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Economic Commission for Latin America and the Caribbean

**CLIMATE CHANGE AND WATER MANAGEMENT IN
LATIN AMERICA AND THE CARIBBEAN */**

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INTRODUCTION

The possibility of global warming is arguably one of the most challenging problems facing the users of water resources in Latin America and the Caribbean. The issue touches potentially every aspect of water use in the region. Many countries could experience serious changes in water availability and quality. Even in the areas where precipitation might increase, its positive effects may be more than offset by seasonal changes in run-off and even more by increases in demand and evaporation due to higher temperatures. The frequency, intensity and spatial distribution of floods, drought, tropical cyclones and other weather extremes could change. The impact of climate change would be greatest in areas of water scarcity, heavy pollution, or hazardous weather extremes.

Many important decisions made on water resource projects rely on the assumption that past climatic data serve as a reliable guide to the future. If there are strong grounds to believe that the climate will change during the life time of most hydraulic structures, future engineering design procedures will have to accommodate the expected change in climatic and hydrometeorological conditions over the life of the project.^{1/}

Large gaps still exist in the information available and in the analysis of the sensitivity of water use patterns to climatic change in developing countries, including Latin America and the Caribbean. The objective of this report is to explore the most significant possible impacts of global climate change on water use in Latin America and the Caribbean. Although, there remains considerable uncertainty about projected climate changes, the responsible course of action today is to examine how climate change might affect patterns of water use in the region. The countries of the region need to know the possible consequences of climate change to be able to adopt adequate response measures. The regional economies could be relatively more vulnerable to global climate change, because a greater percentage of their gross national product depends on climate-sensitive and water-related branches of economy.

Since the problem of global climate change was first placed on the agenda of global environmental problems, there have been numerous attempts to critically evaluate the predictions for climate change and its possible impact. The Intergovernmental Panel on Climate Change (IPCC), created in 1988 under the auspices of the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) undertook one of the latest and most detailed assessments. The report of the IPCC assessed the likelihood, magnitude and rate of global climate change; the resulting impacts; and possible policy responses and their implications. This study draws heavily on the work of the IPCC.

The investigations of the IPCC suggest that present trends could increase the present global mean temperature by about 1°C by 2025 and 3°C before the end of the next century. There is some 4.5°C difference between the current mean global temperature and that during the last ice age, about 20 000 years ago. A worldwide (eustatic) average sea-level rise per decade of some 6 centimetres over the next century could accompany the increase in temperature. There remain, however, many uncertainties both regarding the timing, magnitude and regional patterns of climate change and of its significance.^{2/}

Two things put current concerns about the possibility of greenhouse warming in an entirely different category from past climate change. **First**, It could cause a warming exceeding that experienced in the last 100 000 years. **Second**, while the greenhouse effect could raise temperatures several degrees Celsius in less than a century, when past climate changes of comparable magnitude have occurred over tens of thousands of years.^{3/} A major difference between predicted current climate change and past changes is the rate of change, forecast to be 15 to 40 times faster than in past warming periods.^{4/}

Global climate change of the forecast magnitude would be certain to have major impacts on the hydrologic cycle. The Second World Climate Conference noted that: "Among the most important impacts of climate change will be its effects on the hydrological cycle and water management systems, and, through these, on socio-economic systems".^{5/} Climate change would cause alterations in global temperature and precipitation patterns, the timing and magnitude of run-off, evapotranspiration rates, the seasonal nature of most hydrologic processes, and the frequency and intensity of extreme weather events, such as tropical cyclones, floods and droughts. All these factors would have major impacts on both the availability and the quality of water resources.

Because of inadequate data and the uncertainties regarding global warming, sea-level rise, stratospheric ozone layer depletion and future trends in water resource use and economic and social development, the discussion in this report deals with possibilities, not forecasts.

This report summarizes the most commonly held and generally accepted findings of the scientific community. However, it is important to note that there are scientists who maintain that the effects of climate changes could be much greater, more rapid, and consequently more catastrophic, especially if we do not take urgent measures to drastically reduce or at least stabilize the current levels of emissions of greenhouse gases. On the other hand, there is another body of scientific opinion that maintains that climate change will be minor, possibly "lost in the noise" of other social changes and any possible effects beneficial.

Chapter I

GLOBAL CLIMATE CHANGE

A. "Greenhouse" warming

It is estimated that the mean surface temperature of the earth has increased by between 0.3°C and 0.6°C over the past 100 years (Figure 1), and the years 1990 and 1991 were the warmest years on record, following previous records in 1988, 1987, 1983, 1989 and 1981.^{6/} Other evidence cited in support of global warming includes the substantial, but not continuous, recession of mountain glaciers, which has occurred almost everywhere since the latter half of the nineteenth century, the reduction of the extent of Antarctic sea-ice (Figure 2), and higher sea surface temperatures in many tropical regions over the last decade.^{7/} However, many scientists find that there is no significant evidence of any rise in temperature during the past 100 years.

There is no firm evidence that climate has become more variable over the last decades, neither is there a consensus on whether mean surface temperature has increased globally or not. Some scientists consider that the observed global temperature increase is consistent with, and represents, greenhouse warming, others disagree indicating that natural climate variability could account for the observed temperature increase.^{8/} A recent analysis of the first ten years (1979 to 1988) of satellite measurements of lower atmospheric temperature changes revealed large temperature variability on time scales from weeks to several years, but no obvious trend for the 10-year period.^{9/}

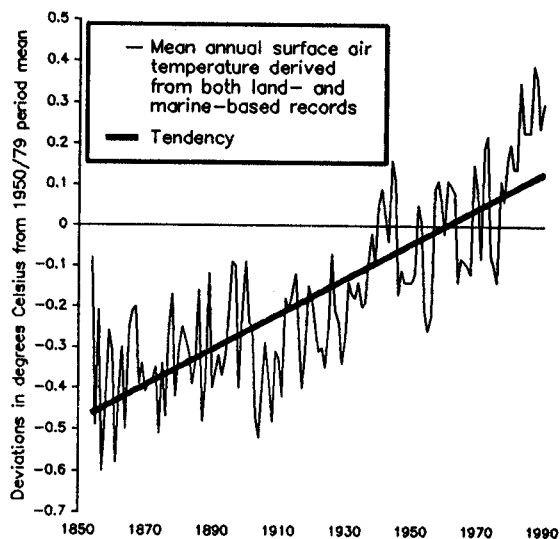
Some scientists argue that sunspot activity could explain the variations in global temperature, not trace gas concentrations.^{10/} Still other have recently suggested that carbon dioxide emissions might not lead to global warming, but to global cooling, potentially even to another Ice Age.^{11/} Some physicists, for example, have concluded that global cooling is occurring, arguing that the albedo (reflectivity of solar radiation) effect caused by changes in the optical properties of clouds exceeds the greenhouse effect.^{12/}

1. What causes global warming?

The greenhouse effect of the atmosphere plays a vital role in the energy balance of the earth and it is essential to the survival of life. Without it, the earth would be some 33°C cooler having an estimated global mean temperature of -18°C as opposed to a current mean of +15°C, and life, as we know it, would not exist.^{13/} The essence of the greenhouse effect is that about 30% of the average 342 watts per square metre of solar radiation reaching the outer layer of the earth's atmosphere is reflected back into space, while the remainder is absorbed in the atmosphere and on the surface.^{14/} Once heated, the earth-atmosphere system begins to emit spacewards thermal radiation, most of it infrared. The cloud cover and certain gases are capable of absorbing radiation in the infrared band.

Figure 1

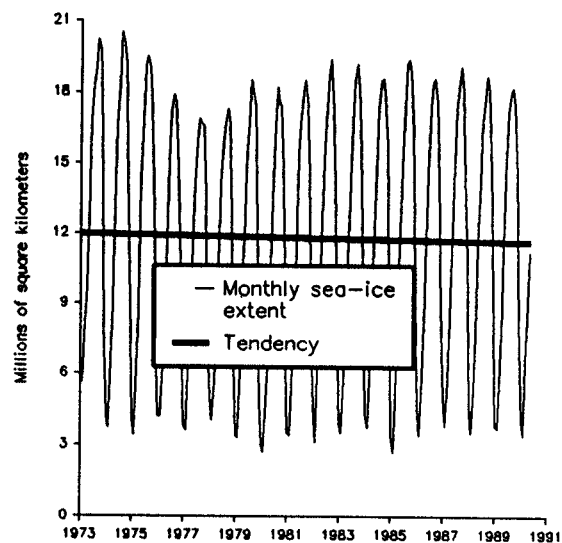
Trends in the Southern Hemisphere mean annual surface air temperatures, 1854-1990



Source: P.D. Jones, T.M.L. Wigley and P.B. Wright, "Global temperature variations between 1861 and 1984", *Nature*, 1986, and P.D. Jones, University of East Anglia, 1990, from UNEP, Environmental data report, 1991.

Figure 2

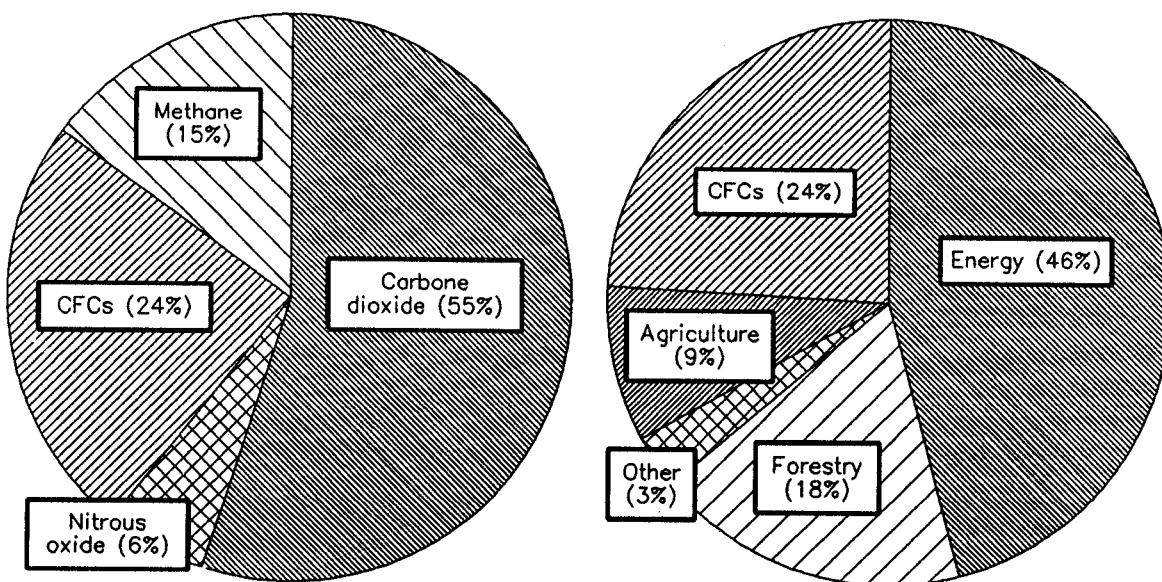
Antarctic sea-ice, 1973-1990



Source: C.F. Ropelewski, 1990, NOAA/CAC, from UNEP, Environmental data report, Third Edition, 1991, p. 137.

Figure 3

Estimated contribution of different anthropogenic greenhouse gases and human activities to the change in radiative forcing, 1980-1990



Source: Intergovernmental Panel on Climate Change (IPCC), Policymakers summary of the scientific assessment of climate change, 1990; and IPCC, Policymakers summary of the formulation of response strategies, 1990.

Note: The contribution from ozone may also be significant, but cannot be quantified at present.

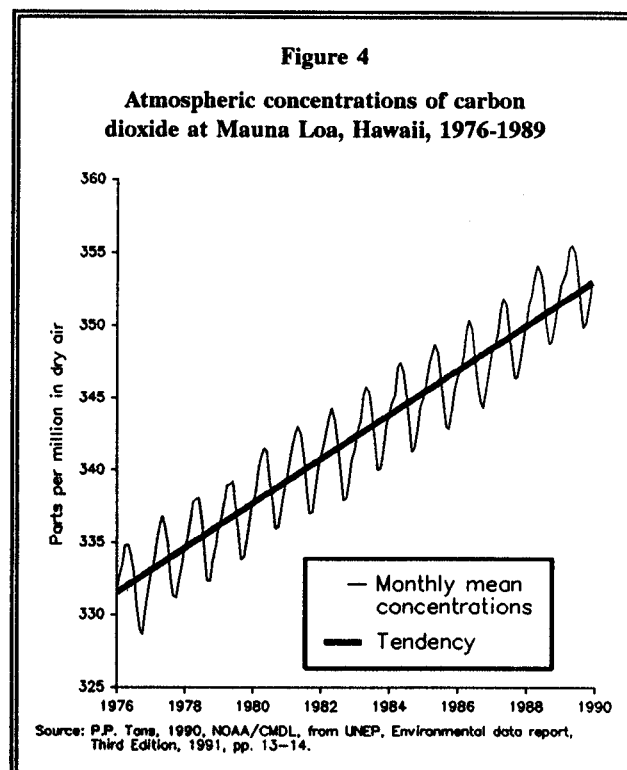
These gases, water vapour, carbon dioxide, nitrous oxide, methane, lower atmosphere ozone, chlorofluorocarbons, among others, are referred to collectively as "greenhouse" gases, but are also known as radiatively important or radiatively active gases. Carbon monoxide and nitrogen oxides are also sometimes included in the list of greenhouse gases because they directly influence the concentrations of other greenhouse gases in the atmosphere.^{15/}

All greenhouse gases share one common property: they are transparent to incoming short-wave solar radiation, but strongly absorb and radiate long-wavelength infrared radiation emitted by the earth. Their presence in the atmosphere, therefore, changes the radiative balance of our planet exerting a warming or "greenhouse" effect. The warming effect of atmospheric water vapour is equivalent to an extra 100 watts per square metre of surface radiation, of carbon dioxide to 50 watts and of cloud cover to 30 watts.^{16/}

The greenhouse effect is both natural and induced. The natural greenhouse effect is the result of the natural atmospheric concentrations of greenhouse gases, commonly assumed to equal the concentrations observed during the pre-industrial period. The induced greenhouse effect, also known as climate or radiative forcing, is the result of additional greenhouse gases put into atmosphere by human activities, including energy production and use, industry, including the production and use of chlorofluorocarbons (CFCs), agriculture, and changes in land-use patterns, particularly, deforestation and the burning of biomass (Figure 3).

The interactions of the atmosphere, oceans and biosphere control the natural concentration of greenhouse gases in the atmosphere. Emissions of greenhouse gases from human activities, upset the natural balance, leading to a net increase in atmospheric concentrations enhancing the natural greenhouse effect. Past and continuing anthropogenic emissions of greenhouse gases may cause the global mean surface temperature to rise - the phenomenon popularly termed "global warming". The rate, magnitude and spatial distribution of the changes are far from certain, although most scientists agree that increased concentrations of greenhouse gases will provoke a change in global climate.

Concentrations of all the major greenhouse gases have increased markedly since the pre-industrial period. The atmospheric concentration of carbon dioxide is currently 356 parts per million by volume or 27% higher than in the period 1750-1800.^{17/} This is the highest level of carbon dioxide in the 160 000 years of records based on ice core samples.^{18/} Carbon dioxide concentration is rising at a rate of about 0.5% a year (Figure 4). Concentrations of the other greenhouse gases are also increasing. The concentration of methane is now almost 120% higher than in the pre-industrial period and is rising at about 0.9% a year. Atmospheric concentrations of nitrous oxide are 8% higher



than during the pre-industrial period and are rising at about 0.25% a year. Chlorofluorocarbons are entirely man-made and have been released into the atmosphere in quantity only since World War II. The present day atmospheric concentration of CFC-11 is 290 parts per trillion by volume and is rising at 4% a year. The atmospheric concentration of CFC-12 is 500 parts per trillion and increasing at 4% a year.^{19/}

Carbon dioxide is estimated to account for some 55% of the increase in the greenhouse effect over the 1980-1990 decade, methane for 15%, CFCs for 24% and nitrous oxide for 6% (Figure 3). The concentration of water vapour in the troposphere is determined within the climate system, and, on a global scale, is not affected by human sources and sinks, although it has the largest greenhouse effect. Water vapour will increase, however, as a result of warming and further enhance it.^{20/}

2. How quickly could the global climate change?

The equilibrium climatic conditions most commonly simulated with the help of general circulation models are those corresponding to a doubling of the carbon dioxide equivalent, the common point of reference for analyzing the extent and timing of global warming. These conditions correspond to a point, perhaps between the middle and end of the next century, where the combined radiative effect of carbon dioxide and other greenhouse gases will be double that of the pre-industrial value for carbon dioxide, about 560 compared to 275 ± 10 parts per million by volume.^{21/}

The intergovernmental Panel of Climate Change (IPCC) has developed 4 possible future scenarios for emissions of greenhouse gases (Box 1):

- **High Emissions "Business as usual" Scenario:** equivalent carbon dioxide concentrations reach a value double that of pre-industrial atmospheric concentrations of carbon dioxide by 2030.
- **Low Emissions Scenario:** equivalent carbon dioxide concentrations reach a value double that of pre-industrial atmospheric concentrations of carbon dioxide by 2060.
- **Control Policies Scenario:** equivalent carbon dioxide concentrations reach a value double that of pre-industrial atmospheric concentrations of carbon dioxide by 2090 and stabilize thereafter.
- **Accelerated Policies Scenario:** equivalent carbon dioxide concentrations stabilize at a level less than double pre-industrial atmospheric concentrations of carbon dioxide.^{22/}

An aggregation of national forecasts of emissions of carbon dioxide and methane to the year 2025 suggests global emissions some 10 to 20% higher than in the "Business as usual" scenario.^{23/} Other assessments delay carbon dioxide doubling, however, until after 2100.^{24/}

3. How is climate expected to change?

Two approaches are used to obtain quantitative and qualitative estimates of the future climatic changes associated with greenhouse warming. The first is the use of general circulation or three-dimensional mathematical models of the global climate system. The second is the use of past warming periods as an analogue of how future warming might affect regional climates. Each approach has advantages and disadvantages.

Box 1

The Intergovernmental Panel on Climate Change emission scenarios

The Response Strategies Working Group of the IPCC formed an expert group to develop scenarios for future emissions of greenhouse gases. These scenarios depict the different ways that future emissions of greenhouse gases might evolve over the next century and serve to illustrate the types of changes needed to stabilize emissions while continuing to allow growth and improvement in the standard of living.

2030 High Emissions Scenario

This scenario depicts a world in which few or no steps are taken to reduce emissions. Continued population and economic growth produce increases in the use of energy and in the rate of clearing of tropical forests. The Montreal Protocol comes into effect but without strengthening and with less than 100% compliance. Fossil fuels continue to dominate energy supply with coal taking a much larger share of energy supply in the future. Emissions of greenhouse gases increase continuously throughout the next century with emissions of carbon dioxide doubling within 40 years. Emissions of many of the chlorofluorocarbons stabilize and decline due to compliance to the Montreal Protocol but emissions of substitutes such as HCFC-22 increase. These increases yield increases in atmospheric concentrations of greenhouse gases with an equivalent effect to a doubling of carbon dioxide concentrations from pre-industrial levels by 2030 and continued increase throughout the rest of the next century.

2060 Low Emissions Scenario

This scenario portrays a world in which a number of environmental and economic concerns result in steps to reduce the growth of emissions. Energy efficiency improves and there is a universal adoption of emission controls, reducing emissions of carbon and nitrous oxides. The share of primary energy provided by natural gas increases. There is full compliance with the Montreal Protocol. There is a halt to tropical deforestation and global reforestation begins. These steps reduce growth in emissions by 50 to 75% and significantly slow down the growth in atmospheric concentrations of greenhouse gases. Carbon dioxide emissions do not double until 2100, but, by 2060, the equivalent greenhouse effect to a doubling of carbon dioxide concentrations over pre-industrial levels is

reached and emissions continue to grow, albeit at a slower rate than in the first scenario.

Control Policies Scenario

This scenario reflects a future where concern over global climate change and other environmental issues, such as stratospheric ozone layer depletion, motivate steps beyond those taken in the *2060 Low Emissions Scenario*. Technological development, commercialization, and government efforts result in rapid penetrations of renewable energy sources in the last half of the next century. There is a strengthening of the Montreal Protocol to include a full phase out of CFCs and freezes on methyl-chloroform and carbon tetrachloride. Agricultural policies yield reduction in emissions of greenhouse gases from enteric fermentation in domestic animals, from rice paddies, and from fertilizer. Emissions of carbon dioxide, nitrous oxide and methane grow slowly through the middle of the next century then start to decline. Emissions of carbon and nitrous oxides decline sharply along with emissions of CFCs. These trends yield increases in atmospheric concentrations of greenhouse gases equivalent to slightly less than a doubling of carbon dioxide from pre-industrial levels by 2090 with concentrations stable thereafter.

Accelerated Policies Scenario

This scenario is similar to the Control Policies Scenario but features much more rapid development and penetration of renewable energy sources encouraged in part by a worldwide adoption of carbon fees. Biomass energy represents 10 to 25% of primary energy supply by 2025, depending on economic growth assumptions. Carbon emissions from energy continue to increase through 2000 while total emissions of carbon decline, due to the sequestering of carbon through reforestation. After 2000, carbon emissions from all sources decline through the next the century to levels less than half those in 1985. Atmospheric concentrations of greenhouse gases continue to increase but stabilize by the middle of the next century at levels 25% greater than current levels but well below an equivalent doubling of carbon dioxide over pre-industrial levels.

Source: WMO/UNEP/IPCC (World Meteorological Organization/United Nations Environment Programme/Intergovernmental Panel on Climate Change) (1990), *IPCC Working Group III (Response Strategies). Emissions Scenarios. Draft Report of the Expert Group on Emissions Scenarios*, April.

General circulation models are considered the better tool, but they are not yet capable, due to their coarse spatial resolution and other limitations, of reliable global climate change predictions, let alone regional projections. Their results do not represent, therefore, scientific proof of climate change and must be treated with extreme caution. The results obtained are only possibilities and in no way represent a prediction and still less a forecast.^{25/}

General circulation models divide the global atmosphere into tens of thousands of discrete boxes and use dynamic equations of motion, energy, and mass to project the changes in winds, pressure, and water vapour mixing ratio. The vertical domain of a typical general circulation model consists of from 2 to 20 computational levels and extends from the earth's surface to about 35 kilometers, while the horizontal domain covers the planet with grid cells, each of which is several hundreds of kilometers on a side.^{26/} Their definition is too coarse to produce accurate representations of regional and local features of climate as these are strongly influenced by topography. They also have relatively simplistic parameters, including, but not limited to, convection, cloud cover, ocean circulation, and hydrologic interactions. In addition there remains considerable uncertainty about just how the biosphere will respond to global warming and increases in atmospheric concentrations of greenhouse gases.

The same limitations are essentially true of analogue forecasting which is frequently criticized because it is based on climatic cause and effect processes that could be very different from those operating today. Paleoclimatic analogues, based on prehistoric climates reconstructed from proxy data, constitute a useful source of data on possible directions of climate change, especially regionally. Knowledge of paleoclimates is, however, limited. The approach and the method suffer from high uncertainty due to the lack of quantitative and qualitative detail.

The overwhelming majority of current studies focus on the climate changes resulting from a doubling of the carbon dioxide equivalent. The difficulty with this approach is that if emissions of greenhouse gases continue to exceed sink capacity, as they may well do, concentrations will eventually more than double. This possible eventuality has not been systematically addressed.

Global circulation models usually simulate the equilibrium climatic response resulting from a one-time change in greenhouse gases concentrations, but in reality there would be a lag between changes in the concentration levels of greenhouse gases and changes in surface temperatures. The same is also largely true for empirical climate forecasting. This delay occurs because the earth's climate needs time to adjust to the additional heat retention caused by the enhancement of the greenhouse effect. The principal influence is the thermal inertia of the oceans, which slow climate change for between 10 and 20 years. On the other hand, lags in adjustments and the thermal inertia of the oceans mean that any atmospheric warming and associated climate change could take several decades, possibly centuries to reach equilibrium, and from this point of view, equilibrium experiments can be misleading if taken as forecasts of actual climatic change.^{27/}

The transient change due to the natural lags in the climate system is of particular importance for water resources. Different levels of global warming can have unlike, even opposite, implications for water availability. For example, while a warming of up to 1°C or so would produce drier conditions in many temperate areas, further warming up to 1.5°C would probably make some dry subtropical areas more humid and subtropical deserts would shrink on both sides of the equator. Further warming by 2.5°C would cause serious subtropical aridity while a 4.0°C increase would lead to desertification between 20°S and the equator and would make summer droughts become frequent

and increasingly severe in much of the temperate zone.^{28/} In the Amazon basin, to take one example, models indicate a possible increase in soil moisture if there is a doubling of carbon dioxide, but a deficit if it is quadrupled.^{29/} Most current studies assume that global mean temperatures would increase gradually and that climates would change slowly and little. In this sense, the models do not produce discontinuities, sudden unexpected changes, or catastrophes. There is evidence, however, that relatively fast climate changes could occur regionally.^{30/}

There is also a possibility that global warming may cause some atmospheric or oceanic circulatory systems to switch to alternative equilibria, producing regional changes that are both sudden and extreme. One of the major sources of discontinuous change lies in ocean behaviour. Changes in ocean circulation could produce pronounced local anomalies in sea surface temperatures particularly near major current systems or the main areas of deep water formation, with profound effects on the local climate.^{31/} There is some evidence that in earlier interglacial periods ocean currents may have pursued different courses.^{32/} Additionally, at the end of the last ice age, changes in the ocean circulation may have led to periods of comparatively rapid climate change. On the whole, the ocean circulation is still not well observed, understood or modelled.^{33/} If some of the currents in the oceans washing Latin America and the Caribbean switched into an alternative pattern, the subsequent changes in regional climate could be both sudden and severe.

The estimates of scientific confidence in projections of the climate response to increased greenhouse gas concentrations are presented in Tables 1 and 2. Ranges of possible climate changes reflecting current interpretation of state-of-the-art modelling results are provided in Table 3. These are believed to provide plausible estimates about the direction or magnitude of some important anthropogenic climatic changes over the next 50 years or so - a typical estimate for an equivalent doubling of carbon dioxide - together with a simple high, medium, or low level of confidence for each variable.^{34/}

(a) Surface air temperature changes

The projections made by the IPCC for its different emission scenarios (Box 1) are particularly useful for understanding the likely increase in the global mean surface temperature under a doubling of the carbon dioxide equivalent. Even the most optimistic of the scenarios implies an unprecedented increase in the global mean temperature within a shorter time span than ever before in the history of mankind.

