# IMPACTS OF PRESENT AND FUTURE CLIMATE VARIABILITY AND CHANGE ON AGRICULTURE AND FORESTRY IN THE ARID AND SEMI-ARID TROPICS

M.V.K. SIVAKUMAR[1], H.P. DAS[2] AND O. BRUNINI[3]
[1]*World Meteorological Organization, 7bis Avenue de la Paix, 1211 Geneva 2, Switzerland*
[2]*India Meteorological Department, Shivaji Nagar, Pune 411005, India*
[3]*Center for Ecology and Biophysics, 13.020-430-Campinas, Sao Paulo, Brazil*

## Abstract

The arid and semi-arid regions account for approximately 30% of the world total area and are inhabited by approximately 20% of the total world population. Issues of present and future climate variability and change on agriculture and forestry in the arid and semi-arid tropics of the world were examined and discussion under each of these issues had been presented separately for Asia, Africa and Latin America.

Several countries in tropical Asia have reported increasing surface temperature trends in recent decades. Although there is no definite trend discernible in the long-term mean for precipitation for the tropical Asian region, many countries have shown a decreasing trend in rainfall in the past three decades. African rainfall has changed substantially over the last 60 years and a number of theoretical, modelling and empirical analyses have suggested that noticeable changes in the frequency and intensity of extreme events, including floods may occur when there are only small changes in climate. Climate in Latin America is affected by the ENSO phases and there is a close relationship between the increase or decrease of rainfall depending upon the warm or cold phases of the phenomenon.

Over land regions of Asia the projected area-averaged annual mean warming is likely to be $1.6 \pm 0.2^0$C in the 2020s, $3.1 \pm 0.3^0$ C in the 2050s, and $4.6 \pm 0.4^0$C in the 2080s and models show high uncertainty in projections of future winter and summer precipitation. Future annual warming across Africa is projected to range from 0.2 °C per decade to more than 0.5 °C per decade while future changes in mean seasonal rainfall in Africa are less well defined. In Latin America, projections indicate a slight increase in temperature and changes in precipitation.

Impacts of climate variability and changes are discussed with suitable examples. Agricultural productivity in tropical Asia is sensitive not only to temperature increases but also to changes in the nature and characteristics of monsoon. Simulations of the impacts of climate change using crop simulation models show that crop yield decreases due to climate change could have serious impacts on food security in tropical Asia. Climate change is likely to cause environmental and social stress in many of Asia's rangelands and drylands. In the arid and semi-arid tropics of Africa, which are already having difficulty coping with environmental stress, climate change resulting in increased frequencies of drought poses the greatest risk to agriculture. Impacts were described as those related to projected temperature increases, the possible consequences to water balance of the combination of enhanced temperatures and changes in precipitation and sensitivity of different crops/cropping systems to projected changes. In Latin America, agriculture and water resources are most affected through the impact of extreme temperatures (excessive heat, frost) and the changes in rainfall (droughts, flooding).

Adaptation potential in the arid and semi-arid tropics of Asia, Africa and Latin America was described using suitable examples. It is emphasized that approaches need to be prescriptive and dynamic, rather than descriptive and static.

## 1. Introduction

The World Atlas of Desertification (UNEP, 1992) defines arid regions as the areas where the ratio of mean annual rainfall (R) to mean annual potential evapotranspiration (PET) varies between 0.05 and 0.20 and the semi-arid regions as those where the ratio ranges between 0.2 to 0.5. In an assessment of population levels in the world's drylands, the Office to Combat Desertification and Drought (UNSO) of the United Nations Development Programme (UNDP) showed that the arid and semi-arid regions account for approximately 30% of the world total area and are inhabited by 1.10 billion people or approximately 20% of the total world population. The arid and semi-arid regions are home to about 24% of the total population in Africa, 17% in the Americas and the Caribbean, 23% in Asia, 6% in Australia and Oceania, and 11% in Europe (UNSO, 1997).

Climate variability has been, and continues to be, the principal source of fluctuations in global food production in the arid and semi-arid tropical countries of the developing world. Throughout history, extremes of heat and cold, droughts and floods, and various forms of violent weather have wreaked havoc on the agricultural systems in these regions. In conjunction with other physical, social and political-economic factors, climate variability and change contribute to vulnerability to economic loss, hunger, famine and dislocation. Hence it is imperative that these aspects are well understood in order to formulate more sustainable policies and strategies to promote food production in the arid and semi-arid tropics.

Increasing greenhouse gas accumulation in the global atmosphere and increasing regional concentrations of aerosol particulates are now understood to have detectable effects on the global climate system (Santer et al., 1996) and global average temperatures and sea level are projected to rise under all the scenarios from the Special Report on Emission Scenarios (IPCC, 2000). According to IPCC (2001a), the global average surface temperature increased over the 20$^{th}$ century by about 0.6 C and temperatures have risen in the past four decades in the lowest eight kilometers of the atmosphere. New analyses of data for the northern hemisphere indicate that the increase in temperature in the 20$^{th}$ Century is likely to have been the largest during any century since 1000 AD.

In this paper, we examine the issues of present and future climate variability and change on agriculture and forestry in the arid and semi-arid tropics of the world. For the sake of convenience, the discussion under each of these issues had been presented separately for Asia, Africa and Latin America. In view of the relatively smaller proportion of area, no attempt has been made to cover the arid and semi-arid tropics in the developed world.

## 2. Present climate variability and change in the arid and semi-arid tropics

### 2.1 ASIA

Tropical Asia, including arid and semi-arid tropics, has a unique climatological distinction because of the pervasive influence of the monsoons. The summer southwest monsoon influences the climate of the region from May to September, and the winter northeast monsoon controls the climate from November to February. The monsoon brings most of the region's precipitation and is the most critical climatic factor in the provision of drinking water and water for rain-fed and irrigated agriculture. The El Niño-Southern Oscillation (ENSO) phenomenon, which is geographically very extensive, has an especially important influence on the weather and inter-annual variability of climate and sea level, particularly in the western Pacific Ocean, South China Sea, Celebes Sea, and the northern

Indian Ocean. Suppiah (1997) has found a strong correlation between the Southern Oscillation Index (SOI) and seasonal rainfall in the dry zone of Sri Lanka; Clarke and Liu (1994) relate recent variations in south Asian sea-level records to zonal ENSO wind stress in the equatorial pacific. The influence of Indian Ocean sea-surface temperature on the large-scale Asian summer monsoon and hydrological cycle and the relationship between Eurasian snow cover and the Asian summer-monsoon also have been substantiated (Zhu and Houghton, 1996).

Several countries in this region have reported increasing surface temperature trends in recent decades. The warming trend over India has been reported to be about 0.57 $^0$C per 100 years (Rupakumar et al., 1994). In Pakistan, annual mean surface temperature has a consistent rising trend since the beginning of 20$^{th}$ century (Chaudhari, 1994). In most of the Middle East, the long time series of surface air temperature show a warming trend. In Vietnam, annual mean surface temperature has increased over the period 1895-1996, with mean warming estimated at 0.32$^0$C over the past 3 decades. Annual mean surface air temperature anomalies over Sri Lanka during the period 1869-1993 suggest a conspicuous and gradually increasing trend of about 0.30$^0$C per 100 years (Rupakumar and Patil, 1996).

In general, an increasing trend in temperature has been observed in southern and central India in recent decades in all seasons and over all of India in the post monsoon seasons. This warming has generally been accompanied by increases in diurnality except over northern India in the winter, pre-monsoon and post-monsoon seasons. Srivastava et al. (1992) observed increase in trends of annual mean, maximum and minimum temperatures south of 23$^0$N and cooling trends north of 23$^0$N. The diurnal temperature range (DTR) shows an increasing trend in all the seasons over most of peninsular India. This is in contrast to many other land regions of the northern hemisphere (Nicholls et al., 1996).

Mean annual rainfall is considerably low in most parts of the arid and semi-arid region of tropical Asia, and temporal variability quite high. In some places in the region, as much as 90% of the annual total is recorded in just 2 months of the year. Although there is no definite trend discernible in the long-term mean for precipitation for the region or in individual countries during this time period, many countries have shown a decreasing trend in rainfall in the past three decades. In India, long-term time series of summer monsoon rainfall have no discernible trends, but decadal departures are found above and below the long time averages alternatively for 3 consecutive decades (Kothyari and Singh, 1996). Recent decades have exhibited an increase in extreme rainfall events over northwest India during the summer monsoon (Singh and Sontakke, 2001). Moreover, the number of rainy days during the monsoon along east coastal stations has declined in the past decade. A long-term decreasing trend in rainfall in Thailand is reported (OEPP, 1996). In Pakistan, seven of 10 stations have shown a tendency toward increasing rainfall during monsoon season (Chaudhari, 1994).

Chattopadhyaya and Hulme (1997) analysed the trends in potential evapotranspiration (PE) for 10 stations in India including stations in arid and semi-arid tropics. In the monsoon and post-monsoon seasons, PE was found to have decreased over the last 15 years over the whole country, whereas in the winter and pre-monsoon seasons the trends are less consistent. The decreasing trend in PE is up to a maximum of about 0.3 mm day$^{-1}$ decade $^{-1}$ over west-central India in the monsoon and post-monsoon seasons (Fig.1). These trends are generally lower than for surface evapotranspiration ($E_p$) and represent a reduction in PE of less than 3% per decade. Changes in PE were most strongly associated with changes in relative humidity, particularly in the winter and pre-monsoon seasons. In the monsoon season, radiation was the dominant variable for regulating the PE variation at nearly all stations. Changes in both radiation and relative humidity are associated with decreases in PE in the post-monsoon season.

No identifiable variability in the number, frequency, or intensity of tropical cyclones or depressions has been observed in the northern Indian Ocean cyclone region (Bay of Bengal and Arabian Sea) over the past 100 years, although Gadgil (1995) has shown decadal-scale variations with a rising trend during 1950-75 and a declining trend since that time. No conclusive increasing or decreasing trends in time series data of flooded areas has been noticed in various river basins of India and Bangladesh (Mirza et al., 1997). Drought can reach devastation proportion in Tropical Asia, although the incidence is variable in time and space. Drought or near-drought conditions occur in parts of Nepal, Papua New Guinea, and Indonesia, especially during El Niño years. In India, Laos, the Philippines, and Vietnam drought disasters are more frequent during years following ENSO events. At least half of the severe failures of the Indian summer monsoon since 1871 have occurred during El Niño years (Webster et al., 1998). When several decades were combined to provide an understanding of the decadal scale variability of drought occurrence in India, it is found that the 1891-1920 and 1961-80 periods witnessed frequent droughts while few droughts occurred during 1930-1960 and 1980-2000. This suggests some kind of low frequency oscillation of the monsoon system on the decadal scale (Das, 2000). Gregory (1994) observed that over arid and semi-arid regions of India there have been periods in the last decades of the nineteenth century and first two decades of twentieth century when drought frequencies have been markedly higher than in recent years, although individual recent droughts may have been intense ones in some regions. There are also reports of an increase in thunderstorms over the land regions of tropical Asia (Karl et al., 1995). The frequency and severity of wild fires in grassland and rangelands in arid and semi-arid Asia have increased in recent decades (Pilifosova et al., 1996).

Low rainfall in arid and semi-arid regions dictates the formation of shallow soils which are poor in organic matter and nutrients. Coupled with the conversion of grazing lands to farming, the arid region of India is undergoing an aggravation of desertification through erosion of lands and aeolian shifting of soil particles. In some locations there has been a rise of water table with simultaneous increase of salinity and deterioration of soil regime. The variation of the aridity index line, computed by Penman method, over arid regions of India reveals an possible spread of arid conditions in the southeast direction (Jain, 1986).

