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HYDROLOGICAL RESPONSE OF GREENHOUSE EFFECT WITH EMPHASIS ON EVAPORATION AND EVAPOTRANSPIRATION

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PREFACE

Concentrations of several gases viz. carbon dioxide, methane, nitrous oxide, chlorofluorocarbons in the atmosphere have significantly increased since the dawn of the industrial era. The observed built up of the gaseous pollutants has enhanced the so called greenhouse effect and hence increased the radiative heating of the globe. The global warming is expected to have profound impact on meteorological and hence hydrological parameters. The direct assessments of impacts and realistic evaluations of the climate sensitivities of water resource systems, specially on a regional scale are a matter of concern and need considerable study.

The National Institute of Hydrology established the Atmospheric Land Surface Modelling Division with the major objective of carrying out studies and research on coupled atmosphere land surface processes. In the present report an attempt has been made to review the status of hydrological response of greenhouse effect with emphasis on evaporation and evapotranspiration.

The report has been prepared by Dr. Divya, Scientist 'B' in Atmospheric Land Surface Modelling Division and it has been typed by Shri Ram Kumar, Shri A S Kotwal and Shri Rajneesh Kumar Goel,

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ABSTRACT

The scientific community has expressed a great concern in the recent past over the increasing temperature of the earth's surface due to rapidly rising concentrations of various greenhouse gases viz., carbondioxide, methane, nitrous oxide, chlorofluorocarbons etc. The greenhouse gases, produced by human activities allow the solar energy to pass through while absorb and re-radiate to the earth much of earth's long wave radiation, thus contributing to the ' Greenhouse effect'.

The global warming due to enhanced greenhouse effect is expected to cause major changes in various climate variables as absolute humidity and precipitation , annual rainfall regime, and net, terrestrial and global solar radiations etc. This, in turn ,would also have profound impact on various hydrological parameters ,viz. runoff, evapotranspiration ,soil moisture, ground water etc. Evapotranspiration ,a major component of water cycle would also be affected but in a more complicated manner than generally expected.

The present report gives a review of the recent trends of increase in greenhouse gases, impact of increase in greenhouse gases on meteorological and hydrological parameters and also discusses the status of these aspects for India. The methodologies used by hydrologists to study the hydrological response of enhanced greenhouse effect has also been reviewed. Special emphasis has been given on effect of climatic change on evaporation and evapotranspiration.

1.0 INTRODUCTION

Recent investigations have provided ample evidence that with use of fossil fuels the carbondioxide content in the atmosphere has been rising steadily over the past decades. The problem of increasing concentrations of CO_2 and possible future climate change has attracted the scientific workers and the policy makers in the recent years. It has become clear that by strengthening the so called 'greenhouse effect', the observed CO_2 increase may affect the meteorological parameters and hence the climate appreciably. Besides CO_2, some other infrared absorbing gases present in the troposphere, which contribute to the greenhouse effect are methane (CH_4), nitrous oxide (N_2O), Ozone (O_3) and chlorofluorocarbons (CFC). The increasing concentrations of the CFCs may diminish the average concentrations of the stratospheric ozone and because the stratospheric ozone is an element in the determination of the earth's radiation balance, the increasing concentration of CFCs may influence the climate in more subtle ways. The climatic change will also have profound impact on hydrological parameters.

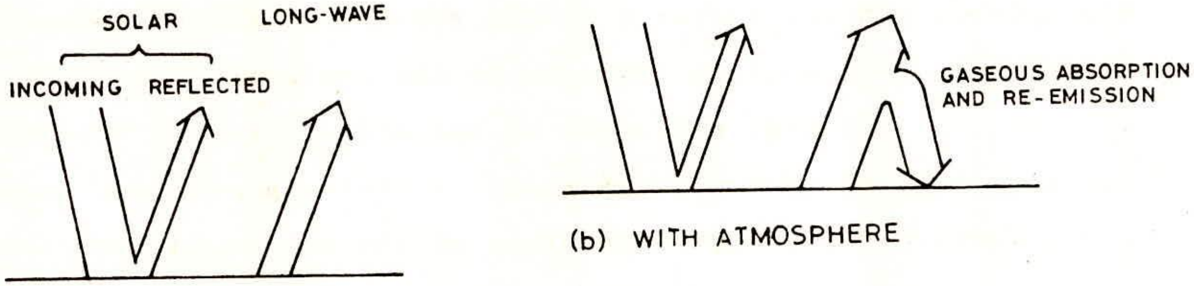
A number of assessments have been made on the problem of climatic change due to increasing greenhouse gases by various national groups notably in United States. The World Meteorological Organization (WMO) has co-ordinated various research activities under an over-arching framework- the World Climate Programme (WCP) to study world's climate system and possible major changes in global climate. The research activities in this area have also been convened by United Nations Environmental Programme (UNEP) and the International Council of Scientific Unions (ICSU). The water related activities as the impact of climate change on water resources have been implemented by World Climate Programme - Water (WCP-Water). The conferences held in Villach (1985), Toronto (1988), New Delhi (1989) and Hamburg (1989) have identified the problems in this complex subject area. It was concluded in these conferences that if the present trends continue, the carbondioxide in the atmosphere would double from its pre-industrial levels by the year 2030. This will result in global warming and considerable climate changes and influence on hydrological regime. A number of impacts on hydrological parameters viz. precipitation, evapotranspiration, soil moisture storage, runoff etc. have been predicted in the literature. It has also been emphasized that the expansion of sea water due to warming and from melting of ice around poles would result in sea level rise, which in turn, would affect the population in coastal areas.

1.1 Earth's radiation balance

The atmosphere plays a complex and an important role in the global energy balance. Despite the vast amounts of energy continually being added to and taken away from the atmosphere by radiation and other energy transfer processes, the storage of energy in the atmosphere is not systematically increasing or decreasing. Thus, to a very close approximation, in the long term average (over the entire mass of the atmosphere and long time period like an year), there is a balance between energy sources and energy sinks for the atmosphere as a whole, i.e.

$$[H_1 + H_2 + \ldots\ldots\ldots\ldots\ldots] = [S_1 + S_2 + \ldots\ldots\ldots] \qquad (1.1.1)$$

Where H_i and S_i denote the various energy sources and sinks respectively.



(a) NO ATMOSPHERE

(b) WITH ATMOSPHERE

FIG. 1. SCHEMATIC REPRESENTATION OF THE RADIATIONS AT THE EARTH SURFACE FOR (a) NO ATMOSPHERE AND (b) AN ABSORBING ATMOSPHERE

The earth atmosphere system is heated by solar (short wave) radiation at a mean rate of $S_o(1-\alpha)/4$, where S_o is the solar constant (solar irradiance incident upon a normal plane surface at the top of the atmosphere and is equal to 1380 Wm^{-2}), α is the fraction of radiation reflected by the earth and atmosphere, and the factor 4 allows for the spherical geometry of the earth. This must be balanced by the emission of long wave (thermal or infrared) radiation to space (Fig. 1 a). The rate of cooling is given by σT_e^4, where σ is Stefan's constant and T_e is the effective radiating temperature of the system. At equilibrium

$$S_o\,(1-\alpha)/4 = \sigma T_e^4 \tag{1.1.2}$$

This gives a value of T_e corresponding to 255 K (-18^oC) assuming a current albedo of 0.30. In the absence of an atmosphere T_e will be earth's surface temperature.

Figure 2 shows one of the estimates of the global energy balance for the earth-atmosphere system, calculated on the basis of actual data. The 100 units of solar radiation incident on the top of the atmosphere represent an irradiance of S/4 = 345 $W\ m^{-2}$. Of the 100 units of incident solar radiation 19 are absorbed during the passage through the atmosphere : 16 in cloud free air and 3 in clouds. A total of 30 units are reflected back to space : 20 from clouds and 6 from cloud - free air and 4 from the earth's surface. The remaining 51 units are absorbed at the earth's surface. The earth disposes of this energy by a combination of infrared radiation and sensible and latent heat flux as given on the right-hand side of Figure 2. The net infrared emission which represents the upward emission from the earth's surface minus the downward emission from the atmosphere

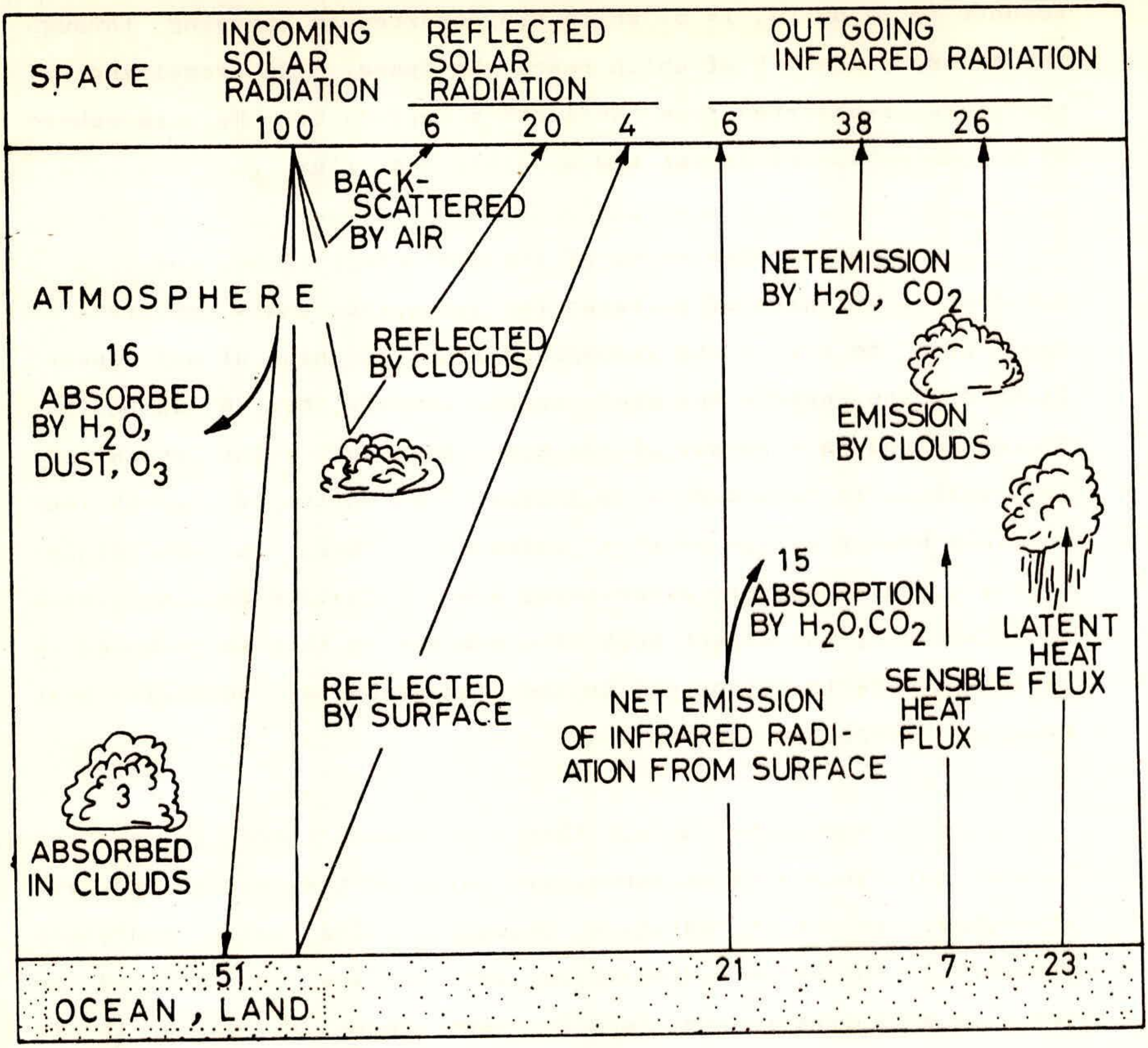


FIG. 2 THE ANNUAL MEAN GLOBAL ENERGY BALANCE FOR THE EARTH ATMOSPHERE SYSTEM

amounts to 21 units, 15 of which are absorbed in passing through the atmosphere and 6 of which reach the space. The remaining 30 units are transferred from the earth's surface to the atmosphere by a combination of latent and sensible heat flux.

From the view point of the atmosphere alone, there is a net loss of 49 units of infrared radiation (70 units emitted to space from the top of the atmosphere minus 21 units of net upward flux from the earth's surface) which exceeds by 30 units the energy gained as a result of the absorption of solar radiation. This deficit is balanced by an influx of 30 units of latent and sensible heat from the earth's surface. Thus, in the global average, the atmosphere experiences a net radiative cooling which is balanced by the latent heat of condensation that is released in regions of precipitation and by the conduction of sensible heat from the underlying surface.

It should be noted that, although there is a heat balance for the planet as whole, all parts of the earth and its atmosphere are not in radiative balance. The solar radiation absorbed by the earth's atmosphere and surface is radiated to space at much longer wave lengths than those at which it is absorbed because of the much lower temperature of the earth-atmosphere system as compared to temperature of the sun (255 K as compared, to 6000 K). (Fig. 3 a). The sun emits most radiation in the range of 0.2-4 μm (including ultraviolet visible and near infrared wavelengths), whereas the earth emits mainly in the range 4-100 μm (longwave radiation).