- **High Emissions "Business as usual" Scenario:** Global mean surface temperatures are forecast to increase by between 0.2°C to 0.5°C per decade in the next century, producing a 1°C rise in temperature by 2025, and 3°C by 2100.
- **Low Emissions Scenario:** Global mean surface temperatures are expected to increase by 0.2°C per decade, producing a 2°C rise in temperature by 2100.
- **Control Policies Scenario:** Global mean surface temperatures would still rise, but by only slightly more than 0.1°C per decade.
- **Accelerated Policies Scenario:** Control measures would hold the global mean surface temperatures rise to about 0.1°C per decade.^{35/}

All models agree that the global surface air temperature will rise as a result of a doubling of the carbon dioxide equivalent. The lower atmosphere will also warm, but the stratosphere will cool. Most current models show that a doubling of the carbon dioxide equivalent would lead to a range of

Table 1
Scientific confidence in projections of the response of climate to increased concentrations of greenhouse gases

Climate change	Confidence of prediction	Notes
Large stratospheric cooling	Virtually certain	Reduced ozone concentrations in the upper stratosphere will lead to reduced absorption of solar ultraviolet radiation and therefore less heating. Increases in the stratospheric concentration of carbon dioxide and other radiatively active trace gases will increase the radiation of heat from the stratosphere. The combination of decreased heating and increased cooling will lead to a major lowering of temperatures in the upper stratosphere.
Global mean surface warming	Very probable	For an equivalent doubling of carbon dioxide, the long-term global mean surface warming is expected to range from 1.5°C to 4.5°C.
Global mean precipitation increase	Very probable	Increased surface heating will lead to increased evaporation and, therefore, to greater global mean precipitation. Some individual regions might well experience decreases in rainfall.
Reduction of sea ice	Very probable	As the climate warms, total sea ice is expected to be reduced.
Polar winter surface warming	Very probable	As the sea ice boundary is shifted poleward enhanced surface warming in winter polar regions is likely. Warming of the polar surface air may be as much as 3 times the global mean warming.
Summer continental dryness/warming	Likely in the long-term	Several studies have predicted a marked long-term drying of the soil moisture over some mid-latitude interior continental regions during summer. This dryness is mainly caused by an earlier termination of snowmelt and rainy periods, and an earlier onset of the spring-to-summer reduction of soil wetness.
High-latitude precipitation increase	Probable	As the climate warms, the increased poleward penetration of warm, moist air should increase the average annual precipitation in high latitudes.
Rise in global mean sea-level	Probable	A rise in mean sea-level is generally expected due to thermal expansion of sea water in the warmer future climate. Far less certain is the contribution from melting of land ice.

Source: NAS (National Academy of Science) (1987), Current issues in atmospheric change, National Academy Press, Washington, D.C., as quoted in US EPA (United States Environmental Protection Agency, Office of Policy, Planning and Evaluation, Office of Research and Development) (1988), The potential effects of global climate change on the United States. Draft. Report to Congress. Volume 1: regional studies, Joel B. Smith and Dennis A. Tirpak (editors).

Table 2
Confidence in the projections of the Intergovernmental
Panel on Climate Change (IPCC)

Climatic variable	Degree of confidence	O b s e r v a t i o n
<i>Temperature</i>	★ ★ ★ ★ ★	Warming of lower atmosphere and earth's surface.
	★ ★ ★ ★ ★	The stratosphere cools.
	★ ★ ★	Near the earth's surface, the global average warming is between +1.5°C and +4.5°C, with a "best guess" of 2.5°C.
	★ ★ ★	The surface warming at high latitudes is greater than the global average in winter but smaller than in summer.
	★ ★ ★	The surface warming and its seasonal variation are least in the tropics.
<i>Precipitation</i>	★ ★ ★ ★ ★	Increase in the global average precipitation, the larger the warming, the larger the increase.
	★ ★ ★	Increases at high latitudes throughout the year.
	★ ★ ★	Increases globally by 3 to 15% (as does evaporation).
	★ ★	Increases at mid-latitudes in winter.
	★ ★	The zonal mean value increases in the tropics although there are areas of decrease.
	★ ★	Changes little in subtropical arid areas.
<i>Soil moisture</i>	★ ★ ★	Increases in high latitudes in winter.
	★ ★	Decreases over northern mid-latitude continents in summer.
<i>Snow and sea-ice</i>	★ ★ ★ ★ ★	The areas of sea-ice and seasonal snow cover diminish.

Source: Mitchell, J.F.B., S. Manabe, V. Meleshko and T. Tokioka (lead authors); and G. Boer, H. Cao, S. Grotch, R. Haarsma, B. Hunt, R. Keshavamurty, G. Meehl, E. Oladipo, B. Pittock, D. Randall, D. Rind, C. Senior, R. Stouffer, K. Vinnikov and R. Wetherald (contributors) (1990), *Section 5. Equilibrium climate change and its implications for the future. Peer reviewed assessment for WG1 plenary*, April 28.

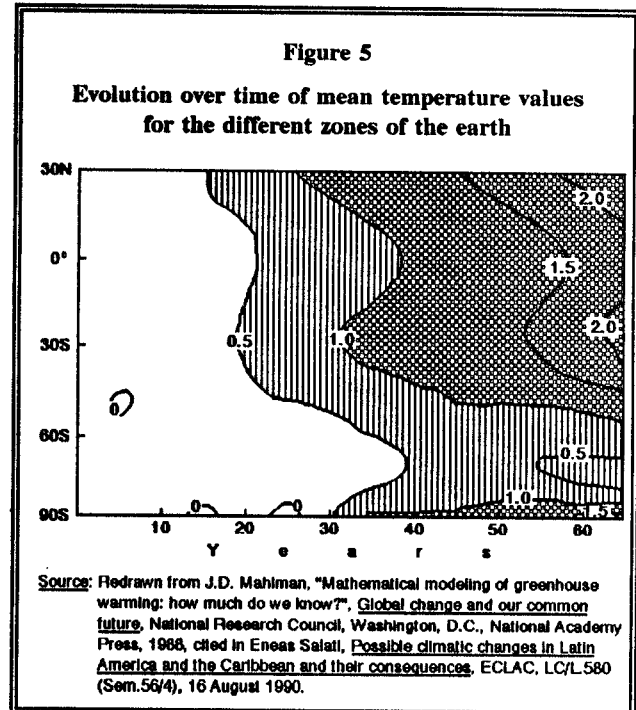
Table 3
Range of climate changes with a doubling of the carbon dioxide equivalent

Phenomena	Projection of probable global annual average change	Distribution of change		Interannual variability	Significant transients	Confidence of projection		Number of years for research to lead to consensus
		Regional average	Change in seasonality			Global average	Regional average	
Temperature	+2°C to +5°C	-3°C to +10°C	Yes	Down (?)	Yes	High	Medium	0-5
Sea-level	10 to 100 cm	n/a	No	?	Unlikely	High	Medium	5-20
Precipitation	+7% to +15%	-20% to +20%	Yes	Up	Yes	High	Low	10-50
Direct solar radiation	-10% to +10%	-30% to +30%	Yes	?	Possible	Low	Low	10-50
Evapotranspiration	+5% to +10%	-10% to +10%	Yes	?	Possible	High	Low	10-50
Soil moisture	?	-50% to +50%	Yes	?	Yes	?	Medium	10-50
Run-off	Increase	-50% to +50%	Yes	?	Yes	Medium	Low	10-50
Severe storms	?	?	?	?	Yes	?	?	10-50

Source: Schneider, Stephen H., Peter H. Gleick, and Linda O. Mearns (1990), "prospects for climate change", Paul E. Waggoner (editor), Climate change and U.S. water resources, Report of the American Association for the Advancement of Science Panel on Climate Variability, Climate Change and the Planning and Management of U.S. Water Resources, John Wiley & Sons.

increase in the global average equilibrium temperature of between 1.9°C to 5.2°C with most results being between 3.5°C and 4.5°C.^{36/} The new climate model of the Max Planck Institute in Hamburg, regarded by some as the most authoritative, projects increases in mean global temperature of 0.8°C to 2.9°C by the year 2085.^{37/} A temperature increase of this magnitude could be considered minor, but the difference in surface air temperature between winter and summer over the Southern Hemisphere is only around 5°C.^{38/} It is estimated that the earth's average temperature has risen only $0.45 \pm 0.15^\circ\text{C}$ since the late nineteenth century and is likely to have not varied more than from 1°C to 2°C in the last ten thousand years.^{39/}

Global warming will be unevenly spread over the globe and changes in surface air temperature will vary latitudinally (Figure 5). All models show enhanced warming in higher latitudes in late autumn and winter, although in high latitudes over the southern ocean, there is little or no warming at any time of the year in time dependent simulations.^{40/} Temperature increases at the poles would range from 200% to 300% of the global average while it would be only 50% to 100% of the average near the tropics.^{41/} The warming would be smaller than the global mean over sea-ice in the Arctic and around Antarctica in summer. The winter and annual average warming would be largest in high latitudes, but the summer warming is smaller than the annual average warming.^{42/} This would affect the annual temperature cycle in high latitudes. Temperature changes in lower latitudes would probably be somewhat smaller and slower again in comparison with the global averages.^{43/} A probable shift in ocean currents, however, could moderate the climate of certain high-latitude countries.^{44/}



Mean annual temperatures in the mid-latitudes, 30°S to 60°S, are estimated to rise by 2°C to 5°C.^{45/} In low latitude regions, they are expected to rise by 1.5°C. Warming may exceed 1.5°C in some semi-arid regions of low latitudes where soils are dry and there is, therefore, less compensation from evaporation.^{46/}

Any temperature increase would be somewhat slower and smaller in the Southern Hemisphere because of the greater thermal inertia of the oceans. Oceans comprise about 61% of the Northern Hemisphere and 81% of the Southern Hemisphere.^{47/}

In temperate zones, the winter periods could become shorter and warmer, while the summer periods could become longer and perhaps hotter.^{48/} Tropical warming could be both less than the global mean and to vary little with season being typically 2°C to 3°C. In tropical regions, global warming may increase evaporation from the oceans placing a limit on increases in temperature.^{49/} No seasonal changes in temperature are anticipated for tropical regions.^{50/} There is, however, evidence that climate changes would be smaller but quicker in equatorial areas than in temperate zones.^{51/}

In South America for the months of December, January and February, the temperature increase could range from 2°C for the Amazon region to 8°C for the southern cone (Figure 6). The increase could range up to 4°C in most regions of greatest agricultural production, including Argentina, Brazil, Chile, Uruguay and part of Paraguay.^{52/} In Mexico and Central America, the doubling of the carbon dioxide equivalent could increase air temperatures by 3.3°C to 5.4°C.^{53/}

Direct warming

Various human activities, especially those concentrated in urban areas, generate heat directly. These activities in combination with other human transformations of the natural environment associated with urbanization, construction of buildings and roads, removal of natural vegetation, etc., cause annual average surface air temperatures in urban areas to exceed those observed in adjacent rural areas, perhaps by as much as 1°C to 2°C or even more.^{54/}

This so-called "urban heat-island effect" has a number of other consequences. Specifically, it causes convection and other changes in the environment that have effects on wind, including the general reduction of wind speed, cloudiness, including contribution to fog formation, and enhanced cloud formation and rain, including rain enhancement over urban areas as well as over suburban or rural areas downwind.^{55/}

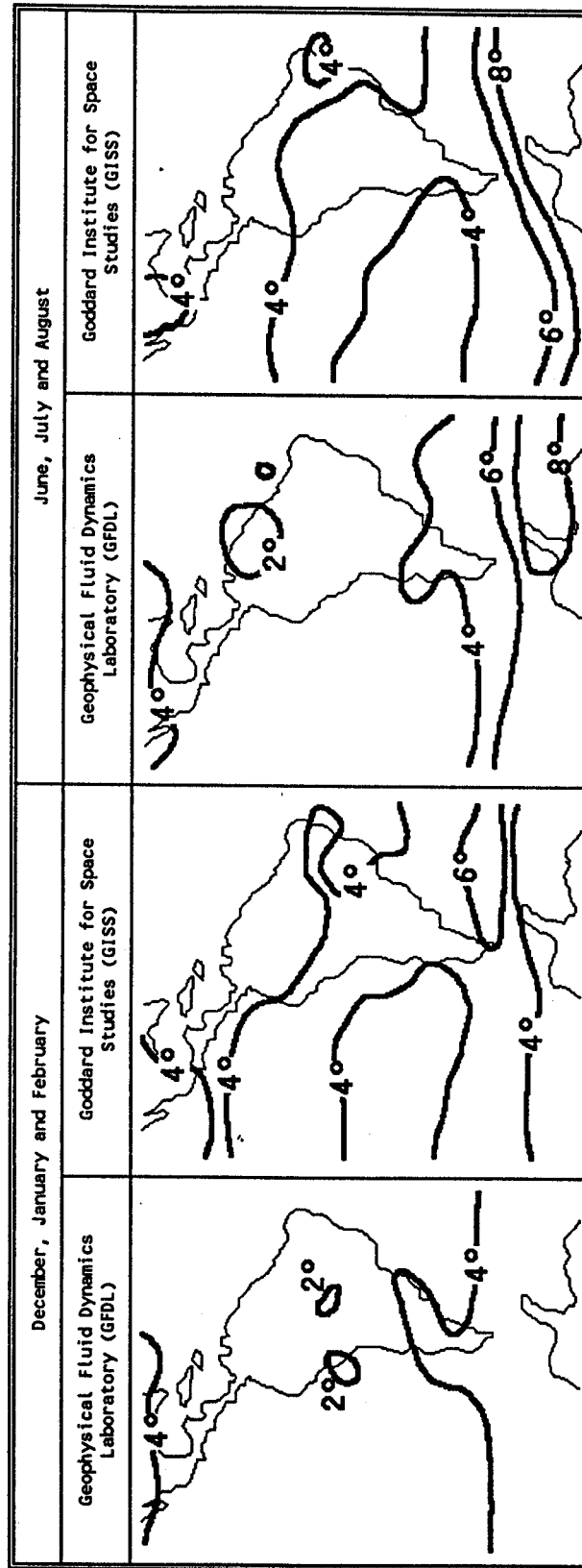
In 1990, 72% of the population of Latin America and the Caribbean, 448 million people, were urban dwellers.^{56/} From 1950 to 2000, according to ECLAC estimates, the urbanized area of Latin America and the Caribbean will have increased from 3 120 to over 27 400 square kilometers, almost 0.14% of the total surface area.^{57/} The continuing growth of urban areas is likely to cause a profound alteration in the local climate. It is quite possible that a temperature amplification as well as other changes in the urban environment, including those in wind, cloudiness, precipitation, etc., attributable to the heat-island effect might add in urban areas to the projected temperature increases from greenhouse warming.

(b) Changes in precipitation

It is more difficult to simulate changes in the hydrological cycle and the results of global circulation models are very crude and unreliable even at the world scale. The air temperature forecasts of the different climate models show agreement at least qualitatively, whereas for precipitation the results of even various versions of the same model often vary widely.^{58/}

An increase in the surface infrared flux would increase the energy available for evaporation.^{59/} Because capacity of the atmosphere to hold water vapour is an exponentially increasing function of temperature, global warming will lead to a fairly uniform increase in evapotranspiration and, therefore, potentially to soil drying. Increased evapotranspiration will transport large quantities of water vapour to the atmosphere and all models project a substantially moister atmosphere with increased specific, though not relative, humidity in the lower atmosphere.^{60/} A temperature rise of 2°C would raise water vapour concentration by 10% to 30%.^{61/} The atmosphere has a limited capacity to absorb water vapour (the saturation vapour pressure), although it increases exponentially with temperature, and precipitation will return the excess to the surface. Precipitation would increase in areas of frontal convergence, where moist air ascends and cools, removing the resulting excess concentration of water vapour above the now reduced saturation point.^{62/} This implies higher global mean precipitation and changes in regional and seasonal rainfall

Figure 6
Latin America and the Caribbean: geographical distribution of the surface air temperature change under conditions of carbon dioxide equivalent doubling



Source: Adapted from Michael E. Schlesinger and John F.B. Mitchell, "Climate model simulations of the equilibrium climatic response to increased carbon dioxide", *Reviews of Geophysics*, Volume 25, Number 4, 1987.

Note: The boundaries and place names shown on this map do not imply official endorsement or acceptance by the United Nations.

patterns. For example, an increase in the mean global atmospheric surface temperature of 0.5°C could increase annual atmospheric precipitation by as much as 10%.^{63/} Thus, the hydrological cycle will intensify and the greater the warming then the greater the intensification.

Global warming should increase humidity and precipitation, although there will not necessarily be more clouds. Simulations with general circulation models indicate that the opposite could occur.^{64/} An enhancement of the greenhouse effect would warm the lower atmosphere and cool the stratosphere. As the saturation-point mixing ratio varies positively with temperature and negatively with pressure, a cooler stratosphere would mean a lower saturation-point mixing ratio and thus a higher relative humidity for a given water vapour content. This implies that there would be greater cloud formation at higher altitudes. At the same time, with a warmer lower atmosphere, there would be less cloud formation at lower altitudes.^{65/} Simulations with general circulation models tend to show that greenhouse warming could reduce total cloud cover and redistribute it upwards.^{66/}

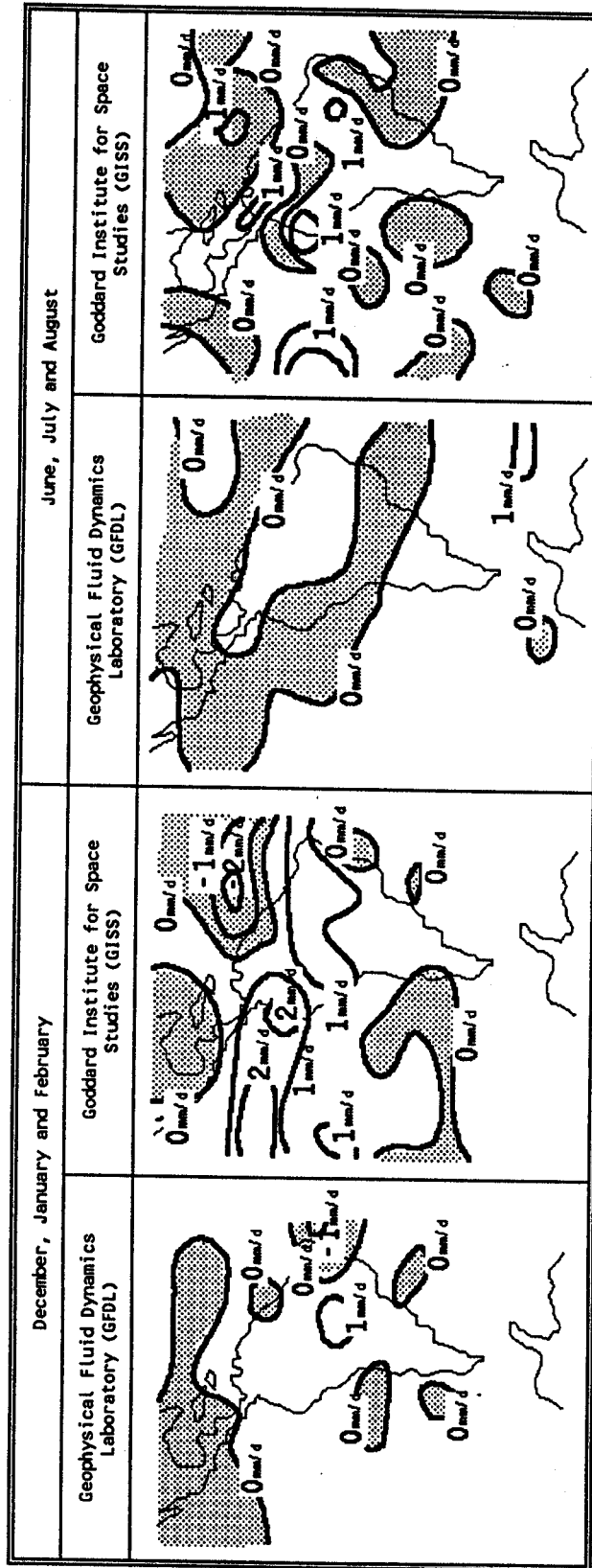
General circulation models project an increase in evaporation and precipitation in a range of 3% to 15%.^{67/} On the whole, the models predicting the largest temperature increases, also predict the largest increases in precipitation.^{68/} More precipitation does not necessarily imply a wetter land surface as global mean evaporation would increase in proportion.^{69/}

The distribution of any change in precipitation would not be uniform (Figure 7). Precipitation would increase most in the belt between 30°N and 30°S, but it would decrease in the adjacent zones, at least, during parts of the year.^{70/} The increase may be greatest in equatorial regions, but diminish towards higher latitudes where arid and semi-arid rainfall mechanisms may continue to operate.^{71/} The models often disagree, however, about possible changes in rainfall levels in subtropical and tropical latitudes.^{72/}

All models agree that precipitation will increase in both high latitudes and in the tropics throughout the year, as well as in mid-latitudes in winter.^{73/} In low latitudes, precipitation may increase 5 to 10% and in the higher mid-latitudes 5% in summer and as much as 15% in winter. In the lower mid-latitudes, such as the semi-arid Mediterranean climates, precipitation might be limited in summer and decrease 5 to 10% in winter.^{74/} Some studies suggest that summer precipitation may decrease in mid-latitudes.^{75/} The increase in precipitation would occur in regions of lower level convergence, including the mid-latitude storm tracks and the inter-tropical convergence zone (ITCZ).^{76/}

The models suggest that rainfall could intensify in tropical areas in the current rainy low latitudes. In the semi-arid tropics, global warming might entail a decrease in precipitation in one or more seasons.^{77/} According to other studies, however, precipitation would increase in most, but not all, semi-arid tropics, in the form of convective rainfall, which could imply a higher intensity, rather than an increased frequency, of precipitation.^{78/} In the humid tropics, global warming could increase the frequency and intensity of tropical storms.^{79/} Further, although in tropical regions, temperature increases may be smaller than the global average, potential evapotranspiration probably will increase and convective rainfall could increase in moister areas.^{80/} In many models, there is a tendency for the tropical maximum precipitation to shift further into the summer hemisphere, while in others, the tropical rain belt tends to shift either into the winter hemisphere or southwards throughout the year. Precipitation changes would be generally small in the dry subtropics with some areas experiencing more and others less precipitation than at present.^{81/}

Figure 7
Latin America and the Caribbean: geographical distribution of the precipitation rate change under conditions of carbon dioxide equivalent doubling



Source: Adapted from Michael E. Schlesinger and John F.B. Mitchell, "Climate model simulations of the equilibrium climatic response to increased carbon dioxide", *Reviews of Geophysics*, Volume 25, Number 4, 1987.

Note: Stippling indicates a decrease in precipitation rate.

The boundaries and place names shown on this map do not imply official endorsement or acceptance by the United Nations.

Some models predict that global warming may increase precipitation in coastal areas.^{82/} An increase in precipitation may occur on the eastern edges of the continents, but continental interiors could become drier.^{83/}

In Argentina, Chile and the north Andean region, rainfall would increase in currently moist areas and decrease in the semi-arid areas in the rain shadow of the Andes. Precipitation could also increase in the centre west areas of Brazil. Projections are uncertain for Mexico and Central America where rainfall may either considerably decrease or slightly increase.^{84/} Some authors expect, however, a decrease in precipitation in central and southern regions of Chile, but an increase in the extreme south.^{85/} An intensification of convectional meteorological systems could benefit highland areas in northern Chile.^{86/}

Greenhouse warming could lead to an acceleration of coastal upwelling. The cool foggy summer conditions that typify the coastal areas of upwelling regions, such as off western South America, might become, therefore, even more pronounced. In contrast inland areas, under the direct influence of coastal stratus and fog, might become even more arid during upwelling seasons.^{87/}

Other characteristics of global and regional precipitation, including the annual, seasonal, and daily variability, storm frequency and intensity, the duration of rainfall events within a given season, the proportion of the precipitation deposited in the form of rain, dew, and snow may also change. Changes in precipitation, evapotranspiration, winds, humidity, and cloud cover could lead to important changes in global and regional run-off and its characteristics, including the spatial, annual, and seasonal, variability.

Changes in wind patterns can cause important alterations in regional precipitation patterns. Unfortunately, the possible influence of global warming on wind patterns and changes in low-level circulation at any particular location is little understood. Most models simulate a weakening of the north-south pressure gradient in the southern hemisphere extra-tropics throughout the year. This could imply a weakening of the mid-latitude westerlies. The intensity of the subtropical anticyclones and the Antarctic circumpolar low pressure trough also diminish.^{88/} The poleward displacement of the circumpolar vortex and the storm tracks associated with it also support a reduced windiness in mid-latitudes.^{89/}

(c) Groundwater recharge

Current general circulation models do not simulate changes in groundwater availability and distribution directly, but the effects of global warming on groundwater recharge can be estimated from forecast changes in precipitation.

- **In mid-latitude, mid-continental areas**, there is some evidence that reduced amounts of precipitation (both rain and snow) could significantly reduce rates of groundwater recharge.^{90/} In some maritime mid-latitude regions, because of a warmer climate, a larger proportion of the total rainfall could come from convectional thunderstorms. This may lead to increased rainfall intensity, increased run-off and reduced percolation.^{91/}
- **In tropical regions**, the total amount and intensity of rainfall could increase resulting in more run-off, less percolation and less available groundwater.^{92/}

Reductions in groundwater recharge coupled with increasing demand for groundwater could accelerate rates of aquifer depletion.

(d) Soil moisture changes

The representation and validation of soil moisture in current climate models are relatively crude.^{93/} Some studies suggest that, in some areas, the effects of global warming on the final hydrological balance could be such that there will be a smaller amount of available ground water and a tendency towards semi-aridity and aridity.^{94/} As temperature rises, less water remains at the surface on land or lakes and rivers, and more transfers to the atmosphere in the form of water vapour, with water availability falling with the increase in temperature.

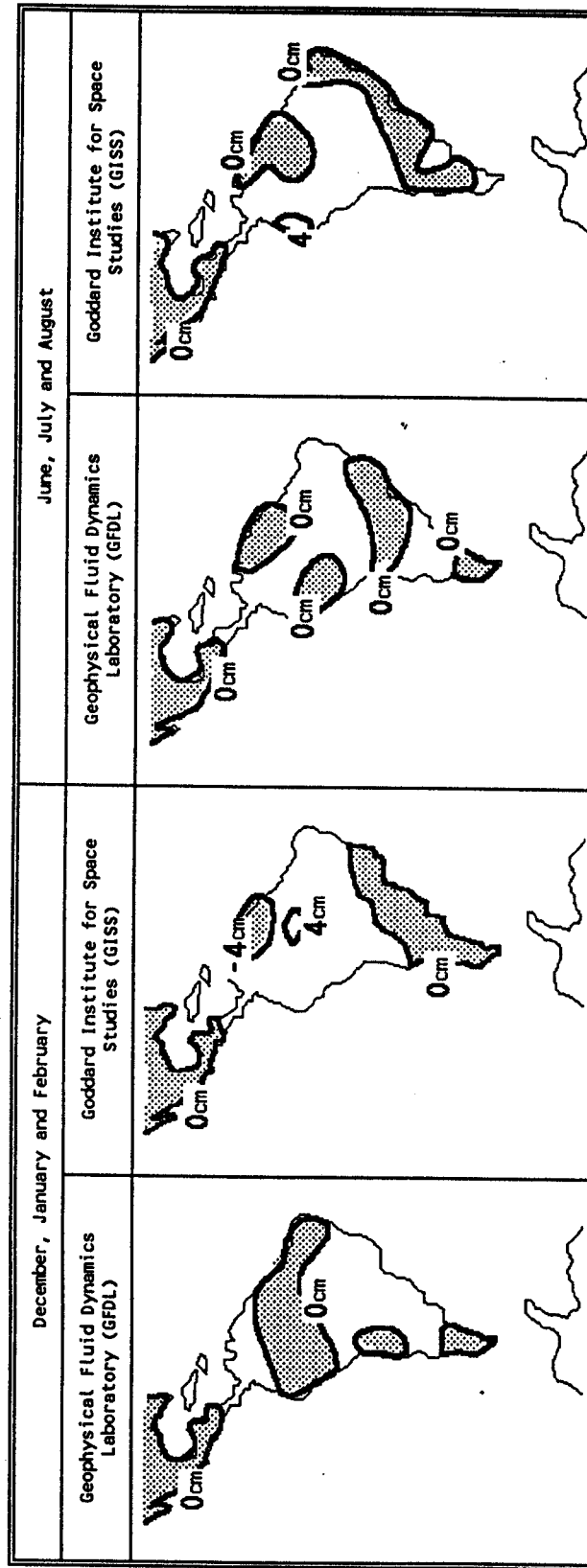
An increase in potential evapotranspiration could occur of 5% per degree of warming. Only in the humid tropics and in the high middle and high latitudes would an increase in precipitation compensate this increase.^{95/} In other areas, global warming would lead to increased evapotranspiration and, therefore, potentially to soil drying. This implies reduced soil water availability particularly in mid-latitudes, in mid-summer, and at low latitudes. Even in the tropics, where temperature increases may be smaller than elsewhere and where moisture loss may decrease somewhat due to the greater humidity and increased cloudiness during the rainy seasons, the loss could be pronounced in the dry season. In some semi-arid and arid regions it is possible that the combination of decreases in rainfall amounts and increases in rates of evapotranspiration could lead to marked desiccation and desertification.^{96/} With a doubling of the carbon dioxide content of the atmosphere, some studies show soil humidity increasing in most of South America.^{97/}

Some scientists argue that any increase in precipitation would concentrate around the equator and beyond 50° latitude in both hemispheres. Since evaporation increases fairly uniformly with latitude, there tends to be a deficit in the soil water balance in mid-latitudes, with a seasonally shifting zone of soil humidity reduction. In the middle latitudes, a reduction in the snow cover in winter and earlier melting in spring coupled with more intense evaporation may lead to drier soil in spring and autumn, while drying in summer may become stronger and occur earlier. The latter factor would increase the duration and intensity of summer droughts in the continental interior.^{98/}

The regional pattern of soil water changes that may occur under global warming is highly uncertain, but there are regions where three models show decreases in soil water (Figure 8). In Latin America and the Caribbean, these areas include northern Argentina where soil water may decrease in December, January and February, Central America, and eastern Brazil where soil water may decline in June, July and August.^{99/} In Mexico and Central America, global warming may reduce soil moisture by 10 to 20%.^{100/} Central America is also particularly vulnerable to decreases in soil moisture.^{101/} Global warming may also reduce the availability of water for plant growth in the north of Mexico and in the semi-arid region of northeast Brazil.^{102/}

The comparison of simulated with observed soil moisture indicates that the model simulations generally show greater seasonal variations, especially in the tropics. The errors in simulating soil moisture vary considerably among models.^{103/} The models typically do not consider the direct effects of carbon dioxide on vegetation. This is of particular importance since carbon dioxide enrichment is expected to increase water efficiency that, without other changes, could reduce surface evapotranspiration.^{104/}

Figure 8
Latin America and the Caribbean: geographical distribution of soil water change
under conditions of carbon dioxide equivalent doubling



Source: Adapted from Michael E. Schlesinger and John F.B. Mitchell, "Climate model simulations of the equilibrium climatic response to increased carbon dioxide", *Reviews of Geophysics*, Volume 25, Number 4, 1987.

