POSSIBLE EFFECTS OF GLOBAL WARMING ON AGRICULTURE AND WATER RESOURCES IN SAUDI ARABIA: IMPACTS AND RESPONSES

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Abstract. This study assesses the possible impact of climatic change on Saudi Arabia's agriculture and water supplies using climatic change scenarios from GCMs (General Circulation Models) and related research. The resulting assessment indicates that an increase in temperature and decrease in precipitation could have a major negative impact on agriculture and water supplies in Saudi Arabia. To find signs of climatic change in Saudi Arabia a preliminary assessment of systematic changes in temperature and precipitation was made, based on the records of four Saudi weather stations. The analysis of this data, which dates back to 1961, shows no discernable signs of climatic change during the study period. Such data is, however, limited both spatially and temporally and cannot provide conclusive evidence to confirm climatic changes projected by GCMs. Nevertheless, in the light of recent climatic conditions and rapid population growth, Saudi decision-makers are urged to adopt a 'no regret' policy. Ideally, such a policy would include measures to avoid future environmental or socioeconomic problems that may occur in the event of significant climatic change.

1. Introduction

Saudi Arabia, one of the driest and hottest countries in the world, is roughly located between north latitudes 17 and 31 and east longitudes 37 and 56. Except for the southwestern mountains, the average annual precipitation in the Kingdom ranges from 80 mm to 140 mm. Maximum summer temperatures often exceed 45 degrees Celsius, relative humidity is very low and skies are clear most of the time.

High temperatures and low precipitation together with high variability of both factors increase evapotranspiration, reduce soil moisture, and damage the soil by mechanical weathering. These conditions have a negative impact on agriculture and water availability and render Saudi Arabia a very poor country in terms of agricultural potential and water resources. Any increase in temperature, decrease in precipitation, or change in their variability as expressed by General Circulation Models (GCMs), may adversely effect climatic conditions in Saudi Arabia. Changing climatic conditions may have deleterious consequences in many areas, particularly with regard to water supplies for agricultural, domestic, and municipal use.

This paper aims to examine the impact of possible global warming trends on agriculture and water resources in Saudi Arabia with a view to suggesting appropriate responses to such trends. The first task will be to provide a general review

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of the existing literature to find out whether Saudi Arabia is included within areas thought to be vulnerable to climatic change. Here, we will consider the possible impact of predicted climatic change on agriculture and water supplies in the country. The second task will be to provide a preliminary assessment of any systematic changes in temperature and precipitation in Saudi Arabia over the period 1961–1997. Such an assessment is important since it sheds light upon possible changes in the climate of the study area as postulated by GCMs. The paper concludes by suggesting appropriate responses to the possible effects of climatic change upon agriculture and water supplies in the country.

2. GCM Predictions for Saudi Arabia

General Circulation Models (GCMs) are mathematical representations of atmospheric, oceanic, and continental processes and interactions. These models can be formulated in terms of equations processed by computers (Hillel and Rosenzweig, 1989). GCM computer models can take a long time to calculate because they utilize a very large number of variables upon which a set of complicated mathematical equations are applied. For instance, to complete the modeling experiment for the Hadley Center a GCM requires three months on one of the world's fastest supercomputers (WMOWMO, 1994).

GCMs are limited by complex as well as non-linear interactions among atmospheric and oceanic processes. This problem is discussed by Hillel and Rosenzweig (1989) who identify five main factors limiting these climatic models:

- poorly understood ocean circulation processes,
- lack of knowledge on cloud formation and feedback,
- crudely formulated hydrological processes,
- coarse spatial resolution, and,
- an inability to simulate current regional climates realistically.

Because of such limitations, GCM computer models are not in themselves considered to provide sufficient evidence of impending climatic change. Moreover, a fully realistic simulation of climatic change due to the combined effects of all anthropogenic and natural forcing mechanisms is yet to be developed (Barnett et al., 1999).

In spite of these limitations, GCMs are the most reliable predictors of climatic change available (Mintzer, 1993); there are strong similarities in the output of most known GCMs including the NASA, GISS, NCAR, and GFDC models. Most of these models suggest a global mean warming of 1.5° to 4 °C with doubling of the pre-industrial era CO_2 (Hansen et al., 1998).

Some of the most important GCM based predictions for tropical and subtropical regions, in which Saudi Arabia is located, indicate that:

– increase in surface warming and its seasonal variability are least in the tropics,
– there is little change in the subtropical arid areas,
– The Middle East, as a water-stressed region, will experience a decrease in the water supply.

The above scenarios are concluded by the Intergovernmental Panel on Climatic Change (Schneider, 1993).

Schmandt and Clarkson (1992) indicate that GCMs predict the following:

– warming will be more pronounced in winter than in summer across the globe, including the tropical deserts,
– reduced likelihood of rain in the Mediterranean and North Africa. This region includes Saudi Arabia,
– increased desiccation in continental interiors of the Northern Hemisphere, including the Arabian Peninsula.

Liverman (1992) indicates that the most serious reduction in precipitation will be felt in regions with insufficient rainfall under current conditions. Furthermore, Hillel and Rosenzweig (1989) indicate that exacerbated drought stress might occur particularly in the semiarid tropics and subtropics because of an increase of potential evapotranspiration.

While the GISS General Circulation Model suggests that increases of high-latitude glacial ice cover would strengthen winter Asian trade winds and impose cooler and drier conditions over Arabia (DeMenocal, 1993), global warming may conversely reduce high-latitude glacial ice cover and weaken the cold Asian trade winds. This, in turn, may increase the strength and the frequency of the warm southerly winds, leading to a rise in winter temperatures over Arabia and allowing more moisture to advance into the region bringing with it the possibility of more winter rainfall.