Populations in arid or semi-arid areas of south Asia are most vulnerable because of their heavy dependence on agriculture and high population density. Monsoon depressions and tropical storms are important features of the climate in this region from agricultural production point of view. These storms can be destructive but also are the main source of moisture. An estimated 31% of cropland is already irrigated, which may reduce vulnerability somewhat, provided water resources remain adequate. Chronic hunger remains a problem, however, for the poorer segments of the population particularly in semi-arid and arid parts of the region (IPCC, 1995).

## 2.2 AFRICA

Africa is the largest tropical land mass with an east-west extent of about 6,000 km. It is the only continent which has roughly equal landmasses within both hemispheres on either side of the equator. The vast continent is characterized by a wide range of climatic regimes. The poleward extremes of the continent experience winter rainfall associated with the passage of mid-latitude air masses. Over the rest of the continent, annual cycle is strongly determined by the position of the Inter-Tropical Convergence Zone (ITCZ) which is a primary feature of the meridional Hadley Circulation (WCRP, 1999). The mean climate of Africa is further modified by the presence of large contrasts in topography and the existence of lakes across the continent (Semazzi and Sun, 1997). This basic climatic state is further significantly modified by the asymmetry of the continent, the adjacent ocean basins circulation, and the global Walker circulation, to produce the observed continental climatology (Hastenrath, 1985).

Rainfall is one of the most important natural resources for many of mainland Africa's 48 nations (Hulme, 1992). Inter- and intra-annual variability in rainfall is perhaps the key climatic element that determines the success of agriculture in these regions where the climatic control of soil water availability through rainfall and evaporation is most prominent. In low-rainfall years, there may be droughts; in high-rainfall years or even for short periods in low-rainfall years there may be floods. Extensive droughts have afflicted Africa, with serious episodes since independence in 1965–1966, 1972–1974, 1981–1984, 1986–1987, 1991–1992, and 1994–1995 (WMO, 1995; Usher, 1997). The aggregate impact of drought on the economies of Africa can be large: 8–9% of GDP in Zimbabwe and Zambia in 1992, 4–6% of GDP in Nigeria and Niger in 1984 (Benson and Clay, 1998).

African rainfall has changed substantially over the last 60 years. Over tropical north Africa this change has been notable as rainfall during 1961-1990 declined by up to 30 per cent compared with 1931-1960. From an analysis of recent rainfall conditions in West Africa, Nicholson et al. (2000) concluded that a long-term change in rainfall has occurred in the semiarid and subhumid zones of West Africa. Rainfall during the last 30 years (1968-97) has been on average some 15% to 40% lower than during the period 1931-60. A similar but smaller change has occurred in semiarid and subhumid regions of southern Africa.

Dennett et al. (1985) pointed out that, although the rainy season includes June through to September in most of the Sahel, the annual rainfall anomalies are related primarily to rainfall in August and, to a lesser extent, September. Sivakumar (1992) showed that at several locations in Niger, a significant decline in the annual and August rainfall has occurred since 1966. From examination of the change between 1931-1960 and 1961-1990 in mean seasonal rainfall over Africa, Hulme (1992) showed that rainfall change has been dominated by the reduction in June-July-August rainfall in the Sahel with widespread decreases of well over 0.4 mm day$^{-1}$. Such a large relative rainfall change between these two 30-year climatologies is unparalleled elsewhere in the world (Hulme et al., 1992). Hulme (1992) also showed that in the Southern Hemisphere tropical margins, December-January-February rainfall rates have declined, with decreases of more than 0.4 mm day$^{-1}$ over parts of Botswana and Zimbabwe. Nicholson et al. (2000) also showed that mean August rainfall during the 1968-97 period was 55%, 37% and 26% below the 1931-60 average in the Sahelo-Sahara, Sahel and Soudan zones, respectively.

In certain semi-arid regions, persistence in the rainfall deviations is significant. Using time series of regional rainfall anomalies, Hulme (1992) showed a striking persistence of Sahelian rainfall anomalies in marked contrast to East Africa and south-western Africa. In West Africa, there has been a pattern of continued aridity since the late 1960s that is most persistent in the more western regions (Nicholson et al., 2000). Rainfall fluctuations are also associated with a geographic pattern. Sivakumar (1989) showed that the reduction in mean annual rainfall in both Niger and Burkina Faso after 1969 was characteristic of the entire region. After 1969, the rainfall isohyets were displaced further south showing that rainfall changes affect large areas. Using latitudinal profiles of mean rainfall rates over Africa, Hulme (1992) showed that southward shifts of JJA rainfall zones of just over 1° latitude (*ca.* 120 km) between 1931-1960 and 1961-1990 and just under 3° latitude (*ca.* 330 km) between 1950-54 and 1983-87. Using normalised vegetation difference index (NDVI) data, Tucker *et al.* (1991) estimated a shift of up to 2.2° latitude (ca. 240 km) in the position of the 200 mm annual isohyet in the Sahel during the decade 1980-1990.

A number of theoretical, modelling and empirical analyses have suggested that noticeable changes in the frequency and intensity of extreme events, including floods may occur when there are only small changes in climate (Wigley, 1985; Katz and Acero, 1994; Wagner, 1996). Mason et al. (1999) identified significant increases in the intensity of extreme rainfall events over about 70% of the country in South Africa between 1931-60 and 1961-90. Le Barbé and Lebel (1997) showed that the average number of rainy events in August was reduced by about 30%.

Hulme (1992) categorized the possible causes for rainfall changes into three broad areas: those related to land cover changes within the continent; those related to changes in the global ocean circulation and associated with patterns of sea-surface temperatures (SSTs); and those related to the changing composition of the global atmosphere.

Air temperatures in the Sahelian and Sudanian zones of West Africa (SSZ) are usually high because of the high radiation load. From south to north temperatures increase and rainfall decreases. Environmental conditions during the stage of crop establishment in the SSZ, especially in the low rainfall areas, are usually harsh since the sowing rains follow a long and hot dry season. Mean maximum temperatures could exceed 40 °C at the time of sowing and absolute temperatures could be much higher (Sivakumar, 1989). Diurnal variations in the air temperature and soil temperatures at the surface and 5-cm depth before the onset of rains (Fig. 2) show that the surface soil temperatures can increase rapidly from 27 °C at 0700 hrs to 56 °C at 1400 hrs. Although the surface soil temperatures decrease after a rain, with a short dry period and clear skies, atmospheric conditions can quickly return to those described in Figure 2. The highland areas of eastern and southern Africa are substantially cooler than lowland regions, and there is evidence that recent warming trends may have been exaggerated in these mountain areas (Hulme, 1996a).

The widespread deterioration of large areas of savannah in the semi-arid regions of Africa is believed to be associated with the overexploitation of marginal land via the removal of wood and overgrazing (Barrow, 1987). The net change of forest area in Africa is the highest among the world's regions, with an annual net loss based on country reports, estimated at 5.3 million ha which contributes to 56% of the total destruction of forests worldwide. Because the open forests are mainly an unmanaged ecosystem, their regeneration may pose problems.

Increasing land degradation leaves the bare surface soil susceptible to wind erosion. Data collected in Niger show (Fig. 3) that the increasing wind erosion is leading to decreased visibility. As compared to the 60s, during the 80s there was a significant increase in the number of days with poor visibility (< 5 km). The problem is becoming particularly serious at the beginning of the rainy season, when rains are usually preceded by dust storms with violent winds. Moving sand particularly affects crop establishment by damaging the seedlings by "sand blasting" and the high soil temperatures during this period cause further damage. Lack of adoption of appropriate strategies at the farm level, especially in the Sahelian zone, to reduce wind erosion and sand blasting is leading to sub-optimal plant stands and replanting over large areas. This has a feedback effect on land degradation.

## 2.3 LATIN AMERICA

The existing climatic differences in South America are very great, climatic extremes such as the semi-arid, arid and desert are present in several countries. Due to topographic characteristics and geographical location, these climatic variations and their impact on economic activities and human beings are different from region to region.

Even though air temperature in some regions is not a limiting factor, except in the southern portion of the continent, the lack of precipitation or its irregularity is a serious problem, specially considering agricultural aspects.

Datsenko et al. (1996) analyzed the rainfall variations in the Brazilian northeast taking the city of Fortaleza as a reference. The study was carried out using the total annual precipitation data from 1849 to 1994. They observed that while the average air temperature tends to increase 0.57 °C/100 years, a defined tendency of increased or decreased precipitation was not observed.

Vergara et al. (2001) evaluated the precipitation trend in the 1921 to 2000 period in the northeast of the Pampa Province (Argentina), a region that is a transition area between moist and semi arid climate which extends to the western portion of Argentina, with high vulnerability to fluctuations in rainfall pattern. For the period analyzed, a drought cycle with a peak in 1940 and lasting until 1960 was observed. Subsequently, a tendency for an increase in precipitation reaching a peak in the 1990s and with a subsequent stabilization was observed.

Scian and Donnari (1996) analyzed the history of the droughts in the semi-arid regions of Argentina using historic data from 12 locations during 1930 to 1990. Use of various indices such as the Palmer Drought Severity Index (PDSI), rainfall abnormalities etc., permitted the consideration of the intensity and duration of droughts and it was concluded that the most severe drought affected the region from 1936 to 1942.

Another severe drought period in Argentina was studied by Navarro et al. (1996). It was observed that 1995 was exceptionally dry, quantified both by the rainfall index abnormality and by the Hansen drought index. These indices indicated that for the region under study (Azul), since 1984 the precipitation levels were below the historic average, with a peak low decreasing until 1995.

There are close to 20 regions in the world whose climate is affected by the ENSO phases, and Latin America is also affected with different characteristics throughout the continent: in Brazil the most affected regions are the northern portion of the Northeastern Region, the Eastern part of the Amazon (tropical zone) and the Southern Region (extra-tropical zone). The most well known climatic abnormalities and whose impact are largest are those related to the rainfall pattern, even though the temperature pattern may also be modified.

During the positive phase, normally the northeastern region of Brazil shows an increase in the intensity of the drought with the decrease of rainfall while in the south of Brazil the region is favored by an increase in precipitation (Cunha, 1999). Martelo (2000) evaluated the impact of the El-Niño phenomenon in Venezuela observing that the precipitation pattern follows this parameter as well as the temperature in the North Atlantic. Olmedo (1999) evaluated the effects of the El-Niño in the Pacific coast of the Republic of Panama, observing that the effect of this disturbance is not homogeneous in the weather behavior. When El-Niño events are sequential, they observed that in general in the first year a reduction in the number of days and in the total amount of rainfall would occur, and an increase in these two parameters would occur in the second year. They observed that the most severe phase of the El-Niño would take place in the dry period of the second year (January to March), and in 1997 the average temperature registered was 2° C higher than the average value for some months.

Alves and Repelli (1992) analyzed the influence of El-Niño on several sub regions in the northeast of Brazil, comparing the climatic contrast in El-Niño years in the abnormality indices of Sea Surface Temperature (SST). They observed that there is a relationship between precipitation and the SST indices in the different phases of El-Niño , and that in both cases, there is a reduction in rainfall in the Brazilian northeast.

Moschini et al. (1996), studying the effects of the El-Niño in the region of the Pampas (Argentina), observed a close relationship between the increase or decrease of rainfall depending on the warm or cold phase of the phenomenon respectively, which was also observed by Cunha (1999). In both the studies, the authors proposed agricultural techniques to mitigate the adverse effects of these abnormalities.

Dias and Rebella (1996) evaluated the probability of changes in monthly rainfall patterns in the Pampas region (Argentina), due to El-Niño . They detected that in 78% of the cases the probability of rain in the 1961-1990 series increased when compared to the 1921-1955 series.

Marengo (2001) and Marengo et al. (2001) analyzed the various conditions and forecast models of climatic changes in Brazil and Latin America and concluded that the study of climatic changes as well as the different scenarios to be determined need better qualification and quantification for Latin America. The authors emphasized that detailed studies of these aspects, which conclusively point out the changes or tendencies of average or extreme climate, that identify a regional warming, are scarce. Although in some regions systematic changes in rainfall or in temperature are shown, they attribute this to changes over 10-year periods such as those which occurred in the Amazon in the period.