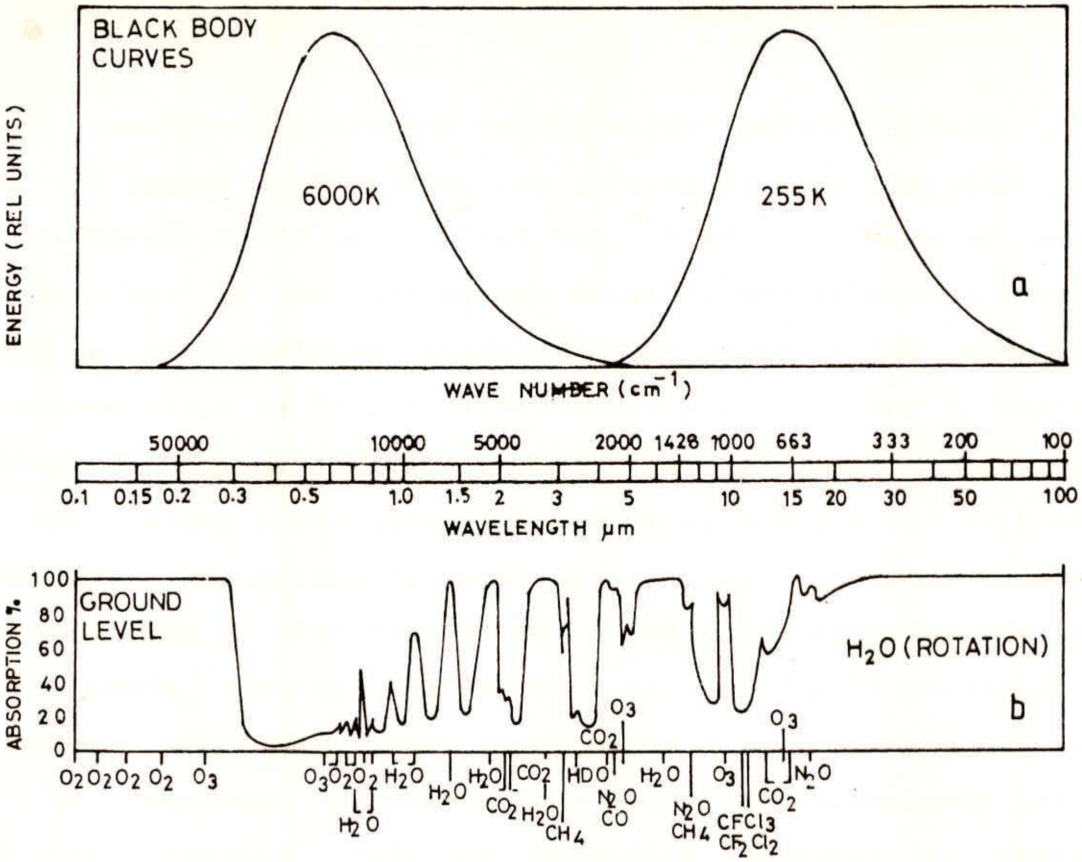


FIG.3 (a) SPECTRAL DISTRIBUTION OF THE RADIATIONS FROM THE SUN AND THE EARTH CORRESPONDING TO TEMP. OF 6000 AND 255K

(b) ATMOSPHERIC ABSORPTION OF THE SOLAR RADIATIONS BY GREENHOUSE GASES

1.2 Role of CO_2 and other greenhouse gases in affecting the radiation balance

Carbon dioxide, water vapour and other greenhouse gases play an important role in keeping the earth warm. Except for the 'windows' between about $8x10^{-4}$ and $13x10^{-4}$ cm, these gases block the direct escape of the infrared energy emitted by the earth's surface (Fig. 3b) Although the atmosphere absorbs only a small percentage of the shortwave solar radiation, it is quite opaque to the long wave terrestrial radiation. The long wave radiation emitted from the surface is absorbed by greenhouse gases, and is re-radiated both back to the surface producing an additional warming and to space maintaining the balance with the incoming solar radiation (Fig.1 b) . As a result the current global mean surface temperature is substantially warm than the effective radiating temperature Te. The heat-retaining behaviour of the atmosphere is somewhat analogous to what happens in the greenhouse, where the glass roof and sides permit the sun's energy to enter and be absorbed by the plants and earth but prevent much of the interior heat from escaping thus blocking mixing of the inside air with that on the outside. To a lesser extent, it also prevents escape through the glass of energy radiated at long wavelengths from inside the greenhouse. The role of CO_2 ,moisture and other greenhouse gases in the atmosphere, allowing solar energy to pass through while absorbing much of the earth's long-wave radiation, has thus come to be known as the GREENHOUSE EFFECT. Mathematically, the increase in surface temperature above T_e (Eq.1.1.1) is termed as greenhouse effect. On a global basis the effectivenesss of the greenhouse effect can be illustrated by the fact that the mean air temperature near the surface is about $15^{o}C$ while the overall planetary temp. is only about $-18\,^{o}$ C.

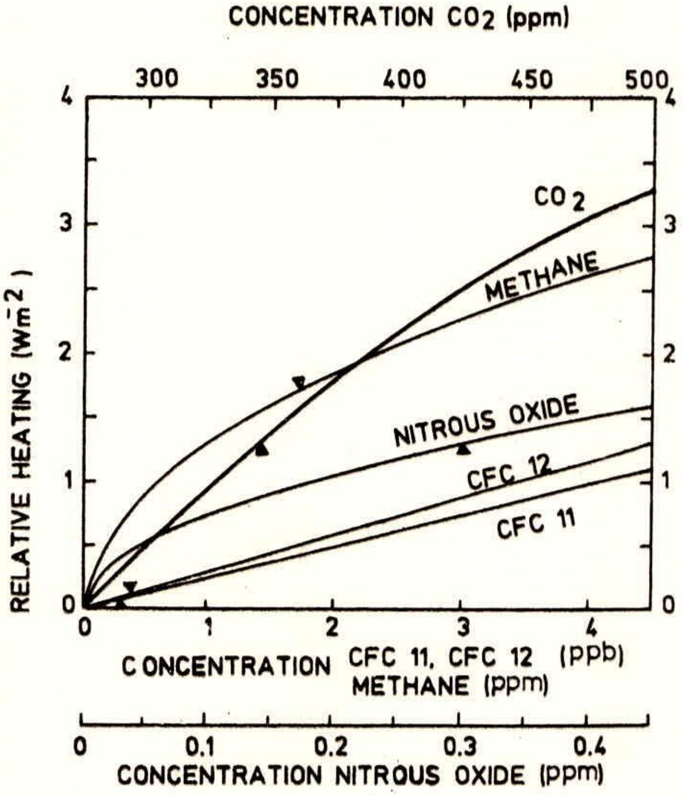


FIG. 4 - GREENHOUSE HEATING DUE TO TRACE GASES

Table [illegible] : Past and projected greenhouse gas concentrations and associated changes in greenhouse heating (Mitchell,1989)

Gas	Assumed 1850 concentration ppm	1850-1985 W/m²	Estimated 2035 concentration ppm	Estimated 1985-2035 W/m²
Carbon dioxide	275	[illegible]	47[illegible]	1.5
Methane	1.[illegible]	0.[illegible]	2.[illegible]	0.5
Nitrous oxide	0.28	0.05	0.[illegible]	0.15
CFC11	0	0.06	1.0 × 10[illegible]	0.35
CFC12	0	0.12	2.4 × 10[illegible]	0.69
Total		1.		3.5

Table -2 : A comparison of the assessments of the CO_2 problem

(Bolin et al.1989)

Study	Projection of fossil fuel in GTC/year*	Net emissions from the biosphere in GtC/year*	Future atmospheric CO_2 concentration ppmv**	Globally averaged surface temperature response for CO_2 doubling
WCP(1981)	13.6 in 2025	present release 0-4 past total=75-175 GtC	410-490 in 2025 (most likely 450)	1.5-3.5 °C
CDAC (1983)	10 in 2025 (best guess)	present release 1.8-4.7 past total=180 GtC	408 in 2025 (best guess)	1.5-4.5 °C
EPA(1983)	10 in 2025	-	440 in 2025	1.5-4.5 °C
Clark et al.(1982)	growth rate of 2%/year likely until 2030	present release 2 past total 160 GtC	371-657 in 2030 based on literature review)	2-3 °C
Julich (1983)	1-16 in 2030	present release 0.5-4 (probable 1)	370-500 in 2030 (probable =400)	1-3 °C
Bolin et al (1989)	2-20 in 2050	present release 1.6+0.8 past total 150-50GtC	380-470 in 2025	1.5-5.5 °C

* 1 GtC/year = 10^9 ton carbon/year

** ppmv = parts per million volume

- 2.0 REVIEW

2.1 Recent trends of increase in greenhouse gases

The concentrations of carbondioxide, methane, nitrous oxide and chlorofluorocarbons have increased in the recent past and are expected to increase with a more alarming rate, if the present trends continue. The increase in CO_2 concentration may be attributed to considerable increase in the consumption of fossil fuel and deforestation during the recent century. Figure 4 shows the greenhouse heating due to trace gases and Table 1 gives the past and projected greenhouse gas concentrations and associated changes in greenhouse heating by the year 2035. Table 2 gives a comparison of the assessments of the CO_2 problem by various national bodies.On the basis of estimates of anthropogenic emissions of carbon into the atmosphere, a release of 5.2 gigatons (10^{15}g) carbon per year comes from fossil fuel combustion (Bianchi et al. ,1986) and a flow from deforestation ranges between 0.5 and 4.2 gigatons carbon per year (Houghton et. al.,1985). Figure 5 shows the changes in atmospheric CO_2 resulting from the combustion of fossil fuels. The concentration of CO_2 has increased from about 290 ppm (part per million) in 1880 to 340 ppm in 1980.

Besides carbon dioxide, rapidly increasing concentrations of other greenhouse gases as methane, nitrous oxide, CFCs may also eventually affect the global temperature as carbon dioxide or even more. Therefore, the concern about global warming due to these gases has received considerable attention in the recent years. Methane, which has an origin in the paddy fields, domestic ruminants, biomass burning, leakage of natural gas when exploiting gasfields, is increasing at a rate of about

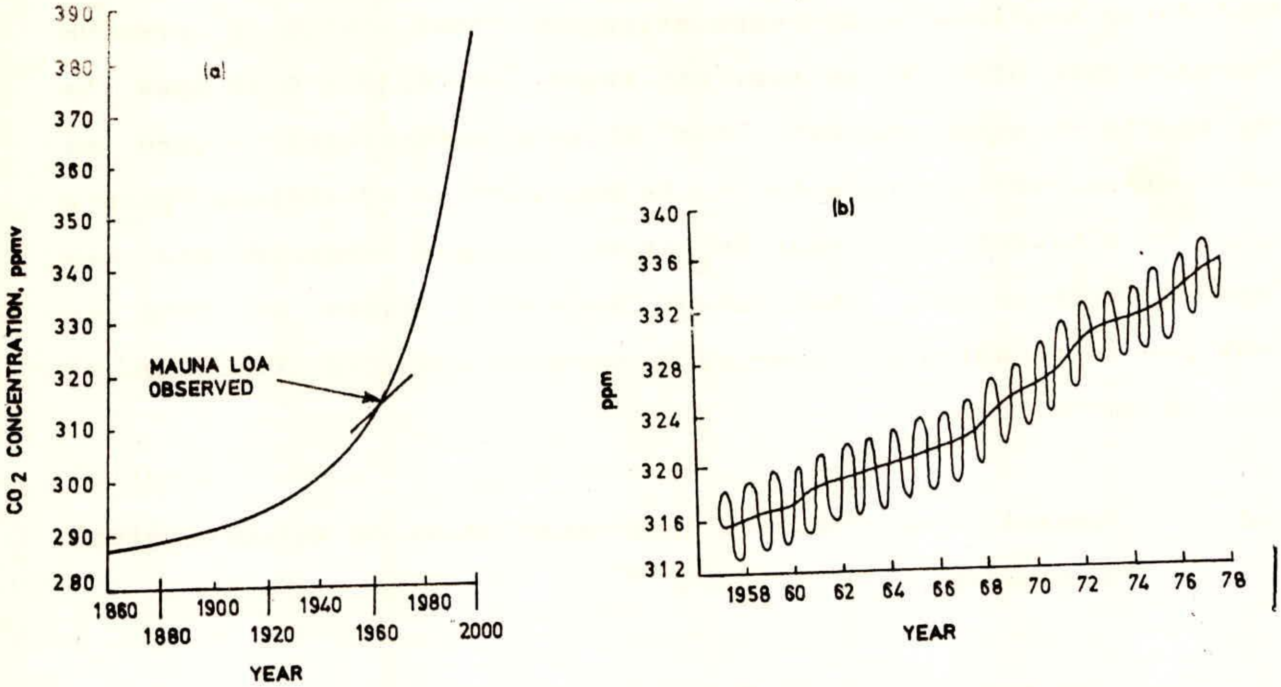


FIG. 5(a) CHANGES IN ATMOSPHERIC CARBONDIOXIDE RESULTING FROM COMBUSTION OF FOSSIL FUELS (MACHTA AND TELEGADAS,1974)

5(b) CARBONDIOXIDE CONCENTRATIONS MEASUREMENTS MADE NEAR MAUNA LOA IN HAWAI. SUPERIMPOSED ON STEADY INCREASE ARE THE SEASONAL FLUCTUATIONS DUE TO THE LARGE UPTAKE OF CO_2 IN SUMMER BY PLANTS IN THE SUMMER HEMISPHERE AND OXIDATION OF PLANT TISSUES IN WINTER (KEELING et al,1976)

1.1-1.3% per year (present average global concentration 1.65 ppmv) presumably. Due to more extensive use of the latter the concentration may rise to 2.0 - 2.5 ppmv during the next fifty years. The concentration of nitrous oxide, produced from fertilizer application and combustion of fuel, with a present increase rate of 0.3% per year can reach upto 0.34 - 0.40 ppmv by the middle of next century. The chlorofluorocarbons used as refrigerants and as solvents in the manufacture of various paints could be a bigger worry than CO_2 if no further restrictions are imposed on their use. The present increasing rates of CFCS is 5-6% per year, which is expected to decline provided the use of CFCs is curtailed.

