolution (50 km) climate scenarios. PRECIS were used to downscale four types of boundary data; (1) 31-years (1960-1990) integration of HadAM3P, a 150 km resolution Hadley Center's global atmospheric model. (2) 31-years (2070-2100) integration of HadAM3P consistent with the IPCC SRES A2 emissions scenario. (3) 31-years (2070-2100) integration of HadAM3P consistent with the IPCC SRES B2 emissions scenario. (4) 31 year (1960-1990) of {ERA-40 (1957-2001)} reanalysis data derived from ECMWF (European Center for Medium-Range Weather Forecasting). In addition to local meteorological data for the years 1961 to 2005 provided by Presidency of Meteorology and Environment (PME). Several analysis tools were used to compare the present climate to the future for six regions and thirty seven selected locations over Saudi Arabia. GIS technology (ArcGIS 9.2), VCDAT software and KalidaGraph software were used to study the changes in surface temperature, precipitation, surface evaporation, surface wind speeds, and runoff. High resolution results indicate that A2 scenario tends to force warmer temperature, more precipitation, less evaporation, and more runoff than B2 scenario. A mean increase of 4.2 degrees Celsius of the daily surface mean temperature over Saudi Arabia is apparent for A2 scenario while it is 3.0 degrees Celsius for B2 scenario. The change values for precipitation, evaporation, runoff and winds for A2 scenario were 37.1 mm/year, 20.8 mm/year, 1.1 mm/year and 0.01 m/sec respectively. A slight decrease of the mean surface wind speeds of 0.1 m/sec was registered by B2 scenario. The mean precipitation change for B2 scenario was 9.8 mm/year which is 23% of the present value and about half of A2 percentage increase (41% of the present). The mean evaporation for B2 was 48.9 mm/year, and the runoff was

0.5 mm/year which is 79% of the present, but much less than the corresponding percentage increases for A2 (226% of the present).In

Key words: PRECIS, Climate Change, Water Resources, Saudi Arabia.

Introduction

Climate change is recognized as an important issue, and international communities through the United Nations created special groups to focus on climate change. In 1988 the Intergovernmental Panel on Climate Change (IPCC) was created by World Meteorological Organization (WMO) and the United Nation Environmental Program (UNEP) to aid decision-makers and public understand the issues of climate change. In 1992, an Earth Summit was conducted where representatives of 172 governments were present at Rio de Janeiro, Brazil to discuss the threat of global warming. Since then, the IPCC published several important and trustworthy publications and reports regarding human induced emissions of greenhouse gasses and various aspects of climate change. The IPCC's four assessment reports on climate change became a standard reference to scientists, students and the general public. Global increase in temperature has been observed from mid 1970's to be in the average of 0.15 degrees Celsius per decade (Brohan et al., 2006). The warmest year was 1998 with 0.546 degree Celsius above the normal calculated for the years 1961-1990 which is 14 degrees Celsius. The year 2007 was 0.40 degree Celsius above normal global mean temperature, which is the eighth warmest in record, preceded by 1998, 2005, 2003, 2002, 2004 and 2001 (Figure 1.1).

In spite of the fact that this research about generating high resolution climate scenarios applied to Saudi Arabia using PRECIS is probably the first of its kind, there are many studies that assessed the impacts of climate change over Saudi Arabia using other methods, (Alkolaibi, 2002) and (Abderrahman and Al-Harazin, 2008).

(Serrat-Capdevela et al., 2007) created climate scenarios from 17 GCMs to study the impacts of climate change on the water budget and dynamics of aquifer in southeastern Arizona and northern Sonora in the USA. The data from the GCMs were obtained from easy to use window software called MAGICC (The Model for the Assessment of Greenhouse gas Induced Climate Change) which has a horizontal cell of 5 degrees X 5 degrees. It has accompanying software to show outputs called SCENGEN (Wigley, 2002). Further statistical downscaling was carried out to get high resolution values for precipitation and temperature that were used to derive a hydrological model. Results for the years 2000 to 2100 indicate a decrease of 17-30 % in the recharge affecting the dynamics of the aquifer.

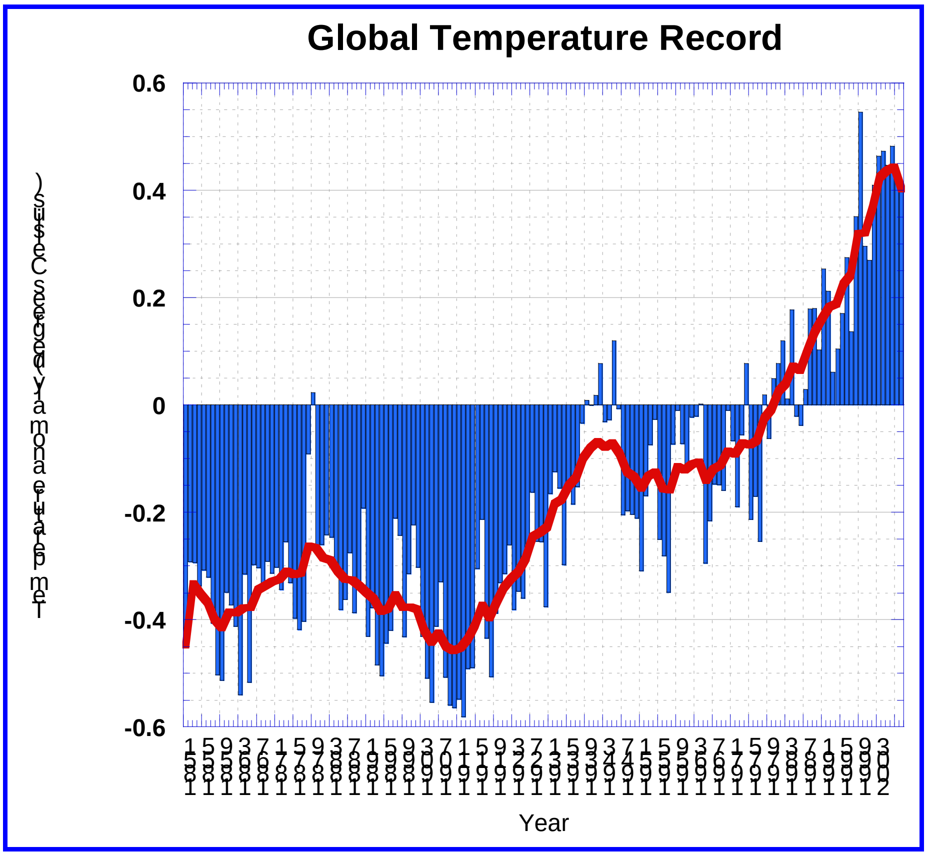

Figure 1.1: Global mean anomaly air temperature for the years 1851 to 2007. (Data source: CRU, UK, 2008).

An attempt to project future climate changes by the 2050's on arid and semi-arid regions was investigated by (Ragab, and Prudhomme, 2002) using the U.K. Hadley Center's Global Model HadCM2 at a special resolution 2.5 degrees x 3.75 degrees. Their results indicate a decrease in precipitation by 20 – 25 %, and an increase of 1.5 – 2.5 degrees Celsius in temperature over Saudi Arabia.

Climate modeling research in China is taking a serious look on the impacts of climate change. A study by (Yenlong, et al., 2006) indicated an increase in temperature both A2 and B2 scenarios for the end of 21st century compared to the baseline 1961 – 1990, using PRECIS to process initial and lateral boundary conditions of the Hadley Center's HadAM3H which is the atmospheric component of the coupled ocean-atmosphere GCM HadCM3. It is concluded that China will face an average increase of 3 degrees Celsius in temperature with a 10% increase in precipitation under A2 and B2 scenarios. Another study by (Tao, et al., 2007) focused in assessing the impacts of climate change at the end of the 21st century on the rice production in China by considering five GCMs and 20 IPCC scenarios. The yield of rice is found to decrease in a range of 4.2 % to 10.8 %, 8.7 % to 23.6 %, and 12.5 % to 27.9 % for changes in temperatures 1, 2, and 3 degrees Celsius respectively.

Climate modeling experiments were done over India by (Kumar et al., 2006) in which PRECIS with a 50 km horizontal resolution was used to downscale data from HadAM3H as in the Chinese experiments. Temperature was found to increase by 3 to 5 degrees Celsius and 2.5 to 4 degrees Celsius for A2 and B2 scenarios respectively at the end of the 21st century. Precipitation was projected to increase by 15 % to 40 % by the end of the 21st century compared to the baseline of the period 1961-1990.

A regional climate model with an 88 km horizontal resolution with 19 vertical levels called RCA for “Rossby Centre Regional Atmospheric Climate Model” was used to downscale outputs from two GCMs for investigating the impacts of climate change on water resources in Sweden (Graham et al., 2001). The used GCMs were the UK Met Office HadCM2 of Hadley Center and the ECHAM4/OPTC3 of the Max-Plank-Institute for Meteorology in Hamburg. Temperature and precipitation calculated from RCA were fed to a hydrological impacts assessment model focusing on six drainage basins distributed over Sweden. A range of modeled average percent change in annual runoff from – 41 % to + 25 % was detected for the six Swedish basins.

The Siginificance of this Research

Saudi Arabia is about 2.3 million square kilometers of mostly desert area surrounded by the red see from the west side, the Arabian Gulf from the eastern side and close to the Arabian sea from the south. Along the red sea the western highlands rise up to 3000 meter and the land dips gently towards the east. There are neither lakes nor rivers in the entire vast country. Al Rub Al Khali , Ad Dahna and Nafud basin consist of sand dunes that cover 40 percent of the Saudi Arabia.

The climate of Saudi Arabia is an arid mostly characterized by hot and dry summer with cool and slightly wet winter. The southwestern region of Saudi Arabia has the biggest average annual amount of rainfall. Summer rainfall occurs over the southwest mountains due to the easterly jet and the monsoon. Saudi Arabia has limited renewable water resources. There are 215 dams mostly located in the southwest of Saudi Arabia with a storage capacity of 833 million cubic meters (m^3) (Abderrahman and Al-Harazin, 2008). The groundwater is the main source of water in Saudi Arabia satisfying more than 90 % of its water demand. Groundwater is stored in several aquifers (Figure 1.2) over Saudi Arabia with minimum annual recharge. It is estimated that the total groundwater storage in the Arabian Peninsula is 80 000 km^3 (Abderrahman, et al., 2001), and the total groundwater reserve in Saudi Arabia is estimated to be 2259 billion cubic meters (Abderrahman and Al-Harazine, 2008). Distillation of sea water from 30 plants along Red Sea and Arabian Gulf are the main source of 50 % of domestic demand. The government of Saudi Arabia is aiming to expand the desalination by building more plants. along the Arabian Gulf and the Red Sea. There is an increasing effort by Saudi Arabia to treat waste water, and reuse the recycled water to irrigate crops, as most of the fresh water used in Saudi Arabia (89%) goes to agricultural use (Gleick, 2006).