The change in temperature and precipitation predicted by GCMs for the Mediterranean region will affect water availability and resource management, critically shaping patterns of future crop production in the region (Rosenzweig and Tubiello, 1997).

In conclusion, GCM predictions indicate that the tropical deserts, including Saudi Arabia, will experience an increase in temperature and a decrease in precipitation and that the variability of both will increase. The combination of these factors will increase the evapotranspiration processes which will pose a multi-faceted threat to Saudi Arabia in general and to its agriculture and water supplies in particular.

3. Impact of Climatic Change in Saudi Arabia

The impact of climatic change will be negative in most regions of the globe. In fact, GCM scenarios suggest that the negative impact of climatic change to agriculture and water resources may even extend to wetland areas such as Bulgaria, the Czech Republic, and Russia (Hartig et al., 1997). However, the areas most vulnerable to climatic change are tropical and subtropical desert areas that already suffer adverse climatic conditions. Any rise in temperature or reduction in precipitation, along with increases in these factors' variability, will exacerbate the current negative impact of the climate in these areas, including Saudi Arabia. We will now review the impact of the predicted climatic change upon Saudi agriculture and water supplies.

3.1. IMPACT ON AGRICULTURE

Cultivated land in Saudi Arabia accounts for less than 1% of the total area (Saudi National Report to UNCED, 1992). The most important agricultural crops in Saudi Arabia are winter wheat, dates, vegetables, and citrus fruits. All of these crops depend on irrigation and may be adversely affected by climatic change. In Egypt, a neighboring subtropical country, a simulation study characterized potential yield and water use efficiency decreases on two reference crops in the main agricultural regions with possible future climatic change and variation (El-Shaer et al., 1997). Saudi Arabian crops, with so limited water resources, would be more vulnerable to such variations.

The winter wheat crop covers all wheat needs of the country. The main production areas are found in the central and northern regions. Saudi Arabia is one of the largest producers of dates in the world. The total date production in 1996 was 620,695 tonnes, with most of the production coming from the central and eastern regions (Alhudaithy, 2000). Vegetables are grown in most parts of the country and about 30% of vegetable crops are produced in greenhouses.

Projected climatic changes represent a great threat to these main crops. Even the relatively small projected temperature increase of about 1.5 °C in the lower latitudes would increase evapotranspiration by 5 to 15% (Parry and Swaminathan, 1992). The association between the high evapotranspiration and decrease in precipitation puts Saudi agriculture at high risk.

According to a quantitative estimate by the British Hadley Center GCM experiment (Had CM3), predicted climatic change is expected to lead to decreases in agricultural food production in arid regions located in the lower latitudes (Parry et al., 2000). This clearly applies to Saudi Arabia where, in recent times, there has been a high annual variation in crop yields. The reason for this is that about fifty percent of Saudi irrigation systems depend upon water tables in the valley basins that sometimes dry up as a result of low precipitation. Any increase in temperature and temperature variability, even with no decrease in precipitation, would increase crop yield variability.

In the case of increases in temperature, the most threatened product is winter wheat. With warmer temperatures, wheat production may shift north due to a lowering of winter chilling by between 10 to 30 percent for each 1 °C temperature increase. This tends to move thermal limits of cereal cropping northward by about 150–200 km in the middle latitudes (Parry and Swaminathan, 1993).

Winter wheat in tropical areas, including Saudi Arabia, is subject to variations in winter temperature because it grows in this tropical desert under its maximum temperature tolerance limits. In such cases an increase in temperature pushes the crop 'over the brink' and seriously affects crop yields in the country (Hillel and Rosenzweig, 1989).

About 30% of Saudi vegetable production is produced in greenhouses. The remaining vegetable crops, however, are highly affected by the recent fluctuations in temperature and precipitation and by the scarcity of water. This sometimes causes a shortage in these products. Any increase in temperature, decrease in precipitation, or increase in the variability of either, will put these crop yields at a high risk.

3.2. IMPACT ON WATER SUPPLY

Since Saudi Arabia is located in one of the driest regions in the world, shortage in water supplies represents a constant threat to life and development. Saudi Arabia has no perennial rivers and there is almost no surface water except for a few reservoirs that are dry for most of the year. Furthermore, the run-off rate in the country is one of the lowest in the world (Sagga, 1998). Predicted climate change will place additional stress on water resources in this arid country (Ferrari et al., 1999). Water supplies in the country are already under stress and threatened by depletion. Saudi water supplies fall under three categories: shallow groundwater, deep groundwater, and desalinated water.

3.2.1. *Shallow Groundwater*

Shallow groundwater is found in sediments and in weathered and fractured rocks. The quantity of shallow groundwater depends on the frequency and intensity of rainfall (Saudi National Report to UNCED, 1992). Except for the southwestern mountain region, the annual mean rainfall for most of the country is between 80 mm to 130 mm (Sagga, 1998). Shallow groundwater in Saudi Arabia dries up frequently as a result of low precipitation and excessive use.

3.2.2. *Deep Groundwater*

Deep groundwater is found in sedimentary rock areas as geological water stored in aquifers (Ministry of agriculture, Saudi Arabia, 1984). Due to very low precipitation, the huge withdrawal from the aquifers is not replenished by sufficient natural recharge. Most of the water supply for the country comes from these aquifers. This water is not only used for irrigation but also for drinking purposes in many parts of the country (Othman, 1983).

3.2.3. *Desalinated Water*

The production of desalinated water in the country, mostly from seawater, started in 1974 (Alshareef, 1995). Many places in the country, especially major cities, rely on desalinated water. The total production of desalinated water reached 9.1 million cubic meters per day in 1997 from twenty-seven water desalination plants (Sagga, 1998).

