

**THE RELATIONSHIP BETWEEN PRECIPITATION AND TEMPERATURE  
OVER THE CONTINENTAL UNITED STATES**

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**DEDICATION**

To my wife, Jinhua Li,  
and  
my parents, LIU Jiyun and ZHAO Tai.

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## ABSTRACT

### The Relationship between Precipitation and Temperature over the Continental United States

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There has been growing concern that if the earth warms up due to the increasing greenhouse effect of CO<sub>2</sub> and other trace gases in the atmosphere, the patterns of rainfall will shift and greatly affect agricultural productivity and availability of fresh water. One way to study what might happen is to look at the relationship between precipitation and temperature in the past. Within the continental United States, there are extensive data of monthly precipitation and temperature records at over 1000 stations and spanning the last 100 years. Seven regions were defined in the United States based on the ecological and climatological considerations, including areas of major agricultural productivity such as the Corn Belt. This study investigated the relationship between temperature and precipitation over an 80-year period from 1905 to 1984 in the continental United States to see whether the climate tends to be wetter or dryer when it gets warmer. These past patterns might be indicators of future climate as the earth warms from increasing greenhouse effect. The correlation coefficients between precipitation and temperature have been computed for individual stations, for state averages and for regional averages for each month and each season of the year. The linear regression analysis has also been conducted on each region for each of four seasons. Areas of both negative and positive precipitation-temperature correlations were found in the United States. Over most areas, summer precipitation and

temperature are negatively correlated, which indicates that warm summers tend to be dryer and colder summers tend to be wetter. The only notable area where a significant positive correlation was found is south of the Great Lakes bounded in the east by the Appalachian Mountains. The contribution to the total correlation from variations of various time-scales was also analyzed in terms of moving-average filtering technique. The correlation between precipitation and temperature were analyzed for three frequency bands - short (shorter than 5 years), medium (between 5 and 15 years), and long (longer than 15 years) cycles. Although both negative and positive precipitation-temperature correlations were found for all cycle bands, over most areas of the United States, significant correlation mainly occurs from variations of short and medium cycles.

## CHAPTER 1. INTRODUCTION

The impact of increasing levels of carbon dioxide and other infrared-absorbing trace gases in the atmosphere due to human activities is a contemporary environmental problem that has generated considerable scientific and, now, political concern [Kellogg, 1987]. The observed increase in the atmospheric concentrations of these gases, principally carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and chlorofluorocarbons (CFCs), is altering the heat balance of the Earth by retaining long-wave radiation that would otherwise be lost to space. There is a consensus that this man-enhanced "greenhouse effect", most likely will result in a global warming and climate change which will affect human life.

Despite recent improvements in our understanding of atmospheric dynamics and large-scale climatic processes, the climatic effects of greenhouse gases are still only partially understood, particularly as they relate to regional climate changes. However, it is the regional changes that are most important in assessing the impacts of climate change on human life and planning strategies for the future. Among others, the changes and shifts of the regional and seasonal patterns of precipitation or soil moisture are of most concern for agriculture, forestry, and natural ecosystems which have a direct effect on human life. Three approaches have been considered in evaluating the regional climate changes and drawing up regional patterns [Kellogg, 1987]. They are:

- 1) use of various kinds of complex numerical models of the atmospheric circulation to simulate or predict climate change;
- 2) paleoclimatological analogues of warmer periods in the distant past;

- 3) analysis of modern meteorological data to develop climate patterns during past 100 years or so.

Many numerical climate models have been developed and enormously improved over the past few decades. Climate models are widely used to predict the climate change due to the increase of greenhouse gasses, particularly CO<sub>2</sub>, and generally agree that if CO<sub>2</sub> were doubled, then the earth's surface temperature would eventually warm up somewhere between 1°C and 5°C [Dickinson, 1986]. Climate models may be accurate in calculating the results given the information that is put into the model, but the complexity of the interactions of the world's atmosphere, oceans, land, biosphere and ice sheets is not fully understood at present and therefore not represented or greatly simplified in current models. These missing or incomplete connections make the predictions unreliable. Furthermore, the spatial resolution of the climate models is not nearly fine enough to give the detail of regional changes.

An alternative to the use of climate models in studies of climate change is the record of past climatic variations. For this century there is a fairly detailed global data set on temperature and precipitation from both paleoclimatological and instrumental records, and it is possible to see the patterns of changes of precipitation or soil moisture during warmer periods in the past. These climate patterns may be indicators of what may happen if the earth warm up. In this study we will focus on the recent climate data from the United States, specifically surface temperature and precipitation. The following is a brief review of previous studies using paleoclimatological and instrumental data particularly for the continental United States.

### 1.1. Paleoclimatological Analogues

Various kinds of evidence are used to infer past climates. Climatic information from pre-instrumental times of about 1000 years is provided by various historical sources: accounts of severe climatic events, information about recurring phenomena such as crop yields and harvest dates, and statements concerning weather-related events such as the dates of freezing of lakes and rivers. However, historical records are subjective and generally qualitative. Over longer time spans, any variable that responds in an identifiable manner to climatic change, particularly temperature and precipitation or soil moisture, and that can be dated is used as indirect evidence. Table 1.1 lists the various paleoclimatological data sources that are used to reconstruct past climates. These data sources are generally divided into three main categories: the faunal and floral (including plant and animal fossils, pollen and tree rings), the sedimentological and stratigraphic, and the geomorphological.

The earliest attempt of paleoclimatological analogues of warmer period was Kellogg's study of the Altithermal Period which occurred roughly 4000 to 8000 years ago. During the Altithermal (also known as the Hypsithermal or Climatic Optimum), at the dawn of civilization, the world was generally 1°C to 2°C warmer than present. Kellogg (1977) prepared a map of precipitation or soil moisture conditions in this period. Since it was published in a World Meteorological Organization Technical Note in 1977 and also discussed later [Kellogg, 1978a, 1978b], Kellogg's map has been quoted in a variety of publications. His map was based on a fairly extensive survey of the literature on the climate of the Altithermal Period. The map indicates that some of the places seem to have been wetter than present while the others were drier.

Part of the evidence concerning moisture consisted of data on the kinds of plants that

TABLE 1.1. Characteristics of paleoclimatological data sources.

Proxy Data Source	Variable Measured	Continuity of Evidence	Potential Geographical Coverage	Period Open to Study (YBP)	Minimum Sampling Interval (yr)	Usual Dating Accuracy (yr)	Climatic Inference
Layered ice cores	Oxygen isotope concentration, thickness (short cores)	Continuous	Antarctica, Greenland	10,000	1-10	±1-100	Temperature, accumulation
	Oxygen isotope concentration (long cores)	Continuous	Antarctica, Greenland	100,000+	Variable	Variable	Temperature
Tree rings	Ring-width anomaly, density, isotopic composition	Continuous	Mid-latitude and high-latitude continents	1,000 (common) 8,000 (rare)	1	±1	Temperature, runoff, precipitation, soil moisture
Fossil pollen	Pollen-type concentration (varved core)	Continuous	Mid-latitude continents	12,000	1-10	±10	Temperature, precipitation, soil moisture
	Pollen-type concentration (normal core)	Continuous	50° S to 70° N	12,000 (common) 200,000 (rare)	200	±5%	Temperature, precipitation, soil moisture
Mountain glaciers	Terminal positions	Episodic	45° S to 70° N	40,000	—	±5%	Extent of mountain glaciers
Ice sheets	Terminal positions	Episodic	Mid-latitude to high latitudes	25,000 (common) 1,000,000 (rare)	—	Variable	Area of ice sheets
Ancient soils	Soil type	Episodic	Lower and mid-latitudes	1,000,000	200	±5%	Temperature, precipitation, drainage
Closed-basin lakes	Lake level	Episodic	Mid-latitudes	50,000	1-100 (variable)	±5%	Evaporation, runoff, precipitation, temperature
Lake sediments	Varve thickness	Continuous	Mid-latitudes	5,000	1	±5%	Temperature, precipitation
Ocean sediments (common deep-sea cores, 2-5 cm/1000 yr)	Ash and sand accumulation rates	Continuous	Global ocean (outside red clay areas)	200,000	500+	±5%	Temperature, precipitation, Wind direction
	Fossil plankton composition	Continuous	Global ocean (outside red clay areas)	200,000	500+	±5%	Sea-surface temperature, surface salinity, sea-ice extent
	Isotopic composition of planktonic fossils; benthic fossils; mineralogic composition	Continuous	Global ocean (above CaCO <sub>3</sub> compensation level)	200,000	500+	±5%	Surface temperature, global ice volume; bottom temperature and bottom water flux; bottom water chemistry
(rare cores, >10 cm/1000 yr)	As above	Continuous	Along continental margins	10,000+	20	±5%	As above
(cores, <2 cm/1000 yr)	As above	Continuous	Global ocean	1,000,000+	1000+	±5%	As above
Marine shorelines	Coastal features, reef growth	Episodic	Stable coasts, oceanic islands	400,000	—	±5%	Sea level, ice volume

SOURCE: National Academy of Sciences (1975)



were growing during this period. These data were deduced from the distribution of pollen types and spores found in ancient lakes and peat bog sediments. Hence, it is probably fair to conclude that the vegetation was controlled largely by rainfall and soil moisture during the growing season [Lamb, 1977; Nichols, 1975]. In middle and high latitudes this would be in the early summer months. Another source of information on average rainfall conditions during the Altithermal is the reconstructed record of lake levels and stream flows, especially in parts of Africa [Nicholson and Flohn, 1980; Street and Grove, 1976; Butzer et al., 1972]. In the tropics the rainy season tends to be in the spring and summer, depending on the influence of the Asian monsoon.

Subsequently, Butzer (1980) published his study of the Altithermal Period. His map, similar to Kellogg's, also displayed the "wetter" and "drier" regions, though disagreed in some areas with Kellogg's. Figure 1.1 indicates the areas where Butzer and Kellogg agree on the climate changes during the Altithermal Period compared to the present. The regions that are now subtropical deserts were apparently wetter than the present: such areas are Sahara in North Africa, most of east Africa, northwestern India, part of Mexico and western Australia. The central United States (now part of the "grain belt") seems to have had definitely less summer rainfalls during the Altithermal Period.

In somewhat the same vein, Flohn (1979) has looked at further climate epochs as a guide to scenarios for future climate. He suggested four periods which are believed to have been warmer than the present: the Medieval warm period (900-1050 AD,  $\sim 1.0^{\circ}\text{C}$  warmer than present), the Holocene warm episode or Altithermal (around 4000-8000 years before present,  $\sim 1.5^{\circ}\text{C}$  warmer than present), the last interglacial epoch or Eemian (around 75,000-130,000 years before present,  $\sim 2.5^{\circ}\text{C}$  warmer than present), and the last period in which the Arctic Ocean is believed to be ice-free year around ( $12-2.5 \times 10^6$  years before present,  $\sim 4.0^{\circ}\text{C}$

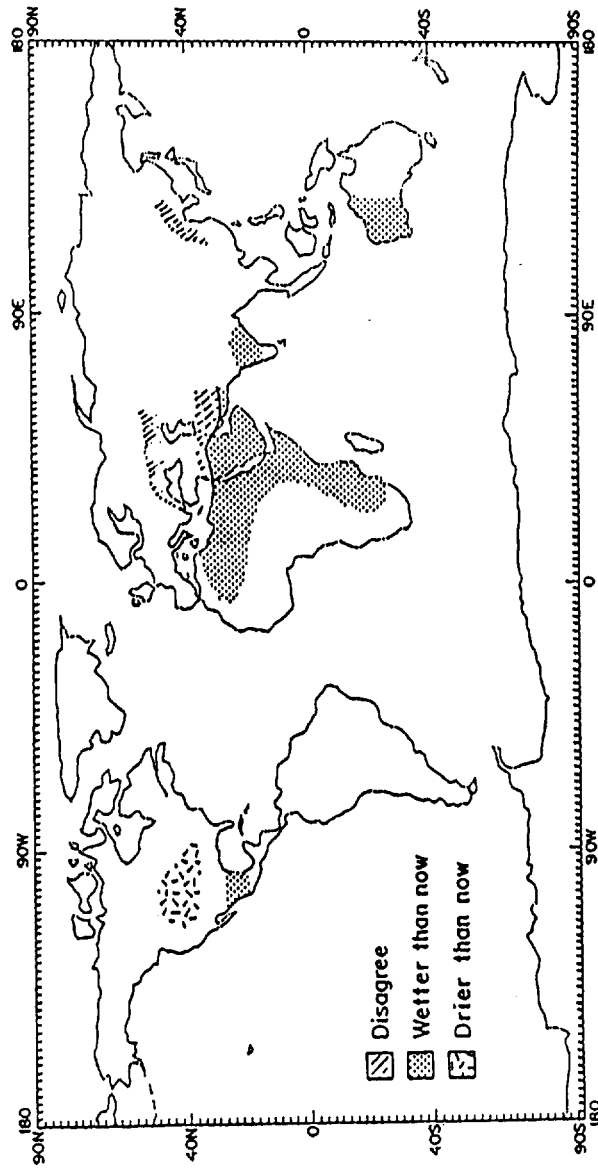


FIGURE 1.1. Area where the maps of Kellogg (1977) and Butzer (1980) agree as to conditions during Alithermal Period of about 4000-8000 years ago. (After Kellogg and Schware, 1981)

warmer than present).

