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California Drought: Global Warming

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S	61	6	3	2

Changing Climate

Report of the Carbon Dioxide Assessment Committee

Board on Atmospheric Sciences and Climate
Commission on Physical Sciences,
Mathematics, and Resources
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1983

7 Effects of a Carbon Dioxide-Induced Climatic Change on Water Supplies in the Western United States

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In this chapter we show that warmer air temperatures and a slight decrease in precipitation would probably severely reduce both the quantity and the quality of water resources in the western United States. Similar effects can be expected in many water-short regions elsewhere in the world. We have not attempted to estimate these, primarily because we do not know enough to be able to do so. But we hope that hydrologists of other countries will be stimulated by our calculations to investigate the probable consequences of a CO_2-induced climate change on water resources in their own countries. In all countries, planning and construction of large-scale water-resource systems takes many decades. The time involved is of the same order of magnitude as the time over which a significant change in climate from increase of carbon dioxide and other greenhouse gases can be expected. Thus, we believe that planners and managers of water systems throughout the world should be able to make good use of forecasts of the hydrologic consequences of a warmer climate and of possible changes in precipitation.

7.1 EMPIRICAL RELATIONSHIPS AMONG PRECIPITATION, TEMPERATURE, AND STREAM RUNOFF

To assess the effects on the United States' water resources of probable climatic change we used the empirical relationship found by Langbein et al. (1949) among mean annual precipitation, temperature, and runoff. This was based on representative data from 22 drainage basins in the conterminous United States. Their relation in Table 7.1 gives the estimated annual runoff for different values of mean annual precipitations and weighted mean annual temperatures. The latter were computed for each catchment basin by dividing the sum of the products of average monthly temperature and precipitation by the mean annual precipitation. In this way, the average temperature during each month is weighted by the precipitation during that month.

The catchments studied by Langbein and his colleagues were distributed over climates from warm to cold and from humid to arid, but in Table 7.1 we have shown the relations among runoff, temperature, and precipitation only for relatively arid areas. In these arid areas, the value of actual evapotranspiration is less than the potential evapo-

TABLE 7.1 Runoff (mm yr^{-1}) as a Function of Precipitation and Temperature[a]

Weighted Average Temperature (°C)	Precipitation (mm yr-1) 200	300	400	500	600	700
- 2	54	92	154	230	330	440
0	40	74	124	190	275	380
2	28	57	95	154	225	320
4	17	40	78	125	190	265
6	9	25	60	100	155	220
8	0	17	42	82	128	185
10		8	29	64	103	155
12		0	19	47	80	130
14			10	32	65	105
16			0	20	50	85

[a]Source: W. B. Langbein et al. (1949).

transpiration that would occur if sufficient water were present and evapotranspiration was controlled mainly by temperature. For example, at a temperature of 4°C, potential evapotranspiration is about 450 mm yr^{-1}. Yet Langbein's data show that even when annual precipitation is only 300 mm, there is still significant runoff, about 13% of the precipitation. Correspondingly, average actual evapotranspiration must be only 260 mm yr^{-1}.

From Table 7.1 we observe that for any given annual precipitation, runoff diminishes rapidly with increasing temperature. Similarly, for any given temperature, the proportion of runoff to precipitation increases rapidly with increasing precipitation. For example, at a weighted mean annual temperature of 4°C and annual precipitation of 200 mm, runoff is only 8.5% of precipitation, whereas for the same temperature and an annual precipitation of 700 mm, runoff is 38% of precipitation. At an annual temperature of 8°C, runoff is zero when precipitation is 200 mm or less and is 185 mm--or 26.4% of precipitation--when the average annual precipitation is 700 mm.

For any particular region, the relations shown in Table 7.1 are rather crude approximations because many physical factors, including geology, topography, size of drainage basin, and vegetation, may alter the effect of climate on runoff. We believe, nevertheless, that these relationships can be used without serious error to describe the effects of relatively small changes in average temperature and precipitation on mean annual runoff.

In Table 7.2, we have used the data in Table 7.1 to compute the approximate percentage decrease in runoff for a 2°C increase in temperature. Climate models (e.g., Manabe and Wetherald, 1980) indicate that a temperature change of this magnitude or greater is likely as a result of the doubling of carbon dioxide and increased concentration of "greenhouse gases" expected during the next century. We see that for a

TABLE 7.2 Approximate Percent Decrease in Runoff for a 2°C Increase in Temperature[a]

Initial Temperature (°C)	Precipitation (mm yr-1) 200	300	400	500	600	700
- 2	26	20	19	17	17	14
0	30	23	23	19	17	16
2	39	30	24	19	17	16
4	47	35	25	20	17	16
6	100	35	30	21	17	16
8		53	31	22	20	16
10		100	34	22	22	16
12			47	32	22	19
14			100	38	23	19

[a]Computed from Table 7.1.

present weighted mean annual temperature of 4°C and annual precipitation of 300 mm, a 35% diminution in runoff would follow a 2°C warming. The percentage decrease in runoff from a warming diminishes with increasing precipitation and becomes greater for successively higher values of the initial temperature.

Table 7.3 shows the approximate percentage decreases in runoff for a 10% decrease in precipitation. According to the results of climate models (see Chapter 4), such a diminution in precipitation is likely, at least in certain regions of the United States, with a doubling of atmospheric CO_2. Again we see that the effect becomes larger with higher average annual temperatures. There is a relatively small difference in the percentage decrease in runoff at a given temperature over the range of initial precipitation values shown in the table. Comparison of Tables 7.2 and 7.3 shows that below an initial mean annual precipitation of 500 mm, the effects of a 2°C warming are larger than those caused by a 10% decrease in precipitation. The reverse is true when mean annual precipitation is 500 mm or more.

7.2 EFFECTS OF CLIMATE CHANGE IN SEVEN WESTERN U.S. WATER REGIONS

Stockton and Boggess (1979) have used Langbein's empirical relation to estimate the effects of a climatic change on water in the 18 water regions of the conterminous United States defined by the U.S. Water Resources Council (1978). They find that a 2°C warming and a 10% reduction in precipitation would not have serious effects in the humid regions east of the 100th meridian. In the West, however, the impact would be severe on seven water regions: the drainage basins of the Missouri, Arkansas-White-Red, Rio Grande, and Colorado rivers; the river basins draining into the Gulf of Mexico from the northern two thirds of Texas; and the rivers of California. The only western water

TABLE 7.3 Approximate Percentage Decrease in Runoff for a 10% Decrease in Precipitation[a]

Temperature (°C)	Initial Precipitation (mm yr-1)				
	300	400	500	600	700
- 2	12	16	17	18	18
0	14	16	17	19	19
2	15	16	19	19	20
4	17	19	19	21	21
6	23	23	21	21	21
8	30	24	24	22	22
10		24	27	23	23
12		40	30	25	25
14			34	30	27
16			50	36	29

[a]Computed from Table 7.1.

regions that would not be severely affected are the water-rich Pacific Northwest and the Great Basin (parts of Nevada, Utah, and Idaho), where demand is relatively small and groundwater reserves are large.

In estimating the impact of climate change, Stockton and Boggess assumed:

1. The region-by-region variation in annual runoff is predominantly influenced by climate, although other factors such as geology, topography, vegetation, and many other variables may be important, especially in smaller drainages.
2. The empirical curves associating total annual precipitation and total annual runoff with weighted mean annual temperature are appropriate for all 18 regions although derived from a relatively small (22 drainage basin) sample.
3. Changes in land use have relatively small influences on regionwide annual runoff.
4. Annual runoff is not greatly affected by large-scale groundwater overdraft.
5. Evapotranspiration is controlled solely by temperature.
6. The postulated climatic change does not modify the present monthly distribution of temperature and precipitation; only the amplitude of the present distribution is increased or decreased.
7. Selection of a few meteorological stations for each region adequately establishes the relation of the weighted mean temperature and annual precipitation to annual runoff.

In Table 7.4 we have summarized the estimates by Stockton and Boggess of the effects of a 2°C increase in temperature and a 10% reduction in precipitation in the seven water regions of the western United States in which climate change would have the most serious

TABLE 7.4 Comparison of Water Requirements and Supplies for Present Climatic State and for a 2°C Increase in Temperature and 10% Reduction in Precipitation in Seven Western U.S. Water Regions[a]

	Present Climate						Warmer and Drier Climate		
Water Region[b]	Area ($10^{10}/m^2$)	Mean Annual Runoff (10^{10} m^3 yr^{-1})	(mm)	Mean Annual Supply (10^{10} m^3 yr^{-1})	Mean Annual Requirements[c] (10^{10} m^3 yr^{-1})	Ratio of Requirement to Supply	Mean Annual Supply (10^{10} m^3 yr^{-1})	Percent Change in Supply	Ratio of Requirement[d] to Supply
Missouri	132.4	8.50	64	8.50	3.63	0.43	3.07	-63.9	1.18
Arkansas-White-Red	63.2	9.35	148	9.35	1.67	0.18	4.32	-53.8	0.39
Texas Gulf	44.9	4.92	110	4.92	1.74	0.35	2.47	-49.8	0.70
Rio Grande	35.2	0.74	21	0.74	0.67	0.91	0.18	-75.7	3.72
Upper Colorado	29.6	1.64[e]	55	1.64	1.63[f]	0.99	0.99	-39.6	1.65
Lower Colorado	40.1	0.38	10	1.15[g]	1.37	1.19	0.50[g]	-56.5	2.68
California	42.9	9.56	222	10.18[g]	4.22	0.41	5.71[g]	-43.9	0.74
For the 7 regions together	388.3	35.09	90.4	35.09[h]	14.93	0.43	16.53[h]	-53	0.90

[a]Source: Stockton and Boggess (1979) and calculations in this paper for Upper Colorado Basin.
[b]As defined by the U.S. Water Resources Council (1978).
[c]Projected through year 2000 A.D.
[d]Assuming no increase in requirement because of increased evapotranspiration from irrigated farms or reservoirs.
[e]Average "virgin flow" of the Colorado River at Lee Ferry from 1931 to 1976.
[f]Includes allocation to Lower Basin States, California included, of 0.93 x 10^{10} m^3 yr^{-1}.
[g]Includes water received from Upper Colorado Basin, but not mined groundwater.
[h]Total is less than sum of the column because of flow of Lower Colorado derived from Upper Colorado (g).

impact. These regions cover about half the area of the conterminous United States, but they produce only about 15% of the mean annual stream runoff. The table shows the present mean annual water supply for each region, not including mined groundwater, in millions of hectare meters (10^{10} m^3 yr^{-1}) and the estimated mean annual requirement in the year 2000. The mean annual requirements listed in Table 7.4 represent "consumptive" use of water plus evaporation from reservoirs, that is, the total quantity of water that is evapotranspired in the course of beneficial human use. Although actual withdrawals from streams and underground aquifers are considerably larger, portions of these withdrawals are returned to the streams or back into the ground where the water may be reused. In the present climate the ratio of estimated requirements to supplies is less than one for all regions except the Lower Colorado River. In this region today, the deficit of supply is presently made up by extensive mining of groundwater.

