Climate Variability, Climate Change, and Western Water

Kathleen A. Miller
Environmental and Societal Impacts Group
National Center for Atmospheric Research

Report to the Western Water Policy Review Advisory Commission

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September 1997

The Western Water Policy Review Advisory Commission

Under the Western Water Policy Review Act of 1992 (P.L. 102-575, Title XXX), Congress directed the President to undertake a comprehensive review of Federal activities in the 19 Western States that directly or indirectly affect the allocation and use of water resources, whether surface or subsurface, and to submit a report of findings to the congressional committees having jurisdiction over Federal Water Programs.

As directed by the statute, the President appointed the Western Water Policy Review Advisory Commission. The Commission was composed of 22 members, 10 appointed by the President, including the Secretary of the Interior and the Secretary of the Army, and 12 members of Congress serving *ex-officio* by virtue of being the chair or ranking minority member of the 6 congressional committees and subcommittees with jurisdiction over the appropriations and programs of water resources agencies. A complete roster is provided below.

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This is an Independent Report to the Commission

The report published herein was prepared for the Commission as part of its information gathering activity. The views, conclusions, and recommendations are those of the author(s) and are not intended to represent the views of the Commission, the Administration, or Members of Congress serving on the Commission. Publication by the Commission does not imply endorsement of the author's findings or recommendations.

This report is published to share with the public the information and ideas gathered and considered by the Commission in its deliberations. The Commission's views, conclusions, and recommendations will be set forth in the Commission's own report.

Additional copies of this publication may be obtained from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia, 22161; phone 703-487-4650.

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Introduction

Variability is a fundamental characteristic of the water resources of the Western U.S.. Water availability varies geographically, and streamflows fluctuate on daily, seasonal, annual, and decadal time scales. Runoff depends on climatic processes that, to some extent, follow regular seasonal patterns. For example, there are regular seasonal changes in the global distribution of solar radiation, leading to predictable patterns of seasonal change in global atmospheric circulation. However, within those seasonal patterns, there is a great deal of intraseasonal and interannual variability. The variability is, to some extent, the random outcome of complex nonlinear interactions among independently varying components of the climate system. However, at times, variability in precipitation and runoff in the Western U.S. is linked to the El-Niño/Southern Oscillation (ENSO) phenomenon. The alternating episodes of sea surface warming (El Niño) and cooling (La Niña) in the eastern and central tropical Pacific Ocean caused by ENSO modify storm tracks and, thus, the locations where droughts and floods are most likely to occur. The close link between climatic variations and water availability suggests that water resources will be sensitive to the regional effects of global climate change.

Western water management practices, storage infrastructure, and patterns of use are tuned to the expected range of variation in surface runoff and groundwater availability. Floods and droughts are part of this natural range of variation, although the probabilities of such extreme events may be difficult to discern from limited historical experience. Prospective climate change complicates long-term water resources planning because it will alter streamflow probability distributions and the characteristics of aquatic ecosystems in ways that are not yet entirely clear.

The available evidence suggests that global warming may lead to substantial changes in mean annual streamflows, the seasonal distribution of flows, and the probabilities of extreme high or low flow conditions. Recent climate model studies project that significant warming may be apparent in this region within the next 50 to 100 years. Such warming will be accompanied by changes in precipitation, evaporation, and runoff, but those changes cannot yet be forecast reliably at the watershed scale. Runoff characteristics may change appreciably over the next several decades. In the near term, however, the effects of global warming are likely to be masked by ongoing year-to-year climatic variability.

Rapid population growth, increasing environmental concerns, and resulting changes in the character of water demands have led to increased competition for water even under normal flow conditions. These same changes contribute to increased vulnerability to hydrologic extremes. Under low flow conditions, the risk of shortages now falls on a growing set of competing uses and values,

while residential, commercial, and industrial development in flood plains has increased the value of property at risk to extreme high flows. Environmental values are often quite vulnerable to hydrologic extremes. At the same time, efforts to preserve those values constrain traditional engineering approaches to managing variable streamflows.

Thus, the significance of water resource variability is growing at a time when anticipated global climate change has increased our level of uncertainty regarding the future hydrologic characteristics of western river basins. Effective design of long-term policy will require an understanding of the existing relationship of climate to water resources in the West, the nature of potential climate changes, the sources of uncertainty, and the prospects for resolving the uncertainties. This report provides an overview of these topics, placing the impacts of global climate change in the context of existing climatic variability.

Effective policy also will require attention to developing options for responding to a wide range of possible changes in water availability or flood frequencies. That task should be an integral part of the work of the Western Water Policy Review Commission. This report describes some factors that should receive consideration in Federal efforts to contribute to the type of adaptive and responsive policy environment that will be needed to cope with the effects of a changing and variable climate.

The first section of this report describes the present distribution of water resource availability across the West and the variability of streamflows on multiple time scales. This description of contemporary climate examines some of the evidence for links between the ENSO phenomenon and anomalously wet or dry periods in some parts of the West. The next section describes the current state of scientific understanding regarding the effects of fossil fuel burning and other human activities on the global climate system and on broad-scale regional patterns of climate change. The report then focuses on efforts to develop scenarios of the possible impacts of climate change on western streamflows and lays out the results for a sample of such studies. The relevance of climate variability and climate change for western water policy is then addressed.

Current Climate and Water Resources of the West

The Western U.S. is remarkable for its variety of landscapes and local climates. Alpine meadows, dry open pine forests, and sagebrush semideserts

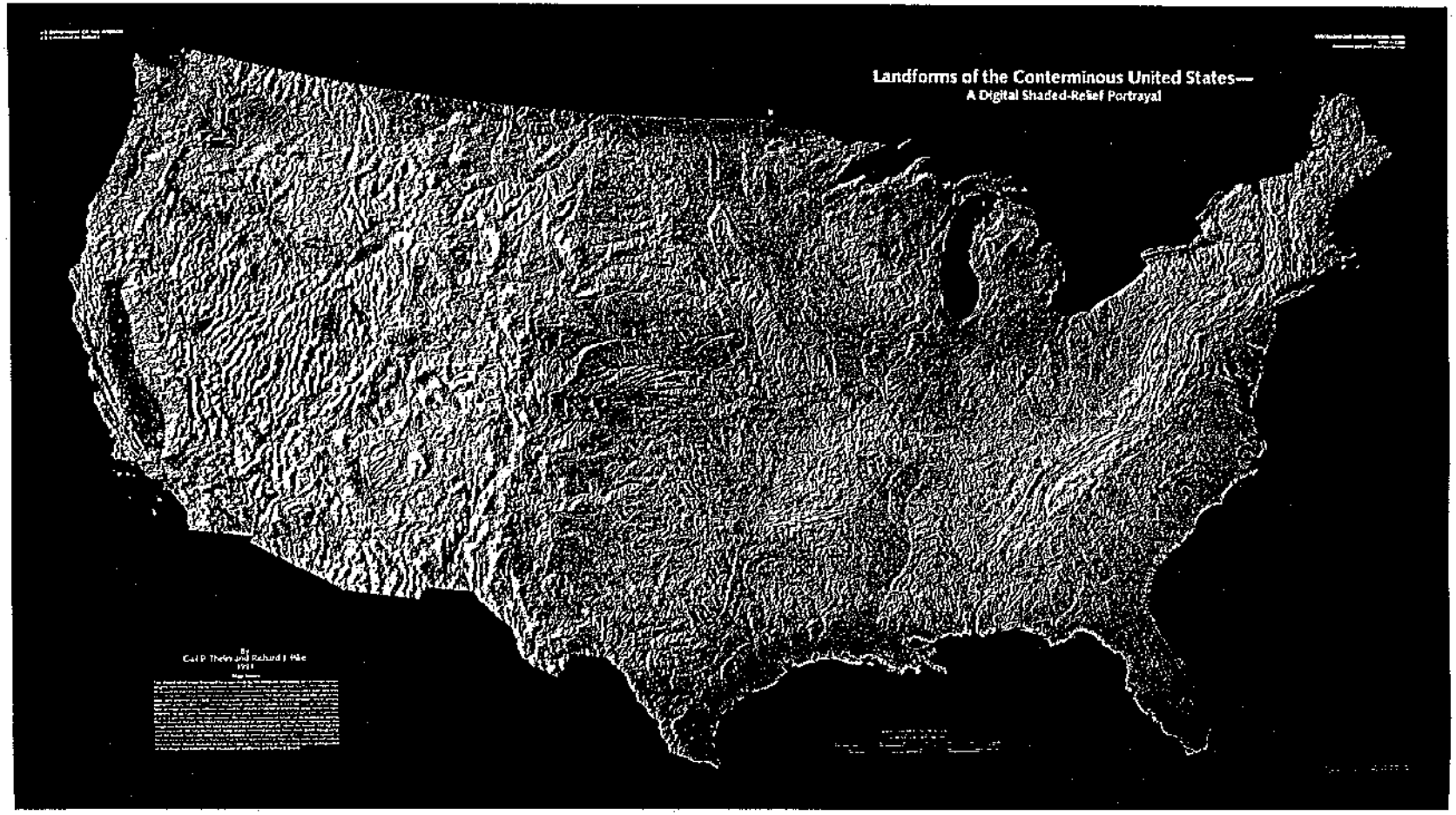

Figure 1.—Landforms of the conterminous United States.

Source: U.S. Geological Survey

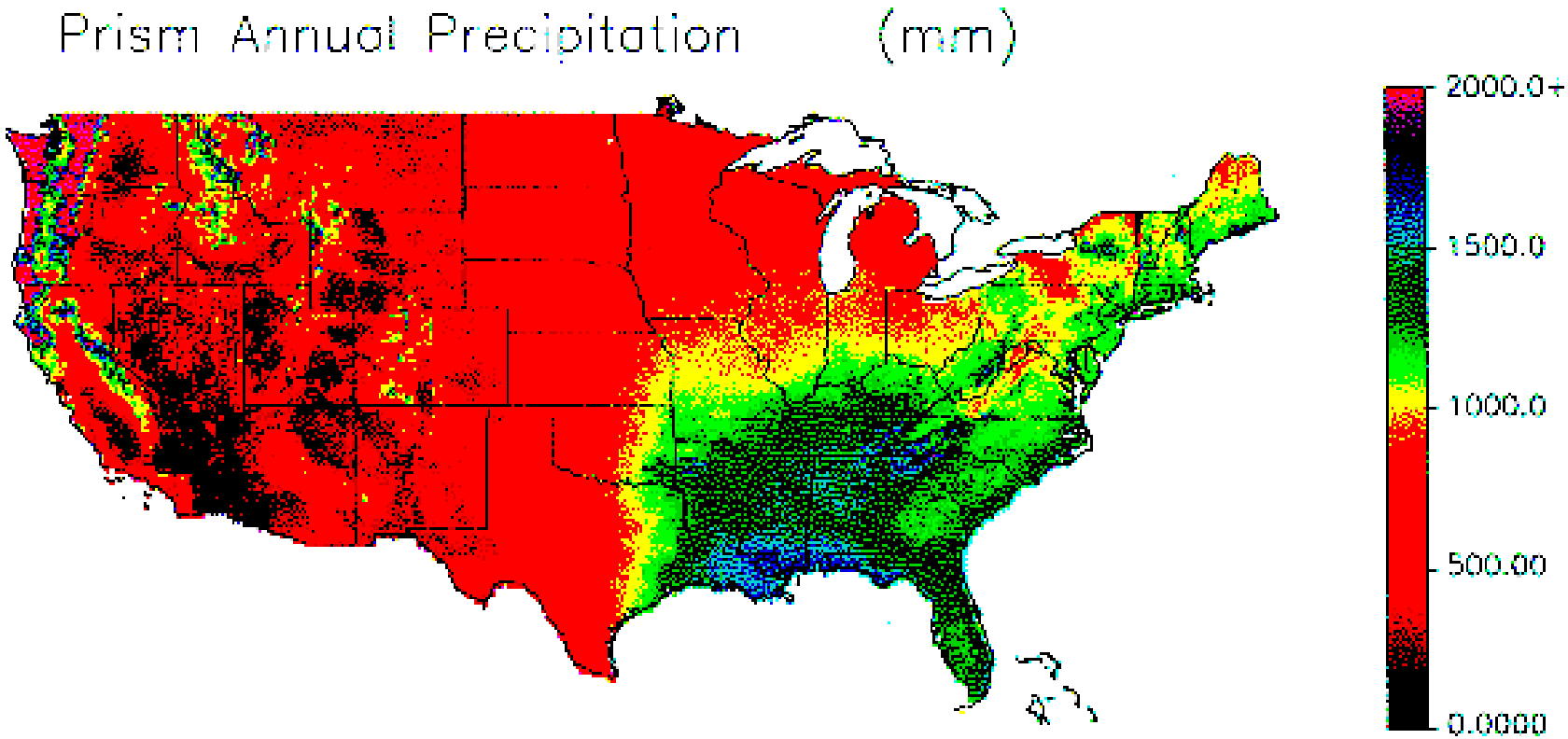

Figure 2.-Prisim model output: Mean annual precipitation calculated at 2.5 kilometer grid spacing.

Source: Courtesy of David Schimel and Hank Fisher, Climate and Global Dynamics Division, NCAR

often can be found in proximity to one another. This heterogeneity provides graphic evidence of the effects of differences in temperature, precipitation, and other climate variables on vegetation characteristics, primary productivity and water resource availability.

Topography and marine influences interact to determine precipitation regimes across the West. One can clearly see the effects of the West's mountainous landscape on average annual precipitation by comparing figures 1 and 2. The coastal ranges, the Cascades and the Sierra Nevadas, capture most of the precipitation and create downwind rain shadows. Other precipitation maxima occur over the Rockies and other high elevation areas. Figure 3 provides another view of the contrast between the complicated precipitation patterns of the West and the smooth transition from drier to wetter regimes as one moves eastward from the high plains.

In addition to this spatial variability, precipitation and runoff also vary considerably over time, with drier areas generally affected by greater relative variability than wetter areas (Bryson and Hare, 1974). Figure 4 displays the coefficient of variation (standard deviation/mean) of annual precipitation across the U.S. This measure of variability reaches a maximum in the desert Southwest.

The Western States experience pronounced seasonal changes in precipitation, with winter storms supplying the bulk of the annual moisture in the West Coast States, while precipitation peaks in June on the Great Plains and in August in New Mexico and eastern Arizona (Bryson and Hare, 1974). These seasonal precipitation patterns and the variability around the patterns are determined by changes in global atmospheric circulation that are partly predictable.

In the winter, temperature and pressure differences between the northern polar region and the equator intensify, which, in turn, causes the polar jet stream to shift southward and increase in velocity (Eagleman, 1980). This band of strong westerly winds in the upper atmosphere is often referred to as the "stormtrack" because storms form and migrate along its meandering path. The seasonal migration of the jet stream from its mean summer position at about 50° N latitude to its mean winter position of about 35° N latitude causes the number and course of Pacific storm systems entering North America to change in a recognizable seasonal pattern. However, the shape of the jet stream fluctuates chaotically between modes with relatively large or small waves. A pattern of strong alternating high and low pressure systems is present when there are deep waves in the jet stream. To some

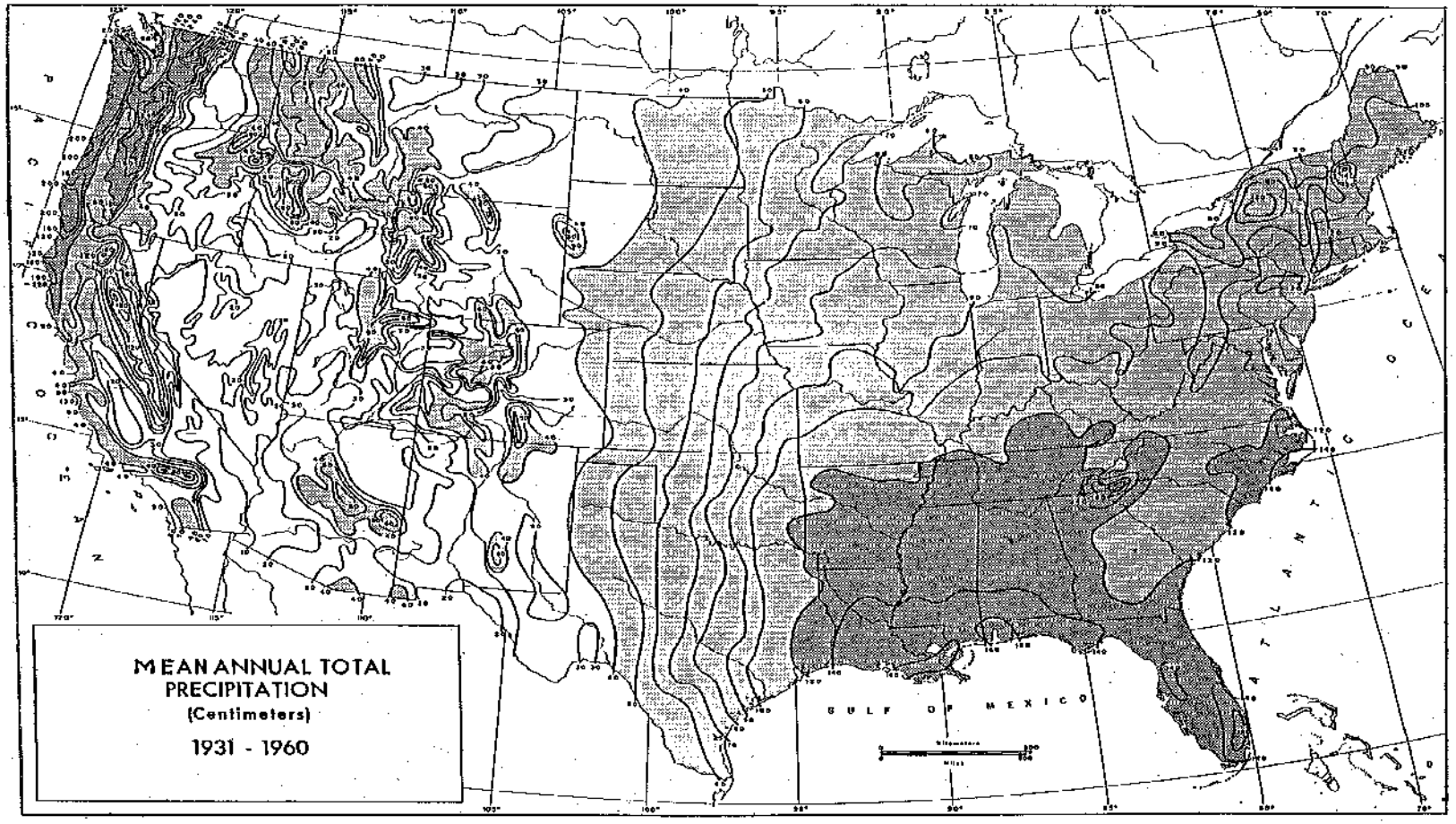

Figure 3. - Mean and total precipitation, based on all available stations adjusted to standard period 1931-1960 (after U.S. Weather Bureau).