Note: Stippling indicates a decrease in soil water.

The boundaries and place names shown on this map do not imply official endorsement or acceptance by the United Nations.

(e) Changes in variability

At any particular location, changes in the variability of weather and the frequency of extreme events will generally have more impact on water use than the slow changes in the mean climate (Box 2). Such changes may take three basic forms:

- The mean of the frequency distribution could change although the shape of the distribution remains unchanged, leading to an increase in the frequency of extreme events at one end of the frequency distribution with a corresponding decrease at the other.
- The shape of the frequency distribution could change while the frequency of distribution remains unchanged. For example, an increase in the standard deviation or spread of the frequency distribution implies that more extreme events will occur at both ends of the distribution.
- The mean and the shape of the frequency distribution could change simultaneously.^{105/}

There is no conclusion on possible changes in the degree of annual climate variability.^{106/} Yet this is one of the most important considerations for many water uses. Some possible changes include an increase in the global mean temperature, with no change in variability, an increase in the number of days with temperatures exceeding a given threshold at the high end of the distribution, while at the low end the number of days with temperatures below a given value will decrease.^{107/} This appears to imply an increase in the number of very hot days, but a decrease in the number of frosty nights.

The simulation of the mean and variability of precipitation show some indication that annual variability increases where mean precipitation increases and vice-versa, although this is not always so. The models also simulate a consistent increase in the frequency of convective precipitation, which usually occurs at the expense of precipitation from large scale vertical motions. This could increase more intense local rain storms at the expense of gentler, but more persistent rainfall associated with large-scale disturbances.^{108/}

The simulation of the likely changes in winds and disturbances provides some indication of a general reduction in day-to-day and interannual variability in the mid-latitude winter storm tracks. Available studies suggest a decrease in the intensity or frequency (or both) of disturbances resolved on a model grid, typically greater than about 1 000 km, but do not allow one to conclude the same for smaller-scale synoptic disturbances. There is also slight evidence, supported by empirical considerations, that the frequency, intensity and area of occurrence of tropical disturbances may increase (Box 2).^{109/}

Changes in the position of the large scale weather regimes, such as anticyclones or depression tracks, would also effect the variability and weather extremes at any particular location.^{110/}

4. Empirical climate forecasting

Past warming periods are used as an analogue of how a future greenhouse warming may affect regional climates (Table 4). A description of past climates is obtained from the analysis of data on changing climatic conditions over the period of instrumental meteorological observations or from paleoclimatic analogues. The advantage of relying on analogues is that this approach gives a realistic sense of how regional and local weather patterns change as global climate warms.^{111/}

Box 2

Climate change and water-related natural disasters

There is strong empirical evidence that the probabilities of certain extreme weather events are non-linearly correlated with mean temperatures, increasing as mean temperature rises.^{a/} In addition, the increased intensity of convective processes and a larger quantities of water vapour in the atmosphere, would generally raise the frequency and severity of tropical cyclones, tornadoes, thunderstorms, hailstorms and storm surges.

From a cybernetic systems viewpoint, climate can be thought of as a complex, non-linear multiple feedback system with dominant positive feedbacks. A rapid forced change in such a system would destabilize it. Since the magnitude of the destabilization tends to be proportional to the rate of change of the forcing function and considering that the rate of change of carbon dioxide concentration is expected to be greatest between 2000 and 2060, these decades could experience chronic and severe weather variability.^{b/}

Storms

Tropical cyclones

Many studies agree that under global warming tropical cyclone intensity may greatly increase. Changes in maximum tropical cyclone intensity are related to changes in sea surface temperature.^{c/}

Some studies suggest that global warming may change the previously observed paths of tropical storms encouraging the formation and shifting of tropical perturbations to higher latitudes than at present. Sea-level rise could further aggravate hurricane damage in coastal areas.

On the whole, however, there is no consistent indication whether the incidence or intensity of tropical cyclones will increase or not, and there is no evidence of change over the past decades. The argument that climate changes induced by greenhouse warming will increase the frequency and intensity of tropical storms remains to be convincingly demonstrated.^{d/}

Mid-latitude storms

The factors governing mid-latitude storms differ considerably from those of tropical storms. Mid-latitude storms are driven by equator-to-pole temperature contrast and global warming will probably weaken this contrast because surface temperature would increase more in high latitudes than at equator.^{e/} This could imply that mid-latitude storms will weaken or change their tracks. On the other hand, global warming is projected to strengthen the temperature contrast higher in the atmosphere and the subsequent increase in vertical temperature gradient would seem likely to increase storm intensity.^{f/} Increased atmospheric water vapour could also supply extra energy to storm development. The current state of knowledge does not permit the determination of the factors which will be more important or how they may change the frequency, intensity and location of mid-latitude storms.^{g/} There is some indication, however, of a general reduction in day-to-day variability in the mid-latitude storm tracks in winter in model simulations.^{g/}

Droughts

The effects of global warming on the final hydrological balance could be such that there will be a smaller amount of available water and a tendency towards greater aridity. Global warming may increase the incidence and intensification of droughts at some middle- and low-latitude land areas. According to the IPCC, increased drought risk represents potentially the most serious impact of climate change on agriculture.^{h/}

Even if climate change were to cause relatively small changes in annual streamflows, this could have dramatic impacts on drought duration and severity.

The "state-of-the-art" in global climatic modelling is not yet good enough to provide agreement as to how drought incidence and intensity will change under a greenhouse warming. There is some evidence

suggesting that drought incidence and intensity will not necessarily increase as climate warms, and, according to some researches, careful examination of projections of some global climatic models raises the possibility that, at least in some areas, droughts might actually be moderated by forthcoming climatic change.^{j/} In addition, scrutiny of historic drought assemblages does not reveal a clear cut association with periods of greater or lesser warmth.^{j/}

Floods

An increase in air temperature and evapotranspiration may result in larger thunderstorms, an increase in the number of intense showers and a greater risk from flash flooding. As sea-level rises, coastal flooding could increase substantially.

The relative contribution of changes in precipitation and temperature to changes in flood frequency and intensity varies among climatic zones, depending on whether a major part of the annual run-off depends solely on rainfall or there is a major contribution from spring floods from snowmelt.

In areas where a major part of annual run-off comes from rainfall, an increase in average precipitation and in its variability could both lead to increased run-off and, therefore, to a greater frequency of flooding. A change from a more evenly distributed rain to fewer, heavier rainstorms could

enhance flooding. Because there remain large uncertainties about changes in regional precipitation patterns and soil moisture, it has not proved possible to make useful prediction of changes in flood intensity and frequency on a regional basis.

In areas where precipitation is currently dominated by winter snowfall, any noticeable temperature increase could produce serious changes in seasonal run-off patterns if snow melts earlier in the spring and more precipitation comes in the form of rain.

Flood control structures are sensitive to increased run-off and weather extremes, and might be unable to withstand more severe and frequent floods and storms. Changes in intensity and frequencies of floods, sea-level, tides, and direction, intensity and frequencies of storms would require modification of flood control ordinances, warning systems, building regulations, reservoir release policies, and flood insurance.

Land and mudslides

Intensification of rainfall in mountainous regions would increase the risk of land and mudslides. In colder regions, masses of debris on steep slopes will become exposed if glaciers recede and, would become, therefore, unstable and vulnerable to the effects of erosion.^{k/} This might increase debris flows and landslides. Glacial retreat would also contribute to mudflows.

Source: ^{a/} - Arrhenius, Erik and Thomas W. Waltz (1990), *The greenhouse effect: implications for economic development*, World Bank Discussion Papers No 78, The World Bank, Washington, D.C.

^{b/} - Markley, O.W. and Hurley, T.J., III (1983), "A brief technology assessment of the carbon dioxide effect", *Technol. Forecasting Soc. Change*, 23, 185-202, as quoted in Sinha, S.K., N.H. Rao and M.S. Swaminathan (1989), "Food security in the changing global climate", World Meteorological Organization (WMO), Government of Canada, Environment Canada, United Nations Environment Programme (UNEP), *Proceedings. World Conference, Toronto, Canada, June 27-30 1988. The Changing Atmosphere: Implications for Global Security*, WMO - No 710, Secretariat of the World Meteorological Organization, Geneva, Switzerland.

^{c/} - Emanuel, Kerry A. (1987), "The dependence of hurricane intensity on climate", *Nature*, April, Volume 326, Issue No 6112.

^{d/} - World Bank (1992), *World development report 1992. Development and the environment*, Oxford University Press.

^{e/} - Policy Implications of Greenhouse Warming-Synthesis Panel, Committee on Science, Engineering, and Public Policy, National Academy of Sciences, National Academy of Engineering, Institute of Medicine (1991), *Policy implications of greenhouse warming*, National Academy Press, Washington, D.C.

^{f/} - Cline, William R. (1992), *The economics of global warming*, Institute for International Economics, Washington, D.C.

^{g/} - WMO/UNEP/IPCC (World Meteorological Organization/United Nations Environment Programme/Intergovernmental Panel on Climate Change) (1990), *Policymakers summary of the scientific assessment of climate change*, Report prepared for IPCC by Working Group I.

^{h/} - WMO/UNEP/IPCC (World Meteorological Organization/United Nations Environment Programme/Intergovernmental Panel on Climate Change) (1990), *Overview and conclusions. Climate change: a key global issue*, Draft, July.

^{i/} - Rosenberg, Normal J. (1987), "Drought and climate change: for better or worse?", Donald A. Wilhite and William E. Easterling with Deborah A. Wood, *Planning for drought. Toward a reduction of societal vulnerability*, Westview Press.

^{j/} - UNESCO/WMO (United Nations Educational, Scientific and Cultural Organization/World Meteorological Organization) (1985), *Hydrological aspects of drought*, A contribution to the International Hydrological Programme, Prepared by a joint UNESCO/WMO panel, M.A. Beran and J.A. Rodier, rapporteurs.

^{k/} - WMO/UNEP/IPCC (World Meteorological Organization/United Nations Environment Programme/Intergovernmental Panel on Climate Change) (1990), *Policymakers summary of the potential impacts of climate change*, Report from Working Group II to IPCC.

Table 4

**Atmospheric carbon dioxide content equivalent and temperature differences
during selected paleoclimatic periods**

Period	Analogue (year)	Temperature difference from present	Past CO ₂ concentration	Assumed CO ₂ concentration
Holocene Optimum	2 000	+1°C	280 ppm	380 ppm
Eemian Interglacial	2 025	+2°C	280 ppm	420 ppm
Pliocene	2 050	+4°C	500 - 600 ppm	560 ppm

Source: IPCC (Intergovernmental Panel on Climate Change) (1990), *Policymakers summary of the potential impacts of climate change*, Report from Working Group II to IPCC, June.

If the greenhouse effect leads to a mean temperature increase in the lower atmosphere of 2°C or 3°C or more with little changes in the tropics but somewhat greater change in middle and higher latitudes, the closest paleoclimatic analogue for such conditions would be the warmest phases of certain Pleistocene interglacial periods. However, paleoclimatic reconstructions for the interglacials are insufficiently detailed to provide a useful model for potential climatic changes. The next best analogy is the mid-Holocene 8 000 to 5 000 years ago. This period had mean temperatures 1.5°C to 2.5°C higher than today in middle latitude regions.^{112/}

Studies of the mid-Holocene climates have reached the following conclusions:

- Changes in winter temperature in the marine climate areas in low and middle latitudes could be quite small. Winter cold would become less severe in the middle and high latitude interior continental regions. Summer warming would be greater mainly in high latitude zones. There would be some areas of cooling in low latitude continental regions.^{113/}
- Studies of the Eemian climate, analogue for 2025, indicate that precipitation was considerably greater than at present in all regions for which data exist. During the Pliocene, analogue for 2050, precipitation increased over all land areas for which data are available, particularly in a number of areas that are now deserts.^{114/}

According to recent paleoclimatic reconstructions, climate change could be quite favourable, particularly for arid and semiarid regions, as well as, for the low tropical latitudes. The scenarios for these regions show an insignificant rise or even invariability of air temperature accompanied by a sharp increase in annual precipitation, which would result in a considerable increase in total water resources. Paleoclimatic scenarios suggest that the total river run-off would increase by 10 to 12% with a 1°C global warming and by 16 to 19% with a 2°C warming, although in individual regions, a 10 to 15% decrease in annual run-off is possible.^{115/}

There is little knowledge of climatic conditions prevailing in Latin America and the Caribbean during past warming periods. On the whole, the basic mid-Holocene pattern may involve negative deviations of 20% to 30% in the hydrological balance in middle latitude areas and positive anomalies

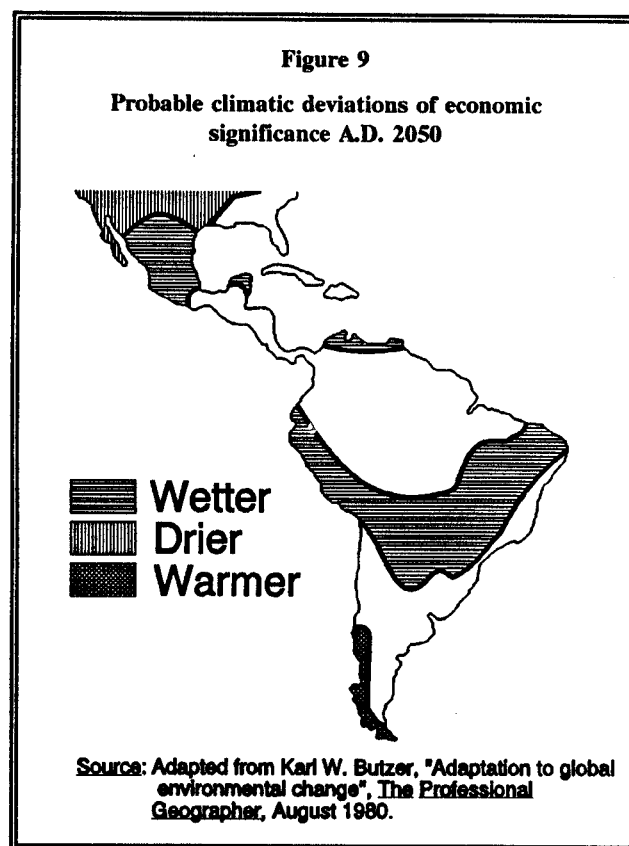
of 30% to 50% in lower latitude areas (Figure 9). There are some indications that rainfall possibly increased in tropical South America, although interrupted by several marked dry spells.^{116/} Some studies suggest that the foothills of the Argentinean Andes were drier, but that parts of Chile were warmer in the mid-Holocene.^{117/} Present subtropical arid areas were wetter during the Holocene, most probably due to greater rainfall.^{118/} Between 9 000 to 5 000 years ago, there were several short warm epochs each accompanied by increased precipitation and higher lake levels in both subtropical and high latitudes, although the level of some mid-latitude lakes fell.^{119/}

5. The climatic effect of changes in land use

Land use changes may have several possible impacts on climate, for example, related changes in the carbon and nitrogen cycles can lead to an increase in concentrations of greenhouse gases. The net effects are likely, however, to be relatively small, the removal of all the tropical forests would warm the climate by only 0.3°C.^{120/} Changes in the albedo of cleared terrain may lead to a decrease in precipitation and an accentuation of desertification, and finally there is an impact on the hydrological cycle and surface roughness.^{121/} Land-use changes affecting smaller areas may only affect local climate, but those affecting large areas may result in significant changes in regional climates, even in areas distant from the site of change.

Deforestation can have significant effects on both microclimates and the hydrologic cycle, especially if the forestry practice in use is close to clear-felling. Potential consequences include the loss of forest soils, reduced water retention capacity of the soil, increased erosion and increased lowland vulnerability to flooding, changes in stream channels, reservoir silting, and changes in delta formation.^{122/} Such changes can have an impact on flood control, hydroelectric power generation, inland fisheries, inland navigation and among other water uses. In addition, widespread deforestation appears to make the climate of the surrounding region drier, such effects may have occurred in parts of the area around the Panama Canal and in north-western Costa Rica.^{123/} The effects of deforestation in the Amazon Basin are discussed in Box 3.

Deforestation is closely related with biomass burning, which is widespread in the region, especially in the tropics. Burning serves a variety of purposes, such as to convert forests to agricultural land or pasture, to clear land for shifting cultivation, to remove dead vegetation to promote agricultural productivity and the growth of higher yield grasses, to control pests, insects and weeds, among others. Biomass burning is a major source of greenhouse gases and other climatic impacts including emissions of nitric oxide and hydrocarbons that lead to



Box 3

Changes in the hydrological cycle due to deforestation

Tropical forests play an extremely important role in the local, regional and perhaps even the global climate. Fed by nearby oceans and seas, the evaporative processes circulate the abundant moisture that flows across tropical forest areas through the vegetation. In a tropical forest most of the evaporation comes from the trees themselves, not from the ground, and this process is very energy intensive.^{a/}

The most closely studied case of the impact of deforestation on this process in Latin America and the Caribbean is the Amazon basin, which is estimated to contain about half of the world's tropical rainforests.^{b/}

The most important characteristics of the Amazon hydrological cycle are:^{c/}

- The primary flow of water vapour, of the order of 8-10 trillion tons per year, originates from the Atlantic Ocean and is brought to the region by the Trade Winds which blow from East to West.
- A flow of water vapour of 3-5 trillion tons per year leaves the Amazon region for other regions of the globe forming part of the process of transfer of energy from the equatorial region to higher latitudes.
- The flow of water to the ocean is of the order of 5.5 trillion tons per year.
- The precipitation amounts to 13.8 trillion tons per year, while evapotranspiration amounts to 7.2 trillion tons per year.

Various studies suggest that heavy recirculation of water vapour within the basin explains this type of water balance. In the Amazon, far more than elsewhere, rainfall is derived from water recycled into the atmosphere through evapotranspiration, rather than being blown into the region in the form of clouds from the ocean.^{d/}

Local evaporation accounts for approximately half of the local rainfall, while the moisture advected from the surrounding oceans accounts for the remainder.^{e/} The plant cover plays an extremely important role in this process: it can lengthen the residence time of the

water, increase catchment and regulate transpiration. Alterations in the plant cover will change the components of the water balance and consequently the distribution of the net energy balance ratio. Any reduction in evapotranspiration means a reduction in the proportion of the radiation balance which is converted into latent heat and an increase in the proportion corresponding to sensible heat, that is, an increase in temperature.^{g/}

Besides local changes, which would reduce precipitation and raise temperature, there would also be a reduction in the flow of water vapour to surrounding regions. The immediate consequence of which would be to lower the rate of flow in the Amazon and its tributaries.^{h/}

Various attempts, with the help of global circulation models, have been made to predict changes in the probable regional climate of the Amazon Basin under conditions of deforestation. A recent study used a coupled numerical model of the global atmosphere and biosphere to assess the effects of Amazon deforestation on the regional and global climate. When the tropical forests in the model were replaced by degraded grass (pasture), there was a significant increase in surface temperature and a decrease in evapotranspiration and precipitation over the Basin.^{f/}

Surface and soil temperatures were warmer by 1°C to 3°C with deforestation than in the control cases. Reductions in calculated annual precipitation and evapotranspiration averaged about 26% (643 mm) and 30% (496 mm), respectively. The simulated reduction in precipitation over the Amazon is larger than the corresponding regional reduction in evapotranspiration implying a decrease in the dynamic convergence of moisture flux as a result of deforestation. The simulation also projected a lengthening of the dry season. The study concluded that *"changes in the region's hydrological cycle and the disruption of complex plant-animal relations could be so profound that, once the tropical forests were destroyed, they might not be able to reestablish themselves."*^{f/}

Another recent experiment investigated the impact of setting the vegetation cover to desert (albedos similar to those of the most reflective parts of the Sahara were used) over South America north of 30°S. Annual rainfall was reduced by 70% and its seasonal distribution changed to that typically observed in semi-arid regions.g/ This suggests that widespread deforestation of the South American tropics could lead to an irreversible decline in rainfall over at least part of the region.b/

The changes in the components of the hydrological cycle take place immediately after the change in land use, especially with the replacement of forests by pastures or annual crops. Observations indicate an increase both in the amount of water lost through surface run-off and in the incidence of erosion. The changes in the physical characteristics of the soil (increased compacting and a reduced rate of

infiltration) constitute an ongoing process that can be observed one or two years after the change in land use has occurred. This leads to an alteration in the radiation balance, so that changes in microclimates occur over a very short period, in some cases, virtually simultaneously with the change in land use.c/

At the regional level, changes in microclimates will depend on the combination of the degree of alteration and the time scale covered by the effects. The mean period of retention of water vapour in the Amazon Basin, for example, is of the order of 3-4 months, and the hydrological cycle repeats each year. It may be expected, therefore, that any regional effects could be felt within a few years when the changes are substantial. There are indications that, for changes in the hydrological regime, the effects of the deforestation of the upper reaches of rivers will be felt within a single hydrological cycle.c/

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- Source: a/ - UNESCO/IHP/MBP (United Nations Educational, Scientific and Cultural Organization/International Hydrological Programme/Man and the Biosphere Programme) (1991), *The disappearing tropical forests. Water-related issues and problems of the humid tropics and other warm humid regions*, May.
- b/ - Mitchell, J.F.B., S. Manabe, V. Meleshko and T. Tokioka (lead authors); and G. Boer, H. Cao, S. Grotch, R. Haarsma, B. Hunt, R. Keshavamurty, G. Meehl, E. Oladipo, B. Pittock, D. Randall, D. Rind, C. Senior, R. Stouffer, K. Vinnikov and R. Wetherald (contributors) (1990), *Section 5. Equilibrium climate change and its implications for the future. Peer reviewed assessment for WG1 plenary*, April 28.
- c/ - Salati, E. (1990), *Possible climatic changes in Latin America and the Caribbean and their consequences*, United Nations, Economic Commissions for Latin America and the Caribbean (ECLAC), LC/L.580(Sem.56/4).
- d/ - Fearnside, Philip (1984), "Brazil's Amazon settlement schemes: conflicting objectives and human carrying capacity", *Habitat International*, 8, Nº 1, as quoted in World Bank (1992), *Brazil. An analysis of environmental problems in the Amazon*, Country Operations Division, Brazil Department, Latin American and Caribbean Region, Report Nº 9104-BR, May 21.
- e/ - Salati, E., J. Marques and L.C.B. Molion (1978), "Origem e distribuicao das chuvas na Amazonia", *Interciencia*, 3, as quoted in Mitchell, J.F.B., S. Manabe, V. Meleshko and T. Tokioka (lead authors); and G. Boer, H. Cao, S. Grotch, R. Haarsma, B. Hunt, R. Keshavamurty, G. Meehl, E. Oladipo, B. Pittock, D. Randall, D. Rind, C. Senior, R. Stouffer, K. Vinnikov and R. Wetherald (contributors) (1990), *Section 5. Equilibrium climate change and its implications for the future. Peer reviewed assessment for WG1 plenary*, April 28.
- f/ - Shukla, J., C. Nobre and P. Sellers (1990), "Amazon deforestation and climate change", *Science*, Volume 247.
- g/ - Lean and Rowntree (1989), personal communication, as quoted in Mitchell, J.F.B., S. Manabe, V. Meleshko and T. Tokioka (lead authors); and G. Boer, H. Cao, S. Grotch, R. Haarsma, B. Hunt, R. Keshavamurty, G. Meehl, E. Oladipo, B. Pittock, D. Randall, D. Rind, C. Senior, R. Stouffer, K. Vinnikov and R. Wetherald (contributors) (1990), *Section 5. Equilibrium climate change and its implications for the future. Peer reviewed assessment for WG1 plenary*, April 28.

high ozone concentrations in the tropics during the dry season. Burning also releases large quantities of smoke particles that can serve as cloud condensation nuclei with repercussions for the radiation budget and the hydrological cycle in the tropics and which can also promote acid deposition.^{124/}

6. El Niño-Southern Oscillation Phenomenon: the shape of things to come?

El Niño related events are the most spectacular instances of annual variability in the ocean and have profound consequences for climate and the ocean ecosystem.^{125/} The meteorological episodes associated with these events provide an excellent example of the potential economic and social implications of climatic change for Latin America and the Caribbean. In addition, El Niño events may reflect the conditions resulting from projected future regional climatic changes even though the phenomenon is never of long duration.^{126/}

An El Niño event is typically defined by the appearance and persistence, for from 6 to 18 months, of unusually warm water in the coastal and equatorial ocean off Peru and Ecuador. This anomaly, however, is only one of many facets of a large-scale phenomenon that involves the entire tropical Pacific and the global atmosphere.^{127/}

The El Niño-Southern Oscillation events occur periodically, at intervals of 2 to 10 years, a three-year interval being most common. The event tends to start around the beginning of one calendar year and end at the beginning of the next. It begins with a buildup of warm water in the central or eastern Equatorial Pacific.^{128/} The global pattern of atmospheric anomalies becomes most widespread and intense near the end of the first year and during the early months of the second year. The event then enters a period of decay that typically lasts several months. The effects can vary both regionally and seasonally, and the amplitude of regional anomalies varies from episode to episode.^{129/}

