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CLIMATE SCENARIOS FOR THE AMERICAN SOUTHWEST IN THE NEXT CENTURY

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ABSTRACT: The climate of the Southwest United States is governed by two separate large-scale regimes during the course of the year. In the winter half-year, disturbances in the westerlies supply 40-80% of the annual total precipitation in the region. The precipitation is associated with frontal systems sweeping from the west and north through the area, and with the development of upper level troughs and occassional cutoff lows in the upper atmosphere. During the summer half-year, and particularly during the months of July-September, a monsoonal-type circulation system develops along western Mexico and extends into the desert areas of the U.S. Southwest producing locally heavy thunderstorms and floods. In early fall, eastern Pacific hurricanes, occassionally recurving to the north and east across northwestern Mexico, can also produce widespread rains and locally severe flooding in the region.

With regards to future changes in climate forced by increasing atmospheric greenhouse-gas concentrations, the question arises, as to whether the annual precipitation in the region will be more affected by changes in the winter-time regime, that is, through a modification of the polar jet stream and associated extratropical cyclone tracks, or whether an increase in the summer monsoon system will, at least in part, make up for a potential winter decline in precipitation. An increase in convective summer-season rainfall will also be accompanied by enhanced soil erosion, arroyo cutting, greater sediment loads in the region's streams, and other problems. Climatic changes resulting from the enhanced greenhouse effect will be superimposed on a rich spectrum of naturally occurring climatic variability at the relevant time scales that are of interest here, namely, decadal to century fluctuations. I will consider these alternatives based on what is known about climatic variability in the past several hundred years, and offer plausible climate scenarios for the next hundred years.

KEY WORDS: ENSO, Southwest U.S.A., climate change, precipitation.

INTRODUCTION

Among the important forcing mechanisms that operate on the decadal to century time scales of interest here are those associated with internal climate mechanisms that result from unstable air-sea interactions, such as El Niño/Southern Oscillation (ENSO), (Graham *et al.*, 1994; Kumar *et al.*, 1994; Latif and Barnett, 1994; Diaz and Kiladis, 1995), and interactive couplings of the land-ocean and atmospheric systems (Meehl,

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1994). Also important are external forcings such solar irradiance variations, and hence in the amount of energy received by the earth-atmosphere system (Rind and Overpeck, 1993); climate shocks, such as could arise from large explosive volcanoes (Bradley, 1988; Hansen *et al.*, 1992), are important, as are rapid changes in the cryosphere and in the meridional transfer of heat by the ocean thermohaline circulation (Broecker, 1991). These natural perturbations can alter the general atmospheric circulation on hemispheric to global spatial scales, and can result in climatic signals which may persist, to a variable extent, at large regional scales. In addition, one now has to consider the changes in the earth's energy balance that will result from human activities (the enhanced "greenhouse effect", aerosol cooling, etc.), and also how the climate may respond to the interactions of the natural forcings with anthropogenic climatic forcings (Broecker, 1987).

The region considered here, the Southwest United States, is strongly affected by changes in atmospheric and oceanic conditions in the Pacific Basin, and to some extent over the Asian continent (Horel and Wallace, 1981; Douglas *et al.*, 1982; Yarnal and Diaz, 1986; Kiladis and Diaz, 1989; Graham *et al.*, 1994). This region, has also been shown to exhibit considerable variability on a broad range of time scales, in observational (Roden 1989; Cayan and Peterson, 1989), and modeling studies (Chen and Cayan, 1994; Graham *et al.*, 1994). These and other studies demonstrate that both tropical and extratropical ocean-atmosphere processes modulate climatic variability in the West. The question being considered here is how the climate of the Southwest United States may vary over the next century in response to both natural variations, and from anthropogenically-induced changes of the global climate system.

DATA AND METHODOLOGY

The climate data used to evaluate the various climate scenarios consist of monthly averages of temperature and precipitation for the set of climate divisions in the Southwest United States (see Figure 1) and daily values of mean, minimum and maximum temperature and total precipitation for selected long period stations in this region. Data were obtained from the archives of the National Climatic Data Center of the National Oceanic and Atmospheric Administration, NOAA, in Asheville, NC. Changes in circulation patterns in the middle troposphere, from (700-500 mb, about 3-6 km asl) at a broad range of temporal scales are closely associated with changes in precipitation and temperature at the surface at similar time scales (Namias, 1978; 1980; Klein and Bloom, 1987; 1992). I have concentrated on the surface variables since there is a much longer record available for these compared to the upper air record. Where appropriate, reference is made to the use of proxy climate records, primarily tree-ring reconstructions of seasonal temperature and precipitation, to evaluate potential future changes in the climate of the Southwest. In California, for instance, cold-season precipitation reconstructions have been shown to explain 50-60% of the interannual precipitation variance of station records located near the tree-ring sites (Graumlich, 1993; Haston and Michaelsen, 1994).