However, while Flohn has presented such scenarios for a possible future climate, he pointed out that it is questionable whether climatic history could be repeated and that the evidence from examples of past warm climates can be used with confidence when taking into account the changes in the boundary conditions such as ice extent, coastlines, and vegetation changes that may be different in future warming of the Earth.

## **1.2. Modern Meteorological Record**

The most reliable information of past climates comes from instrumental observations of various meteorological parameters including direct measurements of temperature and precipitation. The earliest meteorological records go back to the 1650s. Two general approaches have been taken to use instrumental data to study climate change: (a) developing a climate scenario by looking at anomalies of precipitation and temperature during warmer years; (b) looking at the relationship between precipitation and temperature to see whether climate becomes wetter or drier when it is warm.

### **1.2.1. Temperature and precipitation anomalies of warmer years**

It was suggested at a workshop sponsored by the Aspen Institute [Aspen, 1978] that one way to gain insight into how regional climate would change on the warmer earth would be to study years when it was unusually warm in the Arctic in the past 100 years. The reason for choosing warm Arctic years rather than global warm years is that both model and observational studies have shown that the Arctic is more sensitive to climate changes and CO<sub>2</sub>-induced climate changes could be greatest in high northern latitudes [Williams, 1980;

Wigley *et al.*, 1980].

The earliest such studies were carried out independently by Williams (1980) and Wigley *et al.* (1980). The two studies differed somewhat in the assumptions made and the approaches taken.

Williams (1980) used 70 years (1900-1969) of meteorological data for the Northern Hemisphere. She drew maps of the differences between the long term seasonal means for sea-level pressure, surface temperature, and precipitation and the 10 warmest Arctic winters and 10 warmest Arctic summers. She concluded that there were large areas of increase and decrease of precipitation, and that in the summer these were statistically significant. She found that, in the midwest of the United States, the significant decrease of summer precipitation corresponded to more than 1°C increases of summer temperature - that is, precipitation and temperature are inversely correlated.

Wigley *et al.* (1980) used a shorter data period - 50 years from 1925 to 1974. They presented the patterns of differences of mean annual surface temperature and precipitation between the five warmest years and the five coldest years as measured in the latitude band between 65°N and 80°N. Their maps shown that the same decreasing precipitation with increasing temperature in the midwest of the United States as did Williams.

In 1983, Jäger and Kellogg (1983) published their study on this issue. They used the precipitation and temperature data collected for the World Weather Record over the period 1931-1978 and adopted two methods of selecting "scenarios" for a warm Arctic. First, for each season the 10 warmest individual seasons were selected and compared with the remaining long-term mean. Second, for each season the warmest five consecutive years and the coldest 5 consecutive years in the Arctic were compared. Their results were similar to those of Williams (1980) and Wigely *et al.* (1980). However, the precipitation anomalies were found

to be much less similar than the temperature anomalies in the two methods.

### 1.2.2. Precipitation-temperature relationship

Efforts have been made to reveal the relationship of precipitation and temperature in the United States and other places in the world by directly comparing the time series of precipitation and temperature records.

Blair (1931a) examined the winter precipitation-temperature relationship in the United States by checking the times of departures of precipitation and temperature expressed in State averages. Regions of positive and negative relationships were found. In the Pacific Northwest and the Southwest to Northeast region extending through New Mexico and Maine, bounded on the northwestern flank by Oklahoma-Missouri-Wisconsin and on the southeastern flank by the extreme southwestern Appalachians to Pennsylvania, wet and warm or dry and cold winters occurred more than 50% of the time. When the temperature departure was 2°F (~1°C) or more, more than 75% of the winters in Oregon, Michigan, New York, and New England exhibited these characteristics. Blair pointed out that the positive correlation extending northeastward from New Mexico to the Great Lakes and New England is associated with the winter cyclones which appear in the southwest and move northeastward.

Later Blair (1931b) presented some global relationship of the temperature-precipitation regimes, showing the inverse relation in the United States. It appears that a negative correlation between precipitation and temperature prevailed in both colder-than-normal years of 1883-1888 and warmer-than-normal years of 1919-1924. The cold winters were wet and the warm winters were dry except in the southern Great Plains. This may be associated with the persistence of pressure anomalies during abnormally cold or warm winters as discussed by Blair (1931b). During the cold winters, the subnormal pressure was observed

in the central United States; in the warm winters, high pressure was found through the North American continent except in Florida and southeastern United States.

Hamrick and Martin (1941) compared summer rainfall and summer temperature records from 1898 to 1938 in Kansas City, Missouri. The curves of ten-year means of precipitation and temperature in their graph show a distinct negative correlation between rainfall and temperature during the summer months throughout the entire period.

Madden and Williams (1978) also indicated that warmer summers in the central United States were usually dryer. They calculated the correlations of seasonal total precipitation and mean temperature for summer and winter, based on the 64-year time series from 1897 to 1963 at 65 stations in North America. Besides the warm and dry summers in the central United States, they found that the warm and wet or cold and dry weather occurred frequently during winters in the region extending from Arkansas northeastward to New England, bounded on the southeastern flank by Appalachians and on the northwestern flank by Missouri-Illinois-Indiana-Ohio, and also in the small area along the coast of the Pacific Northwest. This result is consistent with Blair's (1931a) to some extent. Their results also show that the warm and dry or cold and wet winters appeared in the middle of North America.

In a more comprehensive study, Cruther (1978) has further defined these relationships by computing correlations between temperature and total precipitation within the United States for each month of the year. 40 and 102 stations were used for the respective periods 1906-1948 and 1949-1970. The relationships noted by Blair (1931a) and by Madden and Williams (1978) hold. In the strip from Texas to New England, cool summers are wet and hot summers are dry, while warm winters are wet and cold winters are dry. Cruther indicated that the cool and wet summers in the central United States are associated with the fact that

moisture has a damping effect, particularly with respect to maximum temperature prior to rainfall and also with evaporative cooling after rainfall. Convection begins at an earlier time of day, preventing increasing surface temperature. If sufficient moisture is available, clouds are formed and surface insolation is restricted. If still more moisture is available, precipitation is produced, the released latent heat of condensation and fusion are carried away, and the evaporating rain in the atmosphere and on the ground produces further cooling during the day.

### **1.3. Objectives of This Study**

This study extends the research of recent climate data by looking at the relationship between precipitation and temperature in the continental United States based on the data base - Historical Climatology Network - provided by the Carbon Dioxide Information Analysis Center at Oak Ridge, Tennessee. The data base probably represents the best monthly precipitation and temperature data set available for the United States. The issues addressed in this study are:

1. Correlation between precipitation and temperature which can provide information on the closeness of the two variables and indicate whether precipitation tends to increase or decrease when temperature increases;
2. Linear regression of precipitation on temperature which provides information on how much of the change of precipitation can be attributed to the change of temperature;
3. Correlations between precipitation and temperature contributed by various time-scale variations which can provide the information on whether the correlation between precipitation and temperature reflects a relationship that is common to variations over all

climate cycles or one that is favored for a particular climate cycle.

Chapter 2 is a review of the climate on the United States and defines the regions within the continent for regional studies. Chapter 3 describes the data which are used in the study and the analysis procedures. Chapter 4 presents and discusses the results of relationship between precipitation and temperature. Finally, Chapter 5 summarizes the results of this study.



## CHAPTER 2. CLIMATE OF THE UNITED STATES

### 2.1. Topography and Climates

The United States continent consists of areas with varied topography. The Rocky Mountains dominate the western United States; the Great Plains are in the central United States; in the east there are the Appalachian Mountains; and the huge inland waters of the Great Lakes occupy the northern border of the eastern United States.

In larger measure, the variety of climates in the continental United States is a reflection of the topography. This general climatic pattern can be seen in Figure 2.1, in which an indication of the average annual temperature range is provided by showing continentality  $K$  defined as Conrad's index

$$K = \frac{1.7A}{\sin(\phi + 10)} - 14 \quad (2.1)$$

where  $A$  is the average annual temperature range in °C and  $\phi$  is the latitude angle.  $K$  ranges between -12 at extreme oceanic stations and 100 at extreme continental stations. The spatial distribution of annual average monthly total precipitation also shows this feature (Figure 2.2). The west coast area is strongly influenced by the Northern Pacific ocean and has a high annual precipitation; but this oceanic influence is restricted to a narrow band along the coast west of the Rocky Mountains. The mountains are a barrier to the movement of moisture from the ocean. In the central United States, climates are relatively uniform: precipitation is almost

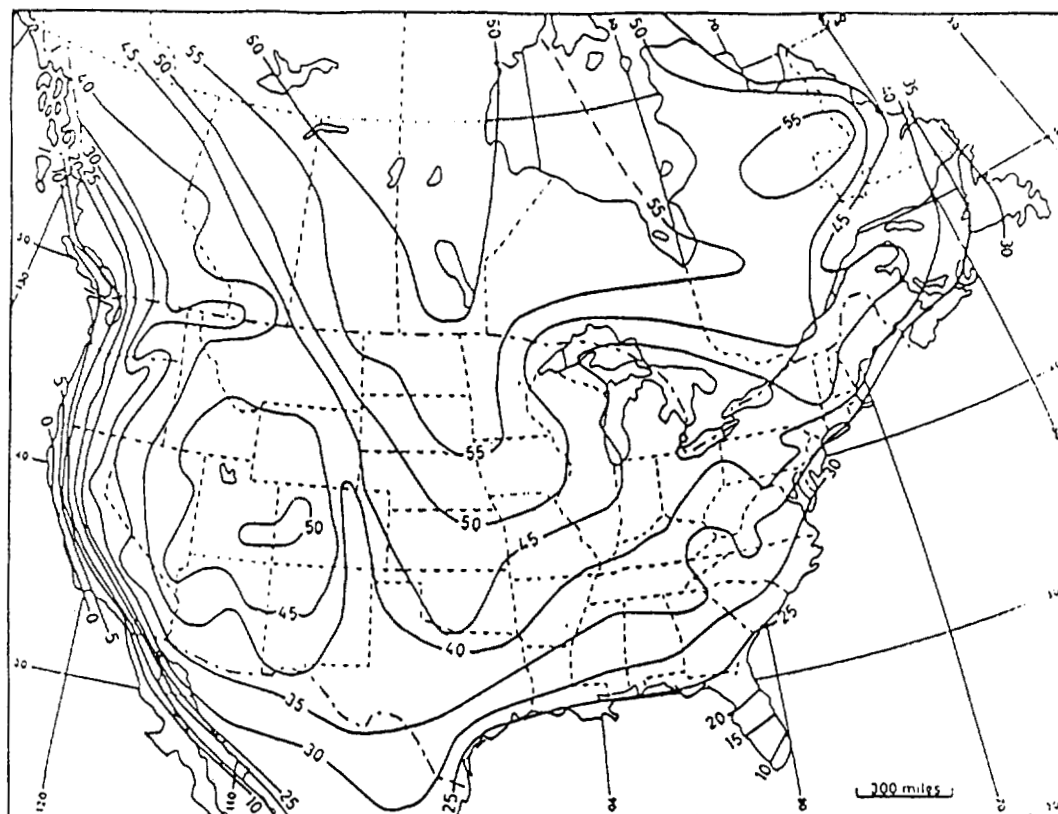


FIGURE 2.1. Continentality in North America according to Conrad's index. (After Barry, 1987)

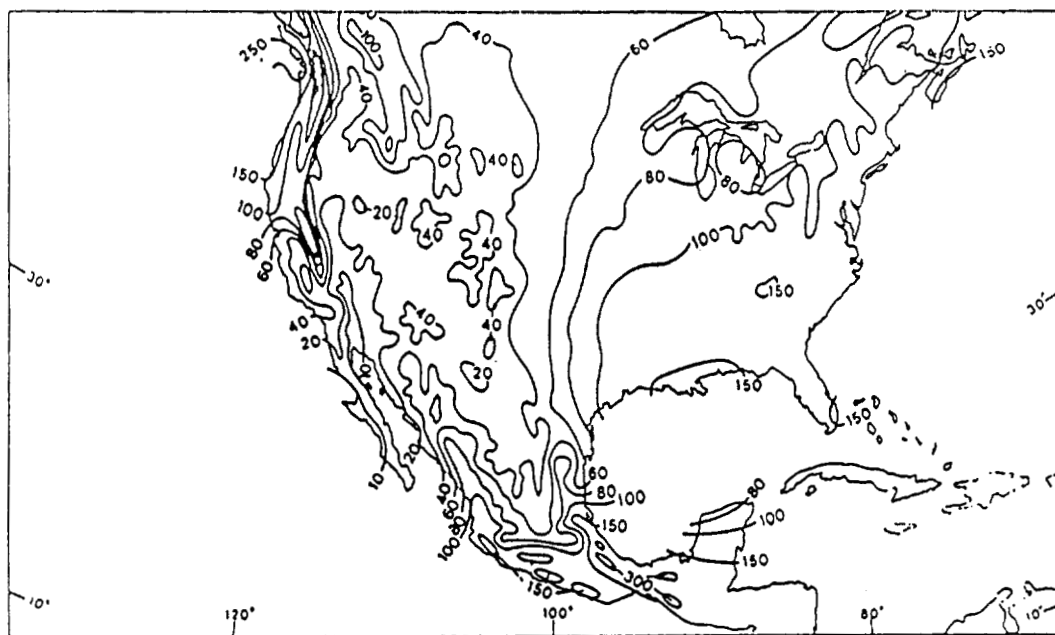


FIGURE 2.2. Mean annual precipitation (in centimeters) over the United States. (After *Barry*, 1987)

equally strong from the north to south, where the annual isohyets are approximately parallel to the meridians; the continentality gradually decreases from the north to south. The Great Lakes have significant ocean-like effects on surrounding areas and have more annual precipitation than surrounding areas.