Source: Bryson and Hare, 1974 (with kind permission from Elsevier Science-NL, Sara Burgerhartstraat 25, 1055 KV Amsterdam, The Netherlands)

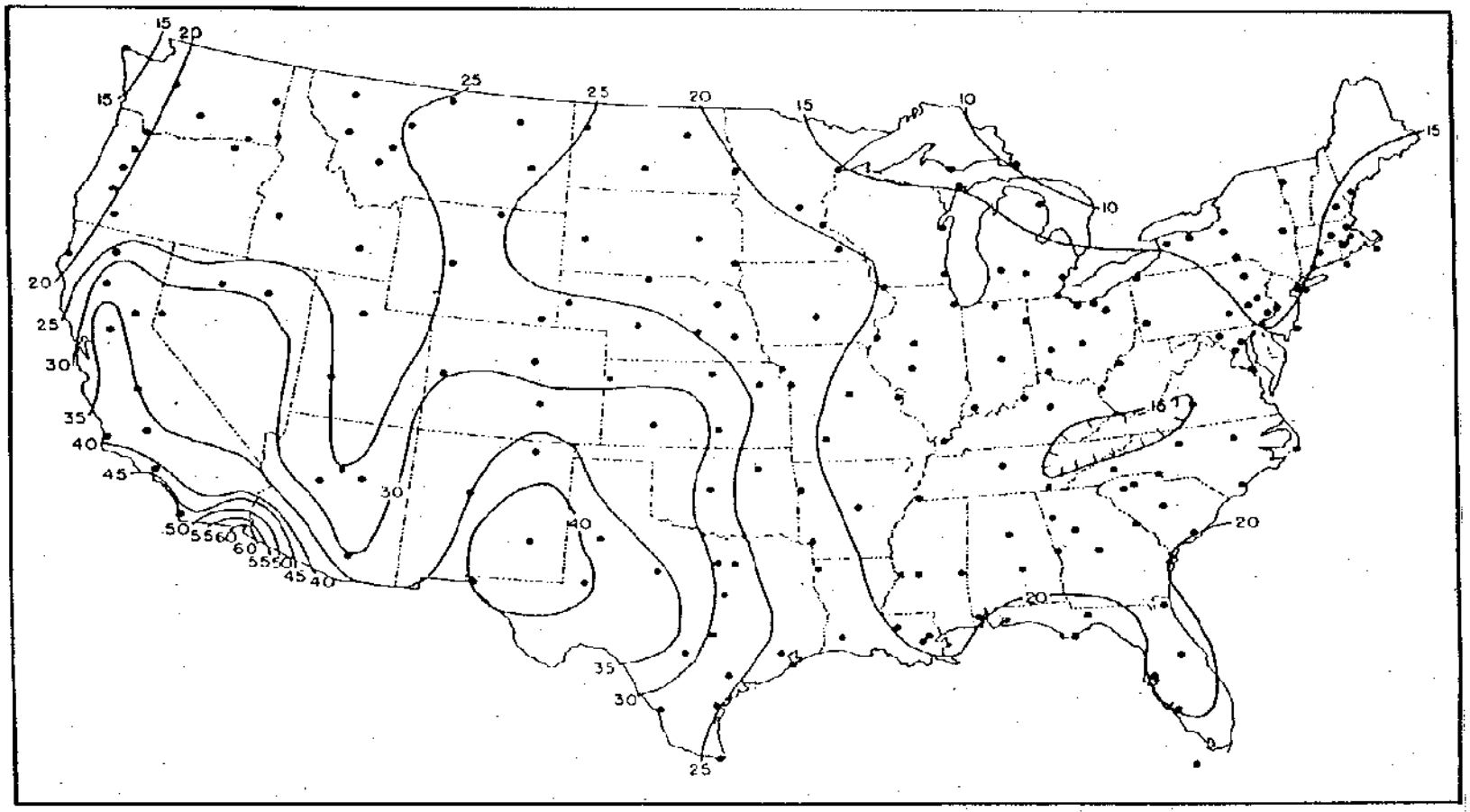

Figure 4.-Coefficient of variation (%) of annual precipitation, 1931-1960, at 220 first-order stations. Station locations indicated by dots.

Source: Bryson and Hare, 1974 (with kind permission from Elsevier Science-NL, Sara Burgerhartstraat 25, 1055 KV Amsterdam, The Netherlands)

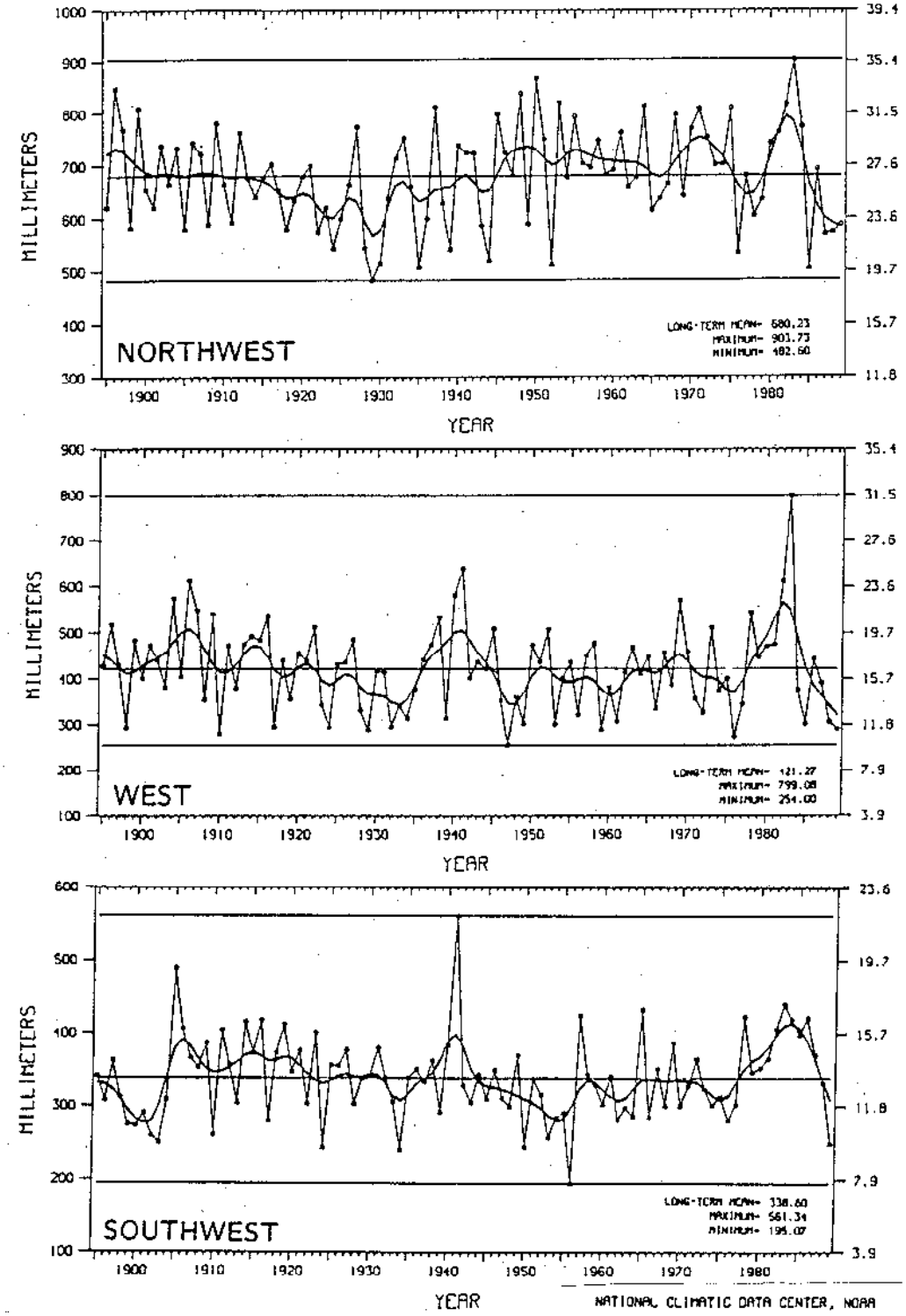

Figure 5.-Time series of annul mean precipitation in hte Northwest, West, and Southwest regions in millimeters (left) and Inches (right). The long term mean and extreems are given at the lower right, and lines are plotted for each. A low pass smoother shows interdecadal fluctuations.

Source: Trenberth, 1991 (courtesy of the National Academy Press, Washimngton DC)

extent, jet stream waves, and thus the location of predominant patterns of high and low pressure, are affected by fixed geographical features such as coastlines and mountains (Trenberth et al., 1996). But the shape and location of the jet stream and the intensity of the high and low pressure systems that it carries eastward are dynamic phenomena that vary considerably over the course of a season as well as from year to year. As pools of unusually warm or cool ocean water shift with the waxing and waning of El Niño and La Niña events, these sea-surface temperature anomalies exert an influence over the jet stream, thus altering the distribution of precipitation across Western North America.

There is considerable interannual and interdecadal climate variability throughout the Western States. Rain-gage and selected stream-gage records can be used for the period beginning in the late 19th century to examine these long-term precipitation and runoff variations. Figure 5 displays the record ofannual precipitation variability averaged over large sections of the Western States, as calculated from weather station records (Trenberth, 1991). In addition to substantial interannual variability, longer-term excursions into relatively wet or dry periods are evident. For example, the three decades from 1945-75 were relatively wet in the Northwest, with the exception of a couple of drought years. In the Southwest, that same period was relatively dry, with record dry conditions prevailing in 1956. The early 1980s were wet across the west, and unusually wet conditions in 1983 have been linked to the strong 1982-83 El Niño (Redmond and Koch, 1991). Other, less intense, El Niño events have had neither as strong nor as consistent an impact on annual Westwide precipitation. The influence of those other events is evident, however, in the precipitation records for particular seasons and locations, as will be discussed below.

Relatively short instrumental records may not provide an adequate picture of the full range of climatic variability affecting western rivers. A longer-term view is provided by the work of several researchers who have developed proxy records for precipitation and streamflow based on tree rings (Meko et al., 1991).

Figure 6 provides examples of such proxy records for the reconstructed streamflow of the Colorado River at Lee Ferry and for the Four Rivers Index in northern California (Sacramento, American, Yuba, and Feather). These 20-year moving averages indicate that both regions have experienced extended periods of drought as well as periods of sustained above average flow.

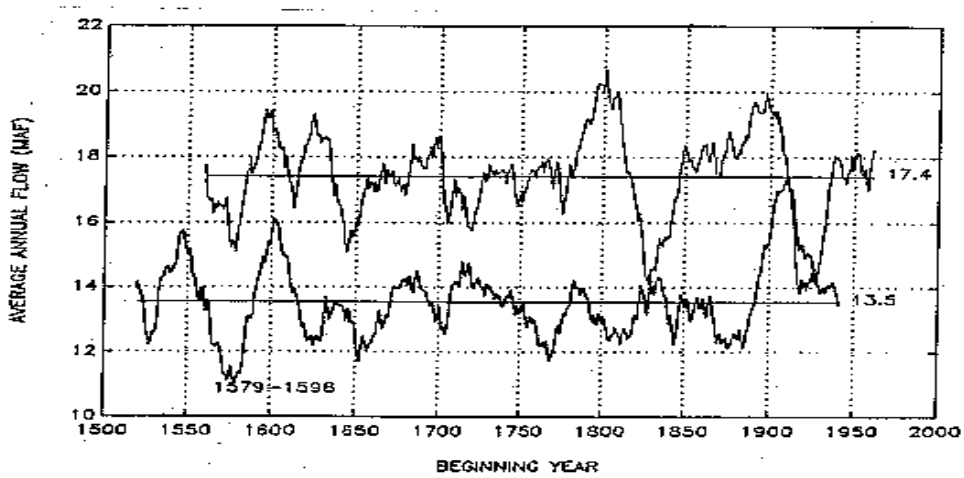

Figure 6.-Time series plots of 20-yesr means of reconstructed flows for the Colorado River at Lee's Ferry (lower line) and for the Four Rivers Index, Northern California (upper line).

Source: Meko, et al., 1991 (courtesy of the National Acedemy Press, Washington, DC)

While there is a very weak positive correlation between annual flows in the two regions, there is no consistent pattern of association for the longer-term fluctuations between wet and dry conditions. For example, northern California experienced an extended dry period from 1918-37, during which time the Four Rivers Index dropped to 13.55 million acre-feet (Maf) from its long-term mean of 17.4 Maf. At the same time, conditions in the Upper Colorado River were much wetter than the long term mean of 13.5 Maf. On the other hand, the most severe extended drought in the Upper Colorado River Basin occurred during the period 1579-98, when average annual flow was only 10.95 Maf. That same period was among the driest in the northern California tree ring record (Meko et al., 1991).

Role of ENSO

Efforts to understand the causes of these fluctuations between wet and dry conditions have recently focused on the ENSO phenomenon. The Southern Oscillation (the atmospheric part of ENSO) is evidenced by a pattern of inversely fluctuating atmospheric pressures at Darwin, Australia and Tahiti. The Southern Oscillation Index (SOI) measures this pressure differential (figure 7). When the SOI is negative and very low, an El Niño event develops. El Niño (the ocean part of ENSO) refers to a period of unusually warm sea surface temperatures in the eastern and/or central equatorial Pacific Ocean (Glantz, 1996).

Several analysts have attempted to discover consistent relationships between ENSO and precipitation or streamflow variations across the Western U.S. These efforts are complicated by the fact that no two El Niño

events are exactly alike, and that influence of an El Niño on the timing and

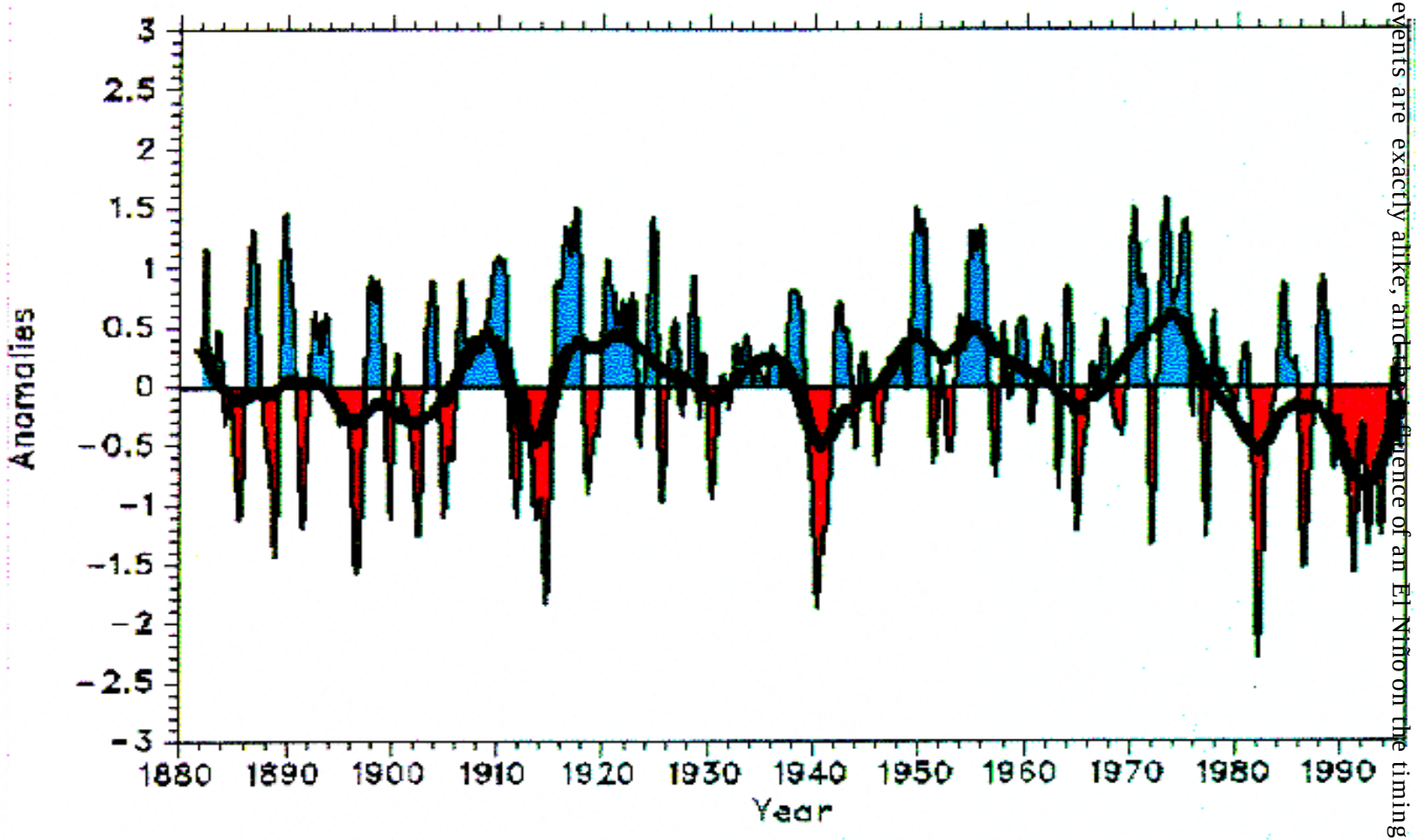

Figure 7.-Darwin Southern Oscillation Index.

Source: Courtesy of Kevin Trenberth, Climate and Global Dynamics Division, NCAR

location of precipitation anomalies depends on the strength of the event, the timing of its onset and decay, and the exact location of the pool of unusually warm ocean water.

While there are no simple, consistent relationships between ENSO and western streamflows, the SOI is statistically correlated with both streamflows and snowpacks in parts of the West. A study by Cayan and Webb (1992) examined the relationship of the SOI to snow water content (SWC) at 400 snow courses and to streamflow at 61 gaging sites across Western North America. They found that SWC on April 1 and December-August streamflow in large sections of the Northwest and Southwest are significantly correlated with the value of the SOI in preceding months. Specifically, they found that:

> *Seasonal SWC and streamflow tend to be enhanced in the southwestern U.S. and diminished in the northwestern U.S. during the mature Northern Hemisphere winter El Niño phase of ENSO. Opposite behavior occurs during the La Niña phase of ENSO.* (Cayan and Webb, 1992:29).