The following methodological approaches have been followed. First, exploratory data analysis techniques were applied to the observed climate record, in order to ascertain the response of the climate of Southwest United States to major large-scale features of the Northern Hemisphere circulation, and to obtain some quantitative bounds of its range. It has been shown that characteristic modes of variability in the large-scale atmospheric circulation over North America and the eastern North Pacific Ocean, such as the Pacific-North American (PNA) pattern, are often associated with extreme climatic anomalies at annual to decadal time scales in the southwestern United States (see Trenberth and Hurrell, 1994). Second, I have relied on the analog approach to estimating plausible climatic conditions for the next 100 years, by projecting past known climate changes within the region as possible analogs, while taking into account various climate forcing factors that likely could influence climatic characteristics of the region in the future.

The climate projections consist of empirical estimates of seasonal precipitation changes in the Southwest, and of possible changes in the seasonality and intensity of daily to annual amounts.

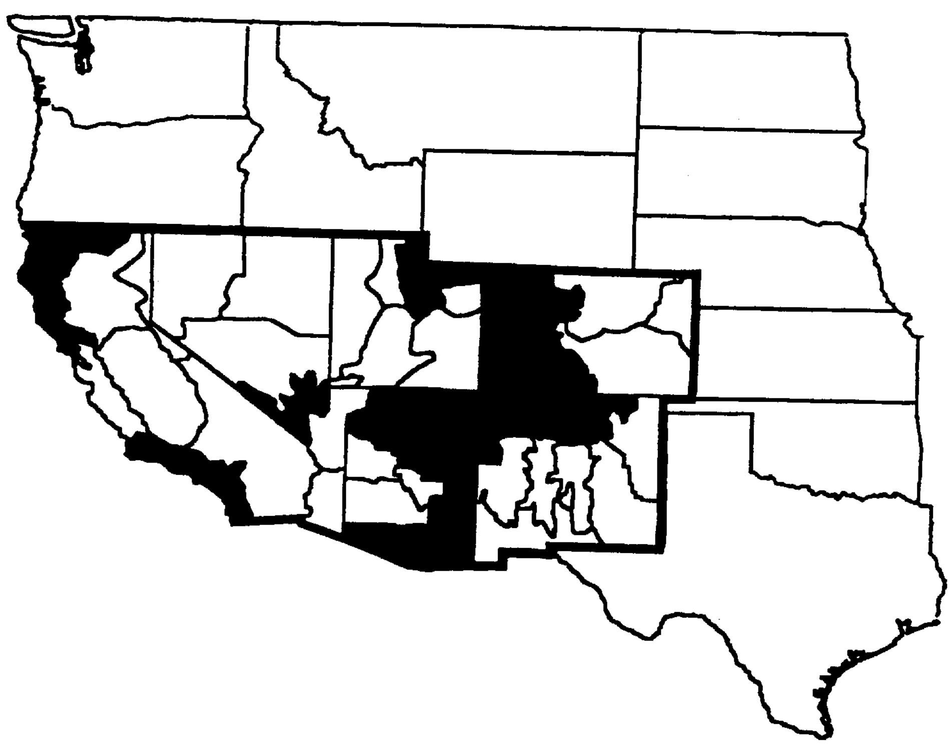

Figure 1. Map illustrating the area of the western United States that is the focus of this study, and the boundaries of the State climatic divisions. The eight divisions where precipitation data were analyzed in detail are highlighted in black.

RESULTS

Relevant climatic controls - The modern setting

The area comprising the Southwest United States encompasses much of the arid zones of the contiguous United States, with moister conditions occurring mainly in areas of high terrain (Fig. 1). I have included Colorado because it contributes heavily to the water supply of the other states through its large contribution to Colorado River streamflow (see Diaz and Anderson, 1995), and New Mexico, because it lies within the same broad physiographic province. Major mountain ranges stretching from the Sierra Nevada in the west, the middle Basin and Range and Colorado Plateau regions, and the Rocky Mountain ranges farther to the east, intercept moisture associated with disturbances in the westerlies and store it as snowpack that subsequently provide the necessary water to sustain both human and animal populations in the region. The great deserts along the southern margins of this region are found in the broad rainshadow of California's Sierra Nevada Range and in the low terrain found between the uplands. Because the westerlies are displaced farthest south during northern winter, the zone of westerly disturbances is also displaced farthest to the south during the months of November through March. This period comprises the primary winter rainy season in the region that is farthest west (California, Nevada and Utah). During summer, the presence of relatively cool sea surface temperatures (SST) off the U.S. west coast caused by upwelling of subsurface water forced by prevailing winds blowing parallel to the coast promotes the development of a stable lower atmosphere throughout the summer months. The intrusion of moist tropical air into parts of the Southwest during summer results in the development of intense thunderstorms with occassional flash flooding, and is a primary contributor to the summer rainfall total and to a climatological peak in seasonal precipitation during summer in Arizona and New Mexico. Occassional tropical cyclones may affect the southwestern desert regions of the contiguous United States, producing significant rainfall and flooding. These storms, however are relatively infrequent, and typically will affect areas no farther north than Las Vegas.