Excessive use of ground water and projected climatic change and variability threaten all available sources of water. In the not so distant past, there was a natural balance between the population and water supply. Whenever the population exceeded the availability of water people would migrate north. The population of Saudi Arabia has doubled at least four times since the 1950s (Muhamadeen, 2001). This increase is associated with rises in household water use (expressed in liters per person per day). In addition, the agricultural, municipal, and industrial use of water substantially increased in the last three decades. This has put tremendous pressure on natural sources of water, especially upon non-renewable resources which comprise about eighty-five percent of Saudi water supplies (Sagga, 1998).

Recently, Saudi Arabia has had one of the highest indexes of water shortage (the ratio of water demand to the available renewable water supply) in the world. Gleick (1992) listed Saudi Arabia as one of the few countries whose present water withdrawal exceeds one-third of the total renewable water supply. He also indicated that assuming an increase in population with no change in climate, water availability per capita would decrease from the recent 160 cubic meters per person per year, to 50 cubic meters per person per year by the year 2025. This is ten times less than the minimum requirement for a modern society in an arid region suggested by Falkenmark (1992). Anticipated water availability would be even less had projected climatic changes also been taken into account. A rising world population coupled with anticipated climatic changes will put even more stress on water resources, particularly in the arid regions (Ferrari et al., 1999). Consequently, future water scarcity in Saudi Arabia could be worse than currently anticipated.

4. Have Climatic Changes Started in Saudi Arabia?

In the last section, we examined the possible impact of climatic change on agriculture and water resources in Saudi Arabia. This section attempts to explore whether climatic changes have already begun in Saudi Arabia. To do this we will examine the temperature and precipitation records from the four oldest Saudi weather stations.

As presented in the previous section, many studies and computer models project global climatic change. It is not the purpose of this analysis to prove or disprove global climatic change but rather to find a statistical representation or sign of the projected climatic changes in this country.

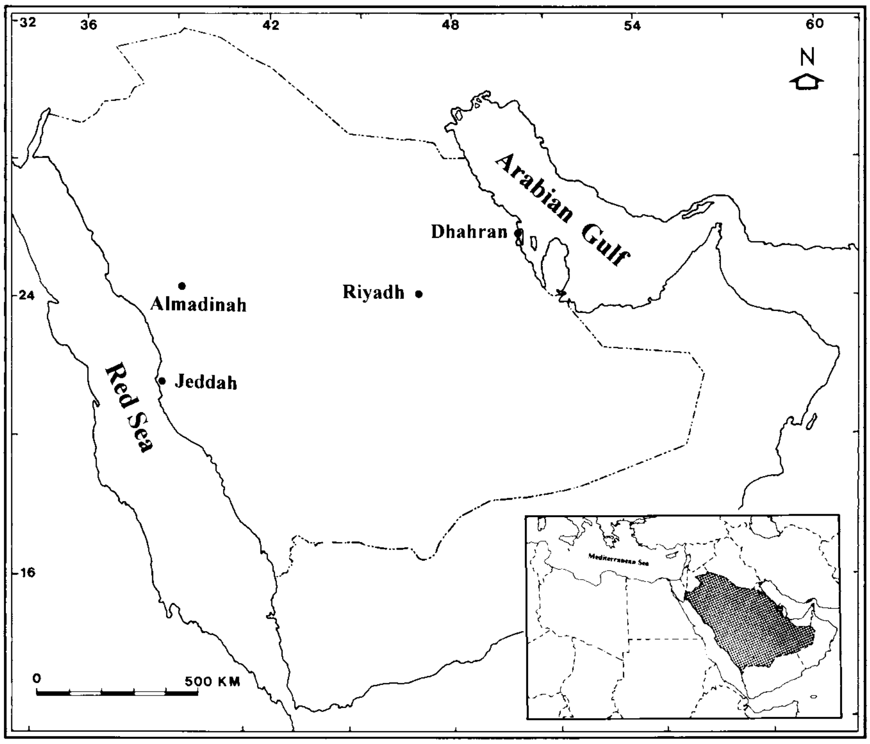

Figure 1. The locations of the studied climate stations.

4.1. DATA AND METHODOLOGY

To investigate the existence of any signs of climatic changes in Saudi Arabia the climatic data of temperature and precipitation for the four Saudi weather stations during the period 1961–1997 were analyzed. These four stations are located at Riyadh in the central part of the country, Dhahran in the east, Jeddah in the west, and Almadinah in the northwest. The special distribution of these four stations covers wide areas of the country (Figure 1). In addition to this, the climate records from Riyadh's new airport were utilized to investigate the nature of temperature trends in Riyadh. The record of the new airport station extends from 1985 to 1997. The weather stations studied are presented in Table I.

Both time series and regression analyses were used. A five-year centered moving average technique was employed. In this technique, each value of the actual observation is replaced by the average of the sum of the value itself plus the two preceding and the two subsequent values.

Five-year centered moving average and regression analyses covering the thirty-seven year period 1961–1997 for each of the four stations was applied to the following data:

Table I
Weather stations studied

Station	WMO code	Latitutde dg mn sc	Longitude dg mn sc	Elevation (meters)
Dhahran	40416	26 15 34N	50 09 39E	17
Jeddah	41024	21 40 42N	39 08 54E	4
Riyadh Old	40438	24 42 40N	46 44 18E	620
Riyadh New	40437	24 55 31N	46 43 19E	613
Almadinah	40430	24 32 53N	39 41 55E	626

– January and July mean temperatures;
– annual mean temperatures;
– annual total precipitation.

Twelve regression models were produced for the five-year centered moving averages of the temperature data for the four stations studied. These models represent the data for January and July, as well as the annual data. To investigate the precipitation trends, four regression models were produced for the five-year centered moving average of the annual total precipitation for the four stations.