Cunha et al (2001) observed that in those years of the El-Niño phenomenon, in the southern region of Brazil and part of Argentina and Uruguay are favored by above average rainfall. On the other hand, evaluating the El-Niño and La-Niña events from 1938 to 1998 regarding the barley crops they concluded that in most cases La-Niña had a positive impact and El-Niño a negative one.

More recently the Standardized Precipitation Index or SPI (Mckee et al., 1993) was employed to monitor and quantify the dry periods in various regions of Latin America (Seiler and Bressan, 2000; Brunini et al., 2000). Murphy et al. (2001) correlated the SPI values with the productivity of the corn crop in Argentina. The correlation coefficient between SPI and yield was significant ($r^2$ =0.78). Dos Anjos and Santos (2001) evaluated the correlation between the SPI values and the El-Niño and La-Niña phenomenon for the semi arid region in the Brazilian Northeast. They observed that in the phase in which these abnormalities had greatest impact were correlated with the values of SPI-6 and SPI-9.

Through a system of dynamic monitoring, Solano Ojeda et al. (2000) determined the advance of droughts, the most affected regions and the crops that suffered the impact of this abnormality during the 1998 and 1999 period in Cuba. They observed that the frequent climatic abnormalities registered in Cuba in the last decades culminating with the 1998/1999 period, had a noticeable negative impact on all socio-economic activities. Among the adverse phenomena, drought was most outstanding, since it duplicated its chance of occurrence as well as increased considerably the extremes and intensity.

Andressen et al. (2000) evaluated the changes in precipitation of the Bolivian high plains and the effects of these variations in the desertification and drought processes. Desertification in this area is highly relevant, since 41% of the area in Bolivia was subject to this phenomena (MDSMA, 1996, cited by Andressen et al., 2000). The authors also showed that the loss of productive land amounts to 1.8 million tons per year. The variations in precipitation observed in this period were large with amplitudes of up to 5000% and with highly elevated inter-annual and special oscillation. Comparing the aridity index and the P/ETP, the authors concluded that for all locations of the Bolivian high plains, 75% of the months were classified as very dry or extremely dry.

Silvia el al. (1991) observed that the rainfall distribution and the stability of the rainfall pattern in the northeast of Brazil are intrinsically related. By analyzing the annual values for temperature and rainfall in 34 locations of the Brazilian northeast and the humidity index terms according to Thornthwaite (1948), the authors concluded that there is not strong correlation between the intensity of the drought and possible climatic changes in the arid region.

A typical case of arid region can be defined through the evaluation of the conditions of the State of Rio Grande do Norte in the Brazilian northeast, located in the area of the Drought Polygon (Medina and Maia Neto, 1991). The study showed that the region above presented serious limitations for operational and profitable agriculture due to the long periods of drought. Even irrigation may be affected if techniques for the preservation of the reservoirs are not adopted.

The inter-annual and intra-annual variations for two locations representing the semi-arid and the sub-tropical regions are presented in Figure 4. During the El Niño years, rainfall is considerably reduced in the semi-arid regions, while in the sub-tropical area such a reduction was not so noticeable.

The use of irrigation to complement the lack of precipitation has substantially increased in the arid and semi arid regions of Latin America. However, the most important element to keep the reservoirs at an adequate level for these practices is rainfall, responsible for maintaining the volume of the reservoirs and underground water.

## 3. **Future climate change scenarios in the arid and semi-arid tropics**

### 3.1 ASIA

The multi-century control integration of atmosphere-ocean global climate models (AOGCMs) unforced by anthropogenic changes in atmosphere composition offer an excellent opportunity to examine the skill of individual models in simulating the present-day climate and its variability on regional scales. Climate change scenarios based on an ensemble of results as inferred from skilled AOGCMs for Asia on annual and seasonal mean basis are discussed in IPCC (2001a). As a result of increases in the atmospheric concentration of GHGs the projected area-averaged annual mean warming is likely to be $1.6 \pm 0.2^0$C in the 2020s, $3.1 \pm 0.3^0$ C in the 2050s, and $4.6 \pm 0.4^0$C in the 2080s over land regions of Asia. Under the combined influence of GHGs and sulfate aerosols, surface warming will be restricted to $1.4 \pm 0.3\ ^0$C in the 2020s, $2.5 \pm 0.4\ ^0$C in the 2050s and $3.8 \pm 0.5\ ^0$C in the 2080s.

Lal et al. (1995) suggested that the surface air temperature over the Indian subcontinent (area-averaged for land regions only) is likely to rise from $1.0^0$C (during the monsoon) to $2.0^0$C (during the winter) by the middle of the next century. The rise in surface temperature could be quite significant across the semi-arid regions of NW India. The increase in surface air temperature simulated by regional climate model (RCM) over central and northern India is not as intense as in the general circulation model (GCM) and does not extend as far south (Hassel and Jones, 1999). These anomalies are linked with changes in surface hydrological variables. Over the south Asia region, a decrease in DTR on an annual mean basis during the winter and a more pronounced decreased in DTR during the summer are projected. The significantly higher decrease in DTR over south Asia during the summer is a result of the presence of monsoon clouds over the region (Lal et al., 1996). For tropical Asia, Whetton (1994) suggested that warming would be least in the islands and coastal areas throughout Indonesia, the Philippines and coastal south Asia and Indo-China and greatest in inland continental areas of south Asia and Indo-China except from June to August in south Asia, where reduced warming could occur.

AOGCMs projected an area - averaged annual mean increase in precipitation of 3 $\pm$ 1% in the 2020s, 7$\pm$ 2% in the 2050s, and 11 $\pm$ 3% in the 2080s, over the land regions of Asia as a result of future increases in the atmospheric concentration of GHGs. Under the combined influence of GHGs and sulphate aerosols, the projected increase in precipitation is limited to 2 $\pm$ 1% in the decade 2020s, 3 $\pm$ 1% in 2050s, and 7 $\pm$ 3% in the 2080s. The models show high uncertainty in projections of future winter and summer precipitation over south Asia (with or without direct aerosol forcings). The effect of sulfate aerosols on Indian summer monsoon precipitation is to dampen the strength of monsoon compared to that seen with GHGs only (Roeckner et al., 1999). Projected changes in temperature, diurnal temperature range and precipitation over tropical south Asia are presented in Table 1.

On an annual mean basis, the area-averaged rainfall over the land regions of the Indian subcontinent is expected to marginally decline by the middle of the next century. No significant change in rainfall is projected during the winter months (January-February). During the monsoon season, a decline of about 0.5 mm $day^{-1}$ in rainfall over the central plains of India is likely. The simulated decline in monsoon rainfall is due to a decrease in high intensity rainfall events throughout the season and is found to be statistically significant at 90% confidence level. Moreover, a decline in the frequency of heavy rainfall spells (>10 mm $day^{-1}$) is likely. No significant changes are discernible in the inter-annual variability of monsoon rainfall in enhanced $CO_2$ simulations with respect to those in the control simulation.

Whereas an increase in rainfall is simulated by RCM (Hassel and Jones, 1999) over the eastern region of India, northwestern deserts see a small decrease in the absolute amount of rainfall. Changes in soil moisture broadly follow those in precipitation except in eastern India, where they decrease as a result of enhanced drainage from the soil. The largest reductions (precipitations reduced to <1 mm $day^{-1}$; 60 % decline in soil moisture) are simulated in the arid regions of northwest India and Pakistan. Relatively small climate changes cause large water resource problems in many areas, especially in the semi-arid regions such as NW India. If water availability decreases in this region, it could have significant implications for agriculture for water storage and distribution and for generation of hydroelectric power. For example, under the assumed scenario of a $1^{O}$ C to 2 $^{O}$ C temperature increase, coupled with a 10 % reduction in precipitation, a 40 to 70 % reduction in annual runoff could occur.

Recent observations suggest that there is no appreciable long term variation in the total number of tropical cyclones observed in the north Indian, southwest Indian, and southwest Pacific Oceans east of $160^{0}$ E (Neumann, 1993; Lander and Guard 1998). Some of these studies (Krishnamurthi et al., 1998; Royer et al., 1998) suggest an increase in tropical storm intensities with carbon dioxide ($CO_2$) induced warming. Some of the most pronounced year to year variability in climate features in many parts of Asia including arid and semi-arid tropics has been linked to ENSO. Meehl and Washington (1996) indicate that future seasonal precipitation extremes associated with a given ENSO event are likely to be more intense in the tropical Indian Ocean region; anomalously wet areas could become wetter, and anomalously dry areas could become drier during future ENSO events. Several recent studies (Kitoh et al., 1997; Lal et al., 2000) have confirmed earlier results indicating an increase in interannual variability of daily precipitation in the Asian summer monsoon with increased GHGs. The intensity of extreme rainfall events is projected to be higher in a warmer atmosphere, suggesting a decrease in return period for extreme precipitation events and the possibility of more frequent flash floods in parts of India, Nepal and Bangladesh. However, Lal et al. (1995) found no significant change in the number and intensity of monsoon depressions (which are largely responsible for the observed interannual variability of rainfall in central plains of India) in the Bay of Bengal in a warmer climate.

## 3.2 AFRICA

In view of the uncertainties in GCMs, it is important to interpret model outputs in the context of their uncertainties and to consider them as potential scenarios of change for use in sensitivity and vulnerability studies. While there is a good degree of certainty regarding future increases in atmospheric $CO_2$ concentrations and there is confidence in the range of projections of global-mean temperature and sea level, there are many uncertainties about regional patterns of precipitation and soil moisture. Much less is known about the frequencies and intensities of extreme events.

With respect to temperature, future annual warming across Africa is projected to range from 0.2 °C per decade to more than 0.5 °C per decade (Hulme et al., 2001). This warming is greatest over the interior of the semi-arid margins of the Sahara and central southern Africa. Land areas may warm by 2050 by as much as 1.6°C over the Sahara and semi-arid parts of southern Africa (Hernes et al., 1995; Ringius et al., 1996). Equatorial countries (Cameroon, Uganda, and Kenya) might be about 1.4°C warmer. Sea-surface temperatures in the open tropical oceans surrounding Africa will rise by less than the global average (i.e., only about 0.6–0.8°C); the coastal regions of the continent therefore will warm more slowly than the continental interior.

Future changes in mean seasonal rainfall in Africa are less well defined. Rainfall changes projected by most GCMs are relatively modest, at least in relation to present-day rainfall variability. Under the two intermediate warming scenarios, significant decreases (10 to 20%) in rainfall during March to November are apparent in North Africa in almost all models by 2050. In southern Africa, decreases of 5-15% in rainfall during the growing season during November to May are projected. Seasonal changes in rainfall are not expected to be large; Joubert and Tyson (1996) found no evidence for a change in rainfall seasonality among a selection of mixed-layer and fully coupled GCMs. Hewitson and Crane (1998) found evidence for slightly extended later summer season rainfall over eastern South Africa (though nowhere else), based on a single mixed-layer model prediction. Great uncertainty exists, however, in relation to regional-scale rainfall changes simulated by GCMs (Joubert and Hewitson, 1997). Under the most rapid global warming scenario, increasing areas of Africa experience changes in rainfall that exceed one sigma level of natural variability. Parts of the Sahel could experience rainfall increases of as much as 15% over the 1961–90 average. Equatorial Africa could experience a small (5%) increase in rainfall. These rainfall results are not consistent: different climate models, or different simulations with the same model, yield different patterns. The problem involves determining the character of the climate change signal on African rainfall against a background of large natural variability compounded by the use of imperfect climate models.

Little can be said yet about changes in climate variability or extreme events in Africa. Rainfall may well become more intense, but whether there will be more tropical cyclones or a changed frequency of El Niño events remains largely in the realm of speculation. The combination of higher evapotranspiration and even a small decrease in precipitation could lead to significantly greater drought risks. An increase in precipitation variability would compound temperature effects.