Figure 2 illustrates the annual cycle of monthly precipitation for three of the climatic divisions in the Southwest region which are representative of the different regional climate regimes. Figure 3 illustrates the time variability of precipitation in these three representative climatic divisions for the winter half-year (October-April). As is generally characteristic of arid and semi-arid regions, the record of precipitation exhibits high interannual variability relative to the mean, with coefficients of variation (interannual standard deviation divided by the mean) in the more arid divisions near 40%. There is an apparent increase in both cold and warm season (not shown) precipitation over the past several decades in some divisions. The recent period of relatively high precipitation is now examined in the context of recent temperature changes occurring in the tropical Pacific Ocean and associated surface and upper-level circulation changes occurring in the extratropical Pacific Ocean.

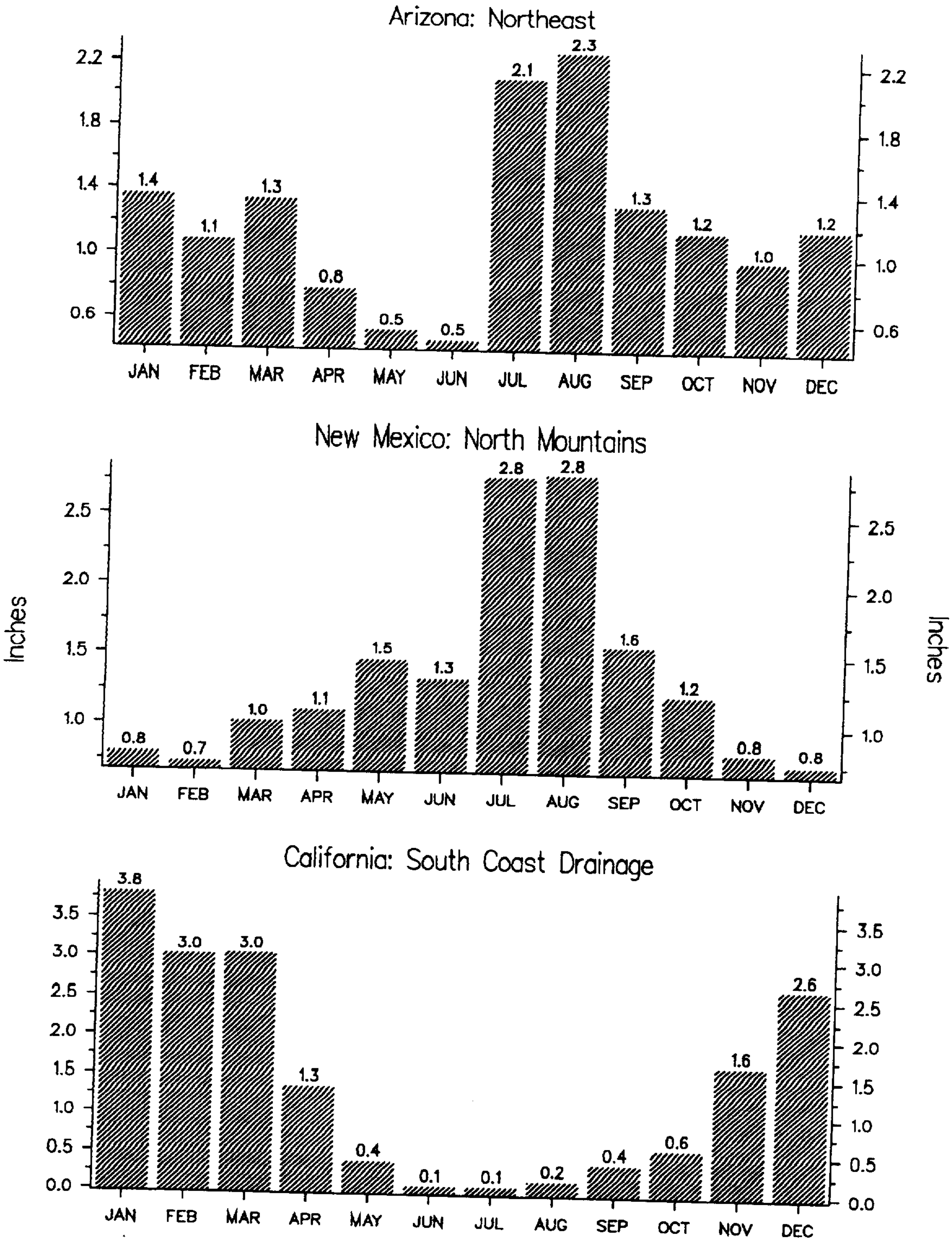

Figure 2. Annual cycle of mean monthly precipitation for the Northeast Arizona (top), North Mountains of New Mexico (middle), and California's South Coast Drainage (bottom) climate divisions. Each division is representative of the different annual cycle climatology in the southwestern United States.