There are few studies investigating the future regional climate change and its impacts over Saudi Arabia. (Abderrahman and Al-Harazin, 2008) assessed the impact of an increase in temperature of one to five degrees Celsius on water demands over twenty one locations in Saudi Arabia using the Penman-Monteith method to calculate the crop irrigation requirements due to an increase of one to five degree Celsius in temperature. The results of the study were a decrease in annual recharge and surface runoff by 241 millions cubic meters and 1435 millions cubic meters at 1 degree Celsius and 5 degrees Celsius increase in temperature respectively, and the total water stress on Saudi Arabia is between 1520 to 4947 millions cubic meters at an increase of 1 and 5 degrees Celsius respectively. (Alkolibi, 2002) studied the results of climate change as predicted by the General Circulation Models and discussed the consequences of temperature increase and precipitation decrease on water resources and agriculture in Saudi Arabia and recommended further studies in this field. The IPCC in its final report (Treut, et al., 2007) predicted that under SRES A1B scenario which has a close scale to A2 scenario, annual mean changes of precipitation over Saudi Arabia for the years 2090 to 2100 relative to 1980 to 1990, will increase slightly over southern, middle and eastern regions with values equal or less than 0.1 mm/day. A slight decrease in precipitation (less than 0.1 mm/day) is predicted over northern Saudi Arabia by the end of the 21st century (Meehl, et al., 2007). For the same periods and scenario, southern, and the Empty Quarter regions tends to have an increase of 5 to 10 % in soil moisture, while a decrease by 0 to 5 % is expected over the northern region. Similarly, changes in annual runoff show slight increases by 0.1 mm/day for most of Saudi Arabia, except a small portion of the northern region. An increase of 0.1 mm/day is expected at the end of the 21st century in the mean annual surface evaporation for most of Saudi Arabia, except for a narrow tong extending from north towards the middle of Saudi Arabia.

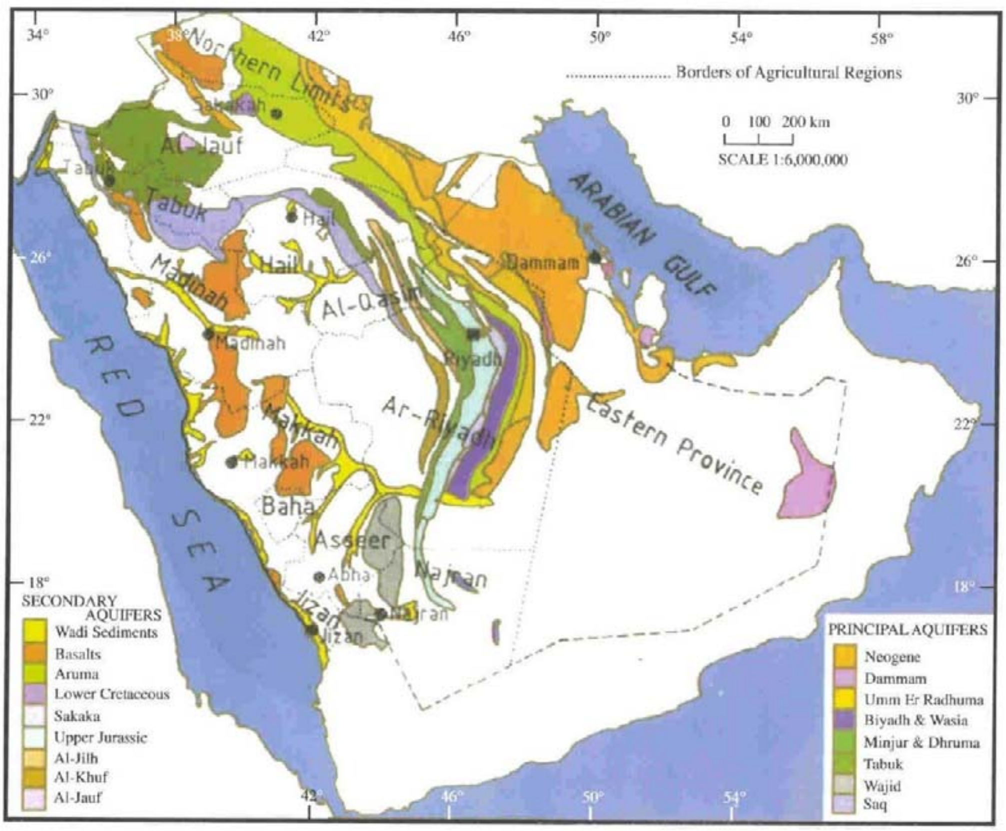

Figure 1.2: Overcrops and the main aquifers of Saudi Arabia.
(Abderrahman, W., Al-Harazin, I., 2008)

Water scarcity in Saudi Arabia is obvious, and knowledge of the effects of climate change on its water resources will provide essential information to design an effective future plans for water management. There is a growing need to explore this important factor in various realms of fields touched by water. Agriculture depends on climatic changes and its water demand is affected very much with even a single field. For instance, agricultural water demand is expected to increase as the temperature increase.

This type of research is pioneering for using the results of the best technology available to predict climate change and forcing the benefits to serve the needs of our region in order to produce the best possible precise results. Those results will help in expanding the climate research by other scientists.

There are two objectives of this research; first is to generate high resolution climate scenarios using précis system. Second is to assess the impacts of climate change on water resources in Saudi Arabia by investigating the changes in temperature, precipitation, wind speeds, evaporation and runoff at the surface.

Methodology

A climate model with horizontal resolution of 50km and 19 vertical levels called PRECIS is used to investigate the climate change at the end of the 21st century (2071 – 2100) over Saudi Arabia. The results are compared to a baseline state of present climate for the period (1961 – 1990). PRECIS (Providing Regional Climates for Impact Studies) is a regional climate modeling system that can be run on a personal computer (PC). The United Kingdom Met Office's Hadley Center for Climate Prediction and Research is the provider and the developer of this software. The data for the boundary condition is supplied by the Hadley Center Global Climate Model (GCM), UK Met Office. PRECIS comes with a user interface to carry on climate experiments (Jones, and etal, 2004).

Prediction of future climate change is done globally with world wide support through United Nations organizations. Very few countries have the capability to designate a dedicated group of highly trained scientists and provide extremely fast computers to run GCMs in order to generate climate change scenarios. The United Nations Development Program (UNDP), The UK Department for Environment, Food and Rural Affairs (DEFRA), and the UK Department of International Development started funding PRECIS to be available to developing countries to generate their own climate change scenarios with using a personal computer only. The UK Met Office's Hadley Centre will supply the software, the boundary conditions and other fields of global quantities required to run PRECIS (Jones, 2004). Emission scenarios describing population, energy, and economics are taken from IPCC SRES (A1T, A1FI, A1B, A2, B1 and B2) (Meehl et al., 2007). The default output data format in PRECIS is PP which is the UK Met Office's format. PRECIS has several tools to manipulate PP format data to extract information or to convert binary PP data into other format (Wilson, et al., 2007).

1. Study areas and locations

Saudi Arabia is divided to 6 regions as in (Tables 3.1), and presented in (Figure 3.1). The regions are chosen in order to produce localized climate details by the model.

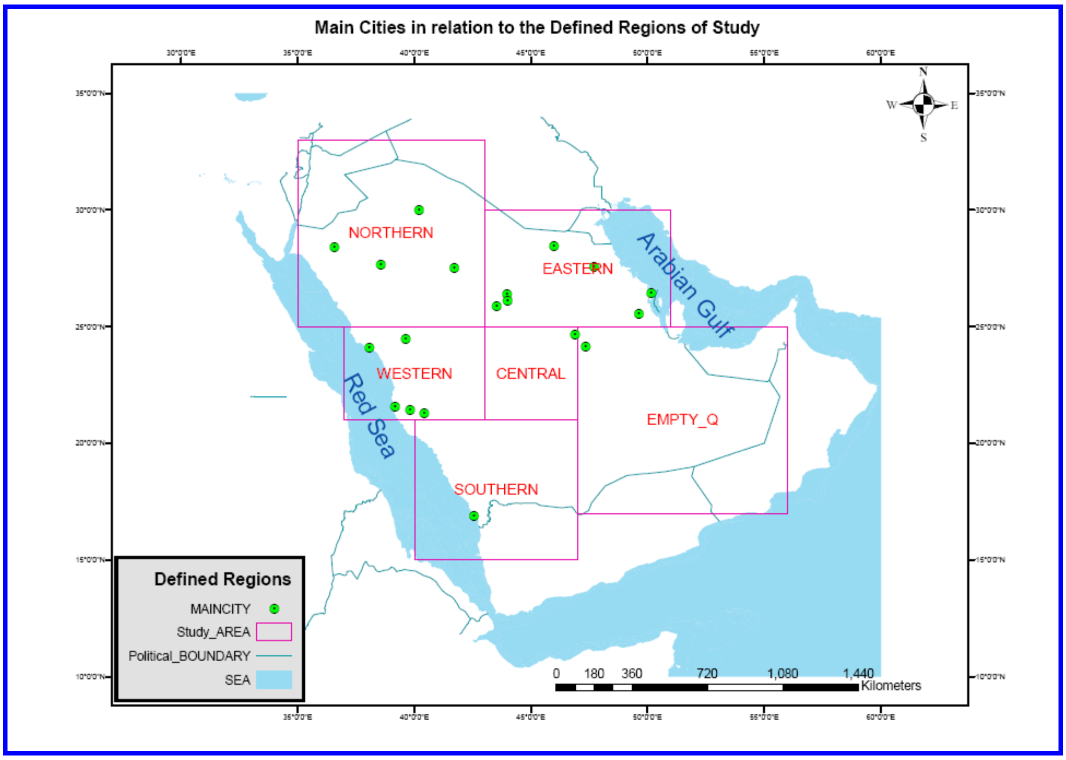

Figure 3.1: shows the regions representing Saudi Arabia.