For the postulated climatic change, supplies would greatly diminish in all regions, ranging from almost a 76% reduction in the Rio Grande region to nearly 40% in the Upper Colorado, with the result that estimated requirements would exceed supplies in the Missouri, Rio Grande, and Upper and Lower Colorado regions. Mean annual requirements would still be less than future mean annual supplies in the Arkansas-White-Red, Texas Gulf, and California regions. But requirements would almost certainly exceed supplies in the Texas Gulf and California regions during future prolonged droughts. Conditions are highly variable in different parts of the Arkansas-White-Red region, with the western part tending to be deficient in water supplies and the eastern part having a surplus. To maintain the present pattern of water use, large-scale transfers between basins might be necessary here even under average conditions, let alone to meet water requirements during prolonged droughts. A serious deterioration in water quality would follow from climatic change in all seven regions.

The ratio of future requirements to supply would probably be even less favorable than indicated in Table 7.4 because evapotranspiration from irrigated farms and reservoirs would undoubtedly increase with a rise in temperature. On a global basis this would be compensated for by an increase in precipitation, but this might or might not occur in the regions we are considering.

At present, California depends for about 15% of its water on imports from the Colorado River. These imports might be eliminated entirely with the postulated climatic change, in which case the ratio of mean annual requirements to mean annual runoff would increase to 0.83, more than double the present ratio.

In all seven regions, irrigation is by far the largest user. Its share of water withdrawals ranges from 68% in the Texas Gulf region to 95% in the Rio Grande region. Total water withdrawals for agriculture are now 13.2 million hectare meters, and in the seven regions the irrigated area is (very approximately) 13 million hectares (Rogers, 1983) so that, on the average, the annual depth of irrigation is about 1 m. Consumptive water use in irrigation is much smaller; a large share of the water that is not consumed reappears as return flows that can be used downstream. Reduction in the irrigated area and an increase in the efficiency of water use in irrigation would significantly lower the overall water requirements in the seven western regions. A 15% increase in water-use efficiency is probably feasible (Jensen, 1982). Reduction in the irrigated area might come about automatically if an interstate economic market for water were to develop, because economic returns to irrigation are relatively low in large parts of the seven western regions. On the other hand, potentially very large Indian claims for irrigation water for their reserved lands must eventually be settled, and this could result in a major reallocation of water rights (Back and Taylor, 1980).

The effects of future droughts in the Arkansas-White-Red, Texas Gulf, and California regions from the assumed climatic change could be significantly mitigated by construction of additional reservoirs for water storage, but increases in storage would help little in the Missouri, Rio Grande, or Upper and Lower Colorado regions because their storage reservoirs are already so large compared to the annual runoff. In these regions strict water conservation would be essential.

The mean annual requirements listed in Table 7.4 represent "consumptive" use of water plus evaporation from reservoirs, that is, the total quantity of water that is evapotranspired in the course of beneficial human use. Although actual withdrawals from streams and underground aquifers are considerably larger, portions of these withdrawals are returned to the streams or back into the ground where the water may be reused.

As Stockton and Boggess show, the one western region where a large surplus would still exist after their postulated climatic change would be the Pacific Northwest. Their estimated ratio of requirements to supplies following a 2°C warming and a 10% reduction in precipitation would be 0.10. The annual supply would then be 23.7 million hectare meters. Transfer of 20% of this total supply to water-short regions through large, long-distance conveyance could increase future supplies in the seven western regions shown in Table 7.4 by nearly 30%, thereby compensating for much of the estimated shortages from climatic change. The ratio of requirements to supplies in the Pacific Northwest region would still be a comfortable 0.18.

From an economic standpoint, however, such a transfer would probably not be desirable. The value of the hydroelectric energy that could be generated from a hectare meter of water in the Pacific Northwest, assuming a total head of 500 m and a price of 5¢ per kilowatt-hour, would be over $600, considerably in excess of the value of a hectare meter of water for irrigating the fodder and cereal crops grown in most of the western regions (Rogers, 1983).

7.3 THE COLORADO RIVER

Except for the Rio Grande, the waters of the Colorado River are more intensively used than those of any other major stream in the United States. Half the estimated "normal" flow of 18,500 million cubic meters per year at Lee Ferry in Arizona has been allocated by interstate compact, confirmed by federal law, to the lower basin states of California and Arizona, with minor amounts going to Nevada. Nearly all of the runoff originates from snow in the high-mountain area of western Colorado, southwestern Wyoming, and eastern Utah.* (As defined, the Upper Basin also includes northwestern New Mexico.)

To check the probable effect of a climatic change on the flow of the Colorado River, we calculated a multiple regression of the relation between annual averages of precipitation and temperature and the "virgin flow" of the Colorado at Lee Ferry, Arizona, which is the southernmost point on the river in the Upper Colorado Basin.

The "virgin flow" is the measured flow at Lee Ferry plus estimated depletions within the upper basin, evaporation from reservoirs, and changes in reservoir storage. Estimates for the annual virgin flows were furnished to us by Myron B. Holbert, chief engineer of the Colorado River Board of California. The flow for each water year--October 1 to September 30--from 1931 to 1976 is tabulated in Table 7.5. It ranges from 9,450 to 25,490 million cubic meters. The average for the 46-year period is 16,430 million cubic meters (13.5 million acre feet). This average value is 2065 million cubic meters, or 11% less than the assumed "normal flow" on which the Colorado River Compact is based, but it agrees well with Langbein's relationship, shown in Table 7.1, among temperature, precipitation, and runoff. Interpolating between the values given in the table for temperatures of 4 and 6°C and precipitation of 300 and 400 mm yr^{-1}, we arrive at a runoff of 53 mm, corresponding to an annual river flow for the 296,000 km^2 in the Upper Colorado drainage of 15,700 million m^3.

The flow of the Colorado is mainly collected in five catchments corresponding to the five climatic divisions in the Upper Colorado Basin outlined in Figure 7.1. Mean annual precipitation and temperature for each drainage area and water-year from 1931 to 1976 were provided to us by Daniel Cayan of the Scripps Institution of Oceanography, who obtained the original data from the National Climate Center, Asheville, North Carolina. The annual data for each division are the areally weighted averages of the records of individual weather stations. As Cayan has pointed out, the number of weather stations was not constant but gradually increased from 1931 to 1976. Between 1951 and 1980, continuous records were obtained from 45 stations in the western Colorado division, 10 stations in the Green and Bear drainages in Wyoming, and 10 in the three drainage basins of eastern Utah (North Mountains, Uinta Basin, and Southeast Utah). By 1980, there were 65 stations in western Colorado, 26 in the three Utah divisions, and 16 in southwestern Wyoming.

We weighted the data from these five drainage basins in proportion to their areas: Colorado drainage in western Colorado, 0.430; Green and Bear drainages in Wyoming, 0.184; North Mountains in Utah, 0.110;

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*See Dracup (1977) and Howe and Murphy (1981) for useful discussions of the economic, social, political, and international problems of the Colorado River compact.

FIGURE 7.1 Basins or drainages of the western United States.

Uinta Basin, 0.053; and southeast Utah, 0.223. The weighted sum of the precipitation in millimeters for the five drainages is called PRECIP in the following equation. It varies from 262 to 439 mm yr^{-1}, with an average for the 46 years of 332 mm yr^{-1}. Weighted annual average temperatures obtained in the same manner are called CELSIUS. They range from 2.52 to 6.75°C and average 4.18°C. The weighted annual averages for 1931 to 1976 are tabulated in Table 7.5.

The relation of the virgin flow to PRECIP and CELSIUS is assumed to fit the equation:

$$\text{FLOW} = b_0 + (b_1 \times \text{PRECIP}) + (b_2 \times \text{CELSIUS}).$$

The regression coefficients, b_i, and their standard errors relating the virgin flow at Lee Ferry to the mean annual precipitation and the mean annual temperature in the watershed from 1931 to 1976 are as follows:

b_0 in millions of cubic meters = 9274 $\pm$ 3838,
b_1 in millions of cubic meters/mm = 52 $\pm$ 7,
b_2 in millions of cubic meters/°C = −2400 $\pm$ 507.

The fit of the equations to the data is represented by the square of the correlation coefficient, R^2, which is 0.73. About 75% of the variation of the flow about the mean is explained by the equations.

We see that a 2°C rise in temperature would decrease the virgin flow by 4800 $\pm$ 1015 million cubic meters yr^{-1}, or about 29% $\pm$ 6%. A 10% decrease in precipitation would reduce the flow by 1730 $\pm$ 230 cubic meters, or an additional 11% $\pm$ 1.4%. The combined effect would be a reduction in flow by 40% $\pm$ 7.4%, very close to the estimate of 44% given by Stockton and Boggess.

Estimates of the virgin flow between 1900 and 1930 were also provided by Holbert, and we attempted a similar analysis for these years, using data published in the Weather Bureau publication, The Climates of the States. Unfortunately, the data for these earlier years are sparse. Only 10 stations recorded precipitation more or less continuously during this period in western Colorado and even fewer in Utah and Wyoming. Temperature data were available from only Garnett, Colorado; Lander, Wyoming; and Modena, Utah, and none of these is in the high-mountain regions of heavy snowpack that contribute most of the runoff to the Colorado River.