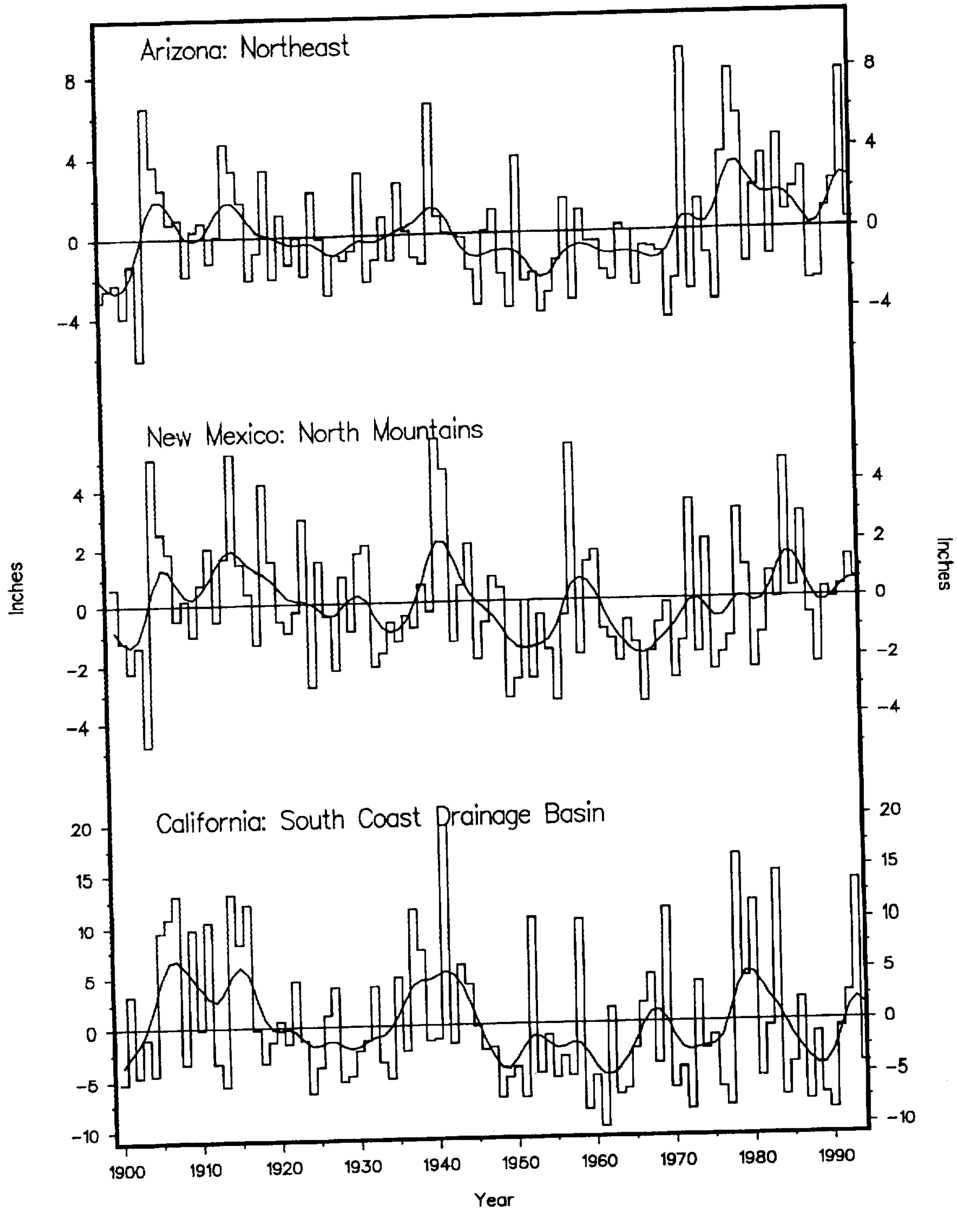

Figure 3. Time series of October-April precipitation anomalies, 1900-1994, for the three divisions considered in Figure 2. A nine-term Gaussian filter (continuous smooth line) is shown to highlight decadal-scale variability.