4.1.1. *Temperature Trends*
Figure 2 represents linear regression models for the five-year centered moving averages of January mean temperatures at the four stations studied. These indicate no significant trends in mean January temperatures for the period of study at any station. While Jeddah and Dhahran, the coastal stations, do demonstrate slight decreases in mean temperatures this is not statistically significant.

Similarly, with the exception of Riyadh, linear regression models for the five-year centered moving average for July mean temperatures from the stations (Figure 3) do not show any significant variations. Riyadh station does exhibit a noticeable increase in temperature with $R^2 = 0.39$ and $F = 0.001$ – a significant value. However, we should remember that Riyadh has been developing tremendously during the past thirty-five years. The population of this city in the early sixties was around 100,000 and the old airport, at which Riyadh weather station is located, was then on the outskirts of the city. The current population of the city is about 4 million and the old airport now occupies a central location in the city. Considering the above factors, and since Riyadh weather station is the only studied weather station that does exhibit a noticeable increase in temperature, it can be suggested that the temperature record of Riyadh is affected by the heat island effect of the city, a non-climatic factor.

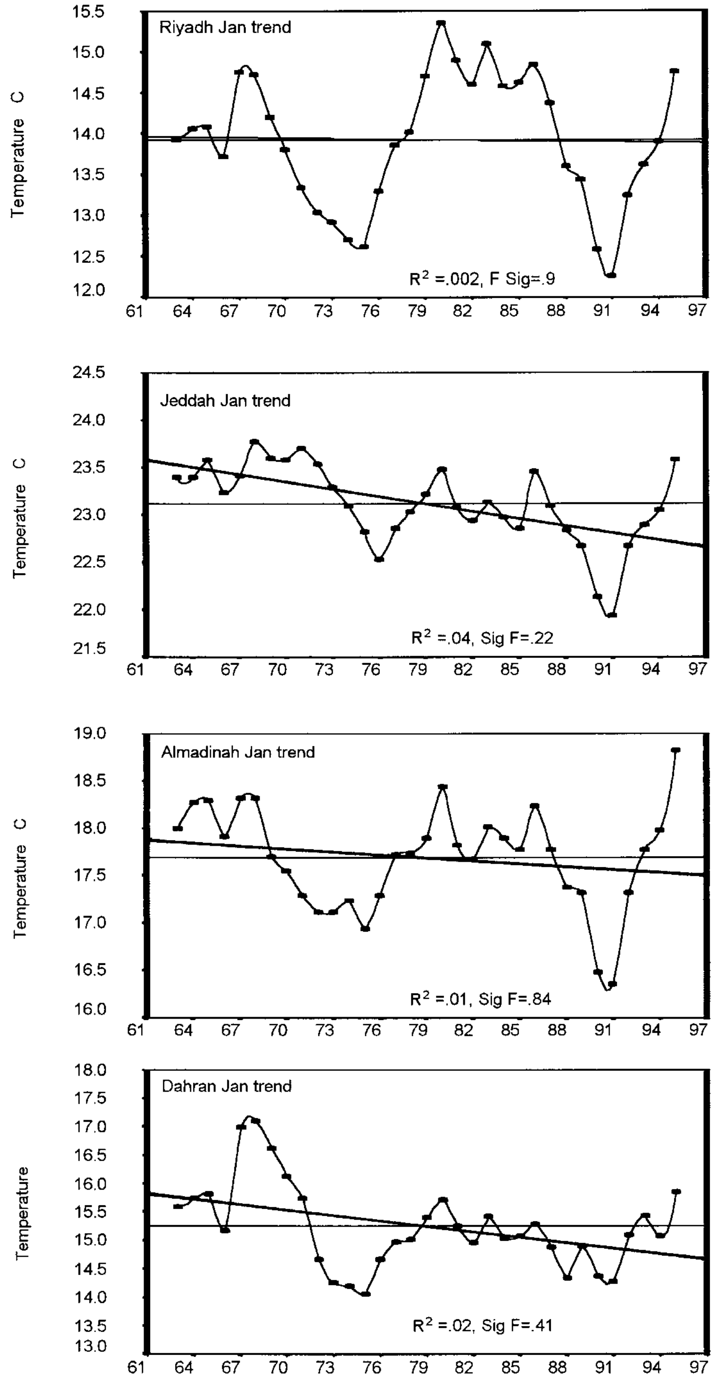

Figure 2. Linear regression models for the five-year centered moving averages of January mean temperature for the four stations studied. Thin line repesents the period mean and solid line represents the regression model line.

