Effect of Temperature Rise on Crop Growth & Productivity

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Abstract

Crop growth and development is mainly a function of temperature if water is available to the optimum satisfaction. Although weather and climate had never been constant and they had always experienced changes either positive or negative but recent atmospheric warming was unprecedented. An increasing glob al warming trend started in 1940s after industrial revolution and it had no end. During the last century, the temperature increase was noticed around 0.7C which has been surpassed by the first decade of 21st century scoring about 1C average global rise. Also it ranked as the warmest decade ever recorded over the surface of earth and it brought numerous anomalies in the processes of the climate system in the form of frequent floods, droughts, heat/cold waves, localized heavy downpour and highly variable weather patterns in different parts of the world. Pakistan also suffered similar happenings which occurred mainly due to rise in temperature leaving the serious challenges for sustainable food production. Day and night temperatures in Pakistan have followed a significant increase during the last 50 years due to which heat stress on plant growth and development has also enhanced. Higher night temperatures have given rise to increase in respiration hence reducing the net gain in the form of grain yield. Sudden shoot up of air temperatures in early spring when wheat and other winter crops were at reproductive stage of their life cycle caused significant reductions in the grain yield despite affecting the apparent health of the crops. Current rise in temperature is likely to continue during this century and extreme events associated with rise are also expected to increase in frequency, intensity and persistence increasing the uncertainty in sustainable crop production. We have to grow more by adopting a multidisciplinary approach to meet the food demand of ever increasing population of Pakistan with fewer amounts of available land and water resources in a highly hostile climate. Increased temperature will affect the physiological processes necessary for crop growth and development of crops and ultimately crop yields are most likely to drop over the present level. Climatic anomalies will play an important role in increasing the uncertainties in crop production.

Introduction

When humans first started planting crops and raising cattle thousands of years ago, the dependence of agriculture on weather and climate was evident. Would there be enough rain for the crops to germinate and grow? Why do only certain crops or plants grow in a region? Would there be enough grass for the cattle to eat? These were probably some of the first questions that our forefathers asked when they planted crops or raised livestock. Of all human endeavours, agriculture was perhaps the first sector where humans realized that there are strong interactions between the sector and the weather. Over time, humans developed practices that were based on their understanding of weather and climate patterns. Some of these included the appropriate time of the year to plant and harvest a crop or move livestock from summer to winter grazing areas. They were, of course, mystified and frustrated by the variability of the seasons and even the day-to-day weather, and as a coping strategy developed folktales and rules of thumb for the weather and climate patterns. Such practices have been used over the centuries, and continue to be used right up to the present day.

Global temperature has increased by 0.3–0.6°C since the late 19th century and by 0.2–0.3°C over last 40 years. In the last 140 years, the 1990s was the warmest period (Jones and Briffa, 1992). In Indian context, Hingane et al., (1985) reported an increase in mean annual temperature by 0.4°C/100 years during the 20th century until 1980s. However, increasing temperature trend is not valid over entire country; the northeast and northwest India shows some cooling. Kothawale and Rupa (2002) reported a rise of 0.5°C in mean annual temperature over last century. However, no systematic change in mean minimum temperature was observed. The pattern of spatial and temporal changes in climatic variables due to global warming need more debate and studies are being conducted globally (Chattopadhya et al., 1977;

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Georgaidi et al., 1991; Iglesias et al., 1994; Feddema, 1999). As a consequence of climatic changes, a significant impact on hydrological parameters, viz. runoff, Evapotranspiration, soil moisture, ground water etc. is expected (Bultot et al., 1988).

Failure of only one critical enzyme system can cause death of an organism. This fact may explain why most crop species survive sustained high temperatures up to a relatively narrow range, 40 to 45°C. The relationship between the thermal environment for an organism and the thermal dependence of enzymes has been well established (Senioniti et al., 1986). Heat stress may be an oxidative stress (Lee et al., 1983). Peroxidation of membrane lipids has been observed at high temperatures (Mishra and Singhal, 1992; Upadhyaya et al., 1990), which is a symptom of cellular injury. Enhanced synthesis of an anti-oxidant by plant tissues may increase cell tolerance to heat (Upadhyaya et al., 1990, 1991) but no such anti-oxidant has been positively identified.