El Niño and the Southern Oscillation

It is now generally accepted that the El Niño/Southern Oscillation (ENSO) phenomenon is one of the key elements affecting seasonal to interannual climatic variability in North America (Mo and Livezey, 1986; Kiladis and Diaz, 1989; Glantz *et al.*, 1991; Barnett *et al.*, 1994). Furthermore, ENSO also appears to be causally involved in the development of decadal-scale climatic variability over the North Pacific and the North American continent (Latif and Barnett, 1994). The ENSO phenomenon also appears to have been operating for a fairly long time - at least for several millennia (see Diaz and Markgraf, 1992 for a review).

Over the southwest U.S., the ENSO signal is relatively well-marked. Figures 4 and 5 illustrate the differences in October to April precipitation for different categorical values of the Tahiti-Darwin Southern Oscillation Index (SOI) for the several climate divisions in the Southwest. The mean SOI for the months December through February is used to characterize the seasonal precipitation amounts, because this is generally the time of greatest "teleconnectivity" between the tropics and the Northern Hemisphere circulation (Bradley *et al.*, 1987; Diaz and Kiladis, 1992). Box and whisker plots are used to illustrate the range of October to April precipitation values for each of three SOI classes (Figs. 5 and 6). The box in each plot illustrates the range of values in the middle 50% of the seasonal precipitation, conditional on the given value range of the SOI. The "whiskers" extend out to 1.5 times the interquartile range (IQR=75th% minus 25%). Clearly, precipitation amounts for eight of the state climatic divisions tend to be different at times when the |SOI|>1. For example, the lower precipitation quartile (25th percentile) in Arizona's Northeast division during warm ENSO events is greater than the upper precipitation quartile (75th percentile) during cold episodes. The pattern is reproduced to varying degrees for the other divisions. On average, cold-season precipitation in the Southwest averages 10-20% above the long-term mean during warm ENSO episodes. *If a situation develops, which favors more frequent and/or more intense El Niño conditions over time, it would probably result in a substantial increase in cold-season precipitation in the region of southwestern United States.*

Climatic Controls at Decadal Time Scales

In the following, I briefly consider some possible impacts of other climate forcing mechanisms that may modify/modulate the climate of the Southwest in the next hundred years.

a. Volcanism

Based on recent modeling work (Hansen *et al.*, 1992) it is estimated that an eruption the size of Mt. Pinatubo (with a Volcanic Explosivity Index of 5 or greater (Self *et al.*, 1981)) may reduce global temperatures by 0.6±0.2°C within 2 or 3 years after the eruption. Tambora is estimated as a VEI-7 explosion; the effects of either a VEI-7 or two VEI 5/6 eruptions occurring within a 10-yr period could result in decadal temperature anomalies in portions of the U.S.A. of about 1±0.5°C and precipitation changes on the