## **2.2. Air Masses Influencing the United States**

The continental United States is surrounded on the east by the Atlantic Ocean, on the west by the Pacific Ocean, on the southeast by the Gulf of Mexico, and on the north by the rest of North American continent and the Arctic. All these geographical features shape the weather and climate of the United States.

Several air masses from different sources around the United States influence the United States through different paths (Figure 2.3). Cold and dry air masses originating in interior Canada and Alaska throughout the year and in the Arctic basin and Greenland ice cap during winters enter the United States from the north. Cool and humid air from the North Pacific influences the West. The Northwestern Atlantic sends cold and humid air into the Northeast. Warm and humid air masses from the subtropical Pacific affect the Southwest through out the year and occasionally reach the western United States. Through the entire year, the unstable warm and humid air masses from the Gulf of Mexico, Caribbean Sea, and western Atlantic influence the east interior and coast areas. During summers, hot and dry air masses form in the Northern interior Mexico and southwestern United States and occasionally bring drought to southern Great Plains. The characteristics of these air masses, their source regions, and their prevailing conditions are listed in Table 2.1.

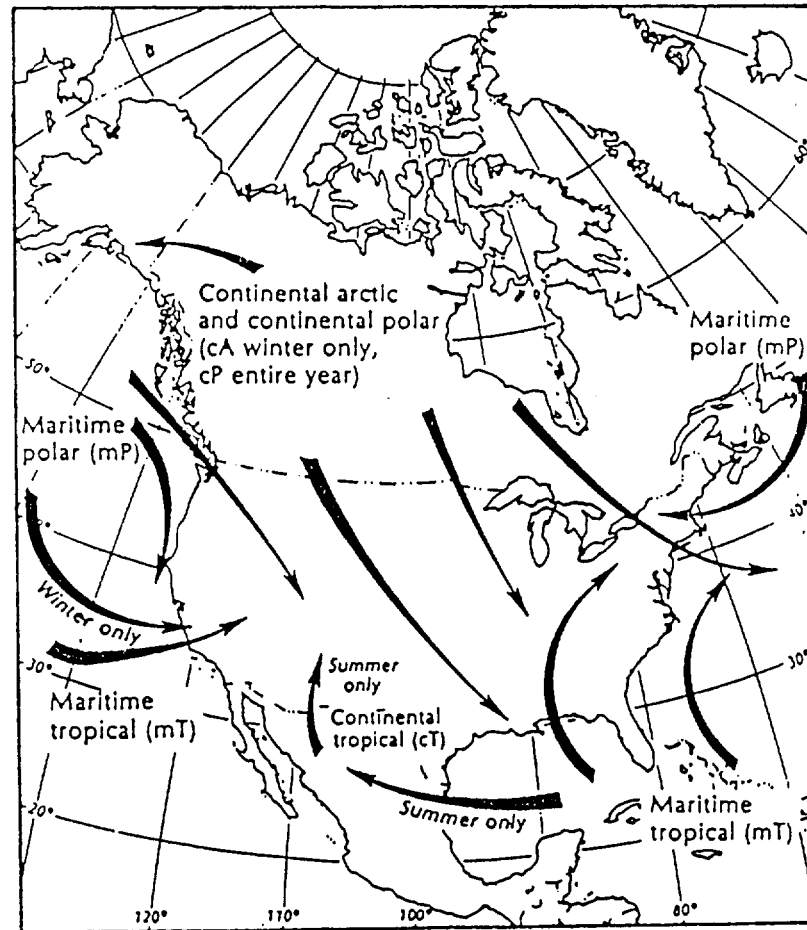


FIGURE 2.3. Source regions and paths of air masses influencing the North American continent. (After Rumney, 1987)

TABLE 2.1. Characteristics of the North American air masses.

Air Mass	Source Region	Temperature and Moisture Characteristics in Source Region	Stability in Source Region	Associated Weather
cA	Arctic basin and Green land ice cap	Bitterly cold and very dry in winter	Stable	Cold waves in winter.
cP	Interior Canada and Alaska	Very cold and dry in winter Cool and dry in summer	Stable entire year	Cold waves in winter. Modified to cPk in winter over Great Lakes bring "lake-effect" snow to leeward shores.
mP	North Pacific	Mild (cool) and humid entire year	Unstable in winter Stable in summer	Low clouds and showers in winter. Heavy orographic precipitation on windward side of western mountains in winter. Low stratus and fog coast in summer, modified to cP inland.
cP	Northwestern Atlantic	Cold and humid in winter Cool and humid in summer	Unstable in winter Stable in summer	Occasional "northeaster" in winter. Occasional period of clear, cool weather in summer.
cT	Northern interior Mexico and southwestern U.S. (summer only)	Hot and dry	Unstable	Hot, dry, and clear rarely influencing areas outside source region. Occasional drought to southern Great Plains.
mT	Gulf of Mexico, Caribbean Sea, and western Atlantic	Warm and humid entire year	Unstable entire year	In winter it usually become mTw moving northward and bring occasional widespread precipitation or advection fog. In summer, hot and humid conditions, frequent cumulus development and showers or thunderstorms.
mT	Subtropical Pacific	Warm and humid entire year	Stable entire year	In winter it brings fog, drizzle, and occasional moderate precipitation to N.W. Mexico and S.W. United States. In summer it occasionally reaches western U.S., providing moisture for infrequent conventional thunderstorms.

Source: From *Lutgens and Tarbuck* (1982).

## **2.3. Climatological Regions**

The continental United States can be divided into five climatic regions based on their geographic and climatological characteristics. These regions are the west coast, desert areas, western mountain areas, central United States, and eastern region.

### **2.3.1. Pacific coast**

From western Washington to northernmost California, in the narrow band of 80 km to 160 km wide along the Pacific coast, the climates are dominated by atmospheric systems of the North Pacific. This is the only part of the United States where higher winter precipitation is the pronounced climatic characteristic. In summer, precipitation is substantially reduced due to the strong North Pacific anticyclone.

From the Washington coast to San Francisco Bay is the region of temperate climate, despite the high latitudes into which it extends. The dominant climatic role of maritime air off the unfrozen sea brings abundant precipitation, persistently high humidity, and cool to mild temperatures. Cool, damp summers alternate with moderate, cloudy winters with much fog and frequent rain and snow. Temperatures for the warmest month are nearly uniform at coastal stations throughout the region during summers and winter temperatures are unusually high for the latitudes.

In the region southward from San Francisco Bay, climate is one of warm to hot, dry summers and mild, wet winters, with an abundance of cloud-free, sunny skies.

### **2.3.2. Desert areas**

Most United States deserts are in the elevated uplands between the Rocky Mountains

and the Cascade-Sierra Nevada ranges, including the deserts in southern Washington and northern Oregon, the Great Sandy Desert in central Oregon, and the Great Basin - the largest desert area in the U.S. - beginning in southeastern Oregon and southwestern Idaho and extending into southern Nevada and eastward to the Salt Lake Desert in Utah. Clear, cloudless skies from dawn until dusk are the overriding atmospheric condition of the desert climate. In summer, most of western deserts receive more than 80% of the possible sunshine. During winter months clear skies are less frequent; even then southern deserts receive more than 70% of the possible sunshine. In the northern deserts, frequent winter storms from the Pacific generally reduce the value to less than 50%. Mean yearly precipitation is usually less than 250 mm over most desert regions.

### **2.3.3. Western mountains**

The western reaches of the United States are dominated by high mountain ranges and intermountainous plateaus and basins that create a climatic pattern of great complexity totally different from the rest of the continent. The Rocky Mountains extend from west Texas northwestward beyond the U.S.-Canada border to Alaska. Atmospheric turbulence is commonly intensified in mountain regions as a product of the barrier effect on normal air movement. Snow is without doubt one of the more significant products of atmospheric activity in mountain regions. Mountain runoff is indeed the chief source of water supply for streams in arid regions of the west.

### **2.3.4. Central United States**

Between the humid forest regions in the eastern United States and the Rocky Mountains are the large areas of open interior plains - the Great Plains. Climates in this



region represent the transition between moisture surplus and moisture deficit condition.

Distinctly continental characteristics in this region feature four well-defined seasons, a large annual temperature range, and a pronounced summer precipitation increase. From 65% to 80% of yearly precipitation occurs in the period between April and September; maximum amounts commonly fall early in the growing season. May-June is the wettest time over the central and northern Great Plains due to more frequent cyclonic activity. Warm, humid air from the Gulf of Mexico and the tropical Atlantic principally contributes moisture for summer precipitation in this region. Frequent summer drought is much more extensive in the Great Plains than elsewhere in the continent, due to frequent west winds off the heights of the Rocky Mountains gaining heat while moving downward across the plains toward the Mississippi River. Winter is dominated by air masses originating in the higher latitudes, most of which are continental in character and thus are often very cold and very dry. Moisture arrives mainly from the North Pacific, and frontal storms bring most of the winter precipitation.

The Great Plains are one of major agricultural areas of the United States. Among the total agricultural production in the United States, more than 50% wheat, about 45% corn, near 40% soybeans and over 90% sorghum are produced in this area (refer to "1982 Census of Agriculture, Vol 2, Part 3, Ranking of States and Counties", Bureau of the Census, WDC, 1985). The growing season varies in length from about 240 days in central Texas to fewer than 150 days in North Dakota.

#### **2.3.5. Eastern United States**

In the eastern United States, southward from the Great Lakes-St. Lawrence Valley to the Gulf of Mexico much climatic variety is encountered due to the influence of major

water bodies and the Appalachians. Two major climates are commonly identified in this region: 1) *humid continental* extending southward from the north border approximately to the Chesapeake Bay, the Great Smokies and the Ozarks, beyond which 2) *humid subtropical* reaches the Gulf of Mexico and the shores of peninsular Florida. The four seasons that characterize humid continental area become much less distinct farther south, and the growing season lengthens from under 80 days in the north to more than 350 days in the south.

Mean annual precipitation increases southward from about 800 mm near the Great Lakes and northeast areas to over 1600 mm along the Gulf Coast and in southern Florida. Greater atmospheric moisture content is partly responsible for this. In the southeast there is considerable evapotranspiration and this helps to maintain moderate annual precipitation totals northwards and eastward from the Gulf by providing additional water vapor for the atmosphere. Along the east coast, the Atlantic Ocean is an additional significant source of moisture for winter precipitation. Thunderstorms account for a much larger percentage of yearly precipitation, occurring on fewer than 30 days in the north but on over 100 days in southwest Florida.

South of the Great Lakes, the area including southern Wisconsin, southern Michigan, Illinois, Indiana and Ohio is the so-called Corn Belt, which could extend westward to Iowa and Missouri; about 55% corn, 35% soybeans and 10% wheat of the total U.S. agricultural production are produced in this area.

#### **2.4. Region Division in this Study**

Based on both climatic and agricultural considerations, we divided the continental United States into seven regions which are shown in Figure 2.4.

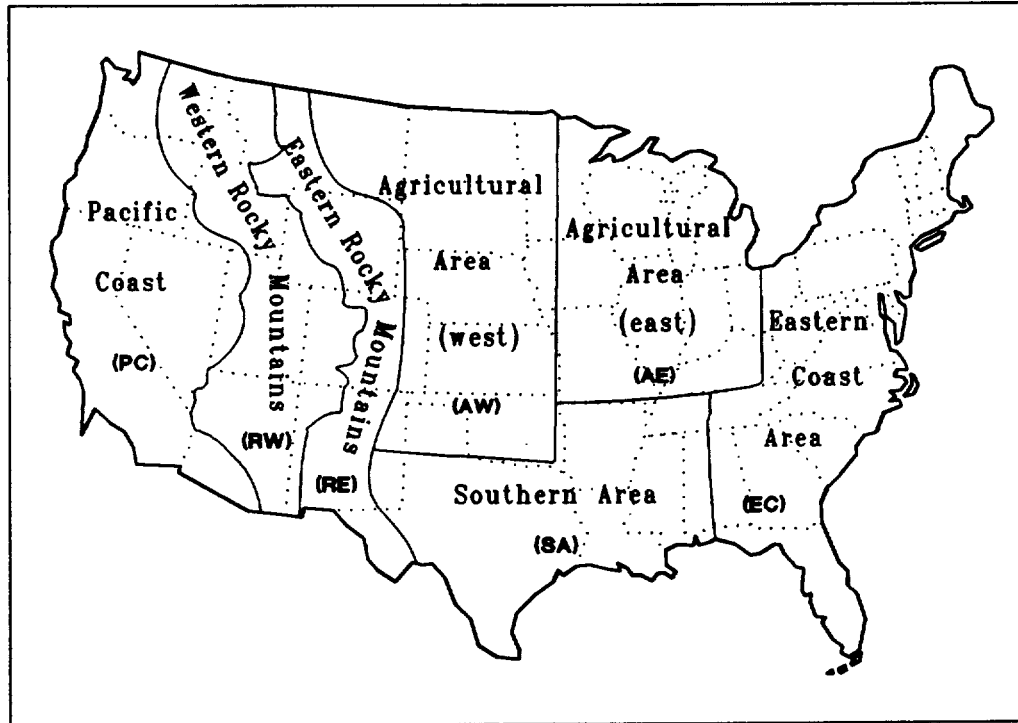


FIGURE 2.4. Seven regions in the United States.