2.2 Impact of increase in greenhouse gases on meteorological parameters

The changes in the future climate have been set on the basis of the changes that have occurred over the past 100 years. Both regionally and in terms of global mean values, climatic conditions have fluctuated noticeably on annual to decadal and longer time scales. The greenhouse effect is expected to cause major changes in global mean temperature, which will necessarily be accompanied by the changes in various climatic variables as absolute humidity and precipitation , annual rainfall regime and net terrestrial and global solar radiations. However, superimposed on these changes, will also be the inter-annual and inter-decadal variability (which arises due to complexity of interactions between the oceans, cryosphere, atmosphere and land surface). This variability is a natural characteristic of the unperturbed climate system and is less as compared to the changes due to external forcing factors as greenhouse effect.

The changes mentioned in the previous paragraph will differ from region to region. The best information on the overall response of the atmosphere to increasing CO_2 and other trace gases and the possible future climate can be obtained with the use of General Circulation Models (GCM) (Dickinson, 1982; Meehl, 1984). Some broad scale GCM results that can be expected with confidence for possible future changes in the climate due to doubling or quadrupling of CO_2 are given in Table 3.

Table 3: Possible future climate changes due to doubling or quadrupling of CO_2 in GCMs with the degree of confidence (WMO ,1987)

Model Results	Confidence
Global scale (i.e. global mean values)	
Warming of lower troposphere	High
Increased precipitation	High
Cooling of stratosphere	High
Warming of upper troposphere (specially the tropics)	Moderate
Zonal-mean to regional scale	
Reduced sea-ice	High
Enhanced polar warming in Northern Hemisphere (specially winter half year)	High
Increased P-E (precipitation minus evapotranspiration) in high latitudes	High
More absolute high temperature extremes	High
Increased continental summer dryness	Moderate
Stronger monsoons	Moderate
More tropical storms	Unknown
Greater/less interannual variability	Unknown
Spatial details in general	Unknown
Rainfall extremes	Unknown

In recent years, five major groups in the world have carried out studies on changes in surface temperature and precipitation due to doubling of carbon dioxide based on GCMs. These studies have been done by Goddard Institute for Space Studies (GISS), National Centre for Atmospheric Research (NCAR), Geophysical Fluid Dynamics Laboratory (GFDL), Meteorological Office (MO) and Oregon State University (OSU). Table 4 lists the results obtained regarding surface temperature and the precipitation changes.

Table 4- Recent CO_2 doubling studies by five major groups assessing global mean changes (Mitchell,1989)

Study	Source	Surface Temp. Change, K	Precipitation Change, %
GISS	Hansen et al (1984)	4.2	11.0
NCAR	Washington and Meehl (1984)	4.0	7.1
GFDL	Wetherald and Manabe (1986)	4.0	8.7
MO	Wilson and Mitchell (1987)	5.2	15.0
OSU	Schlesinger and Zhao (1987)	2.8	7.8

2.2.1 Temperature

Manabe and Wetherald (1975) have shown that doubling of CO_2 in their model raises the temperature of the troposphere and cools the stratosphere. The increase in the average global surface temperature is 3^oC- with maximum of 10^oC in polar regions. In tropics this warming is spread throughout the entire troposphere by intense moist convection and so the temperature rise is smaller. Lal and Jain (1988) have found that the warming due to doubling of CO_2 is pronounced in the lower troposphere in nigh latitudes and in upper troposphere in low latitudes.

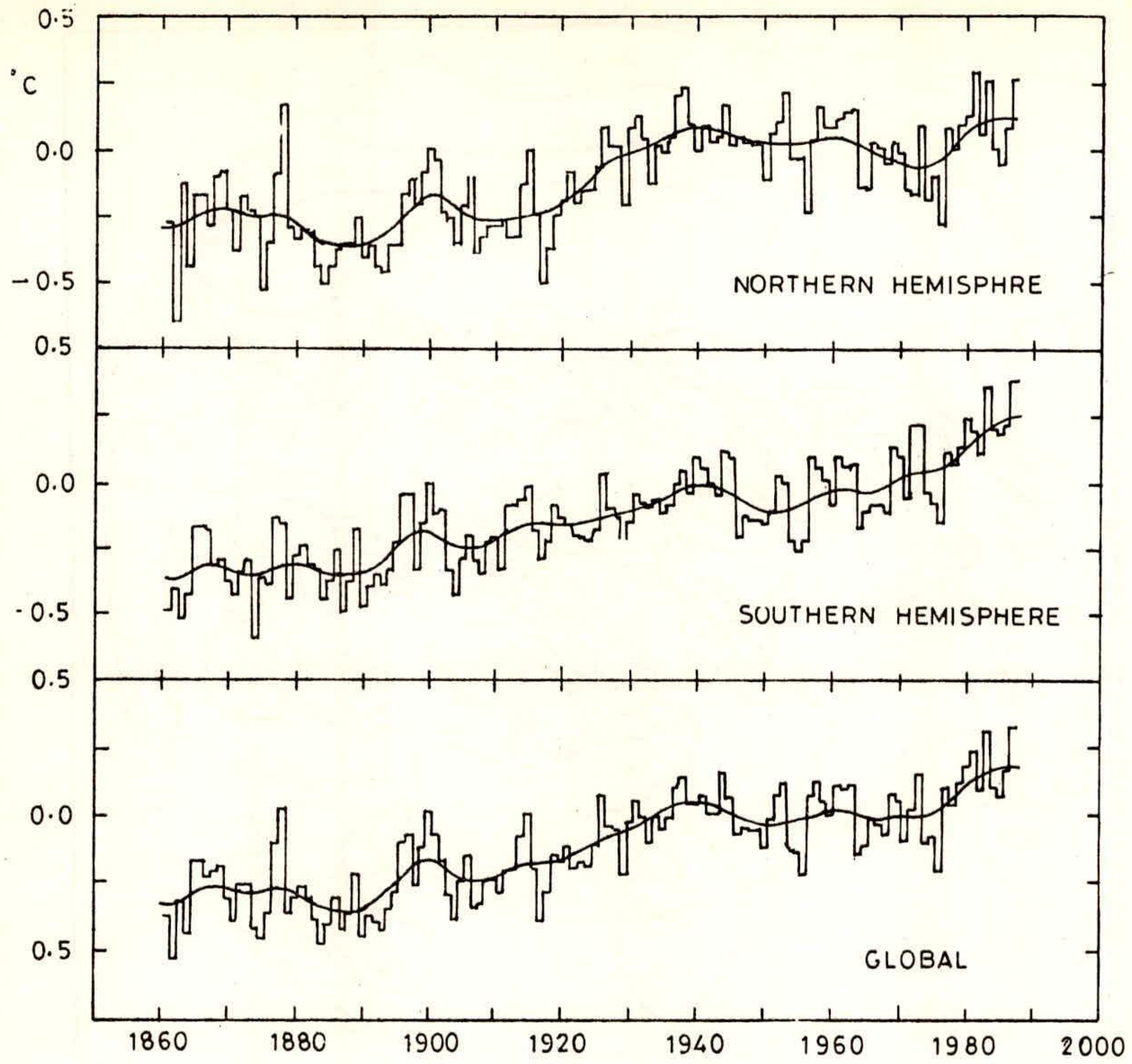


FIG.6. OBSERVEED CHANGES IN TEMPERATURE RELATIVE TO THE 1950-79 REFERENCE PERIOD MEAN (WMO, 1987)

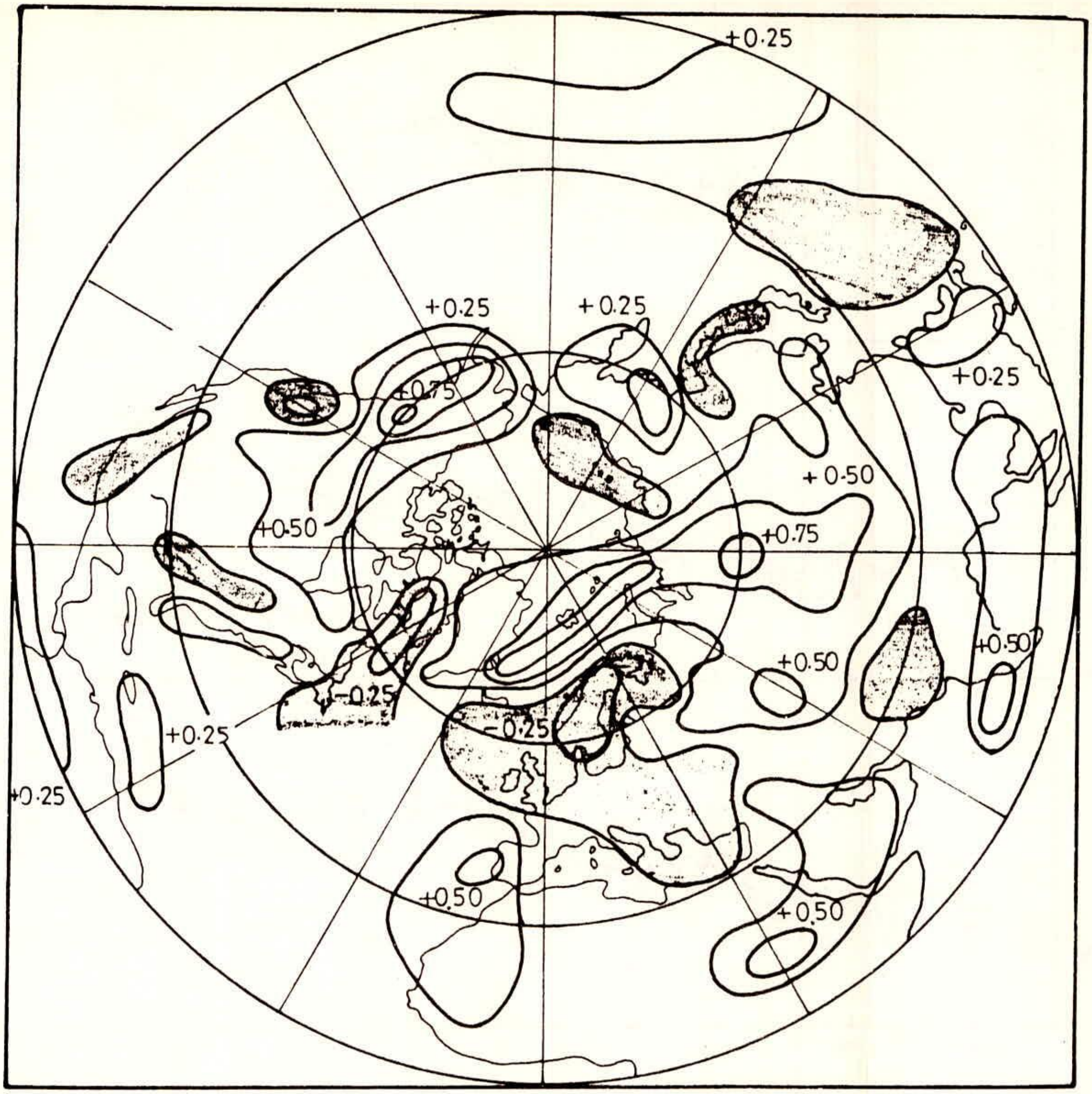


FIG.7. LINEAR TREND IN TEMPERATURE OVER NORTHERN HEMISPHERE LAND MASSES, 1967-86 (UNITS IN °C PER DECADE, SHADED AREAS SHOW REGIONS OF COOLING) (JONES, 1988)

Jones et.al. (1986) have shown that the near surface air temperature has increased by about 0.5°C since the late 19th century. Figure 6 shows the observed changes in temperature relative to the 1950-79 reference period mean for the northern, southern hemispheres and the globe (WMO, 1987). Linear trend in temperature over northern hemisphere land masses (1967-86) in units of degree centigrade per decade is shown in Figure 7. The curves show a long time scale warming trend, which is consistent with the hypothesized warming due to increased greenhouse gases. Current rate of emissions of greenhouse gases are expected to increase global warming by 0.2-0.5°C per decade.

Mabbutt (1989) reviewed the postulated effects of carbondioxide warming on semi-arid tropical climates .Mabbutt (1989) mentioned that overall warming could be most marked in a rise in dry season temperatures, including both daytime maxima and overnight minima, in semi arid tropics.

2.2.2 Precipitation

The quantization of large scale area average precipitation changes is difficult as compared to that of temperature changes because of the higher spatial variability of the former. Bradley et.al. (1987) have shown an upward trend for land based data from 1920 in mid to high latitudes (35-70°N) and a marked downward trend in tropical to sub-tropical latitudes (5-35°N) of the northern hemisphere (Figure 8). Barnett (1985) has concluded that it is extremely difficult to establish the trends over the ocean. On smaller spatial scales some regions of the world have experienced marked changes in precipitation on decadal time scales, for example - Sahel region of Africa (Fig.9).