The data for 1900 to 1930, Table 7.6, indicate that the average runoff was about 20% greater than between 1931 and 1976, while the average precipitation was about 7% less and the average temperatures for the three available stations were about 2°C higher. The low estimate of average precipitation may reflect a deficiency in estimating the quantities of water precipitated as snow. These estimates were very uncertain before the advent of the "snow courses" initiated by the U.S. Soil Conservation Service in the 1930s. The extreme variations in average annual temperature for the three stations were only 2.45°C, in contrast to the range of 4.23°C for the average of the much larger number of stations in 1931-1976.

TABLE 7.5 Annual Averages of Precipitation, Temperature, and Virgin Flow of the Colorado River at Lee Ferry, Upper Colorado Region, 1931-1976

Year	Precipitation ($mm\ yr^{-1}$)	Temperature (°C)	Flow ($10^6\ m^3\ yr^{-1}$)
1931	268	4.95	9583
1932	355	3.23	21270
1933	283	3.51	14009
1934	228	6.75	6958
1935	316	5.14	14247
1936	349	4.62	17023
1937	378	3.80	16948
1938	392	5.04	21643
1939	301	4.22	13666
1940	323	5.71	10609
1941	451	4.11	22386
1942	357	3.51	23592
1943	362	4.68	16164
1944	334	3.99	18693
1945	355	3.97	16542
1946	305	4.08	12860
1947	418	4.39	19083
1948	346	4.13	19258
1949	385	3.32	20199
1950	320	3.68	15904
1951	298	4.60	14366
1952	424	3.20	25490
1953	273	4.63	13119
1954	308	5.64	9450
1955	291	3.57	11333
1956	255	4.31	13259
1957	429	4.25	24787
1958	323	4.28	20339
1959	294	4.75	10619
1960	262	4.49	13893
1961	340	4.82	10432
1962	300	3.38	21338
1963	305	5.44	10423
1964	286	3.61	12527
1965	439	3.30	23329
1966	282	4.06	13825
1967	350	4.20	14687
1968	326	3.45	16854
1969	361	3.84	17745
1970	352	4.05	19002
1971	302	3.78	18645
1972	303	3.46	15021
1973	435	2.52	23893
1974	254	4.22	16355
1975	347	3.51	20447
1976	300	4.27	14064
Mean	333	4.18	16432

TABLE 7.6 Annual Averages of Precipitation, Temperature, and Virgin Flow of the Colorado River at Lee Ferry, Upper Colorado Region, 1901-1930

Year	Precipitation (mm yr^{-1})	Temperature (°C)	Annual Sum (m/sec)
1901	229	6.56	16753
1902	195	6.71	11586
1903	285	5.35	18264
1904	240	6.55	19297
1905	314	6.10	19769
1906	370	5.86	23585
1907	350	6.78	28865
1908	274	6.49	15857
1909	364	6.05	28709
1910	233	6.57	17574
1911	327	7.49	19770
1912	313	5.05	25311
1913	269	5.71	17852
1914	355	6.68	26176
1915	308	6.47	17303
1916	304	7.08	23684
1917	346	5.04	29650
1918	263	7.32	18951
1919	253	6.43	15372
1920	331	5.58	27076
1921	355	6.57	28389
1922	300	6.60	22580
1923	336	6.04	22535
1924	252	5.63	17517
1925	338	6.41	16077
1926	303	6.28	19554
1927	404	6.88	22963
1928	253	6.58	21314
1929	392	5.46	26432
1930	309	6.44	18361
Mean	306	6.29	21098

The multiple regression for the earlier period showed a smaller effect of temperature and a somewhat larger effect of precipitation than during 1931-1976. But during the earlier period the standard deviations for the effects of both temperature and precipitation were almost twice as great, and the square of the correlation coefficient was only 0.57.

We conclude tentatively that the weakness of the correlation and the relatively larger standard errors from 1901 to 1930 resulted from the paucity of precipitation and temperature data, the probable inaccuracy of estimates of the quantity of water precipitated as snow, and the probably unrepresentative character of the stations used for average temperatures. In both the earlier and the later periods, variations in precipitation were reflected almost linearly in variations in runoff without the amplification that might be expected from the results obtained on smaller watersheds (Schaake and Kaczmarek, 1979) or from Table 7.3.

After the postulated climatic change, the mean annual flows at Lee Ferry computed from our multiple regression equation for 1931 to 1976 would be only 9900 million cubic meters. This last amount is 2060 million cubic meters, or 17%, less than the historically lowest 10-year average annual flow of 11,960 million cubic meters, calculated by Stockton from tree-ring records for the decade from A.D. 1584 to A.D. 1593 (Dracup, 1977). A similar prolonged drought in the middle of the twenty-first century with the same percentage decrease in runoff as in 1584-1593 could bring the 10-year annual average flow down to 7200 million cubic meters, or about 44% of the annual average virgin flow from 1931 to 1976.

Although a 2°C warming is probably a conservative estimate of the effect over the next hundred years of increase of greenhouse gases for the northern United States, the magnitude and even the sign of possible changes in precipitation are uncertain. According to our regression equation, a 10% increase in average annual precipitation combined with a 2°C rise in average temperature would result in an 18% decrease in runoff. To counteract the effects of a 2°C warming completely, a 28% increase in precipitation would be required. Clearly, higher spatial resolution in climate models is needed for more credible forecasts of the effects of increasing atmospheric carbon dioxide and other greenhouse gases on the quantity of water supplies. Possibly, also, seasonal variations from year to year in precipitation and temperature may be more critical in determining Colorado River runoff than annual averaged variations. This possibility could be investigated by statistical analysis of monthly averages of temperature and precipitation for each year against the annual "virgin flow" at Lee Ferry.

7.4 CLIMATE CHANGE AND WATER-RESOURCE SYSTEMS

Planning and construction of major water-resource systems have a time constant of 30 to 50 years. In the past, these activities have been based on the explicit assumption of unchanging climate. The probably serious economic and social consequences of a carbon dioxide-induced climatic change within the next 50 to 100 years warrant careful consideration by planners of ways to create more robust and resilient water-resource systems that will, insofar as possible, mitigate these effects.

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ENVIRONMENTAL AND SOCIO-ECONOMIC RESEARCH NEEDED FOR BETTER APPRAISAL OF THE CO_2 PROBLEM

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Submitted

July 31, 1981

to

Subcommittee on Natural Resources and Agriculture Research and Environment
James H. Scheuer, Chairman

Subcommittee on Investigations and Oversight
Albert Gore, Jr., Chairman

COMMITTEE ON SCIENCE AND TECHNOLOGY
U. S. House of Representatives

ENVIRONMENTAL AND SOCIO-ECONOMIC RESEARCH

NEEDED FOR BETTER APPRAISAL OF THE CO_2 PROBLEM

In adding CO_2 to the atmosphere, mankind is unintentionally conducting a great biological and geophysical experiment. This experiment can be expected to increase scientific understanding of ecological systems and of the processes in the ocean and the atmosphere that partially determine world climates. But from the standpoint of governments and peoples, the major problem to be solved is to understand the nature of the impacts on societies of rising levels of atmospheric CO_2, with the objective of avoiding or ameliorating unfavorable impacts and gaining most benefit from favorable impacts. Environmental and socio-economic research is necessary to provide the needed understanding. On the basis of this research, we should be able to make better qualitative estimates of the range of probable outcomes. Such estimates could be used to lay a rational groundwork for policies and actions which would change the rates at which costs and benefits are incurred and increase the likelihood that benefits will exceed costs.

I. THREE KINDS OF RESEARCH ARE NEEDED

Three kinds of research on the consequences of rising levels of atmospheric carbon dioxide and possible climatic change are called for:

A- Assessment of risks (and potential benefits) that could be averted only by limiting carbon dioxide emissions. This category includes possible changes of physical processes in the ocean and the cryosphere and effects on the biology of marine, freshwater, and terrestrial ecosystems in which effective human intervention is unlikely.

B- Research to enhance beneficial effects and lessen harmful ones, where this is possible, and to slow down rates of carbon dioxide emission.

C- Study of potential social and institutional responses to the consequences of higher atmospheric carbon dioxide and projected climatic changes.

A. RISK ASSESSMENT

1. Possible disappearance of the West Antarctic Ice Sheet. This portion of the Antarctic ice cap is believed by some glaciologists to be unstable. If there were a marked warming in polar regions, it might disappear, causing a worldwide rise in sea level that would inundate many coastal cities and much valuable agricultural land. We need to be able to estimate the probability that this event could occur and the approximate rate, that is, whether the time involved might be measured in decades or centuries. As an analog of possible future deglaciation, an attempt should be made to determine if the West Antarctic ice cap disappeared during the last Interglacial period, about 120,000 years ago. Better understanding is needed of the dynamics of the ice streams flowing from West Antarctica, the relationships of these streams to ice shelves, and the effects on the ice shelves of the disappearance of seasonal pack ice and of heating of the surrounding ocean waters.

2. Effects on Arctic Ocean Sea Ice. The Manabe-Weatherald model indicates that with a four-fold increase in atmospheric CO_2, the cover of sea ice over the Arctic Ocean would disappear, at least in the summer time, with possibly profound changes in oceanic and atmospheric circulation. To be able to estimate the likelihood of this event and the possible consequences, greater understanding is needed of the dynamics of formation and dissolution of sea ice in the Arctic Ocean and the surrounding seas and of the interactions between the sea ice and the underlying waters.

3. Melting of Permafrost in High Northern Latitudes. With a sufficient increase in atmospheric CO_2, climatic warming of 5-10°C. might occur over land in high latitudes. This could result in extensive thawing of permafrost, with marked effects on the hydrology and ecology of the tundra. These areas of frozen ground contain large reservoirs of organic carbon in peat deposits, and probably also in methane hydrates a few hundred feet below the surface. Thawing of the permafrost, caused by climatic warming from an atmospheric CO_2 increase, could result in oxidation of the peat and release of methane gas, and thus in a positive feedback effect on atmospheric carbon dioxide. The magnitude of this effect would depend on the size, location, and present temperature-depth relationships of the peat and methane hydrate deposits. Reconnaissance surveys should be made to determine these quantities. Scientific cooperation with Canada and the U.S.S.R. is necessary because of the vast areas of frozen ground within these countries.