Table 3.1: The boundaries of the six selected regions.

Number	Name of the region	Western Longitude	Southern Latitude	Eastern Longitude	Northern Latitude
1	Eastern	43 E	25 N	51 E	30 N
2	Central	43 E	21 N	47 E	25 N
3	Western	37 E	21 N	43 E	25 N
4	Northern	35 E	25 N	43 E	33 N
5	Southern	40 E	15 N	47 E	21 N
6	Empty Quarter	47 E	17 N	56 E	25 N

In addition, thirty seven separate locations (Figure 3.2, Table 3.2) were chosen to present the spread effects of climate change and to determine the more sensitive areas to changes in climate. There are 28 stations that are supervised by PME and have continuous records of hourly and daily observations. The need arise to adopt other locations to have a better representation of the area. Reanalysis data (ERA-40) is used as a historical data for those stations as will as each of the six regions. PME data is used as historical data for available stations.

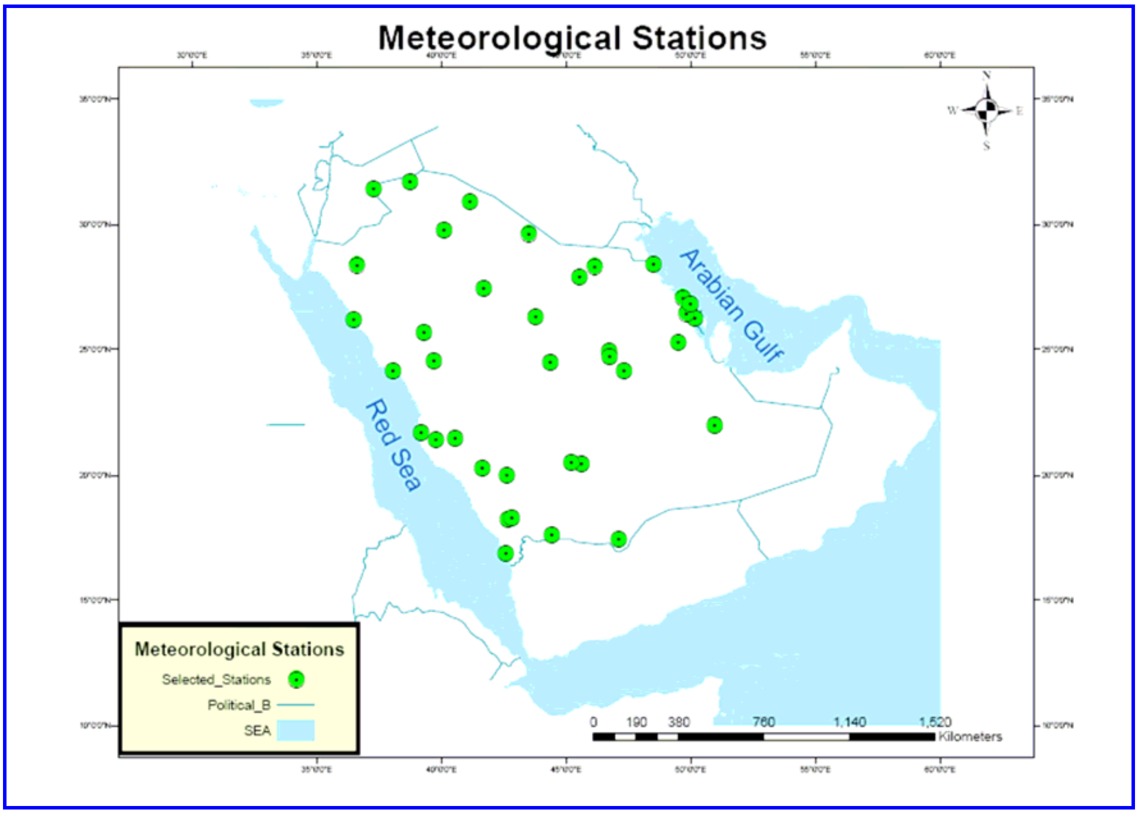

Figure 3.2: shows the 37 locations studied over Saudi Arabia.

2. Data:

Several types of data were used to run the model software (PRECIS):

1. 31-year of boundary data (1960-1990) integration of HadAM3P, a 150 km resolution Hadley Center's global atmospheric model. This is used as the baseline.
2. 31-year of boundary data (2070-2100) integration of HadAM3P consistent with the SRES A2 emissions scenario.
3. 31-year of boundary data (2070-2100) integration of HadAM3P consistent with the SRES B2 emissions scenario.
4. 31 year of boundary data (1960-1990) of {ERA-40 (1957-2001)} reanalysis data derived from ECMWF (European Center for Medium-Range Weather Forecasting). This data is used for validation of the model and as historical records.
5. Local historical data (1961- 2005) provided by Presidency of Meteorology and Environment (PME).

Data from HadAM3P and ERA-40 were used as inputs to be downscaled by PRECIS. Six climate fields were investigated for their future values and compared to their corresponding baseline values to determine the change in climate according to the adopted IPCC Emission scenario.

Table 3.2 The geographical location for the selected 37 locations over Saudi Arabia.

No	Name	Latitude	Longitude
1	TURAIF	31.68764	38.73932
2	AR-AR	30.90231	41.14048
3	GURIAT	31.40762	37.28212
4	AL JOUF	29.78871	40.09872
5	RAFHA	29.62138	43.49467
6	QAISUMAH	28.31878	46.13028
7	TABUK	28.37649	36.60686
8	HAFR-AL-BATIN	27.91199	45.52217
9	AL KAFJI	28.43226	48.50037
10	HAIL	27.43444	41.69101
11	AL WEJH	26.20524	36.47684
12	GASSIM	26.30783	43.76748
13	KHAYBER	25.6734	39.30006
14	DHAHRAN	26.25957	50.16083
15	AL AHSA	25.29798	49.48645
16	MADINAH	24.54796	39.69873
17	DAWADAMI	24.48518	44.35826
18	KING KHALED INTER. AIRPORT	24.9254	46.72184
19	RIYADH OBSERVATORY	24.71118	46.73826
20	YANBU	24.13986	38.06391
21	MAKKAH	21.43785	39.76886
22	TAIF	21.47879	40.54887
23	AL BAHA	20.29479	41.64299
24	SULAYEL	20.46238	45.61518
25	BISHA	19.99115	42.61927
26	ABHA	18.23305	42.66071
27	KHAMIS MUSHAIT	18.29952	42.80628
28	NAJRAN	17.61127	44.41352
29	SHARORAH	17.46774	47.10796
30	GIZAN	16.89693	42.58472
31	AL KARJ	24.1469	47.31301
32	JUBAIL	27.0791	49.66716
33	KING FAHAD INTER. AIRPORT	26.44427	49.81023
34	QATIF GOSP-3	26.83487	49.96545
35	WADI DAWASSER AIRPORT	20.5	45.2
36	OBAYLAH	21.98467	50.93853
37	JEDDAH	21.71024	39.18668

Estimating the final values for climate fields under a specific scenario is taken after (Loa'iciga, 2007) in which temperature, wind speed, precipitation; surface evaporation, soil water balance and runoff are calculated according to equations 3.1 to 3.6 respectively. Where T, W, P, E, (P-E) and Q accordingly represent temperatures in degrees Celsius, wind speeds in meters per seconds, total precipitation, surface evaporation in millimeters per day, the resultant of subtraction of surface evaporation from total precipitation in millimeters per day, and the mean runoff in millimeters per day. The subscript (Future) indicates the future projected value, and the subscript (Baseline) indicates the present value of the climate field.

$$T_{Scenario} = T_{Historical} + (T_{Future} - T_{Baseline}) \quad (3.1)$$

$$W_{Scenario} = W_{Historical} + (W_{Future} - W_{Baseline}) \quad (3.2)$$

$$P_{Scenario} = P_{Historical} * \left(\frac{P_{Future}}{P_{Baseline}} \right) \quad (3.3)$$

$$E_{Scenario} = E_{Historical} * \left(\frac{E_{Future}}{E_{Baseline}} \right) \quad (3.4)$$

$$(P - E)_{Scenario} = (P - E)_{Historical} * \left(\frac{(P - E)_{Future}}{(P - E)_{Baseline}} \right) \quad (3.5)$$

$$Q_{Scenario} = Q_{Historical} * \left(\frac{Q_{Future}}{Q_{Baseline}} \right) \quad (3.6)$$

3. Validation of the Model

The simulated and observed daily multiannual means are compared for the selected climate fields for the period 1961 to 1990 for the entire used domain (figure 4.1) by visual and single values assigned for each climate field. The Visual Climate Data Analysis Tool (VCDAT) is used to extract the statistical mean and standard deviation. We can see that the model has a cold bias and slightly decrease the actual precipitation and evaporation. The model tends to give slightly higher values in wind speeds and runoff (Table 4.1). If the area covering Saudi Arabia is considered instead of the whole domain, the agreements of the model to observation are much better as it can be seen from Figure 4.1. The statistical standard deviation shows that the mean values for the model are more spread for temperature, evaporation and wind speeds than the corresponding observations (Table 4.1), while the model's means for precipitation and runoff show less spread values than the corresponding observations.

Table 4.1: PRECIS simulation weighted area daily values for the 30 years spanning the years 1961-1990 compared to the ERA40 reanalysis observed values for the same period.