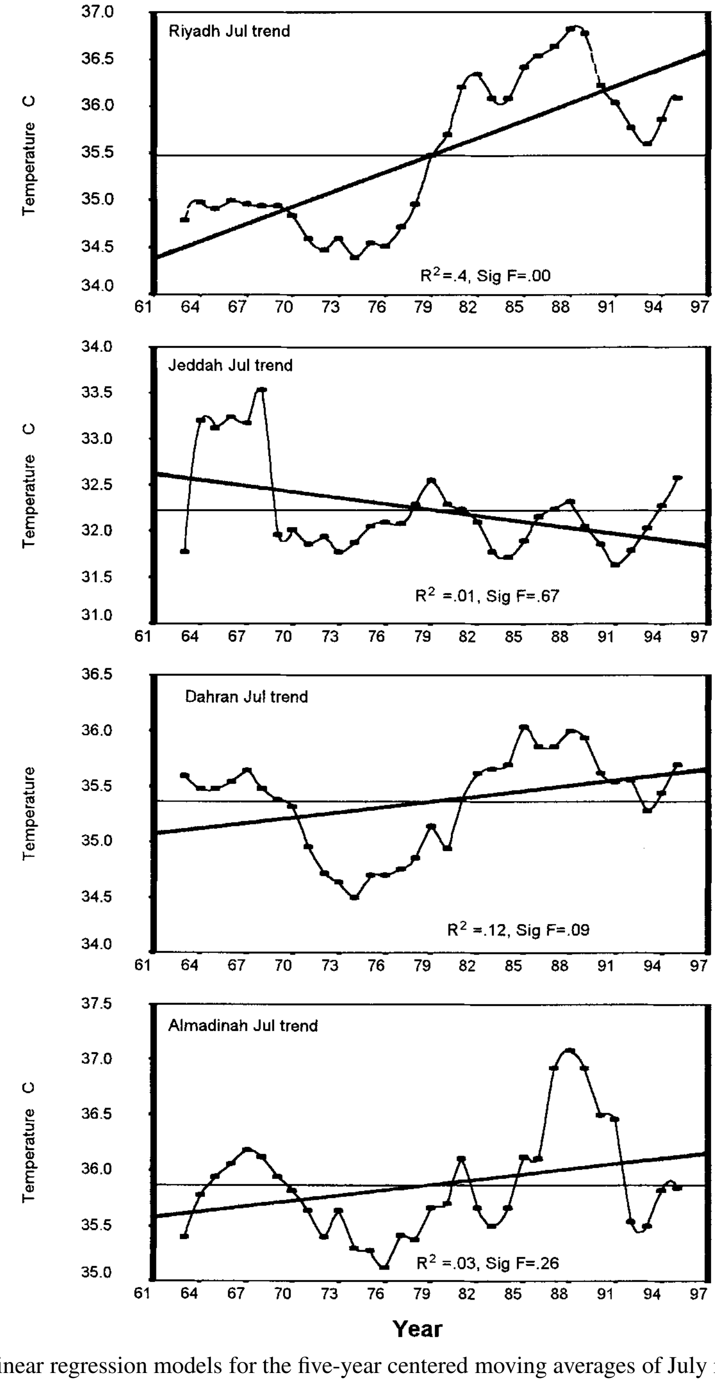

Figure 3. Linear regression models for the five-year centered moving averages of July mean temperature for the four stations studied. Thin line represents the period mean and solid line represents the regression model line.

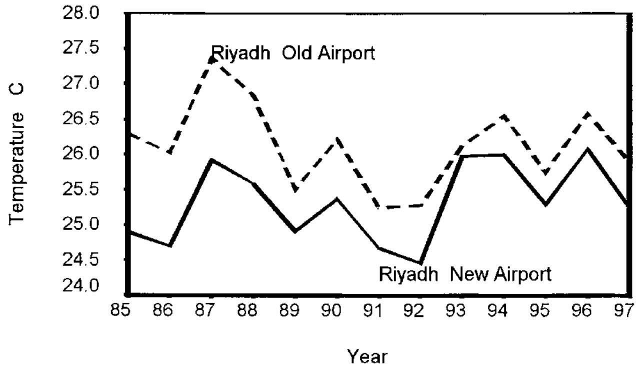

Figure 4. Annual mean temperature for Riyadh old station (dashed line) and Riyadh new station (solid line) from 1985 to 1997.

The heat island effect of big cities is a well-established phenomenon. In the last three decades, numerous articles have demonstrated the existence of this effect. Among them, Hjelmfelt (1982), Vukovich and King (1980), Shreffler (1979), and many others utilized the data of St. Louis Metropolitan Meteorological Experiment (METROMEX) to study the heat island of St. Louis. The main conclusion of these studies is that the temperature in a city center is greater than on its outskirts.

To determine whether the noticeable increase in Riyadh's temperature trend could be attributed to a heat island effect, the temperature records of the old airport station were compared to the temperature records of the new station at King Khalid International Airport, situated about 20 km northeast of the old airport.

The new airport weather station began keeping records in 1985 and the two stations have same topographical features. The temperature time series between 1985 and 1997 for both the old and the new airport stations were compared. The results, presented in Figure 4 and Table II, indicate that there was about one degree Celsius difference between the trends for the two stations, with the old station being the warmer.

Figure 5 represents linear regression models for the five-year centered moving averages for annual mean temperatures at the four stations studied. Although these numbers show a decreasing trend for Jeddah, this is not statistically significant. While both Almadinah and Riyadh show increasing trends, only Riyadh shows a noticeable rise with $R^2 = 0.35$ and $F = 0.002$ – a significant value. This increase is most likely due to a heat island effect.

4.1.2. *Precipitation Trends*

Figure 6 represents linear regression models for the five-year centered moving average of the annual total precipitation at the four stations. The records for Jeddah and Riyadh do not show any signs of increase or decrease in precipitation in the thirty-seven year study period (1961–1997). With respect to Dhahran and Almadinah, there are signs of increased precipitation during this period.