4. Other Possible Effects Not Susceptible to Human Action. We are also concerned with those effects of increased atmospheric and climatic warming which, if they occurred, would be difficult or impossible to modify by deliberate human actions. We need to estimate the probability of occurrence of such effects, the approximate magnitude and timing of the deleterious (or beneficial) consequences, and the costs of societal adaptations to these consequences relative to the costs of stopping or drastically reducing the use of fossil fuels. Examples of such effects are the possible disappearance of the West Antarctic ice cap and of the Arctic Ocean sea ice, melting of permafrost in high northern latitudes, and the consequences for marine phytoplankton communities and coral reefs of a higher hydrogen ion concentration (lower pH) in near-surface ocean waters.

Several questions of this kind relate to human health and behavior and to environmental conservation:

a- What will be the effect of higher ambient CO_2 concentrations on human respiration and how will this - if it exists - affect human life expectancy?

b- Given warmer average temperatures in mid-latitudes, will occasional very hot summers, resulting from inter-annual climatic variations, cause life-threatening stresses on physiologically-vulnerable groups in human populations and among domestic animals?

c- How will the projected fall in upper atmospheric temperatures interact with additions of chlorofluoromethanes and other gases to alter the ozone content of the stratosphere? How will the resulting change in solar ultraviolet radiation reaching the earth's surface affect human beings and other organisms--terrestrial, aquatic, and marine?

d- Will the rates of extinction of endangered species be accelerated by the expected climate changes, particularly species living near the upper limits of their temperature tolerance?

B. RESEARCH TO ENHANCE BENEFICIAL EFFECTS AND LESSEN HARMFUL ONES

Far-reaching results can be hoped for from research of this kind applied to agriculture, forestry and animal husbandry, with the objectives of increasing productivity and attaining greater resiliency of agricultural systems under climatic change.

1. Biological Effects on Crop Plants of Increases in Atmospheric CO_2. One of the principal benefits of increased atmospheric CO_2 might be higher photosynthetic productivity and water-use efficiency in cultivated crops. Indeed, it is not impossible that a small part of the improvement in agricultural yields experienced during the past 50 years has resulted from the 13 percent increase in atmospheric CO_2 content since the 19th century. But much research is needed to take full advantage of expected future atmospheric CO_2 levels. Studies should be undertaken to determine whether varieties of field crops can be developed, through conventional breeding programs and modern methods of genetic manipulation, that will have higher net photosynthetic production and use less water as the atmospheric CO_2 content increases, but will not respond to a warmer atmospheric temperature by an increase in respiration that would cancel out the effect of CO_2 fertilization. We are concerned both with more total plant production and an increase of the "harvest index," that is, the portion of the plant that can be used by human beings for food, fuel, fiber, or other useful products. The effects of higher temperature and increased carbon dioxide on biological nitrogen fixation and on weeds, insects, and microbiological pests must be taken into account. Programs of genetic improvement should include greater resistance to pests, as well as to other environmental stresses.

2. Improved Stress Resistance in Crop Plants. The climatic changes that are likely to accompany rising levels of atmospheric carbon dioxide will produce environmental stresses in many crop plants, resulting from higher average and extreme temperatures, and possibly also from lower water availability, the presence of atmospheric pollutants, particularly oxidants, unfavorable soil nutrient levels, increased soil alkalinity, or higher soil salinity. Research aimed at alleviating these environmental stresses should proceed along three parallel lines:

a- Studies of the basic biology of plant response and resistance to environmental stresses;

b- Genetic manipulation of crop varieties for greater resistance to environmental stresses;

c- Development of production-management systems that maximize the expression of genotypic stress resistance.

The objective should be to improve average yields over relatively long periods, during which interannual climatic variations can be expected to occur.

In developing stress-resistant crop varieties, advantage must be taken of a wide variety of plant germ plasm. This will require a major expansion of present programs to preserve existing gene pools of important plant species, particularly in the developing countries of tropical and subtropical regions. Three kinds of work are needed:

a- Systematic collection, preservation, description, evaluation, and cataloging of germ plasm of useful plant species;

b- Study of the requirements for long-term storage, viability, and preservation of variability;

c- Research on gene recombinations to develop plant materials adaptable to environmental change and human needs.

3. Effects on Managed Forests. Biomass energy from forest trees can be at least partly substituted for fossil fuels, particularly in the tropics and subtropics, but this substitution will be possible on a sustainable basis only if the productivity of forests can be greatly increased. Research on the effects of increased atmospheric CO_2 and higher temperatures on high-yielding trees of tropical and subtropical regions under different conditions of water stress should be given priority, particularly on species that possess symbiotic nitrogen-fixing bacterias such as *Leucaena*, *Casuarina*, *Sesbania*, and various species of *Acacia*. In the future, the rapidly-growing energy demands of tropical and subtropical developing countries might be met in large part by renewable biomass fuels from forest plantations, with a consequent reduction in worldwide CO_2 emissions.

4. Effects of Climate Change on Animal Husbandry. Meat, milk, eggs, and other animal products make up a large fraction of the world's agricultural output. The greatest concentrations of poultry and livestock production exist in the Temperate zones, where a rise in average temperatures of more than 4°C. could occur if atmospheric CO_2 is doubled. With presently-used animal varieties, nutrient intake and utilization and reproductive rates diminish with rising temperature, and the incidence of diseases may rise. Physiological research on metabolic and endocrine systems in domestic animals under conditions of high average temperature and occasional extremely hot seasons is needed to understand and quantify these effects. This should lead to improved management practices, including better dietary formulations, breeding periods synchronized with seasonal climate variations for most favorable conception and reproduction, low-cost animal shelters to buffer climatic changes, and selection of livestock and poultry varieties best suited to

higher average and extreme temperatures. Attention should also be given to changes in the species composition of forage plants in grazing lands and cultivated pastures that could give higher nutrient concentrations.

In tropical and subtropical regions, the rise in average temperatures is expected to be relatively small, within the adaptive range of existing domestic animal varieties. But changes in precipitation regimes toward both more moisture in some regions and greater aridity in others will require adaptive research on animal feeding systems from range lands, seeded pastures, cultivated forages, crop residues, and trees. Probable geographical shifts of disease and pest zones, following changes in the location of climatic zones, call for intensified research on prevention and control.

5. Better Management of Water Resources in Developing-Country Agriculture. The traditional agricultural systems of many developing countries will be especially vulnerable in regions where increased aridity results from carbon dioxide-induced climatic change. Capital investments in large irrigation systems will often be necessary, but improvements in management of irrigation water, based on site-specific applied research, could be even more important. Dependability of irrigation supplies is essential. In many river basins, this can be attained by conjunctive use of surface and ground waters. The greatest gains can be expected from improvements in on-farm water management. More than a doubling of the efficiency of use of irrigation water can be looked for, from less than 25% to more than 50%, by reducing losses in conveyance systems, controlling depth and uniformity of water applications, lessening evaporation losses, using simple methods for water measurement, and better timing of irrigations. Changes in cropping patterns, times of planting, and area planted will also often be desirable or necessary.

C. RESEARCH ON SOCIETAL AND INSTITUTIONAL RESPONSES

1. Construction of Scenarios. Because of the important feedbacks among atmospheric and ocean dynamics, marine and land biota, and agriculture and energy use, the global CO_2 problem can best be defined by constructing integrated simulation models - that is, scenarios. A range of scenarios created by teams of physical, biological and social scientists working together could constitute a framework for viewing the complex implications of the problem. These scenarios would have three major components:

a- A set of initial conditions, including the projections of world rates of energy use and carbon dioxide emissions discussed above;

b- Cause-and-effect models that relate these initial conditions and perturbing forces (such as specific climatic changes) to outcomes; and

c- Analyses of the implications of these outcomes.

The objective should be to create plausible and internally-consistent combinations of assumptions and estimates about regional climates, ocean and ice dynamics, changes in marine and land biota, effects on agriculture, and societal responses. One part of these scenarios would be models of future international behavior and institutions that might result from the perceived self-interests of different nations. Uncertainties must be modelled explicitly, with the aim of estimating the optimum flexibility and resiliency that societies will need in order to deal with uncertainties at the lowest practicable cost. The process of scenario construction should be iterative, with each round aimed at greater consistency and sharper definition of unanswered questions. By integrating available scientific information, scenarios can serve as powerful guides to further research.

2. Impacts on Society of Past Climate Changes. Global and regional climate changes will affect different societies and different segments within societies in a variety of ways. One means to determine the range of impacts is to undertake case studies on ways in which families, political institutions, and social sectors such as agriculture have been affected by changing or varying climates.

How have patterns of settlement, economic development, social relations, and people's attitudes and images about the future been modified? Historical case studies of climatically vulnerable areas such as Iceland and the Great Plains of the United States may be particularly useful in understanding societal adaptations. Studies of societal responses to "surrogates" for climatic change, e.g., long-continued soil erosion or relatively rapid changes in sea level, could also be helpful.

The basic resource for case studies should be a climate-society historical data bank, that is, a uniform, chronological set of data on climatic change over time and the impacts of these changes on societies. Initially, at least, the focus should be on the 13th century to the present and on Europe and North America, but as opportunity offers, the data bank should be expanded to include other times and other cultures.

3. Economic and Political Consequences of a Redistribution of World Water Resources. Using both historical climate data and computations from "general circulation" models of climate, the distinguished German climatologist, Herman Flohn, has recently estimated the changes in average surface temperature and precipitation that are likely to occur in different latitude belts if atmospheric carbon dioxide goes up 560-680 ppm. (The most probable value of 620 ppm is slightly less than twice the present amount of 335 ppm.) This CO_2 concentration could exist by about 2050 if present trends in fossil fuel consumption continue.