Climate Fields	Statistical Means		Standrd Deviation	
	Precis	Observed	Precis	Observed
Temperature	21.98	23.97	5.49	4.54
Precipitation	1.16	1.50	1.45	1.73
Evaporation	2.17	2.22	2.29	1.87
Wind Speeds	4.56	4.42	1.70	1.44
Runoff	0.0029	0.0028	0.011	0.014

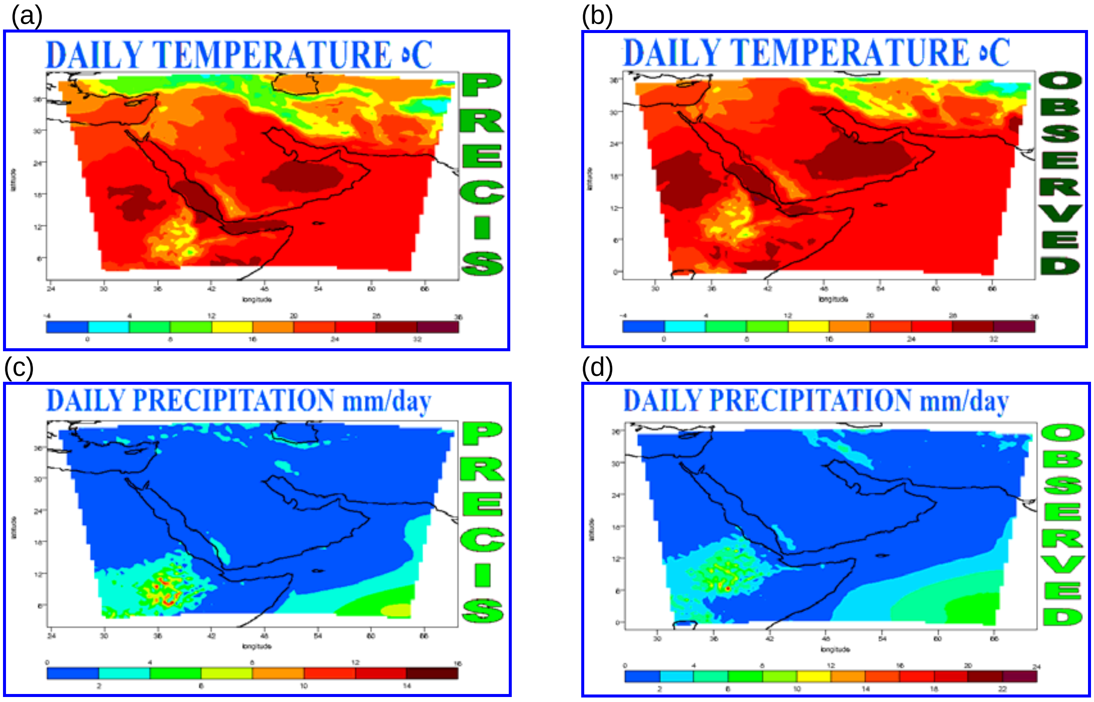

Figure 4.1: Validation of daily mean temperature and precipitation. The model is represented by (a) for temperature and (c) for the precipitation, while (b) and (c) for the corresponding observations based on ERA40 reanalysis data.

Results and Discussion

1. Climate Change by Regions

1.1. Eastern Region

The climate change of the Eastern region under both IPCC A2 and B2 emission scenarios indicates an increase of surface temperature, precipitation, evaporation and runoff, and indicates a decrease in surface wind speeds. The changes in soil water balance (P-E) are deferent for A2 and B2 scenarios. Table 5.1 shows an increase of 4.47 degrees Celsius for A2 scenario and 3.30 degrees Celsius for B2 scenarios. Surface wind speeds decreased by 1% and 2% under A2 and B2 scenarios respectively. Precipitation stands tall with substantial increases of 40% and 23% under each of A2 and B2 scenarios respectively. A slight increase of 0.87% in surface evaporation under A2 scenarios contributed to an increase of 4% in the soil water balance in the region. An increase of 14% in surface evaporation contributed to a 12.5% loss in soil water balance. The model indicates an increase of 162% and 57% in runoff for A2 and B2 scenarios.

Table 5.1: Climate fields of Eastern Province region.

Climate Field	A2_Scen	Historical	B2_Scen	A2_Change	B2_Change	A2_%	B2_%
T (^oC)	28.843	24.37	27.672	4.473	3.301	18.353	13.547
W (m/s)	4.157	4.212	4.125	-0.055	-0.086	-1.307	-2.05
P (mm/day)	0.334	0.256	0.315	0.078	0.059	30.313	22.849
E (mm/day)	0.744	0.737	0.841	0.006	0.104	0.875	14.062
Q (mm/day)	0.003	0.001	0.002	0.002	0.001	162.1	57.272
P –E (mm/day)	-0.461	-0.481	-0.542	0.02	-0.06	4.199	-12.548

1.2. Central Region

An increase in all climate fields under A2 scenario is expected in this region (Table 5.2). The average daily temperature is expected to increase by 4.27 degrees Celsius, surface wind speeds will increase by 0.62%, precipitation will increase by 40% , surface evaporation will increase by 3.4%, soil water balance by 3.6% and runoff will increase by astonishing 312%. In the other hand under B2 scenario an increase of 3.1 degrees Celsius in temperature, an increase of 18.9% in evaporation and an increase of 36% in runoff are expected. A decrease of 4% in surface wind speeds and a decrease of 7% in precipitation are expected in this region under B2 scenario.

Table 5.2: Climate fields of Central region.

Climate Field	A2_Scen	Historical	B2_Scen	A2_Change	B2_Change	A2_%	B2_%
T (^oC)	30.627	26.356	29.441	4.271	3.085	16.205	11.706
W (m/s)	4.369	4.343	4.162	0.027	-0.181	0.617	-4.161
P (mm/day)	0.331	0.235	0.219	0.096	-0.017	40.766	-7.167
E (mm/day)	0.861	0.832	0.99	0.029	0.157	3.44	18.913
Q (mm/day)	0.006	0.001	0.002	0.005	0.001	311.97	36.154
P –E (mm/day)	-0.575	-0.597	-0.739	0.022	-0.142	3.636	-23.857

1.3. Western Region

All climate fields indicate an increase under A2 scenario in this region (Table 5.3). An increase of 4.1 degrees in temperature, an increase of 0.19% in surface wind speeds, an increase of 40% in precipitation, an increase of 1.9% in evaporation, an increase of 3.3% in soil water balance and an increase of 353% in runoff are expected. Under B2 scenario there are expectations that temperature will increase by 3.02 degrees Celsius, evaporation will increase by 25.5%, runoff will increase by 42%, wind speeds will decrease by 5.4%, precipitation will decrease by 12.2% and soil water balance will decrease by 30.6%.

Table 5.3: Climate fields of Western region.

Climate Field	A2_Scen	Historical	B2_Scen	A2_Change	B2_Change	A2_%	B2_%
T (^{o}C)	30.508	26.379	29.397	4.129	3.018	15.651	11.442
W (m/s)	4.409	4.401	4.162	0.008	-0.239	0.19	-5.433
P (mm/day)	0.249	0.177	0.156	0.071	-0.022	40.292	-12.206
E (mm/day)	0.962	0.944	1.184	0.018	0.24	1.931	25.47
Q (mm/day)	0.005	0.001	0.002	0.004	0	353.34	41.97
P–E (mm/day)	-0.741	-0.766	-1	0.025	-0.234	3.293	-30.6

1.4. Northern Region

There is a temperature increase of 4.3 and 3.0 degrees Celsius for A2 and B2 scenarios respectively. Evaporation is expected to increase by 1.2% and runoff by 101% under A2 scenario. Both precipitation and surface wind speeds will decrease in A2 and B2 scenarios. Precipitation will decrease by 4.1% and 11%, and surface wind speeds will decrease by 1.2% and 4.4% for A2 and B2 scenarios respectively. Soil water balances will decrease by 2.6% under A2 scenario, while it will increase by 9.8% under B2 scenario (Table 5.4).

Table 5.4: Climate fields of Northern region.

Climate Field	A2_Scen	Historical	B2_Scen	A2_Change	B2_Change	A2_%	B2_%
T (^{o}C)	26.561	22.275	25.294	4.286	3.019	19.239	13.552
W (m/s)	4.095	4.145	3.963	-0.05	-0.182	-1.194	-4.38
P (mm/day)	0.219	0.229	0.204	-0.009	-0.024	-4.081	-10.699
E (mm/day)	0.755	0.746	0.672	0.009	-0.074	1.243	-9.949
Q (mm/day)	0.002	0.001	0.001	0.001	0	101.31	-21.944
P –E (mm/day)	-0.531	-0.518	-0.467	-0.013	0.051	-2.559	9.763

1.5. Southern Region

All climate fields are expected to increase under A2 scenario (Table 5.5). Temperature will increase by 3.9 degrees Celsius, surface wind speeds will increase by 1.2%, precipitation will increase by 35.7%, evaporation will increase by 15.4%, soil water balance will increase by 6.1% and runoff will increase by 233%. Temperature will increase under B2 scenario by 2.6 degrees Celsius, precipitation will increase by 19.7%, evaporation will increase by 22.2% and runoff will increase by 128%. Surface wind speeds will decrease by 2.3% and soil water balance will decrease by 24.9% under B2 scenario.

Table 5.5: Climate fields of Southern region.

Climate Field	A2_Scen	Historical	B2_Scen	A2_Change	B2_Change	A2_%	B2_%
T (^{o}C)	30.921	27.023	29.642	3.897	2.619	14.422	9.691
W (m/s)	4.134	4.085	3.991	0.049	-0.094	1.197	-2.301
P (mm/day)	1.005	0.74	0.886	0.264	0.146	35.69	19.664
E (mm/day)	1.483	1.286	1.571	0.197	0.285	15.352	22.195
Q (mm/day)	0.007	0.002	0.004	0.005	0.003	233.38	127.69
P –E (mm/day)	-0.512	-0.546	-0.681	0.033	-0.136	6.124	-24.868

1.6. Empty Quarter Region

An increase of all climate fields is expected under A2 scenario (Table 5.6). Temperature will increase by 3.2 degrees Celsius, Surface wind speeds will increase by 1.8%, precipitation will increase by 38.4%, evaporation will increase by 10.8% soil water balance will increase by 3.6% and runoff will increase by 192%. Surface wind speeds and soil water balance are expected to decrease by 0.60% and 16% respectively under B2 scenario. Temperature will increase by 3.2 degrees Celsius, precipitation will increase by 6.5%, evaporation will increase by 12.8% and runoff will increase by 233%.

Table 5.6: Climate fields of Empty Quarter region.

