CLIMATE-CHANGE SCENARIOS FOR THE SIERRA NEVADA, CALIFORNIA, BASED ON WINTER ATMOSPHERIC-CIRCULATION PATTERNS

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ABSTRACT: Precipitation and temperature series for the Sierra Nevada can be synthesized using a probabilistic model conditioned on recurring atmospheric circulation patterns. The classification used herein is based on a principal-components analysis of historical winter 70-kilopascal atmospheric-pressure surfaces over North America and the North Pacific Ocean. Five circulation categories are delineated that correspond to recurring circulation patterns. Transitions between the circulation categories approximate simple Markov processes, and the statistical distributions of precipitation and temperature in the Sierra Nevada are conditioned by the category that prevails in a given 3-day period. Temperature is further conditioned by whether or not precipitation occurs. Climate-change scenarios can be obtained by first modifying the category-transition probabilities or the distributions of precipitation and temperature for each circulation category, and then drawing transitions and weather conditions from their respective conditional probability distributions. The climate change modifications can be arbitrary or derived from the circulation and surface-weather characteristics of specific climate change projections.
KEY TERMS: climate change; hydroclimatology; synthetic hydrology; Sierra Nevada.

INTRODUCTION

Atmospheric concentrations of carbon dioxide are increasing and may be double the preindustrial value within the next century (Watson *et al.*, 1990). Although researchers are uncertain of the effects of increasing carbon dioxide on global climate and especially on regional climates, suggestions are widespread that the increases will lead to global warming and significant regional climatic changes (Schlesinger, 1988; IPCC Working Group I, 1990; but also see Lindzen, 1990, for contrasting views). Regional temperature changes in the middle latitudes may be on the order of 2-5°C, and precipitation changes may be as much as a few millimeters per day (Mitchell *et al.*, 1990). These potential climate changes have raised concerns about potential effects on water resources (Moss and Lins, 1989).

The U.S. Geological Survey is conducting studies in the Sierra Nevada of California and Nevada (Figure 1A) to determine the sensitivity of water resources there to potential climate changes. One task in these studies has been the synthesis of time series of daily temperatures and precipitation rates that reflect plausible scenarios of climate change as it might affect the region. These time series are input to hydrologic models to estimate potential changes in streamflow in selected basins. The sensitivity of water resources in the Sierra Nevada to climate change has been examined in previous studies: for example, Flaschka *et al.* (1987), Gleick (1987), and Lettenmaier and Sheer (1991). Although they are unique in other ways, these studies formulate climate change scenarios either by prescribing a general change in mean temperatures and precipitation rates or by scaling all temperatures and precipitation rates up (or down) to correspond to time-averaged changes at grid cells in selected general circulation climate

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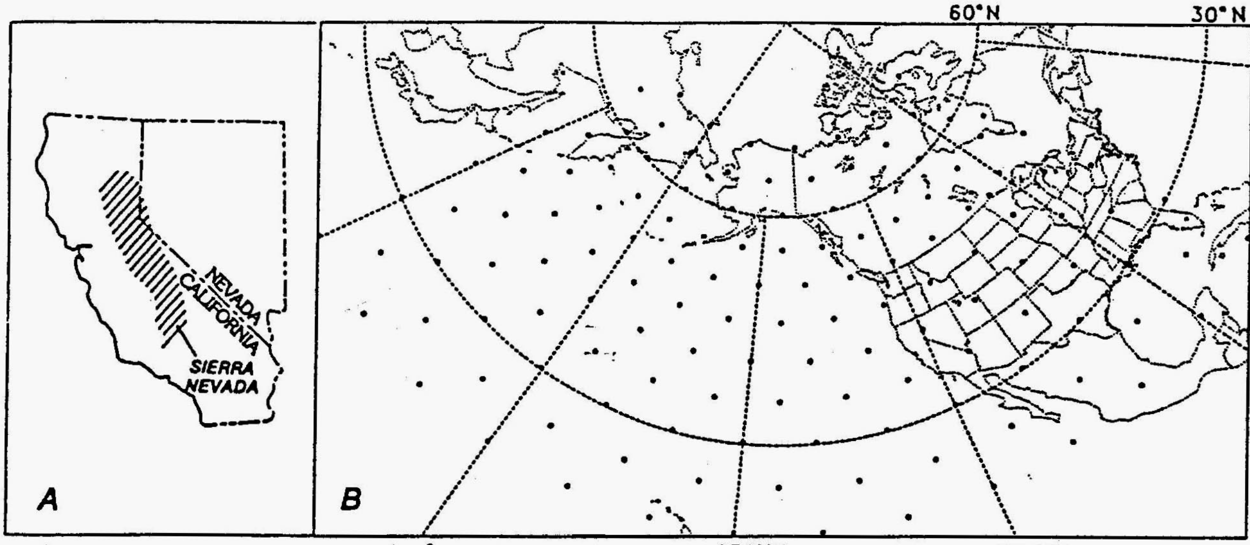