Flohn finds that, in the northern hemisphere, average rain and snow fall may increase by 20 percent between latitudes 10° and 20°N, while the average temperature in this latitude belt is expected to increase only slightly, about 2°C. On the other hand, at 40°N latitude, precipitation may decrease by 14 percent, while average surface temperature rises by 6°C. An even greater decline in average precipitation, about 20 percent, may occur at 10°S latitude, and 5 percent at 20°S, with increases in surface air temperature at these latitudes of 4 - 6°C. At latitudes higher than 25° in the southern hemisphere and 47° in the northern hemisphere, precipitation increases with rising CO_2, but average surface temperature also rises by 4° to 6°C. (See Table)

Probable changes in average annual surface temperature and precipitation at different latitudes with an increase of atmospheric CO_2 to 620 ±60 parts per million (somewhat less than twice present level)

Latitude	Aver. annual change in surface temp. °C	Change in precipitation
60° N	+ 7.5°	+ 18 %
50° N	6°	+ 4 %
40° N	+ 6°	- 14 %
30° N	+ 4.5°	0
20° N	+ 2.5°	+ 20 %
10° N	+ 1.5	+ 20 %
Equator	+ 3°	0 %
10° S	+ 4°	- 20 %
20° S	+ 4.5°	- 5 %
30° S	+ 4°	+ 5 %
40° S	+ 4°	+ 12 %
50° S	+ 3°	+ 12 %
60° S	+ 2.5°	+ 12 %

These changes will have profound effects on the world distribution of water resources. When precipitation exceeds evapotranspiration, the total surface runoff from a river system is simply the difference between precipitation and evapotranspiration (with a slight correction for underground seepage into the ocean). In the Colorado River basin of the United States at the present time, about 85 percent of the precipitation evaporates and only 15 percent is carried by the river. Because potential evapotranspiration depends mainly on surface temperatures, the percentage change in runoff due to climatic change is likely to be much greater, other things being equal, than the percentage change in precipitation. With a rise in average air temperature of several degrees centigrade, and a 10-15 percent fall in precipitation, the average flow of the Colorado could diminish by 50 percent or more. Yet even with large volumes of water storage, the present flow of the river is barely sufficient to meet present demands over a period of years.

With projected water uses for coal mining and transportation, geothermal power, oil shale production, and conversion of coal to synthetic gaseous or liquid fuels, these demands are likely to increase by about 10 percent.

If Flohn's projected changes in precipitation and rises in temperature due to increasing atmospheric CO2 actually occur, radical changes in water allocations to different users or a large augmentation of Colorado River flows by interbasin transfer will be essential. Such changes in use or interbasin transfers would cause immense political and economic repercussions. Decisions made in the next few years can amplify or reduce these repercussions. A combination of economic, political, and technical analyses is urgently called for.

Very large changes in surface and underground water supply could also occur elsewhere in the world. In Northern Africa, the average flows of the Niger, Chari, Senegal, Volta, and Blue Nile rivers could increase by large fractions because of 10-20 percent more precipitation and only slightly higher surface temperatures. The flows of the Narmada and other South Indian rivers would also be expected to increase. On the other hand, the largest river in China, the Hwang Ho, the Amu Darya and Syr Darya in one of the prime agricultural belts of the Soviet Union, the Tigris Euphrates system in Turkey, Syria, and Iraq, the Zambezi in Rhodesia and Zambia, and the Sao Francisco in Brazil could greatly diminish in volume of flows. Somewhat smaller runoff and underground storage could also be expected in the Ganges of northern India, the Indus in Pakistan, the Danube in eastern Europe, the Yangtze in China, and the Rio Grande in the United States. All of these rivers form the basis of very extensive and highly productive irrigation agriculture, and the projected diminutions in their flow could have potentially disastrous consequences. On the other hand, the expected considerable increase in the flow of the Mekong and Brahmaputra rivers could
large areas of Thailand, Cambodia, Vietnam, India, and Bangladesh. The economic and social consequences could seriously worsen the situations of many Third World countries and part of the agricultural basis of the Soviet economy. Careful study should be made of

national and international actions, including investments in river basin development, that should be taken in the next few years to mitigate the effects that may be felt within the next several decades.

4. Risk-Perception, Information and Decision-Making. Societies respond only to conditions they perceive. Consequently, a pivotal aspect of the carbon dioxide question involves how people in different cultures perceive scientific and other information and make decisions based on their perceptions regarding adaptation or other responses. In the industrialized countries, many kinds of experts will provide information on climate changes, and policy-makers at all levels of society will decide how to act on that information. The problem of perception raises several provocative and researchable questions in social psychology.

   How reliable are the judgments of experts and decision-makers?

   Where do personal biases creep into expert judgment?

   What kinds of information does the public need in order to comprehend the knowns and unknowns?

   How will families perceive a problem and make decisions regarding their way of life?

   How do people combine multiple and conflicting risks and benefits of various options into a single decision?

   How can public opinion be accurately appraised as a guide to policy-making officials?

5. Possible Population Redistribution.

   Will the present southward drift of human populations in the United States and other countries such as Finland and Canada be modified by the much warmer temperatures expected at higher latitudes in these countries?

   If climatic conditions for agriculture deteriorate in Mexico and Central American countries, will population pressures for migration to the United States be intensified? Or, if agro-climatic conditions should improve, will economic development accelerate enough to slow migration?

II. CLIMATIC DATA BASES AND MONITORING

A research issue that cuts across all aspects of research on effects of CO_2-induced climate change involves making different kinds of data accessible and useful. Although the work inventory of weather and climate data is extensive, these have not often been reported in a form most useful for predicting biological and societal responses to climate change or climate variations. Improved historical and current climate data bases would be desirable. The form of these data bases should be determined by collaboration among biologists, agronomists, resource managers, social scientists, climatologists, statisticians, and data processing specialists. Different forms may be required for agriculture and for social sciences. In tropical agriculture, crop/climate data systems need to be built and tested that will include information on regional climate and agro-resources such as soil, topography, and socio-economic conditions. Particularly for rain-fed agriculture, these data systems could be used in identifying zoning and mapping areas suitable for different crops and cropping patterns, based on climatic and agronomic constraints. More generally, agroclimate information combined with weather forecasts can be used at the farm level in selecting planting times and scheduling irrigation, fertilizer applications, and pest control measures. At the national level, it can be used for prediction of yields and prices.

Biological monitoring of forests and other natural ecosystems should be undertaken on a continuing basis to identify and evaluate effects of increased carbon dioxide and climatic change. Such monitoring should be carried out both on a reconaissance level and in greater detail at specially-chosen sites to study species successions and other relationships.

Mr. Lave, did you want to comment on that?

Mr. LAVE. I have no comment.

Mr. GORE. Give me, if you will, the simple reasons why the temperature increase at the poles is so much greater.

Mr. SCHNEIDER. I also want to hear this simple reason.

Dr. SMAGORINSKY. It has to do with the fact that we have snow cover at the poles. At the snow perimeter the reflectivity or albedo of the Earth's surface changes rapidly and, most important, by a huge amount.

In addition, near the polar regions, the part of the atmosphere that mixes is shallower than elsewhere. Therefore, heating resulting from an increase in CO_2 and its greenhouse enhancement will melt some of the snow. At the retracting snow perimeter, the surface reflectivity is sharply reduced, more of the sun's radiation is absorbed by the Earth and then reradiated to heat the troposphere. The Earth-atmosphere temperature increase at the latitude of reduced snow perimeter is thus accentuated—a positive feedback—so that the heating is confined to a narrower depth and the surface temperature response is even greater.

Both of these act together. It is known as the snow-albedo feedback.

Mr. GORE. I appreciate the explanation.

Now, looked at from a national point of view, by doing so I don't wish to deny the global perspective which is so obvious but in assessing the importance and severity of the problem for us, I think it is not particularly useful to average in the good effects with the bad effects and conclude that everything comes out in the wash.

If the effect is real, as it appears to be to the censensus of scientists who have looked at it, how likely is it that our grain belt will shift northward to Canada?

Mr. REVELLE. One of the problems here is that it can't shift northward because of the differences in the soil. It is easy enough to talk about a warmer climate in Canada, but the soils there are not the rich black soils of Iowa; they are acid forest soils and they are liable to be very much less fertile and productive.

Mr. GORE. How likely is it that our grain belt—that we will lose our grain belt?

Mr. REVELLE. I wouldn't say it is by any means a certainty, but it seems to me it is very likely we will have to make major adaptations because of a considerable warming of the temperature. Right now in the Corn Belt the optimum climate for corn is a little bit cooler than the average climate. The corn yields are greater when the summer temperature is a degree less than the average.

If you go up by 6° C., about 10° F., if you are going to grow corn there it will have to be a different kind of corn.

Mr. GORE. By the same token, the southwest of the United States will become more dry and arid?

→ Mr. REVELLE. If you take Flohn's model, the drying would be concentrated around latitude 40° N., which goes right through northern California, right through the Missouri and Illinois area, right across to the Atlantic, about the latitude of Pennsylvania or Philadelphia.

That would be the area of greatest drying if Flohn's model is correct, as well as a relatively large increase in temperatures in the United States.

The further north you go, the greater the increase in temperatures.

Mr. GORE. In the news today we read a lot about the policy toward illegal immigrants from Mexico. If this is true, it appears that Mexico is coming out ahead too.

Mr. REVELLE. Mexico might be a little better off if you take Flohn's model.

Mr. SCHEUER. Why would that be?

Mr. GORE. The reason is the moisture patterns at different latitudes are affected in different ways. Some gain moisture and some lose moisture and they do not exactly track the temperature variation patterns.

There is a different combination, a different intersection of the two patterns at each latitude.

Mr. REVELLE. Professor Flohn projects a 20-percent increase in precipitation, at latitude 20° N., which goes right through the middle of Mexico, in contrast to a decrease in precipitation, at latitude 40° N., which goes through the middle of the United States.

This is clearly just one model. Nevertheless, it is a very disturbing model and, as I said, particularly for the river flow, the increase in temperature and a decrease in precipitation might radically change the volume of flow of a river like the Colorado.

Mr. GORE. One of the options that was listed was to do nothing. It seems to me that ought to be rephrased because we are creating the effect, or helping to create the effect by continuing the consumption patterns that we are now pursuing.