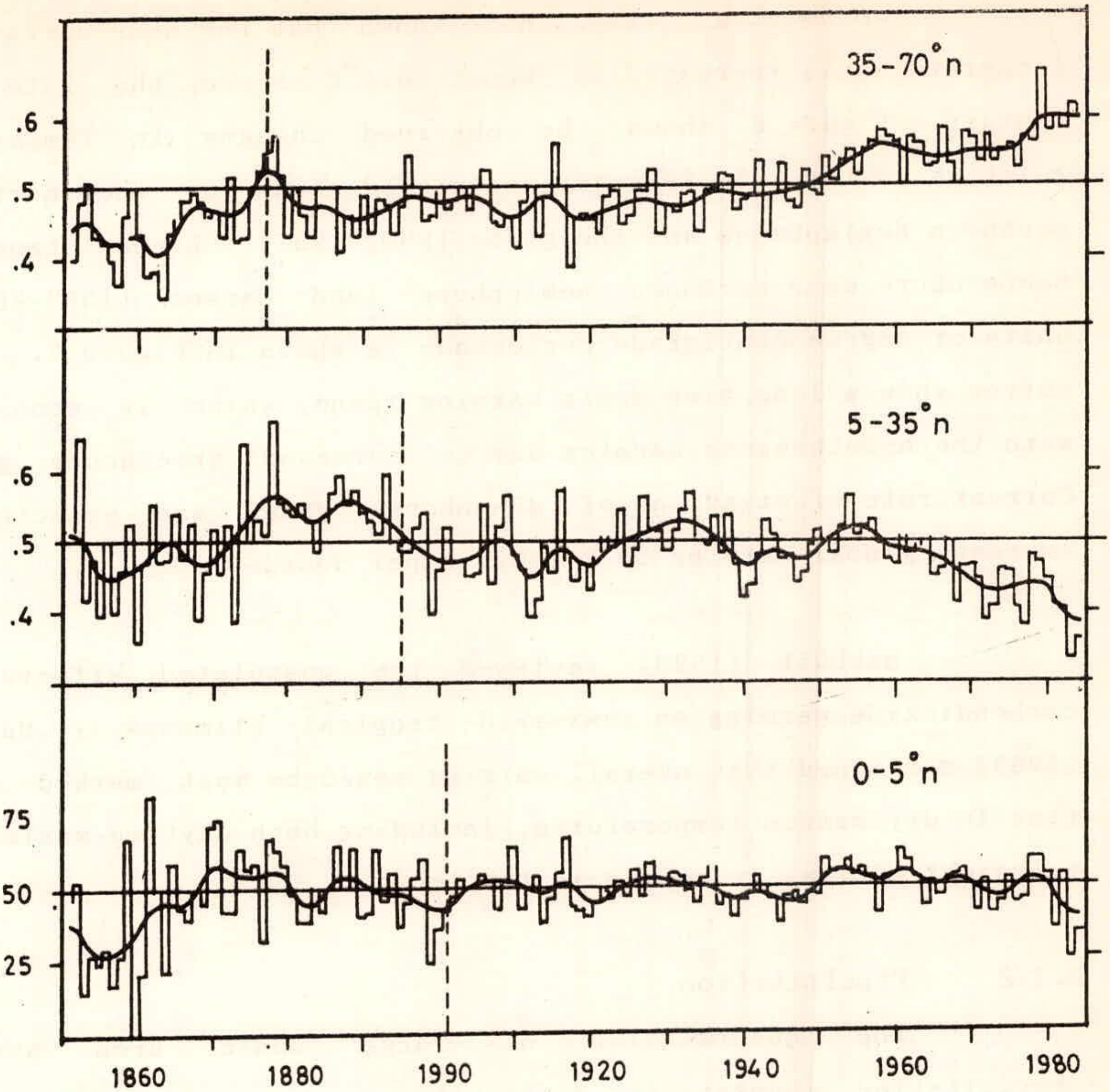


FIG.8-PRECIPITATION INDICES SHOWING CHANGES IN AREA AVERAGED PRECIPITATION OVER THE LAND AREAS (BRADLEY et al,1987)

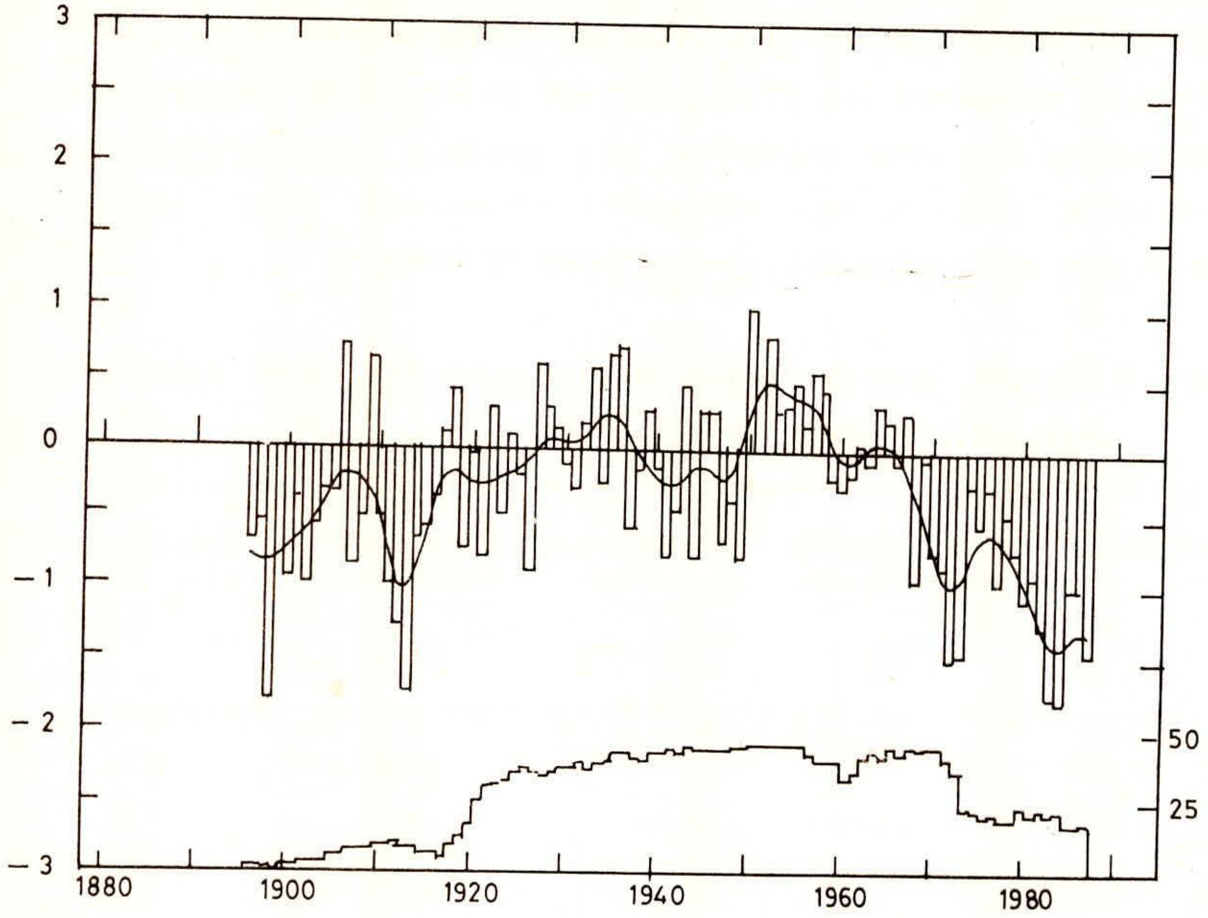


FIG.9–TIME SERIES OF MAY–OCTOBER RAINFALL IN THE WESTERN SAHEL FOR 1896–1987. RAINFALL IS EXPRESSED AS A NORMALIZED ANOMALY FROM THE 1941–70 BASE PERIOD (WMO, 1987)

Mitchell (1986), using the Meteorological Office's 5-layer and 11-layer GCM have studied the effects of enhanced CO_2 concentrations with prescribed increase in sea surface temperature (2^oK) (the increase in sea surface temperatures were those expected to accompany the given increase in CO_2). The changes, due to increasing CO_2 and enhancing sea surface temperatures, in tropospheric temperature, atmospheric humidity, land surface temperatures and precipitation are shown in Table 5.

Table : 5 Changes (increase) due to increasing CO_2 and enhancing sea surface temperatures

Experiment	Tropospheric temperature (^oC)	Atmospheric humidity (%)	Land surface temperature (^oC)	Precipitation (%)
$2xCO_2$ (5LM)	3.02	18	2.86	5.0
*$4xCO_2$ (5LM)	2.05	16	4.00	3.5
$2xCO_2$ (11 LM)	3.08	20	3.05	5.6

*Differences halved to allow comparison.

Manabe and Stouffer (1980) have shown that the CO_2 induced warming of the atmosphere results in the enrichment of the moisture content in the air (hence, humidity) and an increase in the poleward moisture transport. The additional moisture is picked up from the tropical oceans and is brought to high latitudes where the precipitation increases throughout the year. The increase in zonal mean precipitation rate is larger in high latitudes than the corresponding increase in lower latitudes and has significant latitudinal variations. The global mean increase in the precipitation rate is found to be 0.018 cm/day which implies a 6.7% increase in the overall intensity of hydrologic cycle.

Manabe et al. (1981) demonstrated the possible advent of summer dryness, due firstly to the reduction of precipitation in summer and secondly to the rise in temperature leading to disappearance of snowcover is winter and hence, an earlier start of the summer drying season .

The consequences of surface warming for zonal climates including semi arid tropics remain uncertain. This is mainly due to the limitations in the numerical models on which the predictions have been based (Tucker, 1988).Some of the forecasts for precipitation changes by various numerical models in the semi arid tropics are:

(i) tropical summer rains may increase in general (Manabe and Wetherald, 1980);

(ii) there may be a diminished summer rainfall in tropical Australia (Meehl and Washington, 1986);

(iii) there may be an intensification of rainfall within an existing rainy period (Mitchell, 1983; Mitchell et al., 1987);

(iv) a poleward displacement of rainfall belts may take place (Manabe et al, 1981).

Pittock (1980, 1985) found a link between the already observed southern hemisphere mid-latitude warming and, an increase in summer rainfall in northern Australia between 1913-45 and 1946-78, as linked with a poleward shift of the sub-tropical anticyclonic belt and a more positive southern oscillation Index (SOI). He postulated a poleward extension of the area of summer rains by about 2 degrees of latitude in northern Australia and suggested increases in near annual rainfall of between 10% and 20% and some increase in mean daily rainfalls and a lengthening of the rainy season by 2-4 weeks. However ,Pittock (1988) admitted to greater uncertainty regarding changes in rainfall variability and in secondary climatic effects such as the evaporation balance.

2.2.3 Other climatic parameters

The change in surface heat budget also shows latitudinal variations . Chou et al (1982) have studied the change in the surface heat budget (which include the solar radiation, infrared radiation, sensible heat flux, latent heat flux and heating due to ocean transport) due to the change in CO_2. With the doubling of CO_2 content, the solar radiation, absorbed at the surface in the tropics decreases slightly, because of the more humid atmosphere, which reduces the solar radiation reaching the earth's surface (Figure 10). The absorption of solar radiation increases poleward of $40^{o}N$ reaching a maximum at $75^{o}N$. This is consistent with the decrease in surface albedo as shown in Figure 11. Except in the polar region where the increase in surface temperature is the largest, the increase in the downward IR flux exceeds that in the upward flux due to the increase in water vapor content. This results in a reduced net upward IR flux for a doubled CO_2 content. Chou et al (1982) have shown that net upward IR flux at the surface decreases by 4.7 W/m^2 for a doubled CO_2 content. The changes in surface sensible heat flux and oceanic transport of heat are comparatively of less importance.

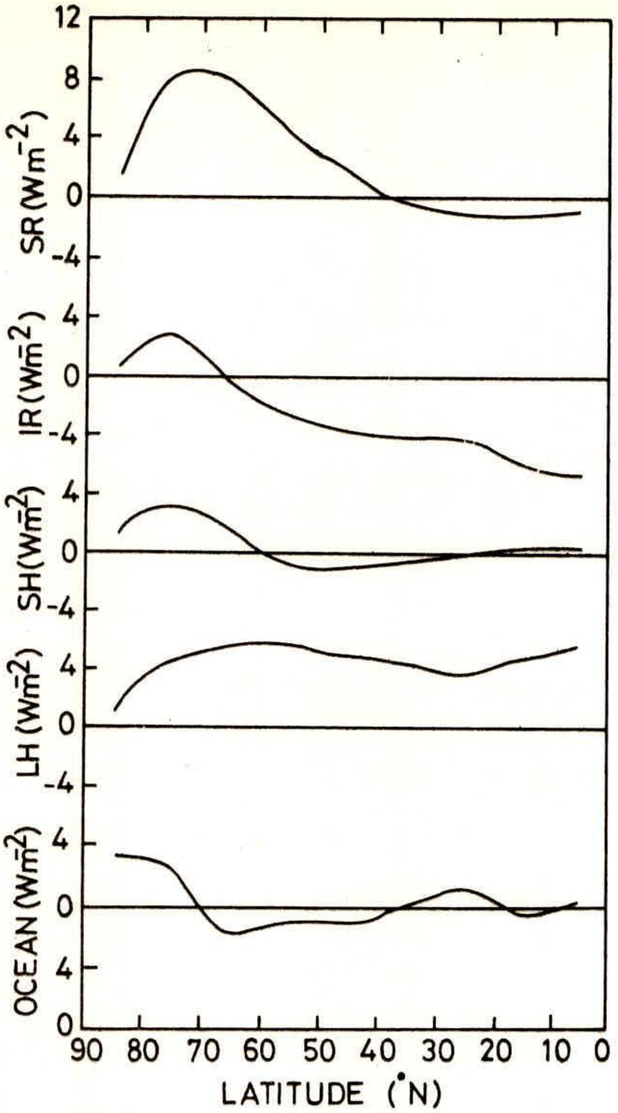


FIG. 10 LATITUDINAL DISTRIBUTION OF THE CHANGES IN SURFACE HEAT FLUX DUE TO A DOUBLING OF THE CO_2 CONTENT (CHOU et al , 1982)