This conclusion is consistent with the results of other analyses. For example, studies by Andrade and Sellers (1988) and Kahya and Dracup (1994) found that the Southwest tends to be wet in the fall-spring following development of an El Niño, while dry conditions prevail following La Niña summers. In the Pacific Northwest, Redmond and Koch (1991) found a tendency for low streamflows in the water year following El Niño events, as defined by low spring-summer SOI, with the opposite tendency for high SOI (La Niña) years. Notable exceptions to that pattern were the wet winter of 1982-83 during the most intense El Niño of this century, and the dry winter of 1988-89 following a La Niña.

Regarding the strength of these relationships, Cayan and Webb conclude:

> *For SOI, correlations are positive (low SWC during winters of El Niño) over most of the Northwest and negative over a broad region of the Southwest. Strongest positive correlations, with magnitudes about 0.5, are found in patches over Idaho, Montana and Wyoming. Maximum negative correlations occur on a broad band over the Southwest, having values of approximately -0.4* (Cayan and Webb, 1992:36).

Their analysis indicates that only 25 percent of the interannual variation in streamflow can be explained by ENSO in those small patches where the

impact is most significant.[1] ENSO explains considerably less of the streamflow variability elsewhere in the West. Because central and northern California constitute a transition zone between opposite ENSO signals in the Northwest and Southwest, there is no consistent relationship between the SOI and snowpacks or streamflows in that region. Particularly strong El Niños, such as the 1982-83 and 1940-41 events, resulted in wet winters as far north as the Pacific Northwest because they pulled subtropical moisture much farther northward than usual.

Other researchers have used the differences between El Niños to develop typologies of these events. Fu et al. (1986), for example, classifies the most common type of event as "type 1," in which the pool of warmest water appears in June-August of year 0, stretching eastward from Tahiti. For that type of event, Kahya and Dracup (1993) found that the subsequent winter tends to be very wet in southern California and wetter than normal in northern and central California, while the Pacific Northwest tends to be wet in the winter preceding such an event. A similar conclusion was reached by Schonher (1987), who also identified other types of El Niños which tended to be dry in northern or northern and central California.

During the past 20 years, El Niño events have occurred more frequently than during the previous decades of this century (figure 7). During the winter following onset of an El Niño, the Aleutian low pressure system tends to be larger and more intense than in other years, and a high pressure ridge tends to set up over western Canada. This pattern is associated with relatively warm conditions over Alaska and western Canada, extending into the Western U.S., and formation of a pool of unusually cold water in the north-central Pacific. These patterns can be seen in figure 8, which displays changes in average land surface air temperatures and sea surface temperatures between the periods 1955-74 and 1975-94.

The period 1990-95 was particularly unusual because a negative SOI and very warm sea-surface temperatures in the central Pacific persisted throughout the period. The pool of warmest water was located much farther west during this "extended El Niño" than during classic "type 1" events. This resulted in climatic impacts rather different from those described above. Its unique character has also led to differing interpretations as to classification of the event (Glantz, 1996). Trenberth and Hoar (1996) estimate that such an extended event would have had a very small chance of occurring in the

[1] The proportion of variance explained is equal to the square of the correlation coefficient.

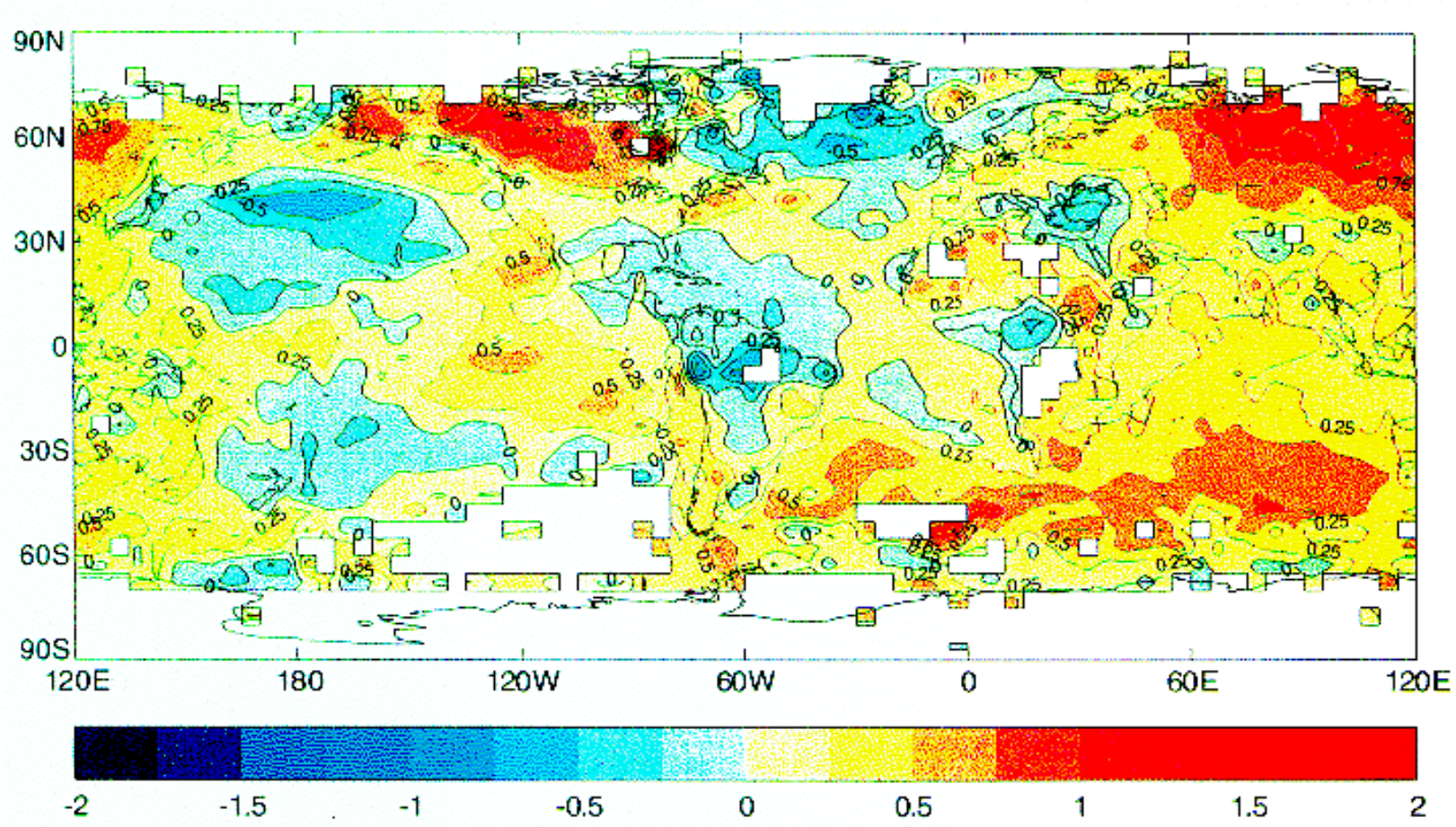

Figure 8.-Change (from 1955-74 to 1975-94) of annual land-surface air temperature and sea surface temperature.

Source: IPCC, 1996a

absence of anthropogenic climate change, and they speculate that the pattern may therefore be a manifestation of global warming. However, there is no scientific consensus regarding how ENSO would change in a warmer world. Gerald Meehl of the National Center for Atmospheric Research notes that:

> *Since there is still active debate about the mechanisms that produce ENSO, it becomes problematic to model future behavior of ENSO under conditions of global warming. Research has shown that there is likely to be a suite of ENSO mechanisms, and one or more in combination may work to produce what we observe and call ENSO. . . . Anything we say about future changes of ENSO must, at the very least, be tempered by our lack of ability not only to simulate present-day ENSO phenomena with models, but also to understand fully the observed behavior of ENSO events.* (Glantz, 1996:136).

During most of 1996, the SOI was positive but too weak to constitute a full-fledged La Niña, or cool event (National Oceanic and Atmospheric Administration [NOAA], 1997a). It does not appear, therefore, that ENSO played a significant role in the recent heavy rainfall and flooding in California and the Pacific Northwest. Rather, a National Weather Service assessment of the atmospheric circulation patterns that contributed to the flooding concludes that: "A large component of these circulation features reflects the normal highly variable nature typical of the wintertime atmospheric circulation" (NOAA, 1997b:3).

While there is considerable evidence that ENSO affects streamflows in the Western States, it is not the only source of variability. Furthermore, changes in ENSO and its relationship to western streamflows under global warming remain unclear.

Anthropogenic Climate Change

There is substantial scientific evidence that the continued accumulation of carbon dioxide and other radiatively active trace gases in the atmosphere is likely to result in global climate change. In its most recent assessment, the Intergovernmental Panel on Climate Change (IPCC)[2] concludes that global average temperatures have increased by between 0.3-0.6 ºC since the late 19th century and that ". . . the balance of evidence suggests that there is a

[2] The IPCC is an organization sponsored by the World Meteorological Organization and the United Nations Environment Program for the purpose of providing objective assessments of the current state of scientific understanding regarding the effects of human activities on the Earth's climate system, the biophysical and socioeconomic implications of climate change, and analysis of mitigation and adaptation options. Its findings represent a broadly based consensus view of the atmospheric and related science communities.

discernible human influence on global climate" (IPCC, 1996a:5). The panel further concludes that the global average temperature in the year 2100 is likely to be approximately 2 °C warmer than at present, assuming a "best-guess" value of climate sensitivity,[3] if global emissions follow a midrange scenario. By varying its assumptions regarding climate sensitivity and future time paths of global emissions, the IPCC produced "high" and "low" projections for changes in global surface temperatures by 2100 of 3.5 °C and 1 °C, respectively. These projections are based on "transient" model runs which estimate climatic responses to gradual increases in atmospheric concentrations of both greenhouse gases and aerosols. The greenhouse gases (carbon dioxide, methane, nitrous oxide, halocarbons and tropospheric ozone) tend to warm the surface of the Earth, while some aerosols (e.g., small dust particles and sulphate aerosols) tend to produce local cooling.

These projections for changes in global mean temperatures include relatively small changes over the oceans and greater warming over land surfaces. For example, by the end of the next century, surface air temperature changes over the Western U.S. may be approximately twice as great as the changes projected for global mean temperature (figure 9) (IPCC, 1996a). It also is important to note that because of the thermal inertia of the oceans, the warming projected for 2100 is not an equilibrium change. Temperatures would continue to rise beyond 2100 even if trace gas concentrations were stabilized at that date.

Although global warming is often discussed in terms of changes in global average temperatures, all climate model results show a complex spatial and seasonal pattern of temperature change with somewhat greater warming near the poles, particularly during the winter, than at the equator and greater warming over land than over the oceans. Regional climate changes, therefore, will be quite different from changes in global averages; and although global average precipitation is expected to increase, the regional pattern of precipitation change is likely to be highly variable. At present, General Circulation Models (GCMs) provide differing projections of changes in large-scale precipitation patterns (Grotch and MacCracken, 1991).

Greenhouse Gases, Aerosols, and the Climate System

The Earth's climate is the product of complex interactions among the many components of the climate system, as illustrated in figure 10. Natural variations in the interacting parts of the climate system cause natural climate variability on a wide range of time scales. This internally varying

[3] Climate sensitivity refers to the equilibrium change in surface air temperature following a unit change in radiative forcing (change in temperature in °C per unit of forcing in Watts per square meter).

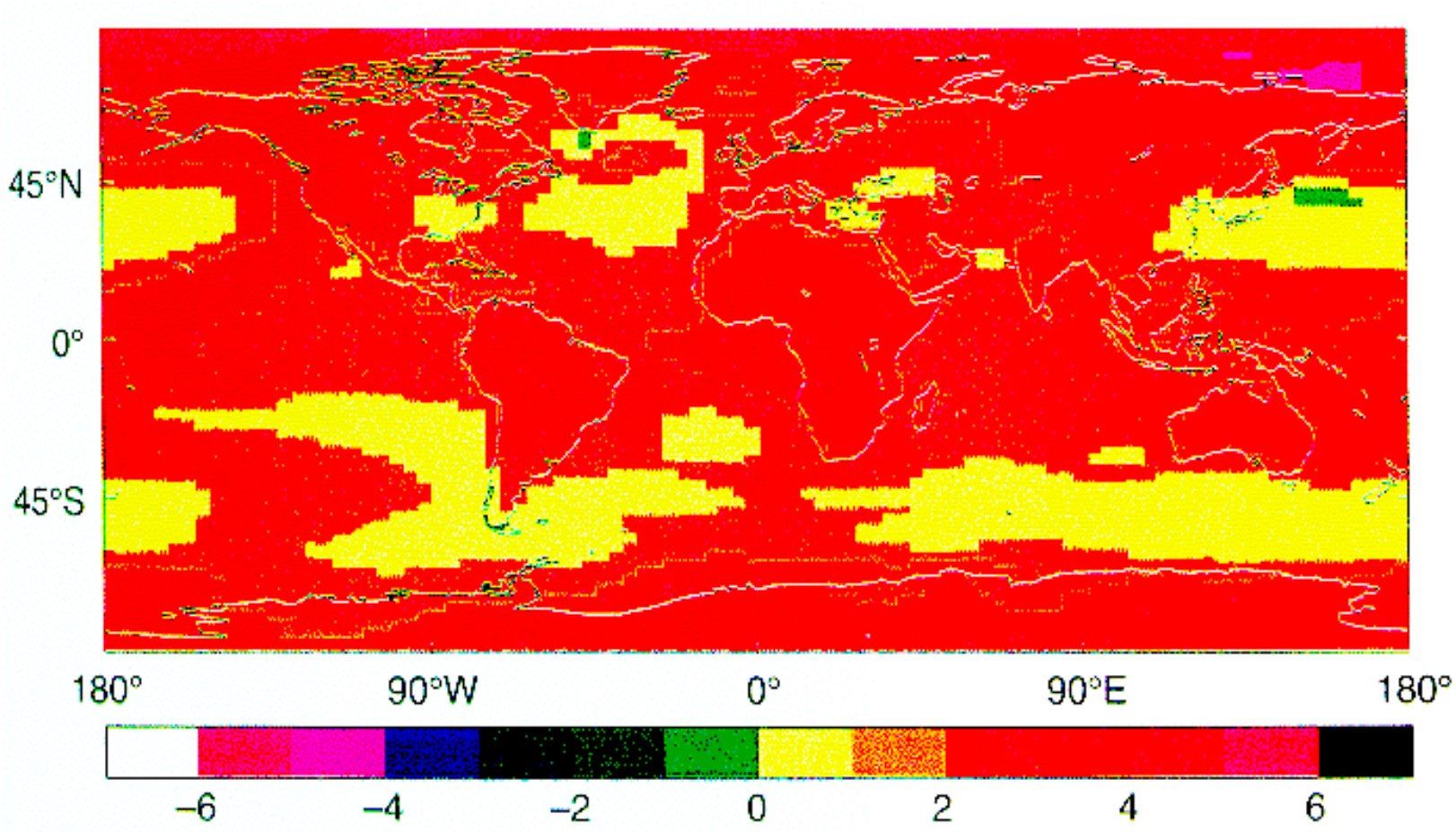

Figure 9.-The pattern of surface temerature change projected by a transient coupled model at the time of CO_2 doubling when both CO_2 and aerosol concentration increases are taken into account.

Source: IPCC, 1996a

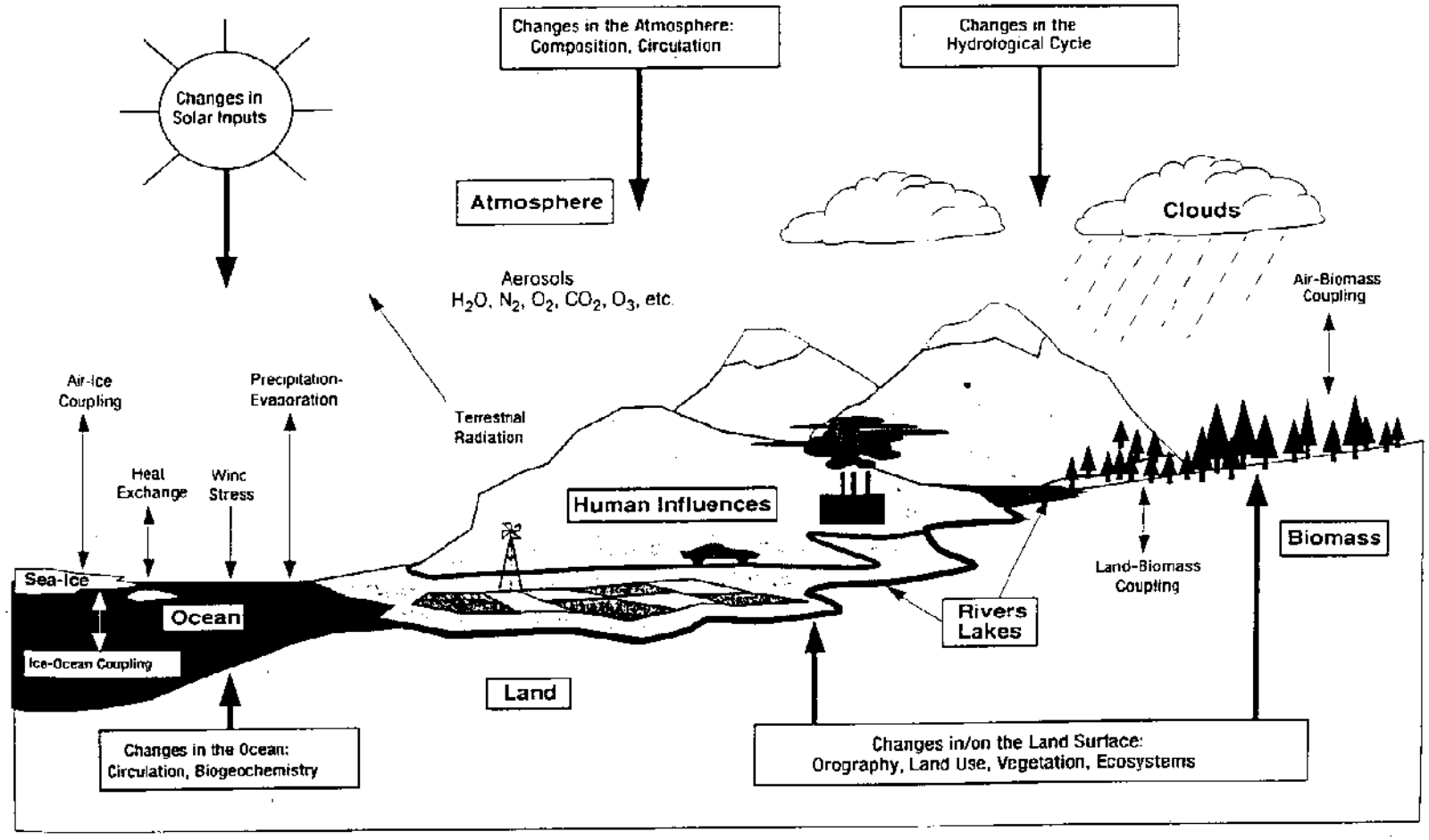

Figure 10.-Schematic view of the componants of the global climate system (bold), thier processes and interaction (thin arrows), and some aspects that may change (bold arrows).