Changes in sea level and climate in Africa might be expected by the year 2050. Hernes et al. (1995) project a sea-level rise of about 25 cm. There will be subregional and local differences around the coast of Africa in this average sea-level rise—depending on ocean currents, atmospheric pressure, and natural land movements—but 25 cm by 2050 is a generally accepted figure (Joubert and Tyson, 1996). For Africa south of the Equator, simulated changes in mean sea-level pressure produced by mixed-layer and fully coupled GCMs are small (~1 hPa)—smaller than present-day simulation errors calculated for both types of models (Joubert and Tyson, 1996). Observed sea-level pressure anomalies of the same magnitude as simulated changes are known to accompany major large-scale circulation adjustments associated with extended wet and dry spells over the subcontinent.

The temperature-precipitation-$CO_2$ forcing of seasonal drought probably is less significant than the prospect of large-scale circulation changes that drive continental droughts that occur over several years. A change in the frequency and duration of atmosphere-ocean anomalies, such as the ENSO phenomenon, could force such large-scale changes in Africa's rainfall climatology. However, such scenarios of climate change are not well developed at the global level, much less for Africa.

### 3.3 LATIN AMERICA

The arid and semi-arid tropics are the ones suffering greatest impacts from climatic fluctuations from adverse phenomena such as the El Niño and La Niña. Government actions should focus on the scenery of these fluctuations, and how to mitigate its possible effects.

The IPCC report (2001a) calls for a troubling situation regarding possible global warming. There are estimates of an increase between 1.4 to 5.8° C, taking 1990 as reference. Even though there are discrepancies about the absolute values for the increase in temperature, everyone agrees that there will be a slight increase in global temperature, and an increase in precipitation as well (Pinto et al., 2001a). Agricultural exploitation in the semi-arid and arid tropic regions will undoubtedly be greatly affected by these temperature increments.

For example, for the coffee crop, largely cultivated in the tropics, it is possible to predict the impact of possible climatic changes and on its cultivation. Pinto et al. (2000) outlined the ecologically viable areas for agricultural exploitation of this crop in the State of São Paulo (BR). Based on mean historical temperature values and precipitation and water balance, areas suitable for agriculture were determined (Fig. 5). Assuming an average increase in temperature of 1.0° C and an increase in precipitation of approximately 15% and by recalculating the water balance, it was shown that the areas suitable for cultivation were drastically reduced as indicated in Figure 6 (Pinto et al., 2001b). It is important to evaluate these scenarios with care, since some assumptions were made concerning water availability in the soil. Besides, this simulation indicates a trend for the next 100 years while assuming that the current trends in global warming would continue. It is important to note that no allowance was made for changes in crop and irrigation management and genetic improvements.

## 4. Impacts of climate variability and change in the arid and semi-arid tropics

### 4.1 ASIA

As reported in IPCC (1998), stress on water availability in Asia is likely to be exacerbated by climate change. Several studies aimed at understanding the nature and magnitude of gains/ losses in yield of particular crops at selected sites in Asia under elevated $CO_2$ conditions have been reported in the literature (e.g., Luo and Lin, 1999). These studies suggest that, in general, areas in mid- and high- latitudes will experience increases in crop yield, whereas yields in areas in the lower latitudes will decrease.

Generally climatic variability and change will seriously endanger sustained agricultural production in tropical Asia in coming decades. The scheduling of the cropping season as well as the duration of the growing period of the crop would also be affected.

Agricultural productivity in tropical Asia is sensitive not only to temperature increases but also to changes in the nature and characteristics of monsoon. An increase in leaf-surface temperature would have significant effects on crop metabolism and yields, and it may make crops more sensitive to moisture stress (Riha et al., 1996). Experiments in India reported by Sinha (1994) found that higher temperatures and reduced radiation associated with increased cloudiness caused spikelet sterility and reduced yields to such an extent that any increase in dry-matter production as a result of $CO_2$ fertilization proved to be no advantage in grain productivity. Similar studies conducted recently in Indonesia and the Philippines confirmed these results. Amien et al. (1996) found that rice yields in east Java could decline by 1% annually as a result of increases in temperature. In tropical Asia, although wheat crops are likely to be sensitive to an increase in maximum temperature, rice crop would be vulnerable to an increase in minimum temperature. The adverse impacts of likely water shortage on wheat productivity in India could be minimised to a certain extent under elevated $CO_2$ levels; these impacts, however, would be largely maintained for rice crops, resulting in a net decline in rice yields (Lal et. al., 1998). Acute water shortage conditions combined with thermal stress should adversely affect wheat and, more severely, rice productivity in India even under the positive effects of elevated $CO_2$ in the future.

Simulations of the impact of climate change on wheat yields for several locations in India using a dynamic crop growth model, WTGROWS, indicated that productivity depended on the magnitude of temperature change. In North India, a $1^0$C rise in the mean temperature had no significant effect on potential yields, though an increase of $2^0$ C reduced potential grain yields at most places (Aggarwal and Sinha, 1993). In a subsequent study, Rao and Sinha (1994) used the CERES-Wheat simulation models and scenarios from three equilibrium GCMs and the transient GISS model to assess the physiological effects of increased $CO_2$ levels. In all simulations, wheat yields were smaller than those in the current climate, even with the beneficial effects of $CO_2$ on crop yield; and yield reductions were due to a shortening of the wheat-growing season, resulting from temperature increase scenario. Wheat yield decreases could have serious impacts on food security in India, in view of the increasing population and its demand for grains. Most of the wheat production in India comes from the northern plains mostly belonging to semi-arid zone. In this tract it is almost impossible to increase the present area of wheat under irrigation. Karim et al. (1996) also have shown that wheat yields are vulnerable to climate change in Bangladesh. Studies on the productivity of sorghum showed adverse effects in rainfed areas of India (Rao et al., 1995). Results were similar for corn yields in the Philippines (Buan et al., 1996). The likely impact of climate change on the tea industry of Sri Lanka was studied by Wijeratne (1996). He found that tea yield is sensitive to temperature, drought, and heavy rainfall. An increase in the frequency of the droughts and extreme rainfall events could result in a decline in tea yield, which would be greatest in the low-country regions (<600 m).

In Asia, where rice is one of the main staple foods, production and distribution of rice-growing areas may be affected substantially by climate change. Disparity between rice-producing countries is already visible. And it is increasingly evident between developed and developing countries. The projected decline in potential yield and total production of rice in some Asian countries because of changes in climate and climate variability would have a significant effect on trade in agricultural commodities, hence on economic growth and stability (Matthews et al., 1995).

Studies of the potential regional impacts of climate change on the forests and forestry of Tropical Asia are limited. Results of research from Thailand suggest that climate change would have a profound effect on the future distribution, productivity, and health of Thailand's forests. Using climate change scenarios generated by the UKMO and GISS GCMs, Boonpragob and Santisirisomboon (1996) estimated that the area of subtropical forest could decline from the current 50 % to either 20 % or 12 % of Thailand's total forest cover (depending on the model used), whereas the area of tropical forests could increase from 45 % to 80 % of total forest cover. Somaratne and Dhanapala (1996) used the same model for Sri Lanka and estimated a decrease in tropical rainforest of 2-11 % and an increase in tropical dry forest of 7-8 %. A northward shift of tropical wet forests into areas currently occupied by tropical dry forests also is projected. In semi-arid regions of Tropical Asia, tropical forests generally are sensitive to changes in temperature and rainfall, as well as changes in their seasonality. Arid and semi-arid lands often carry a sizeable representation of trees and shrubs in the vegetative cover. Changes in climatic condition would affect all productivity indicators of forest (NPP, NEP and NBP) and their ability to supply goods and services. Fires, which are also influenced by these changes, significantly affect the structure, composition, and age diversity of forests in the region. Enhanced level of global warming is likely to make forest fire more frequent in arid and semi-arid regions of Asia. Deforestation along with the potential impacts of climate change, may have a negative impact on sustainable-nutrition security in south Asia (Sinha and Swaminathan, 1991).

The effect of climate change on soil erosion and sedimentation in mountain regions of Tropical Asia may be indirect but could be significant. An erosion rate in the range of 1-43 tons $ha^{-1}$ with an average of 18 tons $ha^{-1}$ was calculated in three small experimental plots in central Nepal. Part of generated sediment may be deposited on agricultural lands or in irrigation canals and streams, which will contribute to a deterioration in crop production and in the quality of agricultural lands. The impact of climate change on coastal areas in Tropical Asia could be severe and in some areas catastrophic. The combined effects of subsidence and sea level rise could cause serious drainage and sedimentation problems in addition to coastal erosion and land loss in deltaic areas of Tropical Asia.

Climate change is likely to cause environmental and social stress in many of Asia's rangelands and drylands. Precipitation is scarce and has a high annual variance in dryland areas of tropics. Very high daily temperature variance is recorded with frequent sand storm, dust ghost and intense sunshine. Nutrient contents of the soils are low. Being exposed to degradation as a result of poor land management, soils could become infertile as a result of climate change. Temperature increases would have negative impacts on natural vegetation in desert zones. Plants with surface root systems, which utilize mostly precipitation moisture will be vulnerable. Climate change also would have negative impacts on sheep breeding and lamb wool productivity. Because soil moisture is likely to decline in this region, the least dryland type (dry sub-humid drylands) are expected to become semi-arid and semi-arid land is expected to become arid.

The survival rate of pathogens in winter or summer could vary with an increase in surface temperature (Patterson et al., 1999). Higher temperatures in winter will not only result in higher pathogen survival rates but also lead to extension of cropping area, which could provide more host plants for pathogens. Thus, the overall impact of climate change is likely to be an enlargement of the source, population, and size of pathogenic bacteria. Damage from diseases may be more serious because heat-stress conditions will weaken the disease-resistance of host plants and provide pathogenic bacteria with more favourable growth conditions. The growth, reproduction, and spread of disease bacteria also depend on air humidity; some diseases-such as wheat scab, rice blast, and sheath and culm blight of rice will be more widespread in tropical regions of Asia if the climate becomes warmer and wetter.

Surface water and ground water resources in the arid and semi-arid Asian countries play vital roles in forestry, agriculture, fisheries, livestock production and industrial activity. The water and agriculture sectors are likely to be most sensitive and hence vulnerable to climate change-induced impacts in the arid and semi-arid tropical Asia. Croplands in many of the countries in the region are irrigated because rainfall is low and highly variable (IPCC 2001b). The agriculture sector here is potentially highly vulnerable to climate change because of degradation of the limited arable land. Almost two-thirds of domestic livestock are supported on rangelands, although in some countries a significant share of animal fodder also comes from crop residue. The combination of elevated temperature and decreased precipitation in arid and semi-arid rangelands could cause a manifold increase in potential evapotranspiration, leading to severe water-stress conditions. Many desert organisms are near their limits of temperature tolerance. Because of the current marginality of soil-water and nutrient reserves, some ecosystems in semi-arid regions may be among the first to show the effects of climate change. Climate change has the potential to exacerbate the loss of biodiversity in this region.

## 4.2 AFRICA

Agriculture constitutes a large share of African economies, with a mixture of subsistence and commercial production. Forestry is an important complement to agriculture in many rural areas, but managed forests are less significant. Several reports (IPCC 2001b; Parry et al., 1988) refer to countries in the arid and semi-arid regions, especially in West Africa, as being vulnerable to projected climate change. Recently, IPCC (2001b) reinforced the concern that climate change resulting in increased frequencies of drought poses the greatest risk to agriculture. Consequently, the arid and semi-arid tropics, which are already having difficulty coping with environmental stress, are likely to be most vulnerable to climate change.