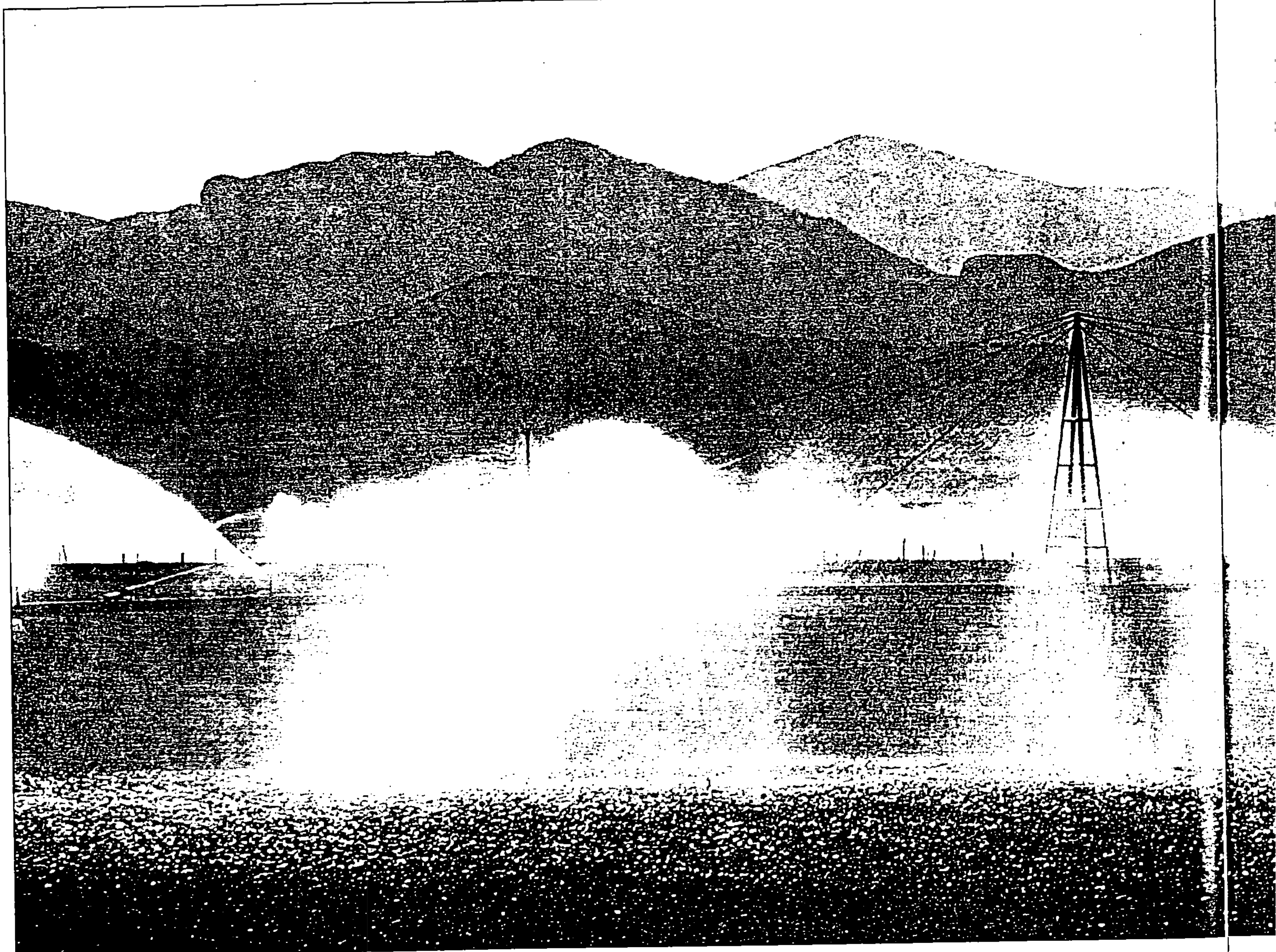
I think it is important at this point in our history to recognize the magnitude of the effect on our global environment of industrial civilization's pattern and that ought to lead us to reevaluate the range of options that are available to deal with this.

If it is real and if the areas of uncertainty continue to narrow, then I believe we ought to discard all of the smaller options of trying to adapt to it like maybe giving some travel tax credit to those people in Florida who have to move from their homes or adapting agricultural policy in Nebraska to come up with sand flea farms and rather to concentrate instead on looking the large problem straight in the eye, recognizing its global cause and selecting the one obvious solution for the problem if it is determined to be in fact real, which is a rather dramatic change in the energy consumption patterns worldwide. It seems pretty obvious that is the appropriate response, but the areas of uncertainty are still large. What I mean by that is, accelerating a moving away from fossil fuel. It is just obvious that that is in fact what is causing the problem. If the cause and the effect relationship is real and if the impacts of the development are of the magnitude that have been described by this panel today, then the response appears to be obvious.

Dr. SCHNEIDER. I will comment briefly on that. Both Lester Lave and I were members of the same Academy of Sciences Panel on Energy, the Committee on Nuclear and Alternative Energy

FROM CARBON DIOXIDE + CLIMATE HEARING JULY 31, 1981.

New Scientist 10 November 1990



High and dry in the global greenhouse

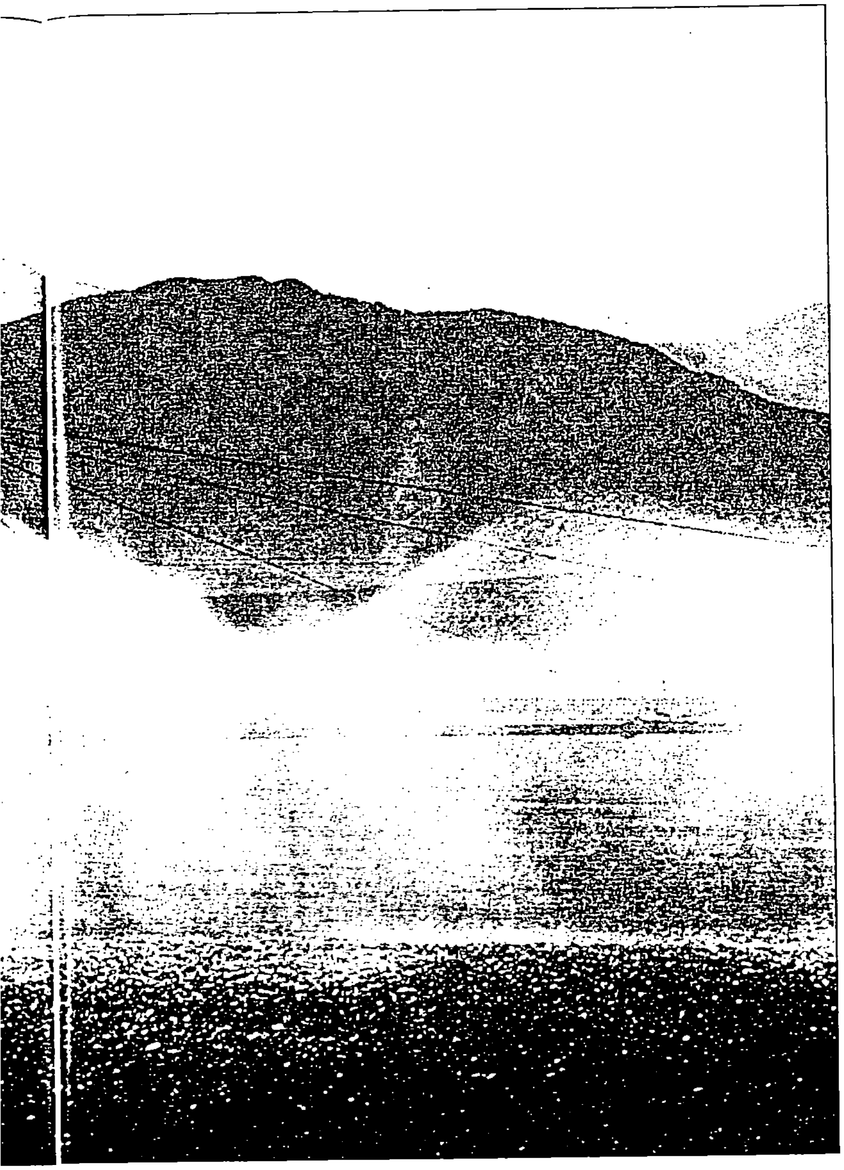
The first and most serious impact of global warming may be widespread drying. And drier soil will need more irrigation from scarcer water supplies

Fred Pearce

THE RIVER Colorado flows through the arid western states of the US. It is home to the world's first and most famous dam, the Hoover Dam, and is the most intensively used major river in the world. Under US law, every drop—17 billion cubic metres per year on average—is earmarked, some for irrigating farms and generating electricity; some for watering cities from Phoenix, Arizona, to California's Los Angeles and San Diego; and some to flow across the border to water Mexican fields. But within 50 years, its annual flow, the lifeblood of the American West, could be cut by half thanks to global warming. Aqueducts, such as the All American Canal, which takes its water to California and the new \$3 billion canal (almost £1·5 billion) that crosses the Gila desert to Phoenix, are in danger of running dry.

Across the globe in Bangladesh, the problem is likely to be too much water rather than too little. After floods that covered half the country in 1987 and 1988, Bangladeshis have embarked on an emergency programme to shore up their defences against floods from the Rivers Ganges and Brahmaputra. The job could eventually cost \$10 billion. And they have not even begun to consider the predictions of climate modellers that flow in the two rivers could increase by 50 per cent or more during the flood season, thanks to an intensified monsoon. For Bangladesh, the threat from inland flooding may turn out to be more serious than the widely publicised threat to the nation's survival posed by rising sea levels.

The impact of rising temperatures and sea levels has grabbed most of the headlines when scientists discuss the possible consequences of the greenhouse effect. But the consequences for the water supply are likely to be greater and much more important for day-to-day life. This is partly because precipitation and evaporation, together known as the



G. Heilman/ZEFA

hydrological cycle, amplify small changes in temperature, making major changes in the water available for rivers, crops and humans alike. The results may be localised, devastating and very hard to predict.