Figure 1. Location of Sierra Nevada (A) and Grid Points Used in Analysis of Atmospheric-Circulation Patterns (*B*).

models. Studies of water-resource sensitivity in other areas have used similar methods to synthesize local climatic time series (Bultot er al., 1988; McCabe and Ayers, 1989). In contrast to this approach in which attempts are made to represent climate change by uniform changes in the (mean) statistics of temperature and precipitation, the present study is an attempt to simulate climate changes from the physics and short-term variations of atmospheric circulations.

This study assesses the usefulness of Northern Hemisphere atmospheric-circulation patterns for synthesizing time series of daily temperature and precipitation in the Sierra Nevada. Most of the precipitation and snowpack in the Sierra Nevada is deposited during winter months (December, January, and February), and consequently this paper addresses that season. The method employed is based on the observed statistics of winter weather in the Sierra Nevada conditioned on the relative strengths of a few recurrent circulation patterns. Similar methods have been described recently by Bardossy and Plate (1991) and Hay et al. (1991). The synthesized series will reflect probabilities of occurrence of important circulation conditions over the North Pacific Ocean and North America. The historical sequence of these conditions is identified through a rotated-principal-components analysis. The synthesized series also will reflect the statistical distributions of temperature and precipitation in the Sierra Nevada during periods dominated by each of the circulation conditions.

IDENTIFICATION OF RECURRING CIRCULATION PATTERNS

The first step in development of a circulation-based method for synthesizing climate time series for the Sierra Nevada was a rotated-principal-components analysis of atmospheric circulations at the 70-kPa (kilopascal) level. Above the planetary boundary layer, the large-scale atmospheric flow is nearly in geostrophic balance, and thus lines of equal height to the 70-kPa pressure surface approximate closely the stream lines followed by winds at the same level. The 70-kPa-height data used were derived from twice-daily Northern Hemisphere analyses provided by the NOAA Climate Analysis Center on a 10-degree longitude by 5-degree latitude diamond grid north of 20°N for the period 1947-87. Anomalies around the mean 70-kPa heights were constructed by subtracting the long-term mean height (for the period of record) from the daily heights at each grid point. Anomalies in the region from 150°E to 80°W and 20°N to 70°N then were projected onto the nearly-equal-area grid used by Barnston and

, Livezey (1987). The total number of grid points used in the present analysis is 133 (Figure 1*B*). Finally, the twice-daily maps were averaged across consecutive but non-overlapping 3-day periods to provide a smoothed representation of circulations at time scales approaching those of individual storms.

A spatial covariance matrix was constructed from grid-point-to-grid-point covariances calculated with expectation taken over the history of 3-day mean maps for December-January-February of 1956-76. The 3-day mean maps from remaining winters of the data set were reserved for later use in verification. The basic patterns underlying all winter maps in this study are normalized eigenvectors of this matrix, which form a complete orthogonal basis set called empirical orthogonal functions (EOF's). Multiplying each map by an EOF yields a time series of the 'strengths' of that EOF; these time series are called principal-components series (PC's). Procedures for obtaining EOF's and PC's are described by Rao and Hsieh (1991). Table 1 lists the percent of 70-kPa variance captured by leading EOF-PC pairs. By the 16th EOF-PC pair, the contribution of each pair is smaller than the contribution that would be expected from purely random patterns, and no further EOF's were considered (in accordance with Guttman's [1954] lower bound). The first 15 EOF's describe 95 percent of the variance of winter 70-kPa anomalies.