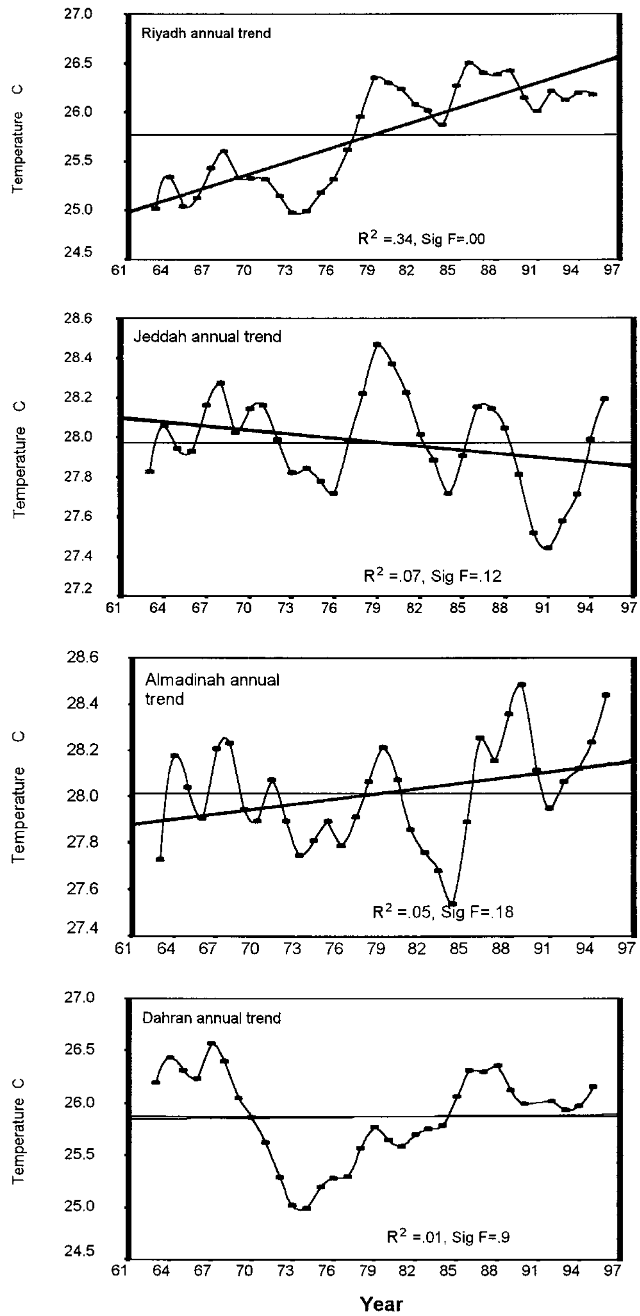

Figure 5. Linear regression models for the five-year centered moving averages of the annual mean temperature for the four stations studied. Thin line represents the period mean and solid line represents the regression model line.

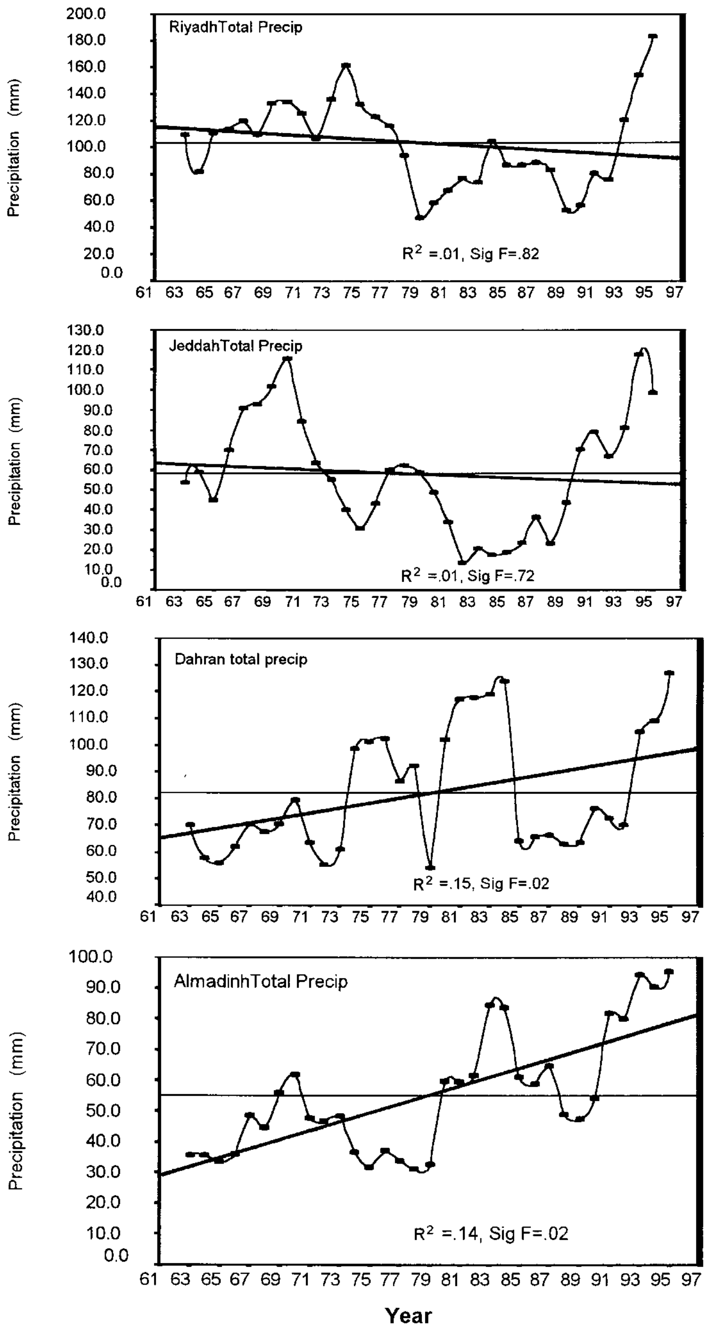

Figure 6. Linear regression models for the 5-year centered moving averages for the annual total precipitation for the four studied stations. Thin line represents the period mean and solid line represents the regression model line.

Table II

Annual mean temperature for Riyadh Old Station and Riyadh New Station for the period 1985–1997

Year	Riyadh Old Station	Riyadh New Station
1985	26.30	24.90
1986	26.03	24.69
1987	27.36	25.92
1988	26.83	25.58
1989	25.51	24.91
1990	26.22	25.37
1991	25.25	24.67
1992	25.27	24.45
1993	26.13	25.98
1994	26.55	26.00
1995	25.74	25.29
1996	26.58	26.07
1997	25.89	25.24
Period mean	26.12	25.31

The R^2 for the relationship between time and precipitation for Dhahran and Almadinah are 0.15 and 0.14 respectively. While these are small values, statistically they are significant since F value $= 0.02$ for both stations (see Figure 6). A noticeable result of the precipitation analysis is that data from more recent years, 1995–1997, for all four stations include record high levels of precipitation. However, this factor is not statistically significant.