SR - ABSORPTION OF SOLAR RADIATION
IR - NET UPWARD IR RADIATION
SH - SENSIBLE HEAT FLUX
LH - LATENT HEAT FLUX
OCEAN - HEATING DUE TO OCEAN TRANSPORT

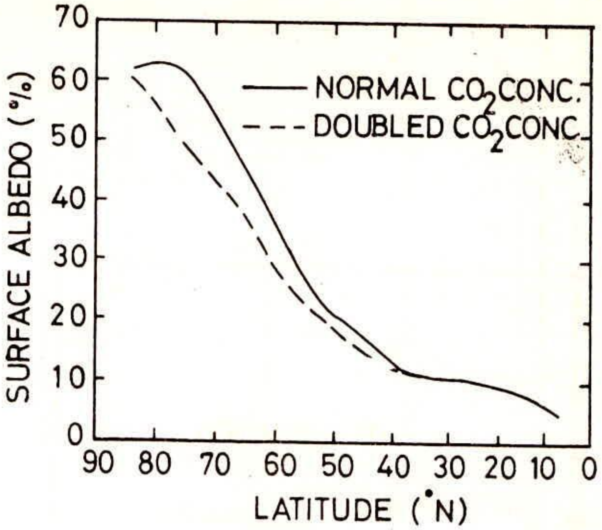


FIG. 11 LATITUDINAL DISTRIBUTION OF THE SURFACE ALBEDO FOR NORMAL AND DOUBLED CO_2 CONCENTRATIONS (CHOU et al , 1982)

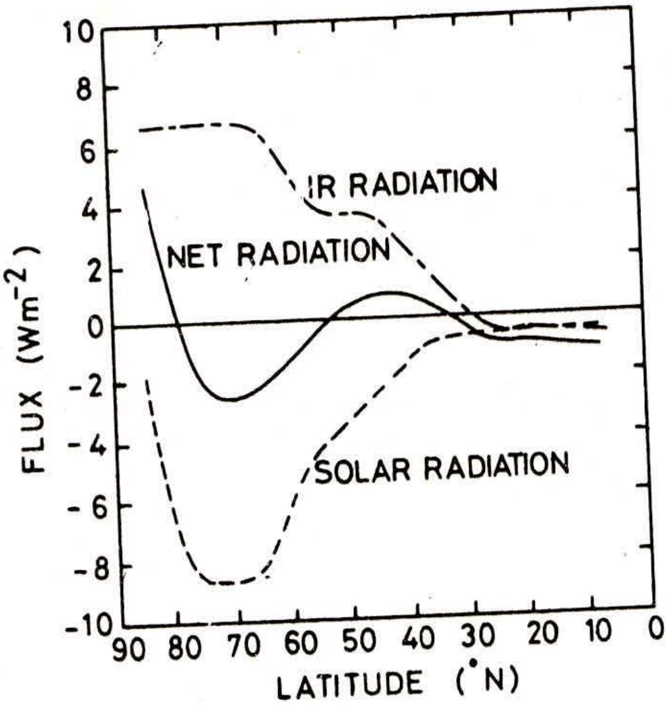


FIG. 12 CHANGES IN UPWARD RADIATION FLUXES AT THE TOP OF THE ATMOSPHERE FOR DOUBLING OF CO_2 CONTENT (CHOU et al , 1982)

The change in the surface latent heat flux is found to be large at almost all latitudes except in the polar region with large surface portion covered by ice and snow. The significant change in latent heat at the surface points to the importance of evaporation in regulating the climate sensitivities. This can be understood as follows. There exists a nonlinear relationship between evaporation and surface temperature, a small increase in temperature at a wet surface will lead to a considerable increase in evaporation. This cools the surface and heats the atmosphere through the release of latent heat. The resulting increases in atmospheric temperature and hence the humidity intensify the downward IR flux and heat the surface. Thus a feedback loop is formed between evaporation, temperature and humidity. The studies of Newell and Dopplick (1979) and Chou et al (1981) also show that the nonlinear relationship between evaporation and surface temperature greatly reduce the surface temperatures response to variations in the CO_2 content.

The thermal structure of the earth-atmosphere system is considerably changed due to changes in solar and IR radiation at the top of the atmosphere. The absorption of the solar radiation increases at all latitudes (Figure 12). Comparing the dashed curve in Figure 12 with SR curve in Figure 10, it can be seen that the increase in absorption of solar radiation at low latitudes is in the atmosphere (due to higher water vapour content) and the increase at higher latitudes is mostly at the surface (due to smaller ice/snow cover). The change also increases from low latitudes to high latitudes in the infrared radiation.

Besides latitudinal variations, the radiation components show seasonal variations also. In spring and summer the net terrestrial radiation decrease over the daylight period, induced

Table 6- Specific changes in climate under the hypothesis of a doubling of the atmospheric CO_2 concentration (Bultot et al., 1988)

	Decrease	Increase	Sources
Net terrestrial radiation	3.1 Wm^{-2}		Chou et.al., 1982
Global solar radiation	2.5 Wm^{-2}		Chou et.al., 1982
Flux of sensible heat	8%		Manabe and Wetherald, 1975
Flux of latent heat of evaporation.		7%	Manabe and Wetherald, 1975
Cloudiness		1.5%	Washington and Meehl, 1984
Air temperature		See below	Manabe and Stouffer, 1980
Water vapour pressure		Linked to air temperature, the relative humidities being assumed invariant.	Manabe and Wetherald, 1975 Washington and Meehl, 1984
Precipitation, P	See blow	see below	Manabe et.al. 1981 Washington and Meehl, 1984

Monthly increments

	J	F	M	A	M	J	J	A	S	O	N	D	YEAR
Air temperature (deg K)	+3.1	+3.4	+3.4	+3.1	-2.8	+2.7	+2.5	+2.3	-2.8	+2.7	-2.5	3.2	2.86
Precipitation (mm/month)	+9.3	+10.5	-9.9	+10.2	-1.2	-2.7	-1.5	-2.2	0.0	+5.3	+8.1	+8.7	54.3

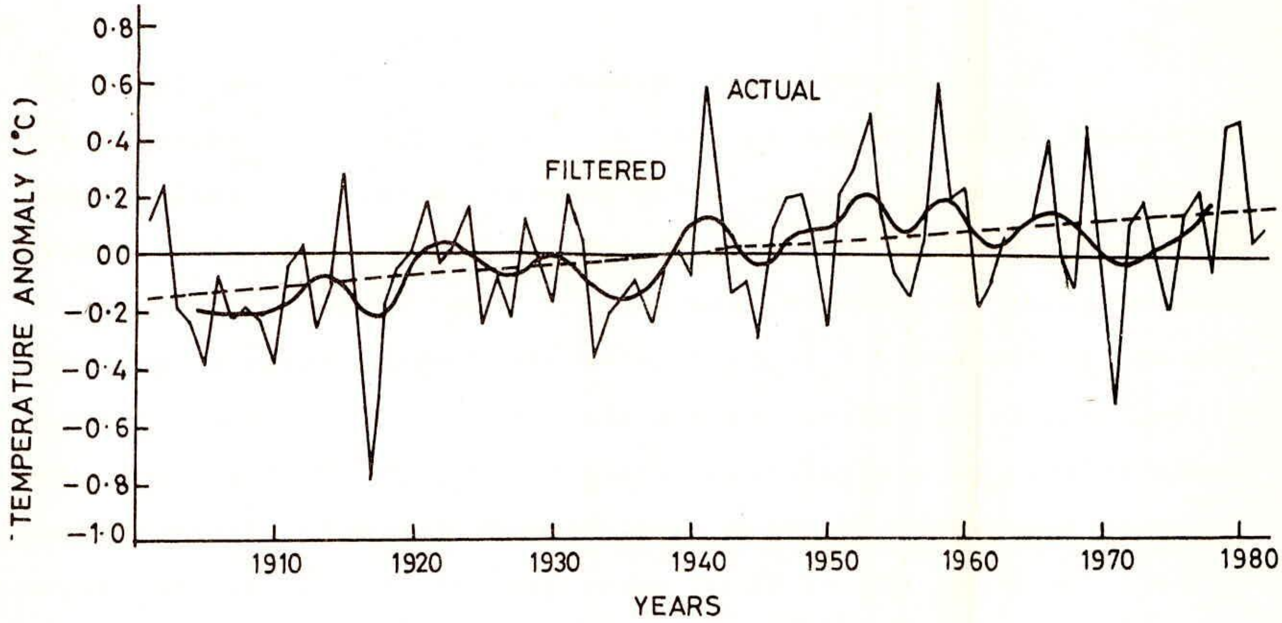


FIG.13 – ACTUAL AND FILTERED VALUES AND THE TREND LINE OF ANNUAL TEMPERATURE ANOMALIES IN INDIA DURING THE PERIOD 1901–1982 (HINGANE et al, 1985)

by CO_2 doubling is such that it induces a slight increase of the net radiation.The changes of different climatic parameters under the hypothesis of a doubling of the atmospheric CO_2 concentration (with sources) are shown in Table 6.

2.3 Greenhouse effect and its meteorological impacts in Indian context

The contributions to greenhouse effect from India is only about 4% and is due to the following factors: agricultural practices, biomass burning, power generation from thermal plants and transportation, and deforestation. India, has the largest area of paddy cultivation, and thus is the largest producer of methane in the world. India is also the fourth largest user of nitrogenous fertilisers. Within the sector of biomass burning India is seen as a significant contributor. The contribution due to power generation is from coal based thermal plants, which account for about 65% of total power generation. Out of the above parameters deforestation is contributing least to the greenhouse effect (Hai et al ,1990)

The mean annual temperature for India during the period 1901-1982 is shown in Figure 13 (Hingane et al, 1985). The trend line indicates a trend of about 0.4°C warming during recent 8 decades. This trend changes seasonally,being 0.7 °C in post monsoon and winter seasons and during pre-monsoon and monsoon seasons become 0.4°C and - 0.3°C respectively. In contrast to the post 1940 cooling which has been observed for the northern hemisphere, a steady increase in mean annual temperature has been observed for Indian subcontinent for the last 8 decades.

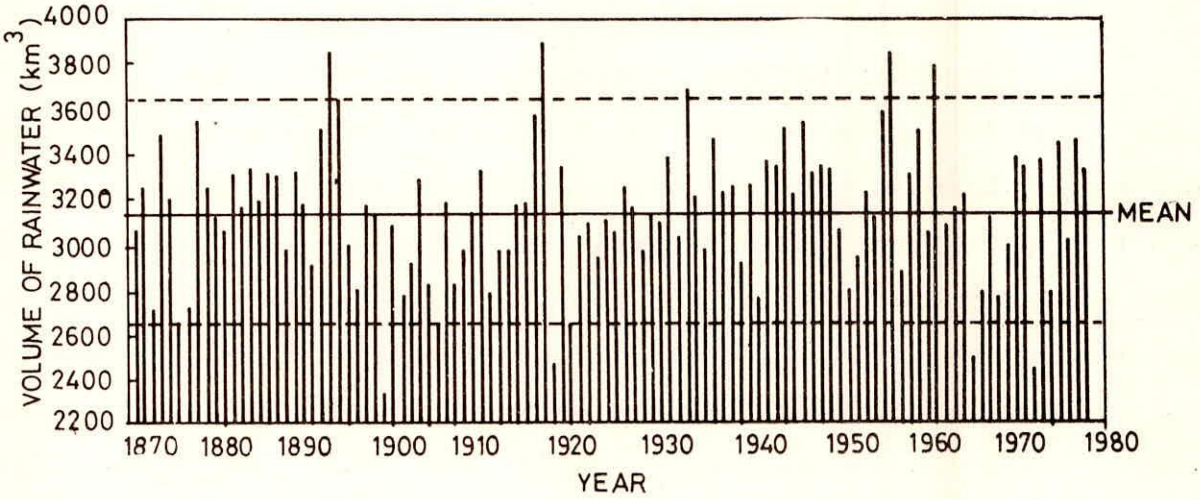


FIG.14 – TIME SERIES OF ANNUAL AVERAGE PRECIPITATION ANOMALY FOR INDIA FROM 1871 TO 1978. 90% CONFIDENCE LIMITS ON THE MEAN (=3143·5 km^3) ARE SHOWN BY THE DASHED LINES (MOOLEY et al, 1981)

1

The precipitation patterns over India have been intensively studied over the years. These studies have been centered mainly on prediction of monsoon rainfall. Mooley et.al.(1981) examined the time dependence of coherent rainfall pattern using 36 rain gauges. They inferred the time series to be both homogeneous as well as random ,but there was no significant trend in the Indian precipitation fields. The large noise levels (Figure 14)(the 90% confidence levels on the mean) indicate the difficulty of detecting the rather small changes that may be due to CO_2 effects.

2.4 Hydrological response of enhanced greenhouse effect

As a consequence of changes in meteorological parameters due to enhanced greenhouse effect ,significant impact on hydrological parameters viz. runoff,evapotranspiration , soil moisture, ground water etc.is expected.To evaluate the hydrological effects of increasing greenhouse gases , one needs the predictions/forecasts of changes in climatological parameters,specially air temperature and precipitation for different regions and periods of time.As the accurate forecasts of regional climatic changes are still not available , various scenarios of future climatic changes are used.These are -

(a) hypothetical scenarios - Many researchers prescribe hypothetical scenarios for climatic change without taking into account a particular time interval.Most of the scenarios assume an air temperature increase from 0.5° C to 4 ° C and precipitation change(increase or decrease) in the range of 10% to 25% .

(b) scenarios obtained by using atmospheric GCMs - These are obtained by models considering doubling of CO_2 in the atmosphere.The scenarios are usually applied to the regions for which similar simulations have been repeatedly carried out by using different methods.

