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Potential Regional Impacts of Global Warming on Precipitation in the Western United States

United States Department of the Interior, Bureau of Reclamation

GLOBAL CLIMATE CHANGE RESPONSE PROGRAM

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Monthly mean precipitation values for areas in western Montana, northern Utah, and east central Arizona were compared with median values for the 1946-89 period to determine if any significant differences existed.

The results suggest that one regional impact of global warming may be a substantial reduction in wintertime precipitation in central and southern intermountain areas such as Utah and Arizona. The study also found the situation in western Montana to be unclear. Finally, a few examples are presented to highlight some of the strengths and weaknesses of the analogue approach, and several questions regarding other potential effects of global warming on winter precipitation are addressed.

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GLOBAL CLIMATE CHANGE RESPONSE PROGRAM

POTENTIAL REGIONAL IMPACTS OF GLOBAL WARMING ON PRECIPITATION IN THE WESTERN UNITED STATES

Verne Leverson

January 1997

UNITED STATES DEPARTMENT OF THE INTERIOR
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ABSTRACT

Snow and melting of the mountain snowpack provides the principal supply of water to much of the Western United States. Whether the perceived threat of global warming carries the potential for serious impacts on this water supply is the focus of this research. This study was designed to build upon a previous Global Climate Change Response Program investigation in which an initial "first guess" climate change scenario was derived for the Western United States. Using the scenario's hypothesized northward shift in the mean wintertime storm track, historical upper-air patterns in the atmosphere were searched to identify winter months (December, January, or February) that would serve as appropriate global warming analogues (GWA). Contour charts were generated of four geopotential height parameters using 500 millibar (mb) constant pressure surface data for a domain covering the eastern North Pacific Ocean and Western North America: mean monthly 500 mb heights, 500 mb height standard deviations, standard deviation anomalies, and 500 mb height departures from normal. Specific pattern configurations of the four parameters were identified that reflected the altered storm track pattern, and guidelines for selecting suitable analogues based on the configurations were developed. Out of 131 total winter months (from 1946-89), 35 were selected as analogues.

Monthly mean precipitation values for the GWA months at three climatological divisions in Western Montana, northern Utah, and east central Arizona were compared with median values for the 1946-89 period to determine if any significant differences existed. In Montana, there was nearly an even split in the number of GWA months with above and below median precipitation. Utah and Arizona were heavily weighted towards drier conditions, with 28 and 26 months, respectively, out of 35 showing below median precipitation. In Utah, median precipitation for the GWA months varied from 60-75 percent of the 1946-89 median values. In Arizona the GWA months' median precipitation ranged from about 25-50 percent of normal values. The average (median) deviations of GWA monthly precipitation from 1946-89 median values varied from -0.23 (0) to 0.14 (-0.14) inches in Montana, from -0.70 (-0.74) to -0.33 (-0.42) inches in Utah, and from -1.02 (-1.35) to -0.47 (-0.68) inches in Arizona.

These results suggest that one regional impact of global warming may be a substantial reduction in wintertime precipitation in central and southern intermountain areas such as Utah and Arizona. The study also found the situation in Western Montana to be unclear. Finally, a few examples are presented to highlight some of the strengths and weaknesses of the analogue approach, and several questions regarding other potential effects of global warming on winter precipitation are addressed.

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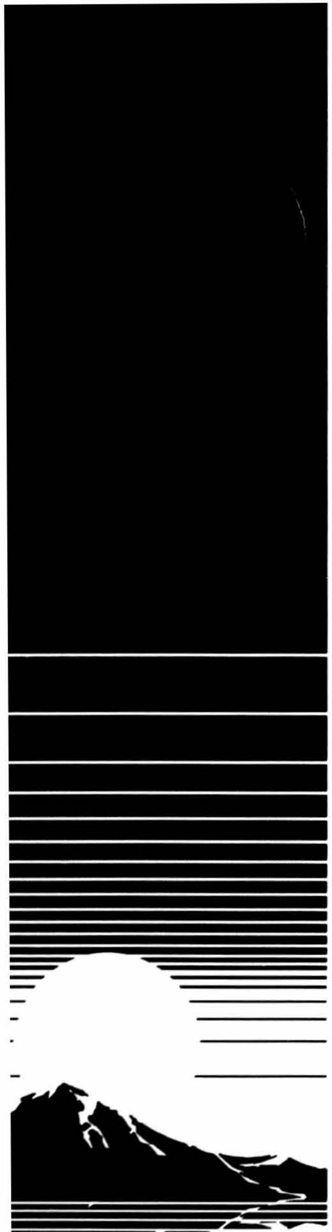

CONTENTS

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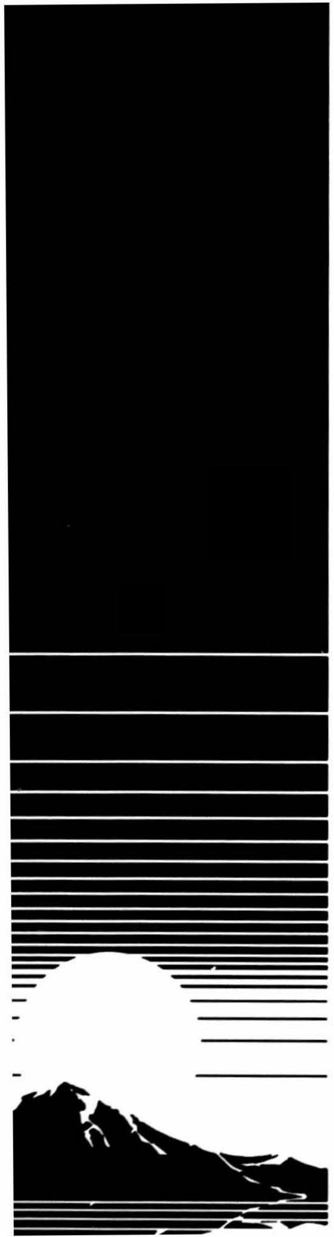
CONTENTS

Potential Regional Impacts of Global Warming on Precipitation in the Western United States

Tables

CONTENTS - continued

Figures

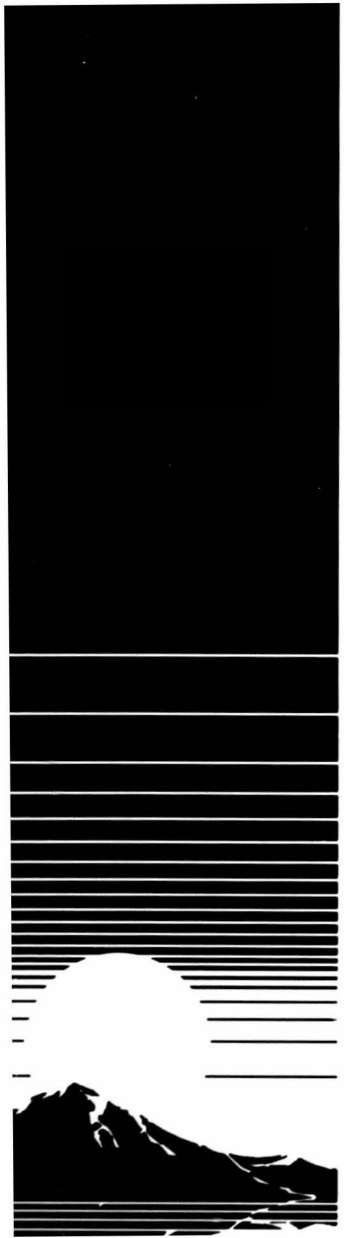


INTRODUCTION

INTRODUCTION

The Global Climate Change Response Program (GCCRP) of the Bureau of Reclamation (Reclamation) was an endeavor directed at identifying specific areas in the field of water resources that could be impacted by global climate change. The overall program encompassed three general areas of interest and concern to Reclamation—water supply, water demand, and water management. This particular study dealt with the fundamental question of the quantity of the water supply by focusing on the potential effects of a possible climate change on precipitation in the Western United States.