From the above analysis of temperature and precipitation data, we can conclude that there has been no strong and clear increase in temperature or decrease in precipitation in Saudi Arabia during the period of study. This is not surprising: much recent research has concluded that indications of climatic change are less than certain in many parts of the world, including Saudi Arabia. For example, Hansen and others (1998) concluded that in most places in the world, with the exception of eastern Asia and western North America, climate trends are too small to stand out beyond year-to-year variability. Nonetheless, alarming signs of increased temperatures do exist in the models of this study. The results of the analysis of this study and the predictions of the GCMs models presented in previous sections indicate that an appropriate policy should be implemented to respond to the potential negative impact of possible climatic change upon agriculture and water supplies in Saudi Arabia.

5. Response and Policy

The most threatening effects of climatic change in Saudi Arabia will be on agriculture and water supplies. While a negative impact upon these two vital resources has wide-ranging social and economic implications, responsive policies can positively affect social and economic conditions in a number of ways. This section will discuss appropriate agricultural and water supply strategies to respond to projected climatic changes.

One may argue that the results of the statistical analyses in the previous section did not support predictions of climatic change. The response to this argument can be shortened to two points:

First, analyses of this data are not sufficient to conclude that no climate change is taking place in Saudi Arabia. In fact, this data does reveal some signs of an increase in mean temperatures.

Second, a ‘no regret’ policy is highly recommended for a country where the climate in recent years has already shown a negative impact on agriculture and water supply, and where there is a tremendous increase in population (Pachauri and Damodaran, 1992). Such a policy would produce long-term benefits whether or not the country is on the verge of a major climatic change.

The recent agricultural, municipal, and industrial use of water poses a great threat to water supplies in the near future. Water use and agricultural policies in Saudi Arabia should be drastically revised.

Many different strategies have been developed to meet this challenge. These are outlined in the relevant literature. For example, Parry (1990) suggests that two main changes should be adopted: change in land use – such as changes in farmed areas and in crop location – and change in management. However, Saudi Arabia has a unique problem that requires unique strategies. The following points illustrate this:

- Saudi Arabia suffers more than most countries in the world from recent negative climatic factors, namely, very high temperature and very low precipitation.
- Saudi Arabia is a large country, and with an area of about 2,250,000 square kilometers it has almost no runoff, no surface water, and no rivers (Alshareef, 1995). In fact, in terms of water supplies, it is one of the driest and poorest countries in the world.
- Saudi Arabia’s geographical location is close to many areas that have a surplus in crops: North Africa including the Nile valley, Europe, and the Indian subcontinent.
- Saudi Arabia is surrounded by countries that already have problems of water supply.
- Saudi Arabia has one of the highest rates of population growth in the world, with a average annual population increase of 7.2% (Mashkas, 1995). This includes natural and migration growth.

– Saudi Arabia is one of the richest countries in the world due to its huge oil production and reserves.

Taking these factors into account, many different measures may be suggested to respond to recent and projected climate change that may threaten progress and development in the country. Let us now turn our attention to some of these measures.

5.1. STOP WINTER WHEAT PRODUCTION

Winter wheat is produced by private sector companies and individuals that receive long-term interest free loans from the government, which in turn buys the wheat from them at SR 3 ($0.80) per kilogram (Al-saleh, 1992). For this reason, wheat production exceeds national requirements and extra production is exported to neighboring countries. While wheat production provides food security for the country, it also has a devastating effect for the following reasons:

– Extensive irrigation has increased salt concentration levels in the infertile arid soil.
– The huge withdrawal of water for irrigation from non-renewable aquifers has caused degradation in the quality and quantity of these aquifers. Some have become salty and others have started to dry up or at least to decline severely. For example, Regional Ground Water Flow Models (REGNLGW) indicate that the drop in water levels at the center of Alwasia aquifer well field could reach 43.3 meters for the period 1981–2010 if the recent water pumping rates of 190,000 m^3 per day continues (AL-Hassaun, 1997). The Alwasia Aquifer is a major supplier of water to the city of Riyadh, the capital. Many other aquifers in Saudi Arabia suffer similar depletion and severe drops in water levels have been observed because of overuse in agriculture. For instance, between 1984 and 1990 the ground water level of the Manjur aquifer, which also supplies the capital and many other urban areas, has dropped 10.8 meters at an average rate of 1.8 meters per year (Al-saleh, 1992).
– Economically speaking, taking into account the depletion of scarce water and soil, one kilogram of wheat costs the government more than SR 3, or $0.80 (Al-saleh, 1992). It would be much cheaper for Saudi Arabia to buy wheat from many countries in the world.

With the exception of some mountain areas where there is enough rainfall to sustain it, subsidized production of wheat should be stopped. Shortfalls in domestic wheat production can be covered by importation. Wheat farms that have been taken out of production could be maintained as strategic resources to be used to cover shortages in supplies due to international instability. Such measures would ensure that ground water supplies remain available, that the required machinery remain in a serviceable condition, and that suitable arable lands remain allocated for this purpose. Thus, everything would be ready for use when needed. This may appear to be a costly measure but it is vital to maintaining sustainable development in the face of projected climatic changes.

5.2. RECHARGE DEPLETED AQUIFERS

Aquifer management should achieve a balance between discharge and recharge. If this balance is not achieved then groundwater levels will fall, possibly leading to increased mineralization of the water and saline intrusion (Hamill and Bell, 1986). In the last decade extensive water has been pumped from aquifers in Saudi Arabia, mainly for irrigation purposes (AL-Hassaun, 1997). The first survey of these aquifers concluded that they held huge quantities of water and would be able to support the nation for a very long period (Othman, 1983). Due to this misleading assessment, to poor water management, and to the uncontrolled pumping of water, some of these non-renewable aquifers have begun to reach exhaustion point.

