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Impact of climate change on hydrological extremes: Floods and droughts

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Abstract: *The two most important hydrological extremes are floods and droughts. These events pose serious hazards to human populations in many parts of the world. India is a flood prone as well as a drought prone country. These water related disasters are caused because of large diversity in climate and topography of the country. The most common issues related to climate change are: accelerated melting of glaciers, sea level rise, submergence of islands/coastal areas and deviant rainfall patterns. Likely impacts include a greater annual variability in the monsoon rainfall, leading to more intense floods and droughts. Thus, climate change in future is expected to have severe implications on river flows in South Asia including India. Global climate change is likely to result in severe droughts and floods in India, with major impacts on human health and food supplies. Developing countries of temperate and tropical Asia already are highly vulnerable to the extreme climate events such as floods, droughts and cyclones. Climate change and variability would exacerbate these vulnerabilities. Annual and seasonal changes in climate would alter the frequency and severity of major droughts. Changing temperature and evaporation rates would alter soil moisture conditions and the amount of runoff from the catchments into reservoirs. There are some evidences of increases in the intensity or frequency of some of these extreme events on regional scales throughout the 20th century. The abnormalities generated due to climate change are likely to trigger shifts in existing biodiversity patterns and demands for totally new set of land uses.*

INTRODUCTION

In future, there would be pressure to live and work in flood-prone areas, which typically feature attractive rich soils, sources of abundant water supplies and ease of transport, will increase as the world's population continues spiraling upward - to a projected 10 billion by 2050. At present about 1 billion people - the majority of them among the world's poorest inhabitants - are estimated to live in the potential path of a 100-year flood and, unless preventative efforts are stepped up worldwide, that number could double or more in two generation period. The number of people worldwide vulnerable to a devastating flood is expected to grow to 2 billion by 2050 due to climate change, deforestation, rising sea levels and population growth in flood-prone lands.

India is one of the most natural disaster-prone countries in the world. Every year floods and droughts affect our country either on small or larger scales. About one-sixth area (~55 mha) of the country is drought prone area and about one-eights (~40 mha) are flood prone. Out of the 40 mha of the flood prone area of the country, on an average flood affect an area of around 7.5 mha per year. Monsoon rainfall is the principal cause of flooding and droughts, i.e. excess rainfall produces floods while deficient rainfall is responsible for drought conditions. In general, floods and droughts emerge out of larger and longer scale weather patterns than our usual day-to-day weather variations. The chronic flood-prone river basins in India are the Ganga and the Brahmaputra. Mean annual precipitation in the Ganges and Brahmputra basins are given in Table I. The magnitude of precipitation over these basins is very high and more than three-quarters occurs during summer monsoon (June-Sept.). These Himalayan Rivers flowing down the hills cause flood problems in several states like Uttar Pradesh, Bihar, West Bengal and Assam due to high discharges concentrated during monsoon months. Cyclones are common in the eastern coast of the country, disrupting especially the lives of the poor.

Table 1. Mean annual precipitation in the Ganges and Brahmputra basins (Mirza *et. al.*, 2003)

Basin	Country	Mean annual precipitation (mm)
Ganges	Nepal	1860
	India	450-2000
	Bangladesh	1570
Brahmputra	Tibet (china)	400-500
	Bhutan	500-5000
	India	2500
	Bangladesh	2400
Meghna/ Barak	India	2640
	Bangladesh	3575

The vulnerability of human societies to droughts, floods, heat waves, avalanches, and windstorms is demonstrated by the damage, hardship, and death caused by these extreme events. Natural hazards such as floods, droughts, earthquakes and cyclones affect an estimated 25 million people every year. India accounts for nearly one-fifth of global death count due to floods. Vulnerability to disasters is increasing as growing numbers of people are forced to live in exposed and marginal areas. Elsewhere, greater vulnerability is being caused by the development of more high value property in high-risk zones. Mortality is often highest in rural areas of poor countries where disaster preparedness and early warning is virtually non-existent and health coverage is usually weak or not easily accessible. In such areas, people are less likely to evacuate from flood prone areas and in some cases fear leaving and potentially losing their possessions or their property claim.

The problem of changes in climate due to emissions of greenhouse gases is considered as one of the most important long-term environmental problems because human systems most sensitive to climate variability. Change in water resources, water related extremes, agriculture, forestry, coastal zones and fisheries, human settlements, energy, industry, insurance and other financial services, and human health are expected under changed climatic scenarios. Recent climate variability and change seems to have adversely affected flood and drought hazard in several areas and this tendency is likely to continue. There is need to study the impact of climate change on floods and droughts along with expected problems in their management due to increased severity of water extreme events.