The middle of the United States is the main agricultural region. The area was subdivided into two portions: eastern agricultural region, covering the Corn Belt and the surrounding areas of the Great Lakes; western agricultural region, mainly the Great Plains ranging from North Dakota southward to north Texas. The future climate change in these areas will have greatest effect on the agricultural productivity of the United States.

The Rocky Mountains are main surface water supplier to the areas west and east to the mountains, and most forests of the United States grow in this area. The Rocky Mountains was subdivided into two parts according the continental divide running through the summits of the mountains.

The other three regions are the Pacific coast, the east coast and the southern area.

## CHAPTER 3. DATA AND DATA ANALYSIS

The precipitation and temperature data used in this study came from the United States Historical Climatology Network (HCN) [Quinlan *et al.*, 1987]. In this chapter we first discuss the data quality including selection criteria of the HCN stations and data adjustments, and the stations considered in this study. Then the analysis methodology and procedure are described.

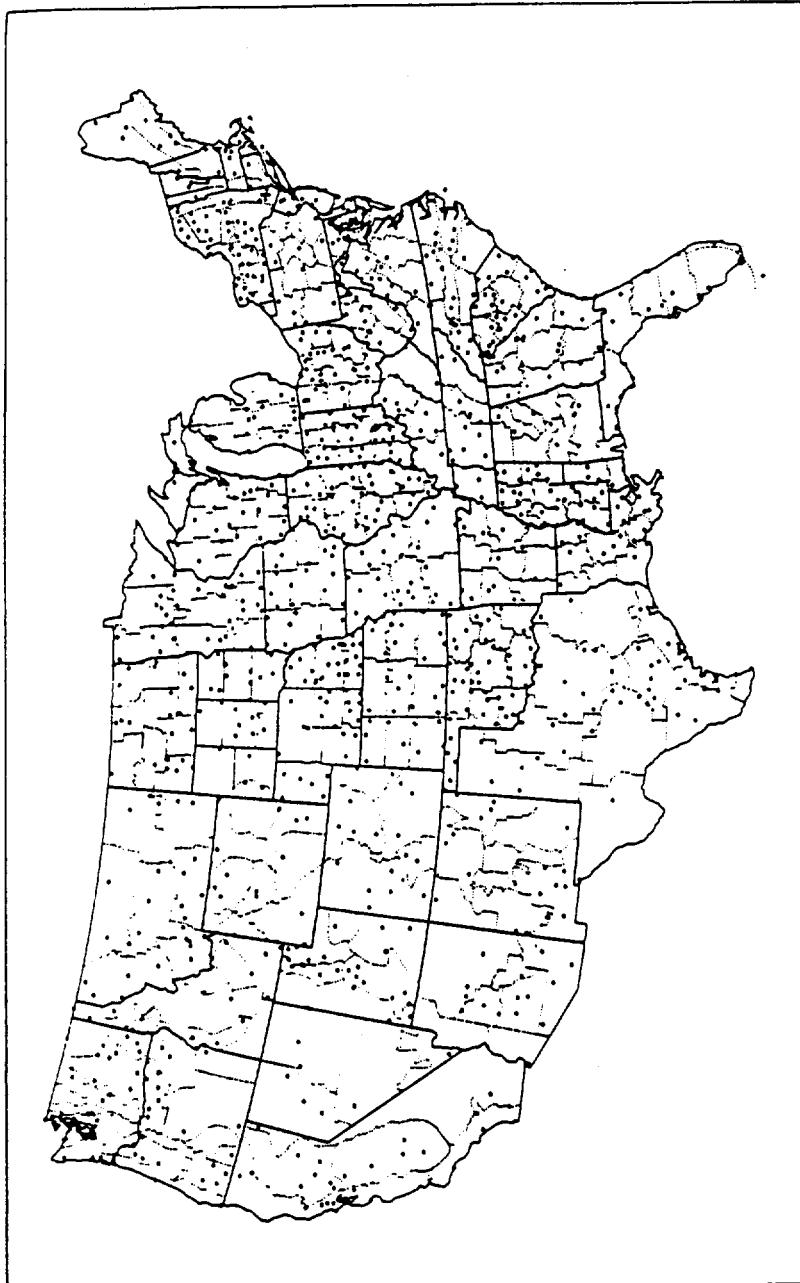
### 3.1. Data Quality

The meteorological stations in the United States were carefully chosen for the HCN network. And the data have been adjusted to reduce potential biases.

#### 3.1.1. Selection criteria of the HCN stations

The HCN is comprised of 1219 stations with relatively uniform distribution in the United States (Figure 3.1). Most stations in this network had long-term records of monthly averages of maximum, minimum and mean temperature and total monthly precipitation over more than 80 years prior to 1984 (Table 3.1). In the United States and in many other countries, the daily mean temperature is defined as the average of the maximum and minimum temperatures.

One unique feature of the HCN network is its minimization of the urban effects; it has been shown that on average the urbanization bias was only  $+0.06^{\circ}\text{C}$  for annual mean



**FIGURE 3.1.** Spatial distribution of the stations in the Historical Climatology Network (HCN). (After *Quinlan et al.*, 1987)

TABLE 3.1 Number of HCN stations with serially complete data starting on, or before, the beginning of the decade.

Decade	Mean Temperature	Maximum/Minimum Temperature	Precipitation
1880	27	0	92
1890	231	36	359
1900	671	607	707
1910	951	912	929
1920	1097	1079	1036
1930	1144	1134	1071
1940	1163	1157	1086
1950	1172	1166	1092
1960	1188	1182	1116
1970	1203	1202	1147
1980	1218	1217	1158
1980+	1219	1219	1165
Unadjustable	0	0	54

Source: From *Quinlan et al. (1987)*

temperature in the period from 1901 to 1984 in the U.S. continent, quite small compared to the year-to-year variability of the annual average and many of the multi-year climate fluctuations [Karl *et al.*, 1988]. Designed to be used to detect secular changes of regional rather than local climate, the HCN network included only stations not believed to be influenced to any substantial degree by artificial changes of local environments; such stations were usually found located in relatively low-population areas [over 85% of all stations had a 1980 population of less than 25,000 and 70% had a population less than 10,000. Karl *et al.*, 1988].

The stations included in the network also experienced few instrument and site changes over the length of data collection to avoid serious observation biases. Previous work has shown that changes in observing schedules and practices produced biases in the mean temperature of up to 1.0°C [Bigelow, 1909; Schaal and Dale, 1977; Karl *et al.*, 1986]; and the changes in station location, instruments, instrument shelters, and the height of the instruments above the ground have lead to biases of 1.0°C or more at many stations [Karl and Williams, 1987].

### **3.1.2. Data adjustment**

In addition to these selection criteria, the raw data have been subjected to an exhaustive set of the data reduction techniques and the quality control procedures that adjust for documented discontinuities including the time of observation bias, station and instrument changes, and relative inhomogeneities to reduce the potential biases [Quinlan *et al.*, 1987]. Karl and Williams (1987) and Karl *et al.* (1986) discussed the methodology used to adjust the data for these discontinuities. Karl and Williams (1987) used the method of differences between neighboring stations and Monte Carlo simulations to assess the significance of any



potential discontinuity, and Karl *et al.* (1986) developed an empirical model for eliminating the bias associated with varying observation schedules at cooperative stations. Some missing data were estimated back to 1900 using data from neighboring stations to make the HCN record as serially complete as possible [Quinlan *et al.*, 1987].

Quinlan *et al.* (1987) provided detail information regarding the data adjustments and edits to the HCN network as well as an objective summary of the integrity of each network station's record for a variety of factors.

### **3.2. Stations Considered in this Study**

The 80 years period from 1905 to 1984 was chosen for this investigation, in order to have the data covering as long a period as possible and, at the same time, to include the largest number of stations. From the total of 1219 HCN stations, a maximum of 949 stations were found to have complete monthly mean temperature and total monthly precipitation records from 1905 to 1984. Another 36 stations which had complete records in some seasons but not through the entire year are considered as well as those 949 stations with complete 80 years records. Therefore, a total of 985 stations were considered in this study. Table 3.2 lists the numbers of the HCN stations included and the totals available in the HCN network for each state; and the number of stations in each region, defined in Chapter 1, for each season is also listed in Table 3.3.

Although the HCN stations were selected with relatively uniform distribution in the U.S., the density of stations is larger in the east than in the west. There are fewer stations in the desert areas, particularly in the Great Basin, including southeastern Oregon, southern Nevada and western Utah. Southwestern Texas is also a nearly "station-free" area. Figure 3.2

TABLE 3.2. Number of HCN stations included in this study in each state.

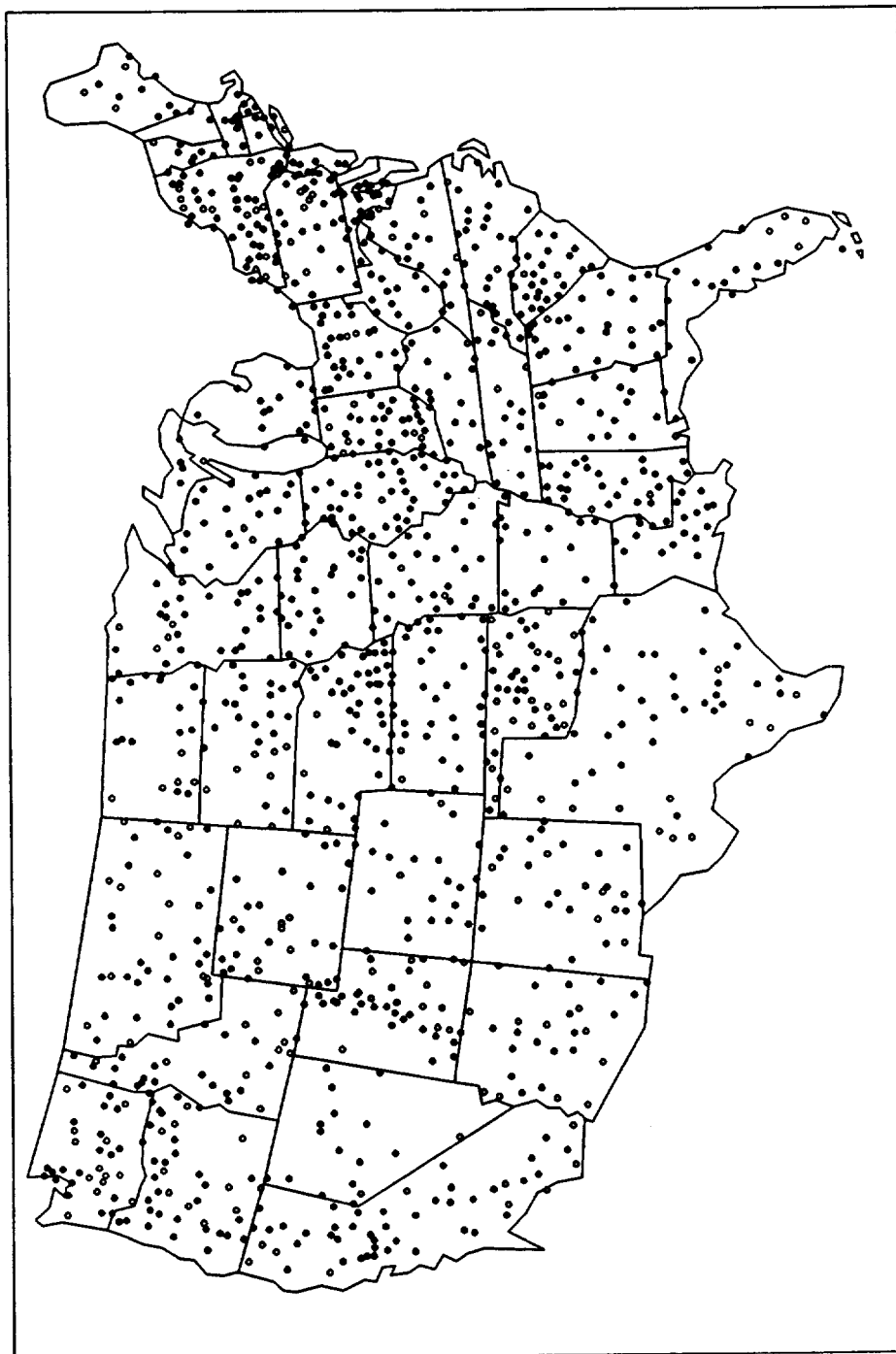
State	Cited	HCN*	State	Cited	HCN*
Alabama	12	15	Nebraska	44	46
Arizona	17	25	Nevada	11	13
Arkansas	14	14	New Hampshire	4	5
California	41	54	New Jersey	12	12
Colorado	21	23	New Mexico	18	28
Connecticut	3	4	New York	44	59
Delaware	5	5	North Carolina	26	29
Florida	18	22	North Dakota	18	24
Georgia	22	23	Ohio	25	27
Idaho	17	28	Oklahoma	26	45
Illinois	35	36	Oregon	27	41
Indiana	28	35	Pennsylvania	18	24
Iowa	23	23	Rhode Island	3	3
Kansas	28	31	South Carolina	26	29
Kentucky	13	13	South Dakota	20	25
Louisiana	18	18	Tennessee	13	15
Maine	9	12	Texas	36	48
Maryland	14	17	Utah	27	40
Massachusetts	11	12	Vermont	7	7
Michigan	23	24	Virginia	15	19
Minnesota	28	33	Washington	31	44
Mississippi	31	33	West Virginia	12	13
Missouri	24	26	Wisconsin	21	23
Montana	30	44	Wyoming	16	30
			<b>Total</b>	<b>985</b>	<b>1219</b>

\* Number of stations available in the HCN network.