Source: IPCC, 1996a

system has been described as acting like a big set of oscillators connected to blobs of jello (Schneider, 1996), so that the behavior of each component and of the system as a whole can be difficult to predict.

Human activities are leading to long-term changes in several of these components. Most importantly, fossil fuel combustion, biomass burning, widespread use of nitrogen fertilizer, and other human activities are changing the chemical composition of the atmosphere. In addition, agriculture, urbanization, and deforestation affect local hydrologic processes and change the reflectivity of the land surface, altering the amount of incoming solar radiation absorbed or reflected back to space.

The greenhouse gases (primarily water vapor, carbon dioxide [CO_2], nitrous oxide [N_2O], methane [CH_4], chlorofluorocarbons [CFCs], hydrochloro-fluorcarbons [HCFCs], and tropospheric ozone [O_3]) absorb outgoing infrared radiation and re-emit most of that back to the surface. An increase in the concentrations of these gases thus tends to warm the surface. The Earth's current radiation budget is depicted in figure 11. Global warming would entail a slight increase in the "Back Radiation" term at the far right-hand side of the figure. As the Earth's surface warms, radiative balance will be maintained by such changes as greater latent heat loss through evapotranspiration.

The moisture content of the atmosphere will increase in a warmer world, and because water vapor is a powerful greenhouse gas, this will produce a positive feedback, reinforcing the warming. Cloud cover and cloud type will also change, which could result in either a positive or negative feedback, depending on the nature of the changes. Uncertainty surrounding the behavior of clouds in a world warmed by increased greenhouse gas concentrations is an important source of the differences between current climate model projections of the change in global mean temperature that would result from a given change in greenhouse gas concentrations (i.e.,"climate sensitivity").

In addition to the greenhouse gases, aerosols, which include a wide variety of very small solid or liquid particles, also have important impacts on the Earth's radiation balance. Sulphate aerosols, which are a byproduct of fossil fuel combustion, reflect incoming solar radiation and thus tend to cool the surface of the Earth (IPCC, 1996a; Wigley, 1996). Unlike carbon dioxide and the other greenhouse gases, sulphate aerosols have a very short lifetime in the atmosphere, with each particle remaining airborne for only a few days. In contrast, once a molecule of CO_2 is released into the atmosphere as a result of fossil fuel combustion, it will remain in the atmosphere for approximately 5 to 6 years. It will then continue to cycle between the atmosphere and biosphere for decades to millennia (Schimel, 1996). CO_2-induced warming is, therefore, expected to eventually overwhelm the cooling

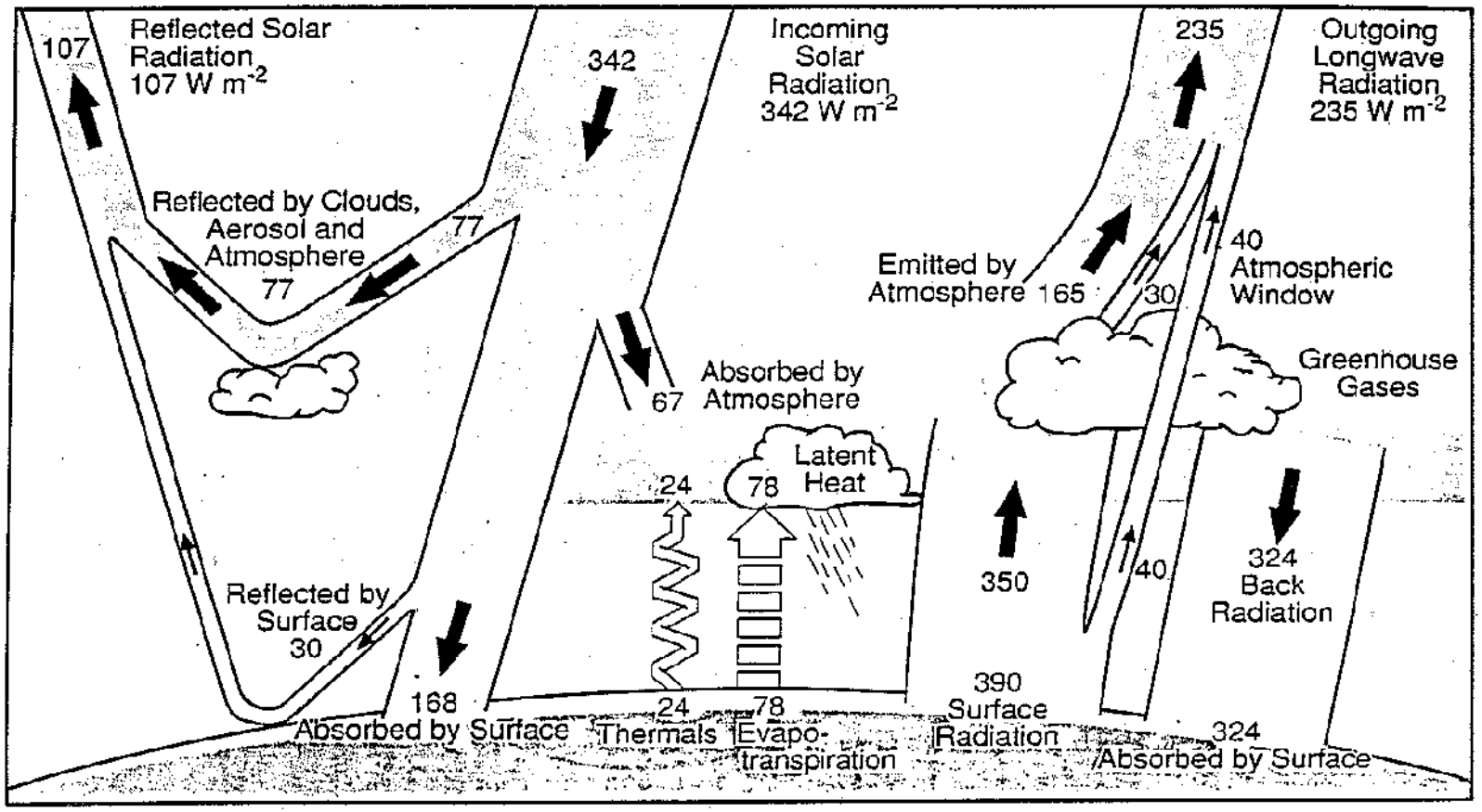

Figure 11.-The Earth's radiation and energy balance. The net incoming solar radiation of 342 Wm^{-2} is partially reflected by cluods at the atmosphere, or at the surface, but 49 percent is absorbed by the surface. Some of that heat is returned to the atmosphere as sensible heating and most evapotranspiration that is realized as latent heat in turn, emits radiation both up and down, producing a greenhouse effect, as that radiation lost to space comes from cloud tops and parts of the atmosphere much colder than the surface. The partitioning of the annual global mean energy budget and the accuracy of the values are given in Kiehl and ternberth (1997).

Source: IPCC, 1996a

effects of sulphate aerosols. However, because both are linked to fossil fuel combustion, CO_2 and sulphate aerosol concentrations have gone hand in hand in the past. At present, sulphate aerosols may be offsetting approximately half of the radiative impact of human-induced greenhouse gas concentrations (Wigley, 1996).

Climate model experiments incorporating the effects of aerosols have been much more successful at reproducing the observed spatial and temporal patterns of warming and cooling over the past century than have model runs including only the observed changes in greenhouse gas concentrations (IPCC, 1996a; Wigley, 1996). While the relative importance of sulphate aerosols is expected to decline by the end of the 21st century, it is increasingly clear that near-term changes in global and regional climates will be influenced by the cooling effects of local aerosol concentrations. However, the effects of sulphate aerosols have been incorporated in climate model studies only recently. Very few model runs have been completed, and the available analyses of hydrologic impacts are not based on model runs incorporating aerosol effects.

In general, because sulphur dioxide emissions[4] are relatively low in the Western U.S., greater near-term warming is expected here than in regions with higher sulphate aerosol concentrations (figure 12). This, together with the eventual dominance of greenhouse gas warming, suggests that the currently available CO_2-only model runs may provide useful first-order climate change assessments for the Western States until a more complete set of model runs including aerosols is available.

Climate Modeling

General circulation models have been the primary tool used to analyze the potential impacts of increased greenhouse gases (and, more recently, the effects of aerosols) on global climate. A GCM is a mathematical representation of the behavior of the atmosphere. A horizontal and vertical grid structure (as depicted in figure 13) is employed to track the movement of air parcels and the exchange of energy and moisture between parcels.

To be useful for the analysis of climate change, the atmospheric model must be coupled to models of other components of the climate system, such as the oceans and sea ice. A fairly elaborate climate model may include several vertical layers in both the atmosphere and the oceans, as well as a dynamic sea-ice model, as shown in figure 14. Climate models differ in the degree of complexity with which the various components of the climate system are

[4] Sulphur dioxide is the precursor to sulphate aerosols (IPCC, 1996a). Emissions vary with the type and quality of the fuel and emission control technology.

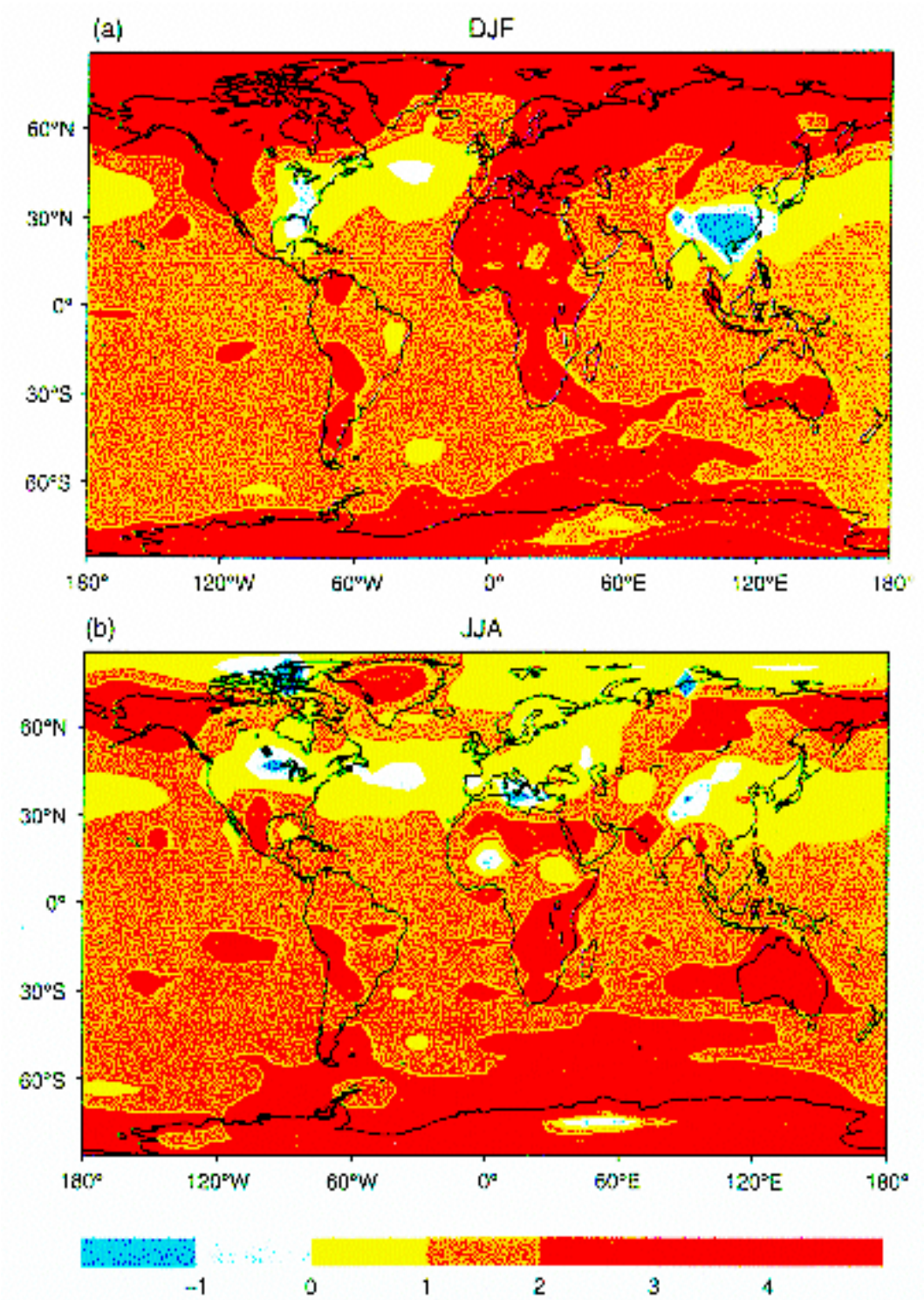

Figure 12.-Seasonal changes in surface temperaturs from 1880-1889 to 2040-2049 in simulations with aerosol effects included from IPCC. Contours every 1° C. (A) December to February; (b) June to August.

Source: IPCC, 1996a

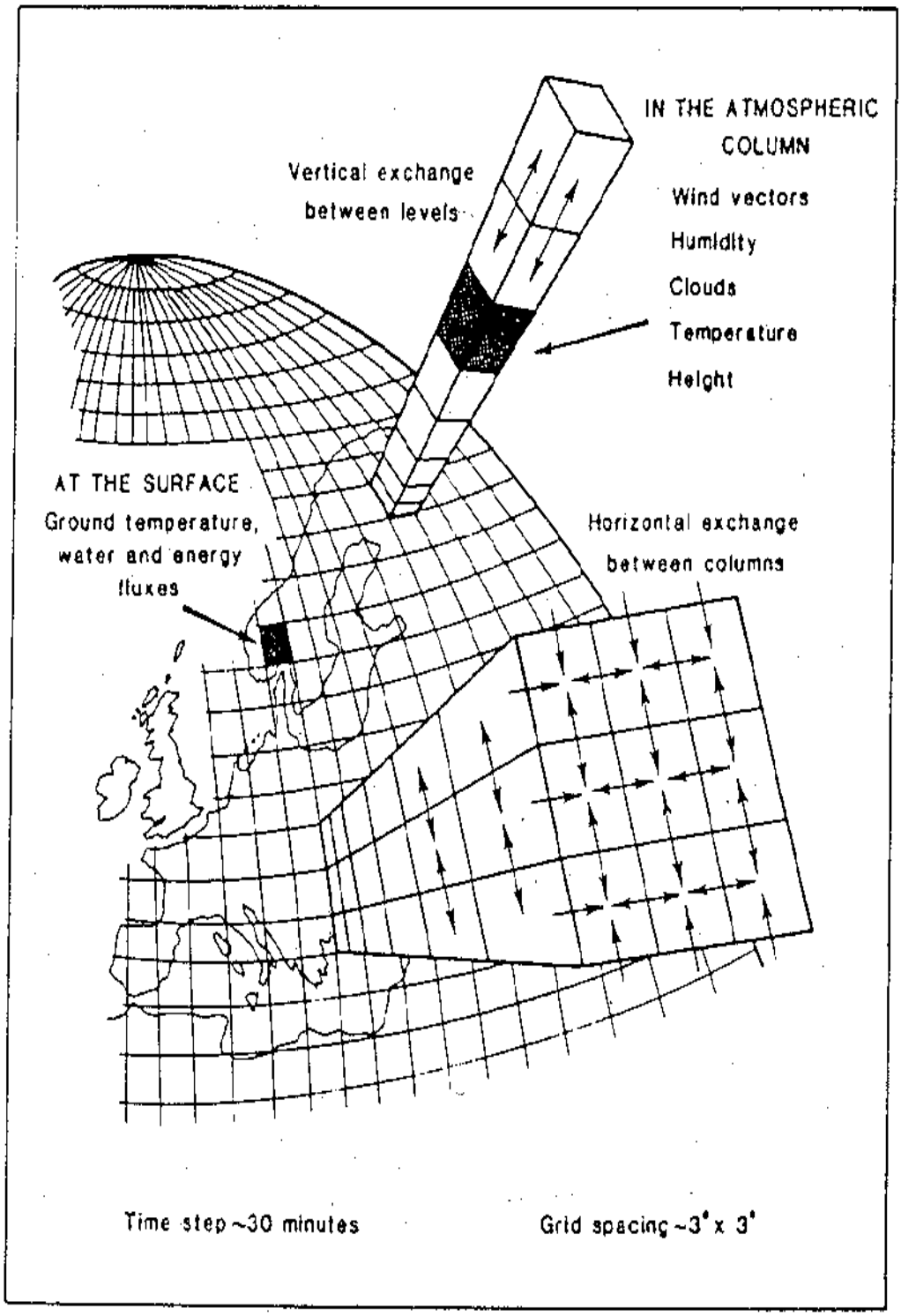

Figure 13.-The Structure of an atmospheric GCM.