Productivity of wheat and other crop species falls markedly at high temperatures. Wheat in India is invariably exposed to extreme temperatures during some stages of development (Abrol et al., 1991). In Australia, wheat is usually exposed to brief periods of heat stress during grain development. Acute effects of high temperature are most striking when heat stress occurs during anthesis. In rice, heat stress at anthesis prevents anther dehiscence and pollen shed, to reduce pollination and grain numbers (Mackill et al., 1982; Zheng and Mackill, 1982).

In India, the growing season for wheat is limited by high temperatures at sowing and during maturation. As wheat is grown over a wide range of latitudes, it is frequently exposed to temperatures above the threshold for heat stress. For example, rainfed wheat depends on soil moisture remaining after the monsoon rains recede in September. High maximum and minimum temperatures in September (about 34/20°C), adversely affect seedling establishment, accelerate early vegetative development, reduce canopy cover, tillering, spike size and yield. Hence, sowing is typically delayed until after mid-October when seedbeds have cooled, though much of the residual soil moisture may be lost. High temperatures in the second half of February (25/10°C), March (30/13°C) and April (30/20°C) reduce the numbers of viable florets and the grain-filling duration. High temperature stress particularly reduces yield of wheat sown in December/January which is necessitated in some regions because of the multiple cropping system.

The arid areas of Pakistan where the evapotranspiration rate is already high and water table is shallow, an increase in air temperature may cause loss of water rapidly and consequently the aridity would increase. If the evapotranspiration rate continues to increase then the water reservoirs in the form of small dams, ponds and tobas etc. would dry more rapidly and water shortage may engrip humans along with plants. Chaudhry et al., 2004 described that almost two third area of the country lies in arid zone. Pakistan fulfills its water requirement from winter and summer rainfall along with the melting of snow fall from the glaciers. Due to global warming, variability of summer rainfall has considerably increased and glaciers have started melting at a much faster rate than observed before (Rasul, 2008).

Global Warming

Global Perspective

The increase in the Green House Gases (GHGs) concentration is blamed to be responsible for the rise in temperature of planet earth. The GHGs layer, with its optimum thickness, envelops the earth above its surface and regulates its temperature at about 15C in the absence of which it may be about -18C. However, denser layer of GHGs trap larger proportion of solar radiations in earth's atmosphere and hence increases the earth's temperature.

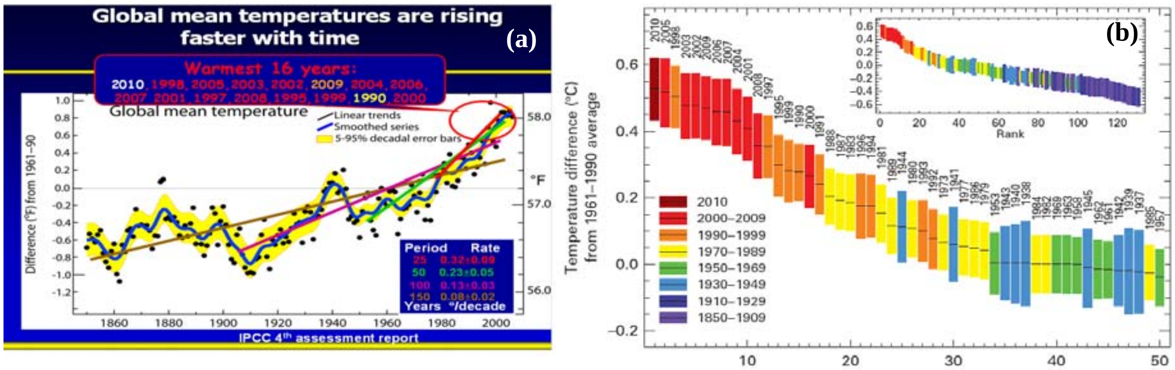

Figure 1: (a) Global temperature trend during last 150 years and the hottest years. Ranking of the warmest years with temperature above normal **(b)**. 2010 tied for warmest year in records dating back to 1880.
The 2010 nominal value of +0.53°C ranks just ahead of those of 2005 (+0.52°C) and 1998(+0.51°C).