Climate Field	A2_Scen	Historical	B2_Scen	A2_Change	B2_Change	A2_%	B2_%
T (^{o}C)	31.887	27.649	30.805	4.238	3.156	15.328	11.415
W (m/s)	4.477	4.397	4.371	0.08	-0.026	1.827	-0.599
P (mm/day)	0.465	0.336	0.358	0.129	0.022	38.434	6.549
E (mm/day)	0.884	0.797	0.899	0.087	0.102	10.847	12.787
Q (mm/day)	0.005	0.002	0.005	0.003	0.004	192.19	233.26
P –E (mm/day)	-0.445	-0.462	-0.536	0.016	-0.074	3.564	-16.046

1.7. Climate Change by Locations

1.7.1. Temperature

Temperatures under A2 scenario are expected to increase 2.5 to 5.1 degrees Celsius with a mean increase of 4.4 degrees Celsius for all 37 locations. The biggest increase of 5.1 degrees Celsius is over Hafr Al Batin and the warmest mean temperature is expected over Obailah in the Empty Quarter with average daily temperature of 35.7 degrees Celsius. There are 15 locations in which the mean increase in temperature equals or greater than 4.8 degrees Celsius (Figure 5.1).

The mean daily temperature under B2 scenario will increase by 3.1 degrees Celsius at the end of the 21st century. Only Dharhan and Gizan had a decrease by a fraction of a degree (-0.19 and -0.67 degrees Celsius respectively) in the mean temperature change from historical records. The maximum difference is 4.9 degrees Celsius. There are 14 locations with a change in temperature greater than 3.5 degrees Celsius, but only Bisha stands with a maximum change of 4.9 degrees Celsius. The warmest temperature is still over Obaylah with a mean temperature of 34.4 degrees Celsius.

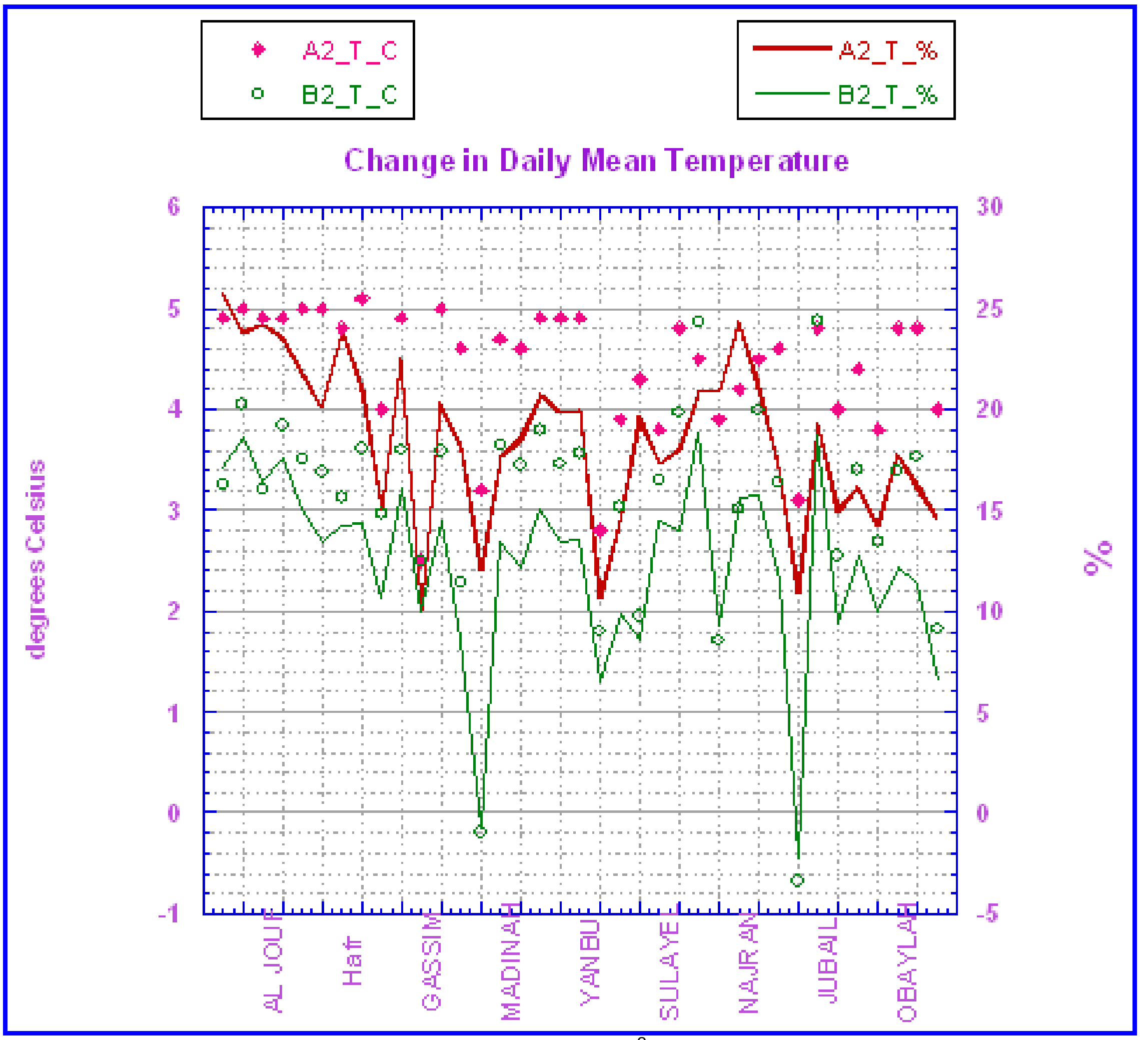

Figure 5.1: The change in daily mean temperature in ^{o}C for the 37 locations in Saudi Arabia for A2 and B2 scenarios.

1.7.2. Precipitation

Under A2 scenario, the average precipitation change for the selected locations is an increase of 39%, distributed in the range – 0.8% for Arar to 111.1% for Dhahran. From the 37 locations, there are 32 locations with a percentage increase of more than 20%, and 11 locations has a percentage increase of more than 50% (Figure 5.2).

Under B2 scenario, the average precipitation change is 6.7% with a maximum change of 57.5% over Guriat and a minimum change of -79.6% over Al Baha. There are 12 locations with a precipitation change of more than 20%.

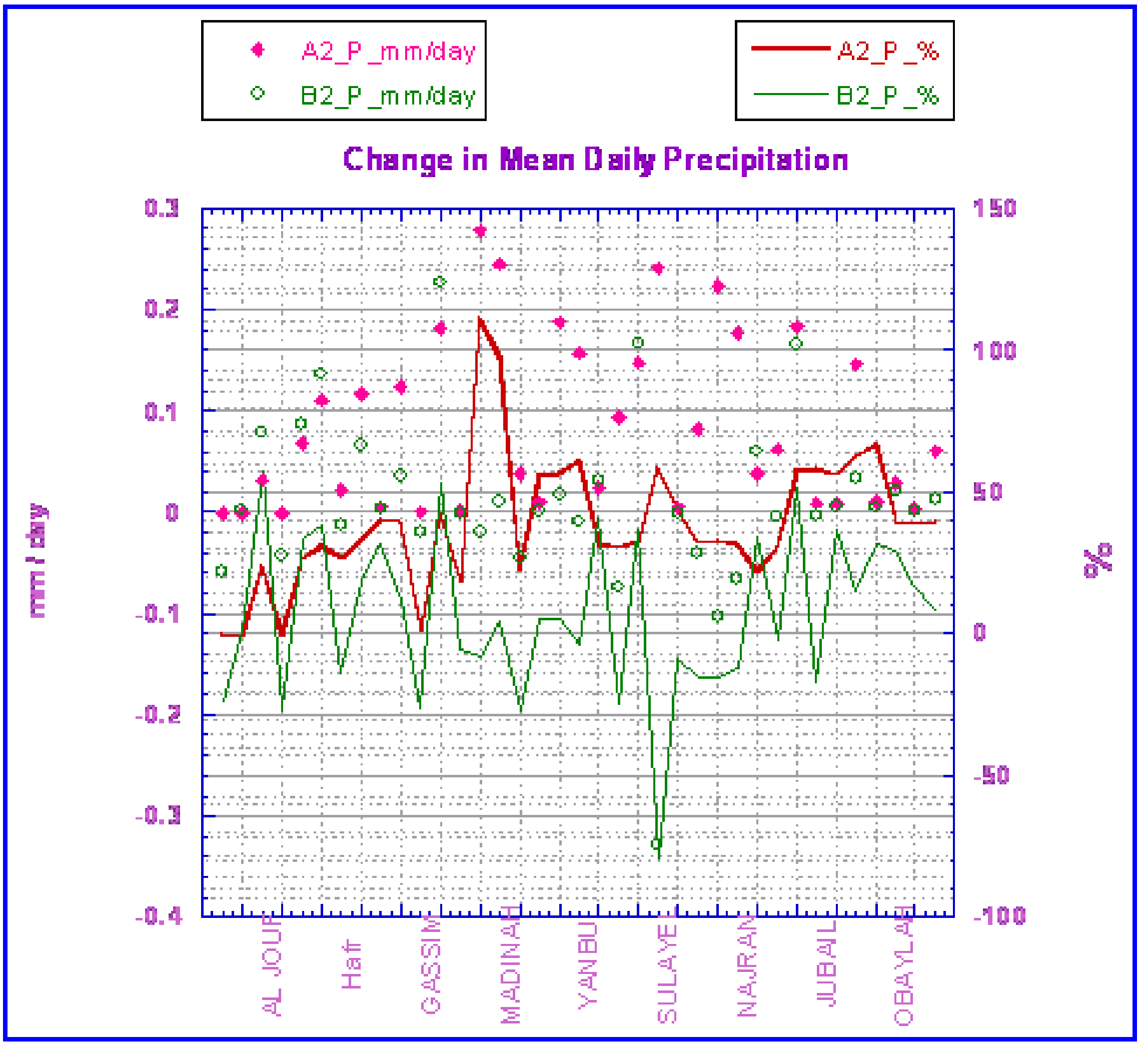

Figure 5.2: The change in daily mean precipitation in mm/day for the 37 locations in Saudi Arabia for A2 and B2 scenarios.

1.7.3. Surface Wind Speeds

Under A2 scenario, the average change of surface wind speeds at the end of the 21st century with respect to the baseline 1961-1990 is -4.4% with a maximum change of 25% over Sharorah and a minimum change of -64% at Al Ahsa. There are 14 locations with a positive change in surface wind speeds, and only 9 locations with a change less than 10%. (Figure 5.3).

Under B2 scenario, the mean change in surface wind speeds is 0.42% with a maximum change of 22.7% at Bisha, and a minimum change of -20.8% at Jeddah. There are only 5 locations with projected changes of less than -10% and there are 21 locations with positive changes.