The original concern over anthropogenic climate change arose from theoretical arguments that suggested a significant increase of the average surface air temperature of the earth due to increases in the concentrations of "greenhouse" gases in the atmosphere. Evidence of increasing greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), and chloroflourocarbons, is well documented by worldwide observations. General circulation models (GCM) of the earth's atmosphere have used these data along with future projections of greenhouse gas concentrations to numerically simulate the potential effects of such increases on the earth's climate. Other investigators have conducted empirical studies of possible climate change by searching for analogues of warmer climates in the instrumental and proxy records and in paleoclimate evidence. Using all these sources of information, researchers have developed climate change scenarios. A climate change scenario can be simply defined as a description of the weather or climate conditions that would exist if a particular change of climate occurred. Such scenarios have been applied across many different disciplines in attempts to anticipate possible future effects of climate change.



BACKGROUND

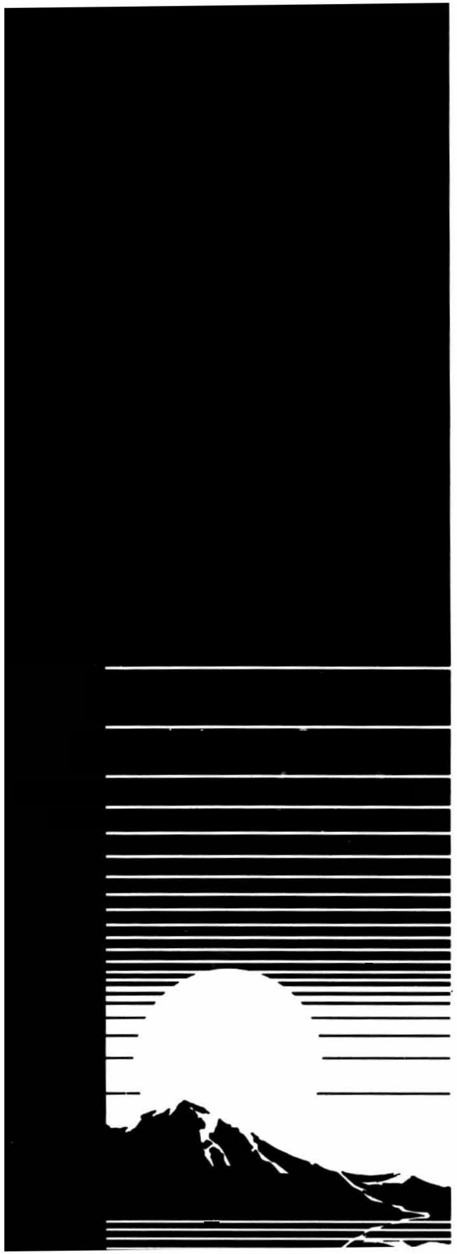
BACKGROUND

One of the early GCCRP studies was reported on by Dennis (1991). In his study, Dennis derived an initial estimate of a climate change scenario for the Western United States. His scenario was meant to satisfy conditions of global warming due to a doubling of the atmospheric CO_2. He stated that the warming would be concentrated at the higher latitudes around the globe. The resulting differential warming of polar and tropical air masses would reduce the present equator to pole temperature gradient, and the reduced latitudinal temperature gradient would weaken the midlatitude westerly winds and polar jet stream that derive their kinetic energy from the thermal contrast between air masses. Being closely associated with the midlatitude westerlies, extratropical cyclones would also be less intense and slower moving on average. Dennis also said that the subtropical high pressure areas would shift poleward about 1 degree (°) to 2° of latitude, and other "weather belts" would correspondingly shift poleward about 2°. Based upon the output of some GCMs, he also suggested that the location of semipermanent atmospheric circulation features could possibly change in the longitudinal direction. For example, the wintertime position of the Aleutian low-pressure system would be found more frequently in the Gulf of Alaska, east of its present average location.

The work summarized in this report was proposed and designed to complement and expand certain aspects of the Dennis climate change scenario study. This study adopted the same definition of climate change as used by Dennis—an increase in the average surface temperature of the earth. Our goal was to strengthen current understanding of potential impacts of global warming on the present wintertime precipitation climate of the Western United States. Since the winter season is so important in establishing the coming year's water supply through the build up of the mountain snowpack, any long-term change to the causative atmospheric processes could obviously have potent consequences.

Historical instrumental records were searched for periods of time during the winter when the atmospheric upper air circulation pattern would serve as a suitable analogue for the Dennis climate change scenario pattern. Many investigations of the relationship between upper air circulation patterns and surface temperature and precipitation anomalies over North America have been carried out over the years (e.g., Diaz and Namias 1983 and Weare and Hoeschele 1983). This work was somewhat different in that specific configurations of the atmospheric circulation were identified and classified as global warming analogues for further study.

Precipitation data for the identified analogue periods were assembled for regional areas in Montana, Utah, and Arizona and compared with the long-term climatological values to determine if significant deviations were evident. While some subjectivity was inevitable in the selection of the appropriate analogue periods, the technique was considered reliable to the extent that there is cause and effect consistency between the atmospheric circulation regime and the resulting surface precipitation.



PROCEDURE

PROCEDURE

Upper Air Patterns

In Dennis's 1991 report, a chart was given showing mean winter storm tracks over North America. The chart was derived from a report by Zishka and Smith (1980) in which figures of the mean tracks and frequencies of January surface cyclones were presented. Their climatology was based on the 1950-77 period. Dennis added an altered storm track that he hypothesized would occur under changed climate conditions (figure 1). His discussion and the caption on the figure indicated that the suggested changes applied to the entire winter season, not just January.

Figure 1 contains the essential information that was used in the analogue search. The storm tracks in the figure represent the average path of low-pressure cyclones or depressions at the earth's surface. To be counted in Zishka and Smith's climatology, the surface cyclones had to have at least one closed contour on a 4 millibar (mb) increment isobaric analysis that persisted for a minimum of 24 hours.

The approach taken in this study was to complement the Zishka and Smith surface storm track climatology with a storm track climatology for a higher level in the atmosphere. Meteorological observations and analyses are routinely made at various points extending up through the atmosphere. One reference location is known as the 500 mb constant pressure surface and is found at roughly 5500 meters above sea level. At this level, airflow is free of the frictional effects of the earth's surface, and the wind blows essentially parallel to the contours that indicate the (geopotential) height of the 500 mb surface above sea level. Lower height (lower pressure) is located to the left of the wind vectors, and greater height (higher pressure) exists to the right.