Figure 1 is primarily taken from IPCC AR4 (2007) in which instrumental record of temperature of earth is presented from 1850 to 2006 is presented. It shows that 12 warmest years recorded over the globe have occurred since 1990 with 1998 (strongest El~Nino). The figure was further updated to 2009 according to World Meteorological Organization (WMO) official statements. The additional three years also proved to be among the warmest years. The rate of increase in temperature in 156 years was 0.08C per 10 years whereas in last 25 years it reached to 0.32C per decade. A continuously warming trend after Second World War is quite evident, however, a well-marked rise in temperature can be seen in recent two decades.

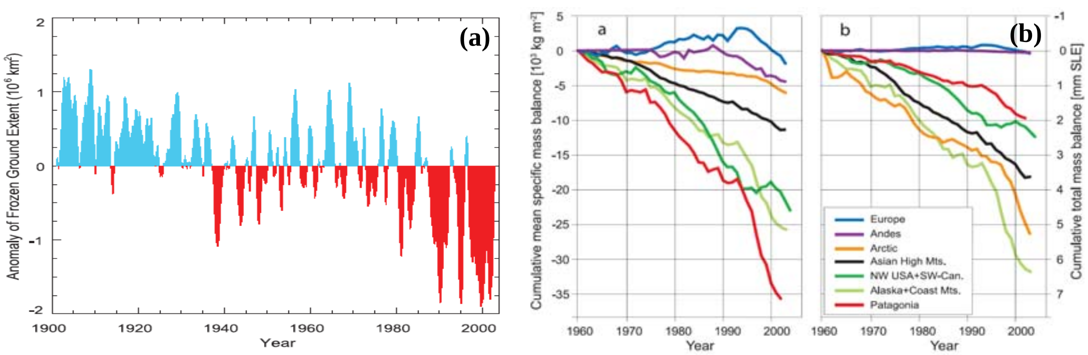

Figure 2: (a) Increasing earth's temperature is causing rapid melting of frozen ground
(b) Depletion of world glaciers and equivalent rise in sea level (IPCC 2007).

Figure 2(a) depicts the rate at which frozen ground has been decreasing in its areal extent since 1900. As seen in temperature trends, the frozen ground depletion accelerated from 1940 and during the last two decades an alarming rate of recession can be seen. Figure 2(b) presented the melting rate of world's major glaciated ice reserves and equivalent rise in the sea level. Glaciers are the fresh water resources which regulate water supply with rise in temperature and ensures the food production for billions of people. Rising global temperatures have started melting these glaciers at a much faster rate than in the past threatening the food and water security of the dependent population. Black line represents the Himalayan-Karakoram-Hindukush (HKH) glaciers which are receding sharply and causing a significant sea level rise.

Pakistan Perspective

The thermal regime in Pakistan has also shown continuously warming trend in accordance with the global estimates. Figure 3(a) presents the deviation of annual mean temperature of Pakistan from the long term average starting from 1900 to 2006 for which the data from Climate Research