GLOBAL TRENDS OF CLIMATE CHANGE, SIGNATURES AND FUTURE SCENARIOS

The important greenhouse gases responsible for global warming are: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and tropospheric ozone (O_3).The major sources of these gases are combustion of fossil fuels, agriculture and land use changes. Combustion of fossil fuels- primarily oil, gas and coal- currently meets about 80% of the global energy demand. Evidently contribution of combustion of fossil fuel to the greenhouse becomes substantial. Concentrations of CO_2 and other trace gases in the atmosphere have increased substantially over the last century. Anthropogenic CO_2 emissions due to human activities are virtually, certain to be the dominant factor causing the observed global warming. The concentrations of some important greenhouse gases before and after industrial era are shown in Table 2, indicating significant change in the Concentrations of these gases. Studies suggest that the concentration of CO_2 in the year 2100 will reach in the range of 540 to 970 ppm.

Table 2. Changes in the concentrations of greenhouse gases in the Earth's atmosphere.

Greenhouse gases	Years 1000-1750	Year 2000	Increase in Concentration (%)
CO_2	280 ppm	368 ppm	31±4
CH_4	700 ppb	1750 ppb	151±25
N_2O	270 ppb	316 ppb	17±5

There are a number of studies to show the increase in temperature particularly since pre-industrial era. Recently, IPCC (2001a) has indicated that the average global surface air temperature has increased by 0.6±0.2°C since the late 19th century. Most of the increase in global temperature since late 19th century has been observe in two distinct periods: 1910-1945 and since 1976. For both periods rate of increase was about 0.15°C/decade. The rate and duration of warming of 20th century has been found to be larger than any other time during the last 1000 years. Globally, 1990s have been the warmest decade and 1998 was the warmest year. The recent records show that 2005 had been the more warmer than 1998 and 2002 as well. Figure 1 shows the trend of changes in globally average temperature over the last century.

The apparent accelerated melting and deglaciation of the world's glaciers is considered as an indication of human-induced global warming and climate change. It is observed that the extent of snow cover on the global scale has decreased by 10% since late 1960s. A widespread retreat of mountain glaciers has been observed in non-polar regions during the 20^{th} century. Further, it is expected that glaciers and

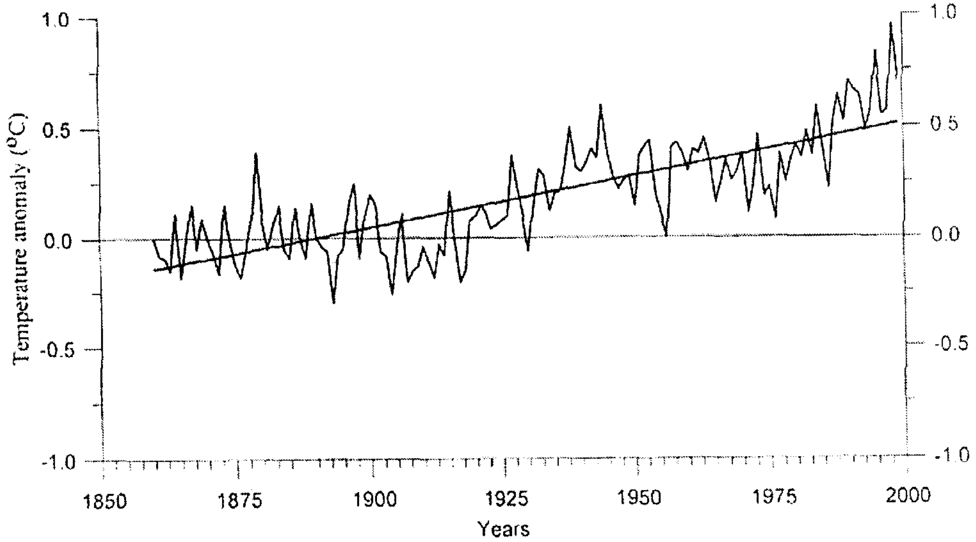

Figure 1. Observed rise in global mean annual temperature since 1860 relative to the average of observations over the period 1900-1930 (IPCC, 2001 a)

ice caps will continue to retreat during the 21st century. Climatic changes had a pronounced effect on the glacial and periglacial regime of the Alps. Since the middle of the past century, the area extent of glacierization in the European Alps is reduced 30-40%, whereas the volume of ice has been reduced by 50% (Haeberli and Beniston, 1998). *IPCC (2001b) indicated that half of Europe's alpine glaciers* could disappear by the end of 21st century. Dyurgerov (2002) reported that existing trend of changes in the volume of glaciers shows that melting of glaciers will accelerate in continental regions, North America, South America, Central Asia, sub-polar glaciers and will contribute to sea level rise. Analysis of global climate has indicated that the climate change is likely to change streamflow volume, as well as the temporal distribution throughout the year over Asian region, imposing significant stress on the water resources in the region (IPCC, 2001 b). The global mean sea level has risen between 0.10 m and 0.20 m during the 20th century.