The phenomena are the manifestations in the atmosphere and the ocean of the same climatic anomaly, which when fully developed, has the form of an extension of warm water throughout the tropical parts of the Pacific Ocean and a reversal of the sea slope.^{130/} In the ocean, the depth of the thermocline increases by tens of metres in the east, the currents reverse, strong eastward currents emerge on the surface and the Equatorial Undercurrent diminishes. In the atmosphere, the trade winds decrease, frequently to the point where they reverse in the western part of the basin. The convection zone, usually over the islands of Indonesia, shifts eastwards. There is a decline in rainfall in the western Pacific and an increase in the central and eastern Pacific. The two zones where the surface winds of the Pacific come together merge forming a single convergence zone over the centre.^{131/}

A change in the distribution of warm water in the tropical Pacific weakens the trade winds, leading to a decline in the east-west temperature gradient and the destruction of the Walker Cell. The movement of warm water to the mid-Pacific and the convergence of the zonal winds towards the warm anomaly causes a reversal of winds in the western Pacific.^{132/}

The appearance of warm waters in the central and eastern reaches of the Pacific seems to relate to the weakening of the trade winds that, under normal circumstances would be maintaining an upwards slope from east to west, but as the trade winds stop, the slope is no longer maintained

and the warm water can flow over the whole of the equatorial region. The Equatorial Undercurrent weakens and the west wind generates surface currents moving eastwards.^{133/}

The physical mechanisms of the Southern Oscillation and El Niño show that the close links between the ocean and the atmosphere are easily destabilized, but neither can develop the anomaly independently.^{134/} The Southern Oscillation component principally involves a seesaw in atmospheric mass between regions near Indonesia and the tropical south east Pacific Ocean near Easter Island, while the El Niño component is an anomalous warming of the eastern tropical Pacific Ocean.^{135/} An anomaly in the surface water temperatures triggers an anomaly in atmospheric circulation. As soon as the latter develops, it helps maintain and amplify the initial ocean anomaly and vice versa. The response is not confined to the zone of the original anomaly, because the equatorial waves rapidly spread along the Equator making the effects of the anomaly felt in the whole tropical ocean reservoir.^{136/}

A buildup of warm water in the eastern and central Equatorial Pacific increases air temperature with a subsequent major increase in precipitation in usually dry areas and a reduction in usually wet areas. During major events, the arid coast of western South America often suffers from torrential rains and floods, while the normally wet areas suffer drought.^{137/} For example, the northern coast of Peru is arid, but the El Niño-Southern Oscillation phenomenon produces a dramatic increase in annual precipitation, a 40 to 60-fold increase in the 1982-1983.^{138/}

During El Niño events, the Gulf of Mexico is often wetter than normal. Central South America, including Argentina and southern Brazil is also usually wetter, but northeastern South America, especially northeastern Brazil, is very dry.^{139/} During the 1982-1983 event, intensive and persistent rains produced extensive flooding in the coastal areas of Ecuador and Northern Peru, as well as in western Bolivia, while an extreme drought affected virtually the whole Bolivian-Peruvian highlands.^{140/} Droughts also affected some areas of Argentina, Brazil, Chile, Mexico, Venezuela, most of Central America, and some Caribbean countries.^{141/} On the other hand, some countries suffered from extraordinary rains. For example, in the state of Paraná, Brazil, heavy rains caused crop damage estimated at almost US\$ 0.8 billion and ruined nearly 40% of crops in the state of Santa Catarina.^{142/} Some sectors of Colombia's Pacific coast also suffered intense rains.^{143/}

The El Niño phenomenon influences hurricane activity in the Caribbean.^{144/} Events appear to bring a mild year for Atlantic and Caribbean hurricanes, because the westerly winds in the upper atmosphere inhibit the formation of hurricane weather systems.^{145/} The 1982-1983 event seems to have favoured hurricane generation in the Pacific, with 19 hurricanes in 1982 and 25 in 1983.^{146/}

The sea area off the coasts of Ecuador, Peru and Chile normally has cold and nutrient-rich surface water from April to December. This is due to the equatorial and coastal upwelling, and varies greatly from summer to winter.^{147/} This normal pattern, however, suffers drastic changes during El Niño events. For example, during the 1982/1983 event, the incursion of large masses of water along the south-east Pacific coast, modified the normal structure of the coastal water to depths exceeding 100 metres affecting the productivity, distribution and survival rate of fish, consequently paralyzing the fishing industries in Ecuador and Peru.^{148/}

The effects on other aquatic and coastal ecosystems can also be severe. The decline in fish populations due to an El Niño event also affects the production of guano - a natural fertilizer important in Peru, depriving the seabirds who produce the guano of food.^{149/} The population of

seabirds in Peru suffered an abrupt decline in the early seventies, following the collapse of fish populations.^{150/} The populations of the guano birds, estimated to be some 30 million in 1950, fell to 6 millions by 1982 and to only 0.3 million after the event.^{151/} When temperature increases reach 30°C, there is a loss of coral and bleaching of reefs.^{152/} The 1982-1983 event led to the death of 95% of the reef-building corals in the Galápagos, about two-thirds of the corals on the Pacific coast of Panama, and about half the corals on the Pacific coast of Costa Rica.^{153/} High temperature and extremely low salinities also lead to high death rates of mangrove associated fauna. However, crab and shell fish fisheries had higher yields.^{154/} The strong tides that occurred in 1983 entailed, however, the massive destruction of fields of marine algae, as well as of shell fish and crabs, from Ecuador to Chile.^{155/}

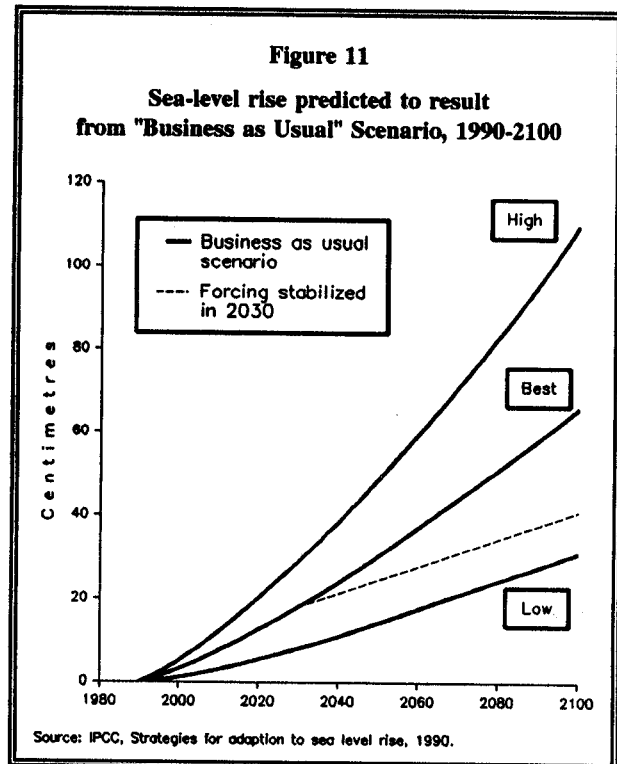
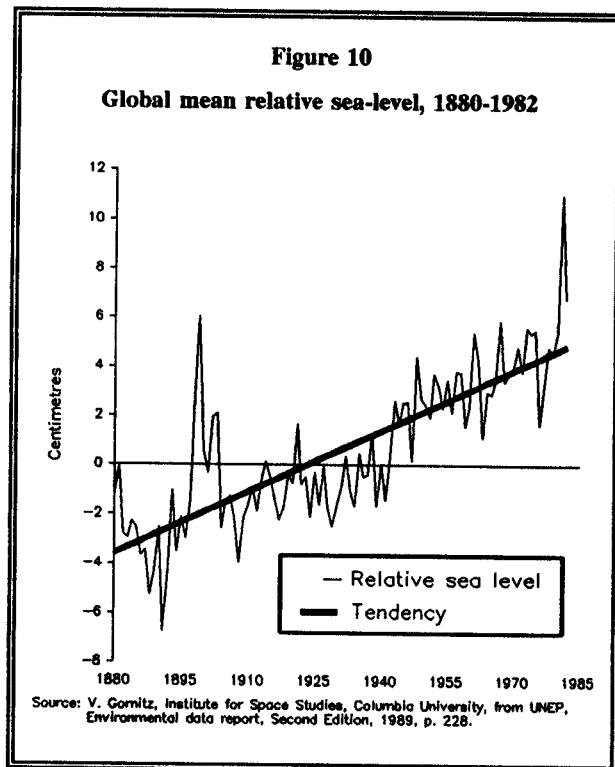
The El Niño-Southern Oscillation phenomenon forms a natural part of the earth's climate and has been documented on the northwest coast of South America for at least 450 years.^{156/} A major concern is whether their intensity and frequency might change as a result of global warming. Many studies suggest that the frequency and intensity of El Niño events have not changed since the little ice age, 1500 to 1850.^{157/} This could imply that the frequency and intensity of El Niño phenomena will continue over the next 100 years regardless of the trend in global warming.^{158/} Greenhouse warming-induced changes in atmospheric circulation could alter, however, the impacts of El Niño-Southern Oscillation event by changing the connections between low and middle latitudes.^{159/}

There are suggestions that an El Niño event can temporarily stop the growth of the atmospheric carbon dioxide concentration. The event apparently causes an additional carbon dioxide uptake from the atmosphere by the ocean in higher latitudes, and, but to a smaller extent, interrupts the upwelling of cold carbon dioxide-rich deep waters in the equatorial east Pacific that normally transport carbon dioxide to the ocean surface and then to the atmosphere.^{160/} Alternatively, processes in the land biosphere, perhaps in response to climatic events connected with the El Niño-Southern Oscillation events, may be responsible.^{161/}

B. Sea-level rise

Global warming would lead to a larger ocean volume as a result of thermal expansion, as the density of water changes due to variations of temperature, and of the melting of mountain glaciers and possibly of polar ice sheets in Greenland and Antarctica (Tables 1 and 3). Variations in the amount of water in the ocean due to changes in precipitation and run-off could also affect sea-level. The global sea-level is estimated to be currently rising at a rate of 12 cm per century (Figure 10).^{162/} It is uncertain, however, if, and to what extent, this is attributable to greenhouse warming.

Projections based on combined oceanic and atmospheric global circulation models suggest that several hundred years would probably be necessary for any global warming to provoke the melting of the ice sheets. The principal effects of global warming on sea-level, up to the year 2100, would come from thermal expansion. Estimates of oceanic thermal expansion from greenhouse warming range from 10 to 50 centimetres, for models assuming that some downward heat diffusion is balanced by upwelling from the deep oceans, to 20 to 110 centimetres for models assuming that heat diffuses down by eddy diffusion. Both estimates are for the year 2100 and an equivalent of doubling the pre-industrial atmospheric concentration of carbon dioxide.^{163/}



The IPCC "Business as usual" emission scenario forecasts the average rate of global mean rise in sea-level to be about 6 cm (with an uncertainty range of 3 to 10 cm) per decade over the next century.^{164/} The predicted rise would be 18 cm by 2030, 44 cm by 2070, and 66 cm by the end of the next century (Figure 11).^{165/} There remains considerable uncertainty about the magnitude of rise in sea-level. The expected rise in sea-level could be much greater, more rapid, and consequently more catastrophic, especially without an urgent and drastic reduction or stabilization in the levels of emission of greenhouse gases. There are some fears, that a rise in sea-levels could be higher if global warming leads to large pieces of polar ice sliding into the sea.^{166/} According to some recent assessments, the potential rise in levels in the very long term would be, at least, 4 metres. With a 10°C warming, the melting of Antarctic ice, 90% of the earth's ice, would become a major contributor to any increase in sea-levels.^{167/} During the last interglacial period 100 000 years ago, when temperatures were only 1°C warmer, the sea-level was approximately six metres higher.^{168/}

There are arguments, however, supporting a smaller rise in sea-level than that currently projected, at least, in the short and medium-term in some areas.^{169/} In Jamaica, for example, during the Holocene the maximum rise in sea-level was only 0.27 centimeters a year, or less than half the 0.6 centimeters implied by the IPCC.^{170/} In the wider Caribbean region, the rise in sea-level has averaged 0.36 centimeters a year during the last 30 years.^{171/} According to the new climate model of the Max Planck Institute, the global sea-level would rise by only between 6 to 16 centimeters by 2085.^{172/}

Besides the uncertainty surrounding projections of the global increase in sea-levels, there is even more uncertainty about regional changes. What is clear is that there will be significant regional variations. Dynamic ocean models suggest a regional doubling or halving of any rise.^{173/}

The increase in sea-levels and climate change-induced alterations in the pattern of waves, winds and tides, go together since flooding of coastal areas and other effects of a rise in sea-level are influenced by a combination of all these factors. It is important to note, however, that alterations in temperature, winds and tides could cause changes in the pattern of ocean currents. These, in turn, could significantly change local sea-levels. One example is the Gulf of Mexico, where current patterns cause a noticeable slope in mean water levels that could change dramatically if the prevailing pattern of ocean currents changed.^{174/}

As a result of differences in land elevation and geological processes, such as tectonic uplift or subsidence in coastal areas, actual sea-levels are higher in some regions than others. For example, a rise in sea-level may affect certain parts of the Caribbean more than others because of land subsidence.^{175/} In areas undergoing natural eustatic uplift from tectonic plate movement, glacial rebound, or volcanism, there probably would be little increase in sea-level in contrast to land areas that are naturally subsiding.^{176/} There is a tendency for uplift in many parts of Latin America, although other sectors of the coast have a tendency to subsidence.^{177/}

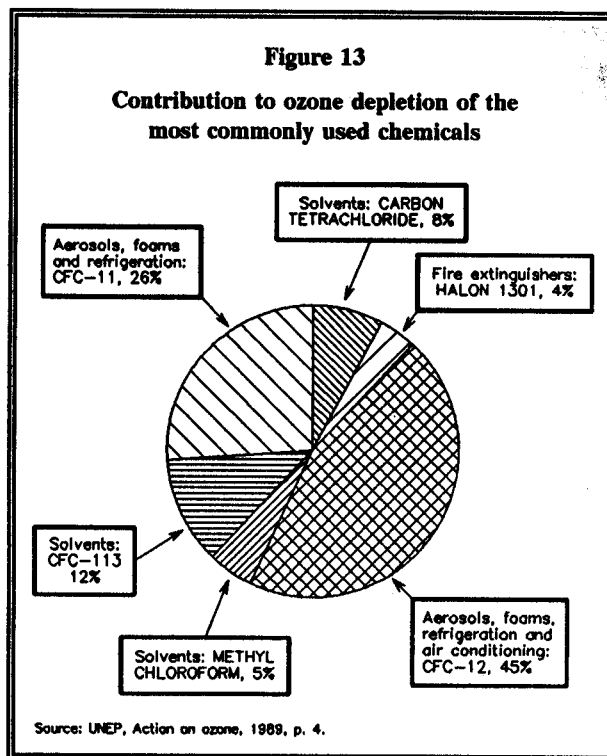
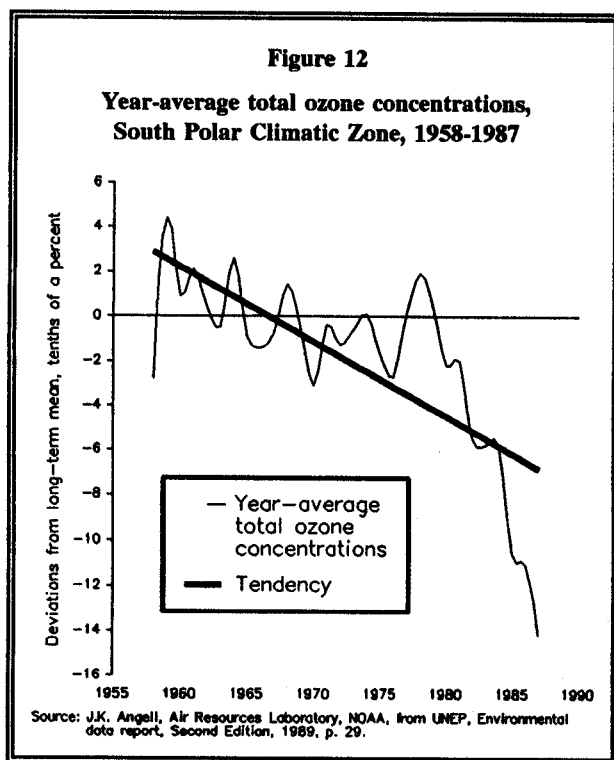
In some areas, the rise in sea-level may be significantly higher or lower due to human intervention. Possible anthropogenic causes of subsidence include over-exploitation of groundwater aquifers, oil and gas production, and limiting the supplies of sediment inflows as a result of river-flow regulation. In the Caribbean, in some areas of significant petroleum or groundwater extraction, the relative sea-level is rising by 10 to 15 centimeters per decade compared to the estimated 2 to 3 centimeters per decade rise due to climatic change.^{178/}

C. The depletion of the stratospheric ozone layer

The issue of stratospheric ozone depletion only became a focus of public attention following the discovery by British Antarctic Survey scientists in 1985 that the amounts of ozone over Halley Bay had abruptly decreased since the early seventies.^{179/} Between 1957 and the early seventies, the ozone concentrations in October remained approximately constant, but since October 1979 ozone thinning has become progressively more severe (Figure 12).^{180/}

Concentrations of ozone (O₃) in the atmosphere are very low, rarely exceeding 5×10^{12} molecules per cubic centimeter, and most of it, about 90%, is in the stratosphere, with maximum concentrations occurring at altitudes of about 25 kilometers over the Equator, declining gradually to 16 kilometers over the Poles.^{181/} Despite the low concentrations, ozone plays a very important role in determining the radiation budget of the planet. Ozone is a strong absorber of ultraviolet radiation. A one percent reduction in ozone would result in about a ten percent increase of radiation at the earth's surface.^{182/}

The absorption of ultraviolet radiation by ozone is a major source of heat for the stratosphere that causes the atmospheric temperature inversion at altitudes from 15 to 50 kilometers.^{183/} The stratospheric ozone layer also contributes towards regulating the earth's temperature.^{184/} Any change in the ozone layer will have an impact on climate. Specifically, a decrease in stratospheric ozone would act to cool the earth's surface, thus providing a small potential offset to greenhouse warming.^{185/}



Ozone exists in equilibrium in the stratosphere. A balance in the chemical reactions that generate and destroy ozone maintains this equilibrium. Ozone forms in the stratosphere from the photo-degradation of molecular oxygen by short-wave ultraviolet radiation, but ultraviolet radiation also breaks down ozone molecules to maintain a balance in the stratosphere.

The increasing presence of hydroxyl, nitrogen and chlorine radicals in the stratosphere, which accelerate the process of ozone destruction, disturbs the ozone equilibrium. The natural sources of hydroxyl and nitrogen radicals are oxidation of water vapour and nitrous oxide generated in soil denitrification. The natural breakdown of methyl chloride and photo-dissociation of CFCs, now the main source, produces chlorine atoms (Figure 13).^{186/} These chemicals act as a catalyst and can participate in many ozone-destroying reactions before being removed from the stratosphere. The chemistry of ozone destruction is very complex, some 200 chemical reactions have been identified involving CFCs.^{187/}

As a result of human activities, there are already enough ozone-destroying substances in the atmosphere to cause further stratospheric ozone depletion. If all CFCs and other chlorine sources were cut off, chlorine levels would continue to rise for a further 20 or 30 years.^{188/} Atmospheric levels of CFCs may increase until around 2000 and then return to the levels of the late seventies by about 2050. This implies that the ozone layer will probably continue to deteriorate for at least a decade before beginning to slowly recover.^{189/} Recent assessments suggest that the Antarctic ozone hole will recur each spring and that, in addition, the depletion of middle and high-latitude stratospheric ozone will continue unabated through the nineties.^{190/}

Recordings from the Nimbus 7 satellite have shown a more marked decline in the ozone layer in the Southern Hemisphere. Recordings also show that the decline has large seasonal variations with

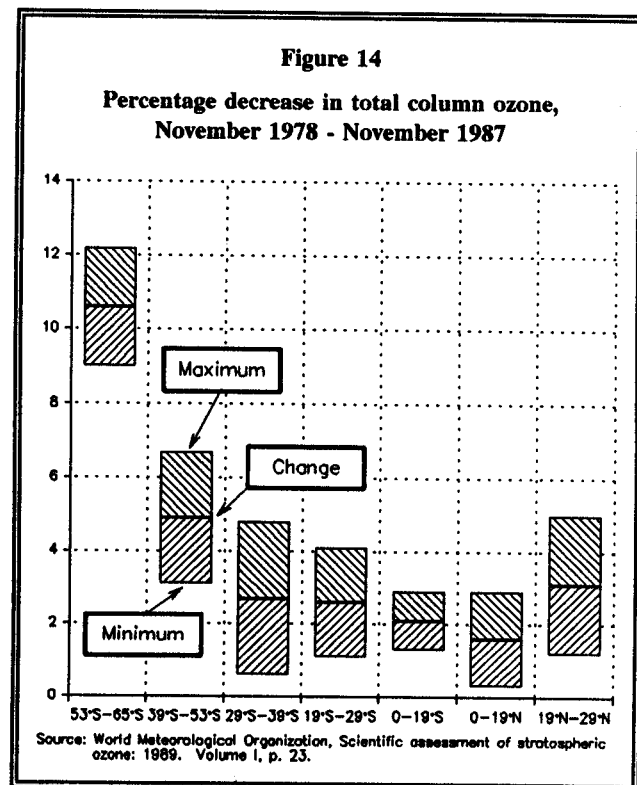
a hole appearing over Antarctica during the southern spring.^{191/} The unique meteorology of the Antarctic helps in the formation of the ozone hole. It provides ideal conditions for ozone destruction by creating an extremely cold isolated mass of air around the South Pole. Chemical reactions on the surfaces of the ice crystals, that make up the polar stratospheric clouds, play a crucial role in its development.^{192/}

Significant decreases, larger during the eighties than in the seventies, have occurred during the last twenty years in total column ozone at all latitudes, except the tropics, in spring, summer and winter.^{193/} Ozone depletion might have begun even over the tropics: the Microwave Limb Sounder on the recently launched NASA's Upper Atmosphere Research Satellite has observed ozone levels in the tropics 10% lower than any previous measurements.^{194/} The largest depletion of ozone, about 50% compared with earlier levels, has been over Antarctica. Decreases are considerably smaller, 5% to 10% during the past decade, over the middle and high latitudes in both hemispheres, although further "dilution" is to be expected.^{195/}

The ozone layer is likely to get thinner above about 25 kilometers, while ozone concentrations could even increase between about 20 kilometers and ground level. This gross distortion of the strata of the ozone layer is likely to have unknown, although, considerable effects on the composition of the earth's climate.^{196/} There are indications that the ozone reductions observed during the eighties have caused reductions in the radiative forcing of the surface-troposphere systems at middle and high-latitudes. This reduction in radiative forcing from ozone depletion could, averaged on a global scale and over the last decade, be approximately equal in magnitude and opposite in sign to the enhanced radiative forcing due to the increase in CFCs.^{197/} The implication could be that with more progress in controlling stratospheric ozone depletion a backlog of unrealized global warming would materialize.

Latin America and the Caribbean are relatively small contributors to the destruction of the ozone layer, only accounting for about 3% of world usage of CFCs.^{198/} The region will probably be, however, among the first areas to experience the consequences of the destruction. The most severe consequences are likely in the tropical and subtropical regions where the intensity of ultraviolet radiation is already high because of the high angle of the sun. The countries of the Southern Cone are also vulnerable to ozone depletion (Figure 14). Since the Antarctic ozone hole cannot get much deeper, there are fears that it may spread outward, encompassing larger areas of Argentina and Chile and expanding above portions of Brazil and Uruguay.^{199/}

Another source of concern is the seasonal breaking up of the polar vortex, a mass of rapidly rotating air constrained by surrounding weather systems.^{200/} The vortex



forms over Antarctica during the polar night. The air masses in it are very cold and remain relatively isolated from the middle latitudes. In early September, the amount of ozone begins to fall rapidly inside the vortex, by as much as 50% to 60% by the end of October. This has occurred in almost every year since 1980.^{201/} When the vortex breaks up in the Antarctic spring, it sends forth massive jets of high-altitude ozone-poor air towards other parts of the globe, including the southern tip of South America.^{202/}

Chapter II

IMPLICATIONS OF GLOBAL CLIMATE CHANGE FOR WATER MANAGEMENT

A. "Greenhouse" warming

Climate change is potentially one of the most challenging problems facing water resource managers in Latin America and the Caribbean. Any change in climate would touch on virtually every aspect of water use in the region (Figure 15).

The most significant characteristics of the potential impact of climatic change for the water resource management include:

- The universal effects of climate change which would be felt, either positively or negatively, by all water uses everywhere, although the impact would be geographically uneven.
- Any changes will occur slowly.
- The uncertainties in all aspects of the relationship between climatic change and water management.
- The potential severity of the economic and social consequences.

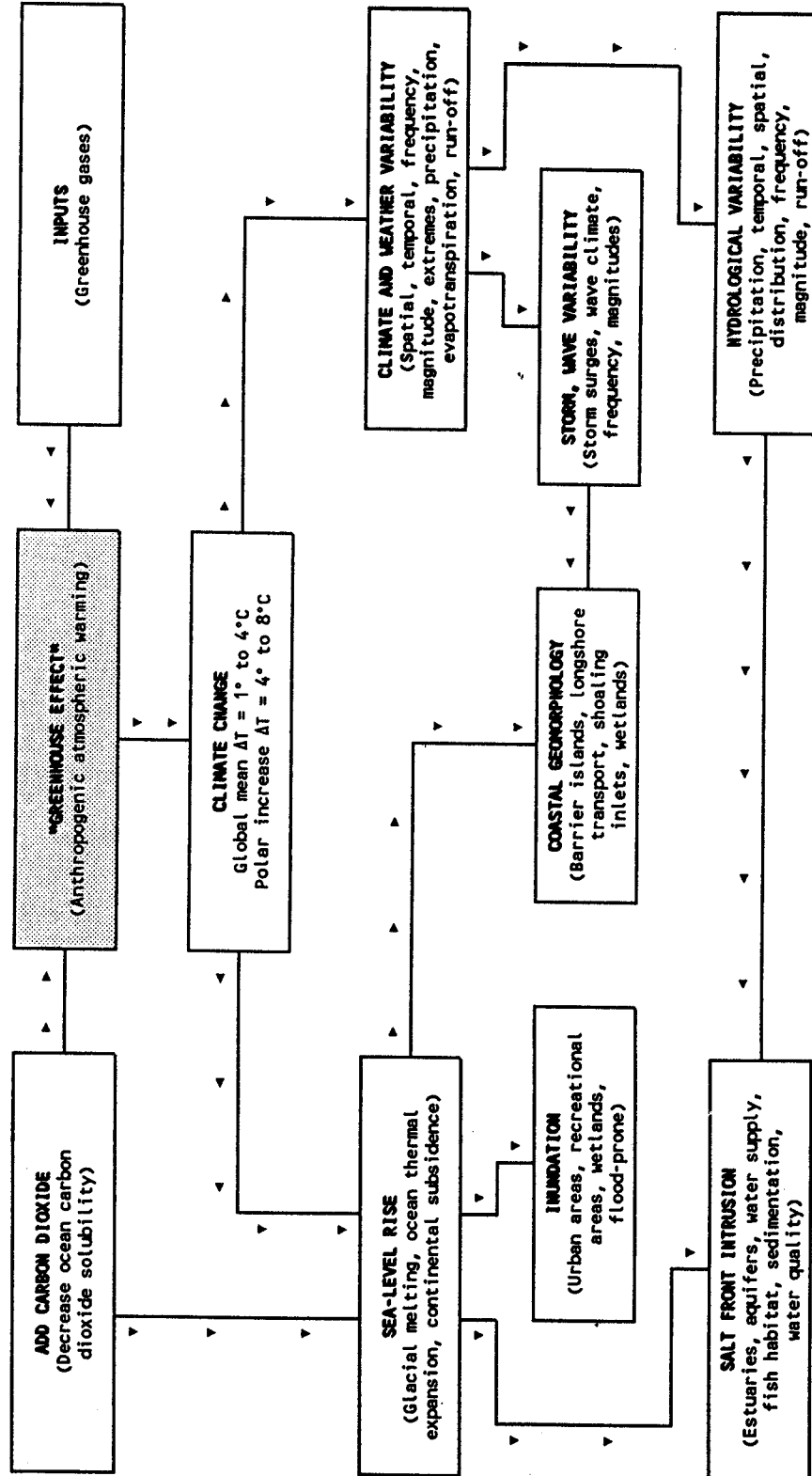
1. The sensitivity of water systems to variations in climate

Any variation in climate exerts a profound effect on the temporal and spatial distribution of temperature, precipitation, evapotranspiration, clouds, storminess, and air currents and winds. In 1990, the Second World Climate Conference noted that: "Among the most important impacts of climate change will be its effects on the hydrological cycle and water management systems, and, through these, on socio-economic systems".^{203/}

Global climatic change could pose a bigger threat to water management than to any other human activity for many reasons. Virtually all activities related to water critically depend on its spatial and temporal availability and can be adversely affected by extreme weather events (Table 5). Climate change is certain, therefore, to have a major impact on the overall hydrologic cycle due to the expected alterations in global temperature and precipitation patterns and in the intensity of extreme weather events, such as tropical cyclones, floods and droughts (Figures 16 and 17).