Current computer models of climate predict that a global warming of perhaps 4 °C might follow a doubling of carbon dioxide concentrations in the atmosphere within 50 years or so. This, they say, is likely to increase global rainfall by up to 10 per cent because extra heat at the Earth's surface will evaporate more moisture from sea and land.

This more intense hydrological cycle will generate much stronger changes in precipitation from region to region. There will be two principal effects on this scale. First, the climate zones that form latitudinal rings round the planet will move away from the equator and towards the poles. The desert regions around the tropics of Cancer and Capricorn, including the Sahara and the Kalahari in Africa and the deserts of the American southwest will spread. Secondly, the monsoons—giant sea breezes that blow from cold continents to warm oceans in winter and vice versa in summer—will become more intense as temperature differences between sea and land grow.

These two effects will cause some areas to become much wetter. Others, including many of the lands that produce the world's best grain harvests, will become much drier during the growing season, with reductions in rainfall in summer of 15 or even 20 per cent anywhere from the American Midwest to the Mediterranean and western Australia.

But precipitation is only half the story. In the past four years, climate modellers have been concerned by the likely impact of the greenhouse effect on the amount of moisture held in soil. This, rather than actual rainfall, is what determines whether plants have enough water to grow and how much runoff will reach rivers and reservoirs.

In 1986, Syukuro Manabe and Richard Wetherald of the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey, startled other modellers by predicting that soil moisture in the greenhouse world "would be reduced in summer over extensive regions of the middle and high latitudes, such as the North American Great Plains, western Europe, northern Canada and Siberia". Manabe and Weatherald had simulated conditions in which carbon dioxide levels in the atmosphere were double those of pre-industrial times, a state likely within 50 years or so unless the world changes course. They predicted reductions of as much as 50 per cent over wide areas. The simulations were carried out on the GFDL's General Circulation Model, one of five sophisticated computer models currently in the front line of the world's attempts to predict the impact of the extra greenhouse effect.

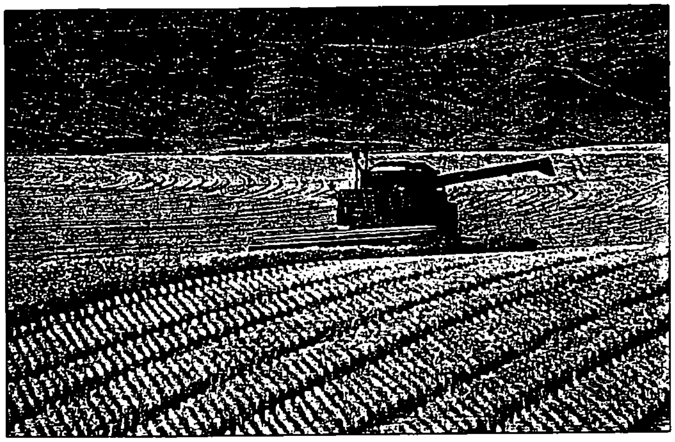
Why should soil moisture drop much more than rainfall itself? The answer, said Manabe and Wetherald, is evaporation. Clearly, in drier, sunnier weather, more moisture evaporates from soils and vegetation. But in the model, this effect is intensified in many places by winter snow melting and frozen soils thawing earlier in the year. Both of these allow a surge of evaporation of water from soils at a time when soils are usually protected, under present climate conditions.

Other researchers have reached similar conclusions for particular regions. For instance, Peter Gleick of the Energy and Resources Group at the University of California at Berkeley looked at the consequences for the Sacramento basin. The basin provides almost a third of California's surface water resources, feeding water into the state's system of aqueducts, one of the world's most expensive civil engineering projects. The aqueducts water the state's Central Valley, an irrigated area frequently described as the most productive agricultural region in the world. That coveted title, and the groves of orange and avocado trees, may not survive the greenhouse. Gleick predicts that within 50 years soil moisture in the Sacramento basin in summer may fall by up to 44 per cent. With major reductions in flows likely from two of its main sources of water, the Colorado and Sacramento basins, the future of farming in the Golden State looks less than secure.

But the scientists remain unsure of the significance of their predictions. This is one of the reasons they have been reluctant to discuss soil moisture in great detail in public forums, such as the Intergovernmental Panel on Climate Change. One critic of Manabe and Wetherald is John Mitchell of Britain's Meteorological Office, which runs another of the "big five" General Circulation Models. He has warned in a letter to the journal *Nature* that "the magnitude of the simulated summer drying is dependent on the physical attributes of the soil and, in certain regions, can be reduced or even reversed by an alternative, but equally plausible, treatment of runoff from frozen ground." In other words, the modellers do not know enough about how water is held in soil to be sure of how these processes will change in a warmer climate.

In most of the areas where there are fears of drier summers, modellers such as Manabe and Wetherald predict more precipitation in winter, much of it as snow. The assumption has been that most of the spring meltwaters will run off quickly over frozen soil and not soak in. But, says Mitchell, this may be a false assumption. If more meltwater infiltrates the soil, it could stay wetter longer through the summer and the dustbowl predictions would prove to be wrong.

One of the most alarming aspects of the debate over soil moisture is the very different views taken by researchers from separate academic disciplines. Most climate modellers are pessimists, predicting widespread and disruptive changes to precipitation and soil moisture. But agricultural scientists, who regard the soil as their domain, are generally much more optimistic. Ten of them, headed by Richard Adams of Oregon State University put their names to an article on global climate change and US agriculture published in May this year (*Nature*, vol 345, p 219). In a thinly veiled assault on the modellers, they concluded that: "A major policy concern is whether climate change is a food security issue for the US. The results of these analyses suggest that it is not."



B. Peterson/ZEFA

Old gold: intensive agriculture could become a thing of the past

They had arrived at this view after linking existing models used by agriculturalists in predicting harvest from weather patterns to two of the big five climate models from GFDL and NASA's Goddard Institute of Space Studies (the GISS model). The GISS model produced much more optimistic predictions than the GFDL model.

Adams pointed out that, while the models differed only marginally in their estimates of average annual rainfall, there was a much greater discrepancy over rainfall in the growing season. At Columbia, South Carolina, average rainfall for the critical month of June is today 113 millimetres. GISS predicts a greenhouse average of 148 millimetres, while GFDL predicts 50 millimetres, resulting in much lower yields of crops.

One place cannot be representative of changes across the globe. Climate modellers always warn against taking individual numbers produced by their computers too seriously. Even so, Adams and the agriculturalists think that predictions of desiccated croplands may have been greatly exaggerated and that extra irrigation could make up for most of the shortfall in land depending on rainfall for its water. But they do not say where this extra water for irrigation might come from.

No one knows how the plant life of the planet, including crops, will respond to a world in which temperatures rise, rainfall patterns lurch unpredictably and the air contains twice as much carbon dioxide as they are used to. Many scientists predict that there will be a widespread carbon dioxide fertilisation effect. Carbon dioxide is the fuel for photosynthesis so, other things being equal, plants ought to grow faster in a greenhouse world. Not only that, they will need less water to grow because photosynthesis is more efficient in an atmosphere rich in carbon dioxide. That, at any rate, is what happens in man-made greenhouses dosed by the gas.

This line of inquiry has led researchers more interested in plants than planetary forces to take a supremely optimistic view about the greenhouse effect. One of the US government's most prestigious agricultural research stations, the Water Conservation Laboratory, in Phoenix, Arizona, is a hotbed of super-optimism. It is difficult to think of a city where the resolution of this debate matters more.

Herman Bouwer, former director of the laboratory puts the case most succinctly. "Greenhouse studies have shown that a doubling of the atmospheric carbon dioxide content will increase crop yields by about one-third, while decreasing water consumption . . . by about one-third," he says. "Crop yields per unit of water consumptively used would double with a doubling of the carbon dioxide content of the air."

Much of the research to sustain this argument has been done by Bouwer's colleagues at the laboratory, Sherwood Idso and Bruce Kimball. Idso has a reputation as a maverick in the greenhouse debate. This dates back a decade, to the time when he argued that modellers had used incorrect estimates for the heat fluxes in the atmosphere, so global warming due to the greenhouse effect would be only a tenth as strong as predicted. Idso no longer argues this case in writing, but stands by his claim, based on experiments under glass, that plants will have more to gain than to lose from global warming.

In a paper published last year in *Soil Science*, Idso adopted, for the sake of argument, Manabe and Wetherald's prediction of a 50 per cent reduction in summer soil moisture over significant parts of the globe. "With no other pertinent factors, of course, such a reduction would be disastrous," he conceded. But if, as he believes, the same forces that caused the reduction also doubled the amount of crops produced for a given amount of water, then the two would cancel each other out and "a 50 per cent reduction in water reserves would only bring productivity back to its current level".

His critics, such as Veerabhadran Ramanathan from the

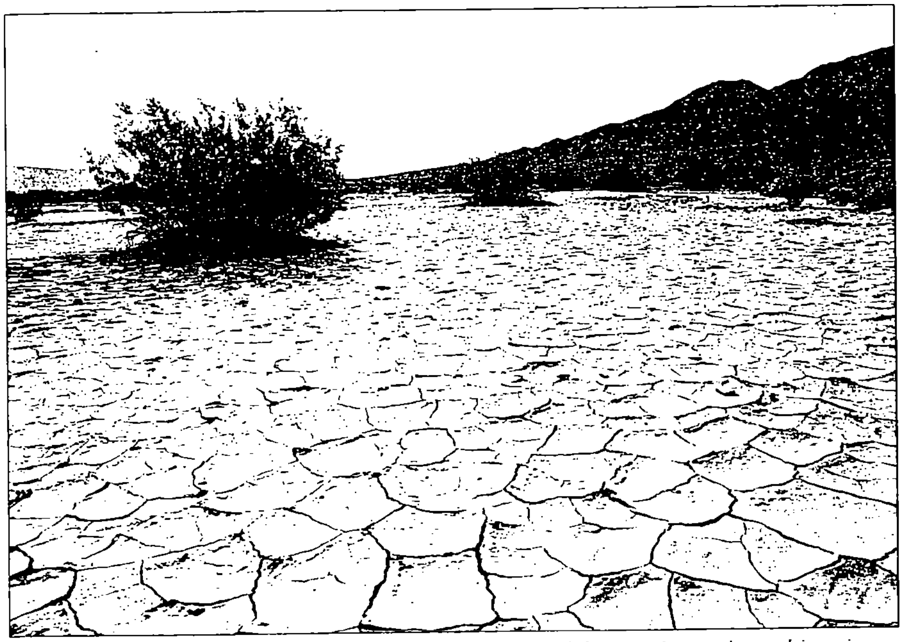
Seasons of change for Britain's water supply

RESEARCH into the likely impact of changing climate on British soils and water supplies is at an early stage. Studies under way at the University of East Anglia suggest that soil moisture could drop by up to 25 per cent in East Anglia, the nearest Britain comes to the dry grain-growing prairies of the American midwest.