The upper air height contours generally exhibit wave-like patterns made up of low-pressure troughs and high-pressure ridges. Cloud cover and precipitation is associated with the low-pressure troughs, while fair weather occurs around the high-pressure ridges. Since storm systems are very three-dimensional, there is a strong spatial correlation between the troughs at the 500 mb level and cyclones at the earth's surface. The idealized model of a midlatitude storm system has a configuration in which the center of the surface cyclone is several degrees of latitude downstream from the 500 mb trough line and is slightly poleward of the maximum upper level wind belt (jet stream). However, depending on the state of the storm's development, substantial variations of

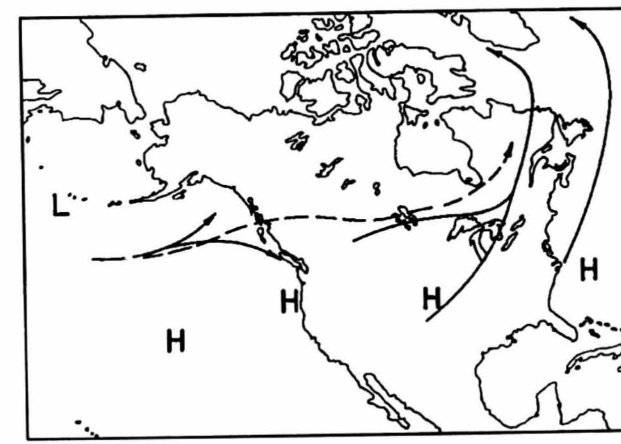


Figure 1.—Winter weather features over North America. Solid lines denote mean surface storm tracks for 1950-77. Dashed line shows hypothetical winter storm track under changed climate conditions. Sting of H's indicates contemporary axis of the subtropical high pressure belt. Prevailing average location of the Aleutian Low is shown by L. (From Dennis, 1991).

this basic configuration usually occur. This means that while storm tracks at the 500 mb level do not perfectly mirror surface cyclone tracks, there is still a strong relationship between them.

Further complicating the relationship between the figure 1 surface storm tracks and upper air height patterns is the fact that winter storms moving in over Western North America from the eastern North Pacific Ocean are often mature systems (occlusions), with long, trailing occluded or cold frontal troughs extending southward from the cyclone's center. In Zishka and Smith's report and in figure 1, only the tracks of the cyclone centers are depicted, yet the frontal systems often produce significant precipitation far south of the cyclone. Even more important for the intermountain West is the fact that weather disturbances frequently move over the area as low-pressure troughs or waves discernible in the upper air height/wind fields while the concurrent sea level pressure patterns have weak, open frontal troughs, or show little, if any, indication of the disturbance at all. By definition, many of these disturbances have been excluded from both Zishka and Smith's storm track climatology and figure 1. Yet, they have a significant impact in the form of orographically enhanced precipitation. Zishka and Smith's constraint that the surface lows remained closed for at least 24 hours on the weather charts used in their analysis further reduced the perceived frequency of surface cyclones and the tracks of weather disturbances in general.

It is generally accepted that upper air patterns, such as those of the 500 mb constant pressure surface, serve as more functional indicators of weather disturbance activity over the intermountain West. Consequently, our search for analogues of Dennis's climate change scenario employed four tools derived from 500 mb height data. The four tools used the following computed parameters:

Parameter 1. 500 mb mean monthly values of the geopotential height

Parameter 2. The standard deviation (root mean square deviation) of monthly geopotential height values

Parameter 3. Standard deviation anomalies (departure of the standard deviation values from climatological values)

Parameter 4. The departure of the mean monthly geopotential height from climatological values

Contour analyses of these parameters were plotted on maps covering Western North America and the eastern North Pacific Ocean from 90°-150° W. longitude and from 25°-60° N. latitude. Maps were constructed for every December from 1946-88 and for every January and February from 1946-89.

Mean monthly geopotential height patterns, parameter 1, indicate where low-pressure troughs and high-pressure ridges prevail during a month. Since the standard deviation is a measure of the scatter of individual data points around their mean, parameter 2, the height standard deviation, provides an indication of the variability of 500 mb heights during a month. In general, areas of high (low) standard deviation are evidence of increased (decreased) shortwave activity. To better depict the regions of above and below normal storm activity, standard deviation anomaly charts, parameter 3, were produced by differencing the monthly standard deviation field from the monthly climatological standard deviation field. Monthly height departures, parameter 4, show if the 500 mb troughs and ridges were stronger or weaker than normal or if they deviated from their normal position. Positive height departures (above normal atmospheric pressure) indicate general lack of storminess, while negative departures (below normal atmospheric pressure) signify increased storm activity.

The 1946-88 and 1946-89 periods of record were used as the climatological means for December and January/February, respectively. The mean 500 mb height patterns for the three winter months are shown for the study domain in figure 2. Monthly climatological means of the 500 mb height standard deviation are also displayed in figure 2.

All 500 mb parameters calculated in this study originated from upper air observations made twice daily at stations throughout the Northern Hemisphere during the period of record. The observations were converted to a 2377 point grid covering the Northern Hemisphere by the National Meteorological Center (NMC) (University of Washington 1990). In this study, the NMC gridded fields were interpolated to a 2.5° longitude by 2.5° latitude grid. Contouring and plotting routines that weigh the nearest 4 grid point values by a 1/distance^2 weighing were used to produce the final patterns of 500 mb height, height standard deviation, standard deviation anomaly, and height departure from normal fields. A total of over 500 charts were produced for analysis.

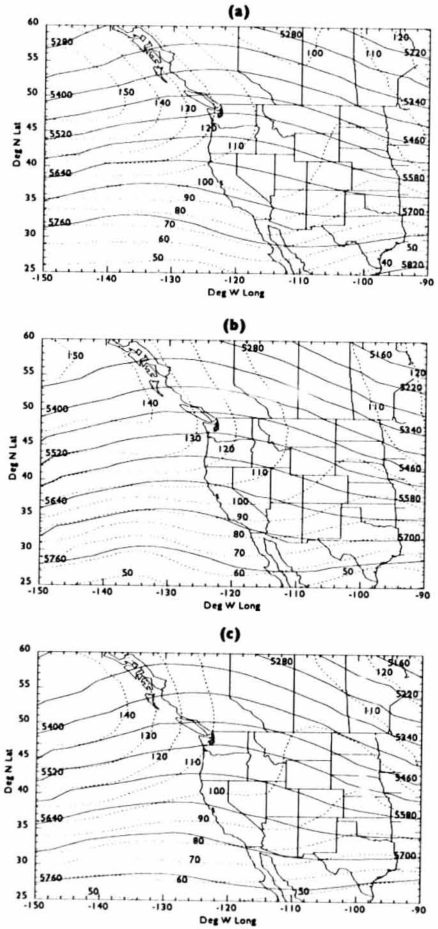


Figure 2.—Mean 500 mb geopotential height patterns (solid contours) and height standard deviation (dashed contours) in meters for (a) December (1946-88), (b) January (1946-89), and (c) February (1946-89).