Scenarios of future climate change are usually developed using the general circulation models (GCMs) with different scenarios of greenhouse gases emissions. Under different greenhouse gas emission scenarios, the global averaged surface temperature is projected to increase by 1.4 to 5.8°C over a period of 1990 to 2100. The striking feature is that the inter-annual variability of global temperature is much larger than the trend. Moreover, it is expected that land areas will warm more rapidly than the global average, particularly those at northern high latitudes during winter. Warming in the northern regions of North America, and northern and central Asia, may exceed global mean warming by more than 40%. In contrast, the warming is expected to be less than the global mean in South and South-east Asia in summer and South America in winter. The global mean sea level has been projected to rise by 0.09m to 0.88m between 1990 and 2100, which is much higher than the range (0.10 - 0.20 m) observed during 20th century.

Global climate modeling studies suggest that the precipitation may increase or decrease by as much as 15% under the assumption of a doubling of atmospheric CO_2. Globally averaged precipitation is projected to increase, but at the regional scale both increases and decreases are projected. It is predicted that increasing atmospheric concentrations of greenhouse gases would result in changes in frequency, intensity, and duration of the extreme events, such as more hot days, heat waves, heavy precipitation events, and fewer cold days. In general, countries North of 50°N expect an increase in rainfall. The impact of climate change is projected to have different effects within and between countries. Clearly, variations in key climatic parameters such as precipitation and temperature will produce significant changes in the hydrological regime (rainfall-runoff, snow and glacier melt runoff, evaporation, streamflow etc.) of a basin/country. Most of the ill effects of climate change are linked to extreme weather events, such as hot or cold spells of temperature, or wet or dry spells of rainfall, or cyclones and floods. Predictions of the nature and distribution of such events in a changed climate are even more uncertain, to the extent that virtually no authoritative predictions exist at all. Despite these uncertainties, it is clear that even the possibility of changes in such extreme events is quite alarming.

On the global scale there are few indicators of sustained trends in climate variability or extremes. Following the projected warmer and wetter conditions, the northern part of the Northern Hemisphere will likely to experience more storms while some continental areas might have drier summers and more risk of drought. Sea levels could rise, fed in part by melt-water from glaciers and ice caps. Along with this, extreme high-water levels may occur with increasing frequency. Higher sea levels could inundate small islands, flood coastal lowlands, and erode sand dunes. It is also necessary to ensure that increasingly freakish climate variability and the gradual forces of climatic change and deforestation are factored into the total picture. However, on regional scales, there is clear evidence of changes in variability or extremes. In areas where drought or excessive precipitation usually accompanies an El Niño, these anomalies have been more frequent and intense in recent years. Other than areas with El Niño -related drought and the few areas with longer-term trends to lower rainfall (e.g., the Sahel), little evidence is available of changes in drought frequency or intensity.

SIGNATURE OF CLIMATE CHANGE IN INDIA

In India several studies are carried out to determine the changes in temperature and rainfall and its association with climate change (Hingane *et al.*, 1985, Sinha Ray *et al.*, 1997). All such studies have shown warming trend on the country scale. Estimates of temperature anomaly are better-estimated using long-term series data. Recent studies have been reported using more than a century data. Pant and Kumar (1997) have analyzed the seasonal and annual air temperatures from 1881 to 1997 and shown that there has been increasing trend of mean annual temperature by the rate of 0.57°C per hundred years. Trend of all India mean animal surface air temperature anomalies is shown in Figure 2. Moreover, studies also suggest that Bangladesh had warmed by 0.5°C over the past 100 years (Ahmad and Warrick, 1996). The trend and magnitude of global warming over India/Indian sub-continent over last century is broadly consistent with the global trend and magnitude. In India, warming was found to be mainly contributed by the post-monsoon and winter seasons. The monsoon temperatures do not show a significant trend in any part of country except for significant negative trend over Northwest India.

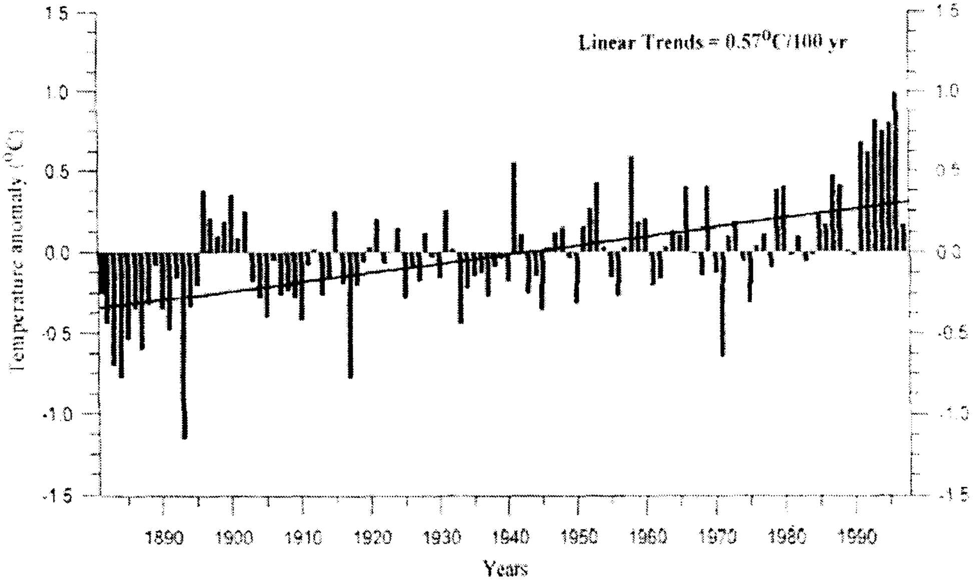

Figure 2. All India mean annual surface air temperature anomalies (1981-1997) (Pant and Kumar, 1997)