In general most models predict that rainfall could increase in the north and west of Britain, but could decrease in the already dry areas of the south and east. The effect of this on the water available for both plants and water supplies depends on what happens to rates of evapo-transpiration. If the dominant change is increased evaporation due to warmer temperatures then parts of Britain will become parched. If the main change is reduced transpiration as plants use water more efficiently in a carbon dioxide rich atmosphere, then river flows could increase, bringing more risk of flooding than drought.

But a review by the Institute of Hydrology for the government last year warned that "changes in the seasonal distribution of flow could well be more significant in practice than changes in the total amount of runoff." Britain can expect wetter winters and drier summers which "will be reflected in stronger seasonal variation in flow". This is a big problem for water companies: to ensure that they have enough water through the hot dry summers they will need larger reservoirs to store winter rain. One calculation by the institute suggests that the chance of a typical reservoir in the English Midlands emptying might rise by half.

Much of south and east England depends on underground aquifers for water, in chalk and limestone, for instance. Here the news is good. Since the soil is not generally frozen or snowy in winter, it will be able to absorb the extra rainfall predicted for winter, causing an overall increase in the amount of rainwater percolating downward to top up these natural reservoirs. □



Philip Dowell/ZEFA

Cracking up: productive soils could become a thing of the past in continental interiors

University of Chicago, point out that other greenhouse gases will contribute to global warming without providing the spin-off of carbon dioxide fertilisation. Idso replies that higher temperatures will magnify the fertilisation, so that a doubling of carbon dioxide in the atmosphere will almost triple the plants' ability to utilise water. He forecasts a "greening of the planet" and believes that it may already have begun.

Decline in fall

But what about water resources in rivers and reservoirs? Climate modellers and hydrologists believe that just as changes in rainfall will be enhanced in soil moisture figures, so they will be magnified further when statistics for the run-off of water from the land into rivers and reservoirs is calculated. Jaromir Nemec, chief of water resources at the UN Food and Agriculture Organisation, says that "the reduction of rainfall volumes by 25 per cent produces in the dry temperate basins (such as the Colorado basin or the rivers of Britain and western Europe) a decrease of runoff of about 80 per cent." Water resource planners will need to increase their reservoir capacity by four times, which, as Nemec comments, "is in most cases a most difficult, if not impossible proposition".

Few countries have begun to consider the consequences of such changes, but the emptying of the Aswan dam on the Nile during the 1980s, which prompted panic in Egypt before the rains returned in late 1988, points to the dangers. Next time, the rains may not return. A study of *Climate Change and US Water Resources*, completed this year by the American Association for the Advancement of Science, concluded that water shortages due to climate change there were "serious, certain and already evident in places".

And few other countries have begun to examine the likely effects in detail. Australia, perhaps the driest and most drought-prone continent, is an exception. Scientists believe the mediterranean climate enjoyed by people in the southern half of Western Australia, around Perth, is particularly vulnerable. Changes in climate belts could push fronts that bring rain further south so they miss the continent altogether.

The Water Authority of Western Australia is now expecting a decline in rainfall in the southern half of its domain of perhaps 20 per cent by the year 2040. It estimates that flows in its rivers, which irrigate a productive region of arable farming as well as fill Perth's taps, could fall by 45 per cent. Recharge of groundwater tapped by local wells and boreholes will also be hit. The authority's economists predict that such a change will increase threefold the capital and operating costs of new dams. With this in mind, the authority has recently been lobbying the federal government to spend $10 billion on constructing a giant aqueduct that would carry water the length of Australia from the River Ord in Kimberley on the north coast to Perth, with a possible branch to Adelaide. Another Australian has study concluded that New South Wales could suffer, too; the area of land under irrigation could fall by 75 per cent.

Australia may not be the only country having to consider vast aqueducts to move water thousands of kilometres. Throughout history, people have established cities where there is water. Within the next few decades, as climate zones shift, we may have to start moving the water to the people. The US may renew its calls to tap into the vast water resources of Canadian rivers. Already Nigeria is backing a scheme to bring water 3000 kilometres from the River Zaire to fill irrigation channels in the north, which has been left high and dry by drought in the Sahel.

But will all this be necessary? Down in Phoenix, the scientists at the Water Conservation Laboratory are not so sure. They believe that plants may save the day by drastically reducing the amount of water that evaporates from the ground. On land covered by vegetation, evaporation should more properly be called evapo-transpiration. The water returning to the air comes from a combination of evaporation by the Sun and transpiration (water released by photosynthesis). Bouwer argues that in the greenhouse world, rates of transpiration will be reduced, counteracting any increase in direct evaporation. Plants that use water much more efficiently will excrete less moisture back into the air. This, he predicts, could mean more rather than less water left over to run into rivers.

In 1984, Bouwer quoted research in two Australia river catchments which, he said, "concluded that a doubling of atmospheric carbon dioxide concentrations would increase streamflow from watersheds by 40 to 90 per cent"—a far cry from the drastic reductions in flow predicted by climate modellers and hydrologists. Today, few would go so far. Bouwer's former colleague, Bruce Kimball and others recently warned in the water study for the American Association for the Advancement of Science: "We cannot be completely confident that the simulated responses (in greenhouse conditions) would actually occur in fields and forests." Nonetheless, they found that increases in evapo-transpiration rates predicted by Manabe and Wetherald on the basis of climate models would be substantially reduced by the effect of plants, and that would be sure to bolster river flows.

The division between the climate modellers and the agriculturalists could hardly be greater. On one side, the modellers predict dust bowls, desiccated crops and empty reservoirs. The other side foresees an agricultural Eden and more water than we know what to do with. It is tempting to conclude that the truth may lie somewhere in the middle. But it is more likely that the real world will show a wide range of responses. The hard part will be predicting where the dust bowls will occur and where the Edens will sprout. It is worth remembering that nobody predicted an ozone hole over Antarctica. ☐

Fred Pearce writes about the environment

They are not prepared to accept it" (Bowie, Baltimore SUN, 8/3).

*8 DROUGHT: CA INACTION DAMAGED ENVIRONMENT, REPORT SAYS

A U.S. EPA-commissioned study on the effects of California's five year drought on the state's economy and environment says that the failure of government officials to deal quickly with the situation may lead to irreversible environmental damage. The report was requested by Rep. Henry Waxman (D-CA), chair of the House subcmte on environment and health.

The study, conducted by the Pacific Institute, was critical of early decisions by state officials to draw down reservoir levels even though it was apparent that wildlife populations were suffering major declines. State officials also adopted very limited conservation measures, the report said.

The failure to deal effectively with the drought shows CA is not prepared for future water shortages that may be caused by global warming, according to the report: "The experience of the drought suggests that California will not address climatic changes with specific policies until long after the impacts are being felt. In the meantime, opportunities to reduce long-run costs may be lost."

Waxman, at hearing Thursday: "We can survive for a while by pumping our groundwater supplies dry, as California is now doing. But when our generation passes away, and we leave a dry and parched world to our children, it will be too late to prevent human catastrophe."

CA Sec. of Resources Doug Wheeler: "I think the lessons of the drought is first, it's not always best to assume the best and second, we do have a need now, if we didn't five years ago, for long-term policy. I would disagree with the suggestion we cannot cope. I don't think we have any alternative but to cope." Wheeler added that Californians now understand that the state does not have enough water to meet demands even in non-drought years.

The report said that as a result of the drought, "many wildlife populations are so strained that their ability to recover must be questioned. ... Some fisheries populations have been brought to the verge of extinction, if indeed they have not been pushed over the edge." Additionally, up to 60% of the trees in Southern CA forests may be dead because of the drought, according to the study (Virginia Ellis, L.A. TIMES, 8/4).

* file - California drought in gr. w. file.

* get a copy of the report. ✓

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============== MARKETPLACE =========

*9 RCRA: PACKAGING AND LABELING PROVISIONS HEARING

The environmental protection subcommittee of the Environment and Public Works Committee heard testimony last Wednesday on issues related to S 976 of the Resource Conservation and Recovery Act which would create an expert review board on products and packaging. The bill, introduced by Sen. Max Baucus (D-MT), Copy -- Pacific copy -- CA drought in J.W. draft

THE NEW YORK TIMES NATIONA

Drought Taking Its Toll on California Environment

By ROBERT REINHOLD
Special to The New York Times

LOS ANGELES, Aug. 3 — The California economy has proved remarkably resistant to five years of drought, but the state's slow and short-sighted response may have inflicted irreversible damage on the environment.

That is a central conclusion of a broad study, made public on Thursday, of the economic and environmental effects of the severe drought that has gripped the West. The study was conducted by the Pacific Institute for Studies in Development, Environment and Security, a nonpartisan research organization based in Berkeley, and was requested by the House Energy and Commerce Subcommittee on Health and the Environment, which held a hearing on the subject Thursday in Washington.

The authors charged that state leaders had been unwilling to recognize that the drought might persist for several years and had continued to support wasteful uses of water by drawing reservoirs down to dangerously low levels for the first four years of the drought. From this, the report drew a pessimistic lesson about how the region might respond to the possibility of permanent climate change. "The experience of the drought suggests that California will not address climatic changes with specific policies until long after the impacts are being felt."

Damage to Ecosystems

The report found that while the effects varied, farming and ranching had survived well by switching crops, pumping more water from under the ground and making more efficient use of irrigation water. Strong demand for California products meant that gross agricultural receipts reached a record high last year, although not so high as they might have been with more precipitation. But the study predicted that the longer-term costs to agriculture

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