Selection of Analogues

Examination of the monthly 500 mb patterns keyed on identifying specific upper air features that would serve as reflections of the Dennis global warming storm track pattern. First of all, a necessary prerequisite was the occurrence of above normal 500 mb heights (positive departures) over most of the Western United States and Canada. It was considered permissible for small portions of the region to be slightly below normal (negative departures), but the majority of the area had to have above normal heights in keeping with the amplified ridging necessary for a northward shifted storm track over Western North America. Secondly, while not taken as a stringent requirement, the occurrence of below normal heights in the vicinity of the Gulf of Alaska (near 50-60° N. latitude and 150° W. longitude) would satisfy the Dennis premise of the Aleutian low being found more frequently east of its normal wintertime position. Thirdly, the 500 mb height standard deviation and standard deviation anomaly fields served as a useful guide in identifying the monthly mean upper air storm track and its relative strength. Experience shows that over Western North America the tracks of surface lows generally occur northward (poleward) of the maximum upper level wind band (storm track) by several degrees of latitude. So, it was believed that conditions of the Dennis scenario would best be met by standard deviation maxima located along or north of the United States-Canadian border.

From the outset, it was believed that none of the monthly 500 mb parameters would be entirely adequate as a stand alone index of the monthly storm track. For example, it was believed that height departures and standard deviation values are well correlated. That is, in areas of negative height departures, standard deviation values are higher because of the increased frequency of weather disturbances. Conversely, standard deviation values are lower in the vicinity of positive height departures where high-pressure ridging and general lack of storminess occur.

High standard deviations indicate considerable variability of 500 mb heights during the month, but in the vicinity of a 500 mb low that persisted for much of the month, storm activity would be frequent. Standard deviation values there might be relatively low because of height values being continuously low and unvarying. Similarly, monthly mean standard deviations could be relatively high in regions of positive height departures, a feature that can be seen in the monthly climatological charts (figure 2). This is a reflection of the fact that the normal winter storm track extends from the Gulf of Alaska inland over the Pacific Northwest while the preferred climatological position of an upper air ridge in the Northern Hemisphere's general circulation exists concurrently over Western North America.

Height standard deviations can also be influenced by the frequency of large height variations. A region that experiences one large storm (relatively large height variation) during the month can exhibit standard deviation values greater than another area that has experienced more frequent, but weaker, short waves. To compensate for this complication, sophisticated techniques have been developed that filter weather disturbances in time and space (e.g., Blackmon 1976). Such procedures were considered beyond the scope of this study and not applied.

By examining and comparing all the monthly information, quasi objective decisions were made regarding the suitability of circulation features as global warming analogues. Additional publications, such as 5-day mean upper air patterns (World Meteorological Organization 1983) and monthly weather and circulation summaries in the *Monthly Weather Review*, provided supporting information regarding storm track and weather pattern evolution during a month. When available, monthly charts of surface cyclone tracks were also examined as additional information.

Based on these guidelines, the monthly mean charts of 500 mb parameters for the 131 winter months from 1946-89 were searched for adequate global warming analogues. The 35 months considered to best represent the requisite pattern characteristics are listed in table 1.

Table 1.—Months chosen as analogues for the global warming scenario

December	January	February
1946	1946	1947
1950	1948	1950
1953	1953	1954
1954	1958	1961
1956	1961	1963
1957	1976	1964
1958	1986	1967
1960	1987	1968
1962		1970
1963		1977
1975		1984
1976		1988
1979		
1980		
1986		

PRECIPITATION ANALYSIS

PRECIPITATION ANALYSIS

To assess the potential effects of the global warming scenario on precipitation in the intermountain West, specific areas in Montana, Utah, and Arizona were chosen for study. The three areas selected are from the State climatological divisions established by the National Oceanic and Atmospheric Administration (NOAA). Climatological divisions are meant to represent as nearly as possible regions of climate homogeneity within each State and were established to provide an intermediate level of climate definition between an entire State and an individual station. Figure 3 shows the climatological divisions for Montana, Utah, and Arizona.

In Montana, division 1 was selected. It comprises that portion of the State west of the Continental Divide. In Utah, division 5, comprising the northern mountains, including the bulk of the Wasatch Range and Uinta Mountains, was chosen. In Arizona, division 4, the east central portion of this State, was selected as the study area. The three divisions represent a full latitudinal distribution across the intermountain West where winter precipitation in the form of snow is an important source of available water year round. It should be noted that while these areas are small compared with the spatial scale of climate, extremes in the temperature and precipitation climates exist within each division because of the elevation effects of topography.

National Oceanic and Atmospheric Administration computes the mean precipitation each month for each division using station groups considered representative of the division's aggregate climate (NOAA 1946-89). This divisional precipitation data set was used in this study. The analysis procedure examined divisional precipitation for each winter month (December, January, and February) of the analogue data set (table 1) to determine any differences from the division's total precipitation data set for the respective month. The differences were defined as deviations from some measure of central tendency of the division's total data set.

More specifically, divisional monthly mean precipitation values were assembled for each December for the 1946-88 period and for every January and February for 1946-89. The mean, median, standard deviation, and related statistics were computed for each division's monthly series. Figures 4-6 show Montana's division 1, Utah's division 5, and Arizona's division 4 precipitation time series for December, January, and February, respectively. Median values are also shown. The median value was used as the measure of central tendency of the monthly precipitation data

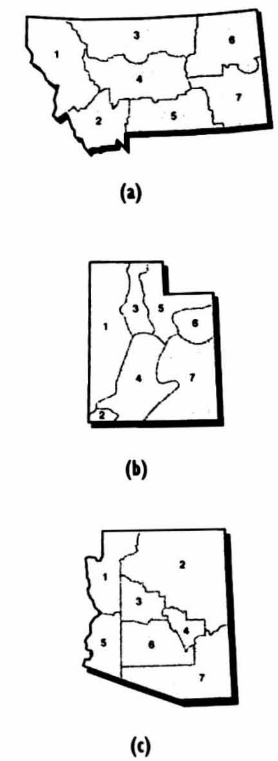


Figure 3.—NOAA climatological divisions for (a) Montana, (b) Utah, and (c) Arizona. Montana division 1, Utah division 5, and Arizona division 4 were studied.

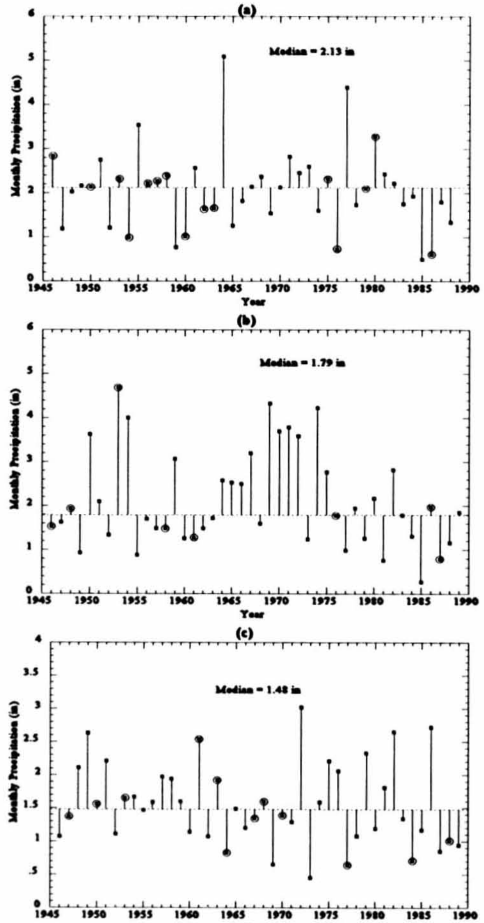


Figure 4.—Montana division 1 monthly precipitation time series for (a) December (1946-88), (b) January (1946-89), and February (1946-89). The median value for each month is shown by the dashed horizontal line. Months selected as global warming analogues have their data points circled.