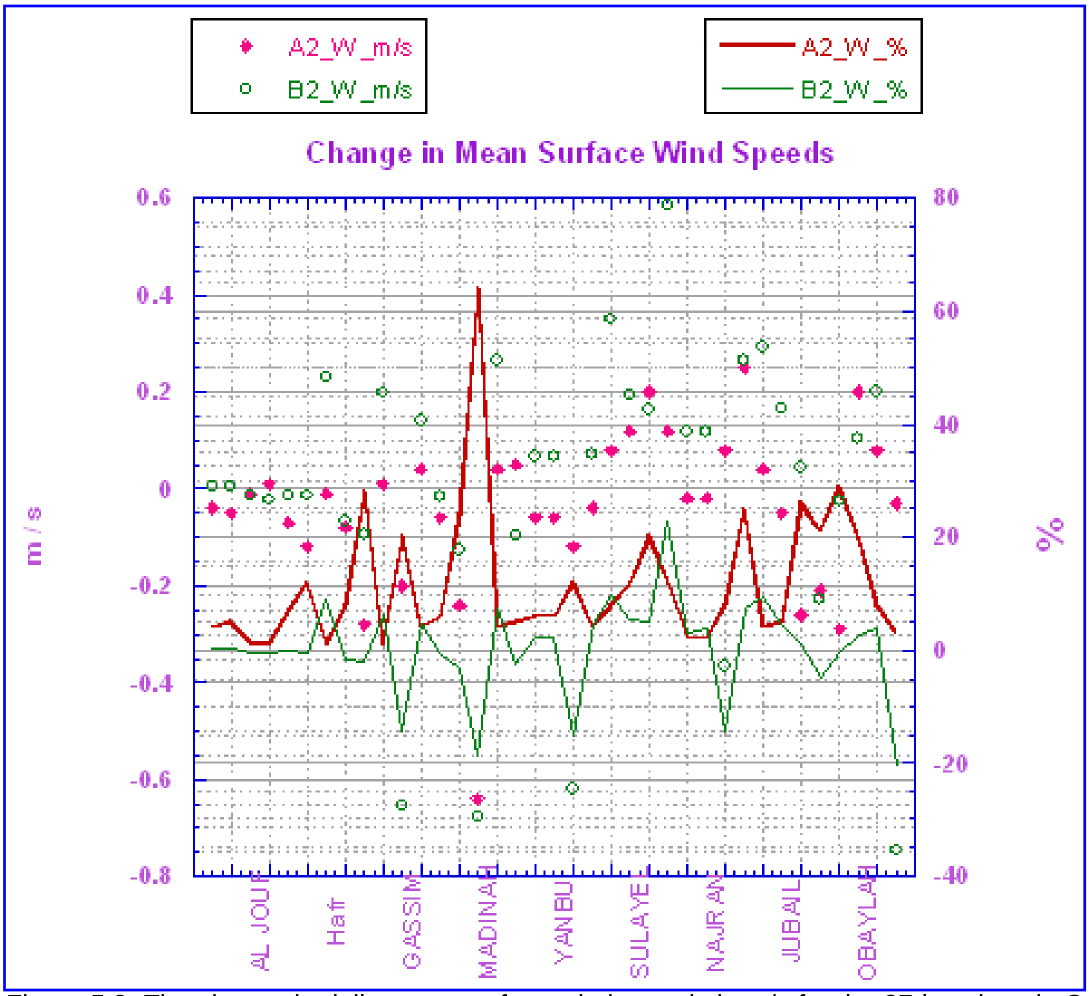

Figure 5.3: The change in daily mean surface wind speeds in m/s for the 37 locations in Saudi Arabia for A2 and B2 scenarios.

1.7.4. Surface Evaporation

Under A2 scenario, the average change of surface evaporation at the end of the 21st century with respect to the baseline 1961-1990 is 23.1% with a maximum change of 69.5% over Al Ahsa and a minimum change of -8.3% over Al Wejh. There are 29 locations with a positive change in surface evaporation, and only 9 locations with a change less than 5% (Figure 5.4).

Under B2 scenario, the mean change in surface evaporation is 7.4% with a maximum change of 300% at Jeddah, and a minimum change of -78% at Yanbu. There are only 5 locations with projected changes greater than 40% and there are 20 locations with positive changes (greater than zero).

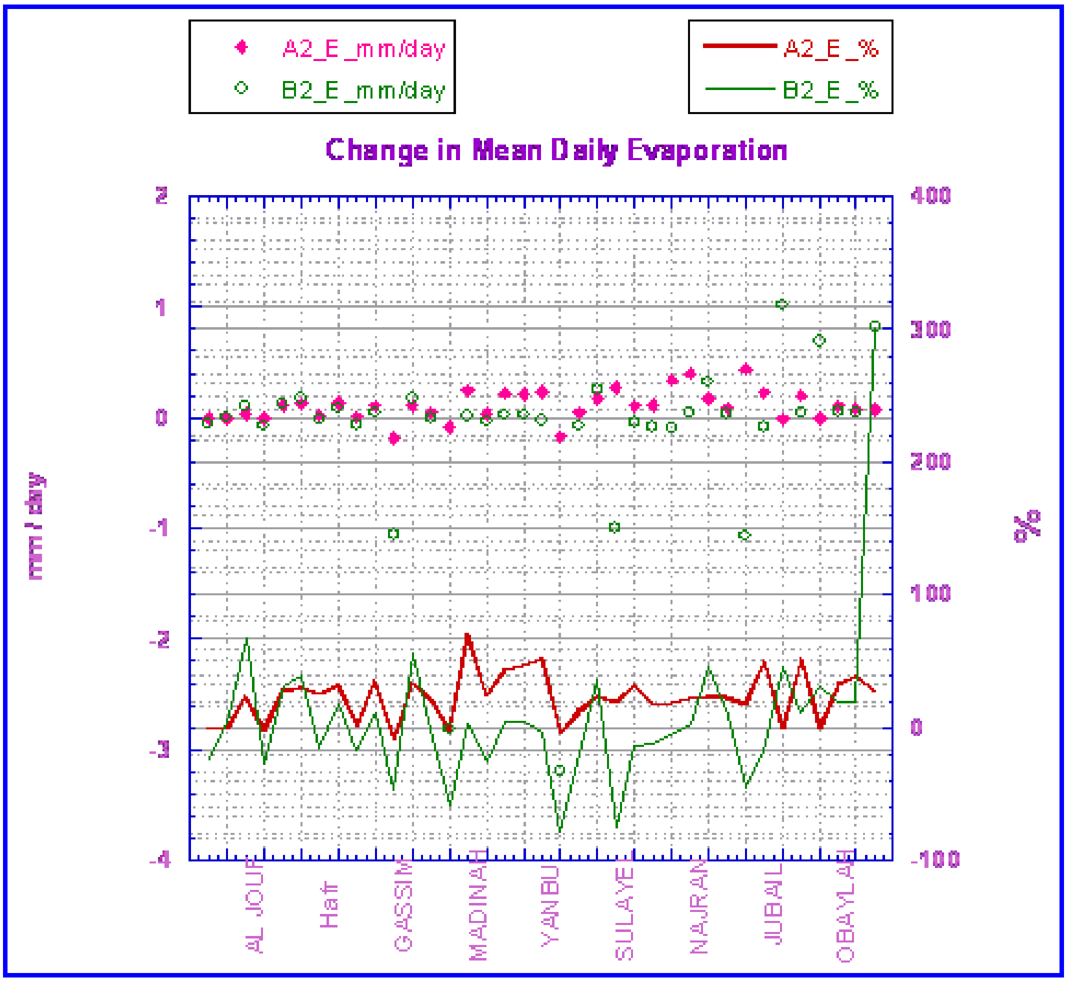

Figure 5.4: The change in daily mean surface evaporation in mm/day for the 37 locations in Saudi Arabia for A2 and B2 scenarios.

1.7.5. Soil Water Balance (P – E)

Under A2 scenario, the average change of soil water balance at the end of the 21st century with respect to the baseline 1961-1990 is 100.9% with a maximum change of 900% over Turaif and a minimum change of -2100% over Al Ahsa. There are 26 locations with a positive change in the soil water balance, and only 7 locations with a change of more than 300%. (Figure 5.9).

Under B2 scenario, the mean change in surface wind speeds is 93.4% with a maximum change of 2246.7% at Jeddah, and a minimum change of -416.2% at Wadi Dawasser (Figure 5.10). There are only 4 locations with projected changes of more than 200% and there are 24 locations with positive changes.