TABLE 1. Percent of Variance Explained by Leading Empirical Othogonal **Function (EOF)/Principal** Component **(PC) Pairs, Prior to and Following Orthogonal Rotation.** 'nr' **indicates** 'Not **Rotated.'**

EOF/PC	Percent of Variance: Unrotated	Percent of Variance: Rotated	EOF/PC	Percent of Variance: Unrotated	Percent of Variance: Rotated
1	24.1	8.6	11	1.9	5.9
2	16.4	8.0	12	1.3	5.6
3	14.4	7.3	13	1.1	5.5
4	10.7	6.8	14	0.9	5.2
5	5.9	6.4	15	0.8	4.3
6	5.5	6.3	16	0.6	nr
7	3.6	6.2	17	0.6	nr
8	3.4	6.1	18	0.5	nr
9	2.2	6.0	19	0.4	nr
10	2.0	6.0	20	0.4	nr

One constraint imposed by the eigenproblem solution is that the EOF's are spatially uncorrelated or orthogonal and, simultaneously, the PC's are temporally independent. This constraint is somewhat artificial and can encumber the analysis so much that the resulting patterns bear little relation to actual circulation patterns. Rotation loosens the orthogonality constraints on either the EOF's or the PC's (or, in some cases, both). For our purposes, of the two constraints, temporal independence of the PC's was judged to be more useful than spatial orthogonality. Furthermore, it was desired that the resulting rotated EOF's closely resemble observed anomaly Patterns. These properties were obtained through a Varimax rotation based on the PC's (time series) rather than the EOF's (spatial pattems), in an approach similar to that used by Anderson and Gyakum (1989) and described by Richman (1986) as a T-mode analysis. The Varimax rotation maximizes the variance of the covariance of the PC's in order to maximize the number of large and small coefficients in each PC series. Because there is a limited amount of variance (overall), this maximization means that at each time only a few PC's can be large. Thus each PC must correspond to a pattern (EOF) that looks as much like actual instances of observed maps as possible. The leading 15 PC's were rotated (although similar patterns are obtained by rotating only 10 PC's). The result is a set of 15 'snapshot' patterns and the time series of their respective strengths in the historical record. Together, these 15 rotated patterns and their PC series describe the same 95 percent of variability in the original maps as did the unrotated EOF's but take forms that look more like real circulation maps. The rotated PC's (strengths) form uncorrelated time series. The rotated EOF's are normalized to unit length, and the rotated PC's vary between about -1,000 and 1,000, carrying the variance from the original data set. Hereafter, references to EOF's and PC's in this paper will refer to rotated EOF's and PC's.

The loading patterns of the first five rotated EOF's are shown in Figure 2. The rotated principal components of these patterns are directly related to the correlation of these loading patterns to the 3-day mean circulation maps. As expected with the rotation scheme used, the first few loading patterns reflect common winter circulation patterns recognized by Barnston and Livezey (1987), by Mo and Ghil (1988), by Cayan (1990), and by application of the weather-typing algorithm of Yarnal (1984) to the 3-day mean maps. When its PC's are negative, EOF 1 is dominated by the strength of the Aleutian Low (Cayan and Peterson, 1989) and the Pacific-North American pattern identified by Barneston and Livezey (1987, figs. 15 and E1). EOF 2 is a combination of the Aleutian Low and the Tropical/Northern Hemisphere pattern (Barneston and Livezey, 1987, fig. 5) EOF 3 may be a representation of their Western Pacific pattern (their fig. 4). Of particular concern in the present analysis, the negative occurrences of EOF's 4 and 5 strongly resemble patterns obtained by Cayan (1990) by averaging 70-kPa anomaly maps for particularly cool-wet and warm-wet winter days (and months), respectively, in the Sierra Nevada. Their positive occurrences are broadly similar to composite patterns that can be obtained by averaging maps for warm-dry (more similar) and cool-dry periods (less so), respectively.