Figure 15

Physical consequences of climate change



Source: Moser, D. and E. Stakhiv (1989), "Risk-cost evaluation of coastal protection projects with sea-level rise and climate change", Risk analysis and management of natural and man-made hazards, Y.Y. Harris and E. Stakhiv (editors), Proc. Engineering Foundation, ASCE New York, as quoted in Tsyban, A. and J. Titus (chairpersons); and T. Agnew, M. Berry, S. Chernyak, D. Etkin, J. Everett, M. Glantz, B. Glebov, C. Griffiths, M. Korsak, N. Kostyleva, A. Krovin, A. Lapenis, E. LaRoe, A. Lukin, J. Meehan, G. Myakisheva, S. Nishitoka, I. Pershina, S. Petrovskaya, M. Rees, S. Rodionov, V. Shigaev, J. Smith, V. Sprigg, E. Stakhiv, R. Stewart, V. Vronskaya and S. Zeeman (contributors) (1990), Chapter 6. World oceans and coastal zones, First draft, April.

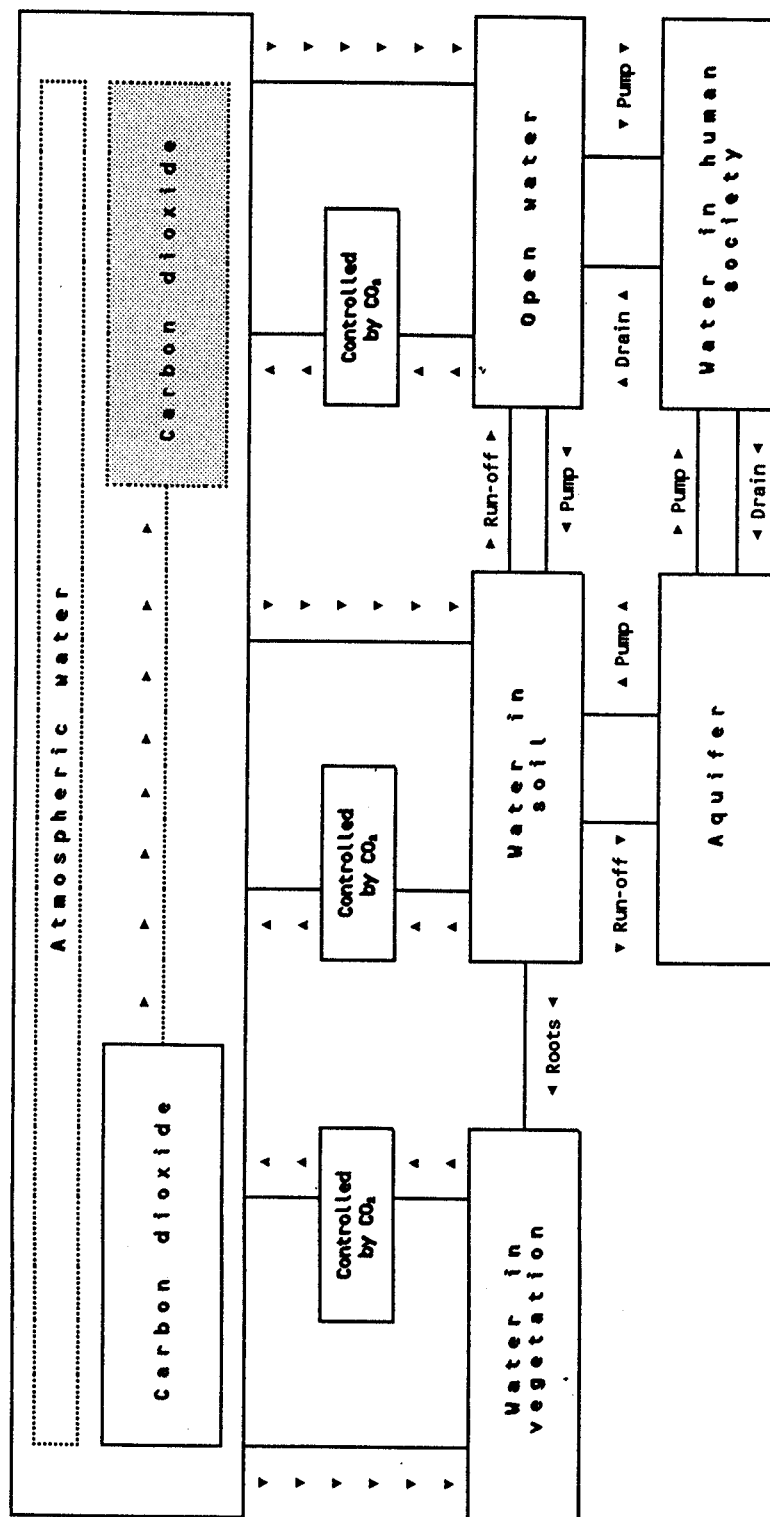
Table 5

**Estimated sensitivity and adaptability of human activities and
nature to climate change**

	S e n s i t i v i t y		
	Low	Adaptation at some cost	Difficult adaptation
Industry and energy	★		
Health	★		
Farming		★	
Managed forests and grasslands		★	
Water resources		★	
Tourism and recreation		★	
Settlements and coastal structures		★	
Human migration		★	
Political tranquility		★	
Natural landscapes			★
Marine ecosystems			★

Source: Chapter 5 of the report of the Adaptation Panel, as quoted in Policy Implications of Greenhouse Warming-Synthesis Panel, Committee on Science, Engineering, and Public Policy, National Academy of Sciences, National Academy of Engineering, Institute of Medicine (1991), *Policy implications of greenhouse warming*, National Academy Press, Washington, D.C.

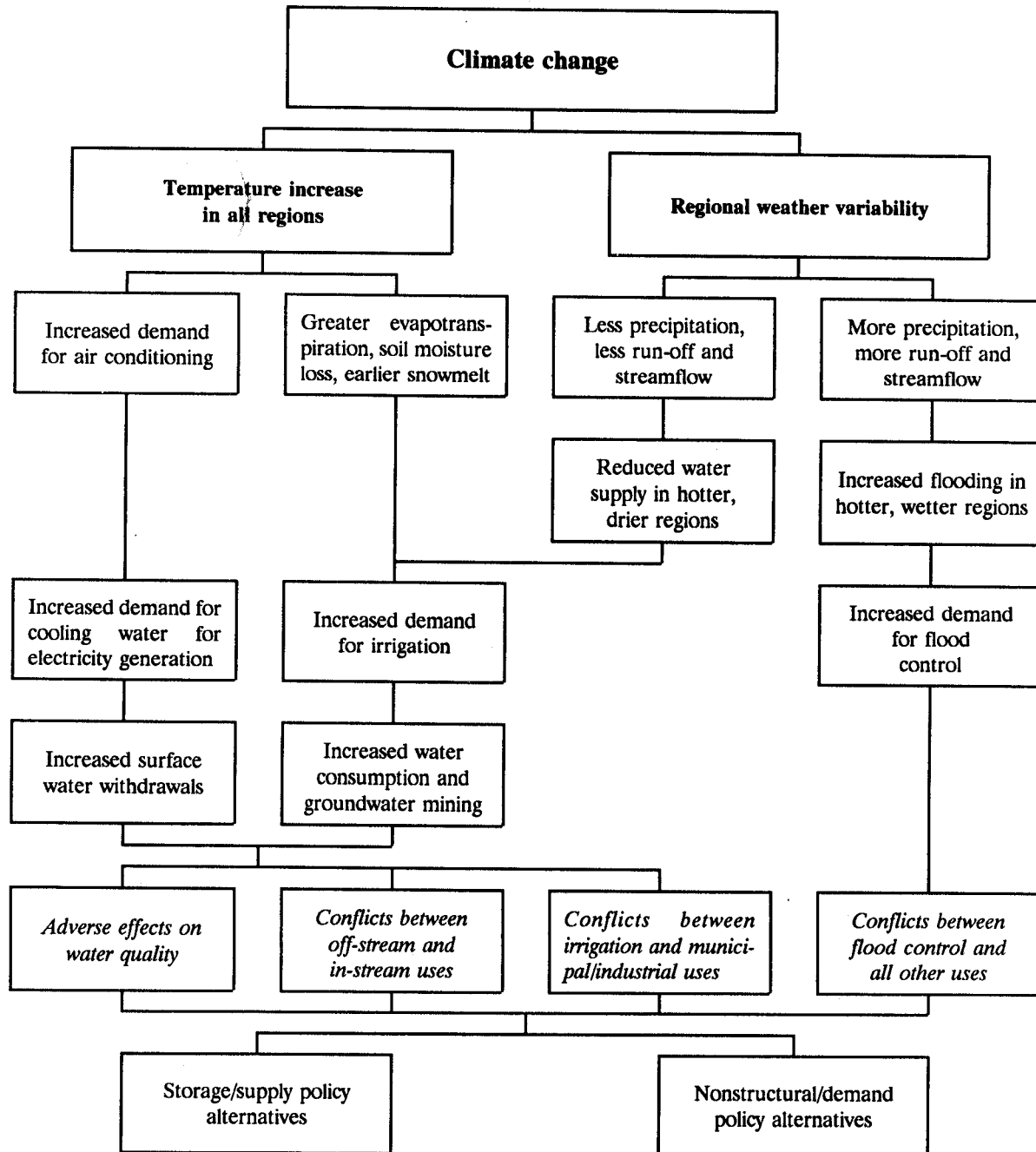
Figure 16
The hydrologic cycle and climate change



Source: Adapted from Waggoner, Paul E. and Roger R. Revelle (1990), "Summary", Paul E. Waggoner (editor), Climate change and U.S. water resources, Report of the American Association for the Advancement of Science Panel on Climate Variability, Climate Change and the Planning and Management of U.S. Water Resources, John Wiley & Sons.

Figure 17

Impacts of climate change on water supply and demand



Source: US EPA (United States Environmental Protection Agency, Office of Policy, Planning and Evaluation, Office of Research and Development) (1988), *The potential effects of global climate change on the United States. Draft. Report to Congress. Volume 2: national studies*, Joel B. Smith and Dennis A. Tirpak (editors).

Moreover, water management structures and design, operation and maintenance procedures are developed on the basis of past local climate and hydrologic patterns. Any significant changes in climate conditions and hydrologic patterns could have serious implications whether the impact of climatic change is negative or beneficial. Finally, although there is a high degree of uncertainty about regional patterns of greenhouse warming-induced hydrometeorological change, it appears that many areas could enjoy increased precipitation, soil moisture and water storage, but water availability could decrease elsewhere.

The vulnerability of water management systems to climate variability falls into three broad groups (Tables 6 and 7):^{204/}

- **Meteorological and climatological vulnerabilities.** The design and operation rules of hydraulic systems are based on the expected magnitude and frequency of extreme weather events. Even structures designed to be resilient and robust are still vulnerable to extreme meteorological events. They are most vulnerable to the timing and magnitude of storms, and to the duration and magnitude of droughts.
- **Hydrologic system and design vulnerabilities.** Hydraulic structures, such as aqueducts, pumps or reservoirs, are physically designed to handle fixed volumes. These may become inadequate, either too small or too large, under changed hydrologic conditions. Hydraulic structures, of course, also fail because of design or construction flaws, and because of incorrect operation and maintenance, as well as due to age, fatigue, etc. Any change in basic hydrologic conditions would amplify such problems. The procedures used for system operation and maintenance are climate specific and, thus, limit the flexibility of response to any changes in the pattern of extreme weather events. Finally, the legal and institutional framework within which structures are designed may place limits on the flexibility of system response to changes in climate. Examples include the creation of barriers to changes in water use or to the transfer of water among users. Areas with already fully appropriated water resources are particularly at risk.
- **Geographical and societal vulnerabilities.** The geographical and societal characteristics of a region can make it more or less vulnerable to changes in water supply patterns. Important risk factors are water scarcity, the degree of pollution, the extent of use of groundwater, the extensive development of floodplains, the degree of dependence on agriculture, and the proportion of energy obtained from hydroelectricity.

(a) Sensitivity of water systems to changes in run-off

Both decreased run-off and increased run-off can have serious consequences for water management. Latin America and the Caribbean, as a whole, has a very abundant supply of water although there are some very arid areas (Figure 18). The effect of global warming on water availability will most significantly affect, therefore, marginal areas where even relatively small changes in precipitation patterns can mean a drought or a flood.

A decrease in average precipitation, an increase in evapotranspiration and in the variability of precipitation can all lead to decreased run-off and, therefore, to a greater frequency of water deficiency and scarcity. Water systems most sensitive to decreases in run-off are those where existing demand is close to or exceeds supply, a situation typical of most arid and semi-arid areas. Problems

Table 6

Vulnerability and sensitivity of water resources management to climate fluctuations

Vulnerability to climate variability ¹				
Vulnerability	Important variables			
Meteorological and climatological vulnerabilities				
• Timing	Annual, seasonal, daily flow			
• Quantity	Absolute and seasonal flow			
Hydrologic system and design vulnerabilities				
• Physical	Storage volume, peak flows, maximum release rate			
• Operational	Timing of flows, timing of demand			
• Legal or institutional	Distribution of water rights and options for transfer			
• Economic	Water pricing, cost of storage or delivery			
Geographical and societal vulnerabilities				
• High demand	Level and timing of demand			
• Flood prone	Peak flow, flood storage volume			
• Water quality	Minimum flows, patterns of use			
• Rain-fed agriculture	Timing of rainfall, evapotranspiration rates			
• Hydroelectricity	Seasonality of flows, reservoir storage volume			
Sensitivity of water resources management to climate fluctuations ²				
Management methods and techniques	Sensitivity to climatic events			
	Within-year	Annual	Multi-year	Century
Protection against floods	★	★		
River regulation		★	★	
Drainage		★	★	★
Water quality management	★	★	★	★
Wastewater renovation		★	★	
Water supply		★	★	★
River canalization (dams)		★	★	
Storage reservoirs		★	★	★
Groundwater utilization		★	★	★
Water transfer		★	★	★
Soil-moisture management	★			
Erosion control	★			

Source: ¹ Gleick, P.H. (1990), "Vulnerability of water systems", Paul E. Waggoner (editor), *Climate change and U.S. water resources*, Report of the American Association for the Advancement of Science Panel on Climate Variability, Climate Change and the Planning and Management of U.S. Water Resources, John Wiley & Sons.

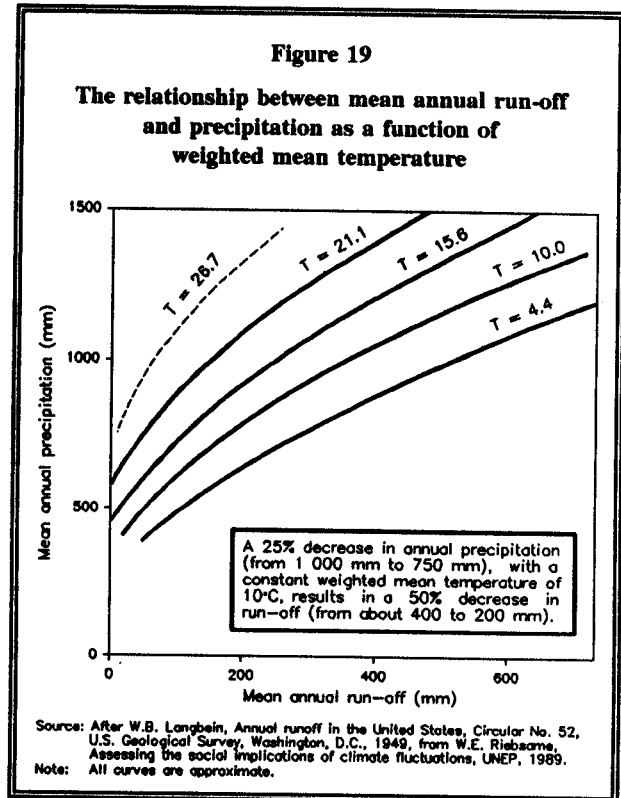
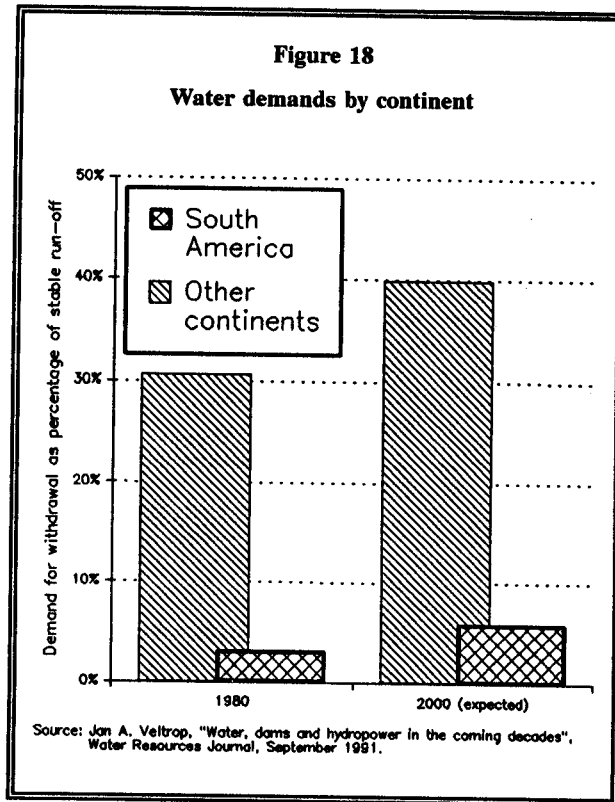
² B. Novaky, et al (1985), "Water resources", R. Kates, J. Ausubel and M. Berberian, eds., *Climate impact assessment*, Chichester, U.K., John Wiley and Sons, as quoted in Riebsame, William E. (1989), *Assessing the social implications of climate fluctuations. A guide to climate impact studies*, United Nations Environment Programme (UNEP), World Climate Impacts Programme.

Table 7

Speculative impact matrix of climatic change

Attributes of water supply systems	Parameters of stream flow				
	Decrease in mean streamflow	Increase in variance of streamflow	Increase in extremes of streamflow	Increase in persistence of streamflow	Speed of change
Yield from unregulated streams	Some effects, but likely not very large unless change in mean is large or combined with other changes	Severe short-term effects	Significant effects as length of low flows increases relative to very high flow periods	Significant effects from duration of low flows more than severity	Not applicable
Yield from reservoirs	Significant to severe effects, particularly if reservoirs provide a high percentage of the average flow	Medium to no effects depending on the size of the reservoir in relation to drainage area; larger reservoirs will suffer smaller effects	Medium to no effects depending on the size of the reservoir in relation to drainage area; larger reservoirs will suffer smaller effects	Significant to severe effects especially if long-term reservoir storage is limited	Not applicable
Yield from groundwater	Significant in the long run, especially if draft on aquifer is near average recharge	Little if any significance	Little if any significance	Effects severe and of long duration	Not applicable
System reliability	Some effects, other than those accounted for above	Some reduction due to constant change in flows	Little or none	Little or none	Sudden changes severely affect reliability, slow ones less or not at all
Magnitude and control of demand	No significant effect	No significant effect	No significant effect	No significant effect; emergency restrictions likely to become less effective in long droughts	Significant and visible effects, relatively fast changes could force major steps toward conservation and demand control
Cost of operation of water system	No significant effects except for any additional construction	Possible increase due to turbidity, increased pumping between systems and possible reservoir construction	No significant effects likely	No significant effects except search for new sources	No effects
Pressure on and ability of the water system to respond to change	Pressure for expansion if shortages repeated. Ability to respond would not be affected by hydrologic events	Pressure for expansion, but rapid return to normal may for some time inhibit expansion	Pressure for expansion would be created if shortages occur repeatedly	Pressure for expansion would mount over time; however, long high flow periods may inhibit development	Sudden or rapid change could increase action; long-term changes would likely be ignored

Source: Schwarz, H.E. (1977), "Climatic change and water supply: how sensitive is the northeast?", Climate, climatic change and water supply, Studies in Geophysics, National Academy of Sciences, Washington, D.C., as quoted in Biswas, Asit K. (1984), "Climate and water resources", Asit K. Biswas (editor), Climate and development, Natural Resources and the Environment Series, Volume 13, Tycooly International Publishing Limited, Dublin.



can also arise, however, in more humid areas when demand exceeds supply. Under such conditions, conflicts could intensify among extractive water uses, especially between large extractive uses, such as irrigation and the rest, and among instream uses requiring the maintenance of minimum flows.

An increase in average precipitation and in its variability can both lead to increased run-off and, therefore, to a greater frequency of flooding. A change from a more evenly distributed rain to fewer, heavier rainstorms could enhance flooding.^{205/} Any significant increase in flood frequency and intensity would have serious implications for flood protection, storm drainage, and the design and operation of virtually all water control systems.

(b) The impact of climate change on run-off

The effects of global climate change on precipitation and temperature would translate into much larger changes in run-off (Figure 19). The impact of any changes in either would be most important in areas where this balance is already precarious, that is where run-off is already in frequent deficit.^{206/}

Run-off sensitivity to changes in precipitation and temperature depends on a number of factors. As temperature rises, more water enters the atmosphere in the form of water vapour and evapotranspiration rises more than linearly with temperature. Some studies suggest that a doubling of both temperature and precipitation increases would quadruple the percentage cutback in summer run-off.^{207/} Run-off may fall even more than this since the non-linear rise in atmospheric water content is likely to lead to a greater increase in evaporation than in precipitation.^{208/}

Changes in precipitation are usually less pronounced than changes in run-off in dry years. The principal reason for this is that as evapotranspiration is relatively constant from one year to another, and most evapotranspiration requirements must be met before surface run-off and groundwater recharge, a comparatively small decline in precipitation tends to lead to a larger reduction in surface run-off.^{209/}

Available studies indicate that stream flow is sensitive to climate change. The affect on low flows would be greater than that on high flows, and dry climates more affected than humid climates. The elasticity of run-off to precipitation change is greater than the elasticity to potential evapotranspiration. This means that, in areas where temperature increase coincides with a decrease in precipitation, run-off will tend to decrease more in comparison with areas where only a temperature increase occurs.^{210/}

The relative contribution of changes in precipitation and temperature to changes in run-off varies among climatic zones, depending on whether a major part of the annual run-off depends solely on rainfall or there is a major contribution from spring floods from snowmelt.

When a major part of annual run-off comes from rainfall, run-off will vary with even small changes in climate, especially in arid and semi-arid regions. For example, a 1°C to 2°C temperature increase coupled with a 10% fall in precipitation could conceivably produce a 40 to 70% reduction in annual run-off in such regions. Empirical data and hydrological models show that annual run-off appears to be more sensitive to changes in precipitation than to changes in temperature.^{211/} In humid areas, a 3°C warming may imply reduced water yield of only 10 to 15%, assuming precipitation remains unchanged.^{212/}

As the majority of Latin American rivers are entirely rain-fed, a variation in rainfall has a significant impact on streamflow.^{213/} Recent studies have attempted to assess the possible impact of global warming on water availability in two wet tropical river basins in Venezuela and for the Plate basin in Uruguay. The results clearly show the effects of changes in precipitation on variations in annual and seasonal surface run-off.^{214/}

In regions where a major part of annual run-off comes from spring floods from snowmelt, a warmer climate implies earlier snowmelt and a smaller share of precipitation in the form of snow. In areas where winter snowfall dominates precipitation and run-off comes mainly from spring snowmelt, any noticeable temperature increase is likely to produce serious changes in seasonal run-off patterns. Even in those areas where precipitation does not decline, warmer temperatures would increase winter run-off and decrease that in summer as the snow melts earlier in the spring and more precipitation comes in the form of rain.^{215/} In those areas and periods where precipitation declines, run-off will fall even further as a result of a combined effect of the lower precipitation and higher evaporation caused by warmer temperatures.

Any prediction of seasonal snow cover in a warmer climate is difficult, but it is fairly certain that the extent of seasonal snow and its duration will decrease in most regions, particularly at mid-latitudes. There has already been a marked but irregular recession of the majority of mountain glaciers since the late nineteenth century.^{216/} There is evidence of glacial retreat on the Equator, in tropical South America, Patagonia, the Antarctic Peninsula and sub-Antarctic islands.^{217/}

In watersheds where seasonal snowfall and snowmelt account for major part of the total water supply, the annual distribution of run-off and soil moisture is more sensitive to changes in air temperature than to changes in precipitation.^{218/} This is important in southern Chile and Argentina, as south of latitude 28°S the upper basins of the rivers rising in the Andean cordillera receive a substantial quantity of water from glaciers and snowmelt.^{219/} A mean annual warming of 2°C may have significant effects on the extent of permafrost ice on Mexico's higher peaks. Disappearance of existing ice fields, although currently not larger than 5 kilometers, would have important consequences for the hydrology of local streams.^{220/}

(c) The impact of climate change on storage

The traditional response to variations in run-off is to increase supply through the construction of storage works. For the world as a whole, reservoir storage makes it possible to increase stable run-off by about 30% and in North America by over 90%. In 1985, South America had the least run-off regulation of any major region.^{221/}

Several studies have attempted to assess the impacts of climate fluctuations on reservoir storage. One such study used altered run-off regimes estimated for several basins to calculate the reservoir size required to achieve a certain level of reliability. In the case of the arid Pease River basin in the southwestern USA a 10% decrease in precipitation led to 150 to 200% increases in storage required to yield 20% of the mean annual run-off at a fixed level of reliability.^{222/} Another recent study shows that, for a 25% decrease in rainfall, the yield could be maintained only by increasing storage by 400%.^{223/}

Global climate change would affect reservoir storage through changes in temperature, as well as through changes in the timing and magnitude of the seasonal streamflow associated with decreased summer and increased winter run-off. A warmer climate would mean increased evaporation. Evaporation losses can be substantial particularly in shallow reservoirs or in reservoirs storing more than annual flows.

In areas where global climate change increases precipitation, heavy rains and more rapid run-off are likely to result in higher rates of land and bank erosion, leading to increased amounts of sediment. In some areas, glacial retreat would also contribute to increased sediment loads in rivers. Increased sediment loads can affect reservoir storage downstream.