Studies carried out on regional basis show that temperature fluctuations do not show increasing trend over the entire country. Temperatures show cooling trends in the northeast and northwest India. Moreover, Hingane *et al.* (1995) observed that trend of increase in mean annual temperature over the whole country was a result of rise in the maximum temperature; but later studies carried out by Sinha Ray *et al.* (1997) have shown that the changes in mean annual temperature are partly due to rise in the minimum temperature related to enhanced extent of urbanization. Recent findings by Mukhopadhyay *et al.* (1999) have confirmed that there is clear signal of urbanization in these warming, i.e. that there is a steeper rise in the minimum temperature also in urban locations.

Studies related to changes in rainfall over India have shown that there is no statistically significant trend in the all India rainfall (Sarkar and Thapaliyal, 1988; Kulshrestha and Thapliyal, 1991; Mooley and Parthasarthy, 1984). In terms of changes in rainfall over India, no clear trend of increase or decrease in average annual rainfall over India has been observed (Figure 3). The examination of trend of annual rainfall over India has indicated that 5-year running mean has fluctuated from normal rainfall within:I: one standard deviation (Thapliyal and Kulshrestha, 1991). Though the monsoon rainfall is trend less over a long period of time, particularly on the all India scale (Mooley and Parthasarthy, 1984), but there are pockets of significant long-term rainfall changes (Koteswaram and Alvi, 1969; Jagannathan and Parthasarthy, 1973; Raghavendra, 1974, Chaudhary and Abhayankar, 1979). A comprehensive study using the monthly rainfall data for 306 stations distributed over India was attempted by (Kumar et al., 1992). The rainfall fluctuations in India have been largely random over a Century, with no systematic change detectable on either annual or seasonal scale. However, areas of increasing trend in the seasonal rainfall have been found along the West Coast, North Andhra Pradesh and Northwest India (+10 to +12% of normal/100 years) and those of decreasing trend over East Madhya Pradesh, Orissa, Northeast India, and parts of Gujrat and Kerala (-6 to -8% of normal/100 years) (MOEF, 2004). Sinha Ray and De (2003) have summarized the existing information on climate change and trends in the occurrence of extreme events with special reference to India. They concluded that all India rainfall and surface pressure shows no significant trend except some periodic behavior.

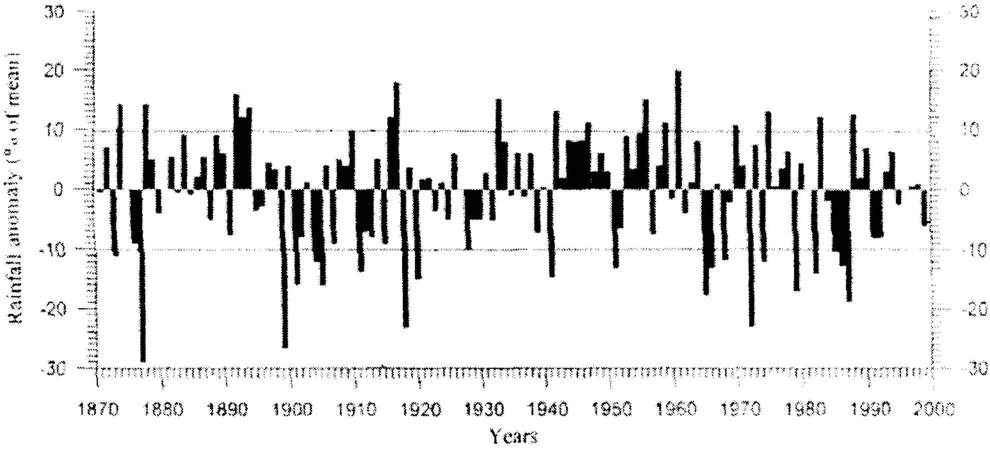

Figure 3. All India summer monsoon rainfall anomalies (1871-1999) (Lal, 2001)

In a recent study, Singh *et al.* (2006) have studied changes in rainfall in different river basins in the northwest and central India. Seasonal and annual trends of changes in rainfall, rainy days, heaviest rain and relative humidity have been studied over the last century for 9 different river basins in the northwest and central India (Figure 4). Majority of river basins have shown increasing trend both in annual rainfall and relative humidity. The magnitude of increased rainfall for considered river basins varied from 2 to 19% of mean per 100 years. Seasonal analysis shows maximum increase in rainfall in the post-monsoon season followed by the pre-monsoon season. There were least variations in the monsoon rainfall