(c) simulations based on palaeoclimatic reconstructions -The paleoclimatic records provide information about the effects of CO_2 forcing as some aspects of past climatic changes are undoubtedly related to past changes in atmospheric CO_2 levels.

The projected climatic changes need to be regarded as the possibilities to study the sensitivity of hydrological and water resources to such changes.This has been evaluated by many methods.The large scale general circulation models have been used to prescribe possible changes in the content of trace gases in the atmosphere(2 x CO_2 usually) and to directly obtain the possible changes in climatic and hydrological characteristics for large regions. By using atmospheric GCMs possible changes in runoff,soil wetness and evaporation have been estimated for USA and Canada(USEPA,1984;Sanderson and Wong,1987;Singh,1987;Stakhiv and Lins,1989)

2.4.1 Limitations of GCMs for direct evaluation of hydrological parameters

The direct use of GCM output in grid scale hydrologic assessment is generally restricted due to two important limitations.Firstly, the hydrological variables such as precipitation,runoff,soil moisture are computed as secondary variables in GCMs in contrast to primary variables such as temperature,humidity and transfer of energy and hence their realism is limited .Secondly ,GCMs have limited spatial resolution(100 x 100 km^2) and most of the hydrological phenomena occur on scales far smaller than the spatial resolution of GCMs.

Besides these two major limitations a few additional limitations further restrict the use of GCM output in hydrological modelling .For example in GCM studies of greenhouse effect only the equilibrium response of doubled or quadrupled CO_2 has been considered and the climate change due to transient response of CO_2 increase has not been taken into account.This study requires the study of an atmospheric GCM coupled to a realistic ocean GCM which are still in their early developmental stages. Furthermore, the GCMs currently used for greenhouse studies are not able to simulate the current atmospheric circulation.

2.4.2 Coupling of GCMs with hydrologic models

To obtain the sub-grid scale information that supplements the coupling of coarse resolution output of GCMs with hydrologic models ,various methods were suggested in the Meeting of Experts on the Sensitivity of Water Resource Systems to Climate Variability(WMO ,1987). These were

1) Development of regression equations using existing instrumental data bases and their application to GCM results for doubled CO_2 scenarios.
2) Embedding of higher resolution model within the course resolution GCMs to produce subgrid scale information.
3) Improvement of the resolution of existing models or development of new high resolution GCMs,which incorporate better hydrologic parameterizations and regional topographical detail.

These methods have several limitations and the progress is being made to improve the hydrologic parameterizations in

GCMs.As the hydrological parameters such as soil moisture ,vegetation evapotranspiration etc. would be incorporated in GCMs more realistically the evaluation of hydrologic effects of climatic change is likely to become more reliable.

2.4.3 Other methodological approaches

Hydrologists from many countries have used various other methodological approaches besides atmospheric GCMs to study the hydrologic consequences of future anthropogenic climate change.These are as follows :

1) Analysis of long term variations in runoff and meteorological elements over the past years

The approach has been realised in two ways .In the first approach , various statistical models of hydrologic characteristics and regression interactions between runoff ,air temperature ,and precipitation are applied .Using this method, studies have been carried out for western regions of the US and the Colorado river basin (Stockton and Boggess ,1979 ;Revelle and Waggoner,1983) and for the annual river runoff in the USSR (Anthropogenic Climatic Changes,1987).

In the second approach , the hydrologic consequences for the past very warm or cold ,wet or dry years periods have been studied.The analysis has been carried out by Schwartz(1977) and Glantz(1988) for the US and by Chunzhen(1989) for the northern China.Studies have also been made for some regions of the Sahelian zone using this approach.

2) Using water balance methods over a long period of time

These methods have been used by Vinnikov et al (1989) for the USSR and Griffiths (1989) for the New Zealand and Babkin(Shiklomanov,1988)

3) Using deterministic hydrological models

This approach has been used by many workers for basins located in various hydroclimatic environments (Nemec and Schaake, 1982; Gleick, 1986, 1987; Mather and Feddema,1986;Cohen,1986;Flashka et al.1987;Bultot et al.,1988;Kuchment et al,1989). Here different models of runoff formation in river basins (including water balance models)are employed for the time intervals of one hour to one month.The deterministic hydrological models seem to be preferable under modern conditions (Linz et al,1990).

2.5 Impact of climate change on hydrological parameters

Linz et al (1990) reviewed the results obtained in different countries on the estimation of influence of climatic change on hydrological characteristics ,water resources and the problems associated with their use.They mentioned that the investigations carried out on changes in annual and seasonal runoff since the late 1970s primarily point to a great sensitivity of river watershed even to insignificant changes in climatic characteristics. This is specially true for the watersheds located in arid and semiarid regions .Studies have also suggested that the annual runoff appears to be more sensitive to changes in precipitation than to changes in temperature.In the regions with seasonal snowfall and snowmelt as a major part of total water supply ,the monthly distribution of runoff and soil moisture is

Table 7 : Six criteria for evaluating the applicability of hydrologic models for climatic impact assessment (Gleick, 1986)

The inherent accuracy of the hydrologic model

The degree to which model accuracy depends upon the existing climatic conditions for which the model was initially developed and calibrated

The availability of input data including comparative historical climatic data

Model flexibility, ease of use and adaptability to diverse climatic and hydrologic conditions

Compatibility with existing general circulation models more sensitive to temperature rather than precipitation .Linz et al.(1990) mentioned that the global warming would lead to changing all the lake water- balance components(precipitation,evaporation, inflow ,and outflow),their levels and heat budget.

One of the most profound impact of climatic changes may be the major alterations in regional hydrologic cycle and changes in regional water availability.Gleick (1986) reviewed different approaches for evaluating impacts of global climatic changes on the regional hydrology .He mentioned six criteria for evaluating the applicability of hydrologic models to climatic impact assessment (Table 7).

Gleick (1986) suggested that the use of modified water balance models offers significant advantages over other methods in accuracy, flexibility and ease of use. These are specially useful for assessing the regional hydrologic consequences of changes in temperature, precipitation and other climatic variables. These models can incorporate month to month or seasonal variations in climate and snowmelt algorithms, groundwater fluctuations and soil moisture characteristics. These can also be combined with the state of the art information from GCMs to generate information on hydrological response of future climatic changes using the plausible hypothetical climate change scenarios.

Gleick (1987) using the basin specific assumptions for precipitation, temperature, runoff, storm runoff, watershed log, soil moisture, ground water developed a modified water balance model for the Sacramento basin. The results showed that the magnitude of winter runoff predicted by the model was too high and it occurred too early in spring, as compared to

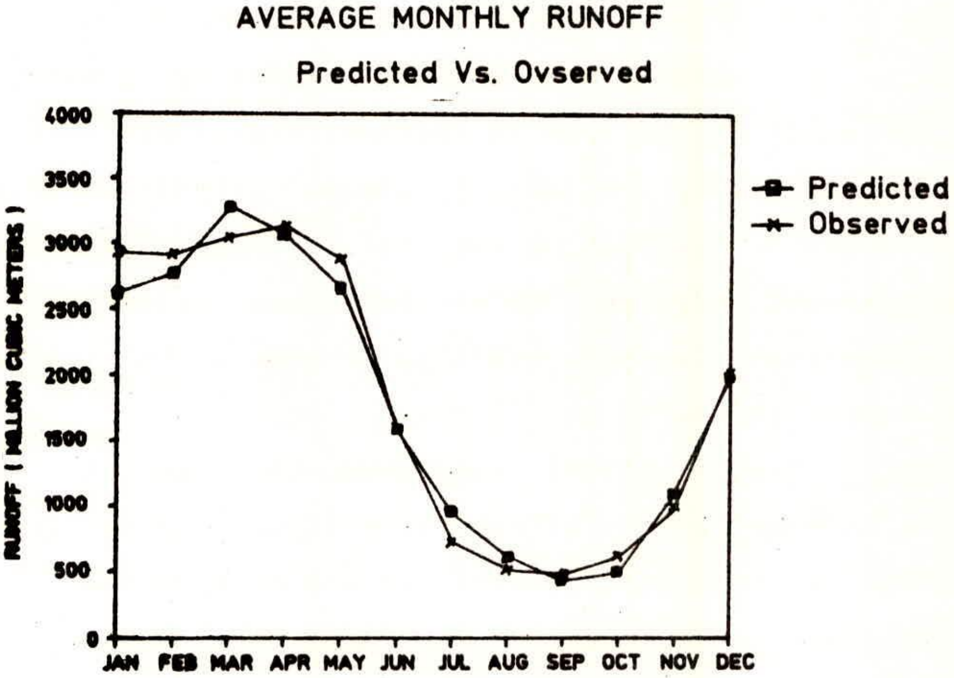


FIG. 15 - AVERAGE MONTHLY RUNOFF (OBSERVED AND PREDICTED). BY TWO BASIN MODEL (GLEICK, 1987)

Table 8 : Effects of climatic changes on runoff :some early results (Gleick,1986)

Author*1	Region	Scale (km^2)	Climatic change	%Change in runoff*2
Stockton and Boggess (1979)	Average for seven western U.S.regions	10^5	+2C;-10% precip.	-40 to -76
Nemec and Schaake(1982)	Arid basin	10^4	+1C +10% precip. +1C;-10% precip.	+50 -50
	Humid basin	10^3	+1C;+10% precip. +1C; -10% precip.	+25 -25
Revelle and Waggoner (1983)	Colorado River Basin	10^5	+2C;+10% precip. +2C;-10% precip.	-18 -40+ 7.4
Flaschka (1984)	Great Basin	10^5	+2C;-10% precip.	-17 to -38
U.S. EPA (1984)	Central U.S.	10^5	Doubled atmospheric carbon dioxide	-26
	NW U.S.	10^5		+20 to + 60

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* 1 Each assessment uses different method,hence the direct comparison of results is not possible.

* 2 annual average changes in runoff

observed values. The principal reason for the discrepancy in the monthly runoff distribution was the absence of snowfall and snowmelt from the model .

Thus the Sacramento watershed was split into two sub-basins based on the above parameters: upper basin - where precipitation during the winter months was almost entirely snow and the soils and terrain rocky; and the lower basin - where all precipitation as rain and the soils are deeper and runoff. Two distinct water balance models were developed and run, one for each of upper and lower basins. The monthly temperature and precipitation data for 50 years were introduced and continuous water balances were computed for the 600 months period. The total Sacramento basin runoff was computed by combining the monthly runoff values from each sub-basin as a function of their relative areas. The results for average monthly runoff & average annual runoff were well within the limits of accuracy of the available data and the water balance method itself (Fig.15) .

The results of some of the early studies on effects of climatic changes on runoff is given in Table 8.These assessments have used different methods of approaches to study the climatic impact on runoff.

2.5.1 Semi arid and arid regions

The hydrological response to greenhouse warming in the semi-arid tropics needs considerable study as there is an uncertainty about the amount, duration, intensity and interseasonal variability of rainfall and in the magnitude, frequency of extreme rainfall events and precipitation-evaporation ratio. The partitioning of precipitation into infiltration and runoff will be affected by the changes in vegetation cover, which itself is linked with uncertainty in rainfall. The change in rainfall alone tends to be amplified in the runoff response by a factor approximately the inverse of the runoff coefficient. Wigley and Jones (1985) suggested a 25% increase in runoff on a 10% increase in precipitation for an area with a runoff coefficient of 0.4, evapotranspiration remaining the same. For semi arid tropics, which have prevailing low to moderate runoff coefficients, any small change in rainfall could bring very significant changes in river discharges .

Linz et al (1990) mentioned that the analysis of annual precipitation data from stations in the Sahel region for the period 1970-85 has revealed this period to be extremely dry; the reason for Sahelian droughts being the decrease in annual precipitation. Ojo (1987), analysing the precipitation trends for 1901-85 for 60 stations of western Africa found that the average precipitation for 1970-79 and 1981-84 were 0.62 and 0.5 of the normal. Mabbutt (1989) mentioned that some indication of the hydrological consequences of rainfall decrease in the semi-arid tropics is given by the reduction in discharges and seasonal flooding in the Niger and Senegal rivers and drastic shrinkage of Lake Chad after two decades of low rainfalls in Sahelian Africa .

A tendency of decrease in total annual precipitation during the period 1972-87 for arid zones of Northern Africa was observed and the total annual amounts of precipitation were found to be much lower then the normal. The succession of dry years led to a decrease in water resources in the region.

This tendency may represent a potential risk of drought which may contribute to the process of desertification and extension of deserts. The changes in precipitation due to the increase in trace gas concentration in the atmosphere may lead to changes in the future water resources ,ecology and economy of the countries in Sahelian and arid and semi arid zones.

For the large rivers having source in rainier uplands in adjoining humid areas and traversing the semi-arid tropics, the hydrological response will be complicated. This will be true for the rivers like Nile and Niger (Mabbutt, 1989).

Nathan et al. (1988) simulating the flood frequency curves for a selected river catchment in summer rainfall zone of north-eastern Australia suggested that the greenhouse effect could have a greater impact on more frequent floods than on extreme events. He had taken the assumptions of increases in seasonal rainfalls and various changes in evaporation and neglected the possible changes in rainfall intensity - frequency - duration relationships .The increases in peak discharges would lead to extent and duration of flooding, which would have potential consequences for riverine landscapes and land use and for the design and performance of man made structures as storage reservoirs and bridges etc. (Mabbutt, 1989).