2. Implications of global climate change for project design

There are more than 1 400 reservoirs behind large dams in Latin America and the Caribbean with a combined storage capacity of almost 10^{12} cubic metres.^{224/} It is not known if the design specifications based on specific climate parameters will weather climate change. Reservoir reliability analysis uses historical records of run-off, with no consideration given to the impact of potential changes in climate parameters.

(a) Project design

Project design is always based on an implicit assumption that the process producing climate variability is stationary and that the expected condition in the future will vary around a stationary mean. The World Meteorological Organization (WMO) has standardized these norms using averages of climatic variables taken over a 30-year period and updated every decade to produce a set of normal values that represent the central tendency.^{225/} Project management criteria normally use hydrological conditions established from historical data for the past 30 to 100 years, and safety margins provide for errors and unusual conditions.^{226/} The assumption, that the climate will remain stable during project life, is implicit in all water-resource engineering.^{227/} For example, in flood control projects the maximum design flood is based on the highest recorded rainfall or snowmelt extrapolated to the entire basin, assuming soil saturation.^{228/}

A change in climate during the lifetime of many existing water projects could present a serious dilemma. If the climate becomes wetter, costly investment works may become unnecessary and limited resources wasted, but if the climate is to become drier, the same works may be insufficient to meet demand.^{229/}

Global climate change implies a change in the statistical properties of climatic elements and, depending on the safety margins incorporated in a project design, climate change will alter the frequency of conditions that approach or exceed failure thresholds. If the design of a project uses a socially acceptable level of reliability, any alteration in climatic elements exceeding the uncertainty inherent in hydrological and climatological analysis will violate both explicit and implicit planning criteria.^{230/} There is an argument, therefore, for considering ways to incorporate the impact of global climate change in design and risk analysis for the construction, as well as, for the repair and replacement of existing projects.^{231/}

It may be necessary to reconsider many of the basic statistical assumptions used in the planning of water control systems. The use of a stationary mean and consistent variance over time are among these. Reservoir reliability, simulated with hydrologic traces generated with the assumption of non-stationary mean can be significantly different from reliability under constant hydrologic conditions.^{232/}

The consequences of climate change will affect all design criteria and yield models using average climate parameters. This will be particularly important for water control systems dependent on a large fixed infrastructure, such as canals, dams, reservoirs, irrigation systems, with high unit investment costs, as well as long construction periods and lifetimes. The major cause for concern for existing hydraulic structures, particularly those designed for flood control, is the possibility of failure under extreme weather conditions. For example, the small probability of great floods may increase with a climate change, and their occurrence could cause dams with inadequate spillways to fail.^{233/} In most countries, the hydraulic infrastructure is, however, of robust and resilient design and capable of withstanding climate extremes, such as unusually high or low flows and their altered timing.

(b) Selection of construction materials and maintenance

High humidity and high temperatures weaken alumina cement, and low humidity and high evaporation rates lead to plastic cracking of concrete.^{234/} Air pollution affects some metals and other building materials and pollution may increase with greenhouse warming.^{235/} Higher levels of

humidity can also aggravate material damage caused by acidic and other types of air pollution and acid precipitation would probably increase under global warming and stratospheric ozone layer depletion.^{236/}

Increased exposure to ultraviolet radiation can affect synthetic materials with plastics being especially vulnerable.^{237/} Specifically, higher levels of short wavelength radiation below 295 nm will lead to a significant acceleration of light-induced degradation processes of plastics and other outdoor coatings.^{238/} Increased resistance of these materials to ultraviolet radiation is possible with the help of chemical stabilizers.

The amount of ozone and other photochemical oxidants at the earth's surface will increase with the destruction of the stratospheric ozone layer. Ground-level ozone contributes to deterioration in paints, fabrics, elastomers and plastics.^{239/} This may have some implications for project design and for the selection of appropriate construction materials.

(c) Project construction

Extreme cold and heat, rainfall, and storms are responsible for many delays in construction. It is not yet possible to determine whether the adverse effects of increased rainfall on construction would be greater or smaller than the beneficial effects of warming on construction during winter months.^{240/} The prevailing climates in Latin America and the Caribbean, would suggest that climatic change would have adverse effects on construction, due to increases in rainfall and in the incidence of heat waves, rather than beneficial effects, except in high mountain areas and the extreme south.

Changes in foundation conditions such as soil shrinkage and swelling as a result of climate change in clay-rich areas could have important implications for the construction of control structures in some areas.^{241/} Similarly, a significant shift in the permafrost zone would prove disruptive to infrastructure in the permafrost region.

Greenhouse-induced warming could lead to a deterioration in the levels of human thermal comfort, especially for outside workers in construction and similar activities with possible reductions in the levels of worker productivity.

3. Possible responses

The uncertainty of the timing, magnitude and regional patterns of the climate change makes the selection of appropriate responses complicated. The most common strategies for dealing with uncertainty of this magnitude include deferring decisions until additional information is available, conserving flexibility in project design and operation and building safeguards or contingencies into project design.

Flexibility in project design and operation will allow beneficial responses as new data becomes available. Any required changes will then be relatively easy and inexpensive. It may be advisable to accept the alternative that affords the greatest flexibility and possibly preferable to substitute flexibility for a portion of current net benefits. A simple example is building large dam, which due to the economies of scale even if under used for a long period, is usually cheaper than building one smaller dam now and a second in several years. On the other hand, building one large dam can mean

that smaller dams are no longer feasible. Small dams leave the larger alternative open, even if at a higher cost. It is true that larger projects are intrinsically capable of taking advantage of economies of scale, but often they are less flexible because of long lead times, difficulties of modification, and potential larger negative impacts. Moreover, smaller projects may offer the added benefit of the possibility of later diversification.

A flexible response to changing climate conditions on the one hand, and promotion of research of new techniques, technologies and management practices on the other will require the development of appropriate institutional mechanisms. Marginal-cost pricing and water marketing, and similar measures to encourage water-saving and the reallocation of supplies in response to changing conditions are examples of the required type of institutional response.^{242/}

Perhaps the most important policy consideration for adapting to hydrologic uncertainty under climate change is the need to develop and introduce mechanisms to facilitate the reallocation of water supplies. A well functioning market mechanism is the only efficient means of adjusting allocations in the face of limited resources. There is, therefore, a clear need to explore the application of market mechanisms in water management. At the same time, it is necessary to identify possible market failures where the market may not generate price signals to guide water users in the reallocation of supplies.

It is possible to ensure robust and resilient water control systems, under a wide range of climates, by building in safeguards or contingencies into project design for new, modified and rehabilitated hydraulic structures and their respective operation and maintenance procedures. The traditional responses to adverse changes in water supply and demand have been either to increase supply, either through structural solutions or through direct restrictions on demand. Analysis of recent experience suggests that market solutions require greater attention.

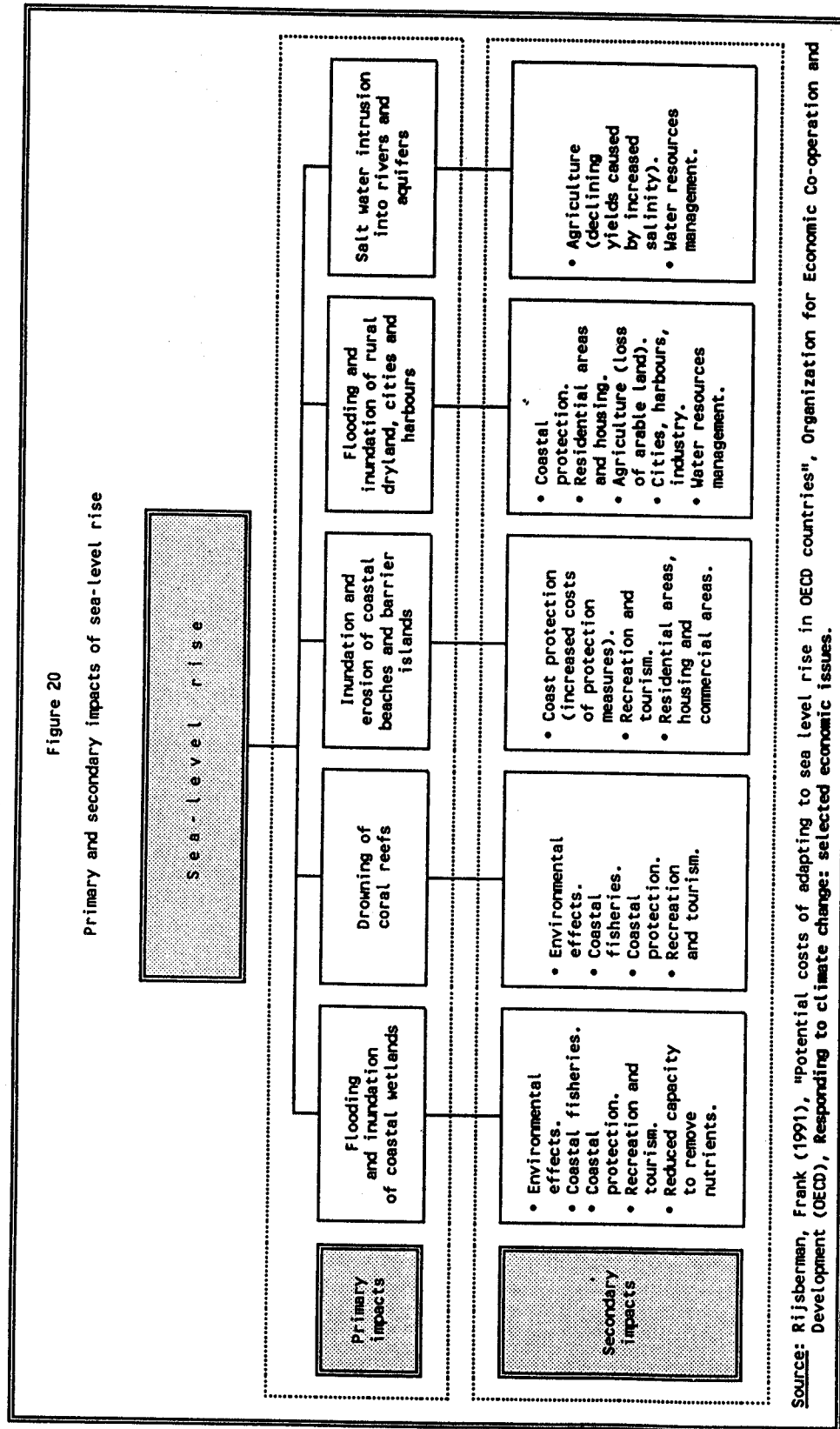
Finally, risk pooling or diversification is, perhaps, the most frequently recommended method for maintaining flexibility in the design of water control systems. Frequently there is a negatively correlation between the benefits and costs of different projects or associated with different purposes of the same project. A change in one is balanced by a change in the opposite direction in another. Diversification is particularly appropriate in situations where there are many interdependent projects. Water yields can increase substantially when structures and both surface and groundwater supplies are operated as one system, rather than as independent projects.^{243/}

B. Rising sea-levels

A rise in sea-level could inundate and displace wetlands and lowlands, erode shorelines, exacerbate coastal storm flooding, increase the salinity of estuaries and threaten freshwater aquifers and otherwise impair water quality, alter tidal ranges in rivers and bays, change sediment deposition patterns, and decrease the amount of light reaching water bottoms (Figure 20).^{244/}

A rise in sea-level of 1 meter over the next century could inundate areas up to 20 kilometers inland from the present shoreline.^{245/} The consequences of the measures adopted to protect areas against inundation, tidal flooding and other effects of a rise in sea-level would be felt many kilometers inland. The social and cultural implications of adaptive response measures may affect people living in coastal zones with an average width of 50 kilometers.^{246/} If maximum storm surges and the upstream effects of flooding and saltwater intrusions are considered, all land up to 5 meters above mean sea-level is, within one to three centuries, potentially subject some way to a rise in

Figure 20
Primary and secondary impacts of sea-level rise



sea-level.^{247/} The land area that would be subject to inundation or indirectly influenced, deteriorated, or made vulnerable by saltwater intrusion would be only about 3% of the present land area, but would be one-third of the total area of cropland.^{248/}

Effects anywhere near this magnitude could have important implications in Latin America and the Caribbean (Figure 21 and Tables 8, 9 and 10). Any rise in sea-level would intensify competition for the remaining areas of coastal plain, resulting in an intensification of their already intensive occupation.

1. Coastal inundation, beach erosion and shoreline recession

As sea-level rises, coastal flooding could increase substantially, as the base for storm surges to build upon will also rise.^{249/} This would be particularly important in areas where hurricanes or severe storms are frequent, such as Central America and the Caribbean. A 1 metre rise in sea-level would enable a 15-year storm to flood many areas now only flooded by a 100-year storm and storm surges would penetrate further inland.^{250/} Beach erosion would make coastal areas more vulnerable to storm waves. Erosion will remove the protective barriers, such as beaches, sand dunes, marshes and mangroves, which currently shield many areas from direct wave attack leaving them more vulnerable to flooding.^{251/}

In addition, higher water levels would reduce coastal drainage. This would increase flooding attributable to rainstorms and river surges and might require additional pumping in artificially drained areas possibly exceeding current pumping capacities. Higher water tables would flood basements and in areas where the groundwater is near the surface may leach it above the surface.^{252/}

The increase in sea-level and the consequent choking of the mouths of rivers will increase the number of areas vulnerable to flooding on many large and small rivers along the coast of Latin America and the Caribbean.^{253/} The impact of such a change would be particularly severe in areas where a rise in sea-level coincides with an increase in precipitation and run-off, particularly in the frequency and magnitude of tropical cyclones, coastal storms and changes in the timing of snowmelt.

The main adaptive measures to deal with the problems of coastal inundation, beach erosion and shoreline recession include:^{254/}

- the abandoning of developed land;
- not developing flood prone areas or

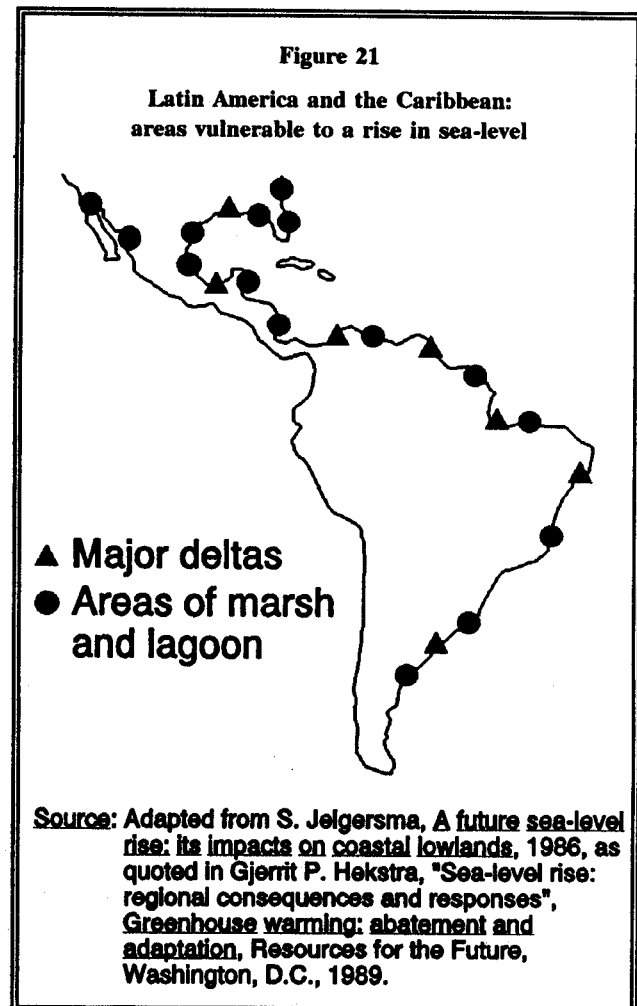


Table 8
Southeast Pacific: impact of a sea-level rise of 28 centimeters
on principal estuaries

Estuary	Impact	Estuary	Impact	Estuary	Impact
<i>C h i l e</i>					
Petorca	Medium	Ñuble	High	Puelo	Medium
Aconcagua	Low	Bío-Bío	Low	Yelcho	Low
Maipo	Low	Imperial	Low	Cisnes	Low
Rapel	Low	Tolten	Low	Palena	Low
Mataquito	Low	Valdivia	Low	Baker	Low
Maule	Low	Bueno	Low	Pascua	Low
Itata	High	Mauñín	Medium	Serrano	Low
<i>C o l o m b i a</i>					
Docapadó	Medium	Micay	Medium	Patia	High
Sal Juan	Medium	Timbiquí	High	Mira	Medium
Dagua	High	Guapi	High	Mataje	High
Cajambre	Medium	Tapaje	High		
Yurumangui	Medium	Sanquianga	High		
<i>E c u a d o r</i>					
Esmeraldas	High	Daule	High	Estuario Interior	High
Guayas	High				
<i>P a n a m a</i>					
Tuira	Low	Chiriquí	Medium		
<i>P e r u</i>					
Tumbes	Low	Jequetepeque	Low	Mala	High
Pisco	Medium	Noche	Medium	Huanra	Low
Piura	Low	Rimac	Low		
Camaná	Low	Lurin	Low		

Source: Aguilera, Rosa, Belisario Andrade, Sergio Avaria, Nora Cabrera, Carlos Canales, Felix Espinoza, Luis Ramorino, Marco Antonio Retamal and Américo Rivera (1992), *Efectos de los cambios climáticos en los ecosistemas costeros y marinos de Chile*, Dirección General del Territorio Marítimo y de Marina Mercante de Chile, compiled and edited by the Servicio Hidrográfico y Oceanográfico de la Armada de Chile, Departamento de Oceanografía, Chile; and UNEP/CPPS/Plan de Acción para la Protección del Medio Marino y Areas Costeras del Pacífico Sudeste (United Nations Environment Programme/Comisión Permanente del Pacífico Sur) (1991), *Efectos de los cambios climáticos en los ecosistemas costeros y marinos del Pacífico Sudeste*, Informe del Grupo de Trabajo Regional, Segunda Reunión, Santiago, Chile.

Table 9
Implications of climatic changes in the Wider Caribbean

	Level of vulnerability	
	Sea-level rise of 20 cm	Temperature increase of 1.5°C
E c o s y s t e m s		
Deltas	High	Low
Estuaries	Moderate	Moderate
Swamps	Moderate	Moderate
Coastal lagoons	Moderate	Low
Coral reefs	Moderate	Moderate
Mangroves	Moderate	Low
Marine meadows	Moderate	Moderate
Fisheries	Low	Moderate
Agriculture	Low	Low
Forests	Low	Moderate
S o c i a l - e c o n o m i c s y s t e m s		
Costal zones	Low	Moderate
Tourism	Moderate	Low
Settlements and structures	Moderate	Low
Public health	Low	Moderate
Tropical storms	Low	High

Source: UNEP (United Nations Environment Programme) (1989), "Perspectiva regional sobre los problemas y prioridades ambientales que afectan los recursos costeros y marinos de la región del Gran Caribe", *Informe Técnico del PAC Nº 2*, Programa Ambiental del Caribe (PAC) del PNUMA, Kingston, Jamaica.

Table 10

Effect of 35 cm sea-level rise by 2050 on major ecosystems

Ecosystem	Tropical/subtropical	Mid-latitude	Polar/subpolar
Deltas	High impact	High impact	High impact
Estuaries	Medium impact	Medium impact	Medium impact
Wetlands	Medium impact	Medium impact	Medium impact
Coastal plains	Medium impact	Medium impact	Low impact
Coral reefs	Low impact	High impact	-
Lagoons	Medium impact	Medium impact	Medium impact
Mangroves	Medium impact	-	-
Ice margin	-	Low impact	Medium impact
Seagrass beds	Medium impact	Medium impact	Low impact
Fisheries	Medium impact	Low impact	Low impact
Rivers	Low impact	Low impact	Low impact
Coastal lakes	Low impact	Low impact	Medium impact
Beaches	High impact	High impact	High impact

Source: Tsyban A., J. Everett and M. Perdomo (co-chairs and lead authors); and D. Albritton, A. Bakun, T. Bigford, D. Dow, B. Glebov, P. Kaplin, M. Korsak, A. Kulikov, V. Mamaev, G. Maul, D. Mountain, J. Scheraga, G. Tanov, J. Whittedge and S. Zeeman (contributors) (1992), "World oceans and coastal zones", World Meteorological Organization (WMO), United Nations Environment Programme (UNEP), Intergovernmental Panel on Climate Change (IPCC), *Draft contribution to the 1992 IPCC supplement. Task 2: prediction of the regional distributions of climate change and associated impact studies, including model validation studies. Supporting material*, IPCC/WG-II/5th/Doc. 4, Add. 1 (15.I.1992), IPCC Working Group II (Impacts), Fifth Session, Geneva, February 6-7.

developing them only when adequate precautions have been taken to minimize future flood damage;

- adapting the existing infrastructure to periodical flooding without increasing the protection of the coastline; and
- protecting the coastline from flooding, and taking additional measures to remedy associated drainage problems, salt intrusion, etc.

2. Salinization of groundwater, rivers, bays and soils

Salt water intrusion into aquifers may render them unusable for drinking water supply and irrigation. A higher sea-level could raise underground saltwater levels reducing the depth of overlying fresh groundwater. In areas of low relief, water tables could fall to saltwater levels in dry seasons causing shallow freshwater reservoirs to disappear.

An increase in sea-level represents a particularly serious threat to groundwater resources in islands that depend for their water supply on freshwater lenses above saltwater. There would be a reduction in the thickness of these lenses, lowering the volume of freshwater stored. The higher likelihood of storm overwash would further aggravate the incidence of saltwater contamination. In general, saltwater would advance upstream in estuaries, threatening freshwater intakes and adjacent aquifers. The greater incursion of salt water into freshwater estuarine areas along with larger tidal excursion would reduce the freshwater portion of estuarine rivers, especially during drought periods or where a decrease in net freshwater run-off is likely because of climate change and increased abstractions from water bodies alters the annual hydrograph.

The costs of saltwater intrusion control may be considerable in areas where it is currently limited. Costly control measures may become necessary, such as diverting water inlets or river flows and the damming of arms of the sea.^{255/}

3. Alterations in sediment deposition patterns

Any change in sea-level would affect processes of sediment deposition. Sediment deposition would continue in estuarine and deltaic areas, but beaches would lose sediments to off-shore sinks resulting in increased rates of shore-line regression.^{256/}

Climate change induced increases in water demand could considerably reduce river-flow in some areas. This could correspondingly effect sediment discharge and the pattern of erosion and deposition along the shore.^{257/}

4. Coastal and inland water systems

A rise in sea-level could negatively affect water systems. For example, an increase in the level of rivers approaching the sea and inhibited outflow would require modifications of land drainage systems and the adjustment of dykes, sluices and pumping systems.^{258/}

Not all Latin American and Caribbean countries are equally vulnerable to a rise in sea-level. Although the level of the sea has fluctuated in the geologic past, areas of future changes are now

inhabited. Many people in Latin America and the Caribbean live in coastal regions and a good number of the region's largest cities are ports. It is perhaps unfortunate that all the human occupation of the coast has occurred over a period in which the average sea-level has not changed and is, therefore susceptible to any change in sea-level.

The areas most vulnerable to increasing sea-levels include deltas, polders, areas subject to marine flood damage, areas with certain soil types, such as young fluvisols and gleysols, small islands and atolls, and wetlands including mangrove swamps and marshes.^{259/} On the whole, rising sea-levels would affect lowland coasts composed of mud and easily eroded sands, but would have little effect on the rocky boulder-strewn coasts, such as those of Chile.^{260/}

A rise in sea-level would inundate and result in the potentially large loss of inhabited areas, particularly in low-lying, flat deltas and estuary areas. In extremely flat deltas, a 1 metre rise in sea-level could cause shores to retreat several kilometers.^{261/} In case of large rivers in flat deltas, with a depth of 10 to 20 meters, and a surface water slope about 2 to 5 centimeters per kilometer, increasing levels may penetrate over some hundreds of kilometers.^{262/} A number of large South American rivers have low slopes including, the Magdalena, Orinoco, Amazon, and Parana.^{263/}

C. The depletion of the stratospheric ozone layer

Stratospheric ozone layer depletion will affect water resource management both **directly**, through increased exposure to ultraviolet radiation, and **indirectly**, through its effects on tropospheric ozone formation.

The direct consequences of the depletion of the ozone layer include an increase in the amount of ultraviolet radiation reaching the ground and still largely unknown effects on the earth's climate. An increase in ultraviolet radiation at the earth's surface could have important implications for certain water uses in Latin America and the Caribbean, including agricultural water use, water pollution control, fishing, and water-related recreation.

Destruction of the stratospheric ozone layer would increase the amount of ozone, and possibly other photochemical oxidants, in troposphere and aggravate the problem of acid precipitation. Photochemical air pollution has adverse health effects and is damaging to vegetation and some building materials.

Chapter III

EXTRACTIVE WATER USE AND CLIMATE CHANGE

A. Agriculture

In most Latin American and Caribbean countries, agriculture uses by far the largest volume of water. Irrigation is by far the largest component of agricultural water demand and it is extremely sensitive to changes in climate and weather. Irrigation accounts for about 78% of total water withdrawals in South America and for almost 90% of consumptive use.^{264/} Even relatively small changes, therefore, in irrigation water demand can significantly affect overall water availability.

1. "Greenhouse" warming

Global climate change would not necessarily create difficulties for agriculture in Latin America and the Caribbean, although some areas would be negatively affected (Box 4). Agriculture may benefit at least in some countries where it may contribute to the expansion of the crop area and improving crop yields. The adaptability and flexibility of agriculture, in the face of changes in climate and other aspects of the environment, would limit any damage. There is no reason that agriculture should not continue to adapt in the future. Furthermore continued technological and managerial improvements, similar to those introduced in recent decades, could also offset losses due to climate change. There has been no exhaustive analysis of the capacity of the agricultural sector to face the challenge of global warming and such capacity may be scarce in some areas, particularly in the subsistence sector.

The most vulnerable areas are those already under stress from present fluctuations in climate and where, because of resource constraints, there is a failure to adjust technologically to change. In such areas, even relatively small changes in climate, especially in moisture availability, usually mean the difference between an acceptable year and a bad one. The transition zone between semi-humid and arid climates, as in northeastern Brazil, is one example, where variations in rainfall coupled with constant potential evaporation, strongly affect agricultural productivity.^{265/} Reduced moisture availability combined with increased heat stress and evaporation losses may reduce productive potential. In areas of rain-fed agriculture, this could imply a significant decline in crop area without the introduction of irrigation. For irrigated areas, the area under irrigation may decline without an increase in water use efficiency or an enhancement of water supply.

The adaptation of agricultural water use to climate change is likely to be easiest in countries, like Argentina, Brazil and Chile, that encompass different climate zones. Adaptation would be much more difficult in small countries, such as in Central America, particularly those producing a limited number of crops. In addition, under the conditions of intense global warming and a great uncertainty for the modification in local climates, countries with large irrigated areas and control over river run-off, would have advantages over regions with predominantly rain-fed agriculture.