Agriculture in the semi-arid tropics of Africa, which is predominantly rainfed, is finely tuned to climate as it relies on the timely onset of rainfall and its regular distribution through the rainy season. Hence even a slow, small change towards a worsening climate can increase climatic risks. Waggoner (1992) concluded that if the present climate is a productive one, warmer and drier will hurt. In the semi-arid tropics of Africa, however the present climate itself is marginally productive and this introduces a greater risk if climate worsens further.

Impacts of climate variability and change in the arid and semi-arid tropics of Africa can be described as those related to projected temperature increases, the possible consequences to water balance of the combination of enhanced temperatures and changes in precipitation and sensitivity of different crops/cropping systems to projected changes.

### *4.2.1 Impacts due to projected temperature increases*

The general conclusion is that climate change will affect some parts of Africa negatively, although it will enhance prospects for crop production in other areas (see Downing, 1992, for case studies of agriculture in Kenya, Zimbabwe, and Senegal). Warmer climates will alter the distribution of agroecological zones. Highlands may become more suitable for annual cropping as a result of increased temperatures (and radiation) and reduced frost hazards. Although C3 crops exhibit a positive response to increased $CO_2$ (as much as 30% with $2xCO_2$), the optimal productive temperature range is quite narrow. Some regions could experience temperature stress at certain growing periods—necessitating shifting of planting dates to minimize this risk.

Expansion of agriculture is important in the east African highlands. For example, agroecological suitability in the highlands of Kenya would increase by perhaps 20% with warming of 2.5°C based on an index of potential food production (Downing, 1992). In contrast, semi-arid areas are likely to be worse off. In eastern Kenya, 2.5°C of warming results in a 20% decrease in calorie production. In some lowlands, high-temperature events may affect some crops. Growth is hindered by high temperatures, and plant metabolism for many cereal crops begins to break down above 40°C. Burke et al. (1988) found that many crops manage heat stress (with ample water supply) through increased transpiration to maintain foliage temperatures at their optimal range. Because a large portion of African agriculture is rain-fed, however, heat-related plant stress may reduce yields in several key crops—such as wheat, rice, maize, and potatoes. At the other extreme of the C3 temperature spectrum, several crops (such as wheat and several fruit trees) require chilling periods (vernalization). Warmer night temperatures could impede vernalization in plants that require chilling, such as apples, peaches, and nectarines. Locations suitable for grapes and citrus fruit would shift to higher elevations. C4 crops are more tolerant, in general, to climate variations involving temperature ranges between 25°C and 35°C. These crops most often are located in warmer, dryer climates; they are quite susceptible to water stress.

According to IPCC (2001a), the globally averaged surface temperature is projected to increase by 1.4 to 5.8 °C over the period 1990 to 2100. The number of days with temperature above a given value at the higher end of distribution will increase substantially and there will be a decrease in the days with temperature at the lower end of the distribution (IPCC 2001a). In certain agroecological zones such as Southern Sahelian zone of West Africa, where the predominant soils are sandy in nature, increased *mean* temperature could affect the *maximum* temperatures at the soil surface substantially. It is conceivable that surface soil temperatures could exceed even 60 °C. Under higher temperatures, enzyme degradation will limit photosynthesis and growth. Increased temperatures will result in increased rates of potential evapotranspiration. In the long term, the very establishment and survival of species in both the managed and unmanaged ecosystems in this region may be threatened resulting in a change in the community structure.

Most livestock in Africa are herded in nomadic areas, although significant numbers are kept in paddocks on farms. Domestic animals, especially cattle, also will be affected by climate change. In the cold highlands of Lesotho, for example, animals would benefit from warmer winters but could be negatively affected by a lowering of the already low nutritional quality of grazing.

#### *4.2.2 Consequences to water balance of the combination of enhanced temperatures and changes in precipitation*

There is wide consensus that climate change, through increased extremes, will worsen food security in Africa. Evidence shows that certain arid, semi-arid and dry subhumid areas have experienced declines in rainfall, resulting in decreases in soil fertility and agricultural, livestock, forest and rangeland production.

Projected temperature increases are likely to lead to increased open water and soil/plant evaporation. As a rough estimate, potential evapotranspiration over Africa is projected to increase by 5–10% by 2050. Since Africa is the continent with the lowest conversion factor of precipitation to runoff (averaging 15%), the dominant impact of global warming is predicted to be a reduction in soil moisture in subhumid zones and a reduction in runoff. The prospect of global climate change has serious implications for water resources and regional development (Riebsame et al., 1995).

*4.2.3 Sensitivity of different crops/cropping systems*

Numerous cases of the devastating affects of interannual variability of rainfall on crop yields and national economies have been seen in the past five decades, but none more dramatic than the Sahelian droughts in the early 70s. Average yields of groundnut in Niger decreased from 850 kg/ha in 1966-67 to 440 kg/ha by 1981 due mainly to drought and diseases (Toukoua, 1986).

Ojima et al. (1996) used the CENTURY (Parton et al., 1992) ecosystem process model of plant-soil interactions to analyze the impact of climate and atmospheric $CO_2$ changes on grasslands of the world, including 7 of 31 sites in Africa. Ojima et al. (1996) looked at the effects of increasing $CO_2$ and climate, using climate change scenarios based on the Canadian Climate Centre (CCC) and GFDL GCMs. They found that changes in total plant productivity were positively correlated to changes in precipitation and nitrogen mineralization (with nitrogen mineralization the most important factor). The response to nitrogen mineralization was consistent with the general observation that grasslands respond positively to addition of nitrogen fertilizer (Rains et al., 1975; Lauenroth and Dodd, 1978). Plant responses to $CO_2$ were modified in complex ways by moisture and nutrient availabilities; their results generally indicated that $CO_2$ enrichment had a greater effect with higher moisture stress. However, nutrient limitations reduced $CO_2$ responses. Ojima et al. (1996) concluded that increased atmospheric $CO_2$ will offset the negative effects of periodic droughts, making grasslands more resilient to natural (and human-induced changes in) climate variability. The strength of this beneficial effect, however, is controlled by the availability of nitrogen and other nutrients, which tend to be limited in many African landscapes.

In Africa, most mid-elevation ranges, plateaus, and high-mountain slopes are under considerable pressure from commercial and subsistence farming activities (Rogers, 1993). Mountain environments are potentially vulnerable to the impacts of global warming. This vulnerability has important ramifications for a wide variety of human uses—such as nature conservation, mountain streams, water management, agriculture, and tourism (IPCC 1996, WG II, Section 5.2).

Using the ACRU/CERES hybrid model—one of the most sophisticated crop-climate models developed in Africa—Schulze et al. (1996) have evaluated the impact of climate change on maize in South Africa. The investigators divided the diverse geography of South Africa into 712 relatively homogeneous zones, each associated with vegetation, soil, and climate data.

Daily values of temperature (minimum and maximum), rainfall, wind speed, and solar radiation are used in the crop evaluation, based on the CERES-Maize model. Recent scenario analysis of the model (see Hulme, 1996a) shows a wide range of potential maize yields in South Africa. For three scenarios of climate change (corresponding to the middle of the next century), yields decrease in the semi-arid west. For most of the country, however, potential yields would increase—generally by as much as 5 t/ha. The $CO_2$ enrichment effect counteracts the relatively modest changes in temperature and precipitation. In parts of the eastern highlands, particularly in Lesotho, dramatic increases in yields result from higher temperatures.

Hulme (1996b) presents an integrated view of climate impacts in southern Africa. Prospects for agriculture depend critically upon changes in precipitation. A “dry” scenario suggests less-suitable conditions in semi-arid and subhumid regions. With little decrease (or increases) in precipitation, agriculture should be able to cope with the average changes. However, shifts in drought risk need to be considered.

The extent of effects of higher temperatures on African vegetation (e.g., effects on respiration rates, membrane damage) is largely uncertain. Temperature is known to interact with $CO_2$ concentration, so expected increases in respiration resulting from a temperature increase alone may be offset or even reduced by higher $CO_2$ concentrations (Wullschleger and Norby, 1992).

The direct impacts of changes in the frequency, quantity, and intensity of precipitation and water availability on domestic animals are uncertain. However, increased droughts could seriously impact the availability of food and water—as in southern Africa during the droughts of the 1980s and 1990s (IPCC, 2001b).

Agricultural pests, diseases, and weeds also will be affected by climate change. Little quantitative research on these topics has been undertaken in Africa, however. Perhaps the most significant shifts could occur in tsetse fly distributions and human disease vectors (such as mosquito-borne malaria). Tsetse fly infestation often limits where livestock can be kept or the expansion of extensive agriculture (Hulme, 1996a). Declining human health would affect labor productivity in agriculture.

## 4.3 LATIN AMERICA

The climatic variations observed in Latin America, both in large scale and regional aspects, carry incisive socio-economic impacts on the populations involved. Agriculture and water resources are most affected through the impact of extreme temperatures (excessive heat, frost) and the changes in rainfall (drought, flooding). However, the variations that have a long-lasting effect and that bring the most damage to society are the dry periods and droughts.

As a matter of fact, there is evidence that many of the Pre-Colombian civilizations had a severe decline in their culture caused by excessive drought or flooding; abnormalities associated with the El Niño phenomenon. The large variations in rainfall, which cause either drought or flooding in these areas, are associated with the El Niño and La Niña phenomena. In many cases however there is a joint effect between these and the variations in the temperature of the surface of the North Atlantic Ocean (Alves and Repelli, 1992).

Peru is a typical example of a country where El-Niño impacts and its distinct phases (cold and warm) affect the whole country, with damaging effects on agriculture. The effects observed during the 97/98 episode were droughts, frosts and flooding in different regions of the country, causing losses in over 2 million hectares of crop land with a reduction in crop yields of up to 50% (Cotrina, 2000).

The impact of climatic variables on economic activities, specially on agriculture, must be analyzed in a careful and pragmatic manner and remedial actions must be pro-active in order to mitigate the effects of these climatic variations. From the stand point of food and fibre production, the remedial actions should be based on scenarios to predict the likely effects. This can be done through statistical analysis of meteorological elements, the occurrence of meteorological and adverse phenomena and how the various crops react to this negative impact. Currently, one of the tools used to reduce the impact of these climatic variations, is the Climatic Risk Zoning, which is being carried out in all States in Brazil (Assad, 2001a), for determining the potential for agricultural exploitation. Figures 7 and 8 depict the Climatic Risk Zoning for the cotton crop in Brazil (Assad, 2001b ) and corn in the State of São Paulo (Brunini et al., 2001a). This methodology helps develop appropriate adaptation strategies so as to reduce any impact from climatic variations, and also offers support to financing programs and agricultural crop insurance allowing the farmer a minimum economic profitability.

In order to follow-up on the effects of the climatic impacts on the various activities, a continuous and systematic monitoring of the meteorological variables, plant response and the effect on economic and social activities is necessary. Several countries in Latin America (Brazil, Cuba, Argentina, Venezuela, Chile among others) have developed this type of work ( Ojeda et al., 2000, Brunini et al., 2000, Brunini et al., 2001a). In the case of Brazil, more detailed information is available from the Integrated Agrometeorological Information Center (CIIAGRO) – in the State of São Paulo, with the emission of two bulletins weekly to support the activities of the various economic sectors (Brunini et al., 1996). Recently, the Standardized Precipitation Index (SPI) was introduced in order to quantify the drought, indicating the impact of the drought in the 1999/2001 period throughout the State (Figure 9).This methodology was useful to support government decision on irrigation policies and water resources management (Brunini et al., 2001b)

The different existing ecosystems in Latin America are subject to a wide variety of impacts, making it impossible to establish a general rule. Nevertheless, in many cases the actions of human beings contribute substantially to the fragility of these ecosystems eg., deforestation in the Amazon region, fires in the central western regions in Brazil, inadequate irrigation management and pollution in southeast Brazil, such as the São Paulo city metropolitan area etc., Other examples could be cited in other countries, however, naming every single one would be to excessively detail.