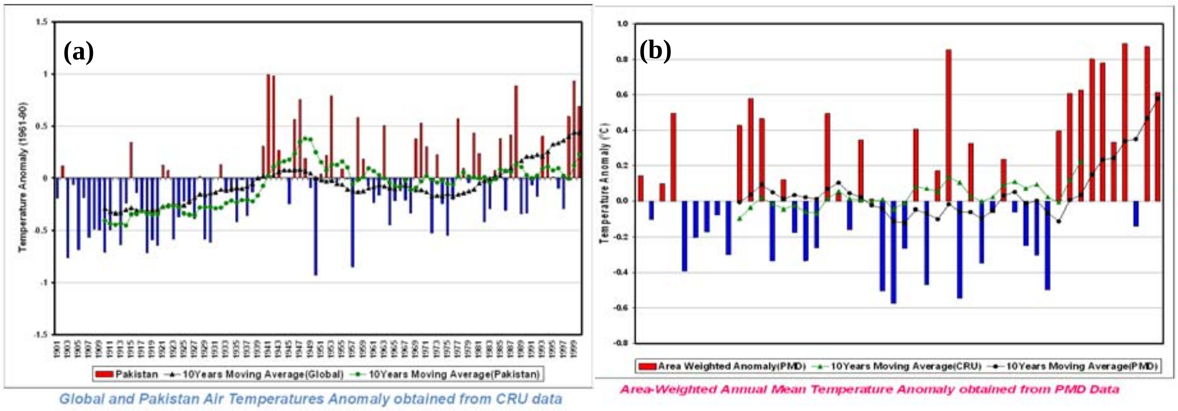

Figure 3: (a) Deviation of annual mean temperature of Pakistan from the long term average.
(b) Mean temperatures 1961 to 2006

Unit (CRU) of East Anglea University of UK has been used. Global and Pakistan temperature anomalies have shown a synchronous trend of mean daily temperature throughout the time series. Figure 3(b) is drawn by using temperature data from PMD archives recorded at Pakistan stations from 1961 to 2006. A sharp rise in temperature substantiates the global warming claims of climate scientists.

Isothermic Dynamics

Daily maximum temperatures from 1981-2008 for generally dry summer period from April to June were analyzed on pentad basis except last one which is two years less yet. Movement of isotherms with time along the elevation revealed the fact that heat is rushing towards the peaks of this elevated complex and highly irregular terrain. To know how fast it is moving upward, the dynamics of 30°C was considered the reference indicator. Figure 4 (a) and (b) shows that in 1980s the changes in isothermic pattern were very slow and hardly a 35m upward shift of reference isotherm was seen from 1981 to 1990. Warming trend increased in 1990s. By the end of this decade, the 30°C isoline existed at about 300m higher than its position in 1981-85. The ever hottest year recorded over the globe was 1998 which co-occurred with the strongest El~Nino event 1997-98 of the recorded history. The ENSO event associated with severe hygrothermal stress conditions contributed a lot to carry the heat to new heights. Overall the decade of 1990s was believed to be the warmest one. (Based on Mean Summer Max Temperature (April-June))

The first eight years of 21st century are seen surpassing all trends in the past among them 2005 believed to be the hottest for Pakistan when a historic snowmelt flood in June created a havoc downstream Indus. Last pentad has completed 3 years so far (i.e. 2006, 2007, 2008 April-June period) and is showing moderate advance of warmth in the upward direction. The dynamics of 30°C isotherm along southern slopes of HKH ranges is shown in Fig 4. Temporal isotherm's spread show that flux of upward creeping heat is more over the eastern part (Himalaya and Karakorum) of the southern slopes than western part comprising Hindukush range. Isothermic advance is not uniform rather skewed due to the complexities of terrain and environmental degradation. On the average, the 30°C isotherm has now moved at 580m above its location in early 1980s.

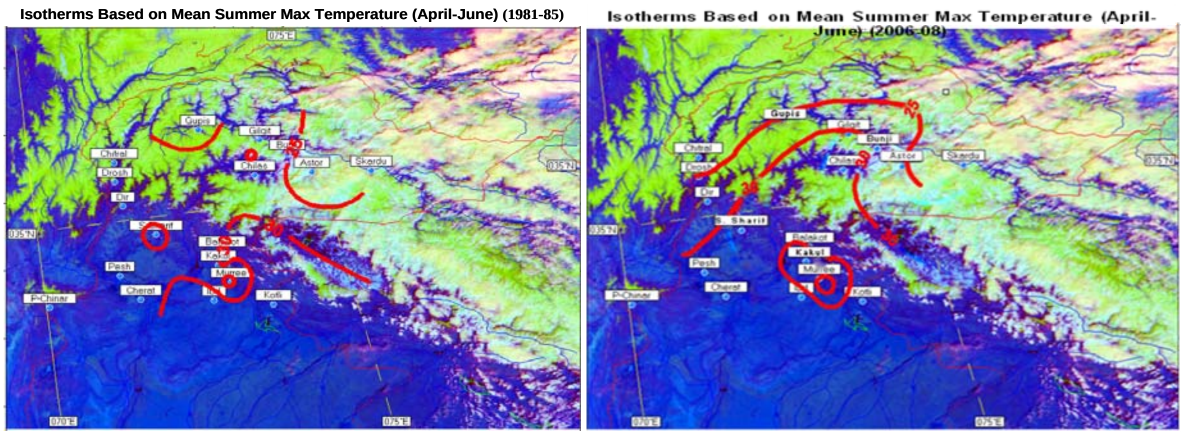

Figure 4: Heat shifting from low elevation to elevated glaciarized regions is represented by isothermic dynamics along southern slopes of HKH ranges.