Box 4

**Intergovernmental Panel on Climate Change estimates
of potential effects of the doubling of the carbon
dioxide equivalent on crop productivity**

Region	Potential effects of climate change on crop productivity
<i>Mexico and Central America</i>	A warming of 3.3°C to 5.4°C combined with changes in rainfall of from -23% to +3%, depending on the circulation model, are likely to produce warmer, drier conditions and reductions in soil moisture of 10% to 20%. This could result in decreases in yields of maize and other rain-fed crops, and, combined with heat stress and irrigation water scarcity, decreases in yields of major irrigated crops such as wheat. If there were increases in rainfall, particularly rainfall intensity, this could lead to enhanced rates of soil erosion and consequent long-term loss of productive potential.
<i>Brazil</i>	In the Northeast, the most vulnerable region, productivity will depend on whether increases in precipitation are sufficient to compensate for the increased potential evapotranspiration due to the higher temperatures. An insufficient increase in rainfall is likely to lead to a serious decline in yield potential. More precipitation in the centre-west would probably increase productivity in soybeans and maize and, in the south, of wheat. A reduction in the frequency of frosts would decrease the risk in citrus and coffee production in the south.
<i>Argentina, Chile and North Andes</i>	Rainfall could increase in currently moist areas and to decrease in the semi-arid areas in the rain shadow of the Andes. Increases of 2°C to 4°C would increase evapotranspiration by at least 10%, possibly leading to a drying of the Pampas. In the more maritime climate of Chile, increased winter precipitation could counter the small increases in evapotranspiration more than in Argentina. Grass production and cattle raising would probably stand to gain most in the centre and south. At high levels in the Andes, where winter minimum temperatures constrain cultivation limits, a 1°C warming would raise limits about 200 metres (3 800 to 4 000 metres in central Ecuador). Increases in rainfall would probably lead to decreases in yields of barley but increases in those of potatoes.

Source: Parry, M.L., G.V. Mendzhulin and S. Sinha (co-chairmen); M.L. Parry (lead author); M.L. Parry and P.N. Duinker (section authors); J.I.L. Morison, J.H. Porter, J. Reilly and L.J. Wright (associate authors); and B. Acock, M. Boko, D. Bond, W. Degefu, T. Farago, R. Heathcote, T. Keane, L. Kettunen, R. Kintanar, D. Linforth, J. Lomas, A. Magalhaes, G. Mendzhulin, P. Mosley, J. Muller, N. Nicholls, Nguyen Hu Ninh, L. Ogallo, J. Oguntinyinbo, S. Panturat, B. Pittock, P. Ramirez, J. Reilly, V. Richter, C. Rosenzweig, J. Salinger, A. Sastri, S. Sinha, O. Sirotenko, B. Smit, Z. Uchijima, J. Williams, M. Yoshino and Jia-cheng Zhang (contributors) (1990), *Chapter 2. The potential impact of climate change on agriculture and forestry*, First draft, April.

(a) The implications of climate change for irrigation

Any changes in climate due to greenhouse warming will influence the extent and location of irrigation development in a number of ways. The principle influence would be, however, changes in water availability, the single most important factor affecting the physiological functions of plant life. Water availability determines the development, survival, and productivity of crops. The process of transpiration governs the amount of water that crops require for their development.^{266/} Temperature, solar radiation, wind and soil moisture among other factors affect transpiration. Transpiration increases with air temperature, insolation and wind so that, even if other environmental factors are unchanged, the projected increases in surface air temperatures will heighten evaporative demands.

Irrigators tend to use more water to help cool plants and compensate for higher transpiration rates. This increase, however, would be partially compensated by a corresponding increase in the efficiency of water use by plants, since plants tend to use water more efficiently in a carbon dioxide-rich environment.^{267/} Some estimates suggest that a temperature rise of 3°C would increase the need for irrigation water by 15%. The same increase in temperature combined with a 10% increase in rainfall would raise irrigation water needs by 7%. If, however, rainfall decreased by 10%, the need for irrigation water would increase by 26%.^{268/}

Irrigated crops could require more water to counteract the effects of reduced precipitation. In some areas, higher peak irrigation water requirements for some crops may require an increase in the capacity of irrigation systems.

With a warmer climate the variations in crop yields are likely to increase and expanding the area under irrigation would be one means to ensure acceptable and stable yield levels.^{269/} The demand for irrigation would increase not only, however, due to increased evaporative demands and changes in precipitation, but also as a result of a longer growing season, more multiple cropping, and changes in the crops grown.

Irrigated agriculture, although less sensitive to short-term fluctuations in rainfall than rain-fed agriculture, is critically dependent on the availability of water. Since the practice of irrigation is mostly in arid and semi-arid regions, where existing demand is close to or exceeds supply, even relatively small changes in water availability can have serious effects. A recent study concluded that a decrease of rainfall of 20% and an increase of evapotranspiration of 15% could result in a reduction in irrigated area of 75%.^{270/}

The reliability of dry land yields is much lower than that of irrigated yields and even small changes in rainfall can cause a disproportionate damage to crops in rain-fed areas. This could mean that a decrease in rainfall or an increase in its variability would provide an incentive for new irrigation development. In areas where the summer growing season becomes warmer and drier, more farmers could shift from dry land to irrigated agriculture, dramatically increasing the demand for water. In addition, a greater share of cropland would require irrigation to compensate for any reduction in soil moisture caused by increased evapotranspiration.^{271/} Increased uncertainty in water supply might also increase the demand for irrigation because farmers view irrigation as one of the principal means to cope with uncertainties in the weather.^{272/}

The pressure for increased irrigation may grow in many regions. This increased demand could, however, increase the stress on and competition for regional water supplies, as well as exacerbate water pollution and other environmental problems. Irrigators would have, however, many ways of adjusting to changes in climate, including reducing water use, scheduling irrigation for the periods most critical to plant growth, and switching to crops that use less water.

**(b) Effects of changes in precipitation
on agricultural water use**

Even small changes in the amount and seasonal distribution of precipitation can have disproportional large effects on crops. Important changes in precipitation patterns, particularly in the semi-arid tropics, could lead either to large spatial shifts of farming activities or to the need for large temporal or regional transfers of water.^{273/} For example, in Ecuador, the agricultural potential may vary substantially with a 10% change in mean annual precipitation.^{274/}

In some areas, climate change would increase precipitation and run-off making some land more suitable for agriculture and benefiting existing irrigated and rain-fed areas with limited water supply. In north central Chile, for example, the projected increase in precipitation may make it possible both to expand farming activities to areas lacking irrigation and to expand existing irrigated areas, as a result of the increased water supply.^{275/} Benefits from increased precipitation are, however, uncertain. If the increase in water supply takes the form of floods and storms, much of it is likely to be lost or damaging to crops.

In areas where changes in precipitation lead to reduced water availability or where a warmer climate significantly increases evapotranspiration rates, to avoid losses and reduce water requirements, farmers will probably have to shift to more heat and drought resistant crops and crops with lower moisture requirements. At high mid-latitudes, a substitution of winter for spring varieties of cereals would be one strategy for avoiding losses due to more frequent dry spells in early summer.^{276/} In rain-fed areas, the expected increase in evapotranspiration rates and greater rainfall variability may increase the premium on soils with a large available water capacity, as well as provide an additional incentive for new irrigation development.^{277/}

With increased rainfall, there might be a higher incidence of waterlogging and higher rates of soil erosion. A reduction in snow cover and earlier snowmelt also might accelerate soil erosion. Improvement in management could be necessary, especially in tropical regions where the overall amount or intensity of rainfall increases.^{278/}

An increase in rainfall alone will not lead to significant increases in soil loss, provided that rainfall intensities remain unchanged, but an increase in rainfall intensities or an increased number of high intensity rainfalls would lead to increased soil erosion.^{279/} Again increased soil erosion is likely to be of particular importance in tropical areas. The potential ability of tropical rainstorms to cause soil erosion is higher because of higher kinetic energy when compared to the gentler rainfall of temperate regions.^{280/} Soil erosion may also become accentuated in tropical areas where climate change leads to more pronounced dry and wet seasons. Longer dry periods would cause greater topsoil loss through wind erosion and would debilitate vegetative cover exacerbating erosion during the rainy season.

Waterlogging may increase in poorly drained areas with heavy soils where rainfall increases during the wet season. Without improvements in drainage, this would adversely affect crops, particularly upland ones, sensitive to waterlogging. The problem of waterlogging could be worse in low-lying coastal areas.

Increased rainfall may accelerate and intensify soil leaching, requiring more intensive fertilizer applications. This may have serious implications for water pollution control. In other areas, global warming may reduce the need for fertilizers by increasing productive potential. Changes in fertilizer use will also depend on the effect of higher concentrations of carbon dioxide on plants, and the effect of any changes in energy prices on the cost of fertilizers. For example, there is some evidence that under increased ambient carbon dioxide, lower nitrogen fertilizer application may produce the same yields.^{281/} On the other hand, there are some indications that the actions aimed at controlling greenhouse gas emissions may include limiting the use of nitrate and ammonium fertilizers.

(c) The effects of increased carbon dioxide on crops

Increases in ambient carbon dioxide may have diverse and significant effects on plant growth (Table 11). Experiments show carbon dioxide enrichment to be beneficial for yield volume, water use efficiency and tolerance to salinity, but difficult to quantify as the magnitude of the effect appears to depend on factors, such as available moisture, solar light, temperature and wind. It remains uncertain, therefore, whether these benefits will be obtained in open fields where they could be reduced over time by increased exposure to ultraviolet radiation, enhanced levels of air pollution, or other stresses. A plant's positive response to elevated carbon dioxide will not necessarily translate into increased growth for entire plant communities.^{282/} Moreover, when nutrients, water and light levels are low, carbon dioxide fertilization has only a slight effect on many plants.^{283/}

There is some evidence that the effect of carbon dioxide enrichment on plant growth is dependent on temperature and could be increased up to threefold by a 3°C rise in air surface temperatures.^{284/} A doubling of carbon dioxide, increases the optimum temperature for photosynthesis by about 4°C to 6°C.^{285/} This may seem to give an advantage to warmer climates, but the optimum range of temperature for photosynthesis narrows. As a result, under elevated carbon dioxide levels, photosynthesis, and by inference the growth rate, may become more variable as temperature conditions change.^{286/} Differences in the response to increased carbon dioxide between different plant groups could change relative crop performance and may force changes in areas sown and, by inference, in patterns of irrigated agriculture.



(d) The effects of elevated carbon dioxide on water use

Increased carbon dioxide concentration in the air around a leaf produces a decline in water vapour loss from the leaf. This leads to a decline in the rate of transpiration.^{287/} Water use efficiency in plant production increases.^{288/} Since plants under carbon dioxide enrichment maintain higher water potential longer under drought stress than plants in a normal atmosphere, the enriched plants are able to photosynthesize more actively.^{289/} Doubling carbon dioxide levels reduces transpiration by a third to half. Across an entire basin this could mean in a substantial increase in run-off.^{290/}

A review of several experiments has shown that with an increase in carbon dioxide from 330 to 640 parts per million, water use efficiency nearly doubles.^{291/} Increases in water use efficiency

Table 11

Biological effects of carbon dioxide enrichment

Group of plants a/	C₃ plants <i>utilize a photosynthetic pathway involving a three-carbon intermediate product</i>		C₄ plants <i>utilize the C-4 dicarboxylic acid chemical pathway for photosynthesis</i>	
Typical examples		Small grains Temperate cereals Root crops Most trees Some weeds		Tropical grasses Some weeds
	Alfalfa, banana, barley, beans, cacao, citrus, coconut, coffee, cotton, cucumber, legumes, mango, melons, onion, papaya, potatoes, rice, rubber, soybean, squash, tea, tomato, wheat		Corn, millet, sorghum, sugarcane	
Expected effect on crop yield b/	+ 10 to 50% (Respond with a significantly increased rate of photosynthetic fixation of carbon)		+ 0 to 10% (Photosynthetic response to carbon dioxide enrichment is less marked)	
Expected effect on water use efficiency b/	Water use efficiency is expected to nearly double (This effect is believed to be not very much different on the average between species of both groups)			
Tolerance to adverse conditions	Plant tolerance to adverse environmental conditions may improve (Nutrient limitation, water shortage, cool temperatures, lack of light, air pollution, poor soils, saline and polluted environments)			
Input requirements	High yields may depend on the availability of adequate inputs (Beneficial effects are expected to be particularly large where plants have plentiful supplies of nutrients, light, water, and other inputs, that is, principally in man-managed artificial environments)			

Source: ECLAC on the basis of various sources.

Note: a/ - A third, but relatively minor, group of plants accomplishes photosynthesis through crassulacean acid metabolism (CAM). This group includes mostly succulent desert plants and can be largely ignored for the purpose of this discussion; the species in this group show little or no response to increased carbon dioxide concentrations.

b/ - For a doubling of carbon dioxide atmospheric concentration.

under conditions of carbon dioxide enrichment may improve the drought resistance of crops offsetting some of the detrimental effects of a drier climate.^{292/} There remains considerable uncertainty, however, about the magnitude of this increase in efficiency under natural field conditions.

Virtually all studies on the effects of a global rise in atmospheric carbon dioxide show beneficial effects for crop yields and water use. There is some evidence, however, that temperatures above 19°C enhance the positive benefits of increases in ambient carbon dioxide.^{293/} In addition, some studies seem to suggest that the carbon dioxide response is higher under adverse environmental conditions that could benefit production in saline and polluted environments.^{294/}

(e) Effects of changes in temperature on agricultural water use

Temperature has important effects on plant development and water use. Any increase in temperature would increase water use by plants, provoke changes in crop location, and by inference in the location of irrigation. It could also enhance the potential for chemical deterioration of soils by accelerating the processes of salinization and alkalization.

Plant response to changes in temperature differs between species and varieties. Despite the potential negative effects of higher global temperatures on net photosynthesis, a positive interaction was found between atmospheric carbon dioxide enrichment and air temperature on the growth of some plant species.^{295/} In addition, high temperatures encourage more rapid maturation of plants and shorten the period of grain filling.^{296/} Temperature induced shortening of phenological stages may negatively affect crop growth even in the areas where adequate water is available.^{297/} As a result, warming may reduce yield potential in the core areas of current production, because higher temperatures encourage more rapid maturation of plants and shorten the period of grain filling.^{298/}

A lengthening of the dry season or an increase in groundwater table levels could intensify salinization problems leading to an increase soil erosion and a reduction in water quality. Salinization is a major contributor to increased desertification.^{299/}

Warmer temperatures would speed up the decomposition of soil organic matter and carbon dioxide fertilization effect could enhance plant residue formation both above and below ground.^{300/}

The projected changes in surface air temperature could cause spatial shifts in agriculture and its associated infrastructure causing significant dislocations in regional economies. Some studies suggest that 48% of the global terrestrial surface would change vegetation type.^{301/} For example, global warming is likely to extend present farm land limits southwards in the Southern Hemisphere reducing the intensity of use in the north and increasing intensity in the south, given adequate soil and relief. Any changes will also depend on regional precipitation patterns, the competitiveness of different crops and their environmental requirements. The general poleward shift of agricultural zones will be most pronounced in mid and high latitudes.^{302/} According to available assessments, a 3°C warming would displace vegetation zones in the world's mid-latitudes about 300 kilometers poleward.^{303/} In the mid and high-latitude cereal growing regions, horizontal shifts of several hundred kilometers per degree change in temperature are possible, assuming unchanged technology and economic constraints.^{304/} Overall, agriculture will tend to shift poleward, provided that water availability and other environmental factors are not a limiting factor. The rapid narrowing of the continent south of 10°S and poor soil quality would limit a poleward shift of agriculture in South

America. Land classified as "cold" accounts for only 3% of total land area in South America and for slightly over 0% in Central America and the Caribbean.^{305/} Increased rainfall could aggravate this problem by provoking changes in the soil base.

Limitation of yields may occur in some semi-arid tropical and subtropical areas where changes in precipitation and temperature reduce crop water availability.^{306/} Temperature changes are expected to be more pronounced, however, in temperate zones than in the tropics. The thermal effects on farming are likely to be generally positive since they will extend the crop's potential growing period and possibly the area. Higher summer temperatures combined with unchanged or diminished cloud cover would tend to increase the potential level of evapotranspiration and increase crop demand for water. This implies an earlier start to irrigation. In continental interiors, lower summer rainfall and projected drier conditions would be a limiting factor for non-irrigated crops. A larger percentage of rainfall in mountain areas than at present would reduce the water stored in the snow cover reducing water availability in spring and summer.^{307/}

Winter temperatures could increase noticeably in high latitude areas. The thermal effect could shift the crop growing southwards and extend the growing season. Increased winter rainfall would have a beneficial effect in zones with deep soil and heavy water storage potential in autumn and winter, but excessive rainfall could be adverse for farming.^{308/} Similarly, temperature increases in mountain areas may expand the area suitable for agricultural development, including irrigation, by increasing the altitude limits for crop production. Upward shifts are estimated to increase the farmed area significantly in high mid-latitude mountain environments.^{309/} For example, at high levels in the Andes, where winter minimum temperatures constrain cultivation, a 1°C warming would raise limits about 200 metres (3 800 metres to 4 000 metres in central Ecuador).^{310/}

(f) Changes in the distribution of agricultural pests and diseases

The southward extension of the range of some crop diseases and pests or the introduction of new pest due to warmer temperatures and changes in precipitation, soil moisture and sunlight may adversely affect irrigated agriculture. Changes are likely to be greatest at higher latitudes. Susceptibility to plant pathogens may also increase with higher ultraviolet radiation.^{311/}

Even where a warmer climate does not extend the geographical range of crop diseases and pests, higher temperatures may lead to earlier infestation of the already existing ones, increase their population densities, enable them to survive the winter better and to produce two generations every season rather than one at present.

Warmer climates would also favour the infestation of aquatic weeds in irrigation systems and reservoirs increasing maintenance costs. Weed infestation can considerably increase losses through evaporation since water weeds have an evaporation potential several times greater than open water.^{312/} Besides increasing evaporation losses, weeds impede the free flow of water requiring more water to be released to ensure adequate water availability. Weeds also tend to increase the incidence of water-related diseases by providing a favourable habitat for vectors and hosts, can interfere with the operation and maintenance of pumping and hydroelectric generation stations, and may adversely affect fish.^{313/}

Finally, any changes in distribution of agricultural pests and diseases are likely to encourage the use of agricultural chemicals. This could raise production costs reducing incentives for new irrigation development and aggravate water pollution problems.

2. Increasing sea-levels and agricultural water use

Increasing sea-levels through the inundation and erosion of coastal lands could affect agricultural water use, rendering such lands unusable for agriculture. Higher levels may also lead to greater periodical flooding from extreme high tides, storm waves or as a result of disrupted river regimes, as well as increase the salinity of fresh water in coastal areas and aquifers and contaminate soils.

For the world as a whole, the land area that would be subject to inundation or indirectly influenced, deteriorated, or made vulnerable by saltwater intrusion is approximately 5 million square kilometers.^{314/} In Latin America and the Caribbean, the most vulnerable areas where losses to agriculture would occur include those parts of the Argentinean Pampas bordering the Plate estuary, parts of the coast and the Amazon delta in Brazil, coastal regions of Surinam and coastal regions of Venezuela.^{315/} Other areas barely above the present sea-level could also lose farmland.

Saltwater intrusion contaminates surface water and groundwater increasing salinity and making them unsuitable for agricultural water supply. Tolerance to salinity varies between crop species and varieties, but on the whole, at high salinity levels, the growth and yield of most plants suffers. Some studies suggest that carbon dioxide enrichment may enhance crop tolerance to salinity.^{316/}

3. Agricultural water use and the depletion of the stratospheric ozone layer

Depletion of the stratospheric ozone layer could affect agricultural water use through increased exposure of plants to ultraviolet radiation, and through its effects on increased tropospheric ozone formation.

Increased exposure to ultraviolet radiation causes some inhibition of plant growth and photosynthesis, but different plant species vary in their sensitivity to ultraviolet radiation. Two thirds of some 300 crops and other plant species, tested for their tolerance, were sensitive to ultraviolet light.^{317/}

The damaging effect of photochemical air pollution, especially ozone, on vegetation was first observed in the Los Angeles area of California in 1944.^{318/} Besides heavily polluted urban areas, the risk of vegetation damage by ozone may become high in the tropics during the dry season when ozone concentrations are already high because of biomass burning. Already ozone volume mixing ratios of more than 40 parts per billion are frequent during the dry season, similar values to those over polluted industrialized regions. The risk may be even higher in mountainous regions, with the possibility of ozone concentrations above 70 parts per billion.^{319/}

B. Other extractive water uses

Other extractive uses of water are of much less significance than agricultural use. Public water supply is the most widespread extractive use, but its withdrawals are relatively small. In South America, water withdrawals for domestic and municipal uses and for industry and power production were each around 11% of total withdrawals in 1980.^{320/}

The direct impact of global climate change on industrial water use is likely to be negligible, as most industrial activities are not climate dependent. Where temperature and humidity conditions are important, space heating, dehumidification and air conditioning are often the solution. Indirectly, changes in the availability and location of raw material resources may affect industrial water use, as in the fish processing and forestry product industries. The general response to global warming could be a shift southwards.

Public water supply and sewage disposal may be among the water uses most sensitive to climate change. Assuming no behavioral adjustment, water demand within public systems would increase under a warmer climate. In urban and suburban areas, outdoor water use usually increases during hotter summers.^{321/} Some studies suggest that warming, especially longer and more severe hot spells, would initially increase water demand, particularly in normally dry regions.^{322/}

Climate change could effect surface and ground water quality, as well as the incidence of water-related diseases. Changes in water quality, higher water temperatures and reduced streamflows could require the adoption of more stringent levels of effluent treatment to maintain water quality standards.

Industrial, residential and municipal water use would be particularly sensitive to climate change in inland areas due to both increased demand and reduced supply. Changes in the frequency and seasonality of run-off extremes could affect reservoir operation, decreasing safe yields and requiring new operating rules.

Salt water intrusion in aquifers and increased saltwater movement upstream in estuaries or bays could make many current water sources unsuitable due to high salinity. Higher salinity would accelerate the corrosion of distribution systems. In addition, facilities located in low-lying coastal areas could suffer damage from any increase in flooding as well as from higher tides.

Half the public water systems in Latin America and the Caribbean depend on groundwater.^{323/} Many large cities, including Buenos Aires, Lima and São Paulo, use wells located throughout the distribution network.^{324/} Groundwater is also important in the supply on many Caribbean islands. For example, Barbados is totally dependent on groundwater.^{325/}

C. The possible impact of control policies

Policies intended to limit emissions of greenhouse gases could have direct and indirect repercussions on water use. Policies intended to limit carbon dioxide emissions could raise the price of energy, change the demand for industrial products, affect rice cultivation and limit the use of nitrate and ammonium fertilizers.

For example, flooded rice fields produce methane from the anaerobic decomposition of organic matter from both crop residues and fertilizers. Wet rice agriculture is estimated to contribute about 27% of anthropogenic methane emissions and its current emissions may grow by about 50 to 60% by 2025.^{326/} There are, however, only 6.7 million hectares of rice paddies, 4.5% of the world total, in Latin America and the Caribbean.^{327/} Current understanding of the complex interaction between methane production and oxidation, suggests that, in the long term, a comprehensive approach including management of water regimes, improvement of plants, more efficient fertilizer use, and other management practices could achieve reduction of 10% to 30% in methane emissions.^{328/} Given current knowledge, however, there are only limited technological options for reducing methane emissions while maintaining output.

The addition of nitrate and ammonium fertilizers to soils increases emissions of nitrous oxide, another greenhouse gas. In recent years, the consumption of nitrogenous fertilizers, in Latin America and the Caribbean, has been slightly over 3.8 million tons (N) a year.^{329/} The rate of emission of nitrous oxide depends on numerous factors including fertilizer type, the amount and the way of application, soil type, soil temperature and moisture, rainfall, and farming practices. By 2025, without changes in technology, the fertilizer-derived release of nitrous oxide could increase by half.^{330/}

Global warming is unlikely to have any significant direct effect on mining, but it could indirectly through policies intended to limit carbon dioxide emissions from fossil fuels. The consequences could be lower water use in the mining of fossil fuels, especially oil and other carbon-rich fuels, and possibly increased water demand for the production of fossil fuels with lower carbon content, such as natural gas and uranium.

Public policies designed to restrain emissions of greenhouse gases could also affect water use in manufacturing. If the cost of energy increases production may decline in industries that are relatively intensive in energy use, for example, the steel, clay, glass, rubber, plastic, and other chemical industries. Control programmes could seriously affect the cement industry, an important source of carbon dioxide emissions. Water use in these industries could fall with any decrease in production. Less energy-intensive industries, such as food, fibers and other agricultural processing industries, might expand because of lower relative prices and consequently increase water use.

Chapter IV

INSTREAM WATER USE AND CLIMATE CHANGE

A. Water pollution and water quality

Higher water temperatures and reduced streamflows will tend to aggravate water pollution problems and require more stringent levels of wastewater treatment to maintain water quality standards (Table 12). Greenhouse induced climate change will also affect groundwater quality. While in some areas climate change could exacerbate already existing water pollution problems and create new ones, it may improve water quality where increasing streamflows provide more water for greater dilution of pollutants.

Climate changes could have substantial effects on streamflows, most importantly on critical low-flows. In the regions of decreased precipitation or where the increase is not sufficient to compensate for higher rates of evapotranspiration, deterioration is certain to occur. Water quality would also be reduced under increased precipitation if wet periods are shifted back toward the winter and spring, leaving drier conditions in late summer when low flows tend to occur.^{331/} Low flows are of particular importance in many parts of Latin American as practically all human and industrial wastes are discharged without prior treatment, and a considerable part of the population does not have access to a safe water supply.

Increases in water temperature could also effect water quality since dissolved oxygen decreases as water temperatures increase. The rates of biological processes would also accelerate with temperature, increasing biochemical oxygen demand. The net result of these two effects could be a significant reduction in the level of dissolved oxygen.^{332/}

Surface temperature warming and a reduction in stream flow could have serious consequences for lake water quality. In some lakes, global warming could lead to an increase in alga growth that, together with increased thermal stratification, would degrade water quality.^{333/}

Climate change and carbon dioxide enrichment may indirectly lead to increased water pollution from agricultural run-off as a result of a southward migration of agriculture to areas where agricultural chemicals are not presently used and from increased applications of fertilizers and other chemicals to offset anomalous climatic conditions. Intensive application of fertilizers may be necessary to reap the full benefits of carbon dioxide enrichment as plants increase in size and more extensive use of herbicides may become necessary to control weeds.^{334/}

Table 12
Climate change and water quality

Pollutant	Change in low flow	Increased temperature	Increased storm flow
Dissolved oxygen	★	★	★
Suspended sediment	★		★
Fecal coliform	★		★
Acidity	★		
Nitrogen	★		★
Phosphorus	★		★
Salinity	★		
Toxic chemicals	★		

Source: Jacoby, Henry D. (1990), "Water quality", Paul E. Waggoner (editor), *Climate change and U.S. water resources*, Report of the American Association for the Advancement of Science Panel on Climate Variability, Climate Change and the Planning and Management of U.S. Water Resources, John Wiley & Sons.

Heavier rains and the associated rapid run-off could lead to higher rates of land and bank erosion and to the leaching of soil nutrients. Increased storm flows when collected in combined sewerage systems may result in hydraulic overloading and the consequent aggravation of pre-existing pollution problems. As much of the region lies in tropical and sub-tropical zones characterized by heavy rainfall, the amount of storm-water run-off from urbanized areas is already significant.

Precipitation tends to absorb some air pollutants and to carry them directly or indirectly, through run-off or percolation, into water bodies. At higher temperatures, there is a greater atmospheric concentration of hydrogen peroxide. This leads to greater conversion of atmospheric sulphur to sulphuric acid and increasing acid rain.^{335/} Higher temperatures also accelerate the formation of acidic materials and a decrease in stratospheric ozone will make more ultraviolet radiation available to drive chemical reactions. Increased rainfall may dilute, however, the impact of acid rain.^{336/} Acid rain is not as prevalent in Latin America and the Caribbean as in other parts of the world, although Brazil may be vulnerable due to having areas of naturally acidic soils, as in the Amazon Basin.^{337/}

Air movement disperses pollutants diluting them rapidly with increasing distance from the point of origin.^{338/} A reduction in windiness under greenhouse warming may reduce dispersal increasing air pollution at the point of origin but decreasing them downwind. Any reduction in cloud cover and warmer temperatures might enhance the formation of temperature inversions in urban areas, increasing the frequency and intensity of serious air pollution events.