## 5. ***Adaptation potential in the arid and semi-arid tropics***

### 5.1 ASIA

Adaptation to climate change in arid and semi-arid tropics of Asian countries depends on the cost of adaptive measures, existence of appropriate institutions, access to technology, and biophysical constraints such as land and water resource availability, soil characteristics, genetic diversity for crop breeding (e.g., development of heat-resistant rice cultivars), and topography. Adaptation measures designed to anticipate the potential effects of climate change can help to offset many of the negative effects. Adaptation measures that ameliorate the impacts of present-day climate variability include sea defences, institutional adaptations, plant breeding and adoption of new technologies in agriculture.

Sustainable development within tropical Asia's agroecosystems is crucial to provide adequate food security for traditional farming communities in developing countries and to ensure *in situ* conversation of crop biodiversity for sustaining high-input modern agriculture itself. Traditional societies have always manipulated biodiversity to ensure ecosystem resilience and to cope with uncertainties in the environment, rather than to increase production on a short-term basis. There is increasing evidence now to suggest that one could learn from their traditional ecological knowledge base (Gadgil et al., 1993) for coping with uncertainties associated with global change.

The resilience of agricultural practices in the face of climate change depends on the nature and magnitude of region-specific climate change, and the threshold and adaptive capacity of agricultural communities. Adjustment of planting dates to minimize the effect of temperature increase-induced spikelet sterility can be used to reduce yield instability, by avoiding having the flowering period to coincide with the hottest period. Adaptation measures to reduce the negative effects of increased climatic variability as normally experienced in arid and semi-arid tropics may include changing the cropping calendar to take advantage of the wet period and to avoid extreme weather events (e.g., typhoons and storms) during the growing season. Crop varieties that are resistant to lodging (e.g., short rice cultivars) may withstand strong winds during the sensitive stage of crop growth. A combination of farm-level adaptations and economic adjustments such as increased investment in agriculture infrastructure and reallocation of land and water would be desired in the agricultural sector (IPCC, 2001b). Other adaptive options included developing cultivars resistant to climate change; adopting new farm techniques that will respond to the management of crops under stressful conditions, plant pests and disease; design and development of efficient farm implements; and improvement of post-harvest technologies, which include among other things, the use and processing of farm products, by-products and agricultural waste.

A commonly prescribed adaptation to climate change in the water sector is to enhance characteristics that offer flexibility hence enhancing resilience. Flexibility issues are particularly important with regard to the development of water resources for industry or agriculture. If hydrological patterns change markedly and irrigated agriculture is required to relocate in response, prior investment may be lost as existing infrastructures become obsolete, and additional investments will be needed. This necessitates critical scrutiny of a range of available choices that incorporate economic and environmental concerns. The potential for adaptation should not lead to complacency (Rosenzweig and Hillel, 1995).

Studies have shown that ecologically important keystone species often are socially selected by many rural societies. The possibility for species selection for rehabilitating a degraded ecosystem should be based on a value system that the local people understand and appreciate; therefore, their participation in the process of developmental activity is important. Community perceptions of soil and water management can be a powerful agent for sustainable management of natural resources. In other words, natural resource management in tropical Asia must be sensitive to social and even cultural perceptions (Ramakrishnan, 1998), as well as traditional resource management practices.

The major impact of climate change in arid and semi-arid Asia is likely to be an acute shortage of water resources associated with significant increases in surface air temperature. Conservation of water used for irrigated agriculture, therefore, should be given priority attention. With increased evapotranspiration, any adaptation strategy in agriculture should be oriented toward a shift from conventional crops to types of agriculture that are less vulnerable to evapotranspiration loss (Safriel, 1995). Expansion of commercial and artesian fisheries also could help reduce dependence on food productivity. Protection of soils from degradation should be given serious consideration. Trying out salt water resistant varieties of crops in the areas where drainage is poor; diversifying agriculture and food habits of the people primarily limited to some specific cereals, improving to management of irrigation systems; implementing crop livestock integration; changing crop varieties in cropping patterns to suit changing climatic conditions; implementing agro-forestry systems etc. are the other adaptive options to be considered, (Luo and Lin, 1999). Optimum use of fertilizers and ecologically clean agrotechnologies would be beneficial for agriculture.

Cropping systems may have to change to include growing suitable cultivars (to counteract compression of crop development), increasing crop intensities (i.e., the number of successive crop produced per unit area per year) or planting different types of crops (Sinha et al., 1998). Farmers will have to adapt to changing hydrological regimes by changing crops. For example, farmers in Pakistan may grow more sugarcane if additional water becomes available and they may grow less rice if water supplies dwindle. The yield ceiling must be raised and the yield gap narrowed while maintaining sustainable production and a friendly environment. Development of new varieties with higher yield potential and stability is complementary to bridging the yield gap.

Improvements in run-off management and irrigation technology (i.e., river run-off control by reservoirs, water transfers and land conservation practices) will be crucial.

Increasing efforts should be directed toward rainwater harvesting and other water-conserving practices to slow the decline in water levels in aquifers. Recycling of wastewater should be encouraged in drought-prone countries in tropical Asia.

Although the core population of the species may become extinct because of global warming, resistant types in peripheral populations will survive and can be used to rehabilitate and restore affected ecosystems ( Kark et al., 1999). The geographic locations of such species usually coincide with climatic transition zones, such as at the edges of drylands or along the transition between different types of drylands. Identifying regions with concentrations of peripheral populations of species of interest and protecting their habitats from being lost to development therefore can play a role in enhancing planned adaptation for semi-arid and arid regions of Asia.

5.2 AFRICA

While there is universal agreement that the direction of climate change, especially at the regional scale, is somewhat uncertain, it should not lead us to a degree of complacency that adaptation to climate change will be easy. The importance of the rate of climate change must be assessed by comparing the rate at which the systems that might be affected change and adapt (Ausubel, 1991). Adaptations are expensive and the level of technological and economic development of a country determines the extent to which countries can cope with climatic changes.

The sensitivity of a crop to climate change depends not only on its physiological response to temperature or moisture stress, but also on other components of the system. The poor soils in the arid and semi-arid regions of Africa with low native soil fertility are a major component affecting this sensitivity. With the reduced ratio of the length of fallows to cropping years, soil fertility has been declining. According to Mudahar (1986), average use of fertilizers in the sorghum (*Soghum bicolor* (L.) Moench) and pearl millet (*Pennisetum glaucum* (L.) R.Br.) growing countries of West Africa was only 5 kg/ha. In the absence of added manure or fertilizers on these poor soils, the nutrient reservoir of the soil under continuous cropping is dropping to levels which can no longer sustain the desired yield levels.

Whether or not there will be a significant climatic change, the inherent climatic variability in the arid and semi-arid regions of Africa makes adaptation unavoidable. Environmental problems facing this zone are serious and certain. The need for development and implementation of sustainable agricultural strategies on a regional scale is crucial in this marginal region that is already threatened by environmental degradation. Premeditated adaptation that begins with anticipation and information (NAS, 1991b) is a good strategy for this region. The approaches we need should be prescriptive and dynamic rather than descriptive and static.

*5.2.1 Improve monitoring:*

In order to assess carefully the impact of future climate change on the managed and unmanaged ecosystems in the SSZ, it is crucial to monitor local climate, and natural changes in species adaptation, if any. It will be necessary to install improved methods of climate monitoring by taking advantage of recent developments in automatic weather stations which enable easy recording of the occurrence of extreme events on a routine basis. For species adaptation, it will be useful to set up phenological gardens at bench mark sites to carefully assess the changes in their adaptation and in the duration of the developmental stages.

*5.2.2 Use Strategies for Efficient Natural Resource Use:*

Increasing the promotion and strengthening of resource conservation is the first step in coping with the climate change. These strategies will include, for example: soil and moisture conservation, better moisture use efficiency, collection and recycling of runoff, reducing deforestation, increasing reforestation, and reduction of biomass burning. Strategies that can increase the water use efficiency, such as relay cropping during years with early onset of rains, are now available and should be transferred to the farm level.

*5.2.3 Implement Sustainable Agricultural Practices:*

It is important to increase the emphasis on the development and adoption of technologies that may increase the productivity or efficiency of crops consistent with the principles of sustainable development. Sivakumar et al. (1991) discussed possible strategies for management of sustainable systems in the SSZ. These include techniques such as minimum/no till systems, traditional agro-silvi-pastoral systems, choice of appropriate crop varieties, intercropping/relay cropping of cereals with legumes, *Faidherbia albida* systems, mixed tree/grass/crop systems, rotations, use of manures with a limited quantity of fertilizer, and use of crop residues.

*5.2.4 Enforce Effective Intervention Policies:*

One of the adaptation strategies recommended by NAS (1991) is the intervention by governments to manipulate the circumstances of choices. The criteria laid down for government action (NAS, 1991) apply to the Sudano-Sahelian zone even now:

a) Amount of time needed to carry out the adaption is so long that we must act now.
b) Action is profitable even when climate does not change.
c) Penalty for waiting a decade or two is great.

The need for good, timely climate information in the drought-prone regions is too well known to be stressed. Recent developments in the information technology now make it possible to quickly acquire and sort the enormous amount of information into items relevant to the end user. Implementation of policies to provide timely information, improved weather and climate forecasts and good markets should help the farmer adapt quickly.

5.3 LATIN AMERICA

The process of potential adaptation of crops and human beings to environmental impacts in the arid and semi-arid tropics is challenging and is highly dependent on existing technologies.

In the humid tropics, where drought is not a constant phenomenon but rather a periodic abnormality, from year to year, or even in the rainy season, several agricultural practices can be used such as: direct planting, irrigation, choice of drought tolerant varieties. This has been a technological adaptation widely used in countries such as Brazil, Argentina, Uruguay, and Paraguay among others. On the other hand, in the arid and semi-arid regions where the low rainfall is a limiting factor, the most feasible solution or technological adaptation is to use supplemental irrigation.

For this purpose, large reservoirs have been built in conjunction with power generation. In many cases perennial rivers are exploited for irrigation. These techniques are quite challenging in many cases, especially when improper irrigation methods bring about more damage to the environment by salinization of agricultural soils or depletion of scarce natural resources.

It is possible that intercropping and techniques for sustainable agriculture are more appropriate for these regions. Many options must involve a combination of efforts to reduce land degradation and foster sustainable management of natural resources.

A number of adaptive processes designed to prevent further deterioration of forest cover are already being implemented to some degree. Some of these measures involve natural responses when particular tree species develop the ability to make more efficient use of reduced water and nutrients under elevated $CO_2$ levels. Other adaptive measures involve human-assisted action programs (such as tree planting) designed to minimize undesirable impacts. These strategies will include careful monitoring and microassessment of discrete impacts of climate change on particular species.

## 6. Conclusions

The agricultural climate of the arid and semi-arid tropical regions in Asia, Africa and Latin America is characterized by low and variable rainfall and consistently high temperatures during the growing season. Climate variability -- both inter- and intra-annual -- is a fact of life in these regions with a traditionally low agricultural productivity. The projected climate change and the attendant impacts on water resources and agriculture in the arid and semi-arid tropical regions add additional layers of risk and uncertainty to an agricultural system that is already impacted by land degradation due to growing population pressures. Farmers in these regions have over centuries adopted cropping strategies, such as inter cropping and mixed cropping, that minimize the risk and ensure some degree of productivity even in poor years. Such strategies are based on their understanding of natural climatic variability, but the projected climate change is not factored into this understanding. Hence it is important to examine crop responses to a range of possible changes, especially in the nature, frequencies and sequences of extreme climatic changes. Issues such as sustainability or land productivity, changes in erosion, degradation and environmental quality also need careful consideration. Improved management strategies are necessary for coping with the projected global climatic change in the arid and semi-arid tropical regions of the world.