Source: Henderson-Sellers and McGuffie, 1987

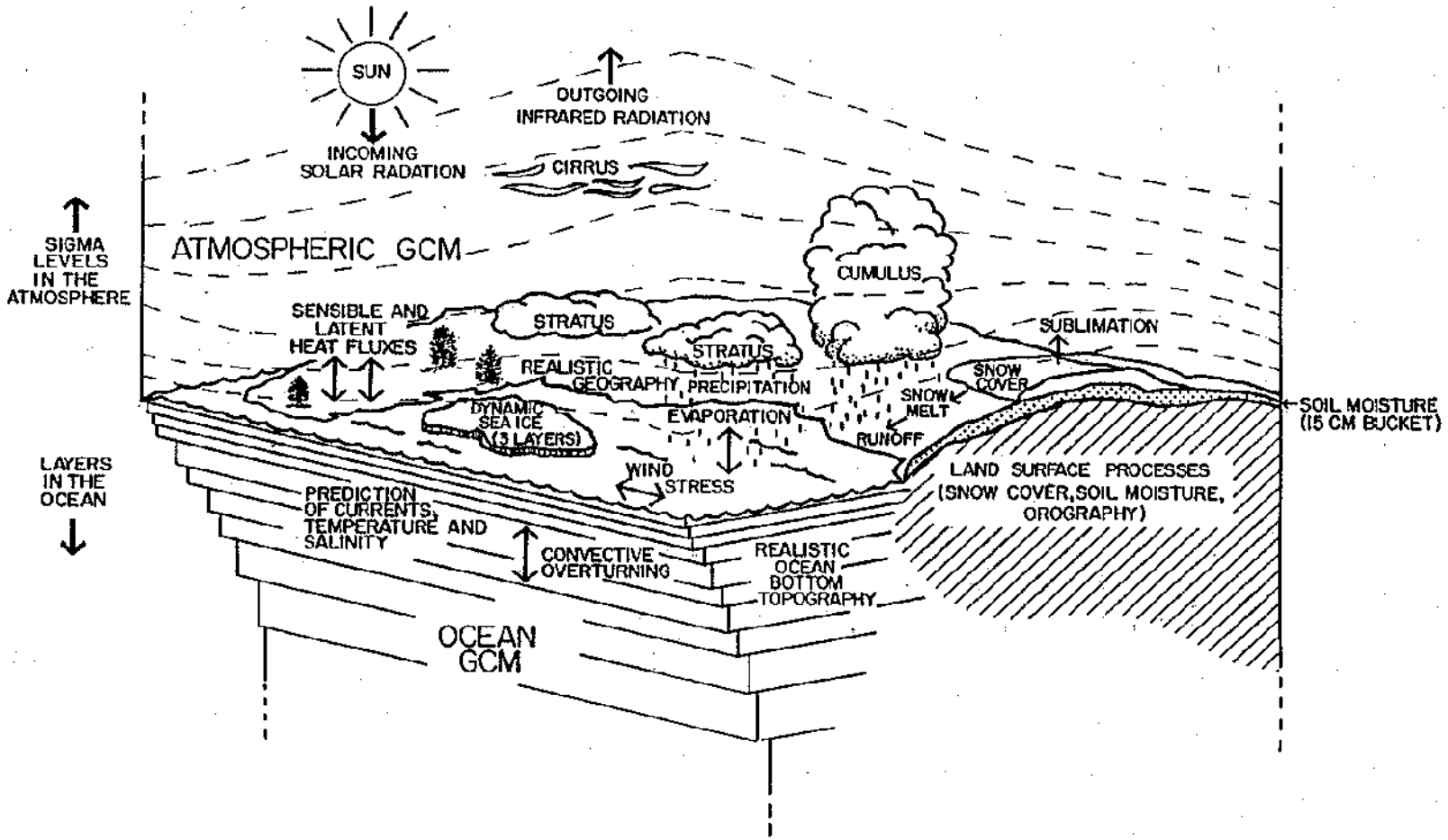

Figure 14.-Schematic of Climate modle.

Source: Washington, W., 1996

modeled and in the way in which the coupling in carried out. While greater detail in the processes represented by a model may provide greater realism, computational costs and uncertainties in process representation also increase. There is no agreement as to a single best approach to climate modeling, but, in general, model development has proceeded from the early, simple atmosphere-only models to present-day coupled models designed to capture responses and feedbacks involving several components of the climate system (Gates et al., 1996; Washington, 1996).

Despite improvements in the ability of these climate models to simulate large-scale climate processes, there continue to be inaccuracies in the represen-tation of current regional climates due, in part, to the coarse spatial resolu-tion on which these models must operate. Computational costs increase rapidly as the horizontal resolution of a model is increased. At present, it is prohibitively costly to run coupled climate models at a resolution that would be sufficiently fine to accurately depict the effects of mountains and other complex surface features on regional climates. Therefore, GCM experiments should be viewed as most appropriate for studying the broad-scale sensitivities of the climate system. Greater confidence is warranted for the global, hemispheric, or continental-scale climate changes predicted by such models than for their regional climate change projections.

The Impacts of Climate Change on Water Resources in the West

Overview

The IPCC provides the following summary of the hydrologic changes that can be expected as a result of global warming.

> *Warmer temperatures will lead to a more vigorous hydrological cycle; this translates into prospects for more severe droughts and/or floods in some places and less severe droughts and/or floods in other places. Several models indicate an increase in precipitation intensity, suggesting a possibility for more extreme rainfall events*
> (IPCC, 1996a:7).

Such a broad-brush assessment suggests that substantial regional changes are possible, but it provides little help in thinking about how climate change may affect water resources in the Western U.S. or what public officials or individuals could reasonably do at present to prepare for those changes.

As a starting point, one must recognize that climate change will occur against a background of ongoing climatic variability. It may, therefore, be helpful to think of global warming as gradually shifting the mean, variance, and shape of the probability distributions of annual, seasonal, or daily streamflow. The

actual sequence of streamflows over the coming decades will be random draws from these gradually shifting probability distributions. Thinking in these terms makes it clear that any projected change in mean flow implies a shift in the entire probability distribution. For example, if mean flow is projected to decline, extreme low flows now at the lower tail of the distribution may occur more frequently. Any change in the variance or skewness of the distribution would also affect the likelihood of extremes.

A large number of studies have focused on the potential hydrologic consequences of global warming for the Western States, and while all such studies are hampered by considerable uncertainties in the available regional climate scenarios, they point to similar general conclusions.

The following general conclusions are derived from that literature:

- There are large uncertainties regarding changes in both temperatures and precipitation at regional and watershed levels, with greater uncertainty for precipitation changes. For example, Grotch and MacCracken compared the current-climate and doubled-CO_2 climate simulations of four GCMs. In addition to shortcomings in the models' ability to reproduce the regional details of the current climate, they found substantial regional differences in the temperature and precipitation change predictions among the four models. For precipitation:

  Globally, the GCMs all show comparable changes with more than 75% of the gridpoints in each model showing positive shifts in precipitation and median percentage increases ranging from 11% to 18%. . . . There are generally equatorial and high latitude bands of maximum precipitation increase seen in all of the models. . . . The agreement among models is generally poorer when focusing more closely on specific subcontinental regions. For example, the CCM model shows a broad band of maximum precipitation increase across the United States from Texas to Nova Scotia. The OSU model shows a similar band, but displaced considerably to the east off the eastern coast of the United States. Neither the GFDL or the GISS models show such a band (Grotch and MacCracken, 1991:301-302).[5]

- For the Western U.S., uncertainties regarding the hydrologic impacts of climate change are compounded by the natural hydrologic complexity of the region. In mountainous areas, precipitation can vary significantly over short distances. "For example, in the Park Range of

[5] GCM = general circulation model, CCM = community climate model (National Center for Atmospheric Research), OSU = Oregon State University, GFDL = Geophysical Fluid Dynamics Laboratory, GISS = Goddard Institute for Space Studies.

the Upper Colorado River Basin, the average winter season (October-April) precipitation varies from 40 to 6 in. within only 6 mi." (Schaake, 1990:181). Schaake also notes that:

> *Topographic variability in the West introduces substantial uncertainty and difficulty into the water balance. Snowmelt is 87% of the annual runoff from the Upper Colorado. Most of this is from a few small source areas, generally above 9000 ft. Although these comprise only 12% of the total area of the basin, they produce fully 77% of the annual runoff* (Schaake, 1990:181).

- Water resources in arid environments are inherently more vulnerable to the effects of global warming. This arises from the fact that such environments are characterized by highly nonlinear relationships between precipitation and runoff. The IPCC Working Group II report notes that:

> *In semi-arid and arid environments, rainfall is short-lived and generally very intense, and soils tend to be thin. A large proportion of rainfall therefore runs directly off the surface, only to infiltrate into deeper soils downslope or along the river bed* (Arnell et al., 1996:329).

This contributes to greater sensitivity of annual streamflow to variations in annual precipitation. An analysis by Schaake of the climate sensitivity of streamflow in rain-dominated river basins found a systematic increase in streamflow response to hypothetical changes in precipitation and potential evapotranspiration as one moves westward from the humid Southeastern U.S. into drier areas in Texas and the Plains States. At the western edge of the area considered in that study, Schaake estimated that a 10-percent change in precipitation would produce a 45-percent change in mean annual runoff, while the same percentage change in precipitation produced only a 20-percent change in mean annual runoff in the more humid regions of the Southeast. In arid areas, this suggests that any decrease in precipitation would tend to have a large impact on runoff, while warmer temperatures will tend to increase soil moisture deficits, further reducing the contribution of precipitation to runoff (Schaake, 1990; Arnell et al., 1996; Kaczmarek et al., 1996). In addition, ". . . severe flood events may be more damaging in drier climates where soils are more erodible . . ." (Arnell et al., 1996:328).

- Mountainous river basins in which the hydrology currently is dominated by annual snowpack accumulation and melting are likely to experience smaller total snowpack accumulations and earlier melt-off. This melt-off will cause increases in winter or spring flows and reduced summer flows. The altered pattern of seasonal flow results primarily from the effects of warmer temperatures on the form of precipitation and the rate of melt (see Cooley, 1990; Lettenmaier and Gan, 1990;

Rango and Van Katwijk, 1990; Lettenmaier et al., 1992; Duell, 1992; 1994; Rango, 1995).

For example, for the north fork of the American River at North Fork Dam, California, Duell (1992) estimates that a 4 ºC temperature increase coupled with no precipitation change would cause winter (January-March) runoff to increase by 38 percent, while late summer (July-September) runoff would decline by 62 percent. If precipitation also increases by 12.5 percent, the figures would change to +96 percent for winter and -55 percent for late summer. That study also found that a somewhat less extreme scenario, with a 2 ºC temperature increase and a 12.5-percent increase in precipitation would result in a 67-percent increase in winter runoff and a 28-percent decline in late summer runoff.

- In the absence of offsetting increases in precipitation, warmer temperatures would lead to reduced annual streamflows. Warmer temperatures may cause runoff to decline even where precipitation increases. For the Colorado River, Nash and Gleick (1993) estimate that a 4 ºC temperature increase would cause inflows into Lake Powell to decline unless annual precipitation increased by nearly 20 percent. A 10-percent increase in precipitation coupled with 4 ºC warming would result in Lake Powell inflows 9.7 percent below the current annual average.

- While global precipitation is expected to increase, changes in precipitation at the regional level will depend on such things as changes in the position of storm tracks and local features such as topography and proximity to large water bodies (Giorgi et al., 1994). Increases or decreases in annual precipitation are possible at the regional level. There is some evidence that the intensity of rainfall events may increase under global warming, due to increases in the precipitable water content of the atmosphere (Trenberth and Shea, 1997; IPCC, 1996a).

- The effects of given temperature and precipitation changes will vary across catchments, depending on the physical characteristics and climatic regime of the catchment (Lettenmaier and Gan, 1990; Schaake, 1990; Arnell, et al., 1996). For example, in an analysis of four sub-basins of the Sacramento, Lettenmaier and Gan (1990) found that the area-elevation distribution of the catchment would determine the extent to which snowmelt remained an important component of seasonal runoff. In addition, differences in soil characteristics and, therefore, in the moisture storage capacity of the subsurface zone can have a substantial impact on maintenance of base flows through the summer. Climate change scenarios for the McCloud River, which drains an area of deep volcanic ash in the area of Mt. Shasta showed

May-June streamflow declining by only approximately one-sixth, while scenarios for other basins showed much larger declines, in some cases exceeding 50 percent.

- In basins that are currently glaciated, declining glacier reservoir capacity may eventually lead to an earlier peak in the annual hydrograph and reduced late summer streamflows. In the near term, increased melting of glacial ice can, in some cases, sustain summer streamflows (Pelto, 1993).

- Warmer temperatures could increase the number of rain on snow events in some river basins, increasing the risk of winter and spring floods (Lettenmaier and Gan, 1990; Hughes et al., 1993).

- Changes in vegetation characteristics will have further, complex impacts on streamflows (Callaway and Currie, 1985; Rosenberg et al., 1990; Riley et al., 1996). An early study by Idso and Brazel (1984) concluded that CO_2-induced stomatal closure would reduce plant water use leading, therefore, to increased streamflows despite warmer temperatures and reduced precipitation. That conclusion has been severely contested by later analysts. Callaway and Currie (1985) point out that increased leaf area growth, increased interception and evaporation of precipitation directly from the larger plant surfaces, and longer growing seasons would tend to negate any positive impacts of CO_2 fertilization on streamflows. Allen (1991) also concludes that increases in growth, leaf area, and physiological response to higher temperatures and related changes in radiation and humidity would tend to offset the water use efficiency effects of CO_2-induced stomatal closure.

- Water quality is likely to deteriorate where flows decline, and warmer water temperatures may have further implications for water quality. Nash and Gleick (1993) found that average annual salinity levels in the lower Colorado River would measure 858 milligrams per liter (mg/L) below Davis Dam and 1,019 mg/L at Imperial Dam in a base-case scenario. Under a scenario in which climate change reduces average annual flow by 20 percent, those levels would increase to 1,010 mg/L and 1,218 mg/L, respectively.

- Crop evapotranspiration may increase, despite increased plant water use efficiency under elevated CO_2 conditions (Rosenberg et al, 1990; Allen, 1991). The study led by Rosenberg examined the effects of climate change and CO_2 enrichment on crop water use in a Nebraska wheat field. Under severe warming scenarios, they found that if stomatal resistance increased by 40 percent, then crop evapotranspiration would increase by between "9 and 18 percent, half or one-third of what it would otherwise be" (Rosenberg et al., 1990). In

other words, CO_2 enrichment reduced, but did not eliminate, the increase in crop water use. Increased potential crop evapotranspiration would tend to increase irrigation water requirements (Peterson and Keller, 1990) and could reduce return flows from irrigated lands (Miller et al., 1997).

- Groundwater levels and recharge and discharge relationships may change, but "there have been very few direct studies of the effect of global warming on groundwater recharge" (Arnell et al, 1996:336). One study of the Ellensberg basin in Washington State found a 25-percent median annual reduction in recharge under a global warming scenario (Vaccaro, 1992).

- Reservoir evaporation could increase under warmer conditions (Callaway and Currie, 1985). However, while warmer temperatures would tend to increase evaporative losses, the losses would diminish if the surface area of the reservoir shrinks. Nash and Gleick (1993) found that a 10-percent reduction in average annual inflow into Lake Powell could cause evaporative and bank storage losses to decline by as much as 500,000 acre-feet per year as a result of the smaller areal extent of the lake.

- Water level declines are likely to be most severe in lakes and streams in dry evaporative drainages and in basins with small catchments (Arnell et al., 1996).

- Out-of-stream users holding junior entitlements are, by definition, more vulnerable than similarly situated senior right holders. Otherwise, the vulnerability of consumptive uses is affected by access to storage, location within the watershed, basin characteristics, and options for coordination with other users or systems.

- Under the existing structure of water rights, contract entitlements, and system operating rules, in many systems, out-of-stream consumptive uses appear less vulnerable to the effects of climate change and climatic variability than instream uses.

- Fish populations and other aquatic resources are likely to be affected by warmer water temperatures, changes in seasonal flow regimes, total flows, lake levels, and water quality. These changes will affect the health of aquatic ecosystems, with impacts on productivity, species diversity, and species distribution (Arnell et al., 1996).

- Wetlands and dependent wildlife resources may be adversely affected by general increases in evapotranspiration and reduced summer soil moisture, which may reduce the extent of semipermanent and seasonal wetlands (Poiani et al., 1995).

- In addition to the potential effects of anthropogenic climate change, western water resource availability fluctuates considerably on both short and long time scales due to natural sources of variability. These natural variations will continue and could, perhaps, intensify as global warming occurs (Trenberth and Shea, 1997; IPCC, 1996a).

Relationship of Climate to Streamflow

There is not a simple linear relationship between streamflow and precipitation. Rather, streamflow is made up of three basic components which are related to precipitation with varying lags (Callaway and Currie, 1985). *Surface runoff* from rainfall events depends on evaporation and plant transpiration, which vary as a function of temperature, humidity, wind speed, and solar radiation, and on the rate at which the precipitation infiltrates through the soil (Schaake, 1990). *Subsurface runoff* consists of precipitation that infiltrates the soil and then moves laterally toward surface water bodies. *Base flow* is precipitation that percolates through the soil into groundwater and then enters the stream channel with time lags (Callaway and Currie, 1985). Snowmelt contributes to streamflow both through overland flow and through infiltration into the soil. Because streamflow is made up of these multiple components, it is less variable on short time scales than is precipitation (Moss and Tasker, 1987). The relationship between annual precipitation and annual runoff varies across the U.S.. In warmer locations, a smaller proportion of precipitation appears as streamflow due to greater losses to evapotranspiration.[6]

Figure 15 provides a schematic representation of the hydrologic balance of a drainage basin. Climate change will affect several of the elements in this balance. For example, the amount, intensity, and temporal distribution of precipitation is likely to change. Warmer temperatures will affect the proportion of winter precipitation falling as rain or snow and will increase evaporation. Changes in soil moisture availability, together with changes in plant characteristics, will lead to changes in plant transpiration. Finally, changes in the quantity of water percolating to groundwater storage will result in changes in aquifer levels, in base flows entering surface streams, and in seepage losses from surface water bodies to the groundwater system.

To estimate the impacts of climate change on water resource availability, one must, in some way, account for the effects of changes in each of these

[6] Evapotranspiration is defined as the sum of evaporation from the soil surface and transpiration by plants (Rosenberg, et al., 1990).