TABLE 3.3. Number of HCN stations with complete 80-years of monthly mean temperature and total precipitation data in each season and each region.

Region	winter	spring	summer	autumn	annual	HCN*
Pacific Coast	98	105	103	104	98	152
Western Rockies	78	80	80	83	78	118
Eastern Rockies	53	55	55	57	54	88
Agricultural West	184	187	186	187	183	237
Agricultural East	174	174	175	175	173	188
Eastern Coast	266	265	270	268	261	321
Southern Area	104	103	105	104	102	115
U.S.	957	969	974	978	949	1219

\* Number of stations available in the HCN network.



**FIGURE 3.2.** Spatial distribution of the HCN stations. Dots symbolize the stations included in this study and circles indicate the ones excluded.

shows the distribution of all the HCN stations with dots symbolizing for the stations included in this study and circles for ones excluded.

### **3.3. Data Analysis**

#### **3.3.1. Data pretreatment**

Time series of seasonal and annual means of monthly total precipitation and monthly mean temperature were obtained for each station by averaging the monthly total precipitation and monthly mean temperature values, respectively. Annual values are determined from January through December; winter values are from December, January and February; spring values are from March, April and June; and so on. The 80 years averages of monthly, seasonal and annual data were computed for each station by averaging monthly, seasonal or annual values from 1905 to 1984. The deviations of monthly mean temperature and monthly total precipitations and their seasonal and annual means from the 80 years averages were determined for each station. The time series of monthly, seasonal and annual data and their 80 year deviations are used for further data analysis.

The monthly deviations have been averaged over the stations within each state to obtain state mean deviations. Since some New England states have very small areas and very few stations are in each states, we simply combined all New England states - Maine, Vermont, New Hampshire, Massachusetts, Connecticut and Rhode Island - into one. For similar reasons, we also combined New Jersey, Delaware, and Maryland with Pennsylvania. Each of these two groups of states is treated as one composite state region in this study.

The monthly, seasonal and annual deviations of monthly total precipitation and monthly mean temperature have been averaged over stations within each of the seven regions

(Pacific Coast, western Rocky Mountains, eastern Rocky Mountains, western Agricultural Area, eastern Agricultural Area, Eastern Coast, and Southern Area), defined in Figure 2.4, to obtain the regional mean deviations. And the average deviations for the United States were also obtained from deviations of all stations within the United States.

### 3.3.2. Correlation analysis

Correlation analysis provides a single summary statistic - the correlation coefficient - describing the strength of the association between two variables. There are a number of forms of correlation coefficients for use with different types of data. One which is most widely used and which is used in this study, is the *Pearson product moment correlation coefficient*. The Pearson correlation coefficient,  $r$ , between two time series,  $x_i$  and  $y_i$ , is defined as

$$r = \frac{\sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^N (x_i - \bar{x})^2 \sum_{i=1}^N (y_i - \bar{y})^2}} \quad (3.1)$$

where  $\bar{x}$  and  $\bar{y}$  are the averages of time series  $x_i$  and  $y_i$ , respectively, i.e.,  $\bar{x} = (\sum x_i)/N$  and  $\bar{y} = (\sum y_i)/N$ ; and  $N$  is the number of data pairs. The correlation coefficient  $r$  describes the degree of closeness to a linear relationship between two variables  $x$  and  $y$ . The value of  $r$  varies from -1 for a "perfect" out-of-phase correlation to +1 for a "perfect" in-phase correlation; and the coefficient of zero indicates that no linear relationship exists.

**Standard significance test** The statistical significance of the linear correlation between the variables  $x$  and  $y$  can be found by testing the correlation coefficient  $r$  and referring to the table of two-tailed significance level of correlation coefficient with  $(N-2)$  df (degrees of

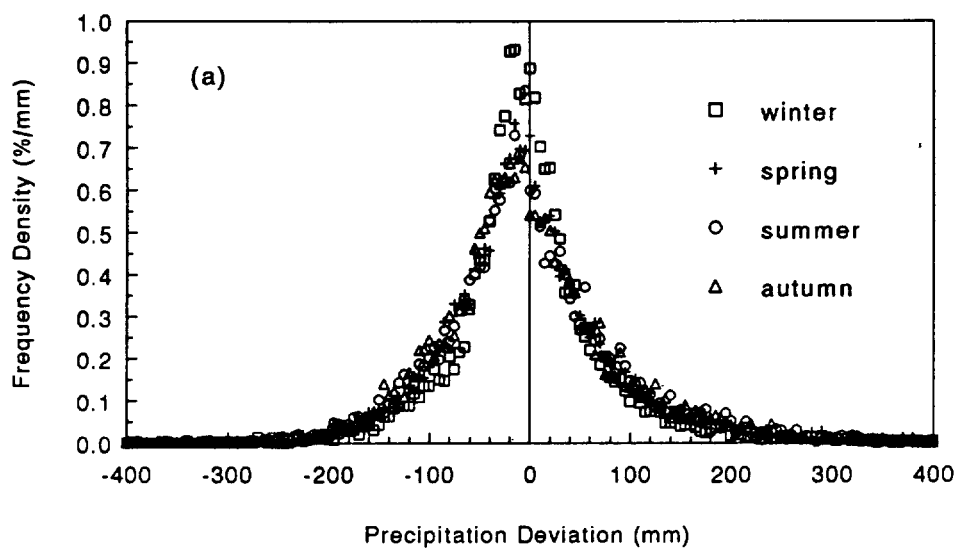
freedom) [Snedecor and Cochran, 1980]. For example, the 95% significant level of  $r$  for 78 df, i.e. 80 data pairs, is approximately  $\pm 0.22$ . This means that if  $r > 0.22$  or  $r < -0.22$  there is a 95% chance that the estimated correlation coefficient is different from zero. To estimate the confidence limits of a correlation coefficient,  $r$  should be first transformed to a quantity  $z$  which is distributed almost normally with standard error approximately  $\sigma_z = (n-3)^{-1/2}$  [Snedecor and Cochran, 1980]. The relation of  $z$  to  $r$  is given by

$$z = (1/2)[\ln(1+r) - \ln(1-r)] \quad (3.2)$$

Then confidence limits of  $z$  are obtained, based on its normal distribution, as  $z \pm z_{95\%} \sigma_z$  for 95% confidence level and here  $z_{95\%} = 1.96$ . Finally the confidence limits of  $z$  are transformed back to  $r$  according to (3.2) to obtain confidence limits of  $r$ .

This standard significance test of correlation coefficient  $r$  is based on an assumption that variables  $x$  and  $y$  have a bivariate normal distribution. However, for the purpose of testing the null hypothesis that there is no correlation between  $x$  and  $y$ , the test of  $r$  is still applicable provided that one of variables is normally distributed [Snedecor and Cochran, 1980]. But often two variables are both far from normal, so distributions of precipitation and temperature data used in this study should be checked to see whether this standard test is applicable or not. For this purpose, 100 stations were randomly selected and frequency distributions of seasonal precipitation and temperature data from these 100 stations were plotted for each of four seasons (Figure 3.3) as well as for all four seasons (Figure 3.4). Each season has the total of 8,000 data for either precipitation or temperature and all four seasons have the total of 32,000 data. The normal curves with the mean and variance of the data were also plotted in the distributions for all four seasons. Obviously distributions of precipitation

### Frequency Distribution of Precipitation (each of four seasons)



### Frequency Distribution of Temperature (each of four seasons)

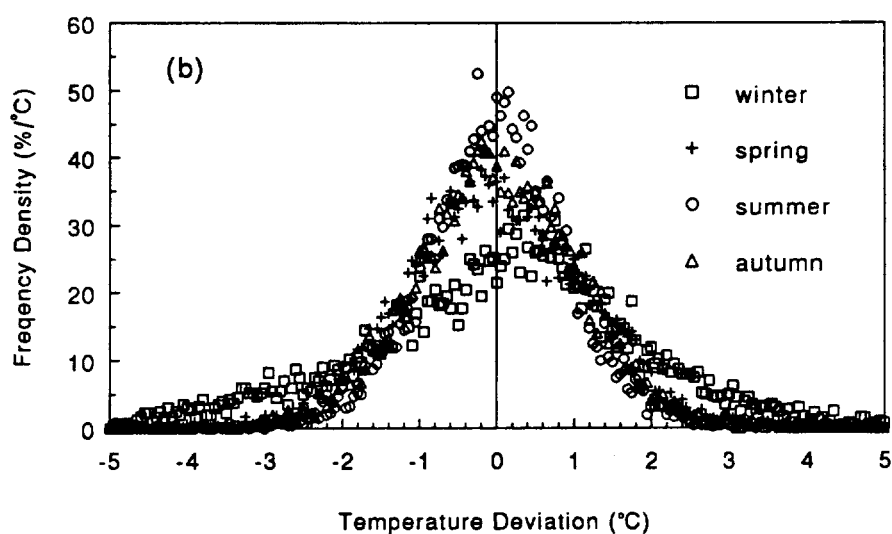
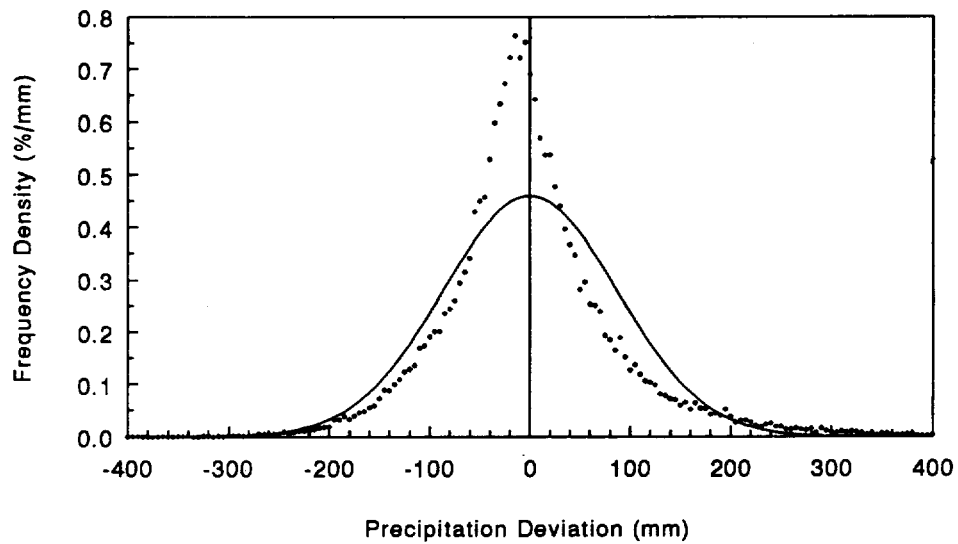


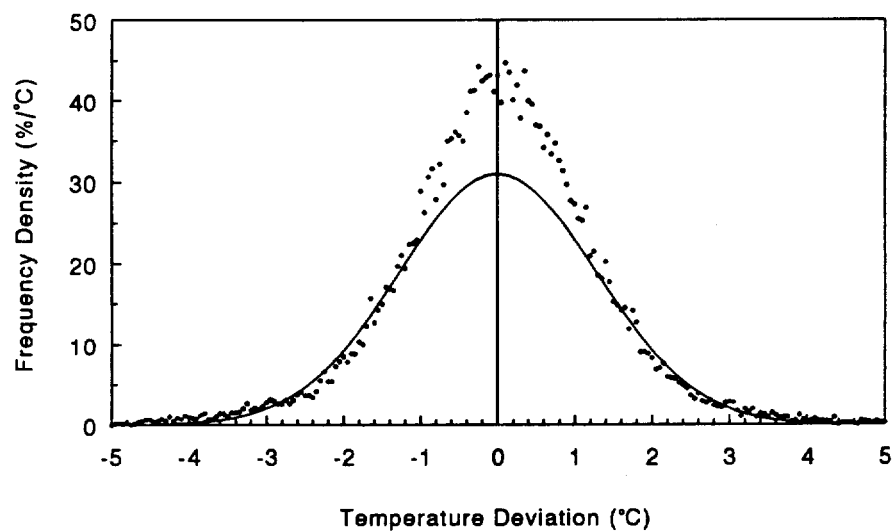
FIGURE 3.3. Frequency distributions of (a) precipitation and (b) temperature of each of four seasons from 100 randomly selected stations. Each season has 8,000 precipitation and temperature data, respectively.