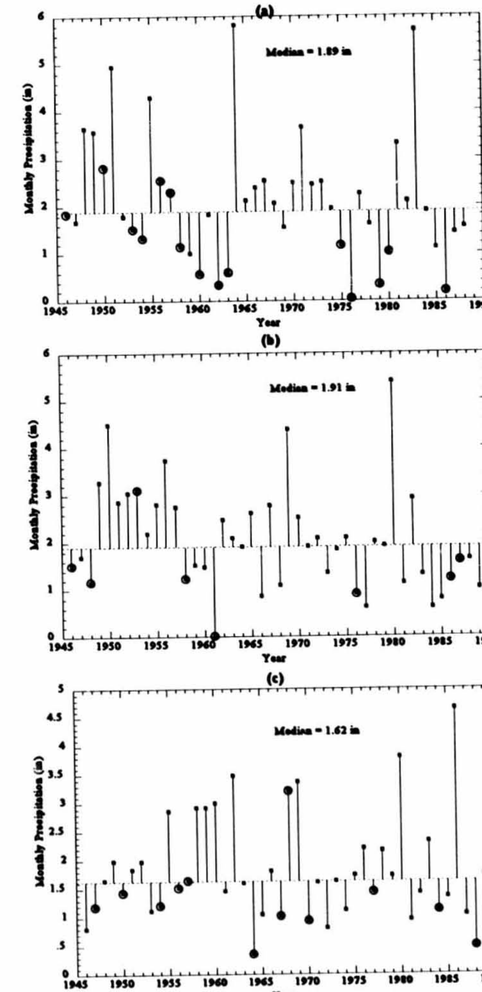


Figure 5.—As in figure 4 except for Utah division 5.

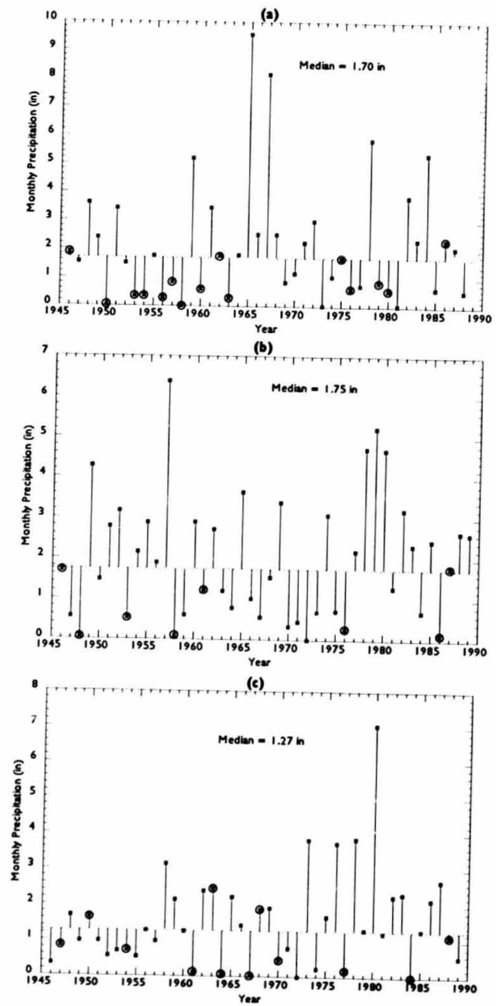


Figure 6.—As in figure 4 except for Arizona division 4.

sets. It was considered slightly more realistic than the arithmetic mean since the frequency distributions of monthly precipitation are typically somewhat positively skewed, and the population mean can be inflated by a few high values. The median is the value that lies midway in the series of monthly precipitation values, i.e., half of the values are greater than and half are less than the median.

Global Warming Analogue Months

The precipitation value for each analogue month listed in table 1 is circled in figures 4-6. The analogue monthly values were categorized by the sign of their deviations from the median, and the number of cases in each category was tabulated. Table 2 summarizes these results.

Table 2.—Categorical listing of division precipitation for each analogue winter month

State climate division	Precipitation category	December (15 cases)	January (8 cases)	February (12 cases)	Total (months)
	Above median	7	3	5	15
Montana division 1	≈ median	2	1	0	3
	Below median	6	4	7	17
	Above median	3	1	1	5
Utah division 5	≈ median	1	0	1	2
	Below median	11	7	10	28
	Above median	2	0	3	5
Arizona division 4	≈ median	2	2	0	4
	Below median	11	6	9	26

In Montana division 1, the number of cases above (positive departures) or below (negative departures) the median precipitation is almost evenly split in all three winter months. Of the 35 analogue months, 15 months had precipitation greater than the median, and 17 had precipitation less than the median, with 2 months receiving precipitation approximately equal to the median value.

In Utah and Arizona, the situation is different. Cases of below median precipitation in Utah division 5 and Arizona division 4 occurred substantially more frequently than did above median deviations. Utah has 28 out of 35 analogue months with negative departures, while Arizona has 26 out of 35 analogue months with below median precipitation. In each of the winter months, precipitation is strongly weighted on the dry side in both States.

A secondary investigation was carried out to determine whether these results could be biased by the selection of study areas and the possibility that particular climatological divisions might have unique precipitation signals based on different exposures to prevailing storm tracks (i.e., storms from the northwest vs. storms from the southwest). Monthly precipitation for division 3 in Arizona (figure 3), an area with better exposure and less sheltering to northwest storms, was analyzed for deviations from its median values. Results were the same as for Arizona division 4. Of the 35 analogue months, 27 registered below median precipitation, 5 had above median precipitation, and 4 received amounts approximately equal to the median precipitation.

In Utah, division 5 is not considered to have any substantial precipitation bias to either northwest or southwest storms. This is because of the north-south orientation of the Wasatch Range, the east-west configuration of the Uinta Mountains, and the lack of any effective upstream sheltering. Montana's division 1 is a large area that responds equally distinctly to all westerly storm tracks.

The sample size of the number of analogue months, 35, is quite small. However, the results in table 2 are not necessarily surprising when the Dennis climate change scenario is considered in terms of the hypothesized change in storm tracks. With a winter storm track shifted northward into Canada, as suggested in figure 1, most storms will produce precipitation there rather than over the intermountain West. The reduction in storm frequency will have the greatest effect on the winter precipitation of the central and southern intermountain regions, for example, Utah and Arizona. Situated closer to the northward shifted storm track, western Montana would experience a less marked effect on its winter precipitation.

It is also revealing to compare the median precipitation for the global warming analogue months to the 1946-89 (1946-88 for December) median values despite the small sample sizes. Table 3 shows the results. There are only slight differences between the two sets of median values for all 3 months in division 1 in Montana. However, both Utah division 5 and Arizona division 4 show significant differences. In each month, the analogue median precipitation value is substantially lower than the 1946-89 median value.

Table 3.—Comparison of median precipitation (inches) for the GWA months with 1946-89 (1946-88 for December) median values. The ratios of the GWA and the period of record median values are also shown as percentages in parentheses.