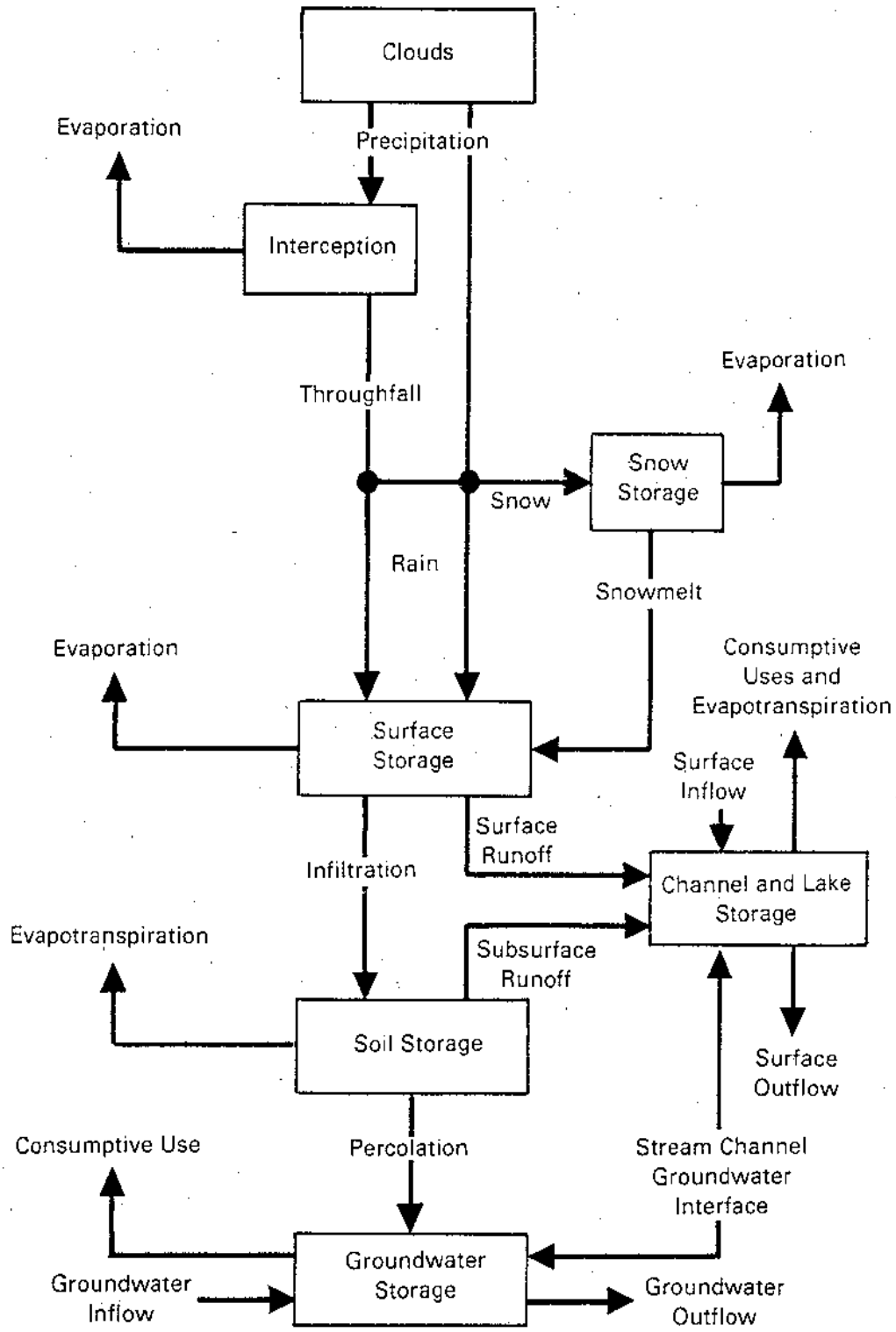

Figure 15.-Schematic diagram of the hydrologic system of a drainage basin.

Source: Callaway, J.M, And J.W. Currie, 1985

elements. Several approaches to modeling the relationship between climate and hydrology are available, each differing in the detail with which these various processes are represented.

The simplest approach uses statistical analysis to identify empirical relationships between climate variables and streamflow. Changes in the climate variables are then plugged into the equations to predict changes in streamflow. Stockton and Boggess (1979) and Revelle and Waggoner (1983) used this approach to assess the impact of hypothetical climate changes on the Colorado River. It is a simple and inexpensive approach, but it assumes that the empirical relationship will remain stable and that assumption is not likely to be valid for large changes from present climate conditions.

Physically based models attempt to represent the water balance in a drainage basin. Models can be either very simple, or they can involve detailed, spatially disaggregated estimates of each of the physical processes outlined in the diagram. More sophisticated models can potentially improve predictions of streamflow response to climate variations, particularly in very heterogeneous watersheds. However, reliable estimates of the parameters of such models require high-quality data at fine spatial and temporal resolutions. Such data frequently are unavailable. In addition, because all hydrologic models are calibrated to current and historical basin conditions, their reliability is likely to deteriorate with significant departures from current climate conditions. The available tools, thus, are better suited to producing sensitivity analyses than reliable hydrologic forecasts (Leavesley, 1994; Lettenmaier, 1995).

Climate Change Scenarios

Scenarios of climate changes for specific watersheds can be developed in several ways. One approach is to compute changes in temperature and precipitation directly from GCM output for model runs based on current climate and a climate warmed by increased CO_2. Some studies have relied exclusively on this technique (e.g., Smith and Tirpak, 1990), with adjustment factors sometimes applied to account for topographic influences (Lettenmaier and Gan, 1990). Other studies include both hypothetical and GCM-based scenarios (e.g., Gleick, 1987; Nash and Gleick, 1993). Caution is required in interpreting the results of such studies because the early generation climate model runs on which they are based generally do a poor job of reproducing current precipitation patterns. The reliability of their future precipitation simulations is similarly questionable.

Coarse model resolution is a factor that seriously limits the value of direct GCM output for assessment of water resource impacts. The significance of model grid scale is illustrated by figure 16, which depicts the terrain of the Western U.S. at four different GCM resolutions. At 480-kilometer (km) grid

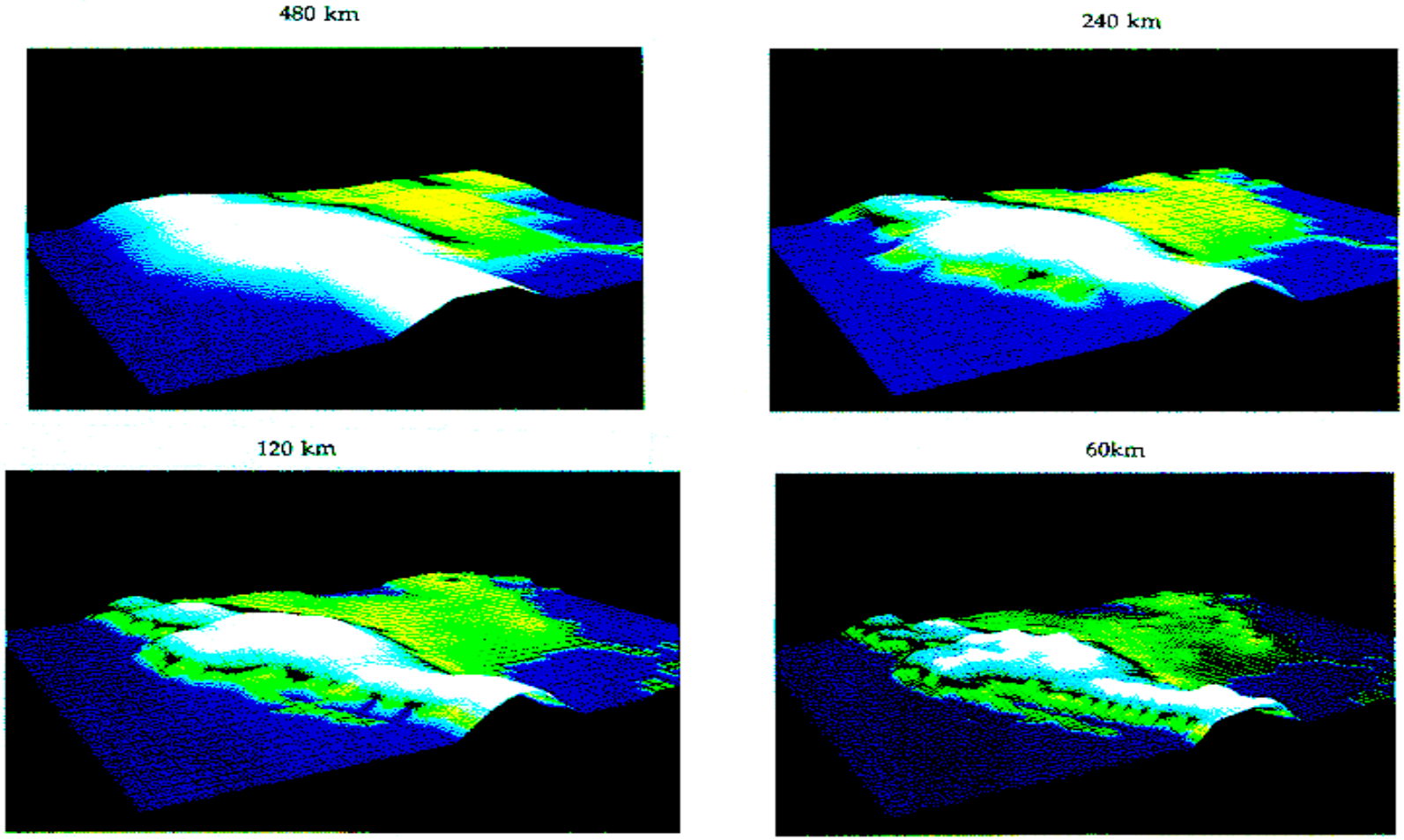

Figure 16.-Model grid scale depicting the terrain of the Western U.S. at four different GCM resolutions.

Source: Copurtesy of NCAR Graphics.

spacing (upper left panel), which is typical of many GCMs, the models see the western mountains as a smooth ridge with a high point in the vicinity of central Utah. Clearly, that spatial resolution is too coarse to reproduce the effects of topography on the region's precipitation and runoff patterns (Grotch and MacCracken, 1991; Giorgi and Mearns, 1991).

For example, the Great Basin area would be predicted to be wet because it would be seen as located on an upslope. The actual rain-shadowing effect of the Sierra Nevada Range cannot be captured until model resolution is increased to about 60-km grid spacing (lower right panel). Full global GCM simulations are not feasible at that resolution (Giorgi and Mearns, 1991). This is problematic because coarse resolution models are likely to give incorrect predictions for the spatial pattern of changes in precipitation (Giorgi, et al., 1994).

GCMs are now being run at somewhat finer spatial resolutions (corresponding to the 240-km grid spacing depicted in the upper right panel of figure 16). This and other refinements are improving the ability of such models to reproduce current precipitation and runoff patterns (Schimel, personal communication, 1996), but the models still differ considerably in their projections of regional precipitation changes resulting from global warming.Nested climate modeling is one promising approach to resolving the inaccuracies arising from coarse resolution. This technique uses the output of a large-scale GCM to provide the meteorological boundary conditions needed to drive a high resolution climate model over a limited geographic area. In other words, the coarse resolution GCM simulates the large-scale climate features, while the effects of topography and other surface features are captured by the nested regional model. This is very similar to methods used to produce daily weather forecasts.

The National Center for Atmospheric Research's RegCM uses a global GCM to drive a 60-km resolution model over North America. It is the first such nested model for which a multiyear climate change simulation has been run for this region. The nested model and its driving GCM are still under development, but the available results provide some interesting contrasts to the results available from the coarse resolution GCMs (Giorgi et al., 1994). Figure 17 compares the temperature change projections over the U.S. for doubled CO_2 runs of three different coarse resolution GCMs (~ 240 km) and of the nested RegCM. Figure 18 shows the same comparison for changes in annual precipitation. The nested model provides a more heterogeneous picture of projected changes, particularly for precipitation. It shows increased precipitation concentrated along the west coast and in parts of the Rockies, with declining precipitation on the leeward side of the mountain ranges. The coarse resolution models, in contrast, show a much smoother pattern of precipitation changes, with increased moisture penetrating

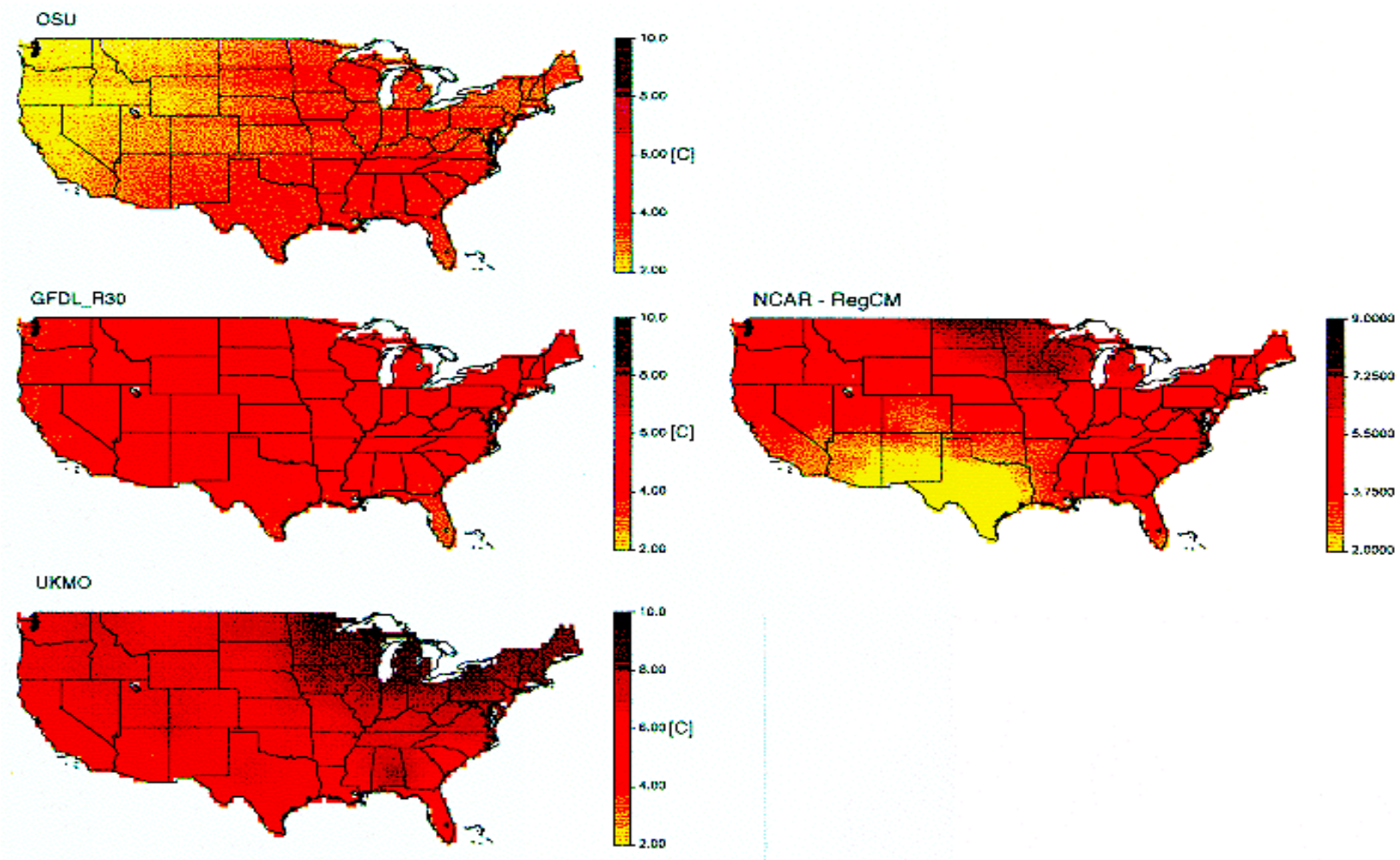

Figure 17.-Climate scenario - annual temperature change difference.

Source: Courtesy of David Schimel and Hank Fisher, Climate and Global Dynamics Division, NCAR

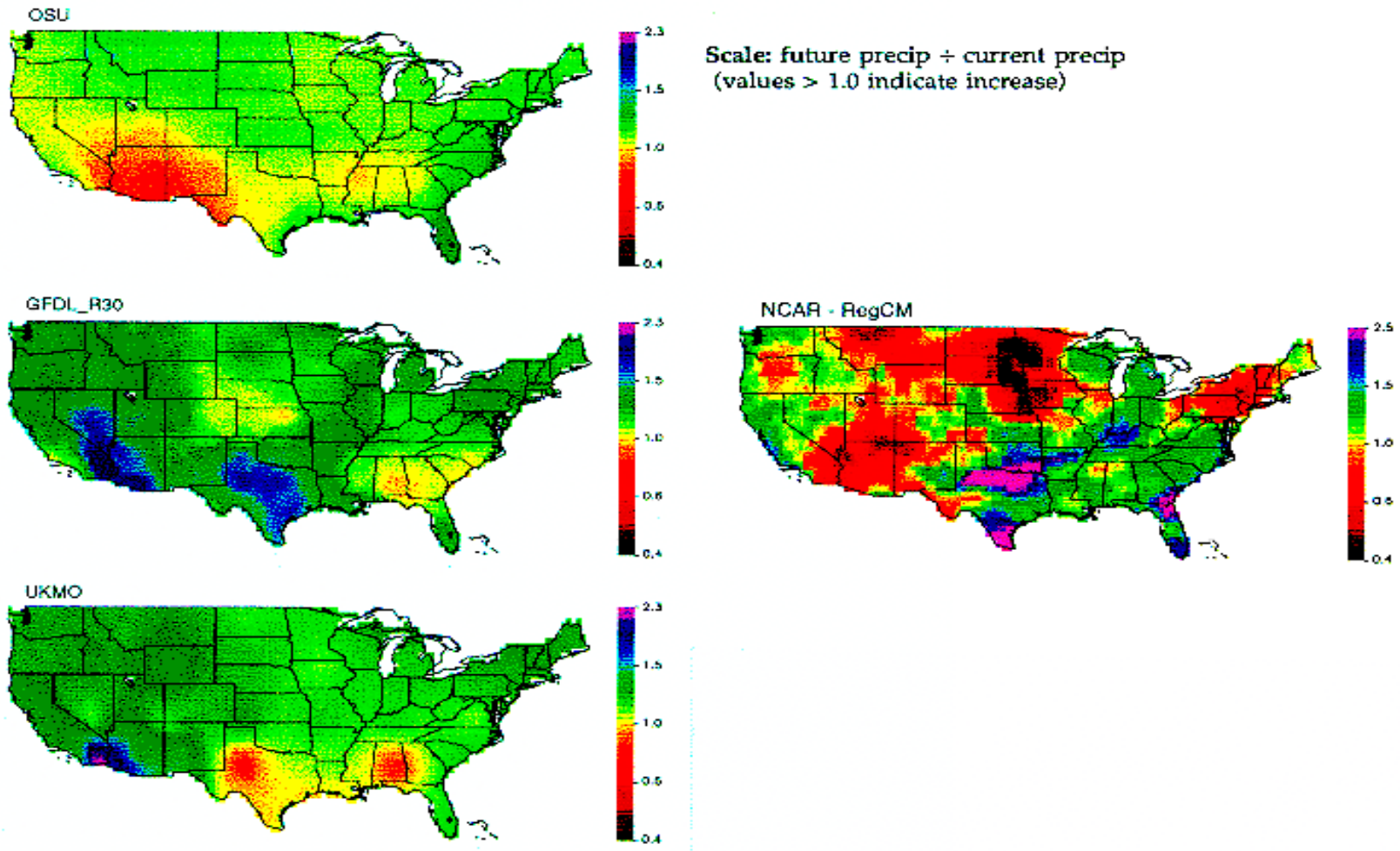

Figure 18.-VEMAP climate scenarios - annual precipitation change ratio.