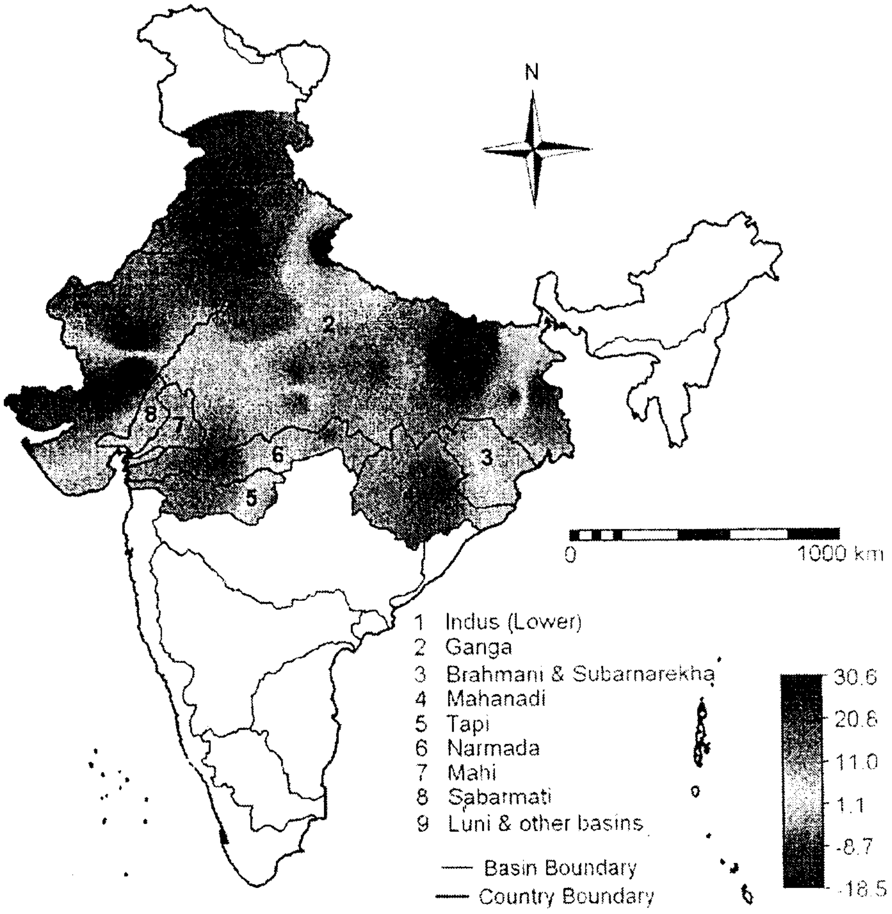

Figure 4: Spatial patterns of linear trends in annual rainfall (% of mean /100 years) for different river basins during last Century (1901-2000).

during the last century and winter rainfall has shown decreasing trend. Most of the river basins have experienced decreasing trend in annual rainy days with maximum decrease in the Mahanadi basin. The heaviest rain of the year has increased by 9 to 27 mm per 100 years over different river basins, being maximum increase for Brahamani & Subaranrekha river basin. A combination of increase in heaviest rainfall and reduction in the number of rainy days suggest for the possibility of increasing severity of floods. Such information is very useful for the planning, development and management of water resources in the study area.

FUTURE CLIMATIC SCENARIOS FOR INDIA

Future warming scenarios have been generated for the Indian sub-continent using General Circulation Models (GCM). Lal (2001) developed climate change scenarios over Indian sub-continent under the four Special Report on Emission

Scenarios (SRES) based on the data generated in numerical experiments with Atmosphere and Ocean coupled GCM (A-O GCM) of the Center for Climate Research Studies/National Institute of Enviromnental Studies (CCSR/NIES), Japan to predict changes in temporal and spatial variability of the monsoon rainfall. It is expected that over the land regions of the Indian sub-continent, the area-averaged annual mean surface temperature is likely to increase between 3.5°C and 5.5°C by 2080s. The area-averaged surface temperature increase during the winter over India by 2080s would be at least 4°C and could reach even 6°C. During summer monsoon, the warming may range between 2.9°C and 4.6°C. The spatial distribution suggests that north India may experience an annual mean surface warming of the order of 3°C or more by 2050s. Over much of the southern peninsula, the warming is likely to be under 2°C during winter season.

The impact of increase in greenhouse gases on temperature and precipitation using the different GCMs has been studied by Lal (2001). It has been found that the average annual mean surface temperature over Indian sub-continent is likely to increase by about 2.7°C and 3.8°C during the decades of 2050s and 2080s, respectively. Moreover, it is likely that over inland regions of the Indian sub-continent, the mean surface temperature may rise between 3.5°C and 5.5°C by 2080 (Lal, 2001). On seasonal basis, the projected surface warming is higher in winter than in summer. The spatial distribution of surface warming suggests that north India may experience an annual mean surface warming of 3°C or more by 2050s. GCM models have simulated peak warming of 3°C over north and central India in winter.