Scarcity of water threatens all regions surrounding Saudi Arabia (Gleick, 1992). Because of this, the importation of water from neighboring countries is not an option, even if Saudi Arabia were willing to pay for it. Desalination plants cannot be relied upon for the nation's water supply security because the continuity of production is vulnerable to many factors, such as missile attacks in the event of military conflict, major machinery defects, or maintenance difficulties.

To confront predicted climatic changes and to see to the needs of national security, Saudi aquifers must be replenished. This can be done by utilizing the large number of reservoirs scattered across the country. These reservoirs are dry most of the time but when rain comes, it comes as a torrent, filling them.

At present, the water of these reservoirs suffers a severe loss due to a high rates of evaporation. The annual evaporation rate in most of the country, except the southwest mountain area, is more than 1200 mm (Aljarash, 1989). To take advantage of this quantity of water well-built holes should be constructed linking each reservoir to the water tables of the aquifers. Another way of refilling these aquifers may be to dig refilling wells at the ends of the major aquifer valleys and basins.

Almuttair and Alturbak (1991) suggested a method to model and predict the infiltration process through a recharge basin in Saudi Arabia. They tested several infiltration runs and concluded that this approach can be used for the artificial recharge of ground water. Such a solution may not be profitable in the short run, but within a few decades the water tables of the aquifers should increase. It has been estimated that the Alsag aquifer in the southwestern part of the country is refilled annually from the run-off of mountain precipitation by 290 million m^3 even without such recharge wells (KFUPM, 1987). Moreover, this way of storing water could protect the country from the predicted increase in severity and frequency of drought.

The safest and securest way of providing sufficient water supplies to face future needs and future climatic changes in Saudi Arabia is by replenishing the aquifers.

5.3. INCREASE MANAGED IRRIGATION

The current irrigation system in Saudi Arabia wastes a huge quantity of water. For example, traditional methods of irrigation are used to water palm groves for date production in most parts of the country. In some areas these traditional methods rely upon surface irrigation, while in others open ditch irrigation is used. These traditional irrigation methods lose huge quantities of water through evaporation. In such an arid country, water should be used as efficiently as possible. In the American great plains and southwestern deserts, especially in Nebraska, and in Arizona, the impact of ground water pumping for irrigation has been mitigated by the adoption of more efficient irrigation systems (Fredrick and Kneese, 1989). Such systems include well-managed drip and sprinkler systems as well as water shade systems. These may be expensive but they prevent a considerable amount of wastage and help avoid depletion of aquifers.

5.4. INCREASE GREENHOUSE FARMING

To meet the rapidly rising demand for agricultural products in Saudi Arabia, agricultural production has doubled at least twice in the past two decades (Mashkas, 1995). Total greenhouse agricultural production in Saudi Arabia in 1997 was only 128,971 tonnes (Ministry of Agriculture, Saudi Arabia, 1998). This number represents a small percentage of the total agricultural production of the country. Greenhouse farming uses much less water due to well-managed irrigation and reduction in evaporation rates and should be encouraged in such an arid country. Greenhouse farming should be given high priority in agricultural subsidization.

5.5. REDUCE GRAZING LIVESTOCK HUSBANDRY

Poorly managed crop production along with extensive grazing have reduced the soil quality and caused soil erosion. Saudi Arabia has a large number of sheep, goats, cows, and camels. In 1997 the total number of such livestock was 15,332,326 (Muhamadeen, 2001). Most of these animals graze freely, damaging the soil and reducing forage. This leads to further desertification which can worsen the possible predicted climatic changes. To restore the natural plants and rebuild the damaged soil, overgrazing must be stopped. Otherwise, the future reduction of soil moisture along with soil erosion will significantly reduce soil fertility.

5.6. ADOPT A STRICTER WATER USE POLICY

Recent agricultural, municipal, and industrial use of water is not based on strict conservation and maximization of efficient uses of water. The main reason behind this is that the government provides water at a very low price for all three main users. A strict water use policy must be applied and should include increases in the water prices, which will promote conservation and efficient use of water (Smith and Dennis, 1989).

5.7. MORE RESEARCH NEEDED

Although Saudi Arabia is one of the most vulnerable countries to the effects of climatic change, there is a lack of climatic, environmental, agricultural, and hydrological research to assess the possible impact of projected changes. The government should encourage such research in order to provide it with a basis for future agricultural, environmental, and hydrological policies.

6. Conclusion

Saudi Arabia, one of the driest subtropical desert countries in the world, is already suffering from adverse climatic effects that negatively affect agriculture and water supplies in particular. Rapid population growth places yet more pressure on agricultural and water resources. If these pressures are combined with increases in temperature and decreases in precipitation, as most climatic change and GCM models predict, this country will face very severe shortages in both agricultural production and water supplies.

Recent climatic and non-climatic indicators in Saudi Arabia point to the fact that action must be taken immediately. There is no time to wait for the world scientific community to come to a firm conclusion with regard to supposed climatic changes. The climate is already negatively affecting Saudi Arabia and a 'no regret' policy will protect it from further negative climatic effects, especially in agriculture and water supply.

The aim of any policy that is responsive to projected climatic changes must be to reduce water consumption and to conserve water supplies for essential future use through a better controlled and managed agriculture. This measure is needed because one of the most serious problems facing the world in general and the arid countries in particular is the rapid depletion of water resources, due both to increases in population and changes in climate (Lundqvist, 1992). Ignorance of climatic factors and possible climatic change are very likely to lead to devastating problems in agricultural and water availability in Saudi Arabia in the foreseeable future.

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