### Frequency Distribution of Precipitation (all four seasons)



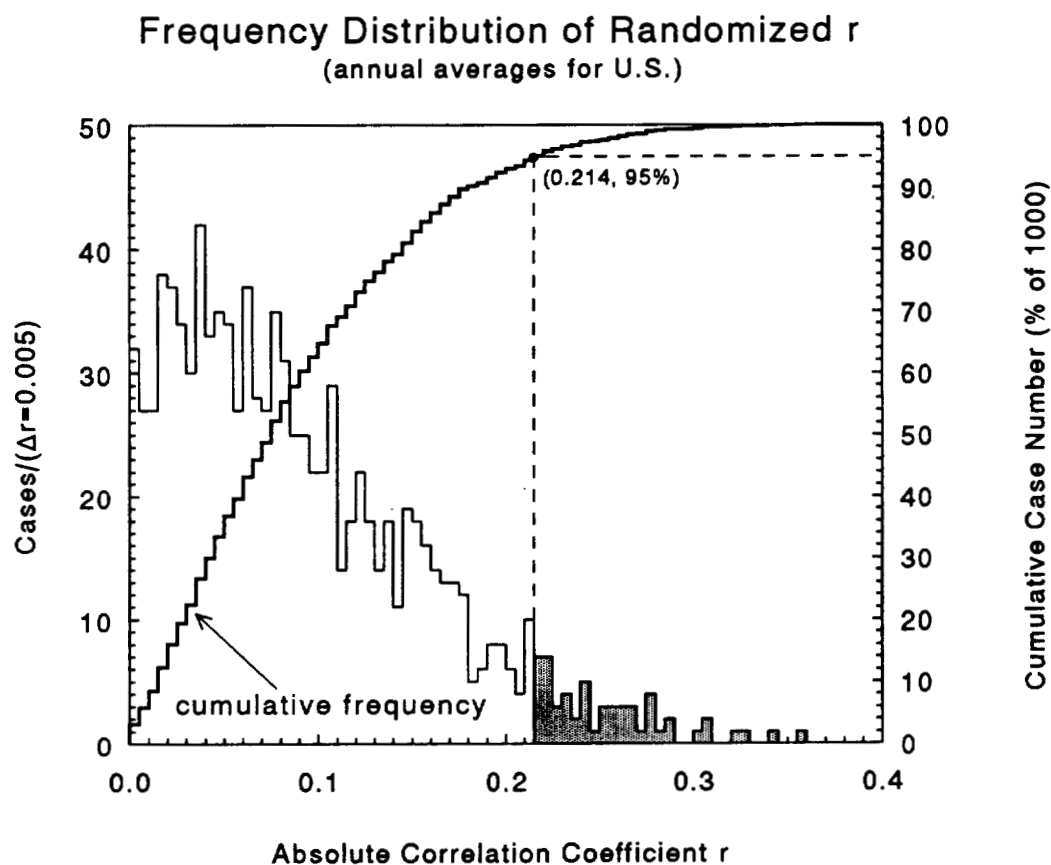
### Frequency Distribution of Temperature (all four seasons)



**FIGURE 3.4.** Frequency distributions (dots) of precipitation and temperature of all four seasons from 100 randomly selected stations. Total of 32,000 data were used to obtain the distributions for precipitation and temperature, respectively. Solid curves are normal distributions with means and variances of the precipitation and temperature data, respectively.

are far from normal and temperature is not normal either though it is closer to a normal distribution, which seems that the standard test of  $r$  is not valid.

*Significance test by Monte Carlo simulations* When the standard test is not applicable, Monte Carlo simulations described by Karl *et al.* (1986) can be used to determine the significance of  $r$ . The essential feature of Monte Carlo methods involves replacing the original ordered set of one of two time series with another randomly reordered set, or randomly mismatching two time series. Then Pearson correlation coefficient between randomly mismatched two time series is calculated and such correlation coefficient can be called as *randomized* correlation coefficient. This procedure is performed enough times with each trial having a new order of the time series to obtain a frequency distribution of randomized correlation coefficients. For each of 100 randomly selected stations and each of the seven regions, 1000 correlation coefficients were calculated by randomly reordering 80 temperature data (it is equivalent if precipitation data are chosen for randomization) for each of four seasons as well as annual means. The 95% significance level were then determined by finding the correlation coefficient corresponding to tailed 5% cumulative frequency of distributions of 1000 randomized correlation coefficients. An example of frequency distribution of randomized precipitation-temperature correlation coefficients is given in Figure 3.5 which shows both of case numbers within intervals of  $\Delta r=0.005$  and cumulative case numbers within range from 0 to particular values of  $|r|$  for U.S. and annual averages. The randomized correlation coefficient at 95% significance level is also indicated in this figure. To be significant at the 95% level, the magnitude of the observed correlation coefficient would be exceeded the value at 95% significance level. The resulting 95% levels for seven regions are listed in Table 3.4. Thus obtained 95% significance levels are very closed from station-to-station, season-to-season, and region-to-region and rarely differed by more than 0.02. Actually,



**FIGURE 3.5.** Frequency distribution of 1,000 randomized correlation coefficients between annual averages of monthly total precipitation and monthly mean temperature of U.S.. Light solid lines are case numbers within each interval of  $\Delta r=0.005$ , while the bold solid curve shows cumulative case numbers between 0 and particular values of  $|r|$ . Shaded area indicates the 5% tailed cumulative frequency. The correlation coefficient at 95% significance level  $r_{95\%}$  for this particular case is approximately 0.219.

TABLE 3.4. 95% significance levels obtained by Monte Carlo significance testing of correlation coefficients between precipitation and temperature for regions and seasons. An absolute correlation coefficient of the tabulated value or larger is statistically significant at 95% level.

Region	winter	spring	summer	autumn	annual
Pacific Coast	0.213	0.221	0.229	0.217	0.216
Western Rockies	0.219	0.230	0.210	0.220	0.217
Eastern Rockies	0.227	0.220	0.229	0.231	0.223
Agricultural West	0.213	0.230	0.218	0.226	0.226
Agricultural East	0.216	0.211	0.215	0.225	0.223
Eastern Coast	0.221	0.215	0.222	0.226	0.235
Southern Area	0.219	0.213	0.216	0.225	0.223
U.S.	0.218	0.220	0.216	0.227	0.219

the 95% significance levels obtained by Monte Carlo method were within  $\pm 0.01$  from one that was estimated by assuming normality of variables. Therefore, single correlation coefficient can be chosen to represent the 95% significance level and it would not be largely different if the value estimated by standard method is chosen as the one (e.g.  $r_{95\%} = \pm 0.22$  for  $N=80$ ).

**Rank correlation coefficient** An alternative way to overcome the difficulty of non-normality of variables is to appraise the closeness of two variables by calculating their *rank* correlation coefficient. The equation (3.1) is still applicable in this method, but instead of  $x_i$  and  $y_i$  themselves, ranks of  $x_i$  and  $y_i$  are used. There are several ways to rank data. Here the way we used is to rank data of each time series based on their magnitude order; that is, for a time series with  $N$  data, the largest data is ranked as  $N$ , the second largest one is ranked as  $N-1$ , ... and the smallest one is ranked as 1. Significance of ranking correlation coefficients can be tested by referring the same table of two-tailed significance level of  $r$  with  $N-2$  df for number of data pairs larger than 10 [Snedecor and Cochran, 1980].

In this study, Pearson correlation coefficients between precipitation and temperature were calculated for data from each station for each month and season as well as for state averages for each month. For regional and the U.S. averages for each season and for the year, both Pearson and ranking correlation coefficients were obtained and comparison of their results was made.

### 3.3.3. Linear regression analysis

Another method to investigate the linear relationship of two variables is by linear regression analysis. The linear regression function of the variable  $y$  on the variable  $x$  takes form

$$y = a + bx \quad (3.3)$$

where  $a$  is the regression constant and  $b$  is regression coefficient. The values of  $a$  and  $b$  can be estimated by the method of *the least square fitting* (see *Draper and Smith, 1966*). In the least square fitting, the criterion for determining the regression coefficients is that  $a$  and  $b$  are chosen so as to minimize the quantity

$$V = \sum_{i=1}^N (y_i - a - bx_i)^2 \quad (3.4)$$

The values of  $a$  and  $b$  are estimated as

$$b = \frac{\sum_{i=1}^N (\Delta x_i)(\Delta y_i)}{\sum_{i=1}^N (\Delta x_i)^2} \quad (3.5)$$

and

$$a = \bar{y} - b\bar{x} \quad (3.6)$$

where  $\Delta x_i = x_i - \bar{x}$  and  $\Delta y_i = y_i - \bar{y}$  are the  $i$ th deviations of  $x_i$  and  $y_i$ , respectively. The significance level can be calculated by using Student's  $t$  test and referring the table of distribution of  $t$  with  $(N-2)$  degrees of freedom for  $N$  data pairs. The  $t$ -value for the estimate of  $b$  is calculated by

$$t_b = b \sqrt{\frac{N}{\sum_{i=1}^N (\Delta x_i)^2 / s^2}} \quad (3.7)$$

and the  $t$ -value for the estimate of  $a$  is

$$t_a = a \sqrt{N \sum_{i=1}^N (\Delta x_i)^2 / \left( s^2 \sum_{i=1}^N x_i^2 \right)} \quad (3.8)$$

where  $s^2$  is an estimate of the regression variance based on  $(N-2)$  degrees of freedom given by

$$s^2 = V / (N-2) \quad (3.9)$$

and  $V$  is defined by (3.3). Actually, the  $t$ -test of the linear regression coefficient  $b$  is identical to the test of correlation coefficient  $r$  [Snedecor and Cochran, 1980].

Another useful quantity for appraising the closeness of the relation between two variables is the ratio of the regression variance to the variance of  $y$  without fitted regression. The ratio measures the "proportion of the variance of  $y$  that is not associated with its linear regression on  $x$ " and has the relation with the correlation coefficient  $r$  as

$$\begin{aligned} \frac{\text{regression variance}}{\text{variance of } y} &= \frac{\sum (y_i - a - bx_i) / (N-2)}{\sum (y_i - \bar{y}) / (N-1)} \\ &= \frac{N-1}{N-2} \left( 1 - \frac{\left( \sum \Delta x_i \Delta y_i \right)^2}{\sum \Delta x_i^2 \sum \Delta y_i^2} \right) \approx 1 - r^2 \end{aligned} \quad (3.10)$$

if  $N$  is at large. Thus  $r^2$  is approximately the estimated proportion of the variance of  $y$  that can be attributed to its linear regression on  $x$ , while  $(1-r^2)$  is the proportion free from  $x$ .

For non-normal variables, the significance testing of linear regression can also be conducted by Monte Carlo simulations. Again data of temperature were randomly reordered and random fitting parameters were obtained as well as  $r^2$ , and the procedure was repeated for 1000 times. The significance levels were obtained by referring the frequency distributions of  $r^2$ . So the Monte Carlo testing for linear regression is identical to its testing for correlation coefficient.

In this study the linear regressions are calculated for the time series of regional average deviations of precipitation and temperature for the seasons and regions where the correlation between precipitation and temperature is significant at 95% level. The significance level of regression coefficient or slope is evaluated by  $t$ -test.

#### 3.3.4. Correlation in various time-scale variations

One approach to describe the contributions from various time-scale variations to the total correlation between precipitation and temperature is first to split up the time series into several portions according to the different time-scales and then to construct the correlations for each of the time-scales. One method that can be used to separate the variations of different time-scales is the digital filtering method.

Digital filtering techniques can be applied to a time series to filter out variations of certain frequencies and retain other time-scale variations. Digital filtering is simply the process by which a set of input data or original time series,  $x_i$ , is transformed into a set of output data or filtered time series,  $y_i$ , by means of a linear transfer function. A simple and frequently used digital filter is the so called "*moving-average filter*". For a time series with  $N$  data points,  $x_1, x_2, x_3, \dots, x_N$ , the  $(2m+1)$  points moving-average filter is defined as



$$y_i = \frac{1}{2m+1} \sum_{j=-m}^m x_{i+j} \quad (3.11)$$

The  $i$ th data point of the filtered time series,  $y_i$ , is an average of  $(2m+1)$  original data points,  $x_{i-m}, x_{i-m+1}, \dots, x_{i+m-1}, x_{i+m}$ . The  $(2m+1)$  points moving average is thus obtained from the original time series by averaging the original data within a window that is  $(2m+1)$  time units wide. This simple moving-average filter is a low-pass filter which can smooth out high frequency or short cycle variations from an original time series. The  $(2m+1)$  points moving-average filter removes variations with cycle less than  $(2m+1)$  time units and retain variations with cycles larger than  $(2m+1)$  time units.