State climatological division	Median precipitation	December	January	February
Montana division 1	GWA	2.14 (100%)	1.66 (93%)	1.38 (93%)
	1946-89	2.13	1.79	1.48
Utah division 5	GWA	1.15 (61%)	1.22 (64%)	1.20 (74%)
	1946-89	1.89	1.91	1.62
Arizona division 4	GWA	0.61 (36%)	0.40 (23%)	0.60 (47%)
	1946-89	1.70	1.75	1.27

If arithmetic averages (means) rather than median values were used to characterize the different samples, would the ratios substantially change? Mean precipitation values for the global warming analogue (GWA) and the period of record categories were computed, and the subsequent ratios calculated. Only slight differences in the ratios percentages were noted. The largest difference occurred for January in Arizona. Using mean precipitation values, a ratio of 37 percent was calculated compared with 23 percent using median values. In all other categories, both the GWA and the period of record means increase proportionately above the median values so that the ratios change only slightly.

Average deviations of analogue monthly precipitation from the 1946-89 median precipitation were calculated for each month (table 4). The magnitude of monthly deviations corresponds to the length of the solid line between the dashed median precipitation line and an individual month's precipitation data point in figures 4-6. The numbers in table 4 are simply the arithmetic averages (means) of the precipitation deviations for the analogue months only. There can be some overwhelming influence on the means from large individual monthly deviations (e.g., January 1953 in Montana division 1). Therefore, median deviations were also computed and are shown in table 4. For example, a monthly deviation of nearly 3 inches in January 1953 in Montana overwhelms the other smaller magnitude deviations to produce a mean of 0.14 inch compared to a median value of -0.14 inch. However, in Utah and Arizona, the tendency for below median precipitation to occur in GWA months is obvious whether one uses the mean deviation or the median deviation. In Montana, the average values again suggest little potential change.

Table 4.—Average deviations (inches) (median deviations in parentheses) of GWA monthly precipitation values from the 1946-89 (1946-88 for December) median values

State climatological division	December (median)	January (median)	February (median)	Average deviation[1] (median)
Montana division 1	-0.23 (0)	0.14 (-0.14)	-0.10 (-0.10)	-0.10 (-0.03)
Utah division 5	-0.70 (-0.74)	-0.57 (-0.69)	-0.33 (-0.42)	-0.54 (-0.60)
Arizona division 4	-0.86 (-1.09)	-1.02 (-1.35)	-0.47 (-0.68)	-0.77 (-1.08)

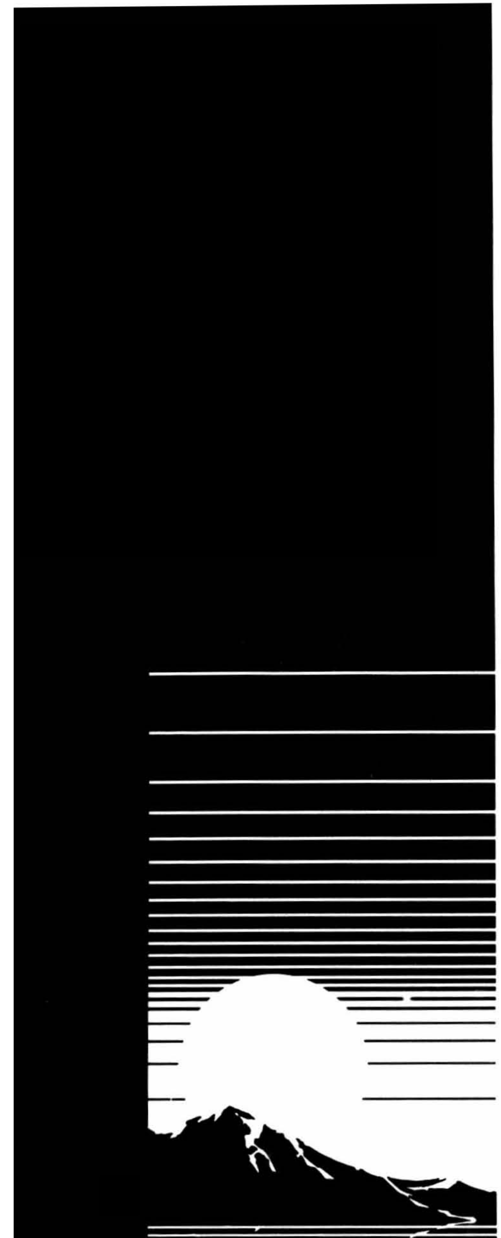
[1] For December, January, and February.

Independence of Monthly Precipitation

The above analysis has assumed that December, January, and February divisional mean precipitation values are independent of one another. That is, in a given winter, the magnitude of December's precipitation has neither a relationship to nor an effect upon the following January or February precipitation, and there is an even chance (50 percent probability) that a month's precipitation deviation (from median values) will be the same sign as the previous month's. Of the 35 analogue months, there are 10 pairings that could bias the results if monthly precipitation values are not independent.

To assess the assumption of independence, cross correlation coefficients were calculated for all period of record December-January, December-February, and January-February pairs of precipitation deviations in each of the three climatological divisions. The largest r value computed was 0.24 for the December-January pair in Utah division 5. All other r values ranged from 0 to 0.19. The small r values indicate that no significant relationship exists between the precipitation deviations that occur in individual winter months.

Contingency tables were also constructed comparing the signs (positive or negative) of the nine pairs of precipitation deviations. Contingency tables indicate the probability of a winter month registering a precipitation deviation sign equal to the prior month's positive or negative deviation. This probability was highest, reaching approximately 60 percent, in the December-February pairings in Montana and Arizona and in the December-January pairing in Utah. All other pairs revealed a virtual 50-50 chance of receiving precipitation deviations of the same sign.



ADDITIONAL COMMENTS

ADDITIONAL COMMENTS

In light of this study's heavy dependence on the use of monthly upper air (500 mb) patterns to define potential effects of global warming on precipitation in the intermountain West, several specific examples are discussed that highlight the strengths and weaknesses of the procedure.

Averaging Period

Of the 35 months selected as reasonable analogues, no month had 500 mb circulation patterns that satisfied the guidelines for the perfect global warming analogue on every day. This is not surprising since atmosphere circulation is dynamic and ever changing. The use of the calendar month as the averaging period in this study is partly due to long-term convention in the meteorological sciences (as well as other disciplines), which, to a great extent, is because of convenience. However, it was also believed that by calculating calendar month averages, the prominent 30-day 500 mb pattern would be spotlighted despite the significant variability that typically occurs during a month.

Choosing an averaging period shorter than 1 month could weigh the results too heavily towards one particular weather regime or precipitation event. There would also be the additional complication of computing division precipitation averages for the shorter time periods since such data sets do not exist to the best of our knowledge. Calculating longer time period averages (e.g., the entire 3 months) might prove to be sufficient and has often been done; yet, in this study, it would seriously reduce the sample size and could give unrepresentative results.

Natural variability is desired in order to provide a realistic analogue. The storm tracks in figure 1 are the predominant location of progressing weather systems and do not imply that all storms follow those exact tracks. Natural variability is always present, as can be seen in Zishka and Smith's original figures from which figure 1 was constructed. However, it is believed that the sample of 35 winter months as global warming analogues realistically approximates the natural variability of that circulation regime over Western North America. A question then arises as to whether the 1946-89 variability will change in a globally warmed world. This study does not quantitatively address the question, but some inferences can be drawn based on atmospheric dynamics, and they are discussed in the summary and conclusions.