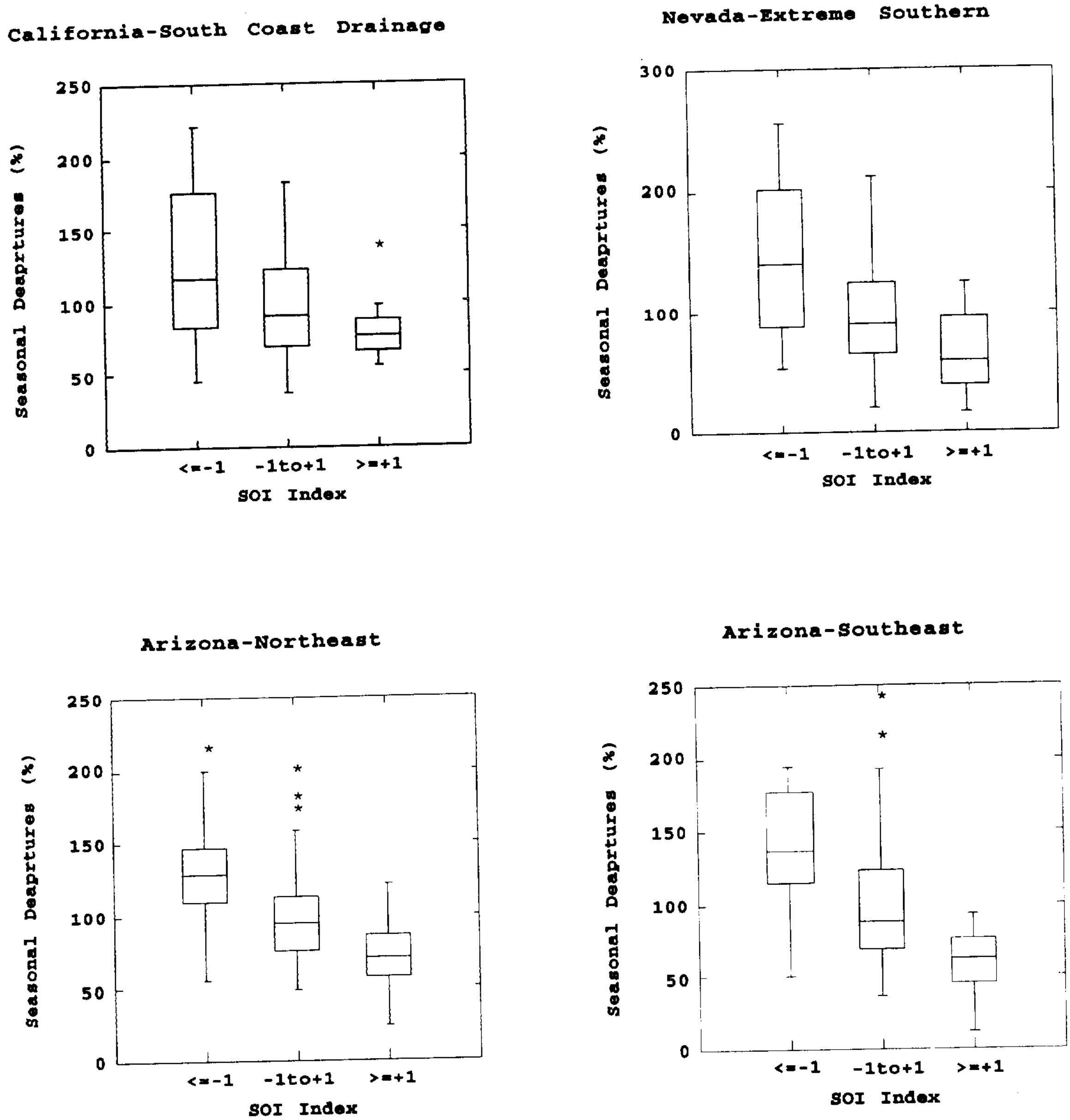

Figure 4. Box-and-Whiskers plot of the distribution of October-April precipitation departures as a function of the mean value of the December-February mean value of the Southern Oscillation Index (SOI) for selected climatic divisions in Arizona, California, and Nevada.