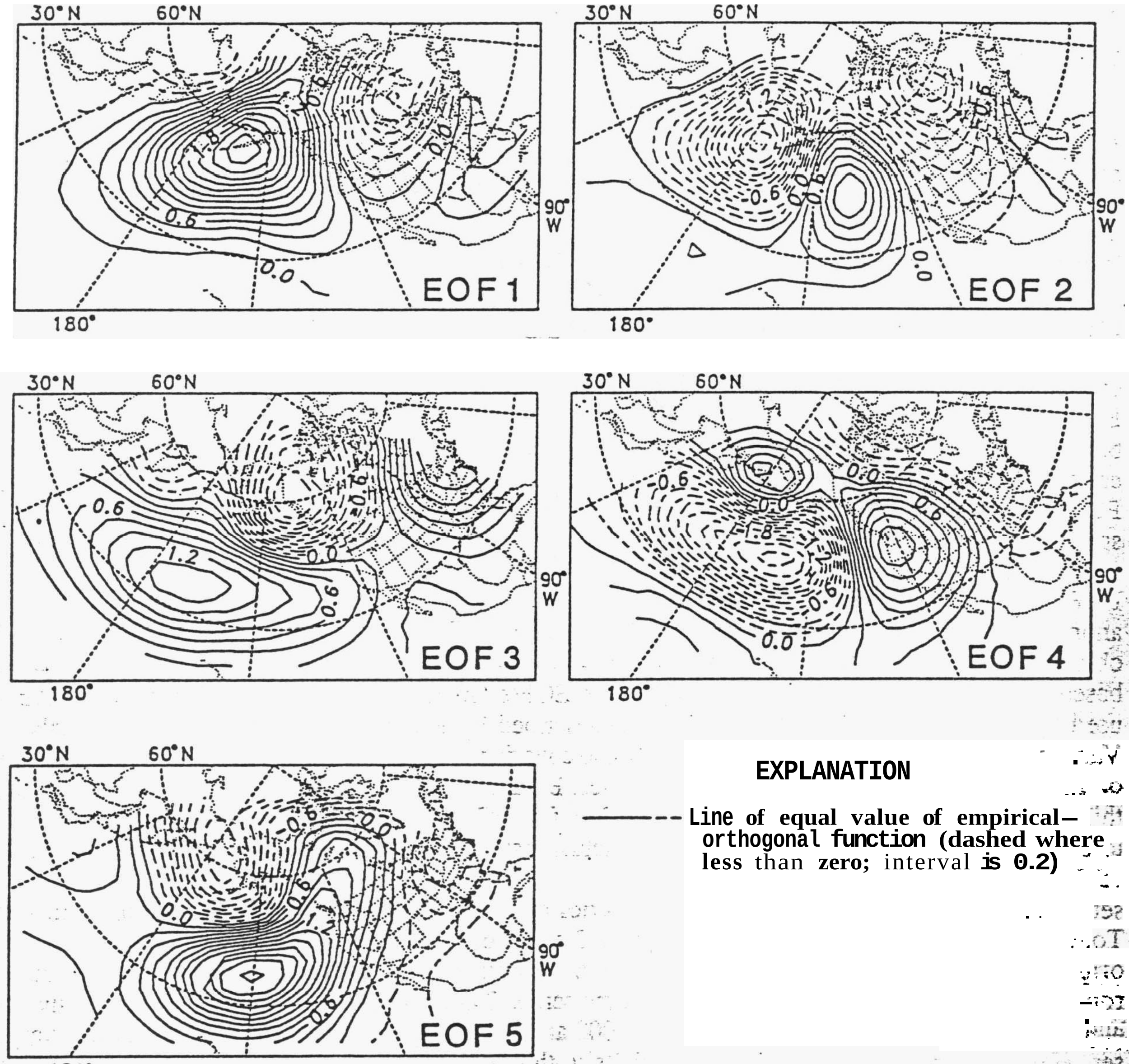

Figure 2. Leading Rotated Empirical Orthogonal Functions (EOF's) of 3-Day Means of 70-kPa Anomalies Over the North Pacific Ocean and North America During December-February, 1948-87.

CONDITIONING WINTER WEATHER TYPES BY CIRCULATION CATEGORIES

Some of the EOF's reflect circulation patterns that have predictable influences on winter weather in the Sierra Nevada. To quantify these influences, statistical distributions of each of the 15 PC series were analyzed in turn for four subsets of the winter periods during 1956-76: (1) the warmest quartile of periods during which no precipitation was recorded in the Sierra Nevada, (2) the coolest quartile of the dry periods in the Sierra Nevada, (3) wet periods that are in the wettest quartile of the warmest quartile, and (4) wet periods in the wettest quartile of the coolest quartile. The joint behavior of temperature and precipitation is an important influence on water supply because it affects the ratio of rain to snow. The subset distributions were searched for two criteria. First, patterns were sought with large PC biases (averages over the subsets that are strongly positive or negative) during two of the subsets but with little bias during the other two subsets (for example, large biases in warm-wet and cool-dry subsets). These biases indicate strong relations between the circulation patterns and extreme weather in the Sierra Nevada. Second, as an indication of a unique link to a given circulation feature, it was useful if the two biased subsets had a minimum range of overlap in their PC values.