Source: Courtesy of David Schimel and Hank Fisher, Climate and Global Dynamics Division, NCAR

considerably farther inland than indicated by the more topographically correct regional model. Also note that the models differ considerably in their temperature and precipitation change predictions. Among this set of model runs, the United Kingdom Meteorological Office model predicts the greatest warming over the U.S. The National Center for Atmospheric Research's RegCM indicates several areas of reduced precipitation, notably over the Southwest and northward through Utah, Wyoming, Montana, and the Dakotas, while the GFDL-R30 model (Geophysical Fluid Dynamics Laboratory) predicts wetter conditions over most of the country. All of this model output should be viewed as experimental and providing, at best, plausible scenarios rather than reliable forecasts of regional climate changes.

Statistical downscaling is another method that has been used to translate GCM output for free atmospheric variables (where the models are more reliable than at the ground surface) into usable projections of watershed-level temperature and precipitation changes. This approach provides model-based scenarios that may represent the effects of local terrain and other climatic features better than can a coarse resolution GCM. It is also considerably less expensive than the nested-modeling approach (Hughes, et al., 1993; Lettenmaier, 1995).

The GCM inadequacies have not precluded useful assessments of the water resource impacts of climate change. The wide range of scenarios that have been examined provides information on vulnerabilities and a sense of the increased uncertainty now attending long-run water resource planning and allocation decisions.

As an alternative to GCM-based scenarios, several analyses have used hypothetical changes in basin temperatures and precipitation amounts to examine the sensitivity of basin hydrology to climatic change (Nemec and Schaake, 1982; Flashcka et al., 1987; Schaake, 1990; Duell, 1992; 1994; Nash and Gleick, 1993). A drawback of this approach is the fact that the hypothetical scenarios may not be internally consistent. It is also difficult to assess the relative plausibility of the various scenarios. Despite those drawbacks, systematic analysis of such scenarios can be very valuable for delineating the relative importance of changes in temperature and precipitation and can provide a fairly inexpensive way to explore vulnerabilities of water supply systems, water quality, and instream resources.

Table 1 displays a sample of the results of studies using such hypothetical scenarios for several western river basins. Some studies estimate only changes in total annual streamflow. These typically indicate that annual streamflows will be reduced by warmer temperatures unless annual precipitation increases substantially. For many western river basins, where competing water demands for irrigation, recreation, and municipal use tend to peak in the summer, changes in seasonal streamflows are perhaps of greater interest. The studies that examine changes in seasonality typically suggest reduced summer streamflows and increased winter and/or spring flows.

Table 1.—Results of studies using hypothetical scenarios for western river basins
[Source: Nash. and Gleick, 1993; Bennett, 1994]

River basin	Temperature change (degrees Celsius)	Precipitation change	Percent change annual runoff	Percent change summer (months)	Citation
Upper Colorado	+2	-10%	-23.3%		Nash and Gleick (1993)
		0	-11.7%		
(Lake Powell inflow)		+10%	+0.6%		
	+4	-20%	-41.0%		
		-10%	-31.2%		
		0	-20.7%		
		+10%	-9.7%		
		+20%	+2.0%		
Colorado	+2	-10%	-40		Revelle and Waggoner (1983)
		+10%	-18%		
Upper Colorado	+2	-10%	-35		Stockton & Boggess (1979)
		+10%	-33		
Lower Colorado	+2	-10%	-56		
		+10%	-2		
Great Basin Rivers	+2	-10%	-17 to -28		Flaschka et al. (1987)
		+10%	+20 to +35		
Animas (at Durango)	+2	0	-2.1	-39.6 (JAS)	Schaake (1990)
		0 (ET +10%)	-8.6	-44.6	
Animas (at Durango)	+2	-20%	-26.1		Nah. and Gleick (1993)
		-10%	-16.7		
		0	-7.0		
		+10%	+3.2		
		+20%	+14.1		
	+4	-20%	-31.5		
		-10%	-22.9		
		0	-14.1		
		+10%	-4.7		
		+20%	+5.1		
Sacramento	+2	-20%	-31	-42 (JJA)	Gleick (1986;1987)
		-10%	-18	-32	
		0	-3	-22	
		+10%	+12	-12	
		+20%	+27	-1	
	+4	-20%	-34	-73	
		-10%	-21	-68	
		0	-7	-62	
		+10%	+7	-55	
		+20%	+23	-49	

Table 1.—Results of studies using hypothetical scenarios for western river basins (continued)

River basin	Temperature change (degrees Celsius)	Precipitation change	Percent change annual runoff	Percent change summer (months)	Citation
Carson	+2	-25.0%	-38	-55 (JAS)	Duell (1992)
		-12.5%	-24	-45	
		0	-8	-32	
		+12.5%	+13	-17	
		+25.0%	+39	+3	
	+4	-25.0%	-41	-70	
		-12.5%	-28	-62	
		0	-13	-53	
		+12.5%	+7	-43	
		+25.0%	+32	-30	
American (North Fork Dam)	+2	-25.0%	-51	-59 (JAS)	Duell (1992)
		-12.5%	-34	-48	
		0	-12	-41	
		+12.5%	+20	-28	
		+25.0%	+67	-14	
	+4	-25.0%	-54	-72	
		-12.5%	-38	-69	
		0	-14	-62	
		+12.5%	+19	-55	
		+25.0%	+67	-48	

Analyses for Specific Basins

Colorado River Basin

Several studies have examined the possible impacts of climate change on the Colorado River and its tributary sub-basins. Revelle and Waggoner (1983) and Stockton and Boggess (1979) used empirical models to assess the impacts of hypothetical climate changes. Both studies suggest that the flow of the Colorado River could be very sensitive to small changes in average temperature and precipitation. For example, the Revelle and Waggoner study concluded that a 2 °C temperature increase, coupled with a 10-percent decrease in precipitation, would result in a 40-percent decline in average basin runoff.

A more recent study by Nash and Gleick used conceptual hydrologic models (i.e., physically based, mathematical descriptions of a basin's hydrology) to examine the impacts of several climate change scenarios on the flow of the Upper Colorado River and three Upper Basin tributaries (the White River at Meeker, the East River at Almont, and the Animas River at Durango). In the hypothetical scenarios, temperature increases of 2 °C and 4 °C were considered, along with precipitation changes ranging from a 20-percent increase to a 20-percent decrease. The GCM scenarios, based on coarse resolution models, generally indicated larger temperature increases than the hypothetical scenarios and precipitation changes ranging from 0 to

+30 percent. The largest change calculated for Lake Powell inflows by this study was -41 percent for a temperature increase of 4 ºC coupled with a 20-percent reduction in annual precipitation. In general, the physically based models support the conclusions of the earlier studies, although the estimated sensitivity of streamflow to changes in the climate variables is slightly lower. To put these modeled changes in context, the authors note that tree-ring evidence suggests that a 20-percent reduction in natural flow from the recent historical record is conceivable even without greenhouse warming. They argue that if such natural variations were coupled with reduced flows arising from greenhouse warming, the impacts would be far more severe than any of the scenarios that they present.

The Nash and Gleick study also considers the impacts of changes in average Colorado River flows, concluding that the incidence of water supply shortages would depend on system operating parameters. They find that: "The variables most sensitive to changes in natural runoff are reservoir storage and power generation, which are particularly sensitive to decreases in runoff" (Nash and Gleick, 1993:75). In addition, they note that salinity levels would increase substantially if flows diminish.

They also discuss the possible utility of increased storage capacity, concluding that:

> *. . . given the already high levels of storage available on the Colorado, additional reservoir capacity would do little or nothing to alleviate potential* ***reductions*** *in flow. Reservoirs serve solely to decrease seasonal and inter-annual variability (over a limited number of years); they do not increase the volume of water available on a long-term basis. In fact, additional reservoirs in highly developed regions may actually decrease water supply over the long-term through evaporative and bank-storage losses (Klemes, 1985; Langbein, 1959). Only if climatic changes were to increase streamflow variability, without decreasing long-term supply, would additional reservoirs in the Upper Colorado River Basin have any benefits* (Nash and Gleick, 1993:83).

The Colorado River Severe Sustained Drought (CRSSD) study includes a more extensive analysis of ecological and socioeconomic impacts. That study was a major multi-institution collaborative effort involving researchers from a variety of academic disciplines. Rather than positing a climate change scenario linked to global warming, the CRSSD study focused on the present-day consequences of the type of severe sustained drought that could occur even in the absence of anthropogenic climate change. Specifically, the study examined the potential impacts of a drought similar to the extremely dry period of 1579-1600 that has been identified in tree-ring records (Young, 1995). The study provides a detailed assessment of the role of institutional factors in determining the level and incidence of damages that would arise from such an event.

The 1922 Colorado River Compact (Compact) divides the water between the Upper and Lower Basins, obligating the Upper Basin to deliver a moving 10-year average of 7.5 Maf per year at Lee Ferry. Except for Upper Basin water rights that were perfected prior to the Compact, this gives the Lower Basin priority in the event of reduced flows (MacDonnell et al., 1995). In addition, the Lower Basin has the larger right because Compact allocations were based on an assumed average flow considerably larger than the long-run average of 13.5 Maf suggested by tree-ring evidence (Stockton and Jacoby, 1976). Later, the Upper Colorado River Basin Compact clarified how the burden of meeting the obligation to the Lower Basin would be divided among the Upper Basin States, clearing the way for Federal support for major storage projects in the Upper Basin. The system of reservoirs now in place in the Colorado Basin is capable of storing approximately four times the average annual flow of the river. The Compact, subsequent statutes, an international treaty, court decisions, and project operating rules together comprise the "Law of the River."

The CRSSD study modeled the operation of the Colorado Basin's system of reservoirs under the current "Law of the River." The study found that the "Law of the River," as currently interpreted and implemented, would leave sensitive biological resources, hydropower generation, recreational values, and Upper Basin water users vulnerable to damages despite the extraordinary engineering attempts to droughtproof the river. In particular, the analysis suggests that nonconsumptive water uses would be more vulnerable to damage than traditional consumptive uses. The study concludes that damages to nonconsumptive uses could not easily be mitigated without changes in statutes or judicial interpretations to give greater voice to those interests (Lord et al., 1995).

The study team also found that certain proposed institutional changes could considerably alter the level and incidence of the damages (Booker, 1995; Lord et al., 1995; Sangoyomi and Harding, 1995). For example, Booker used the Colorado River Institutional Model (an integrated economic-hydrologic-legal model) to develop detailed quantitative estimates of the economic damages of this hypothetical drought under existing operating rules and policy and under a set of possible policy modifications. He found that reallocation from low to high valued uses (e.g., through intrastate or interstate water marketing) and changes in reservoir storage policies to hold water in the Upper Basin in order to reduce evaporative losses could reduce consumptive use damages by over 90 percent. In addition, damages to hydropower production and recreational opportunities could be reduced by emphasizing maintenance of minimum reservoir levels; however, if such a policy were implemented by itself, it could increase consumptive use shortfalls. He therefore concludes that: "Utilizing all three policy responses together would result in the greatest total reduction in damages from a severe and sustained drought" (Booker, 1995:906).

Kenney (1995) and Lord et al. (1995) propose more fundamental institutional changes to facilitate implementation of effective drought responses. They call for creation of a regional organization for the Colorado River, perhaps an interstate compact commission similar to that now in place in the Delaware River Basin. Kenney argues that such an organization would:

> *. . . provide a forum where the basin states could establish (and oversee implementation of) regional water management goals and programs and where interstate bargains could be pursued. . . . A primary objective of this proposed innovation would be to formally shift responsibility for the control of the river away from the federal government to a collective of the basin states* (Kenney, 1995:847).

He notes, however, that protection of Federal reserved water rights and enforcement of the Endangered Species Act should remain Federal responsibilities, which would require formal Federal participation in the regional organization.

Sacramento/San Joaquin River Basin

The work by Gleick, reported in table 1, used a water balance model to calculate the impacts of temperature and precipitation changes on Sacramento Basin annual runoff and its seasonal distribution. Gleick's analysis indicates that total flows would be sensitive to warmer temperatures and that summer flows could decline substantially, even with increased annual precipitation, while winter flows would tend to increase. This conclusion is supported by the work of other analysts who have examined the impacts of climate change scenarios on various parts of the Sacramento/San Joaquin system.

Lettenmaier and Gan (1990) examined the sensitivity of streamflow to climate change in four sub-basins of the Sacramento-San Joaquin system. The sub-basins, the Merced, the north fork of the American River, the McCloud Creek, and Tomes Creek, differ in elevation and geologic characteristics. Three climate change scenarios were based on doubled CO_2 GCM runs. For these, the authors used monthly grid-scale temperature and precipitation changes, for the grid centered on the basin, with precipitation changes adjusted to the elevation distribution of each sub-basin. The authors note that:

> *The marked reduction in average snow water equivalent for all of the study catchments for all of the alternative climates was the most striking result of the study, and most of the other results are related to the reduction in winter snow accumulation* (Lettenmaier and Gan, 1990:74).

Figure 19 shows the locations of these basins and the changes in monthly snow water equivalent under the GCM scenarios. Figure 20 displays the

simulated average monthly streamflows under the base case and GCM scenarios. The basins differed somewhat in streamflow response and flood frequency, with lower elevation basins becoming mostly rainfall dominated systems under the Geophysical Fluid Dynamics Laboratory (GFDL) and Goddard Institute for Space Studies (GISS) scenarios, while the higher elevation Merced Basin still retained the character of a snowmelt dominated system, although melt and runoff occurred much earlier in GFDL and GISS scenarios. Flood frequency increased, and summer soil moisture declined for these scenarios in all basins.

A fourth climate scenario coupled historic precipitation with temperature changes from the GISS (warmest winter) GCM, and a fifth was based on a 1930s analog climate which was drier than the base climate, but not much warmer. These were used for a sensitivity analysis, indicating that the temperature changes and their effects on snowpacks are much more important in determining changes in monthly streamflow than are the precipitation changes.

The study concluded that: (1) there would be substantial decreases in average snow accumulations; (2) this would increase winter runoff and decrease spring and summer runoff; (3) increased occurrence of rain in winter would increase winter soil moisture storage, making more available for spring evapotranspiration (ET), which would be increased by warmer spring temperatures; (4) reduced spring snowmelt, coupled with increased ET, would reduce late spring, summer, and fall soil moisture and runoff; and (5) "for any given catchment the specific nature of the hydrologic change would depend on physiographic characteristics (notably, the area-elevation distribution) of the catchment as well as the geologic and topographic features that control the precipitation-runoff response. Substantial diversity existed between the catchments, especially for the McCloud River, which drains an area of deep volcanic ash in the vicinity of Mount Shasta and has extraordinarily persistent base flow." (p.85).

Lettenmaier and Sheer (1991) extended that study to examine the implications of these climate scenarios for the performance of the combined Central Valley Project (CVP) and State Water Project (SWP) system. They found that the substantial loss of natural storage in the form of winter snowpacks would result in lower reservoir levels in summer and fall and increased spills in winter, particular for the SWP, which has less reservoir storage than the CVP. This would reduce the reliability with which the system could meet current demands. They also note that if winter flood risk were to increase, increased flood storage might be required, which would reduce conservation storage and further decrease system reliability.

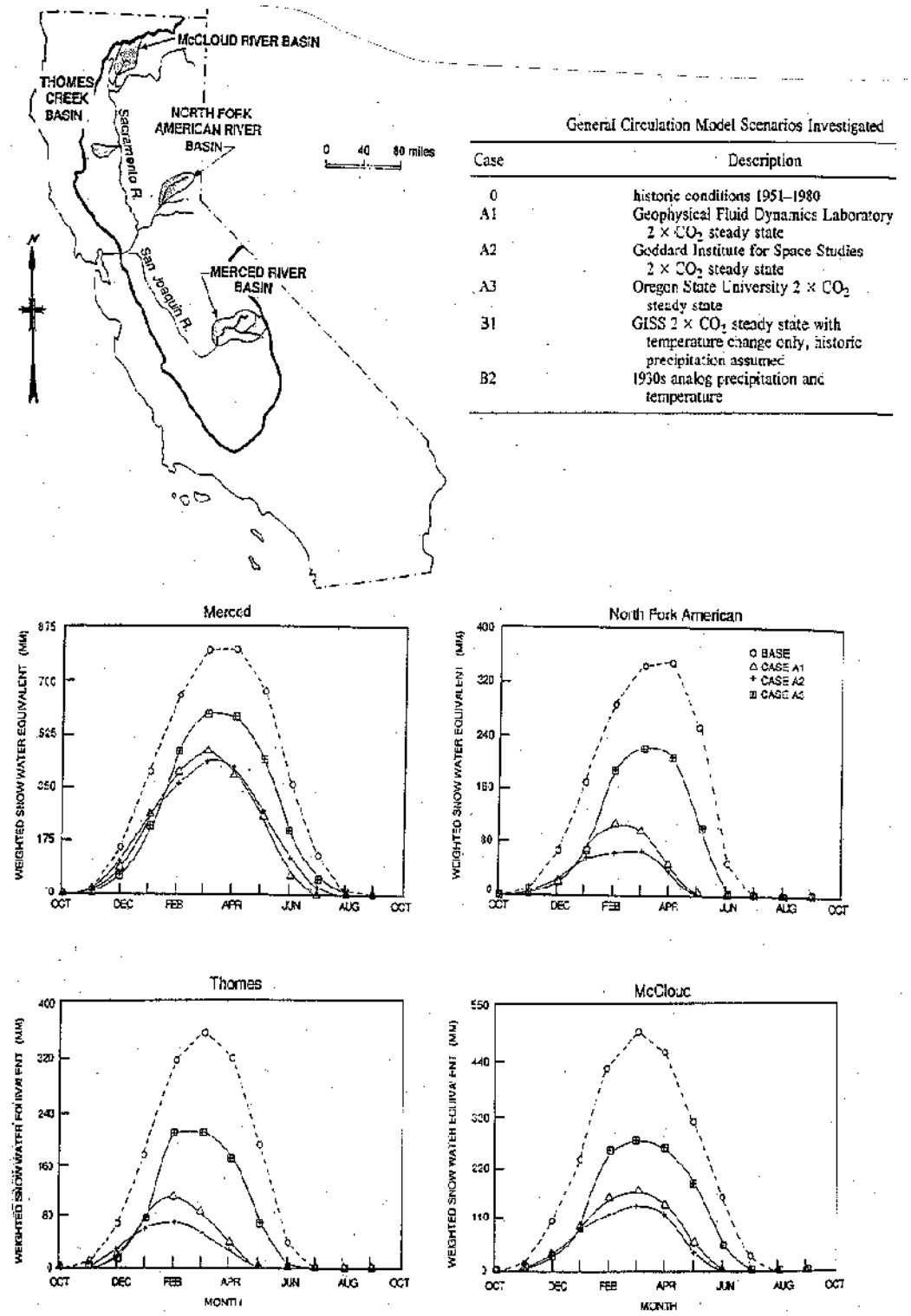

Figure 19.-Study catchment mean weighted snow water equivalent for base case and CO_2 doubling scenarios A1-A3.