B. Water-related diseases

Temperature and precipitation influence the distribution and abundance of vectors of many water-related diseases, including yellow and dengue fever, malaria, hookworms and schistosomiasis. Any changes in average temperature and precipitation will alter, therefore, the temporal and spatial distribution of these diseases. Climatic changes could result in a higher incidence of water-related diseases. Changes in the distribution of wetlands, particularly seasonal wetlands in warmer regions, which provide habitat for the breeding and growth of vectors will also alter the temporal and spatial distribution of water-related diseases. Increased ultraviolet radiation may also contribute to the increase of the incidence and severity of infectious diseases through the suppression of the immune system.

Weather and water conditions closely influence the abundance of disease-bearing insects. In addition, infections, related to the contamination of water and food, also show seasonal periodicity in temperate climates with the highest incidence in the warm season.^{339/} Should mean temperatures increase in colder areas, favourable survival conditions for vector insects, mollusks, and others and pathogenic microorganisms and parasites would expand. The latitudinal and altitudinal limits of waterborne pathogens would similarly expand, although stratospheric ozone depletion may protect against this, as microorganisms are sensitive to ultraviolet radiation.^{340/} For example, climate and vegetation intimately affect the distribution of mosquito species important to the transmission of malaria. Temperatures of 30°C are optimal for reproduction and ample rainfall is necessary for the formation of the stagnant surface waters essential to keep the larvae alive.^{341/} Climate changes resulting in more days between 16°C and 35°C, with humidity levels between 25% and 60%, would favour mosquitoes.^{342/}

Higher temperatures may lead to the spread of tropical diseases in the Caribbean.^{343/} Some scientists also fear that a surface temperature rise could increase the risk of a spread of diseases caused by parasites, such as Ascariasis and Chagas' disease, which are common in Central and South America.^{344/}

C. Hydroelectric power generation

Hydroelectric power stations normally run at their maximum capacity, providing sufficient water is available, since the marginal cost of each kilowatt produced is close to zero. This means that their operation is sensitive to any reduction in average annual rainfall, increases in variability and increases in the frequency of drought episodes. Hydropower projects with limited storage capacities are also vulnerable to strongly pronounced seasonality of streamflows.^{345/}

Hydroelectric power generation may be more sensitive to changes in water supply than other water uses, because power-generation turbines operate within a smaller range of water level variability than do most raw water supply systems.^{346/} In extreme cases, greenhouse warming-induced changes in water availability may even render some hydroelectric power facilities obsolete.

Extensive dependence on hydroelectricity makes a country particularly vulnerable to droughts. Where much hydroelectric generating capacity is on only a few rivers, any reduction in streamflow may disproportionately affect production. On the other hand, countries with large installed capacity are in a good position to take advantage of any increase in water supply. If climate change increases

precipitation, however, increased sediment loads could affect hydroelectric power generation downstream.

Response policies intended to limit carbon dioxide emissions may have profound impacts on the structure of energy investment. These policies could provide a strong incentive for the development of hydroelectric, geothermal and other renewable sources of energy (Table 13). Latin America and the Caribbean possess an economically exploitable hydroelectric potential of about 805 792 megawatts, although, in 1989, less than 11% of this potential was in use.^{347/}

Global warming could change the pattern of demand for electricity and, therefore, generating capacity requirements. A warmer climate would reduce energy demand for heating, but would increase demand for air conditioning and refrigeration. Any additional electricity requirements are likely to be modest. The estimated incremental electricity needs of developing countries from global warming is equal to less than 10%.^{348/} Undeniably, however, possible climate change will introduce additional uncertainty in energy planning.

Table 13
Tons of carbon dioxide emitted per million kilowatt hours by
different electricity generation technologies

Technology	E n e r g y p r o d u c t i o n s t a g e			
	Fuel extraction	Construction	Operation	Total
Large hydropower	-	3.1	-	3.1
Small hydropower	-	10.0	-	10.0
Geothermal	0.3	1.0	55.5	56.8
Conventional coal	1.0	1.0	962.0	964.0
Oil	-	-	726.2	726.2
Gas	-	-	484.0	484.0
Boiling water reactor	1.5	1.0	5.3	27.8
Wind energy	-	7.4	-	7.4
Photovoltaics	-	5.4	-	5.4
Solar thermal	-	3.6	-	3.6
Wood (sustainable harvest)	-1 509.1	2.9	1 346.3	-159.9

Source: San Martin R.L. (1989), IEA/OECD Experts Seminar on Energy Technologies for Reducing Emissions of Greenhouse Gases, OECD, as quoted in OECD/IEA (Organization for Economic Co-operation and Development/International Energy Agency) (1991), *Greenhouse gas emissions. The energy dimension*.

D. Inland water transport

Changes in water levels and increased sediment loads of navigable rivers and lakes, due to altered hydrological and evaporation patterns, would affect inland water transport. Water levels may also decrease as a result of changes in reservoir release policies because of altered rainfall and snowmelt patterns.

In some navigable water bodies, studies on the effects of global warming show that water levels may fall by as much as 2.5 metres.^{349/} Such changes in water levels could obviously have significant impacts on river and lake navigation and could also cause damage to wooden harbour structures, such as slips and docks.

More frequent and more intense floods could also adversely affect river navigation. A rise in sea-level could alter sediment deposition patterns along the coast and in estuaries. Increased sedimentation could significantly increase dredging costs in both navigable waterways and in ports and harbours. A sea-level rise could bring alterations in the water dynamics of coastal areas that could compromise the operation of existing ports. Any sea-level change too could cause damage to port infrastructure and require adaptation to avoid a decrease in port functionality. A sea-level rise could intensify shoreline erosion demanding the stabilization of the tidal inlets and navigation channels used for navigation, although increases in sea-level may benefit water transport by increasing the allowable draught in shallow areas.^{350/}

Finally any regulatory and tax policies designed to limit emissions of greenhouse gases that would increase fuel costs may affect water transport, as well as change its competitiveness with other forms of transport.

E. Fisheries

1. Fishing

Sea-level and temperature rise, along with changes in precipitation and ultraviolet radiation, could have strong impacts on marine ecosystems, including redistribution and changes in biotic production.^{351/} Primarily, freshwater ecosystems would suffer from changes in temperature, precipitation and run-off, but they might also suffer from increased exposure to ultraviolet radiation. Changes in water quality may affect coastal and inland fisheries.

According to recent assessments, projected climate change may be one of the most important factors affecting fisheries now and over the next few hundred years.^{352/} Greenhouse warming could affect both inland and ocean fisheries, but its effects will not be uniform. Fish population may increase in some areas, but decline in others.

A moderate increase in mean water temperature could enhance fish productivity and boost fish yields. On the other hand, many aquatic organisms are quite sensitive to water temperature and may migrate or otherwise adjust to higher temperatures. Since fish can move easily, quickly adjusting to changes of the environment, the impact of any temperature change would be immediate. Extreme variations could occur locally even though the total biomass has not changed markedly.^{353/} Any

increase in water temperatures could cause significant changes in the distribution and range of fish species with serious implications for the fishing industry.

Changes in temperature extremes may affect fish productivity. Even small changes in mean temperature can markedly alter the frequency of hot and cold "snaps" and both can be devastating. The effects of hot "snaps" are particularly harmful during early juvenile stages.^{354/}

The secondary effects of global climate change and sea-level rise, such as greater estuarine salinity, may offset the benefits to fish of warmer water temperatures.^{355/}

Global warming will not affect inland fishing uniformly. Fish population may increase in some areas, but decline in others and the added stresses to freshwater ecosystems could reduce species numbers and genetic diversity within fish populations in the short term.^{356/} The medium and longer term effects may be more beneficial at least in some regions.

Higher temperatures would lead to increased amounts of plankton and other nutrients and in the bodies of water, already rich in nutrients, more aquatic growth is likely to lead to alga blooms and oxygen depletion. The decreased mixing of lakes could deplete oxygen levels in shallow areas and make them less habitable for fish.^{357/}

Changes in water temperature would be relatively greater in rivers, streams, and smaller lakes and lagoons than in larger bodies of water. The effects of higher temperatures on fish productivity could be especially beneficial in those bodies of water where temperature is currently a limiting factor. Warmer water could also change the composition of fish population as warm-water fishes expand their range, while cold-water species may decline.^{358/} Fish in larger water bodies may benefit from increased amounts of nutrients or be able to migrate to new, more appropriate, habitats, but fish in smaller rivers and lakes may be unable to escape temperatures exceeding their thermal tolerance, and in extreme cases their habitants may even disappear.

Climate change could alter the area or living space available for fish. In the areas where a warmer climate produces drier conditions and reductions in run-off, this could decrease the amount of water in rivers and lakes limiting the living and breeding space of fish populations.^{359/} In some areas flooded land provides food and breeding habitat for river fish.^{360/} Changes in river levels decreasing flood plain inundation could adversely affect fish populations.

Increases in soil erosion, silt and sedimentation may have serious consequences for downstream fisheries. Turbidity seriously affects fish, particularly crustaceans, by interfering with gill function. It also results in decreased light penetration and causes an avoidance reaction in many fish species.^{361/} The larvae of all aquatic animals suffer seriously and suspended matter may also damage spawning grounds.

In Latin America and the Caribbean, there is no information on the possible effects of global warming on the productivity of inland fisheries. At the latitude of the North American Great Lakes, a 2°C warming could increase aggregate sustained yield of commercially valuable fish species by about 26%, although catches of some species may decline.^{362/}

In the past, societies have not coped well with changes in biological productivity, regardless of cause.^{363/} Analysis of past changes in climate on fish productivity indicates that inadequate

management may aggravate the likelihood of a collapse in fisheries. As fish stocks have declined, industries have often aggravated the problem by continuing heavy fishing pressure, thus accelerating the collapse of the fishery. Experience has shown that frequently industries and authorities have been unwilling to take meaningful action to protect fish stocks.^{364/}

2. Coastal ecosystems

Wetlands play a vital role in the ecology and economy of coastal areas and their biological productivity may equal or exceed that of any other natural or agricultural system.^{365/} They are vital to the well-being of numerous species of fish and shellfish. Over two-thirds of fish caught for human consumption depend on coastal marshes and swamps for part of their life cycles.^{366/} Wetlands also serve as sinks for pollutants and provide a degree of protection from floods, storms and high tides.^{367/}

Coastal wetlands generally occupy the areas between the highest tide of the year and mean sea-level.^{368/} With a slow rate of sea-level rise, wetlands collect sediment and produce peat upon which they can build. This enables them to build vertically and expand inland when adjacent lowlands flood with higher sea-levels.^{369/} In contrast to most dry land, coastal wetlands have kept pace with past increases in sea-levels and the area of intertidal wetlands has increased several times over the last few thousand years.^{370/} If the speed of sea-level rise exceeds the ability of wetlands to keep pace, their areas could decline. A rapid rise in sea-level could cause productivity of coastal ecosystems to fall, but there may be some decades during which wetlands-based productivity increases before it declines as the sea-level begins to stabilize and in the long-term, the impact on fisheries will probably be negative.^{371/}

Coral reefs are shallow-water ecosystems which represent an assemblage of numerous types of plants and animals with corals being one of the principal components. They have a very high rate of productivity and are important breeding and nursery grounds for many marine organisms. Coral reefs act as a buffer against sea erosion and are important for tourism.

Coral reefs normally thrive between 25°C and 29°C, depending on their location. The narrow temperature range for healthy coral is very close to its upper lethal temperature: an increase on one to two degrees above the usual summer maximum can be deadly.^{372/} Some scientists believe, however, that a warming of 1°C to 3°C of the water surrounding corals would hardly affect them except to stimulate them to better growth toward the margins of their distribution.^{373/} Coral organisms grow 1 to 20 cm/year and reef growth rates as a whole are known to be up to 1.5 cm/year. Not all reefs accumulate at these rates, but most should keep pace with the expected rise in sea-level provided that other factors don't alter growth conditions.^{374/}

Corals are affected by bleaching - a phenomenon which occurs when corals expel the algae that reside within their cells, thereby turning pure white. When bleaching is severe or prolonged, the coral may die.^{375/} Some scientists believe that water temperatures only 2°C above normal can cause corals to bleach, and expect widespread bleaching and die-offs of coral reefs under a 1.5°C to 4.5°C temperature rise.^{376/}

Mangrove forests and their bordering provinces in tropical and subtropical countries frequently represent the most attractive areas for the development of brackish-water aquaculture.

They also play a vital role in the maintenance of water quality and as buffers against shore erosion. An increase in sea-levels could cause a landward displacement of mangrove belts. Mangrove ecosystems may be capable of keeping up with a rise in sea-level of less than 9 centimeters per century, but most would become stressed during rises of 9 to 12 centimeters. If the rates of increase reach 1 to 2 metres per century, most mangals will collapse as viable coastal ecosystems.^{377/}

Mangroves grow best in moderately saline environments where the rate of peat production exceeds the anaerobic decomposition of peat by marine sulphate reducing microorganisms. This implies that mangroves can keep pace with sea-level rise in rain-fed humid areas, but may be overstepped and abandoned in more arid areas particularly if inland retreat is not possible.^{378/} Future changes in patterns of rain and run-off and of over-cutting may be more important, therefore, for mangroves than increasing sea-levels.^{379/}

F. Water-based recreation

The recreational use of water bodies is very popular in Latin America and the Caribbean. Water-based recreation would be sensitive to climate change, which could benefit some activities but damage others. Even if water-based recreation suffers in some areas, it might enjoy rapid development in others with warmer climates or increased water supply.

Recreation is most likely to benefit in areas where low water temperatures currently limit the possibility and enjoyment of water sports. Warmer temperatures could be particularly beneficial for the southern cone. It is possible that, under a warmer climate, water temperature may exceed the limit considered optimal for recreation. Depending on the activity, the maximum temperatures for recreation are between 30°C and 50°C.^{380/} Water temperatures above about 29°C can retard adequate heat rejection by an active swimmer and, in some cases, induce physiological distress.^{381/}

Greenhouse-induced warming could lead to a deterioration in the levels of human thermal comfort, particularly in equatorial and sub-equatorial locations. Changes in the frequency, intensity and duration of conditions of discomfort could hold important implications for the tourist industry and water-based recreation, especially in the humid tropics.^{382/} This could be a particular concern in countries where tourism is an important source of foreign exchange and employment. Longer dry periods and a warmer climate would increase water demand for swimming pools and other recreation facilities, including parks, gardens and fountains.

Pleasure boating and even swimming could be affected in extreme cases in areas where altered hydrological and evaporation patterns cause water levels to drop. Changes in reservoir release policies due to altered rainfall patterns could also affect boating. An increase the rates of soil erosion could affect scuba diving. If fresh water levels decrease, the character and recreation potential of shorelines will change.^{383/} In some areas, there may be a reduction in recreation potential as waters recede and in others, wetlands may migrate with water levels.^{384/}

Sunshine and water-based recreation go hand in hand.^{385/} If total cloud cover declined with greenhouse warming, as it likely would, there would be more sunshine that would provide additional incentive for outdoor activities, including water-based recreation. Increased precipitation could discourage many outdoor recreational activities. The increased incidence and intensity of tropical storms and any change in their paths may adversely affect recreation and tourism.

Increased exposure to ultraviolet radiation increases sunburn frequency, skin damage, including skin cancer, immune system suppression, eye damage, including cataracts, damage to the retina, and snow blindness. The incidence of skin cancer, including melanoma, decreases from low to high latitudes possibly due to the reduction of ultraviolet radiation. The depletion of stratospheric ozone would probably be accompanied by an increase in the incidence of skin cancers and other health effects at higher latitudes. Each 1% decrease in total column ozone could lead to a 0.6% rise in the incidence of cataracts and a 3% rise in the incidence of non-melanoma skin cancer.^{386/} Severe ozone depletion may have catastrophic effects. Radiation due to a 20% ozone depletion would be so intense that it would cause severe burns in two hours of exposure and make it impossible for people to be outside during daylight without protection.^{387/} Such increases in radiation could lead to important changes in recreational behaviour due to people's willingness to expose themselves to sun and light. This could have important implications for many water-based recreational activities.

CONCLUSIONS

Global climate change poses a unique set of difficulties for water resource users. Unlike other environmental problems that usually have local or, at worst, regional consequences, climate change would be truly global in nature and affect all water uses. Any change in climate will operate over a longer time scale than that of most water resource management institutions and will involve many uncertainties, in respect of its speed, geographical incidence and implications for water management.

Reliable predictions of regional hydrologic changes may only become available when it is already costly to adapt water use to changes in supply. The uncertainty as to the local effect of global climate change requires that water management systems be very flexible and capable of effective control of the water resource under different climate conditions. This would call for the development of effective institutional mechanisms on the one hand, and promotion of research of new techniques, technologies and management practices on the other. Adaptation to changing hydrological conditions, will need improved water management practices, such as marginal-cost pricing and water marketing, to encourage the adoption of water-saving technologies, and the conservation and reallocation of supplies in response in changing climate conditions.

Many important water resource development decisions are based on the assumption that past climatic data, without modification, can serve as a reliable guide to the future. Many of the basic statistical assumptions may have to be reconsidered, including the use of a stationary mean and consistent variance over time. It is increasingly being recognized that the idea of the stationary mean is unrealistic in the design of engineering projects for flood control and water supply. Design procedures will have to take into account that climate may change and that structures with an expected life of 50 to over 100 years must accommodate change.

There is an urgency to refine estimates of future climate conditions in Latin America and the Caribbean to improve water management decisions. In particular, it is necessary to define the climatic and hydrologic data required to assess the possible impact of climate change on water management, to examine the sensitivity of water management systems to climatic variables and to determine the possible range of physical, social and economic impacts of climate change; and to reevaluate and revise current water management procedures and institutions.

The uncertainties introduced by the possibility of global climate change could have important consequences for the operation of hydraulic facilities. Large, monolithic structures are likely to be the most affected. Water resource management based on integrated smaller components individually built, operated and continually modified is likely to be more capable of adapting and responding to climate changes. Flexibility and integration may come, however, in conflict with the tendency to define management institutions by administrative or watershed boundaries, as it could require regional cooperation in the operation of water systems.

In many situations, little can be done now in anticipation of climate change, apart from attempting to make systems more robust and resilient within traditional practice for design and operation procedures. For new investments, conventional design and decision methods can be used to determine whether fortifying the system warrants additional costs to make them capable of meeting the challenge of climate change

Technological options are available both for limiting the potential adverse effects of climate change on water use as well as for limiting emissions from the major water-related sources of greenhouse gases. Some of these options may be already economically viable. Continued efforts need to be addressed to remove the barriers which hinder the further use of these options, such as conflicting incentive systems, the lack of technical information, etc.

Global climate change could increase the incidence of extreme weather events and to alter their pattern, spatial distribution and intensity. Global climate change will not necessarily, however, only bring problems. It may even be beneficial for water use in some areas and will undoubtedly afford new opportunities for water management. The region's historic ability to adapt to changes in climate and other aspects of the environment will limit any potential damage. As in the past, the region will be capable in the future of responding to emerging constraints and seizing the opportunities offered. Furthermore continued technological and managerial improvement, similar to those introduced in recent decades, would help to offset losses and to reap new benefits.

The IPCC has suggested a number of strategies by which water management practice could adapt to the challenges posed by climate change. These strategies, summarized in Box 5, offer one basis from which to prepare an action programme for possible climate change in Latin America and the Caribbean.

At the United Nations Conference on Environment and Development (UNCED), held in Río de Janeiro, Brazil in June 1992, 154 countries signed the United Nations Framework Convention on Climate Change. It will come into force ninety days after receipt of the fiftieth instrument of ratification, acceptance, approval or accession by States. The ultimate objective of the Convention is to achieve "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner". To this end the Convention provides for commitments by all Parties to adopt policies and measures to mitigate and adapt to climate change. Developed country Parties are to provide financial and technological support to developing country Parties. All Parties are to communicate information on the implementation of their commitments for review within the mechanisms of the Convention.^{388/}

Box 5

IPCC Proposed Response Strategies For Water Management

1. The timing of strategies

Given the uncertainties over the extent, magnitude, and timing of climate change and its effects on water resources, it may be prudent to delay consideration of more costly adaptation measures until after these uncertainties are reduced. Similarly, many of the less costly response strategies, especially those with other benefits, may be appropriate for present conditions, as well as, if there is climate change. Some strategies and programmes can be implemented in the short term, but others may require more time. Fortunately, current practices already incorporate many responses to climate change, and their general application should be promoted.

2. Determining the flexibility and vulnerability of current water supply systems

Given the uncertainty over the nature of hydrologic changes to be expected in any particular region and the cost of making any significant changes in existing water supply structures, a logical first step would be to evaluate the flexibility of current water systems to climate change. Models could be used to estimate the sensitivity of water systems to increased aridity and increased run-off. Such models would also require assimilating data on current facilities, streamflow, and other statistics.

3. System optimization

Joint use and revised operating rules can obtain significant increases in system yield if different jurisdictions or agencies are willing to execute agreements to do so. In the long-term, once there is a better understanding of the flexibility and vulnerability of a water supply system to respond to a variety of hydrologic changes, the next step would be an attempt to optimize the water yield, hydropower production, flood control, recreational use, maintenance of fish and wildlife habitat, and other outputs from existing facilities under various climate change scenarios, as well as under the current climate. Optimization of international water-resource systems may require

intensified international cooperation among countries sharing river basins.

4. Enhancement of scientific measurement, monitoring, knowledge, and forecasting

One of the initial challenges is to determine whether long-term changes are occurring, or are expected to occur, in a particular region. Comprehensive and accurate monitoring of hydrological and meteorological factors is the basis for such assessments. The interaction of the hydrologic system with the rest of the climatic system, or the detection of trends in water availability and other elements useful for water resources management, require continued study with the eventual goal of enabling area or basin predictions.

5. Water conservation

Irrigation is the largest consumer of freshwater in many areas and relatively small percentage reductions in irrigation water use can make large amounts of water available for new uses. Agricultural water conservation measures could include improved scheduling of the amount and timing of water deliveries, lining canals, tail water recovery, drip irrigation, using more drought-resistant crops, and tillage practices that retain soil moisture.

Education, better measurement and metering, technological improvements, specifying the use of more efficient water-using appliances in building codes, and, in arid climates, use of low-water-use landscaping, rather than grass lawns, can conserve municipal and industrial water supplies. Along with these measures, pricing has potential as an incentive for water conservation.

6. Demand management through pricing

Water prices provide signals and incentives to conserve water, develop new supplies, and for the allocation of limited water supplies among competing uses. Since water use is sensitive to price, water users, facing

higher prices, will generally conserve water and modify technologies and crop selection. Therefore, pricing by water supply authorities to reflect real or replacement costs promotes efficient use. However, the price of water is often below delivery cost or the long-run marginal cost. This leads to overuse of water and the other resources needed to construct water supply facilities.

There is substantial additional opportunity for cities and irrigation districts to use pricing to conserve water by employing marginal-cost pricing or a progressive rate structure. Allowing water entitlements to be traded at market value may achieve results similar to raising prices.

7. Voluntary water transfers or markets

One response to more arid conditions is to establish institutional arrangements to assure the most productive use of water. One means for doing this is to establish a system of tradable property rights in water.

Water transfers could employ mechanisms such as annual rentals, short-term leases, permanent sales, payments for conservation investments in exchange for the conserved water, or dry-year option agreements under which the water transfers occur only under specified drought conditions. The viability of such approaches would vary, depending upon the extent of reliance on property rights and markets in the past.

8. Modification of cropping and tillage systems

Any long-term climate-related changes in hydrology may lead to the modification of cropping practices. These changes could, in turn, affect water demand and supply, as well as having impacts on the volume of contaminants in agricultural run-off.

Certain tillage systems are effective measures for conserving soil and water. Practices that leave drop residue on the soil surface tend to increase surface roughness and organic matter, thereby increasing infiltration and reducing the potential for soil erosion. Surface residues also help to reduce soil loss due to wind erosion. Any tillage system that avoids exposing subsurface soil moisture to evaporative loss, or which creates a surface soil barrier to evaporation, can

contribute significantly to agricultural water conservation especially in rain-fed areas. Thus, tillage systems can make more efficient use of precipitation in more arid areas possible, reduce erosion resulting from excess precipitation, and reduce the off-farm impacts of soil erosion and farm chemicals transported by run-off. The combination of modified tillage practices with other land management practices designed to reduce water use and soil erosion, such as terracing, laser-leveling of fields, and water harvesting systems can recover water run-off.

9. Natural resources management

Programmes, to address deforestation and desertification, may mitigate the impacts of climate change on water resources by including considerations of the potential impacts and risks of climate change.

10. Flood management

Flood management strategies now use the computed magnitude and frequency of historic flood events. The potential effects of climate change include changes in the magnitudes and frequencies of storm events and in the magnitude, rate, and timing of the melting of snowpack.

Along with systems operation studies designed to accommodate a wider range of future climatic conditions, potential response strategies might consider data collection satellites and other advanced systems to improve flood warning and forecasting abilities. Flood plain zoning and flood insurance could also be considered.

11. Disaster relief and emergency preparedness

Because of the uncertainty concerning the impacts of climate change, improving disaster relief programmes may be an effective response.

12. Design modifications

Designing more capacity into spillways at the time of project construction and other design modifications where cost-effective, such as increased capacity for levees and dikes, can assist in handling larger flows of water.

13. Education, technology transfer, and financial assistance

Education, training, and technical assistance efforts directed at water managers and water users could play a role in making water use more efficient and responsive to possible climate change. These programmes could include national, regional, and international efforts such as joint scientific research, exchange of research results and cooperation in training and technical assistance.

Where it does not already exist, governments could develop infrastructure to assist in the rapid dissemination of new and appropriate technology, management techniques, and practices to all managers to enhance the robustness and resilience of water systems.

14. Modification of storage and other augmentation measures

Additional storage, either through raising existing dams, construction of new facilities, transfers of water, or recharge of underground aquifers from available surface supplies, is one method for responding to climate change.

15. Dam safety and other design criteria

Increased run-off due to climate change could potentially pose a severe threat to the safety of any dams with design deficiencies. Design criteria for dams may require reevaluation to incorporate the effects of climate change.

16. Adjustments in the protection of water quality

With changes in the global climate, the efficient operation of systems to manage water quality may become more critical. Transferable discharge permits are a way of meeting ambient water quality standards at the least cost by trading pollution reduction capabilities.

Various existing technologies can mitigate adverse changes in water quality. Modifying the operation of reservoirs with multi-level withdrawals or adding this capability to existing reservoirs would increase the ability to manage changes in water quality conditions. The level of discharges into a stream, including non-point source run-off from the watershed, also affect water quality. Therefore, watershed management programmes to control non-point sources as well as point sources, can help maintain water quality.

In estuaries, it could prove useful to relocate water supply intakes away from areas susceptible to saltwater intrusion and to provide barriers to further saltwater intrusion in estuaries and tidal rivers.

17. Greater use of hydropower

There is considerable potential for developing hydropower in Latin America. Development of these resources could help reduce combustion of fossil and wood fuel, thereby reducing carbon dioxide emissions directly.

Source: WMO/UNEP/IPCC/WG III (World Meteorological Organization/United Nations Environment Programme/Intergovernmental Panel on Climate Change/IPCC Working Group III (Response Strategies)/Resource Use and Management Subgroup) (1990), *First report on adaptive responses to global climate change*, April 25.

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