Two patterns--EOF's 4 and 5—were found to have biases meeting the above criteria. In order to make use of these biases to quantify the association of the patterns with warm and cool, wet and dry conditions in the Sierra Nevada, each 3-day map during 1956-76 was assigned to one of five categories depending on the state of PC 4 and PC 5: whether the magnitude (strength) of PC 4 was larger than PC 5, and positive; whether the magnitude of PC 4 was smaller than PC 5, and negative; and so on. The resulting categories are:

> <u>Cool-wet circulation</u>--periods in which the PC's of EOF 4 are smaller than -125 and in which the absolute value of that PC is greater than the absolute value of the PC of EOF 5 (that is, PC 4 < -125 and $|PC\ 4| > |PC\ 5|$);
> <u>Warm-dry circulation</u>--(PC 4 $>$ 125 and $|PC\ 4| > |PC\ 5|$);
> <u>Warm-wet circulation</u>--(PC 5 $<$ -125 and $|PC\ 4| < |PC\ 5|$);
> <u>Cool-dry circulation</u>--(PC 5 $>$ 125 and $|PC\ 4| < |PC\ 5|$); and
> <u>Intermediate</u>--($|PC\ 4| <$ 125 and $|PC\ 5| <$ 125).

The intermediate category was defined arbitrarily such that all five categories have approximately the same number of members during 1956-76. Notice that this categorization of periods focuses solely on the extent of resemblance of the period's circulation map to EOF's 4 and 5. It neglects the contributions from all other EOF's to the variance of the 70-kPa anomalies over the North Pacific and North America. However, much of the 70-kPa anomaly variance over the North Pacific and North America contributes only remotely to the same day's weather in the Sierra Nevada. Thus the small fraction of 70-kPa anomaly variance need not imply that most information relevant to this study is being neglected. As a practical matter, by limiting the categorization to five broad groups, enough 3-day periods are available in each category to support fitting statistical distributions to weather conditions. As we will see, the simple categories yield a climatologically useful description of winter weather in the Sierra Nevada. The particular EOF's used were selected for their connection to weather in the Sierra Nevada region. Other combinations of EOF's probably would be better suited for other areas.

Although the circulation categories were identified by, and named in-terms of, their expected associations with conditions in the Sierra Nevada (warm-wet, and so forth), they were determined objectively on the basis of the covariance of observed circulation anomalies, not directly on the basis of observed weather in the Sierra Nevada. To quantify the effect of each circulation category on weather in the Sierra Nevada, statistical distributions for each category were fitted to describe the likelihood of precipitation, the amount of precipitation, and the mean temperatures on wet and dry days during all the 3-day periods that fell into that category. Precipitation amounts and temperatures used are weighted averages and means, respectively, for the 3-day winter periods at six sites on the western slope of the Sierra Nevada (courtesy of Lawrence Riddle, Scripps Institution of Oceanography, La Jolla, CA). The weighting scheme is described in Riddle *et al.* (1991). The resulting distributions associated with the five circulation categories are shown in Table 2.

TABLE 2. Statistical Distributions Fitted to Observed Precipitation and Mean Temperature During 3-Day Winter Periods in the Sierra Nevada, by Circulation Category, December-February, for the Periods 1948-55 (Zonal-Winds Verification Period), 1956-76 (Calibration Period), and 1977-87 (Meridional-Winds Verification Period).

[Dry weather indicates 3-day periods with no reported precipitation; wet weather. 3day periods with any reported precipitation. Distributions: G(a,b:c), gamma probability distribution with shape parameter a, scale parameter b, and mean of c; N(d,e), normal distribution with mean d and standard deviation 3. Precipitation values given in mm per day and temperature in °C]

Circulation Category	Period	Number of Occurrences	Percent Wet Weather	Distributions: Wet Weather, Precipitation	Distributions: Wet Weather, Temperature	Distributions: Dry Weather, Temperature
Cool-wet	1948-55	85	78	G(0.8,15.5:12)	N(-.5,3.0)	N(3.8,4.0)
	1956-76	144	77	G(1.0,13.4:13)	N(0.5,2.8)	N(3.0,3.6)
	1977-87	41	76	G(0.7,19.0:14)	N(0.8,2.5)	N(2.1,2.7)
Warm-dry	1948-55	22	46	G(1.2, 8.6:10)	N(3.4,2.5)	N(5.8,4.1)
	1956-76	137	39	G(0.9,13.3:11)	N(3.2,2.7)	N(5.8,2.9)
	1977-87	83	40	G(0.8,11.6: 8)	N(4.0,2.3)	N(6.9,2.8)
Warm-wet	1948-55	49	86	G(1.3,16.0:21)	N(2.5,3.7)	N(5.6,2.1)
	1956-76	99	79	G(0.8,24.7:20)	N(2.5,3.5)	N(4.4,4.2)
	1977-87	79	76	G(0.7,27.9:20)	N(3.4,2.4)	N(4.6,4.1)
Cool-dry	1948-55	49	51	G(0.7, 7.7: 5)	N(2.1,3.5)	N(3.4,3.9)
	1956-76	123	52	G(0.8, 6.8: 5)	N(1.8,2.6)	N(5.5,3.3)
	1977-87	45	59	G(0.8,11.2: 9)	N(1.9,3.2)	N(4.6,3.3)
Intermediate	1948-55	43	63	G(0.9, 9.8: 9)	N(2.0,2.8)	N(5.0,2.9)
	1956-76	130	61	G(0.7,17.0:12)	N(2.5,2.8)	N(4.8,3.4)
	1977-87	73	67	G(0.8,18.3:14)	N(2.5,2.9)	N(4.8,3.0)
Overall	1948-55	242	70	G(0.8,16.6:13)	N(1.3,3.5)	N(4.5,3.7)
	1956-76	633	60	G(0.7,17.5:13)	N(1.9.3.1)	N(4.9,3.4)
	1977-87	311	61	G(0.7,22.9:15)	N(2.7,2.8)	N(5.4,3.4)