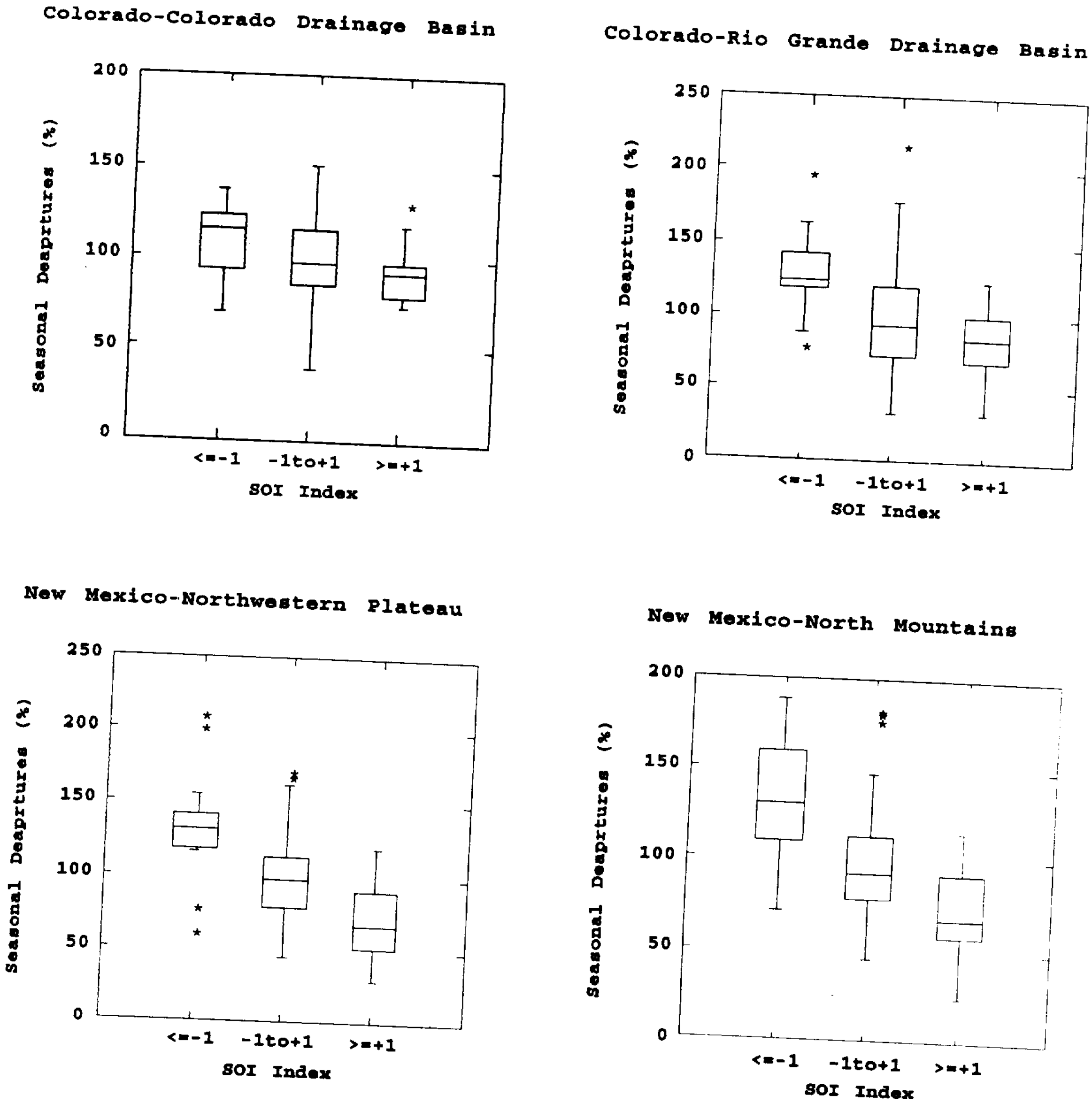

Figure 5. Same as Fig. 4, except for selected climatic divisions in Colorado and New Mexico.

order of 20% (± 20%). Nevertheless, in the absence of other forcing mechanisms, the climate should return to prevailing pre-eruption levels within about 10 years after the eruption.

b. Greenhouse-gas increases

Current projections by IPCC and others of the effect of doubling the atmospheric concentration of carbon dioxide indicate a probable *global* temperature increase of about 2-3^{o}C in the next 100 years. The probable effect of this change in the earth's climate on the climate of the southwestern U.S. is likely to be one of increase annual mean temperature and reduced annual precipitation (Waggoner, 1990). In the short term, it is possible that there will be an enhancement of the Southwest U.S. summer monsoon. However, in the long run, it will probably not be enough to compensate for greater winter precipitation losses due to a decrease in extratropical wave activity due to diminished meridional temperature gradients. Modeling results to date suggest an eventual increase in evapotranspiration losses, reduced groundwater recharge and increased erosion from summer thunderstorms which might be more frequent and/or severe.

c. Ocean thermohaline circulation changes, etc.

Over the past couple of decades a picture has emerged that elements of the climate system can undergo rapid transformations from one stable mode to another (Broecker, 1987; Ramhstorf, 1994)). Given that human activities are threatening to change the earth's climate on a large scale, it is conceivable that the imposed perturbation could have rapid and unforseen regional climatic effects that could affect the climate in the southwestern United States.

Two of the more plausible effects are a change in the tropical-extratropical teleconnection patterns leading to changes in the atmospheric circulation patterns over North America, and changes in the North Atlantic meridional overturning leading to changes in the climate of western Europe and eastern North America. Of these two possiblities, the changes in tropical SST are deemed the most likely to have the greatest impact in the future climate of the region. The most likely impact under the latter scenario may be similar to that considered in the context of changes in the ENSO phenomenon. In that case, an increase of precipitation in the Southwest may result, due to the enhancement of the winter subtropical jet over the southern United States.

REFERENCES

Barnett, T. P., L. Bengtsson, K. Arpe, M Flügel, N. Graham, M. Latif, J. Ritchie, E. Roeckner, U. Schlese, U. Schulzweida and M. Tyree, 1994. Forecasting ENSO-related climate anomalies. Tellus, 46A: 381-397.

Bradley, R. S., 1988. The explosive volcanic eruption signal in Northern Hemisphere continental temperature records. Climatic Change, 12: 221-243.

Bradley, R. S., H. F. Diaz, G. N. Kiladis, and J. Eischeid, 1987. ENSO signal in continental temperature and precipitation records. Nature, 327: 497-501.

Broecker, W. S., 1987. Unpleasant surprises in the greenhouse? Nature, 328: 123-126.

Broecker, W. S., 1991. The great ocean conveyor. Oceanography, 4: 79-89.

Cayan, D. R. and D. H. Peterson, 1989. The influence of North Pacific atmospheric circulation on streamflow in the West. Geophys. Monogr. No. 55, D. H. Peterson (ed.), Amer. Geophys. Union, Washington DC., 374-397.

Chen, S.-C. and D. R. Cayan, 1994. Low-frequency aspects of the large-scale circulation and West Coast United States temperature/precipitation fluctuations in a simplified general circulation model. J. Climate, 7: 1668-1683.

Diaz, H. F. and C. A. Anderson, 1995. Precipitation trends and water consumption related to population in the southwestern United States: A reassessment. Water Resourc. Res., 31: 713-720..

Diaz, H. F. and Kiladis, G. N., 1992. Atmospheric teleconnections associated with the extremes phases of the Southern Oscillation. El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation, Diaz, H. F. and Markgraf, V. (eds.), Cambridge University Press, pp. 7-28.