Examples

December 1975 and December 1953 represent two of the better analogue patterns out of the 35 total months. The December 1975 500 mb height, standard deviation, standard deviation anomaly, and height departure fields are shown in figure 7. The height and height departure fields in figures 7a and 7d, respectively, portray enhanced high-pressure ridging (positive departures) of the December 1975 500 mb heights over Western North America and the eastern North Pacific Ocean. This pattern served to drive the storm track northward from its normal position. Figures 7b and 7c support this notion by showing a ridge of high standard deviation values extending from the Gulf of Alaska inland (7b) where the values are anomalously high (above normal, 7c) over western Canada but below normal nearly everywhere else to the south.

The December 1953 500 mb parameters (figure 8) show a configuration similar to December 1975 except that the amplified 500 mb ridge is located several degrees of longitude farther west. Greatest positive height departures (figure 8d) are concentrated mainly over the extreme eastern North Pacific Ocean but also extend east over the intermountain West. The 500 mb standard deviation field (figure 8b) once again has highest values (greatest short wave activity) in a ridge extending from the ocean inland over western Canada. There is also a pronounced, but smaller, ridge of high values protruding southeastward over the intermountain West. Figure 8c shows that the short wave activity is above normal (positive values) over western Canada, where the global warming pattern criteria require it to be, with a smaller maximum over the southern Rocky Mountains.

This standard deviation pattern appeared relatively frequently in the monthly patterns whenever the ridge amplified over Western North America. This was interpreted as evidence of short waves moving in from the Gulf of Alaska and undercutting the ridge as they intensified over the interior West. In fact, the early portion of December 1953 experienced stronger than normal 500 mb northwesterly flow over the Great Basin and Rockies, and that part of the month undoubtedly contributed to the slightly enhanced standard deviation values there.

One feature of the circulation in both Decembers was the above normal westerly winds in the Northern Hemisphere upper atmosphere. This is at odds with the often claimed premise that midlatitude westerlies should be weaker in the global warmed atmosphere. The stronger winds were accompanied by increased short wave activity which likely contributed substantially to the

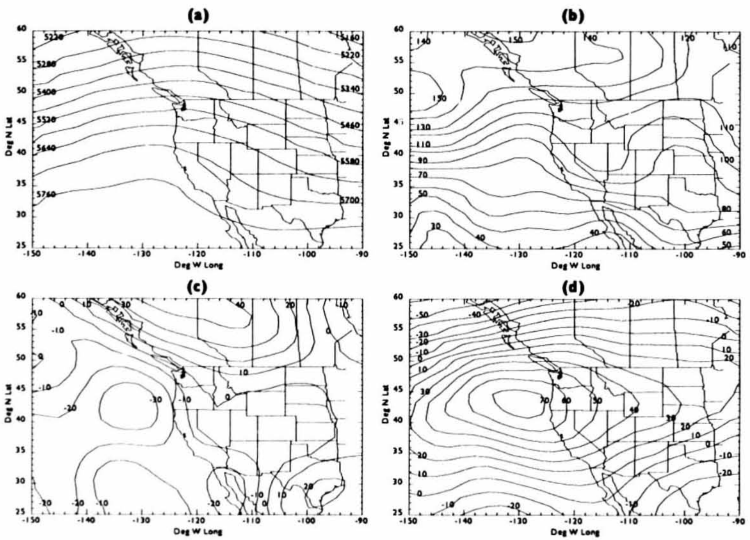


Figure 7.—December 1975 mean 500 mb (a) height, (b) height standard deviation, (c) standard deviation anomaly, and (d) height departure fields. Units are in meters.

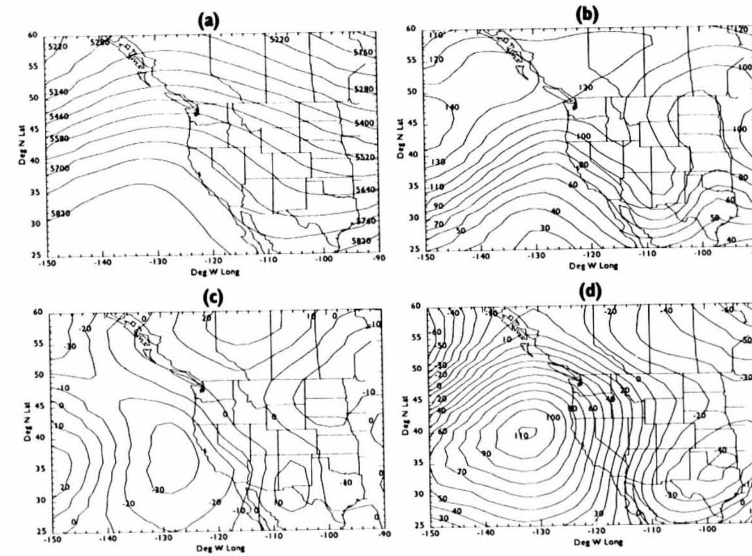


Figure 8.—Same as in figure 7 except for December 1953.

precipitation received in, at least, Montana if not Utah as well. If, in line with some of the common climate change scenarios, fewer weather disturbances were assumed to occur during the two months, it is likely that the monthly precipitation in Montana would have been less.

February 1963 fit the global warming analogue criteria rather well and is an example of how one storm can sometimes dominate the monthly precipitation in a region. This month also highlights the degree of variability that is naturally present. Figure 9 shows the four 500 mb height parameter fields for the month. Again, the monthly pattern was one of amplified high pressure ridging over Western North America. In this case, weaker than normal westerly winds occurred in the upper atmosphere. The standard deviation charts (figures 9b and 9c) show the active storm track over Canada where 500 mb height standard deviation values are maximum (9b) and standard deviation anomaly values are positive (9c). There is also a slight hint of lower latitude storm activity breaking through under the ridge, with the positive standard deviation anomaly values over the southeastern North Pacific Ocean, Mexico, and the desert southwest.

The month saw precipitation in western Montana reach nearly 2 inches compared to a median of 1.48 inches. In northern Utah, precipitation for the month was right at the median value. Arizona division 4 registered about 2.5 inches, which was well above the median value of 1.27 inches. In both Montana and Utah, precipitation occurred off and on during the entire month. However, in Arizona, virtually all of the precipitation fell in 2 to 3 days, from the 10th to the 12th, as the westerlies broke through beneath the amplified ridge over British Columbia. The remainder of the month was essentially precipitation free. One storm in an otherwise dry month raised the precipitation to well above the median level.