Temperatures in each category were well represented by normal distributions, whereas precipitation rates were well represented by gamma distributions. Goodness-of-fit was judged by the probability-plot correlation coefficients using the method of Vogel and McMartin (1991); in addition, none of the distributions could be rejected using Kolgomorov-Smirnov tests at the 95-percent level. The likelihood of precipitation was represented by simple Bernouli trials. Estimated likelihoods—not amounts—of precipitation in each category (except intermediate) were more than 2 standard deviations of the likelihood estimate from the likelihood that would be estimated without considering circulation categories (listed as "overall" in Table 2), using the expected error in estimating the Bernoulli probability of success from a finite sample (Benjamin and Cornell, 1970, p. 384).

To determine whether the distributions obtained can be used in other time periods, PC's for all 3-day periods during winters for the periods 1948-55 and 1977-86 were computed using the rotated EOF's from the 1956-76 period. Each 3-day period was categorized and statistical distributions of precipitation and temperature were fitted for each category in these periods. The periods were chosen in part because of marked differences between their mean atmospheric circulations. During 1948-55 there was a much shallower Aleutian Low (positive 70-kPa anomalies) than in 1956-76 and thus winds were more zonal, whereas in 1977-87 there was a much deeper Aleutian Low (negative 70-kPa anomalies) with more meridional winds. The distributions for the three groups of winters are shown in Table 2. The 1956-76 precipitation distributions cannot be rejected for any of the 1948-55 and 1977-87 categories, and only three of the temperature distributions can be rejected on the basis of Kolgomorov-Smirnov tests at 95-percent levels (and only one at the 99-percent level). The categorizations thus obtained seem to be reflected consistently (on average) in the presentday Sierra Nevada winter weather, regardless of which period is considered.

Given the chronology of prevailing circulation categories in each 3day period, any number of alternate climate scenarios *can* be synthesized using the distributions shown in Table 2. Each scenario would be composed of precipitation and temperature values drawn at random from the distributions appropriate to the prevailing category during each 3day period. If **all** the distributions (as well **as** the circulation chronologies) correspond to current conditions, each scenario would constitute a different realization of the same (current) climate. The required weather distributions can be estimated from local historical records, **as** was done to obtain Table 2. The chronology of time spent in each circulation category might be obtained by (a) using the observed chronology of circulation categories from 1948 to present (repeating it, if necessary), (b) synthesizing alternate circulation chronologies using a simple Markov transition model, or (c) employing a general-circulation model to determine a history of the circulation categories used herein. Approach (c) is beyond the **scope** of this paper, but approach (b), which is readily implemented, *can* provide multiple circulation chronologies in contrast to approach (a). Table **3** lists the observed frequency of transition between each pair of categories during 1948-87. Corresponding transition statistics were computed (but not shown here) for a subset of the record consisting of transitions that immediately follow two adjacent periods spent in a single category--that is, transitions following self-transitions. The probabilities for this subset are quite similar to those shown in Table **3** (all are well within **2** standard deviations), which suggests that the first-order **Markov** transition model described by Table **3** is adequate for the syntheses that follow.

The probabilities in Table **3** imply **a** moderate tendency for each of the circulation categories to persist. The wet categories persist longest; about one-half of the time **a** wet category is followed by another period in the same category. The intermediate category is least persistent; consecutive periods in the intermediate category occur only about one-third of the time. Sudden transitions **from** strong-negative to strong-positive PC values are uncommon: that is, transitions from CW to WD (and vice versa) and from WW to CD (and vice versa) **are** uncommon. **Presumably,** a version **of** Table **3** for climate-model results could **be** developed from simulated daily pressure levels if the same five circulation categories are present in the model.