Source: Lettenmaier and Gan, 1990

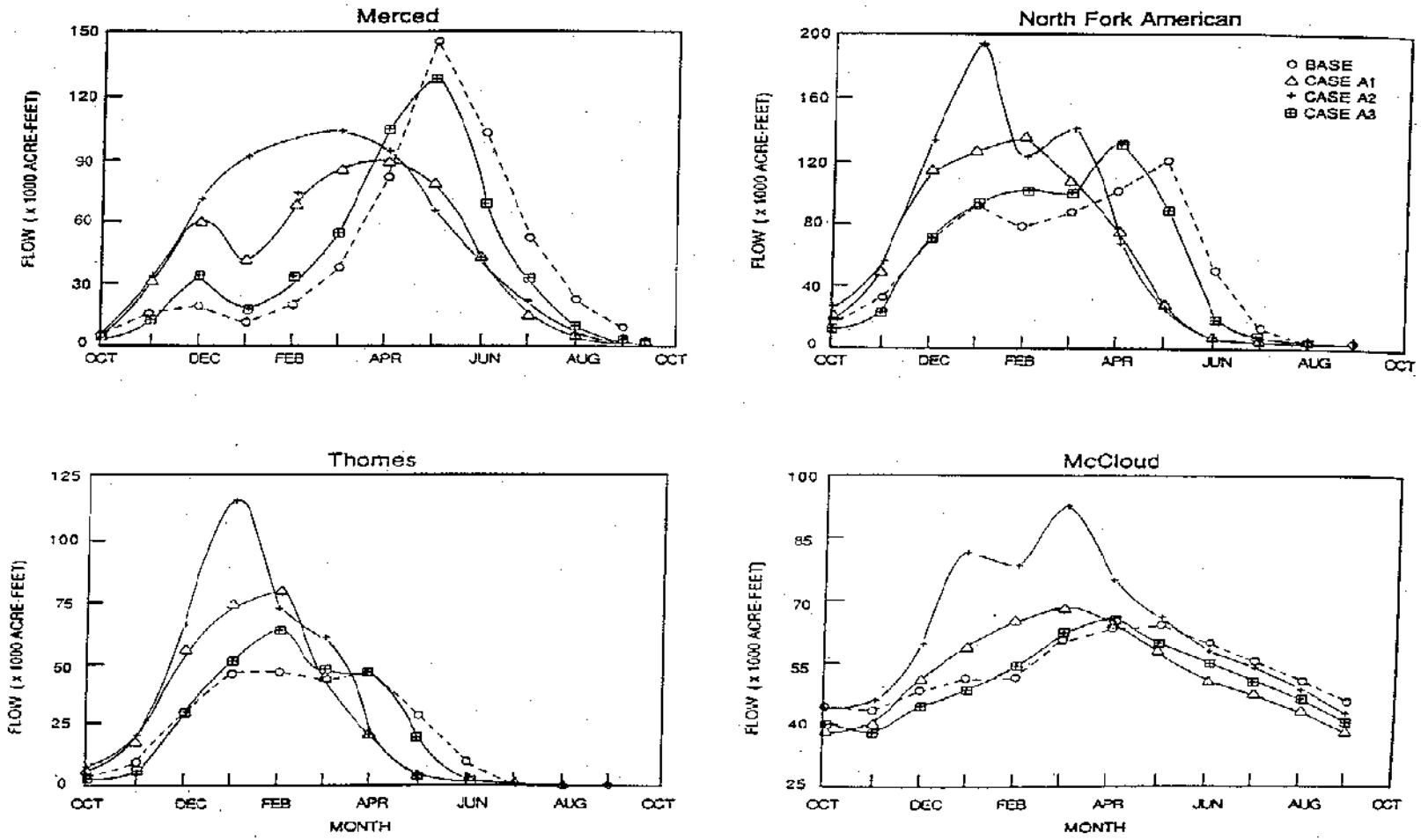

Figure 20.-Study catchment monthly mean streamflow for base case and CO_2 doubling scenerios A1-A3.

Source: Lettenmaier and Gan, 1990

These conclusions are supported by Sandberg and Manza who used the Bureau of Reclamation's Projects Simulation Model (PROSIM) to simulate the operation of the CVP-SWP under the same set of GCM-based climate change scenarios examined by Lettenmaier and Gan (1990). They conclude that:

> *The extent of climate change impacts in the future to the CVP-SWP systems will be proportional to the loss of spring and summer inflow to the Central Valley Basin. The more substantial the shift to heavy winter streamflows and reduced spring streamflows, the narrower the window of reservoir storage filling opportunity becomes in time. For both CVP and SWP, the smaller the window the larger the potential climate change impacts* (Sandberg and Manza, 1991:V-1).

Both studies also note that Sacramento/San Joaquin Delta outflows could increase substantially in the winter months, but impacts on project pumping operations would depend on uncertain changes in the length of time during which the high outflow conditions persist.

Weber Basin

A study by Riley et al. (1996) reports the results of a distributed parameter watershed model for simulating climate change impacts on streamflow in Utah's Weber Basin and its sub-basins. Detailed results for the Causey Watershed (one of the sub-basins) are presented. The model allows inclusion of some CO_2-induced vegetation changes such as reduced stomatal conductance and increased leaf area. The study uses a variety of scenarios to compute changes in average annual streamflow and seasonal flows. Results are similar to those for other mountainous western river basins, with higher winter flows (especially in March), and lower summer and especially spring (April-June) flows for most scenarios. Peak flow shifts 1 to 2 months earlier. Flows are found to be sensitive to both temperature and precipitation, with decreases in precipitation having a larger percentage impact on streamflow than increases. This suggests that the sensitivity of streamflow to precipitation increases as precipitation declines.

The study computed shortages relative to current demand for 20 different service areas within the Weber Basin, but no adjustments were made for possible increased demands or reduced return flows. Considerable differences were found between service areas in their vulnerability to the climate change scenarios, with significant shortfalls in service areas having little upstream storage and no shortfalls in many areas with access to substantial storage.

Basin outflows were calculated using the Weber River Simulation Model of the Utah Division of Water Resources, which accounts for storage and diversions. Basin outflows declined significantly in some scenarios. Since

these are inflows to the Great Salt Lake, that may represent little problem. However, this result suggests that for similar basins elsewhere, where there are downstream demands and/or valuable aquatic ecosystems, the impacts would be more severe than in the Weber Basin.

Policy Considerations

The climate change research indicates that reduced water availability, particularly during the high-demand summer months, is a possible result of climate change for many parts of the West. In addition, the risk of winter or early spring floods may increase, particularly in the West Coast States, where warmer winter temperatures could be coupled with greater precipitation and an increased frequency of rain-on-snow events in some catchments. Wetlands, aquatic ecosystems, and sensitive biological resources also are likely to be further stressed by climate change. Taken together, this body of research suggests that the potential impacts of climate change on western water resources are serious enough to warrant attention in discussions of long-term policy directions and in the design of programs and institutions that are expected to have enduring impacts on the control and allocation of water resources.

However, the exact nature, timing, and location of climate change impacts remain highly uncertain. Furthermore, the inherent natural variability of climate and streamflow in the Western States will complicate detection of global warming impacts, per se, so that recent experience will never be a reliable predictor of changes to come. This suggests that increased uncertainty is a central aspect of the climate change issue. Any policy response, therefore, should focus on ameliorating the effects of the uncertainty itself and improving our capacity to respond to a wide range of possible hydrologic changes.

A sensible first step would be to focus on improving our ability to manage the effects of hydrologic extremes. In areas in which population growth and economic development are contributing to increased vulnerability to droughts or floods, it may be valuable to re-examine the design, operation, and coordination of both Federal and non-Federal facilities and policies. In some instances, further investments in water control infrastructure may be warranted, but the environmental effects of such investments must be carefully considered in the context of the possible environmental stresses that may result directly from climate change.

Recent experience with severe flooding and levee failures in California, and in 1993 along the Mississippi River, suggests a need to re-evaluate both the structural options for controlling flood waters and policies affecting the development of properties in flood plains. The possible effects of climate

change on the characteristics and probabilities of flood events should be considered in such re-assessments.

The Federal Government could help to ameliorate impacts of droughts by facilitating short-term transfers of water from lower to higher valued uses, while taking actions to protect public instream values. The development of such institutional responses to drought would also help to reduce the social and environmental costs of any transition to reduced water availability arising from global climate change.

A recent report of the Office of Technology Assessment (OTA, 1993) concludes that our ability to adapt to changing circumstances is constrained by "rigid and inefficient institutions."

> *Such institutions can add to the stress already on water resources by making adjustments to new situations more difficult. When water rights are unclear, for example, as they continue to be in parts of the West, reallocation of water is difficult. Agreements abound that were negotiated when either information was inadequate or future circumstances concerning supply and demand could not be foreseen. These agreements constrain the responses that water resource managers can make to short- and long-term problems, and they are often difficult to change.* (OTA, 1993:224).

The report goes on to note that:

> *Current stresses on water resource systems are already motivating changes in laws and institutions. The potential for climate change adds another, if currently secondary, reason to make those changes. Given the uncertain impacts of climate change on water resources, however, institutions that are* ***flexible*** *(i.e., those that could facilitate adaptation in a variety of different climates) and that foster an* ***efficient allocation*** *of water would be most responsive to changes caused by global warming. As institutions change,* ***equity*** *in water resource allocation could be promoted by providing more opportunities for the public to become involved in decisionmaking bodies. Such involvement could stimulate healthy debate about the values at stake in water resource decisions.*
>
> *In many cases, promoting flexibility, efficiency and equity will require more coordination and cooperation among the large number of Federal, State and local water resource organizations. . . . River basins and watersheds are rarely managed in an integrated fashion, for example, and there are clearly opportunities for some significant increases in yield by more-efficient joint management of existing reservoir systems. Similarly, water-quantity laws and water-quality laws are seldom coordinated. Surface water and groundwater are often managed separately. The respective responsibilities of Federal and State agencies are sometimes*

> *unclear, and Federal Government agencies that have water responsibilities do not always cooperate with one another* (OTA, 1993:225).

Several analysts have argued that prospective climate change reinforces the need to clarify water entitlements and to improve the functioning of water markets (e.g., Trelease, 1977; Tarlock, 1991; Miller et al., 1997). Tarlock (1991:245), for example, argues that:

> *Water marketing could be the cornerstone of an adaptive strategy because water can be shifted to areas of highest demand regardless of its original priority and use. . . . Overall, however, we now have more water market theory than we have water markets, largely because proponents have underestimated the complexity of water transfers.*

These complexities arise as a result of the legitimate need to protect the vested water rights of third parties and to prevent damage to other third party interests (NRC, 1992).

Water marketing and the definition and documentation of water rights are largely matters of State policy, but adjudications of water rights and increased water market activity will have implications for Federal projects, Federal reserved water rights, Native American water rights, Federal public trust responsibilities, and administration of interstate compacts and international treaty obligations.

It is widely understood that clear documentation of the size and ownership of water rights is a prerequisite to the efficient operation of water markets. Costly and time-consuming adjudication processes have been initiated on many streams, where water rights are now poorly documented. The possibility of significant climate change increases the value of these endeavors and suggests new wrinkles that should be considered as efforts to improve documentation are carried forward. For example, prior appropriation rights are typically quantified on the basis of diversions, but other dimensions of a right (such as consumptive use) can vary, to the detriment of other users, as climatic conditions change (Miller, et al., 1997). The relationship between the quantity of water diverted and consumptive use of that water is not constant. Under warmer conditions, a larger fraction of the water is likely to be lost to evaporation from conveyance channels and to crop evapotranspiration, thus reducing return flows. Such changes in consumptive use would affect the security of all water rights of more junior status. Therefore, it may be valuable to give policy consideration to options for managing that risk.

In addition, the prospect of climate change may complicate efforts to protect third party interests in water transfer cases by making it more difficult to forecast both future consumptive uses and the future availability of water to keep existing uses intact. For example, warmer temperatures could cause

return flows from a new use to be smaller than anticipated by increasing evaporative and seepage losses. Water administrators should give careful attention to the question of how such climatic uncertainties might enter into decisions regarding the development or transfer of water rights and to the issue of who will bear the risk of mistaken assessments.

The effectiveness of water marketing in promoting flexible adaptation to prospective climate change will depend on the nature of the markets. At present, the process for approving water transfers in the Western States involves considerable transaction costs (MacDonnell, 1990). As a result, most transfers between different types of uses tend to be permanent transfers of large blocks of water. Such large transfers are not a particularly effective tool for responding to the effects of climatic variability or to the uncertain prospect of climate change. Rather, policymakers should focus greater attention on promoting shifts of small quantities of water and temporary transfers from senior to junior users during periods of low flows. This could be accomplished by streamlining administrative procedures for temporary transfers or by establishing formal water banks, such as the Emergency Drought Water Banks that California established in 1991, 1992, and 1994 to mitigate the impacts of a persistent drought. Although there have been only a few other examples of functioning water banks to date, experience suggests that rules and procedures can be designed to allow timely transfers of water from lower to higher valued uses while effectively managing the possible environmental and third party impacts of the altered pattern of use (MacDonnell et al., 1994).

Public instream values are especially at risk if streamflows decline. The junior status of most instream rights held by State agencies gives them little practical significance (Wilkinson, 1989). Water transfers among private parties are not likely to adequately protect instream flows and associated environmental values against the impacts of increased water scarcity, because these uses are public goods which tend to be underprovided by markets. However, public agencies could represent such interests in a market setting if they are provided with budgets to buy or rent water rights for environmental purposes.

Regarding the Federal role in the development of water markets, the OTA report concludes that:

> *Of the several options identified in this report for reducing impediments to creating water markets, early action to clarify reclamation law on trades and transfers and to define the Federal Government's interest in facilitating the creation of markets would be most useful. Congress could urge the Department of the Interior to provide stronger leadership to assist transfers.* (OTA, 1993:264).

The report then goes on to advise a thorough evaluation of water marketing by the Western Water Policy Review Commission.

Tarlock (1991:248) also discusses the need to further clarify policies regarding transfers of Federal project waters. He notes that the Bureau of Reclamation's 1988 seven-principle transfer policy ". . . only touches on the volatile issue of subsidy recapture."

Several other aspects of Federal jurisdiction over water resources are likely to be affected by climate change including the Endangered Species Act (Public Law 93-205) and the Clean Water Act (Public Law 92-500). Ten Federal departments and numerous units within those departments currently have some responsibility for water programs and projects (OTA, 1993:233). Each of these could be affected in some way by changes in water quantity and quality or by changes in flood risks arising from climate change.

The OTA report notes that the Endangered Species Act, which in recent years has become a forceful instrument for the protection of aquatic and other water-dependent biota, may restrict future use and development of water supplies. One option for Federal-State cooperation that could provide increased flexibility with regard to both environmental protection and out-of-stream water uses would be to create instream flow buffers to be used to absorb the impact of changing climatic conditions (Miller et al., 1997). Rather than setting a single minimum flow standard to be used as a target for avoiding serious adverse impacts on fisheries and other aquatic resources, a range of environmentally desirable flow levels could be defined. The lower level might serve as a trigger for water authorities to enhance instream flows by purchasing water or implementing restrictions on existing rights, while the upper level would be used as the target for conditioning new rights. For example, administrators could grant new permits subject to the condition that they not deplete streamflows beyond the upper flow-level target. If flows increase, water users could fully exercise the new rights. If flows decline, the impact would fall first on the conditioned permits, then on the buffer, and finally on current water uses. Where water is already fully appropriated, authorities could create such a buffer by purchasing water rights from willing sellers to reduce existing consumptive uses. Where unappropriated water is available, they could more easily create such a buffer by incorporating appropriate conditions in the definition of new rights and by closing some streams to new appropriations unless and until there is considerable evidence that wetter conditions are likely to prevail.

Federal reserved rights and Native American rights have the potential for leading to future conflicts with other water users, particularly if streamflows diminish. In many cases, Native American claims have not yet been quantified or exercised, and controversy has accompanied the exercise of Federal reserved water rights for purposes of environmental protection (OTA, 1993).

The OTA report suggests other response strategies that would make sense, given the uncertain nature of climate change impacts. For example, it discusses the advantages of comprehensive water resource planning and management at the basin level (OTA, 1993). Basin-wide coordination may allow multiple demands to be met more efficiently than would be possible with uncoordinated reservoir management. The value of such coordination may increase if there are significant changes in water availability or streamflow variability. In addition, as the scope of planning and coordination are expanded, a wider range of options for responding to changing water supplies and demands is likely to be available.

At the national level, Congress could reactivate the National Water Council or create a similar high-level coordinating body. The OTA report argues that such a body ". . . could play an important role in improving cooperation and coordination among the many Federal agencies with water-related responsibilities and among Federal State, and local governments and the private sector" (OTA, 1993:249). It could also serve as a clearinghouse for research and data relating to changing hydrologic conditions.

Conclusion

Western water resources are sensitive to climatic variations. Despite considerable past success in outwitting nature to provide reliable water supplies for out-of-stream uses, climate change could impair the reliability of those supplies and could further damage valuable instream resources.

Some would argue that the impacts of climate change are so uncertain and so far in the future that they pale in significance relative to more pressing concerns. However, the risk should not be ignored. In large part, climate change provides further reason to take actions that will improve resilience to the droughts and floods that arise from ongoing climate variability. However, climate change adds new twists to the uncertainties facing water users, water managers, and those who value preservation of environmental resources. It does so because both the hydrologic characteristics of watersheds and the impacts of existing water uses are likely to change. It is not too early to begin thinking about how to improve our capacity to manage those uncertainties and to respond efficiently and fairly to a range of possible streamflow changes, as well as to the effects of ongoing climatic variability.

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