Heat Waves

Heat waves are a continuous stretch of persisting maximum temperatures above certain threshold for a specified time period. Rising temperatures are embedded with thermal extremes which were rare occurrence in the past but now becoming more common year by year. They are grouped into three categories as defined below:

Moderate Heat Wave = Five consecutive Days with Daily Maximum Temperature ≥ 35°C and < 40°C

Mild Heat Wave = Five consecutive Days with Daily Maximum Temperature ≥ 30°C and < 35°C

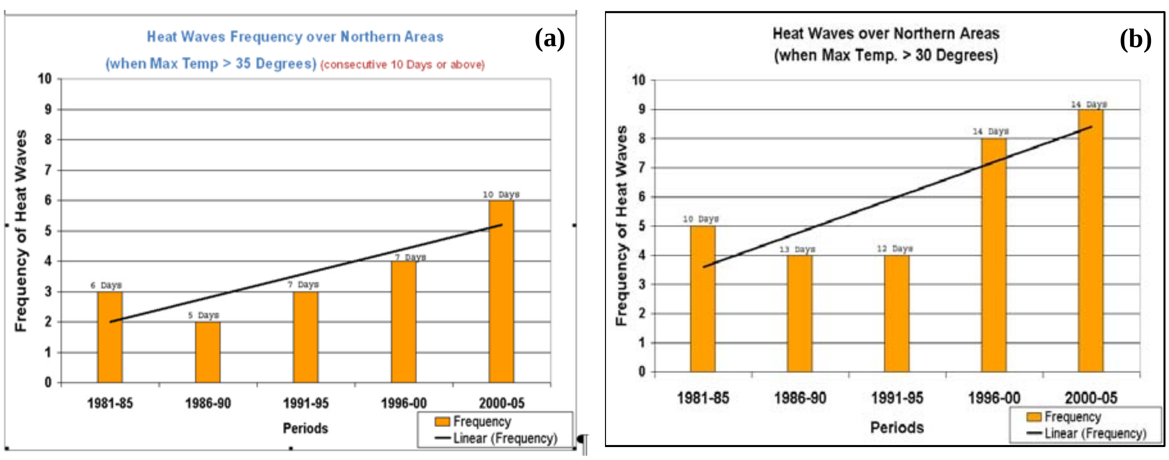

Figure 5: Frequency of moderate and mild heat waves of 10-days duration (bars) and their linear trend are shown for northern areas of Pakistan. The numbers on the top of the bars indicate the longest duration of heat wave persisted during the period.

Frequency analysis carried out over all the above thresholds is presented in figure 5 from 1981 to 2008 using combined data set from all sources on pentad basis. The height of the bar represents the number of events when temperatures reached the mild (a) and moderate (b) stress level in a particular pentad. Frequency of mild stress was quite common even in 1980s during May and June but moderate stress conditions rarely occurred. Not only a significant increase had been noticed in occurrence of mild stress days but a sharp rise in moderate stress events was also registered during the recent decade. It can be observed that the persistence of heat waves has become longer over the temporal scale on one hand while their intensity has increased on the other hand during the recent years. Similarly their areal extent has also increased significantly. The valley areas or shadow zones appearing unaffected by increasing heat in the earlier period are dominated by the heat sweep. However, they are following certain lag period than the exposed elevations.

Day and Night Temperature Trends

The mean daily temperature is the arithmetic average of maximum temperature and minimum temperature which occur usually daytime and night time respectively. Both have their own significance in the growth and development of plants during their life cycle. Day temperatures in their optimum limits help the photosynthesis process in the presence of sunlight while higher night temperatures support respiration process which is the reverse process of the photosynthesis. Dry matter accumulation takes place when Photosynthesis is more than respiration which sustains the plant's growth and development vice versa retards the development process.