Chunzhen (1989) analysed the hydrometeorological observational data for Northern China and found that the warmest period over the last 250 years started since 1981 and the mean air temperature over 1981-1987 was 0.5^{o}C above the normal. The precipitation was somewhat lower than the normal (by 4% for Beijing) for the same period. The estimates for the scales of

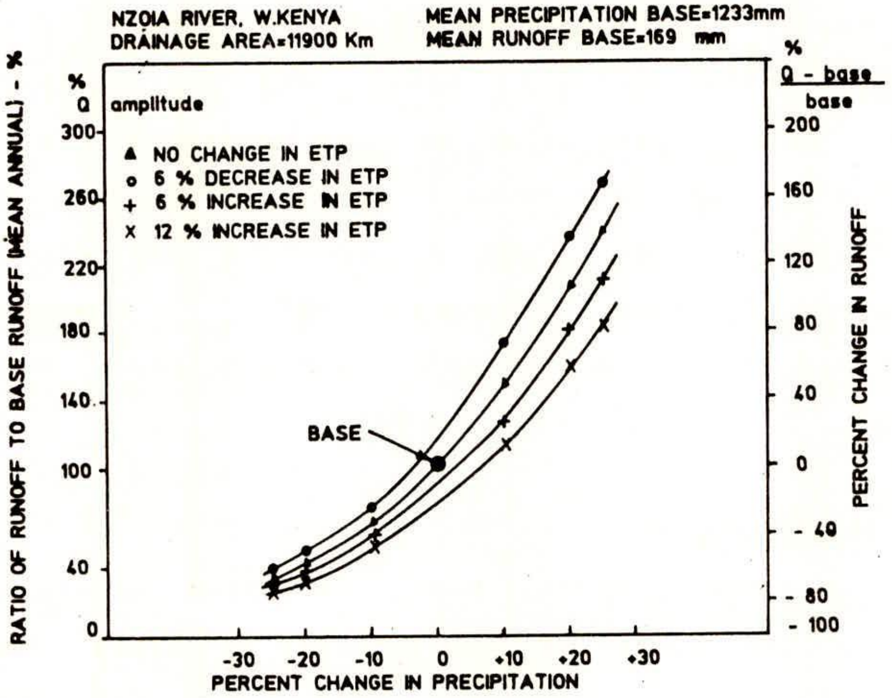


FIG. 16 - CHANGES IN STREAMFLOW DUE TO CHANGES IN PRECIPITATION AND POTENTIAL EVAPOTRANSPIRATION FOR NZOIA RIVER (NEMEC AND SCHAAKE,1982)

influence of increasing CO_2 in the atmosphere on the climate of northern China are as yet unavailable (Linz et al, 1990).Chunzhen(1989) showed that a 10% increase in precipitation and a 40% decrease in evaporation would increase the runoff by 27% in semi-arid regions, whereas a 10% increase in precipitation and a 4% decrease in evaporation would result in runoff rise by 18% .

Soviet climatologists, on the basis of paleoclimatic reconstructions, have found for northern Africa that the annual precipitation is expected to increase considerably in the near decades thus influencing the total moisture, river runoff and accompanying ecological changes (Anthropogenic climatic changes, 1987). However, these estimates are quite approximate and need considerable improvement.

2.5.2 Humid tropics

In the tropical humid condition simulations were conducted in the basin of Lake Victoria in Africa (Nemec and Schaake, 1982). Kite and Waititu (1981) used the Nzoia River basin to study the changes in streamflow as a function of changes in precipitation and potential evapotranspiration. An increase of 25% in precipitation and a 6% decrease in evapotranspiration produced an increase in runoff of about 170%; whereas a 12% increase in evapotranspiration and a 25% decrease in precipitation produced a 75% decrease in runoff (Fig.16) The possible effects of climatic change on level of lake victoria were obtained from these altered in flows. Nemec and Schaake (1982) mentioned that the maximum increase in precipitation could produce a rise of over 3 m above the maximum recorded lake level and climate changes, in the case of maximum reduction precipitation could lead to a fall of about 1 m below the minimum recorded level.

Goma (1989) examined the 50 years data from 1937-1988 to access any effect of climate variation on public water supply in Zambia. He opined that at the moment the weather fluctuations do not affect the water supply from the main source public water reservoir.

2.5.3 Water resource changes in large regions

Linz et al. (1990) reviewed the impact of climatic change due to greenhouse warming on hydrology and water resource changes in large regions and countries .The most probable tendencies in the changes of water resources for certain regions are as follows :

Pacific Northwest	:	some increase in annual runoff and floods
California	:	increase in winter and decrease in summer runoff with insignificant rise in annual runoff
Colorado and Rio Grande river basins ,the great basin	:	decreasing runoff
Great Lakes basin	:	decreasing runoff
Great Plains ,northern and southeastern States	:	uncertain changes in water resources
Northern Africa ,Sahel, Western Eurasia, USSR,most regions of Australia and New Zealand	:	increasing runoff
Central European USSR and western Siberia		decreasing trend

Linz et. al.(1990) also presented the case studies of impacts in critical or sensitive environments as large water

Table 9 - Case studies of impact of climatic change on hydrology for critical or sensitive environments

Critical or sensitive environment	Region	Future changes	Remarks
Large water bodies	Great Lakes basin(US/ Canada)	decrease in precipitation	lake levels expected to be lower and hence navigation would be affected.
		decrease in runoff	
	The Caspian Sea	The dynamics of the sea would change in 15 - 20 years	
Critical agricultural regions	South Platte river basin	less certain consequences of global warming, increases or very large decreases in precipitation.	
	Murray-Darling basin	precipitation increases in spring autumn and summer.	slight reduction in demand for irrigation water
Intensively urbanized areas	Delaware river basin, USA	Probability of occurrence of drought	
Regions of snowmelt generated runoff	The Sacramento-San Joaquin River basin (USA)	Total annual runoff to remain near current levels or to increase	
		Higher runoff in winter months and considerably less in the spring snowmelt - runoff season.	

bodies,critical agricultural regions ,intensively urbanised areas and regions of snowmelt generated runoff . The results are presented in tabular form in Table 9.

2.6 Climatic change and its effect on evaporation and evapotranspiration

Evapotranspiration (ET) is the major component of the water budget after precipitation. It is a compound term which describes two processes which occur simultaneously - evaporation from the soil surface and the canopy, when it is wet, and transpiration, the vaporisation at the leaf surface of the water extracted from the soil by the plant. There are three necessary prerequisites for the evapotranspiration to occur. These are - a source of water, energy to drive the phase change and a sink for water or the moisture deficit in the air above ground.

The surface warming due to enhanced greenhouse effect is likely to alter the evapotranspiration patterns. However, the way in which ET may change due to climatic change is rather complicated. This is because the greenhouse effect is accompanied by changes in cloudiness- and hence radiation, windiness and humidity besides temperature; which affect the above three prerequisites. The climatic changes may alter the plant growth, plant cover of the ground and also the deeper or shallower rooting, which, in turn, also affect ET. Furthermore, it is important to note that carbondioxide affects the plant physiological conditions specially the plant growth and the resistance to the passage, of water to the atmosphere through plant.

Evapotranspiration studies as a consequence of climatic changes have been made by different workers. In these studies ET has been considered as a function of temperature (Revelle and Waggoner, 1983; Gleick, 1987), or a function of the carbondioxide effects on plant resistance (Idso and Brazel, 1984) and using micrometeorological and physiological measurements (Martin et al, 1989)

Aston (1984) used a distributed deterministic process model WATSIM (Aston and Dunin, 1980) to simulate the effects of changed stomatal resistance (the stomatal resistance rises with CO_2 increase) on streamflow of a 5 ha experimental catchment. The evaporation was computed using the combination formulae (Statver and Mc Ilnoy, 1961; Monteith, 1965)

$$EP = [S/(S+\gamma)](R-G) + (\rho\ Cp/ra)\ (T-T_w) \qquad (2.6.1)$$

and

$$ET = EP/[1+\gamma/(s+\gamma)\ (r_c\ /r_a)] \qquad (2.6.2)$$

Where ; EP - potential evaporation,

ET - actual evaporation,

s - slope of the saturation vap. pressure curve

γ - psychrometric constt.

R - net radiation

G - ground heat flux

ρ - air density

C_p - heat capacity of air at constt. pressure

T & Tw - ambient dry & wet bulb temp.

r_a & r_c - aerodynamic and canopy resistances respectively

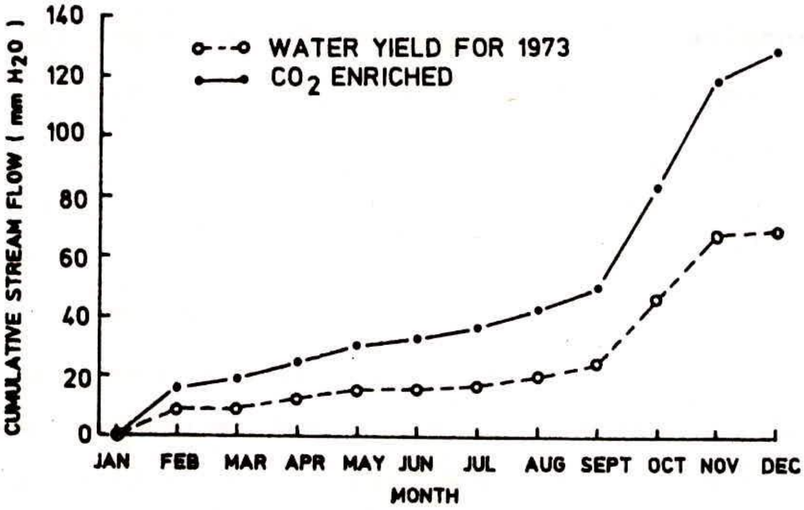


FIG. 17 - SIMULATION OF IMPACT OF CO_2 INCREASE ON CATCHMENT YIELD IN 1973 (ASTON , 1984)

Figure 17 shows the results of simulation of the impact of CO_2 increase on catchment water yield in 1973. The months with small to intermediate yields were relatively more sensitive to CO_2 increase as the evaporation process was limited by the soil moisture.

Aston (1984) simulated a large catchment area (417 km^2) using a hydrological model SHOLSIM evolved from WATSIM. The major difference between the two was in the formulation of evapotranspiration. In SHOLSIM, ET was expressed as a ratio of class A pan evaporation and related to the absolute values of soil moisture content:

$$ET/Pan = S_p (\theta - \theta_w)$$

Where, S_p is the empirically derived slope of the relationship between pan ratio and moisture content for a given vegetation type ,θ and θ_w are the volumetric soil moisture content and moisture content at 15 atm. respectively and Pan is the evaporation from the class A pan evaporimeter. A doubling of resistances in Eq. (2.6.2) resulted in a reduction of ET of around 20-40%, depending on ambient conditions. The present level of water yield of both small and large catchments can significantly increase due to doubling of CO_2 concentrations.

Bultot et al. (1988) evaluated quantitatively the impact of the CO_2 doubling on the annual regime of the effective evapotranspiration and other energy balance components. They used IRMB conceptual daily step model (Bultot and Dupriez, 1976 a, b, 1985) to simulate the daily effective evapotranspiration for a drainage basin in Belgium. Besides daily effective evapotranspiration, the model quantitatively

Table 10 : Climatic and hydrological variables under scenario 0 and scenario 1 (Bultot et al, 1988)

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Potential evapotranspiration (mm d^{-1})													
ETP_0	0.149	0.373	0.805	1.768	2.744	3.130	3.132	2.721	1.881	0.890	0.258	0.167	1.507
ETP_1	0.211	0.551	1.061	2.069	2.950	3.377	3.337	2.997	2.015	0.995	0.359	0.233	1.685
ΔETP	0.062	0.178	0.256	0.301	0.206	0.247	0.204	0.276	0.134	0.105	0.101	0.067	0.178
$\Delta ETP/ETP_0$	42%	48%	32%	17%	8%	8%	7%	10%	7%	12%	39%	40%	12%
Effective evapotranspiration (mm d^{-1})													
ET_0	0.149	0.370	0.793	1.690	2.608	2.778	2.766	2.266	1.611	0.834	0.255	0.167	1.362
ET_1	0.211	0.546	1.042	1.965	2.773	2.936	2.868	2.391	1.655	0.920	0.353	0.233	1.496
ΔET	0.062	0.176	0.249	0.275	0.165	0.158	0.102	0.125	0.044	0.086	0.098	0.066	0.134
$\Delta ET/ET_0$	42%	48%	31%	16%	6%	6%	4%	6%	3%	10%	38%	40%	10%
ET_0/ETP_0	100%	99%	99%	96%	95%	89%	88%	83%	86%	94%	99%	100%	90%
ET_1/ETP_1	100%	99%	98%	95%	94%	87%	86%	80%	82%	92%	98%	100%	89%
Water vapour pressure (hPa)													
e_0	5.96	5.98	6.58	7.46	10.14	12.62	14.09	13.98	11.89	9.55	7.46	6.38	9.36
e_1	7.42	7.60	8.32	9.21	12.19	15.00	16.51	16.18	13.82	11.44	9.05	7.99	11.25
Δe	1.46	1.62	1.74	1.75	2.05	2.38	2.42	2.20	1.93	1.89	1.59	1.61	1.89
$\Delta e/e_0$	24%	27%	26%	23%	20%	19%	17%	16%	16%	20%	21%	25%	20%
Temperature (°C)													
t_0	0.7	1.4	3.4	6.1	10.9	14.0	15.7	15.3	11.8	8.0	3.9	1.6	7.8
t_1	3.8	4.8	6.8	9.2	13.7	16.7	18.2	17.6	14.1	10.7	6.7	4.3	10.6
Δt	3.1	3.4	3.4	3.1	2.8	2.7	2.5	2.3	2.3	2.7	2.8	3.2	2.8
Precipitation (mm d^{-1})													
P_0	3.47	3.42	3.35	2.37	3.07	2.62	2.74	2.12	2.71	2.31	4.77	3.77	3.06
P_1	3.77	3.79	3.67	2.71	3.03	2.53	2.69	2.05	2.71	2.48	5.04	4.05	3.21
ΔP	0.30	0.37	0.32	0.34	−0.04	−0.09	−0.05	−0.07	0.00	0.17	0.27	0.28	0.15
$\Delta P/P_0$	9%	11%	10%	14%	−1%	−3%	−2%	−3%	0%	7%	6%	7%	5%
ET_0/P_0	4.3%	10.8%	23.7%	71.2%	84.9%	106.0%	100.9%	106.9%	59.4%	36.1%	5.3%	4.4%	44.6%
ET_1/P_1	5.6%	14.4%	28.4%	72.5%	91.5%	116.0%	106.6%	116.7%	61.1%	37.1%	7.0%	5.8%	46.7%
Water content of the upper layer of the unsaturated zone (percentage of values at saturation) – Maximum water capacity: WSX = 23 mm													
WS_0/WSX	100%	98%	91%	71%	66%	54%	54%	54%	59%	82%	98%	100%	77%
WS_1/WSX	100%	96%	88%	69%	63%	50%	51%	49%	56%	80%	97%	99%	75%
Water content of the lower layer of the unsaturated zone (mm and percentage of values at saturation)													
WIX	194.1	194.1	195.1	198.7	203.6	208.5	211.1	210.0	205.3	201.0	196.8	193.9	201.0
WI_0/WIX	100%	100%	100%	97%	91%	83%	78%	74%	72%	80%	93%	100%	89%
WI_1/WIX	100%	100%	99%	96%	89%	79%	73%	68%	65%	74%	90%	100%	86%

estimated the annual regimes of net terrestrial radiation and net radiation for the 2xCO_2 case and on the basis of a ten year period daily data for the Semois drainage basin.