Diaz, H. F. and and Markgraf, V. (eds.), 1992. El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation, Diaz, H. F. and Markgraf, V. (eds.), Cambridge University Press, Cambridge, 476 pp..

Diaz, H. F. and G. N. Kiladis, 1995. Climatic Variability on Decadal to Century Time Scales. Chapter 6, in: Climates of the Future, A. Henderson-Sellers (ed.), World Survey of Climatology, Elsevier Publ. Co. (in press).

Douglas, A. V., D. R. Cayan and J. Namias, 1982. Large scale changes in North Pacific and North American weather patterns in recent decades. Mon. Wea. Rev., 110: 1851-1862.

Glantz, M. H., Katz, R. W. and Nicholls, N. (eds.), 1991. Teleconnections Linking Worldwide Climate Anomalies. Cambridge University Press, 535 pp.

Graham, N.E., T. P. Barnett, R. Wilde, M. Ponater, and S. Schubert, 1994. On the roles of tropical and midlatitude SSTs in Forcing interannual to interdecadal variability in the winter Northern Hemisphere circulation. J. Climate, 7: 1416-1441.

Graumlich, L. J., 1993. A 1000-year record of temperature and precipitation in the Sierra Nevada. Quat. Res., 39: 249-255.

Hansen, J., A. Lacis, R. Ruedy, M. Sato, 1992. Potential climate impact of Mount Pinatubo eruption. Geophysical Research Letters, 19: 215-218.

Haston, L. and J. Michaelsen, 1994. Long-term central coastal California precipitation variability and relationships to El Niño-Southern Oscillation. J. Climate, 7: 1373-1387.

Horel, J. D. and J. M. Wallace, 1981. Planetary-Scale Atmospheric Phenomena Associated with the Southern Oscillation. Monthly Weather Review 109,813-829.

Kiladis, G. N. and H. F. Diaz, 1989. Global climatic anomalies associated with extremes of the Southern Oscillation. Journal of Climate, 2: 1069-1090.

Klein, W. H. and H. J. Bloom, 1987. Specification of monthly precipitation over the United States from the surrounding 700 mb height field. Mon. Wea. Rev., 115: 2118-2132.

Klein, W. H. and H. J. Bloom, 1992. Specification and prediction of monthly and seasonal precipitation amounts in California and Arizona river drainage basins. Intl. J. Climatol., 12: 721-732.

Knutson, T. R. and S. Manabe, 1994. Impact of increased CO_2 on simulated ENSO-like phenomena. Geophys. Res. Lett., 21: 2295-2298.

Kumar, A., A. Leetma, and M. Ji, 1994. Simulations of atmospheric variability induced by sea surface temperatures and implications for global warming. Science, 266: 632-634.

Latif, M. and T. P. Barnett, 1994. Causes of decadal climate variability over the North Pacific and North America. Science, 266: 634-637.

Meehl, G. A., 1994. Coupled land-ocean-atmosphere processes and South Asian monsoon variability. Science, 266: 263-266.

Mo, K. C. and R. E. Livezey, 1986. Tropical-extratropical geopotential height teleconnections during the Northern Hemisphere winter. Mon. Wea. Rev.. 114: 2488-2515.

Namias, J., 1978. Recent drought in California and western Europe. Revs. Geophys. Space Phys., 16: 435-458.

Namias, J., 1980. Causes of some extreme Northern Hemisphere climatic anomalies from summer 1978 through the subsequent winter. Mon. Wea. Rev., 108: 1333-1346.

Rahmstorf, S., 1994. Rapid climate transitions in a coupled ocean-atmosphere model. Nature, 372: 82-85.

Rind, D. and J. Overpeck, 1993. Hypothesized causes of decade-to-century-scale climate variability: Climate model results. Quat. Sci. Revs., 12: 357-374.

Roden, G. I., 1989. Analysis and interpretation of long-term climatic variability along the west coast of North America. Geophys. Monogr. No. 55, D. H. Peterson (ed.), Amer. Geophys. Union, Washington DC., 93-111.

Self, S., M. R. Rampino, and J. J. Berbera, 1981. The possible effects of large 20th century volcanic eruptions on zonal and hemispheric surface temperatures, Journal of Volcanology and Geothermal Research, 11: 41-60.

Trenberth, K. E. and J. W. Hurrell, 1994. Decadal atmosphere-ocean variations in the Pacific. Climate Dynamics, 9: 303-319.

Waggoner, P. E. (ed.), 1990. Climate Change and U.S. Water Resources. J. Wiley & Sons, New York, 496 pp..

Yarnal, B. and H. F. Diaz, 1986. Relationships between extremes of the Southern Oscillation and the winter climate of the anglo-American Pacific coast. J. of Climatol., 6:197-219.