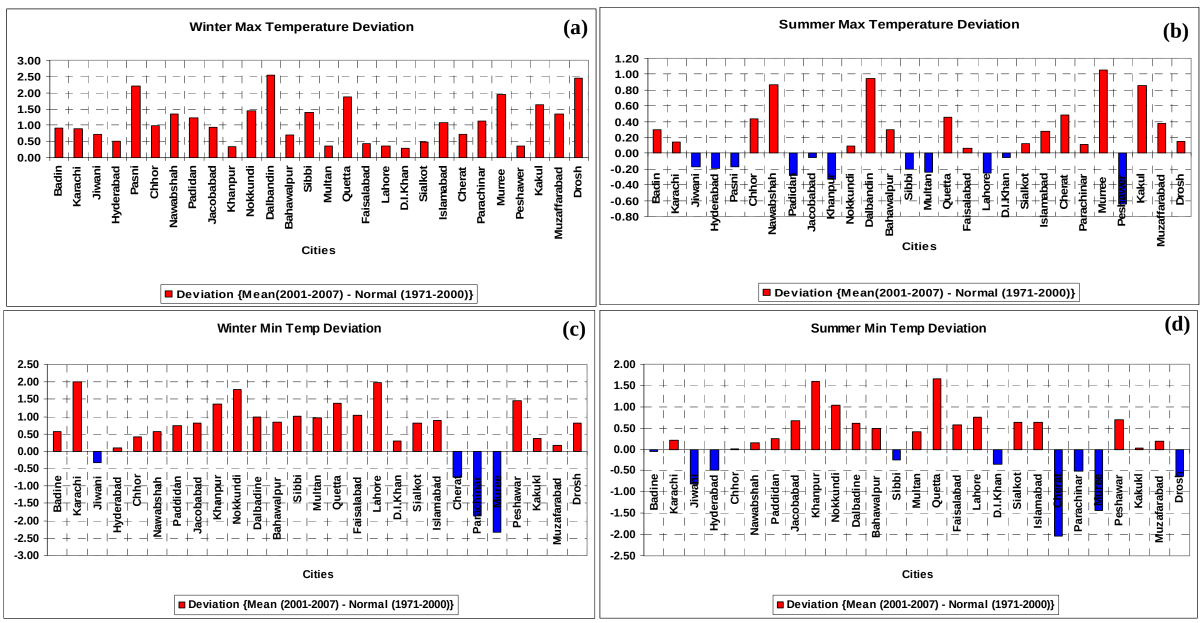

Figure 6: Deviation of Maximum (Day time) and Minimum (Night time) temperature (a-d) over Pakistan from south (left) to the north (right) from 2001-2007 as compared to the long term average of 1971-2000

As compared to long-term average, the day and night temperatures over Pakistan have shown generally an increasing trend with a few exceptions of night temperature decreases during last decade. An increase in day temperature about 1-2C (Fig. 6a) has been noticed over the normal (1971-2000) in all the agriculture plains of Pakistan whereas night temperatures (Fig. 6b) also predominantly show an increase although deviation is small in magnitude as compared to day temperature.

Provincial Temperature Trend

The daily maximum and minimum temperatures area-weighted and averaged over eight years (2001-07) for different stations of each province of Pakistan are presented in Figure 7 a-d. A significant rise in temperature in concurrence with the global pattern of warming can be seen during the first decade of 21st century in all the provinces. Maximum rise in day temperature is recorded in Balochistan during the winter season followed by Khyber-Pakhtoonkhwa.

Minimum temperatures generally occur at night therefore they are commonly termed as the lowest night temperatures. Like maximum temperature which is considered to be the highest temperature during the daytime, the minimum temperature is also showing largely rising trend in the agricultural plains of the country. There are exceptions with a few high elevation agroclimatic zones where nights have shown relatively cooler trend. General behavior shows an increase in night temperatures during the recent ten years over the agriculture plains of all the provinces of Pakistan.