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**Table 1. Projected changes in surface air temperature (top), diurnal temperature range (middle) and precipitation (bottom) over tropical South Asia as a results of future increases in greenhouse gases : Number in parenthesis are changes when direct effects of sulphate aerosols are included (adapted from IPCC, 2001).**

## Temperature change ( $^0$C)

| | 2020 | 2050 | 2080 |
|---|---|---|---|
| **Annual** | **1.36** | **2.69** | **3.89** |
| | **(1.06)** | **(1.92)** | **(2.98)** |
| **Winter** | **1.62** | **3.25** | **4.25** |
| | **(1.19)** | **(2.08)** | **(3.25)** |
| **Summer** | **1.13** | **2.19** | **3.20** |
| | **(0.97)** | **(1.81)** | **(2.67)** |

## Change in Diurnal Temperature Range ( $^0$C)

| | 2050 | 2080 |
|---|---|---|
| **Annual** | **-0.27** | **-0.45** |
| | **(-0.22)** | **(-0.31)** |
| **Winter** | **-0.27** | **-0.46** |
| | **(0.14)** | **(-0.31)** |
| **Summer** | **-3.06** | **-2.89** |
| | **-(4.97)** | **(-4.95)** |

## Precipitation Change (%)

| | 2020 | 2050 | 2080 |
|---|---|---|---|
| **Annual** | **2.9** | **6.8** | **11.0** |
| | **(1.0)** | **(-2.4)** | **(-0.1)** |
| **Winter** | **2.7** | **-2.1** | **5.3** |
| | **(-10.1)** | **(-14.8)** | **(-11.2)** |
| **Summer** | **2.5** | **6.6** | **7.9** |
| | **(2.8)** | **(0.1)** | **(2.5)** |

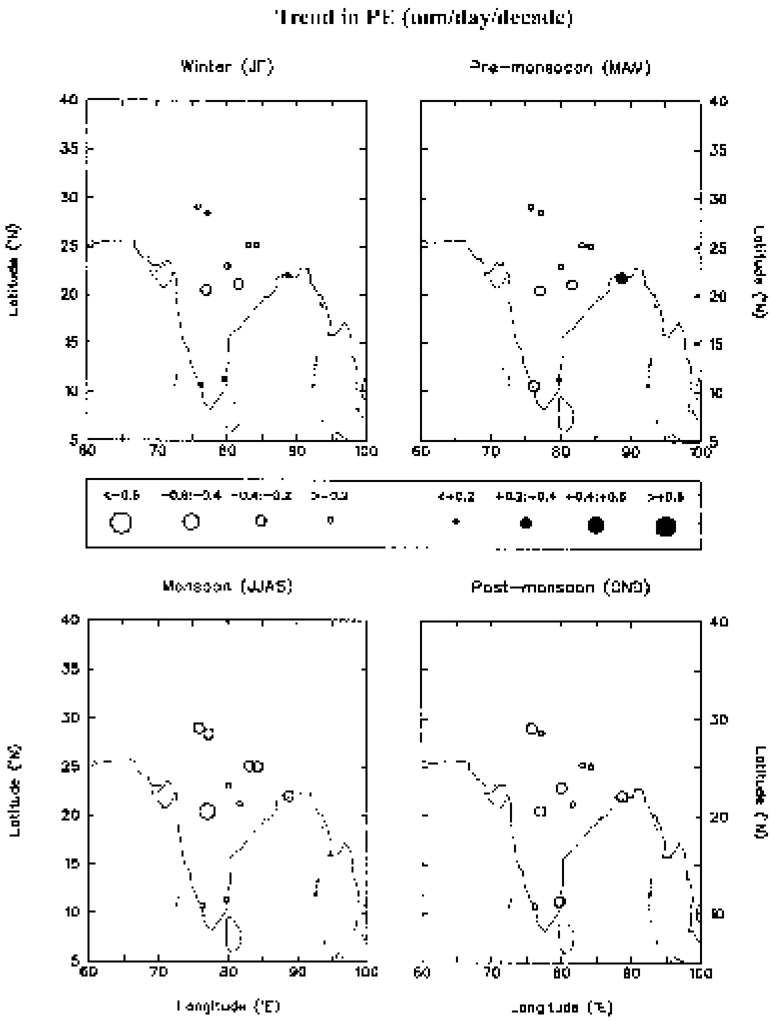


Fig. 1. Mean linear trend (mm day⁻¹ decade⁻¹) in PE for the period from 1976 to 1990 for different seasons over India based on ten stations (dots). Dot size is related to trend.

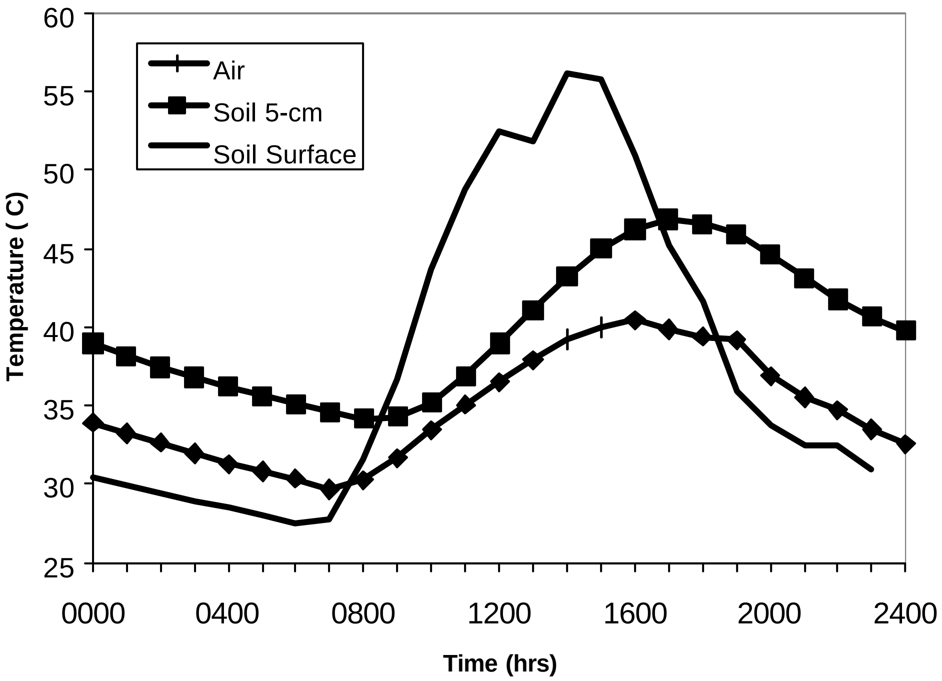


Figure 2. Diurnal variation in the air temperature and soil temperatures at the surface and 5-cm depth before the onset of rains on 10 May 1992 at Sadore, Niger.

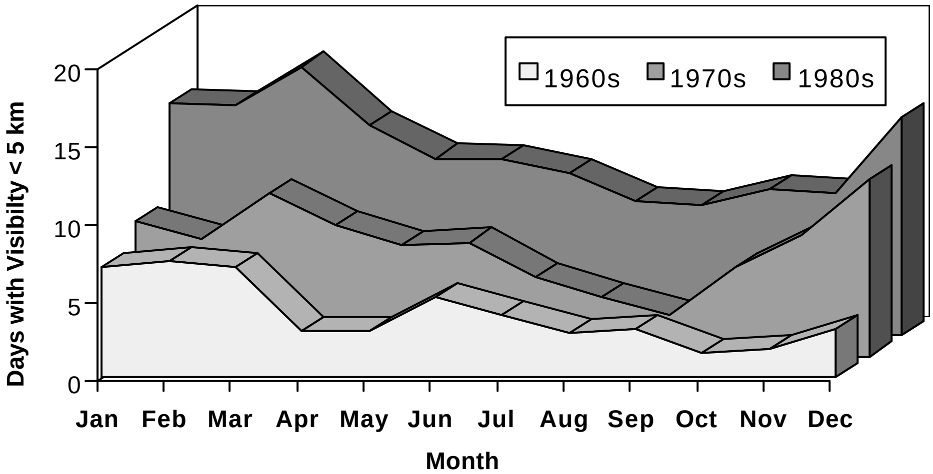


Figure 3. Changes in the visibility from the 1960s to 1980s at Niamey, Niger (Data source: National Meteorological Services of Niger).

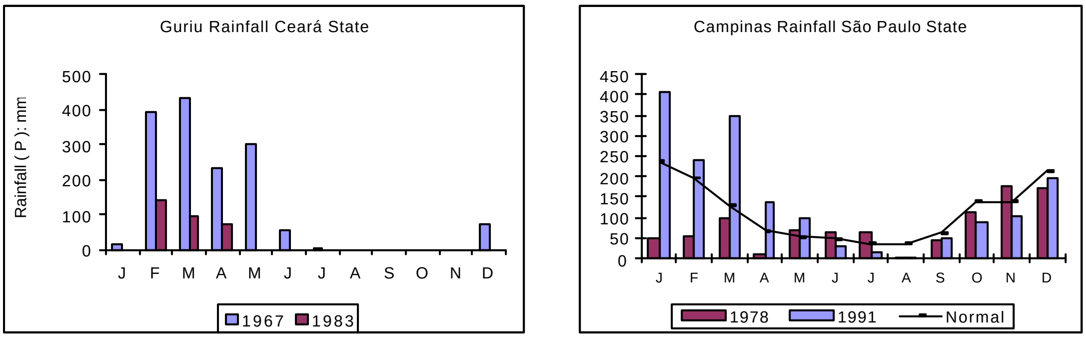


Figure 4. Seasonal rainfall variability in a semi-arid region (Guruiu) and a subtropical region (Campinas) in Brazil.

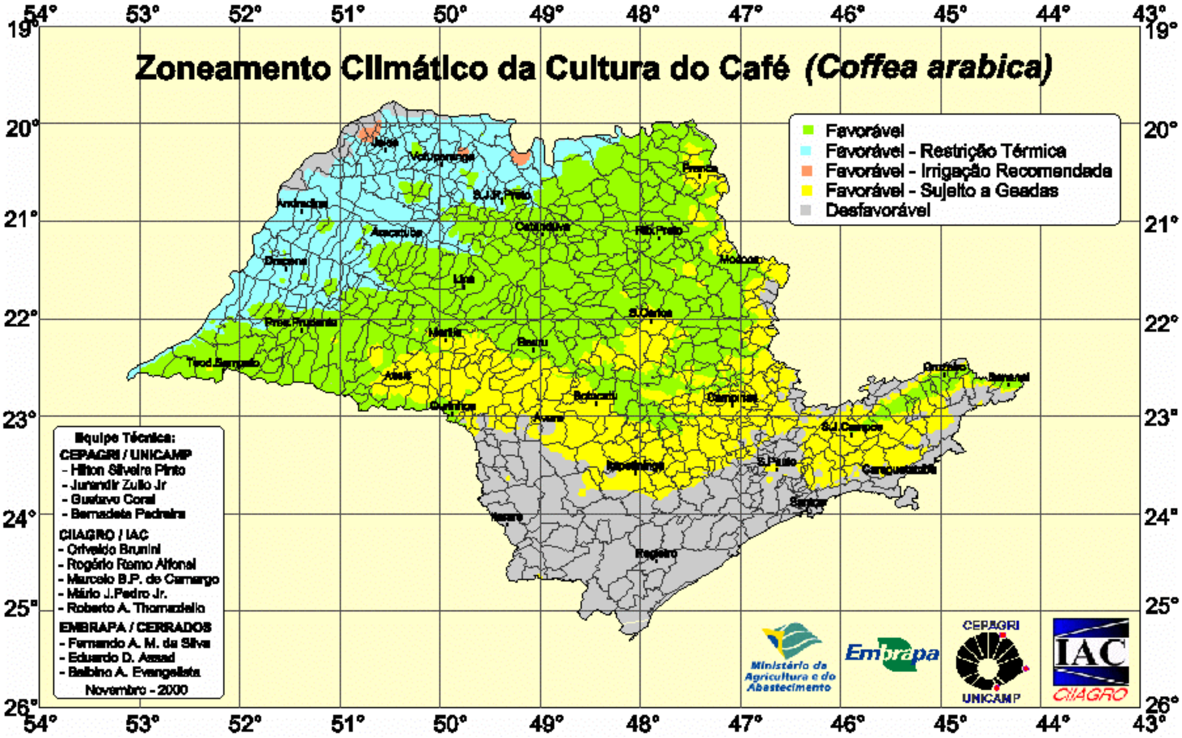


Figure 5. Climatic risk zoning for coffee crop in São Paulo State, Brazil (Pinto et al., 2000).