TABLE 3. Transition Probabilities Among Circulation Categories.

[All **probabilities** in **percent. Categories: CW, cool-wet; WD,** **warm-dry; WW, warm-wet; CD. cool-dry; I, intermediate.** Total **number is overall number of transitions from** this **category]**

From Category:	Into Category: CW	WD	WW	CD	I	Total Number
CW	48	9	15	11	17	*224*
WD	5	42	12	18	22	203
WW	14	19	48	*4*	15	260
CD	22	15	3	42	18	212
I	20	17	IS	17	31	232

Given the previously listed approaches **to** synthesizing near-daily weather series based on circulation categories, climate-change **scenarios** *can* **be** synthesized by (1) changing the transition series or **(2)** changing the probability distributions for precipitation and temperature that are associated with the, **various** circulation categories or **(3)** changing **both. For** example, scenarios could be developed by changing the Markov transition probabilities in Table **3,** by changing the specified conditions in a climate simulation, or by repeating some interesting subset of the historical record of transitions. Other scenarios might **be** developed by changing the likelihood or **mean** amount of precipitation during each of the circulation categories, or increasing **mean** temperatures during some or **all** the categories. These kinds of changes could be purely hypothetical **(as** in **a** sensitivity analysis), could be designed according to broad physical considerations, or could reflect tendencies in climate-model simulations or historical-geological records.

A historical time **series** of precipitation *(A)* and three synthetic series *(B-D)* **are** compared in Table **4** and segments of the **series are** illustrated in Figure **3.** Series *A* (Table 4) is the historical record for winters during 1948-87. Series B) is a synthesis **of** temperatures **and** precipitation **constructed** using

TABLE 4. Precipitation and Temperature Statistics for Four Series of Sierra Winter Weather: (*A*) the Historical Record. December-February 1948-87, (B) a Synthetic Series Using Current Conditions Based on the Statistics from the Historical Record, (*C*) a Synthetic Series in which the Probability of Warm-Wet Circulation Categories is Increased by About 20 Percent—Mostly at the Expense of Warm-Dry and Cool-Dry Categories, and (*D*) a Synthetic Series in which Weather Distributions for 3-Day Periods Spent in Cool-Wet and Warm-Wet Categories Have Increased Likelihood of Precipitation by 15 Percent, Increased Mean-Precipitation Amounts by 12 Percent. and Increased Temperatures by 2°C. Statistics for Synthetic Series are Based on 3-Day Mean Values for 350 Synthetic Winters each.

[Series: See title for explanation; letters correspond to series shown in Figure 3. Precipitation: Likelihood. percent of time when precipitation occurs; mean and standard deviation for all days (wet and dry) in mm per day. Temperature: Mean and standard deviation for all days, in °C]

Series	Precipitation			Temperature	
	Likelihood	Mean	Standard Deviation	Mean	Standard Deviation
(A) Historical	63	8.3	13.8	3.1	3.6
(B) Synthetic—current conditions	62	8.3	14.1	3.1	3.6
(*C*) Synthetic—WW more common	67	10.8	17.2	3.2	3.6
(D) Synthetic—warmer, wetter WW and CW	69	11.1	17.3	3.7	3.4

current category-transition probabilities and associated weather distributions, but constructed from random, new realizations of both circulation chronology and resulting weather. Series *C* and D are two climatechange syntheses constructed using approaches 1 and 2 in the preceding paragraph: synthesis *C* with modified transition probabilities but with precipitation and temperature distributions unchanged from current conditions, and synthesis D with modified temperature and precipitation distributions but transition probabilities unchanged from current conditions.