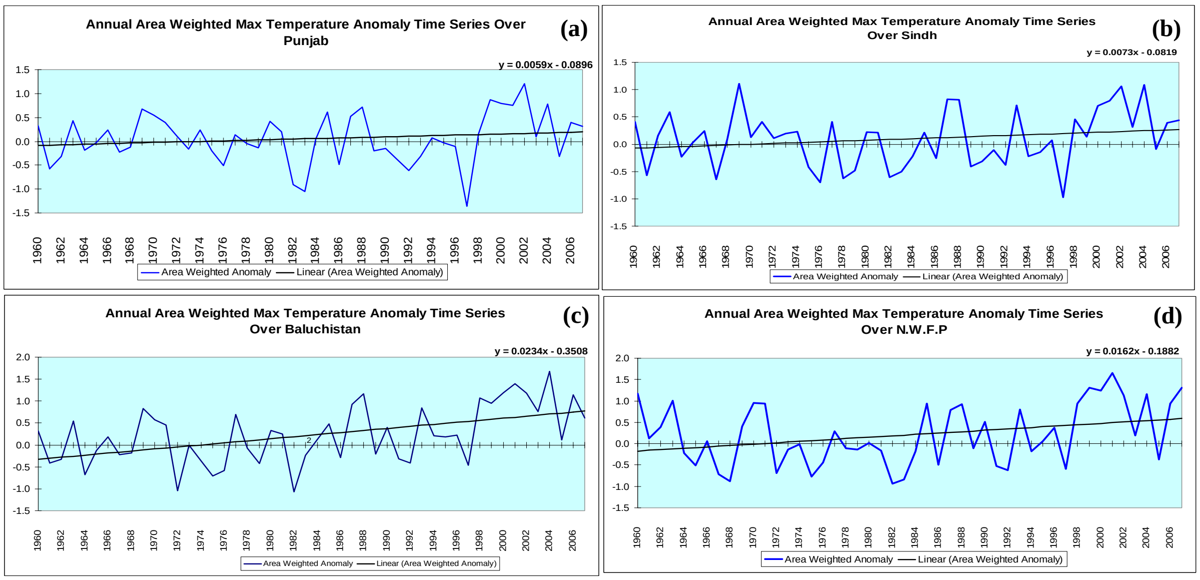

Figure 7: Maximum and Minimum Temperature deviation from normal during 2001-07 over different regions of each province in summer and winter seasons

Adverse Impact of High Temperatures on Crop Yield

Climate change has been causing a drastic change in weather patterns both in summer and winter resultantly adversely affecting the crop yields. Large variability has been observed in the precipitation and thermal regimes but discussion will be focused on thermal one here. Some recent examples in Pakistan and other parts of the world are stated below;

- Goswami et al., 2005 diagnosed the causes of reduction in wheat yield in Ludhehana Province of India while the visible crop condition was the best. They pointed out that the occurrence of mild heat wave (13 days above normal (2-3^{0}C) temperatures) in early spring at reproductive stage caused 28% reduction in the grain yield of wheat.
- In Sindh and southern Punjab of Pakistan, February 2006 was 2-4^{0}C warmer than normal and significant yield reductions were reported. Wheat was in the grain formation phase, high temperatures accelerated the development as the required heat units were met immediately. The grains could not gain proper size and weight rather they were shriveled hence resulted in reduced yield.
- Over most of the low elevation agricultural plains, the mean daily temperatures during the last week of February and first decade of March 2010 remained 3-6^{0}C above normal. Early maturity did not allow the young wheat grains to grow to their normal weight, size and starch contents. Looking at the crop health, it was declared as bumper crop season but it yielded 13% less production per hectare.
- Due to higher night temperatures during 2003, the respiration over ruled the photosynthesis causing reduction in net gain. Rice grain yield declined 10% for each 1^{0}C increase in minimum temperature. (Saobing Peng et al., 2004)

- Smith et al., 2008 reported that yield increased up to 29 ^{0}C for corn, 30 ^{0}C for soyabean and 32 ^{0}C for cotton. Higher temperatures are harmful. They predicted 30-46% reduction for B1 scenario by the end of 21st century.