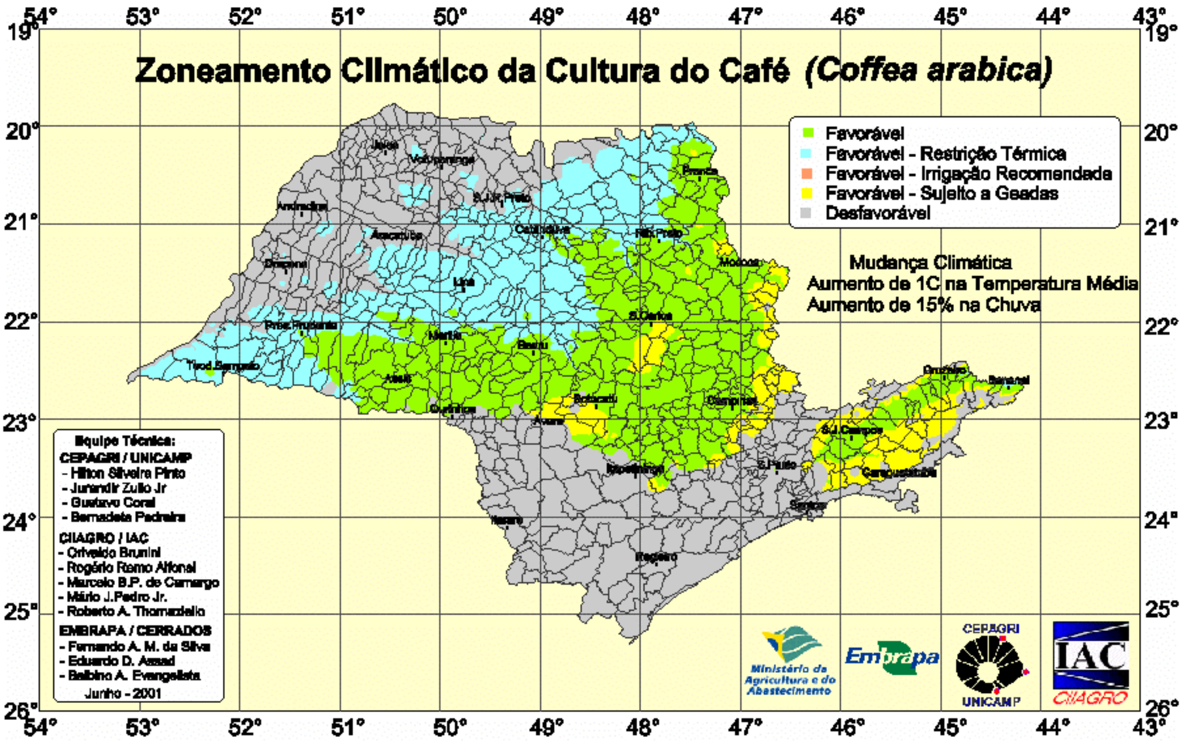


Figure 6. New scenarios for Coffee producing areas in São Paulo State, Brazil, considering a climate change scenario as described by IPCC (Pinto et al., 2001).

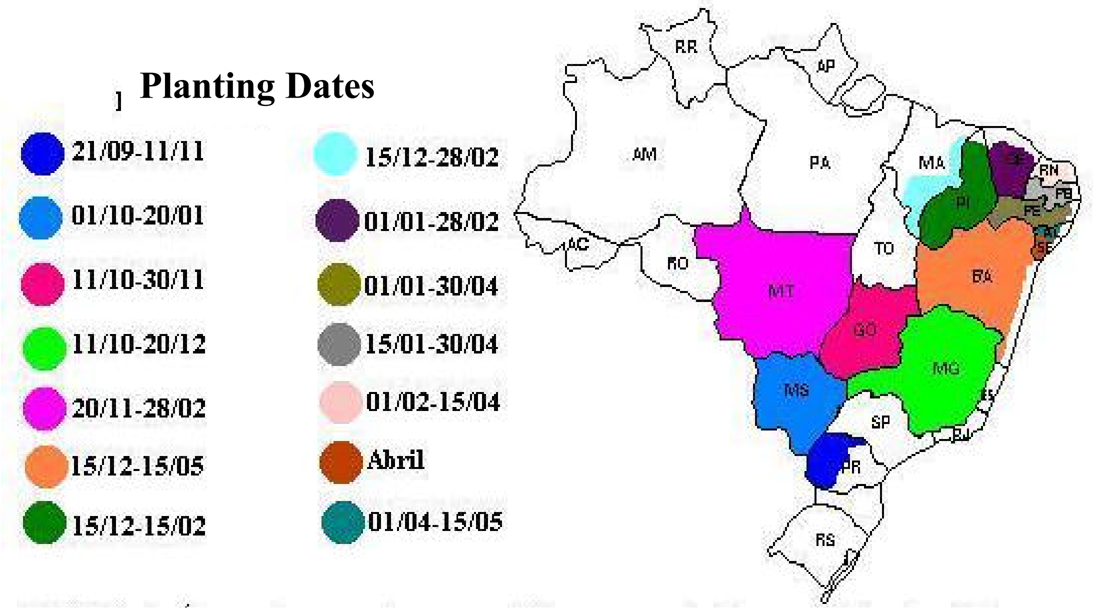


Figure 7. Climatic risk zoning for cotton crop in Brazil (Assad, 2001)

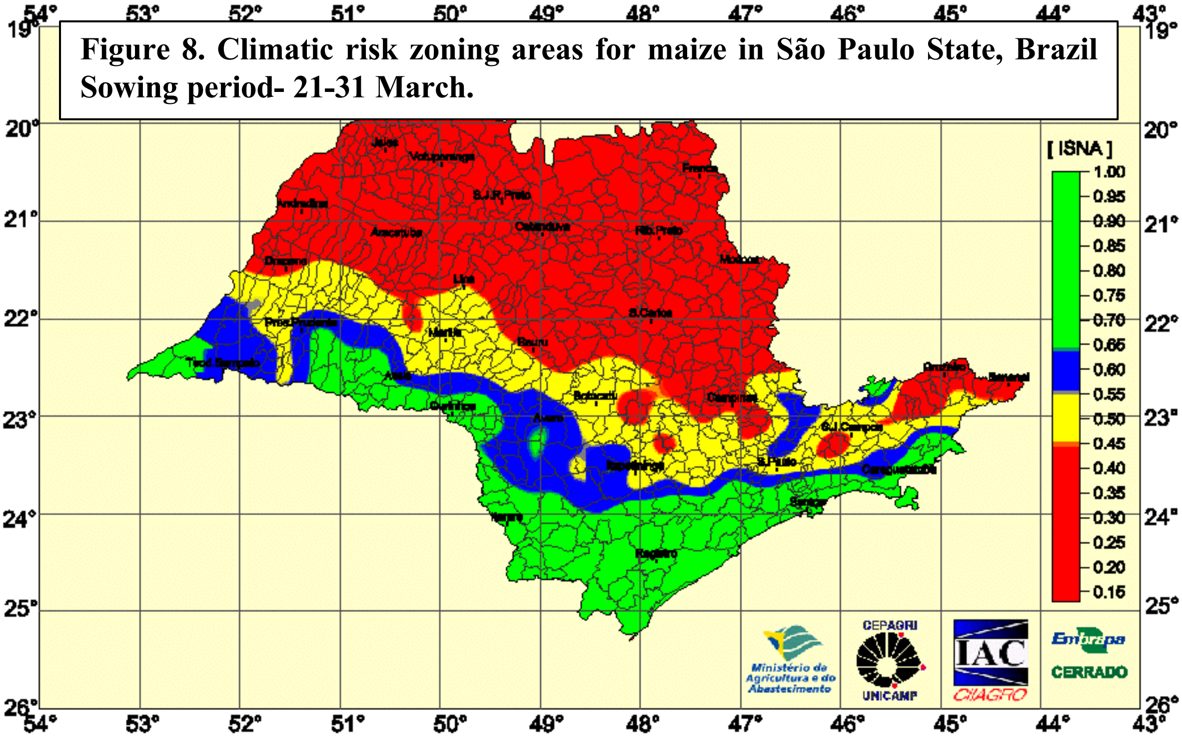


**Figure 8. Climatic risk zoning areas for maize in São Paulo State, Brazil Sowing period- 21-31 March.**

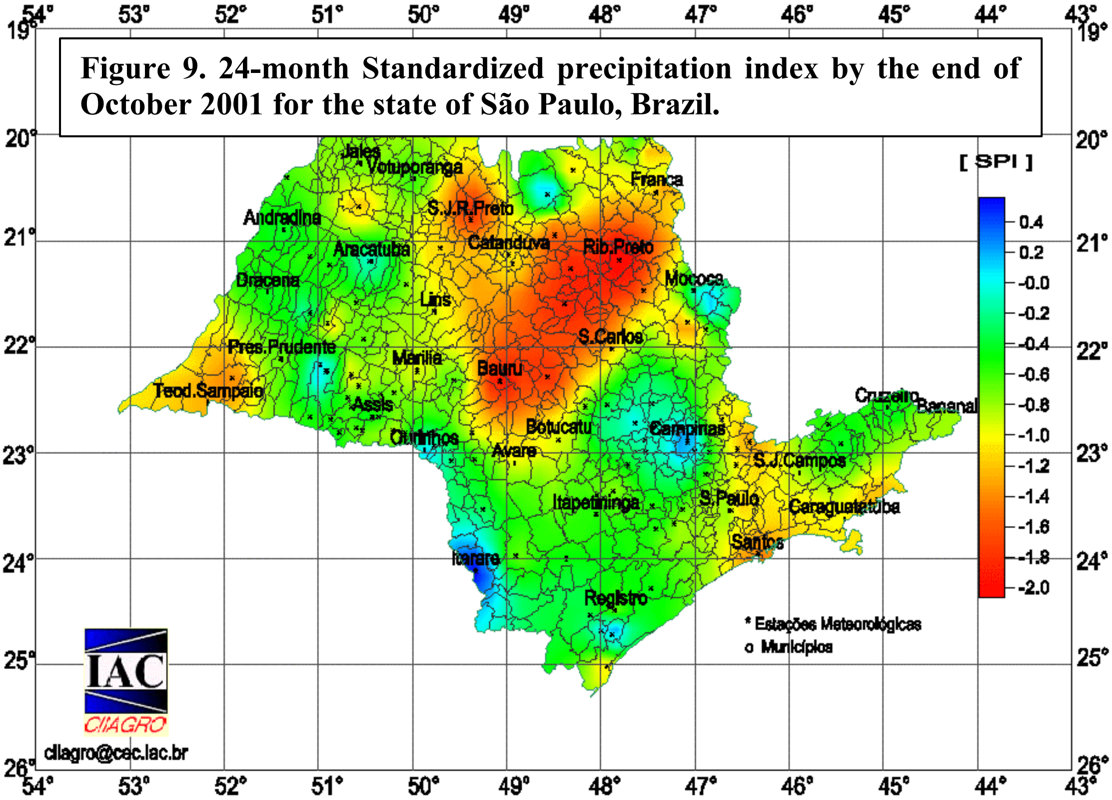


**Figure 9. 24-month Standardized precipitation index by the end of October 2001 for the state of São Paulo, Brazil.**