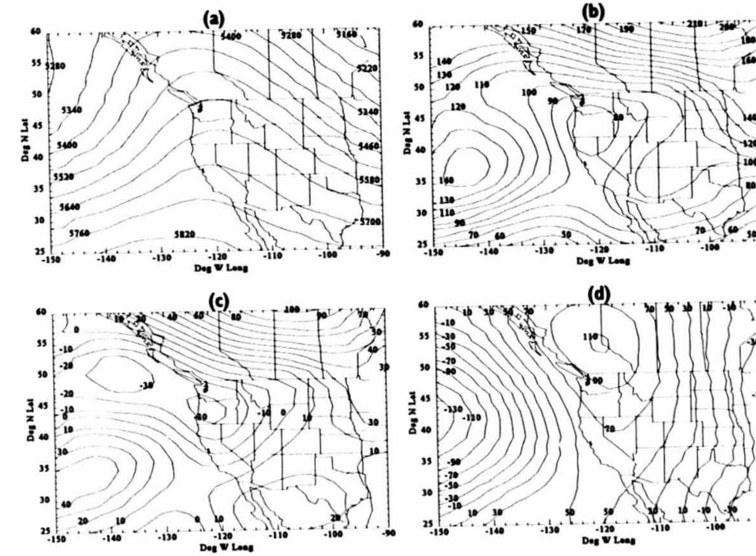
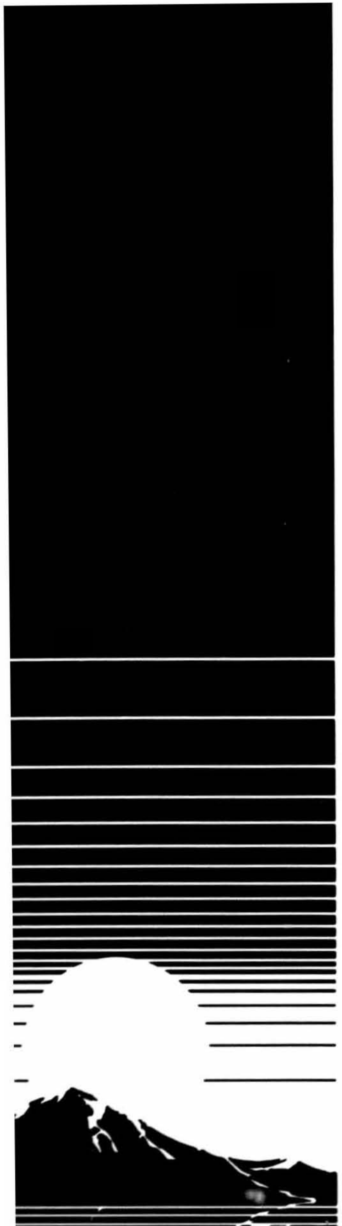


Figure 9.—Same as in figure 7 except for February 1963.



SUMMARY AND CONCLUSIONS

SUMMARY AND CONCLUSIONS

This study has examined historical upper air circulation patterns in the atmosphere in an effort to identify analogues for a hypothesized climate change scenario (global warming) for the Western United States. The study focused on the potential effects of global warming on wintertime precipitation in the intermountain West. Criteria were developed that defined 500 mb height pattern configurations analogous to a global warming induced northward shift of the wintertime surface storm track over Western North America. Fields of mean monthly geopotential height, height standard deviation, standard deviation anomaly, and height departure for a domain encompassing the eastern North Pacific Ocean and Western North America were derived using 500 mb geopotential height data. Monthly charts of the four parameters were produced for every December from 1946-88 and every January and February from 1946-89. Of the total 131 winter months surveyed, 35 were chosen as appropriate analogues for the climate change scenario.

Monthly precipitation data for three climatic divisions in western Montana, northern Utah, and east-central Arizona were analyzed for differences between the monthly analogue totals and the December, January, and February 1946-89 period of record values. In Utah division 5 and Arizona division 4, 28 and 26 months, respectively, out of the 35 global warming analogue months had precipitation amounts that were less than the 1946-89 median values. In Montana division 1, the number of analogue months with above or below median precipitation was split nearly evenly.

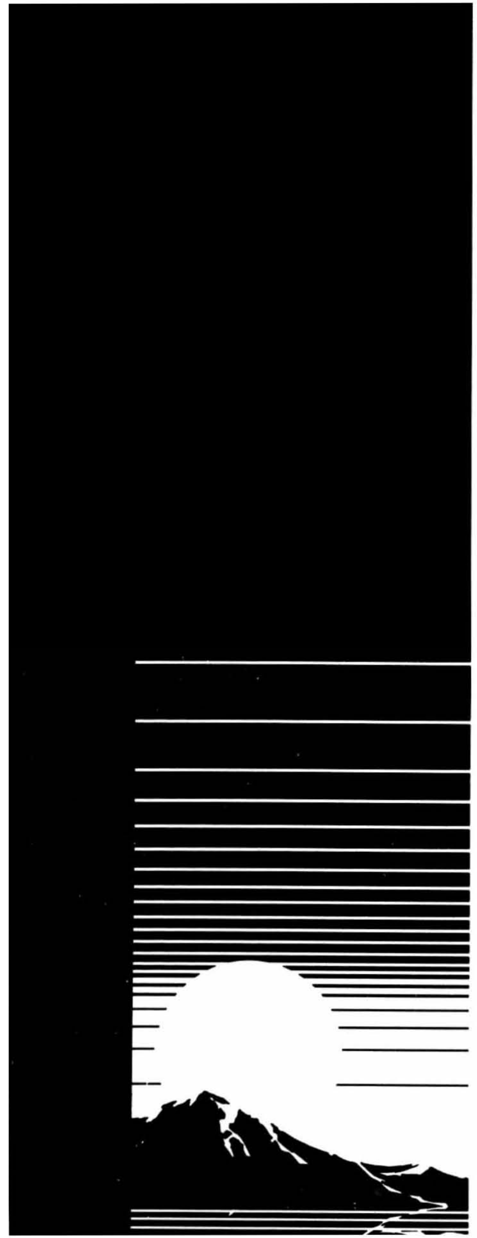
Median precipitation values for the analogue months in northern Utah varied from about 60 to 75 percent of the 1946-89 median values. The monthly average (median) deviations from the period of record medians ranged from -0.70 inch (-0.74 inch) in December to -0.33 inch (-0.42 inch) in February. In east-central Arizona, the analogue months had median precipitation amounts ranging from only about 25 to 50 percent of the 1946-89 median values. Monthly average (median) deviations varied from -1.02 inches (-1.35 inches) in January to -0.47 inch (-0.68 inch) in February.

Such results clearly suggest the possibility of substantially drier wintertime conditions in, at least, parts of the intermountain Western United States if the hypothesized anthropogenic global warming induces changes to the atmospheric circulation suggested by Dennis and examined in this study. Areas of the central and southern intermountain region appear to be the most vulnerable.

This study was unable to identify the direction of any change in the wintertime precipitation climate of the more northern regions.

Several concepts should be discussed in light of these study results. Many of the 35 months chosen as analogues experienced atmospheric circulations with predominantly stronger than normal westerly winds in the study domain. Two of the months, December 1953 and December 1975, both exhibiting stronger than normal westerlies, were discussed as examples of otherwise favorable analogues. A circulation feature often postulated to develop if global warming comes to pass is a relaxation of the midlatitude westerlies and associated jet stream due to a weakening of the latitudinal temperature gradient between equator and pole. Weaker westerlies and jet stream winds imply fewer and perhaps weaker weather disturbances than are represented by some of the analogues studied. Resulting monthly precipitation might be even less than the estimates determined in this study.

On the other hand, both GCMs and theoretical arguments imply that the hydrologic cycle will be enhanced by increases in the moisture content of the warmed atmosphere. In other words, for a given intensity, individual storms should produce more precipitation than they presently do. Whether this effect will compensate for the presumed decrease in storm frequency is one of many questions that will have to await concurrent improvements in the understanding and modeling of the atmosphere ocean biosphere system.



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MISSION STATEMENTS

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