In order to predict the changes in the temporal as well as spatial variability of the monsoon rainfall in response to increases in radiative forcing of the atmosphere, climate change scenario over Indian sub-continent under emission scenarios were studied. These emission scenarios covered a wide range of the main demographic, technological, and economic driving forces of future emissions; each describes a different world evolving through the 21st century and leads to different greenhouse gas emission concentration trajectories. GCMs suggest an increase of over 2°C over Indian sub-continent in the next 100 years. Warming is projected to be significant in post-monsoon and winter seasons. Future projection of increase in temperature and changes in precipitation over Indian subcontinent are shown in Table 3.

As shown in Table 3, increase in annual mean rainfall over the Indian sub-continent is projected to be 7% and 9%, respectively, during the decades of 2050s and 2080s. Earlier, IPCC (1990) projected that precipitation will change little in winter and will generally increases throughout the Indian sub-continent region by 5-15% in summer. Variability in Asian summer monsoon is expected to increase along with changes in the frequency and intensity of extreme climate events in this region. Little change in monsoon rainfall is projected up to 2050s at all India scale level (MOEF, 2004). However, there is over all decrease in the number of rainfall days over a major part of the country. The decrease is greater in the western and central parts of the country (by more than 15 days), while near the Himalayan foothills (Uttaranchal) and in northeast India the number of rainfall may increase by 5-10 days. Simulation studies by Lal *et al.* (1992) using Hamburg global coupled atmosphere ocean circulation model indicated the possibility of an increase of rainfall in parts of northern India while decrease in rainfall in parts of peninsular India.

Table 3. Climate change projections for the Indian sub-continent (Lal, 2001).

Scenarios		Increase in temperature (°C)	Change in rainfall (%)
2020s	Annual	1.00 - 1.41	2.16 - 5.97
	Winter	1.08 - 1.54	(-)1.95 - 4.36
	Monsoon	0.87-1.17	1.81-5.10
2050s	Annual	2.23 - 2.27	5.36 - 9.34
	Winter	2.54-3.18	(-)9.22 - 3.82
	Monsoon	1.81 - 2.37	7.18 -10.52
2080s	Annual	3.53 - 5.55	7.48 - 9.90
	Winter	4.14-6.31	(-)24.83 - 4.50
	Monsoon	2.91 - 4.62	10.10 -15.18

POSSIBLE IMPACT OF CLIMATE CHANGE ON FLOODS AND CYCLONES

Floods are the most significant natural hazard causing sufferings to a large number of people and damages to properties year after year. Changes in streamflow and floods have been observed in different parts of the world. Evidences of regional climate change shifting of peak streamflow has shifted back from spring to late winter in large part of eastern Europe, European Russia, and North America in last decades. Increasing frequency of droughts and floods in some area is related to variations in climate - for example, droughts in Sahel and in northeast southern Brazil, and floods in Colombia and northwest Peru. Extreme weather or climatic events cause substantial and increasing damages. The impacts of climatic extremes are a major concern. Preliminary indications suggest that some social and economic systems have been affected by recent increase in floods and droughts, with increase in economic losses for catastrophic weather events. The number of weather related catastrophic weather events has risen three times than the number of non-weather-related events. Part of this observed upward trend in weather-related losses over the past 50 years is linked to socio-economic factors (e.g., population growth, increased wealth, urbanization in vulnerable areas), and part is linked to regional climate factors (e.g., change in precipitation, flooding events).

IPCC (2001) indicated a likelihood of increased intensity of extreme precipitation over the south Asia region under changed climatic scenarios. In other words, global warming is expected to accelerate the hydrological cycle and thus raise the percentage of precipitation that falls in violent bursts. The amplitude and frequency of extreme precipitation events is very likely to increase over many areas and the return period for extreme precipitation events are projected to decrease. This would lead to more frequent floods and landslides avalanches, and soil erosion with attendant loss of life, health impacts (e.g., epidemics, infectious diseases, food poisoning), property damage, loss to infrastructure and settlements, soil erosion, pollution loads, insurance and agriculture losses, amongst others.

For the period 1871-1984, Parthasarathy *et al.* (1987) identified a range of 2-30 flood years (i.e., years when precipitation is at least 26% higher than normal) in the various meteorological sub-divisions in India. In the same period, the range of severe flood years (i.e., precipitation more than 51% higher than normal) was between 1 and 14. According to country's report to the United Nations Framework Convention on Climate Change (UNFCCC), the global climate change is likely to result in severe droughts and floods in India - and have major impacts on human health and food supplies (MOEF, 2004). High flood levels can cause substantial damage to key economic sectors: agriculture, infrastructure and housing. Although floods affect people of all socioeconomic status, the rural and urban poor are hardest hit.