By subtracting the output of a low-pass filter from the original data, we can obtain a high-pass filter. If the  $(2m+1)$  points moving averages are subtracted from the original time series, we obtain a time series of which the variations of cycle shorter than  $(2m+1)$  time units or higher frequency remain and the variations of cycle longer than  $(2m+1)$  time units or lower frequency are removed. The  $(2m+1)$  points high-pass moving-average filter can be written as

$$z_i = x_i - y_i = x_i - \frac{1}{2m+1} \sum_{j=-m}^m x_{i+j} \quad (3.12)$$

Combining the filters with different numbers of moving average points, we can obtain a band-pass filter which allows cycles within a certain frequency band to pass through the filter and the others are removed. For example, a filter with pass band between  $(2m+1)$  to

$(2n+1)$  time units can be defined as

$$b_i = \frac{1}{2m+1} \sum_{j=-m}^m x_{i+j} - \frac{1}{2n+1} \sum_{j=-n}^n x_{i+j}, \quad (m < n) \quad (3.13)$$

Thus this filter can adjust a time series by removing the variations with cycle shorter than  $(2m+1)$  time units and longer than  $(2n+1)$  time units.

Moving-average filtering is a convenient method to partition a time series based on various time-scales. The original time series,  $x_i$ , can be split up according to

$$x_i = x_i^{(1)} + x_i^{(2)} + \dots + x_i^{(k)} \quad (3.14)$$

by using a bank of moving-average filters. In this study, the original time series are partitioned into three cycle bands - cycles shorter than 5 years, between 5 and 15 years, and longer than 15 years - by using high-pass, band-pass, and low-pass filters respectively. An original time series is first subjected to a 5-year moving-average filter and then the output data are subtracted from the original data, so that we obtain a time series with cycles shorter than 5 years. To obtain the time series in medium frequency band, the original time series is filtered by both 5-year and 15-year moving-average filters and the output data of the 15-year filter are subtracted from the output data of the 5-year filter. The data of low frequency band are obtained simply by passing the original time series through the 15-year moving-average filter. The correlation coefficients between precipitation and temperature for the filtered time series are then computed. The procedure is applied for each individual station.

The main advantage of moving-average filters is the ease of calculation. However, one drawback of moving-average filters is that the total number of output data points is less than

the number of the original data. For example, a  $N$ -point time series, after filtering by  $(2m+1)$  points filter, will have only  $N-2m$  data points. Both the first and last  $m$  points are lost due to insufficient data points for averaging in the beginning and end of the time series.

## CHAPTER 4. RESULTS AND DISCUSSION

In this chapter the results of data analysis are presented. First, the spatial patterns of correlation coefficients between precipitation and temperature at individual stations in the United States are illustrated for each month and each season as well as the correlation coefficients for state and regional averages. Secondly, the results of linear regression analysis on precipitation-temperature relationship are presented. Then, the contribution to the total correlation between precipitation and temperature from three cycle bands are analyzed in terms of the moving-average filtering. Finally, the features of the precipitation-temperature relationship are discussed for two special areas in the continental United States.

### 4.1. Correlation Coefficients between Precipitation and Temperature

#### 4.1.1. Spatial distributions

Figure 4.1-4.4 illustrate the distributions of the total linear correlations between seasonal averages of monthly total precipitation and monthly mean temperature for each season as well as those between monthly total precipitation and monthly mean temperature for each month during 80-year period. The maps show the contours of product-moment correlation coefficients between precipitation and temperature. The 95% statistical significance level of the correlation coefficient is approximately  $\pm 0.22$  and this value is indicated by dashed lines in each of the maps.

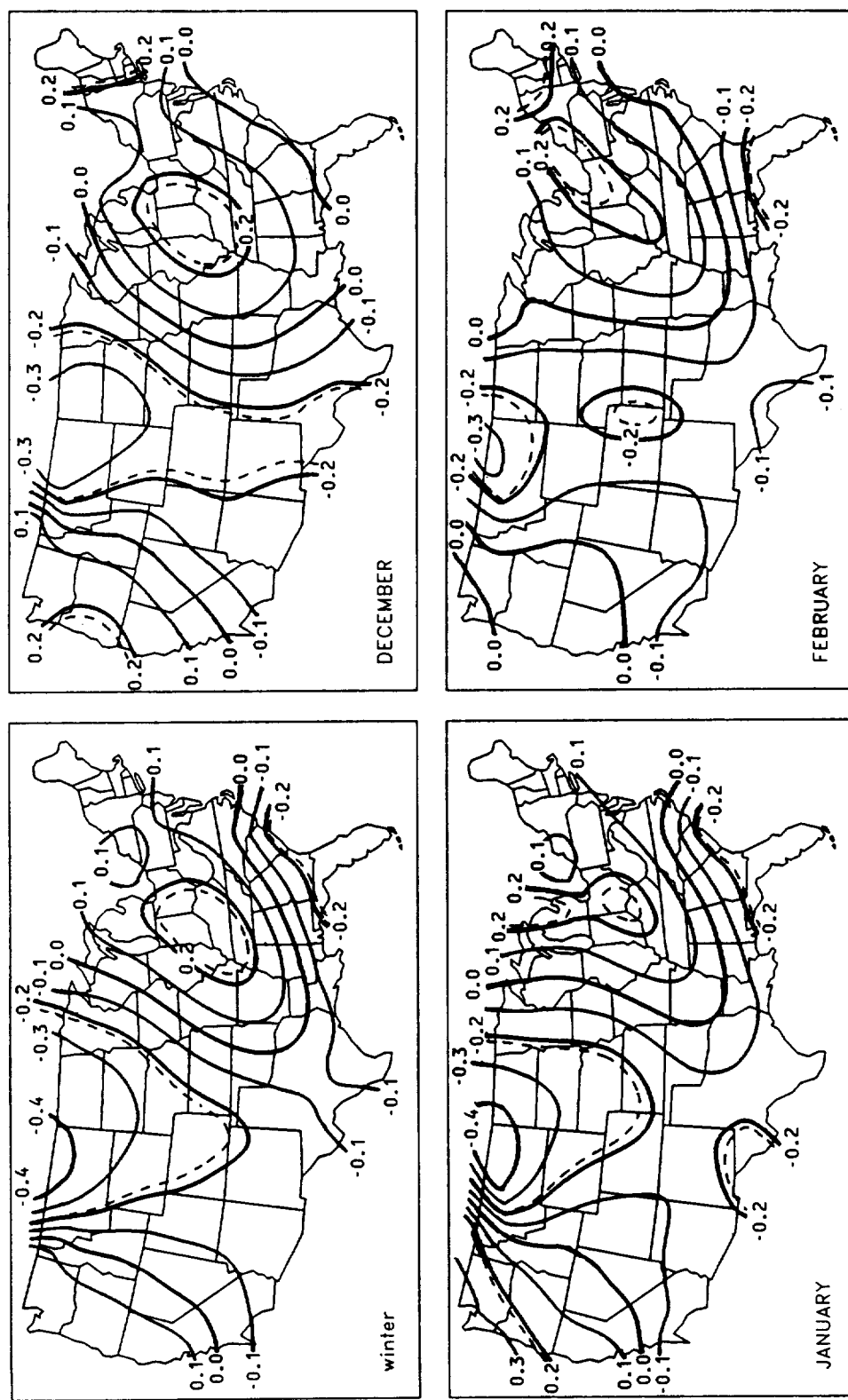
a. Correlation for winter

Figure 4.1 shows the spatial patterns of precipitation-temperature correlation for winter season and three winter months - December, January and February. The regions of positive and negative correlation both were found in winter.

For winter season as a whole, in the northern and central Great Plains, the region extending from Montana and North Dakota in the north to Colorado and Kansas in the south, bounded on the west by the Rocky Mountains and on the east by Minnesota-Iowa, a significant negative correlation was observed; that is, the warm winters were usually dry winters and cold winters were most likely wet winters during the 80 year period in this area. The correlation coefficients can be less than -0.5 at some stations in Montana and the lowest value of -0.63 was obtained at Cascade (Station Cascade 5S, 47.2°N, 111.7°W), Montana. The significant negative correlations between precipitation and temperature were also found in Florida.

There is a region south of the Great Lakes and bounded on east by the Appalachian Mountains, including Indiana, western Ohio, southeastern Illinois, most of Kentucky, and part of Tennessee, where the correlation between precipitation and temperature is positive and significant at 95% level, showing warm and wet or cold and dry weather occurred more frequently in this area. The correlation coefficients are about 0.3 at most stations within this area and reach the maximum value of 0.56 at Tullahoma (35.3°N, 86.2°W), Tennessee. The Great Lakes could be one of contributors to the positive precipitation-temperature relationship in this region. The other areas do not exhibit any remarkable correlations between precipitation and temperature, except a few scattered locations where either significant negative or positive relationship were found.

The patterns of precipitation-temperature relationship for each winter month is similar



**FIGURE 4.1.** Contours of the correlation coefficient between monthly total precipitation and monthly mean temperature for seasonal averages in winter and for three winter months. Dashed lines indicate the 95% statistical significance level of correlation coefficient.

to the seasonal pattern, but the differences among the monthly patterns and seasonal patterns are evident.

The significant negative correlation region in the middle United States extends southward to New Mexico and western Texas in December, which is at its maximum size during winter season; in January, this region splits into two portions: the larger area in the northern and central Great Plains and the small one in the far west of Texas south to New Mexico; in February the significant correlations only remain in the area around Colorado-Kansas border and the area covering eastern Montana and northwestern North Dakota. Therefore, the inter-monthly variation showed that the negative precipitation-temperature relationship in the middle United States gradually lost its significance from early winter to later winter. Similar changes also happened in the area south of the Great Lakes: this positive correlation region in December with similar size and position of seasonal pattern shrinks to a much smaller area covering southern Ohio, northern Kentucky, and northwestern Indiana in January and only Ohio and north shore areas of Lake Erie and Lake Ontario had the significant positive relationship in February. The negative relationship persists in Florida through the entire winter season but is significant only in January and February.

The significant positive relationship was found within New England for both December and January, a feature not revealed in the seasonal pattern. Moreover, western Oregon had a significant positive precipitation-temperature relationship in December; and this warm-wet or cold-dry weather pattern extended to cover northwestern Oregon and most of Washington during January; but became statistically insignificant in February.

b. Correlation for spring

As the transition season between winter and summer, spring does not exhibit strong

relationship between precipitation and temperature (Figure 4.2).

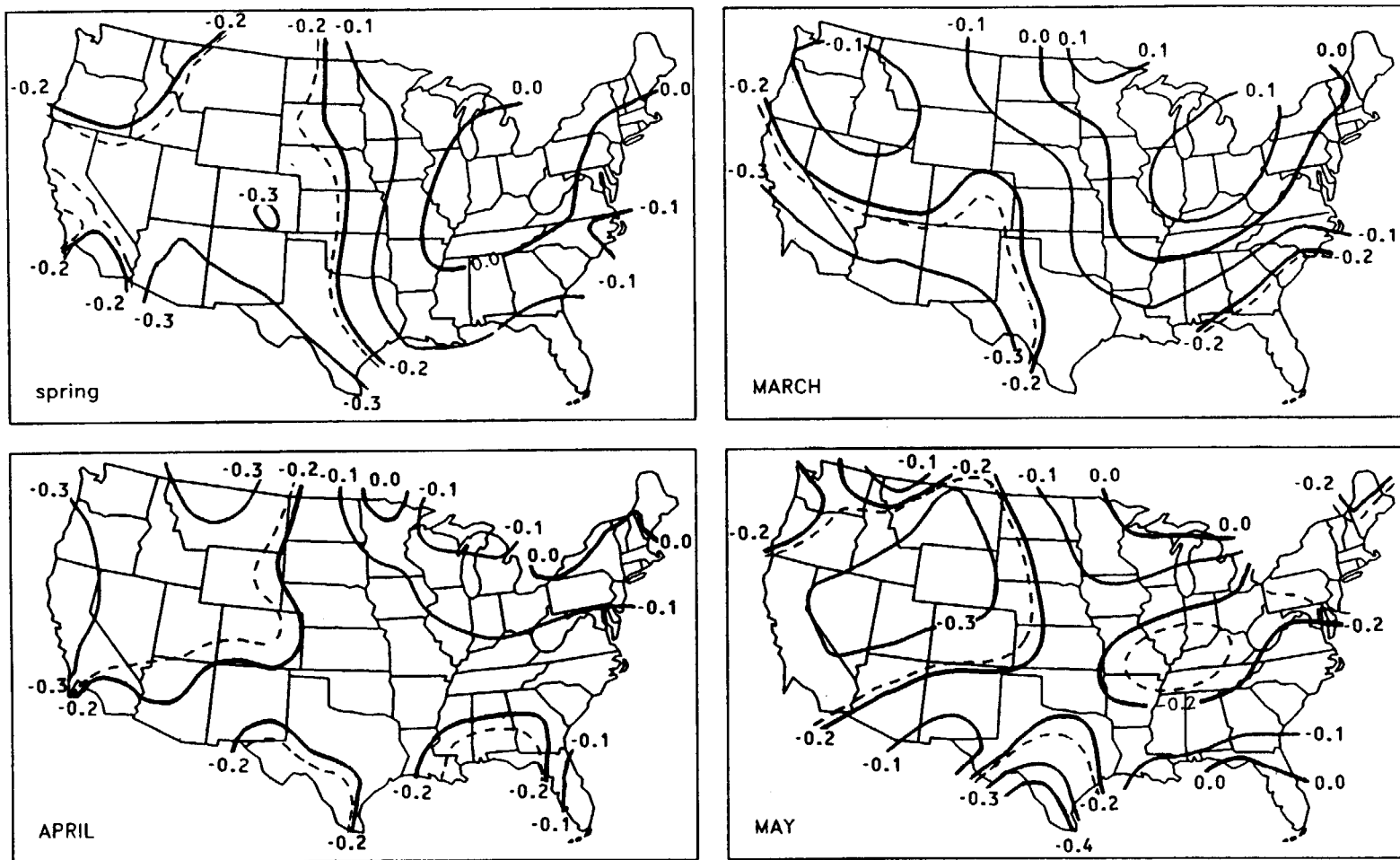
Significant negative correlations were obtained for seasonal averages in the West except the Northeast and southern California. Though significant at 95% statistical significance level for most stations within this region, the correlation coefficients are rarely less than -0.4 and only at a few stations reach below -0.3. Month to month variation of spatial distribution of the relationship in spring reveals the transition process from winter pattern to summer pattern (see Section 4.1.1c for summer pattern). In March, the significant warm-dry or cold-wet weather pattern in the middle continent during winter disappeared; the positive correlation in the area south of the Great Lakes becomes statistically insignificant in March though it is still positive and is reduced to negative but insignificant values in April. In Florida the significant negative correlation occurs in March as well as in January and February, but vanishes during April and May. The significant negative correlation starts to appear in the Southwest in March and extends to cover most of the West in April and May; and in the South and East more and more areas show a significant negative correlation from April to May.