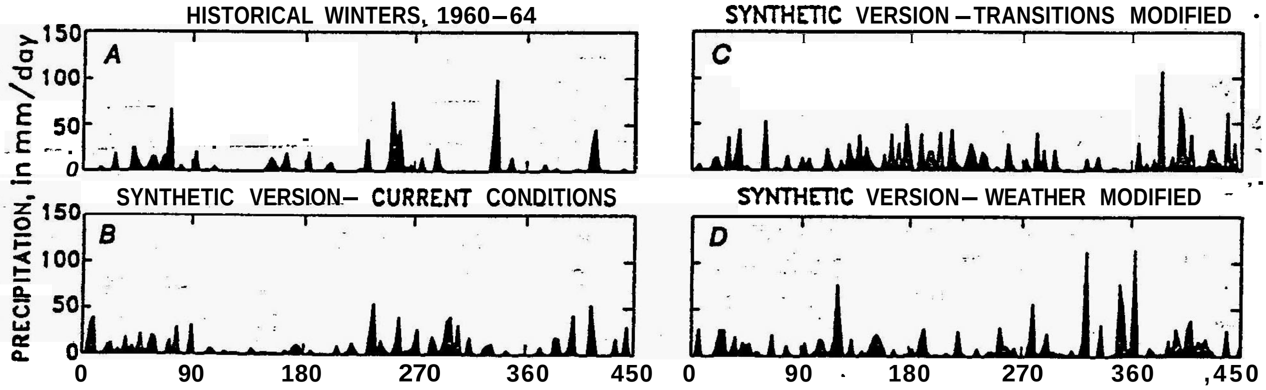

Figure 3. Five-Winter Segments of Historical and Synthetic Precipitation Series (described in text and in Table 4).

The current-conditions synthesis (B) compares well with the historical record (A). In synthesis C, transition probabilities were modified to make warm-wet circulations about 20 percent more common. The result was a relatively large increase in total precipitation—130 percent on average—but little change in temperature. The change in mean temperatures is small mostly because more frequent precipitation leads to cooler temperatures (compare wet and dry temperatures in Table 2), regardless of circulation category. Synthesis C results in more frequent occurrences of moderate precipitation than observed in the historical series because the precipitation amounts have not been directly altered but the likelihood of wet categories has been increased. Thus the series in Figure 3C appears to have less-frequent dry spells. In synthesis D, the precipitation and temperature distributions for the wet categories were changed to make them warmer and wetter (see Table 4 explanation), which yielded precipitation statistics that are similar to synthesis *C* and a precipitation series that **looks** like a scaled version of the historical record (compare Figure 3A and 3D). The synthetic wet and dry spells are about as common as in the historical series but, in this case, the wet days are more frequently very wet. In synthesis *D*, temperatures increased more-or-less directly in response to changes in the weather distributions for the wet categories (Table 4). As a practical matter, however, the specified changes must be large to make a significant difference in overall climate statistics because changes to a single category and its attendant weather distributions are muted by the time spent in other categories. For example, mean temperatures for the wet categories were increased by 2°C in order to achieve the overall mean increase of 0.6°C. Thus, as in the real world, a change to one part of the climate specification in these syntheses leads to less predictable changes in other characteristics of the series.

CONCLUSIONS

Rotated EOF's of 3day mean 70-kPa-height anomalies over North America and the North Pacific Ocean identify two modes that capture important aspects of variability in Sierra Nevada winter precipitation and temperature. The Sierra Nevada temperature and precipitation distributions of the positive and negative extremes of these modes separate into four fairly distinct categories: warm-wet, cool-dry, cool-wet, and warm-dry. Under thresholds imposed here to define these extremes, each 3-day mean map can be described either by one of these categories or else as a member of a fifth intermediate category in which none of the modes is strong. During the intermediate periods, other modes not pursued in this study may be strong. Transitions between the categories approximate simple Markov processes, and the statistical distributions of precipitation and temperature in the Sierra Nevada depend on which category prevails in a given 3-day period. Temperature is further conditioned by whether or not precipitation occurs.

Given observed probabilities of transitions between circulation categories and the observed distributions of precipitation and temperature for days in each category, climate scenarios can be synthesized by: (1) selecting a new, random realization of each day's precipitation and temperature from statistical distributions that are conditioned on the circulation category that prevailed on the day in the historical record or, alternatively, (2) generating a new sequence of circulation categories based on the Markov transition probabilities and then returning to the first approach using the generated sequence in place of the historical sequence. Given the dominating influence of these broad atmospheric circulation patterns on local surface weather, other properties might likewise be synthesized, such as rain-snow contrasts, humidity, and local wind. Climate-change scenarios can be obtained by first modifying the category-transition probabilities or the distributions of precipitation and temperature for each circulation category and then applying one of the synthesis approaches above. Examples were synthesized that demonstrate the sensitivity of the resulting climate to the way in which climate changes are specified. This method may be useful in translating numerical-model results (which may achieve realistic large-scale circulation patterns but lack proper surface characteristics in regions of severe terrain such as the Sierra Nevada). Conversely, general-circulation models run under changed-climate forcing may be useful in testing whether the particular circulation patterns identified herein still are present.

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