Flash floods are likely to become more frequent in many regions of temperate and tropical Asia in the future. A decrease in return period for extreme precipitation events and the possibility of more frequent floods in parts of India, Nepal, and Bangladesh is projected. Increased precipitation intensity, particularly during the summer monsoon, could increase flood-prone areas in temperate and tropical Asia. The tangible and intangible losses due to floods in India are increasing due to speedy growth of population and increased encroachments of the flood plains for habitation, cultivation and other developmental activities. Flood plains, i.e., the lands bordering rivers and streams, are normally dry round the year but get covered with water during floods. Floods can damage buildings or other structures like levees and embankments placed within the flood plains. It is expected that number of people living in flood-prone areas will be roughly double due to more extreme weather systems that accompany global climate change, rising sea levels; and continuing deforestation, especially in mountain regions. Climate variability and extreme climate events will generate increased flood, avalanche, landslide, and mud slides damage, soil erosion. Under such conditions there would be increased pressure on government and flood insurance system and disaster relief. Although greater flood runoff would help to recharge some flood plain aquifers, but it could decrease the amount of surface water captured for irrigation and other purposes.

Higher intensity rains under changed climate would generate high peak floods, which in turn will have major implications for the safety and performance of dams. Increased floods threaten dam safety and may increase reservoir sedimentation.

Climate change will add to existing stresses on riverine ecosystems from dams, channelization, pollution and watershed degradation.

Projected sea-level rise will increase the average annual number of people flooded in coastal storm surges. The areas of greatest absolute increase in population at risk are southern Asia and Southeast Asia, with lesser but significant increase in eastern Africa, western Africa and the Mediterranean from Turkey to Algeria. Significant portions of many highly populated cities are also vulnerable to permanent land submergence and especially to more frequent coastal flooding superimposed on surge heights, due to sea-level rise. This estimate assumes no change in frequency or intensity of storms, which could exacerbate the effects of sea-level rise on flooding risks in some areas.

The intensity of tropical cyclones is likely to worsen over in the coastal areas. Therefore, in coastal areas, the key climate-related risks include more frequent tropical cyclones and rises in sea level that would submerge mangrove forests and increase the salinity of wetlands. In case, sea levels were to rise by one meter, about 7.1 million people in India could be displaced, and more than 5,000 km^2 land and 4,000 kilometers of roads could be lost (MOEF, 2004). The risks include direct threats to human life, epidemics and other health risks, damage to infrastructure and buildings, coastal erosion, and destruction of ecosystems such as coral reefs and mangroves. It is difficult to predict local and regional trends for extreme events. For example, a warming of the tropical oceans would by itself be expected to increase the frequency, and perhaps the severity, of tropical cyclones. But other factors, such as changing winds or storm tracks, might offset this effect at the local level.

Despite the diversity and extent of threats posed to India by climate change, the report says Indian emissions of greenhouse gases have been "very low" (MOEF, 2004), India would continue to meet its development needs, but is concerned about the likely impact of severe floods on its infrastructure, such as roads and railways, as well as the likely increase in electricity needs to pump underground water and cool houses and offices in hot areas.

POSSIBLE IMPACT OF CLIMATE CHANGE ON DROUGHTS

The India has a wide variability of climatic regimes, from super arid to super humid. High rates of evapotranspiration prevail over hyperacid Rajasthan, in western India, with annual rates exceeding 2,500 mm and reaching 3,500 mm in some regions of northwest Rajasthan. Conversely, low rates of evapotranspiration prevail over hyper humid Assam and the Himalayan Bengal, in northeastern India, with annual rates in the range of 1,2001,500 mm. Over central India, which is semi arid evapotranspiration rates vary in the range of 1400-1,800 mm (Abbi, 1974). Gregory (1989) has reported that droughts in hyper humid regions of India such as Assam are very infrequent, with the last documented drought in the region dating back to 1900. Drought prone areas fall in three broad regions of the country. The plateau region covers the states of Andhra Pradesh, Bihar, Karnataka, Maharashtra, Madhya Pradesh, Orissa, Tamil Nadu, Uttar Pradesh and West Bengal; the desert region encompasses the states of Rajasthan and Gujarat; and the third covers a few districts in the states of Haryana, Jammu and Kashmir and Punjab (CWC, 1982). Drought is a natural calamity and brings social and economical hardships to people living in the affected areas.