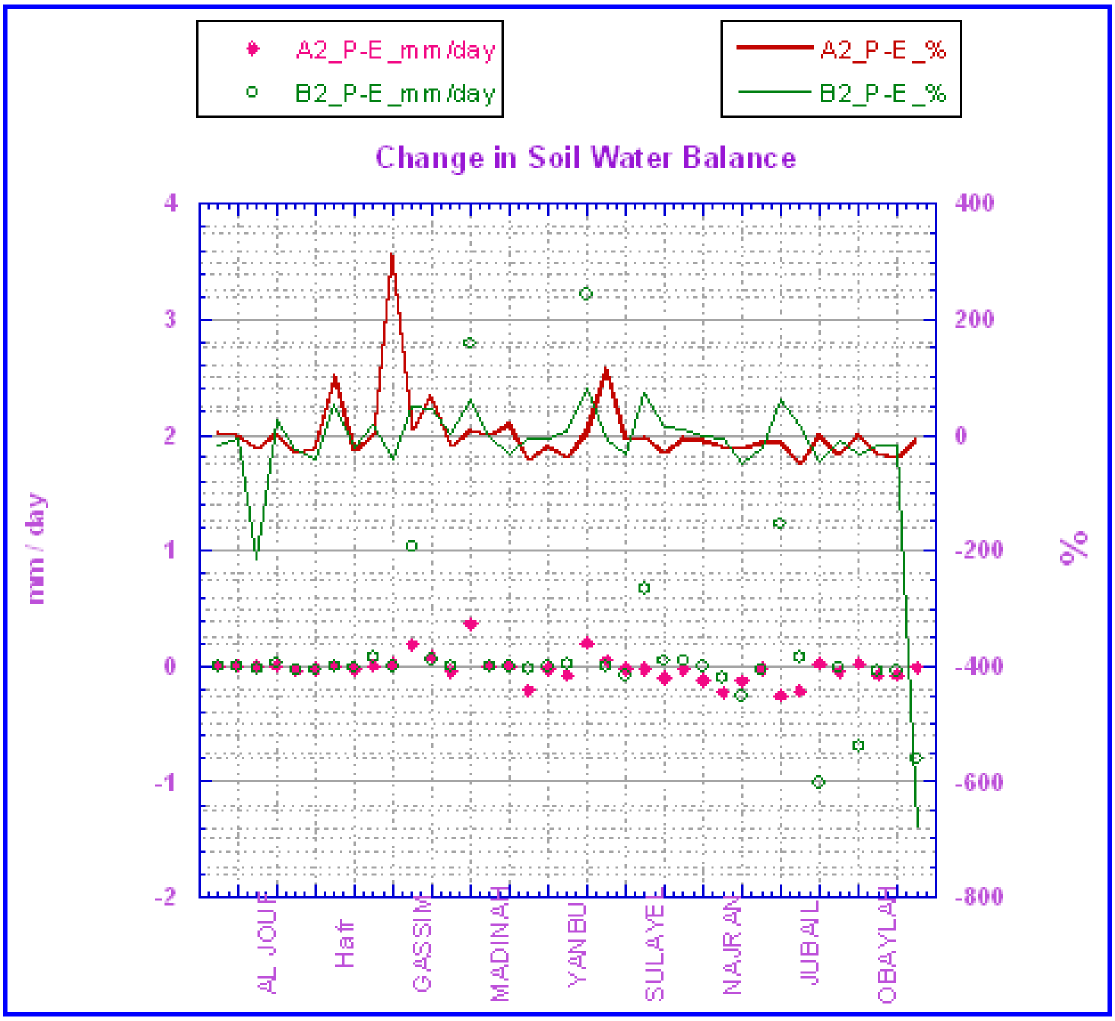

Figure 5.5: The change in daily mean soil water balance in mm/day for the 37 locations in Saudi Arabia for A2 and B2 scenarios.

Discussion

1. Statistical Interpretations

As the RCMs downscale data from GCMs, the error in the used GCM will be adopted by the RCM. PRECIS will always carry the modeling error of HadAM3p and its mother the AOGCM HadCM3 (Johns, et al., 2004). There are techniques some of which embodied in the PRECIS system to minimize the errors. The time needed to complete one experiment (approximately 3 months) limits the repetitions of experiments in order to run ensembles of future climate projections to further minimize the errors involved.

A2 and B2 scenarios were examined in terms of various statistical indicators, like the root mean square (RMS), the standard deviation, the variance, the standard error, the skewness and the kurtosis of all the daily data that span 30 years for each climate field for the six regions (Table 5.7) and for all the 37 locations (Table 5.8). The similarity among temperature values as averaged over all regions or averaged over all locations is apparent. The mean daily temperature of all the regions is slightly higher values than the corresponding values averaged over all locations. The standard deviation calculations over all six regions indicate that data are distributed wider (more spread) around the mean daily temperature for A2 scenario than for B2 scenario, but this is not true for standard deviation values averaged over all locations as data spread almost the same way under A2 and B2 scenarios. Daily temperature values has negative kurtosis which mean that the daily temperature values are distributed with a smaller peak than normal around the mean, and have lower probabilities than normally distributed variables of extreme values. The rest of climate fields have positive values for kurtosis, and the opposite holds. Big values of the kurtosis for precipitation and runoff indicate the present of few sharp peeks in the data contributing to the huge percentage increase in surface runoff.

Table 5.7: The mean of statistical summary of the values of the climate fields for the six regions.

	Temperature		Wind speeds		Precipitation		Evaporation		Runoff	
	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2
Minimum	12.4	10.1	2.4	2.6	7.4E-04	0.001	0.2	0.2	0	0
Maximum	41.6	39.6	8.1	7.5	2.6E+01	23.1	4.2	4.5	3.0	2.5
Mean	29.0	27.8	4.5	4.6	3.4E-01	0.3	1.0	1.1	0.004	0.003
Median	30.0	28.9	4.4	4.5	6.2E-02	0.1	0.9	1.0	5.2E-07	6.2E-07
RMS	29.9	28.7	4.6	4.6	1.2E+00	0.9	1.2	1.3	0.1	0.05
Std Deviation	7.0	6.9	0.8	0.7	1.2E+00	0.9	0.6	0.6	0.1	0.05
Variance	50.7	48.6	0.6	0.6	1.9E+00	1.1	0.3	0.4	0.01	0.005
Std Error	0.1	0.1	0.01	0.01	1.1E-02	0.01	0.01	0.01	0.001	0.0004
Skewness	-0.3	-0.3	0.4	0.4	1.0E+01	12.2	1.3	1.2	33.8	38.2
Kurtosis	-1.2	-1.2	0.2	-0.02	1.6E+02	275.1	2.1	1.5	1574.4	1791.3

Table 5.8: The mean of statistical summary of the values of the climate fields for all 37 locations.

	Temperature		Wind speeds		Precipitation		Evaporation	
	A2	B2	A2	B2	A2	B2	A2	B2
Minimum	8.9	4.6	1.0	1.1	-3.3E-08	-3.4E-08	0.03	0.01
Maximum	44.0	42.5	10.8	10.3	132.7	80.1	8.9	7.o
Mean	28.7	27.3	4.1	4.1	0.5	0.4	1.1	0.8
Median	29.6	28.3	3.9	3.9	0.01	0.01	0.8	0.5
RMS	29.8	28.5	4.3	4.3	3.3	2.2	1.6	1.2
Std Deviation	7.7	7.8	1.4	1.3	3.3	2.1	1.1	0.8
Variance	65.2	66.1	2.0	2.0	25.4	10.5	2.2	1.1
Std Error	0.07	0.1	0.01	0.01	0.03	0.02	0.01	0.008
Skewness	-0.2	-0.3	0.7	0.6	21.9	20.1	3.7	3.8
Kurtosis	-1.1	-1.1	0.5	0.4	784.0	655.7	20.1	21.6

2. Climate Change over Saudi Arabia

The climate changes for all fields are stronger under A2 scenario than B2 scenario. The averages of all the six regions covering Saudi Arabia under A2 scenario indicate an increase in temperature, precipitation, evaporation, wind speeds, runoff and soil water balance, while surface wind speeds and soil water balance experience a decrease under B2 scenario (Table 5.9). Daily average temperature is projected to increase by 4.2 degrees Celsius which is a 16.5 % of the historical value under A2 scenario, and about 3.0 degrees Celsius which is 11.8 % increase under B2 scenario. An increase of 30.2 % in precipitation is projected for the future which is an increase of 37.7 millimeters per year (mm/y) for A2 scenario, and an increase of 8.3 % of precipitation (9.8 mm / y) is projected under B2 scenario. Under A2 scenario the evaporation increase is only 6.5 % (20.8 mm/y) which is less than half the increase under B2 scenario (15.2 % or 48.9 mm / y). Soil water balance (Precipitation - Evaporation) is expected to increase by 3.0 % or 6.2 mm/y under A2 scenario, while it is expected to decrease by 16.4 % under B2 scenario. Runoff is projected to increase by 230.8 % (1.1 mm/y) and by 94.1 % (0.5 mm / y) for A2 and B2 scenarios respectively. Only a slight increase of 0.01 meters per second in wind speeds is projected (0.2 %) under A2 scenario, while a decrease of wind speeds by 3.2 % is projected under B2 scenario.

Table 5.9: Average calculation of the climate fields for all Saudi Arabia.

	A2_Scenario	Historical	B2_Scenario	A2_Change	B2_Change	A2_%	B2_%
Temperature (^{o}C)	29.891	25.676	28.709	4.216	3.033	16.419	11.813
Wind Speeds (m/s)	4.274	4.264	4.129	0.01	-0.135	0.234	-3.158
Precipitation (mm/y)	156.148	118.408	128.193	37.74	9.785	31.873	8.264
Evaporation (mm/y)	341.319	320.531	369.401	20.788	48.87	6.486	15.247
Run Off (mm/y)	1.643	0.497	0.964	1.147	0.467	230.823	94.051
Soil water balance (mm/y)	-0.544	-0.561	-0.661	0.017	-0.099	3.043	-16.359

Further Plans and Recommendations

1. Future Experiments

A continuous investigation on the impacts of climate change over Saudi Arabia is needed. The data from various GCMs and for several scenarios under different boundary conditions is available for PRECIS to run and generate high resolution scenarios. The impacts of climate change over the periods 2010 to 2040 is more attractive to hydrologists and politicians. Investigating the effects of the changes in climate over Saudi Arabia will be a pioneering work for the years 2040 to 2070. This methodology can enrich knowledge of the possible climate impacts on energy, agriculture, human health and various national resources. The fact that Saudi Arabia is a developing country does not mean we are out of reach of the finest, most advanced and best available technology to assess impacts of climate change. Saudi Arabia can take advantage of this capability to generate high resolution climate scenarios to build a national atlas about possible changes of climate change and its impacts to be better prepared to plan and manage long terms national future.

2. National Climate Modeling Center

Establishment of a national center for climate modeling research will bring a great advantage. The preferred location for this center is the near future institution (2009) at King Abdullah University for Science and Technology (KAUST) as it has an institute dedicated to earth science computing. Climate modeling outputs can be generated by KAUST and become available for scientists from various fields to assess the impacts of climate change on health, agriculture and natural resources. The fastest and most advanced computers will aid highly in making semi operational climate predictions. This center will oversee all national reports about the status of climate change. A wide international cooperation adopted by KAUST can add very valuable advantage in providing the most suitable equipped laboratory for running our modeling experiments.

3. Concerned Scientists

This study is a window on the world of climate projections, and it is expected to generate interests from the scientific community. The world is observing sharp climate changes that cause devastations in some areas, and created food and water crises. Saudi Arabia is aware of the scarcity of water resources and established the largest desalination plants, built tens of dams and initiated precipitation enhancements programs to satisfy the increasing national water demand. Keeping up with the latest findings of future climate will improve our readiness to face an abrupt climate change, and help the nation to make effective water management plans.