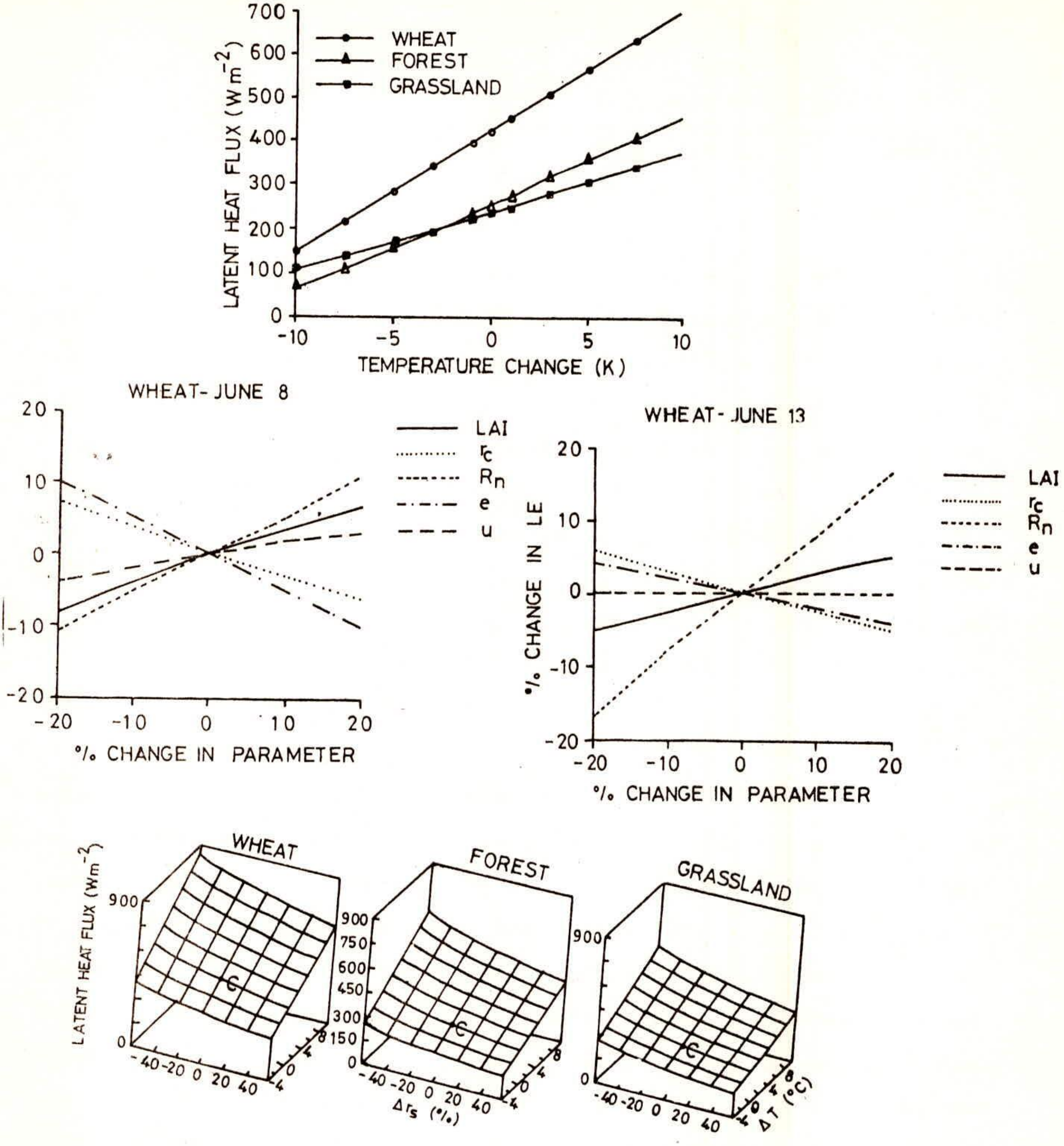
The compared regimes of the evapotranspiration and of other climate and hydrological variables under the present climatic conditions (scenario 0) and assuming a doubling of the atmospheric CO_2 concentration (scenario 1), as studied by Bultot et al (1988) are given in Table 10 . The potential evapotranspiration increases in all seasons, as one goes from scenario 0 to scenario 1; the maximum and minimum being during April (0.3 mm d^{-1}) and January (0.06 mm d^{-1}) respectively. However. in relative values the rise is greatest during winter months the reason being the smallness of the corresponding present day ETP values. In response to the increased potential evapotranspiration, the effective evapotranspiration also augments, though not in the same ratio. This is because in scenario 1, the rainfall is lowered during the late spring and summer and the water supply from the soil cannot meet fully the evapotranspiration requirements.

Martin et al. (1989) studied the sensitivity of evapotranspiration in a wheat field, a forest and a grassland to changes in climate and direct effects of carbon dioxide. They used the Penman Monteith equation (Monteith, 1965) to estimate the evapotranspiration, which has been successfully used to evaluate the ET from crops and forests by Rosenberg et al. (1983). The P-M approach incorporates micro meteorological and physiological parameters and is best used at local level, and with the time scales of the order of a day. It has been found suitable for simulation studies as well (Stewart, 1984). The P-M equation for the latent heat flux, LE, as used by Martin et al. (1989), is expressed as -

$$LE = \frac{s(R_n+S) + \rho_a C_p(e_s-e)/r_a}{s + \gamma \left(\frac{r_a+r_c}{r_a}\right)} \qquad (2.6.3)$$

Where L is the latent heat of vaporization in J kg^{-1}, E the flux of evaporated water in kg $m^{-2}s^{-1}$, R_n the net radiation in W m^{-2}, S the soil heat flux in W m^{-2}, ρ_a the density of dry air in kg m^{-3}, r_a and r_c, the aerodynamic and canopy resistances in sm^{-1}, C_p the specific heat of dry air at constant pressure in J $kg^{-1}K^{-1}$, e_s the saturation partial pressure of water vapour at leaf temperature, e the actual vapour pressure in the air above the canopy, both in Pa, and, s and γ are the derivative of the saturation vapour pressure with respect to temperature and the pyschrometric constt. respectively, both in Pa K^{-1}

Martin et al (1989) calculated the LE flux using actual weather and plant parameter values as temperature, net radiation, air humidity, wind speed, leaf area index, characteristic leaf dimension and stomatal resistance. Then, to test the sensitivity of ET to each individual climate and plant factor, each factor was changed one at a time, twice at a time and then in groups. The range of changes in climatic parameters was obtained from Schneider et al.(1989) and for the physiological changes the values found in Rosenberg et al(1983) were chosen. These changes were ;temperature from -10K to +10K, net radiation from -30 to +30%, absolute humidity from -20 to +20%, wind speed from -20 to +20%, leaf area index from -30 to



C - CONTROL CASE

FIG. 18 - SENSITIVITY OF LATENT HEAT FLUX TO CHANGES IN LEAF AREA INDEX, STOMATAL RESISTANCE, SOLAR RADIATION, HUMIDITY & WIND SPEED (MARTIN et al , 1989)

Table 11 : Sensitivity of evapotranspiration to climate change and direct effects of CO_2 in a wheat field, a forest and a grassland (Martin et al, 1989)

	Change in					Wheat		Forest (avg. all days)		Grassland		Notes
Line no.	T (K)	R_n (%)	e (%)	r_s (%)	LAI (%)	LE ($W\ m^{-2}$)	Change (%)	LE ($W\ m^{-2}$)	Change (%)	LE ($W\ m^{-2}$)	Change (%)	
1	3	10	−10	0	0	562	33	350	40	302	29	*Climate Change Scenario I* 1) Climate change only
2	3	10	−10	20	0	528	25	321	28	276	18	2) Climate change + stomatal resistance increase
3	3	10	−10	40	0	499	18	298	19	254	9	
4	3	10	−10	60	0	473	12	277	11	235	1	
5	3	10	−10	0	15	589	39	372	49	321	38	3) Climate change + leaf area index increase decrease
6	3	10	−10	0	−15	530	25	324	30	279	20	
7	3	10	−10	20	15	556	31	343	37	295	27	4) Climate change + change in stomatal resistance and leaf area index
8	3	10	−10	20	−15	496	17	297	19	253	9	
9	3	10	−10	40	15	527	24	319	27	273	17	
10	3	10	−10	40	−15	466	10	273	9	232	−1	
11	3	10	−10	60	15	501	18	298	19	254	9	
12	3	10	−10	60	−15	440	4	254	1	214	−8	
13	3	−10	10	0	0	455	7	272	9	246	6	*Climate Change Scenario II* 1) Climate change only
14	3	−10	10	20	0	428	1	250	0	225	−3	2) Climate change + stomatal resistance increase
15	3	−10	10	40	0	404	−5	232	−7	207	−11	
16	3	−10	10	60	0	383	−10	216	−14	192	−18	
17	3	−10	10	0	15	477	13	290	16	262	12	3) Climate change + leaf area index increase/ decrease
18	3	−10	10	0	−15	429	1	253	1	227	−2	
19	3	−10	10	20	15	450	6	267	7	241	3	4) Climate change + change in stomatal resistance and leaf area index
20	3	−10	10	20	−15	401	−5	231	−8	206	−11	
21	3	−10	10	40	15	427	1	248	−1	223	−4	
22	3	−10	10	40	−15	377	−11	213	−15	189	−19	
23	3	−10	10	60	15	406	−4	232	−7	208	−11	
24	3	−10	10	60	−15	356	−16	197	−2	174	−2	

+30% and stomatal resistance from -60 to +60% . Figs. 18(a,b,c,d) show the sensitivity of latent heat flux to the changes in the above parameters. Table 11 gives the simulated effects of climatic change on LE, when various parameters are changed simultaneously. These studies showed that when all the climatic and plant factors are considered evaporation estimates can differ greatly from those that consider only temperature.

3.0 REMARKS

The earth's radiation balance is governed by various greenhouse gases viz. carbondioxide ,methane , nitrousoxide, chlorofluorocarbons. Thus,the increasing concentrations of these gases will affect the radiation balance of the earth and hence the climate appreciably.Studies in the recent past have provided evidence that a warming of about 0.7 - 2 °C of earth's surface has taken place upto the early eighties and at current rates of emissions ,the global warming will increase by 0.2 - 0.5 °C every decade. Consequently , precipitation and other meteorological parameters will be affected .However, the exact magnitude of the changes in these parameters as predicted by General Circulation Models is still uncertain,specially for regional scale.

The analysis of mean annual temperature for India during the period 1901-1982 has indicated that about 0.4 °C warming has taken place during recent 8 decades .The studies on precipitation fields for India have not led to inference of any significant trend.

The changes in meteorological parameters will result in alterations in the hydrological parameters The forecasts of changes in climatological parameters ,specially temperature and precipitation are needed to evaluate the hydrological effects of increasing greenhouse gases .For assessment of changes in hydrological parameter on a regional scale ,the scenarios of future climatic changes are used.Studies have been carried out on hydrologic consequences of future climatic changes using various methodological approaches.These include the analysis of long term variations in runoff and meteorological elements over the past years ,use of water balance methods over a long period of time and use of deterministic hydrological models.

The surface warming due to increase in greenhouse gases is likely to alter the evaporation (EV) and evapotranspiration (ET) patterns ,which is a major component of water budget after precipitation .The way in which ET may change is complicated as it depends on radiation ,windiness ,and humidity besides temperature,all of which are expected to change due to enhanced greenhouse effect .The climatic changes may affect the plant growth ,plant cover and plant rooting and therefore ET .The increasing concentrations of carbon dioxide will also affect plant physiological parameters.

Though,the studies have been carried out on hydrological impacts of climatic changes in different countries ,the studies in this direction in India have yet to start . Some studies have been initiated at National Institute of Hydrology ,Roorkee to examine the sensitivity of evaporation and evapotranspiration to expected climatic changes for different agroclimatic zones of India. The results will be reported elsewhere.

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