Droughts are driven by regional meteorological conditions and therefore, they are believed to be regional in nature. Droughts are classified as agricultural drought, meteorological drought, and hydrological drought and there are several definitions to define the drought. The most commonly understood definition of a drought year is a year with less than average precipitation. Duration, intensity and frequency of droughts are known to vary across the climatic spectrum. From the recorded history since 1875, several droughts had experienced in the country some intermittently and consecutively. Some of the critical droughts, which had devastated human and animal lives, were seen during 1904-1905, 1965-1966 and 1986-87. In India, Parthasarathy *et al.* (1987) identified a range of 1-12 severe drought years (i.e., precipitation 51 % less than normal) for the various meteorological sub-divisions of the sub-continent during the period 1871-1984. Chronically drought-affected areas cover the western parts of Rajasthan and the Kutch region of Gujrat (SAARC, 1992). In Bangladesh, about 2.7 million ha are vulnerable to annual drought; there is about a 10% probability that 41-50% of the country is experiencing drought in a given year (GOB, 1989). Drought or near-drought conditions also can occur in parts of Nepal (Sharma, 1979) and in Papua New Guinea and Indonesia, especially during El Niño events.

Many countries in temperate and tropical Asia have experienced severe droughts and floods frequently in the 20th century. Droughts also can reach devastating proportions in tropical Asia, although the incidence is variable in time and place. There is potential for drier conditions in arid and semi-arid Asia during summer, which could lead to more severe droughts. It is projected that under changed climatic conditions the frequency and severity of drought will increase. Higher rate of evaporation are associated with warmer climate, which would add to the severity of the droughts.

Under enhanced drought conditions water resources quality and quantity of water resources is projected to decrease resulting in decreased crop yield and increased damage to building foundations. There is increased risk of forest fire. The agriculture productivity will decrease in the drought prone regions. Increases in the severity and frequency of droughts would reduce hydropower production and water storage in the drought-prone regions. More hot weather will cause more deaths and illnesses among the elderly and urban poor. Together with increased summer drying, it will lead to greater heat stress for livestock and wildlife, more damage to crops, more forest fires, and more pressure on water supplies. Other likely impacts are a shift in tourist destinations and a boost in demand for energy. Meanwhile, fewer cold snaps should reduce cold-related risks to humans and agriculture and reduce the energy demand for heating while extending the range and activity of some pests and diseases. The situation is further aggravated if a back-to-back drought occurs. The potentials of the non-glacier fed rivers are strongly associated with the health of the monsoons. A confidant projection of and better understanding on the impacts of climate change on the monsoons is thus very crucial.

By drying up major river basins and altering rainfall patterns, global warming will significantly affect agriculture and forestry, threatening livelihoods and food security. Most major river basins across the country are likely to become considerably drier, resulting in constant water shortages that will occasionally become acute. This could shift forest boundaries and affect biodiversity in the regions affected. Although centered in the Southern Pacific, the El Niño /Southern Oscillation (ENSO) phenomenon affects the weather and climate in much of the tropics. Climate change could intensify the droughts and floods that are associated with El Niño events in these regions.

CONCLUSIONS AND RECOMMENDATIONS

Water-related extreme events are natural phenomena and will continue to occur in India. Increase in the frequency of floods and droughts during 21st century due to projected climate change would enhance the severity of water extreme events and may prove the greater challenge to society. Changes in the amount of rainfall, rainfall patterns and intensity would affect streamflow and the demand for water. It is very clear that flood and drought management schemes have to be planned keeping in view the increase in severity of floods and droughts and expected changed climatic scenarios over the country. Despite these uncertainties, it is clear that even the possibility of changes in such extreme events is quite alarming. The following studies and suggestions would help in better management.

1. Although floods and droughts are projected to increase with global warming and severity of impacts will increase, but present knowledge of research and simulations of hydrologic scenarios shows that it is difficult to quantify the changes in the frequency or intensity of these water extremes with certainty at regional and local levels. There is need to undertake impact assessment studies related to flooding in terms of magnitude, depth and spatial extent in the country taking into account possible changes in precipitation and temperature. Studies confirming the increase in rainfall intensity, amount, flood peaks, drought severity and extent over the past century are to be carried. The impact of climate change on water resources and extremes related to water is the subject of much scientific research
2. There should be a master plan for flood control and management for each flood-prone area. Adequate flood cushion should be provided in water storage projects, wherever feasible, to facilitate better flood management. In highly flood prone area, flood control should be given overriding considerations in

reservoir regulations policy even at the cost of sacrificing some irrigations and power benefits.

3. The safety of existing dams needs to be reassessed in the light of possible precipitation changes and resulting high peak floods. Feasibility and impact studies for future dams should allow for the hydrological uncertainties of a warming world.
4. A highly developed system with strong base at the grass root level and integrated with district, state and national levels, disaster preparedness at all levels and committed efforts of official and non-official functionaries, as a sustainable drought combating measure by the government machinery.
5. Drought prone areas should be made less vulnerable to drought associated problems through soil moisture conservations measures, water harvesting practices, minimization of evaporation losses, development of ground water potential including recharging and transfer of surface water from surplus areas where feasible and appropriate. Improving long-term predictability, based on climatic variability and sea surface temperature, emerges as an important tool of drought preparedness.
6. Propagation of information at right time on all aspects of drought and mitigation measures would help people, NGOs, Local Bodies, People's representatives to work together for drought mitigation.

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