Conclusion

This study raised important issues to be considered in the fields of water resources management with respect to climate change. The temperature increase is common in all regions under both A2 and B2 scenarios. An increase of 2.5 to 5.1 degrees Celsius under A2 scenario calls for concern in water demand. The precipitation increase of 30% to 41% in all regions of Saudi Arabia except the Northern region under A2 scenario is a surprising result as most of previous studies in the area expected a slight increase only (Meehl, et al., 2007). Other studies expected a decrease by 20 to 25 % in precipitation over Saudi Arabia during the 2050’s (Ragab, and Prudhomme, 2002). This wide variation could be due to the fact that the previous available studies were course with 500 km horizontal resolution, and therefore a bigger uncertainty in projecting the future (section 2.6). On the other hand, PRECIS has a negative bias of 23% of mean daily precipitation (section 2.5.2) which indicates a possible decrease of the projected future precipitation. This could mean that bigger values of future precipitation than presented in this research are possible over Saudi Arabia.

Continuing research will lead to better and more precise information about the impacts of climate change on water resources over Saudi Arabia. Using PRECIS system opens doors to generate high resolution climate change scenarios and to investigate their impacts on a regional scale. This will expand knowledge producing valuable information about future climate change impacts on natural resources in Saudi Arabia.

Acknowledgement

The author thanks the Presidency of Meteorology and Environment for their kind cooperation, assistance and support throughout the research period.

References

1. Abderrahman, W. A., Al-Harazin, I. M., 2003, The Impacts of Global Climatic Change on Reference Crop Evapotranspiration, Irrigation Water Demands, Soil Salinity, and Desertification in Arabian Peninsula, Desertification in the Third Millennium, edited by A.S. Alsharhan, W.W. Wood, A.S. Goudie, A. Fowler and E. Abdeeatif, A.A. Balkema/Swets & Zeitlinger, Rotterdam, The Netherlands, p

2. Abderrahman, W. A., Al-Harazin, I. M., 2008, Assessment of climate changes on water resources in the Kingdom of Saudi Arabia, GCC Environment and Sustainable Development Symposium, 28 – 30 January 2008, Dhahran, Saudi Arabia, pp D-1-1 – D-1-13.

3. Abderrahman, W. A., Ukayli, M., 1984, Strategy of Groundwater Use in Al-Hassa Region of Saudi Arabia, International Journal of Water Resources Development, 2, pp. 45-57.

4. Abderrahman, W. A., Rasheeduddin, M., 2001, Management of Groundwater Resources in Eastern Saudi Arabia, International Journal of Water Resources Development, 17, pp. 185-210

5. Ahrens, D., 2000, Meteorology Today, Brooks/Cole, Pacific Grove.

6. Alkolibi, Fahad M., 2002, Possible Effects of Global Warming on Agriculture and Water Resources in Saudi Arabia: Impacts and Responses, Climatic change 54: 225-245.

7. Beraki, A., Climate Change Scenario Simulations over Eritrea by Using a Fine Resolution Limited Area Climate Model: Temperature and Moisture

Sensitivity, 2005, A Master in science thesis at University of Pretoria, South Africa.

8. Brohan, P., Kennedy, J., Harris, I., Tett, S., Jones, P., 2006, Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850, J. Geophysical Research 111, D12106, doi: 10.1029/2005JD006548, 2006

9. Burdon, D. J., Hydrogeological conditions in the Middle East, 1982, Quarterly Journal of Engineering Geology and Hydrogeology, v. 15, p. 71-82.

10. Cunningham, W., Cunningham, M., 2004, Principles of Environmental Science, Mc Graw Hill.

11. Fleitmann, D., Matter, A., Pint,J.J., and Al-Shanti, M.A. 2004, The speleothem record of climate change in Saudi Arabia: Saudi Geological Survey Open-File Report SGS-OF-2004-8, 40 p., 24 figs, 8 tables, 1 app.

12. Fowler, H.J., Ekstrom, M., Kilsby, C.G., Jones, P.D., 2004, New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. 1. Assessment of control climate. Journal of Hydrology 2004; 300 (2005), pp. 212-233.

13. Fowler, H.J., Ekstrom, M., Kilsby, C.G., Jones, P.D., 2004, New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. 2. Future estimates and use in impact studies. Journal of Hydrology 2004; 300 (2005), pp. 234-251.

14. Gleick, P., 1987, Methods For Evaluating The Regional Hydrologic Impacts of Global Climatic Changes, Journal of Hydrology, 88, 1986, 97-116.

15. Gleick, P., 2006, The World's Water 2006-2007, Pacific Institute for Studies in Development, Environment, and Security, Washington, DC, USA, 2006.

16. Graham, L., Rummukainen, M., Gardelin, M., Bergstrom, S., 2001, Modeling Climate Change Impacts on Water Resources in the Swedish Regional Climate Modeling Programme, Detecting and Modeling Regional Climate Change / M. Brunet and D. Lopez, eds., Springer, 2001, pp. 567-580.

17. Hadley Centre, 2003, Climate Change Observations and Predictions: Recent research on climate change science from the Hadley Centre, U.K. Met Office's Hadley Centre. Available online at: http://www.cru.uea.ac.uk/ downloaded on January 25th, 2006.

18. Houghton, John, 2004, Global Warming: The Complete Briefing, Cambridge University Press.
19. IPCC (Intergovernmental Panel on Climate Change) 1988, The Regional Impacts of Climate Change: An Assessment of Vulnerability, Cambridge University Press.

20. Cubasch, U., Meehl, G., Boer, G., Stoufer, R., Dix, M., Noda, A., Senior, C., Raper, S., Yap, K., 2001: Projections of Future Climate Change. In IPCC WG1 TAR, 2001.

21. IPCC (Intergovernmental Panel on Climate Change) 2001, Climate Change 2oo1: The Scientific Basis, Cambridge University Press.

22. Johnes, R.G., Noguer, M., Hassell, D.C., Hudson, D., Wilson, S.S., Jenkins, G.J. and Mitchell, J.F.B., 2004, Generating high resolution climate change scenarios using PRECIS, Met Office Hadley Centre, Exeter, UK, 40pp.

23. Kumar, K., Sahai, A., Kumar, K., Patwardhan, S., Mishra, P., Revadekar, J., Kamala, K., Pant, G., 2006, High-resolution climate change scenarios for India for the 21st century, Current Science, vol. 90, No. 3, 10 February 2006.

24. Mearns, L. O., Giorgi, F., Wetton, P., Pabon, D., Hulme, M., Lal, M., 2003, Guidelines for use of climate scenarios developed from regional climate model experiments. IPCC task group on scenarios for climate impact assessment guidance note.

25. Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper,I.G. Watterson, A.J. Weaver and Z.-C. Zhao, 2007: Global Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S.,D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

26. Ministry of Agriculture and Water, 1995, The Kingdom of Saudi Arabia: The Land Resources, Obeikkan, Riyadh, Saudi Arabia.

27. Sorooshian, S., Lawford, R., Rossow, W., Try, P., Roads, J., Polcher, J., Sommeria, G., Schiffer, R., 2005, Water and Energy Cycle: Investigating the links, Bulletin of the World Meteorological Organization (WMO), Vol. 54, pp. 58-64

28. Rajab, R., Prudhomme, C., 2002, Climate Change on Water Resources Management in Arid and Semi-arid Regions: Prospective and Challenges for the 21st Century, Biosystems Engineering, 2002, 81 (1), 3-34.
29. Shareef, M, 1998, Multi-objective Water Resources Planning under Demand, Supply and Quality Uncertainties, Master of Science thesis, KFUPM, Saudi Arabia, 1998.

30. Serrat-Capdevila, A., Valdes, J., Perez, J., Baird, K., Mata, L., Maddock III, T., 2007, Modeling climate change impacts – and uncertainty – on the hydrology of riparian system : The San Pedro Basin (Arizona/Sonora), Journal of Hydrology, 2007, 347, 48-66.

31. Tao, F., Hayashi, Y., Zhang, Z., Sakamoto, T., Yokozawa, M., 2007, Global warming, rice production, and water use in China: Developing a probabilistic assessment, Agricultural and forest meteorology, 2007, AGMAT-3787

32. Treut, Le, Somerville, H., Cubasch, U., Ding, Y., Mauritzen, C., Mokssit, A., Peterson, T., Prather, M., 2007: Historical Overview of Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

33. UNU Global Environmental Forum V, 1997, Freshwater Resources in Arid Lands, United Nations University Press, Tokyo.

34. Uppala, S., Kallberg, P., Simmons, A., Andrae, U., da Costa Bechtold, V., Fiorino, M., Gibson, J. Haseler, J., Hemandez, A., Kelly, G., Li, X., Onogi, K., Saainen, S., Sokka, N., Allan, R., Andersson, E., Arpe, K., Balmaseda, M., Beljaars, A., van de Berg, L., Bidiot, J., Bormann, N., Calres, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Holm, E., Hoskins, B., Isaksen, L., Janssen, P., Jenne, R., McNaily, A., Mahfouf, J., Morcrette, J., Rayner, N., Saunders, R., Simon, P., Sterl, A., Treberth, K., Untch, A., Vasiljevic, D., Viterbo, P., Woollen, J., 2005, The ERA-40 re-analysis, Quarterly Journal, Royal Meteorological Society, 131, 2961-3012.do:10.1256/qj.04.176

35. Wilson, S., Hassell, D., Hein, D., Jones, R., Taylor, R., 2007, Installing and using the Hadley Centre regional climate modeling system, PRECIS, UK Met Office, Hadley Centre, Exeter, UK.

36. Wigley, T., 2002, MAGICC/SCENGEN 4.1 User and Technical Manuals, http://www.cgd.ucar.edu/cas/wigley/magicc/index.html (accessed on May 2008).

37. Yinlong, X., Xiaoying, H., Yong, Z., Wantao, L., Erda, L., 2006, Statistical analyses of climate change scenarios over China in the 21st Century, Advanced in climate change research, Article ID: 1673-1719, 2006, Suppl. 1-0050-04

Electronic References

1. United Kingdom Meteorological Office: http://www.metoffice.gov.uk

2. PRECIS website: http://www.precis.org.uk

3. The United Nations Framework Convection on Climate Change (UNFCCC): http://unfccc.int

4. United Nations Devission for Sustainable Development: http://www.un.org/geninfo/bp/enviro.html

5. Climate Research Unit at University of East Anglia, UK: http://www.cru.uea.ac.uk/cru/info/modelcc/