Effect of Future Rise in Temperature on Crop Water Requirement

Crop water requirement is directly related to the evaporative demand of the atmosphere in which the crop is grown. The evaporative demand of the atmosphere is direct measure of crop evapotranspiration which is not a directly measurable physical quantity rather it is estimated by using empirical formulae. Such estimations differ widely on temporal and spatial scales as well as formula to formula. Rasul, 2009 tested four methods of estimation of crop evapotranspiration commonly used in south Asian region for different agroclimatic zones of Pakistan. While comparing the results with evaporation data generated at the same place, he found large intra-seasonal and inter-seasonal under- and over-estimations by different methods. However, the modified FAO Method was recommended for Pakistan as the error of estimation fell in acceptable limits of plus/minus 10%.

Du e to global warming, the temperatures are expected to increase over the present limits at a variable rate simultaneously the water demand of the crops will also increase. Ghazal et al., 2010 computed the future water requirement of the crops generally grown in different climatic zones of Pakistan taking 1 ^{0}C, 2 ^{0}C and 3 ^{0}C rise in temperature. They found an average increase in crop water demand 11%, 19% and 29% respectively. It was further elaborated that the water requirement of crops will increase at a higher rate than the northern sub-mountainous agricultural plains located in active monsoon zone. However, the crops need almost double amount of water at 2 ^{0}C increase in temperatures at higher elevation agricultural plains of northern and western mountains. A good news for those small land holding farmers will be double crop season as the dormancy period will be significantly reduced in the length and the persistence.

Future Temperature Projections and Expected Yields

Global warming has been altering the climate in different ways. It is not only affecting the thermal regime but also influencing the weather patterns by energizing the physical processes which produce heavy rains and persistent drought. According to global climate change projections made by Global Climate Models (GCMs), the temperature of earth surface is most likely to increase by at least 4 ^{0}C at the end of 21st century. In Pakistan, it is expected even more than the global average i.e. 5 ^{0}C. In the following figure 8, the temperature increase under different greenhouse gas emission scenarios is given against decadal scale up to the end of this century. The set of scenarios named as A2 assumes that emissions would continue at present level, current population growth will be maintained and world economies will remain differentiated. Another set A1B is balanced one related to reduced emissions, low population growth rate and convergent economies. B1 assumes an ideal world which seems not possible.

Under the prevailing circumstances, A2 scenarios are the most acceptable set of projections for future. First decade of 21st century is completed in which model predicted 1 ^{0}C rise of temperature in Pakistan and it proved almost true as low elevation plains experienced rise of 0.9 ^{0}C while northern mountains suffered an increase of about 1.5 ^{0}C. During the first half rise is relatively slow but the later half is showing well-marked increase in temperature perhaps due to the stronger build up of the greenhouses gases in the atmosphere. First decade 2001-2010 has been the warmest decade ever

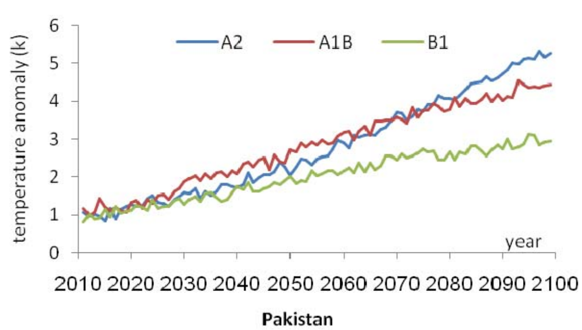

Figure 8: Future temperature projections for Pakistan made by A2 (business as usual), A1B (balanced) and B1 (ideal world) scenarios (SERS Report IPCC 2007) based greenhouse gas emissions likely in 21st century.

recorded over the earth and extreme events such as floods, drought, heat/cold waves, localized heavy downpour and highly variable weather patterns have posed serious challenges to the sustainable crop production. It is very likely that frequency, intensity and persistence of such extreme events will increase in future. We have to grow more by adopting a multidisciplinary approach to meet the food demand of ever increasing population of Pakistan with fewer amounts of available land and water resources in a highly hostile climate. Increased temperature will affect the physiological processes necessary for crop growth and development of crops and ultimately crop yields are most likely to drop over the present level. Climatic anomalies will play an important role in increasing the uncertainties in crop production.

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