c. Correlation for summer

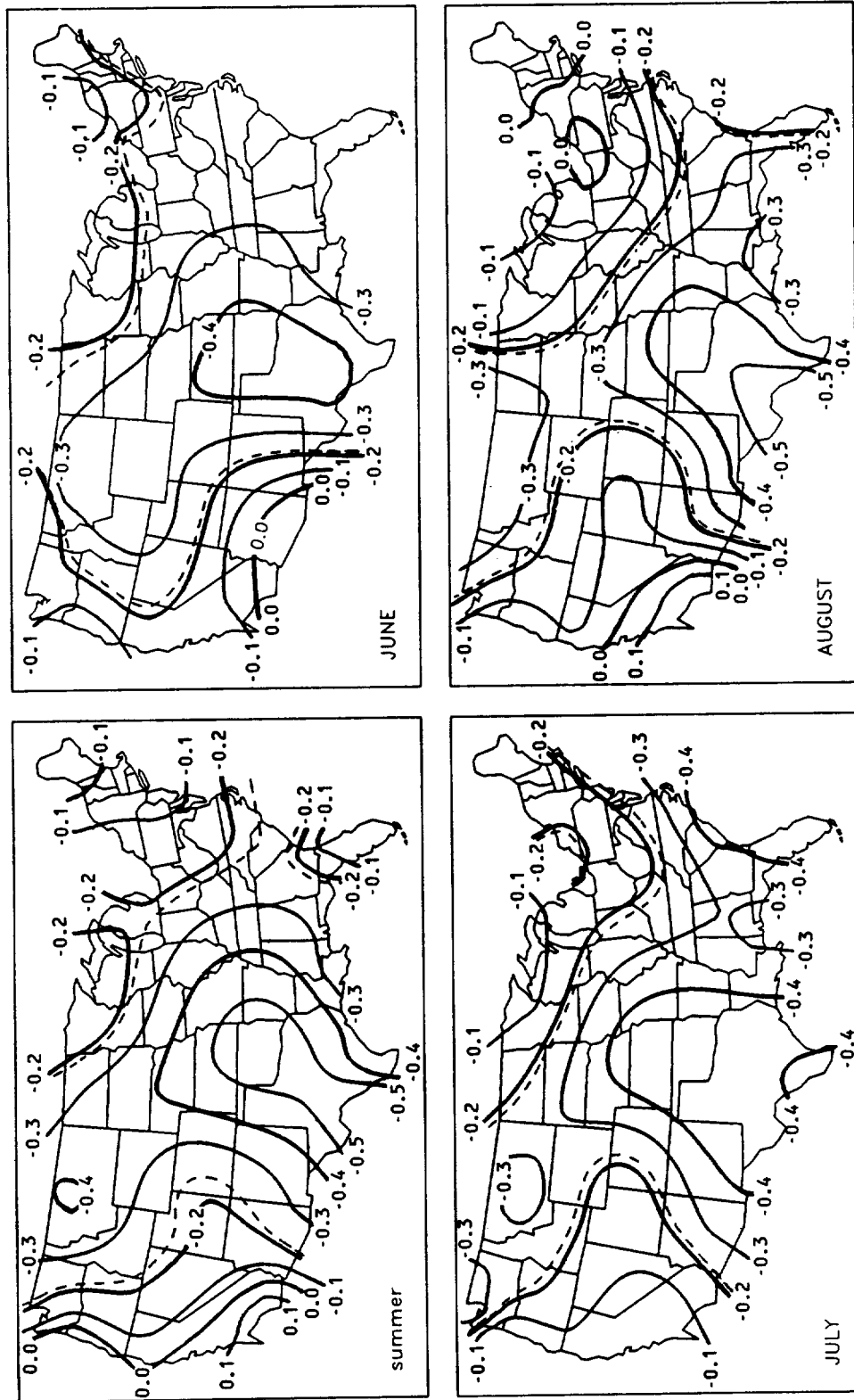
In contrast to winter, the summer pattern of the precipitation-temperature relationship is simple and clear (Figure 4.3).

For summer season as a whole, large parts of the U.S. exhibit a significant negative correlation, except the Pacific coast, northern reaches of Minnesota and Wisconsin, Florida, and the area extending northeastward from Maryland-Pennsylvania to New England. The warm-dry or cold-wet weather, therefore, was the predominant summer precipitation-temperature pattern in the continent, a feature which has been shown before, as mentioned





**FIGURE 4.2.** Contours of the correlation coefficient between monthly total precipitation and monthly mean temperature for seasonal averages in spring and for three spring months. Dashed lines indicate the 95% statistical significance level of correlation coefficient.



**FIGURE 4.3.** Contours of the correlation coefficient between monthly total precipitation and monthly mean temperature for seasonal averages in summer and for three summer months. Dashed lines indicate the 95% statistical significance level of correlation coefficient.

in Chapter 1. The correlation coefficients are below -0.4 in the central and southern Great Plains and Mississippi Valley with minimum center located in Oklahoma. The lowest value is -0.74 and was found at El Dorado (37.8°N, 96.8°W), Kansas.

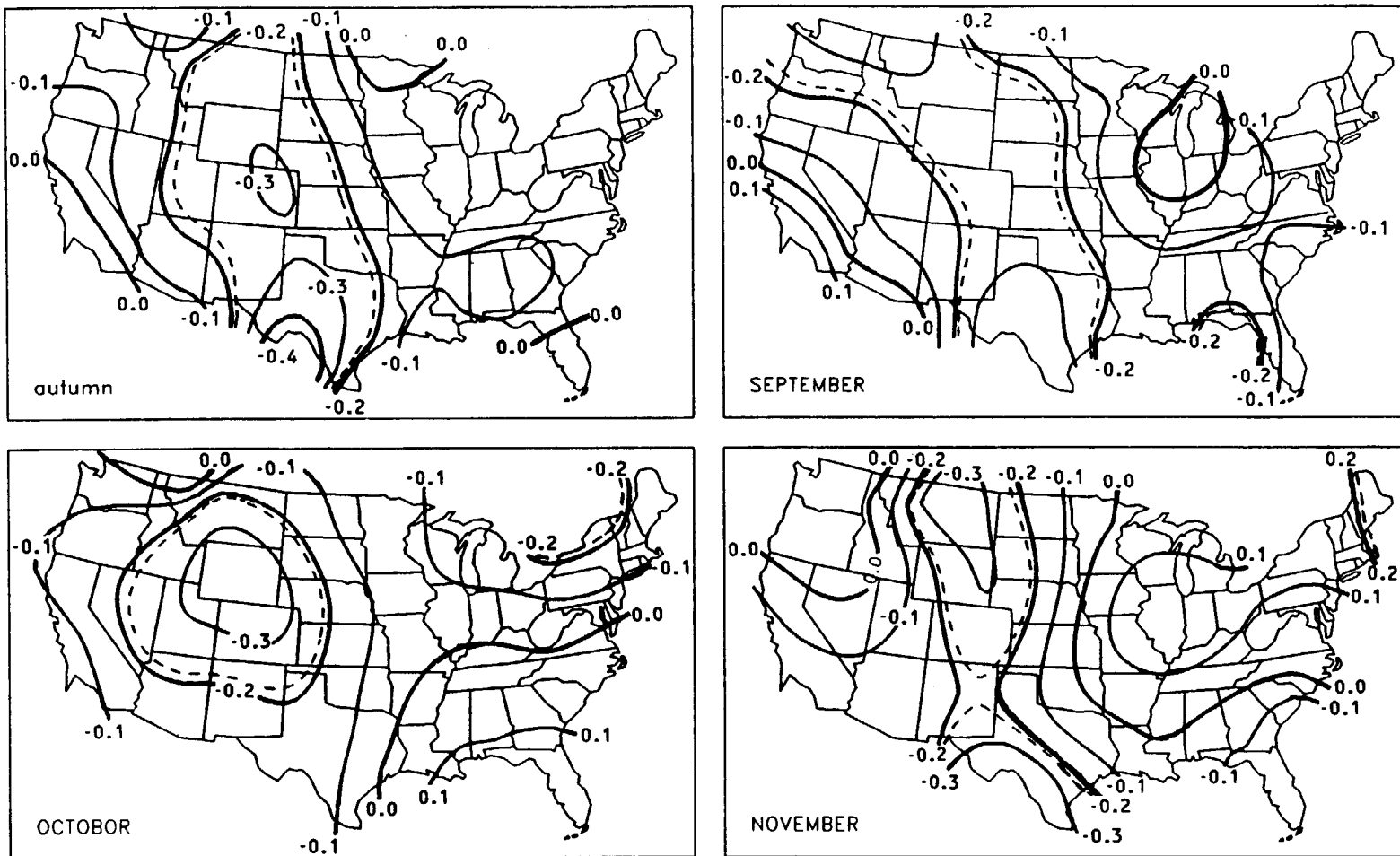
Month to month variation also exists through summer months. The region of negative relationship is at its largest size in June and narrows down from June to August, while the strong negative correlation remains in the central and southern Great Plains through the entire summer season.

d. Correlation for autumn

Similar to spring, autumn is the transition season between summer and winter. The main area of notable negative correlation only shows up in the middle West through the autumn season (Figure 4.4). In November the distribution of the correlation has a pattern similar to that in December. A strong negative correlation exists in the middle U.S. continent; the positive correlation, though insignificant at 95% level, occurs in the area south of the Great Lakes; the significant positive correlation occurs in Maine, the area extends to cover New England in December; and in Florida correlation has insignificant negative value and becomes significant in December.

The fact that monthly patterns are more noisy than seasonal patterns indicates that the distribution of precipitation-temperature relationship could be extremely variable from month to month and this variation is smoothed out for seasonal averages which give the relatively stable results.

Spatial distribution of precipitation-temperature correlation also shows that in general the strong correlation usually exists in the middle and middle west of the United States while



**FIGURE 4.4.** Contours of the correlation coefficient between monthly total precipitation and monthly mean temperature for seasonal averages in autumn and for three autumn months. Dashed lines indicate the 95% statistical significance level of correlation coefficient.

the Pacific coast and east coast do not display remarkable correlations through the entire year. This feature will be further illustrated in the next two sections in which the characteristics of precipitation-temperature relationships are discussed for state and regional averages.

#### 4.1.2. For state averages

To further investigate the features revealed in the last section, we calculated the correlation coefficients between state averages of monthly total precipitation and monthly mean temperature for each state and for each month of the year. The correlation coefficients are listed in Table 4.1 and illustrated as bar charts in Figure 4.5-4.12. The results indicate the variation of the precipitation-temperature relationship from month to month in each state. We categorized the 48 states in the continental United States into 8 geographical groups and discuss them accordingly.

##### a. Pacific States

Figure 4.5 shows the correlation coefficients between precipitation and temperature in three Pacific states - Washington, Oregon, and California.

Washington and Oregon have similar month to month variation of precipitation-temperature relationship. During winter months, both states show the positive precipitation-temperature relationship and the correlations are statistically significant in December and January. The relationship mostly represents the feature of the west portion of two states - the area of the United States where winter is the wettest season. The significant precipitation-temperature correlation is probably related to the frequent passage of winter cyclonic depressions which originate on the North Pacific. Northern depressions are attended by warm and wet weather; southern depressions by cool and dry weather in this area [Blair, 1931a].

TABLE 4.1. Correlation coefficients between monthly total precipitation and monthly mean temperature in each state.

State	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
WA	0.46	0.13	-0.06	-0.40	-0.37	-0.35	-0.57	-0.34	-0.46	-0.07	0.18	0.37
OR	0.30	0.17	-0.13	-0.49	-0.36	-0.33	-0.51	-0.25	-0.41	-0.19	0.20	0.38
CA	0.15	0.02	-0.30	-0.45	-0.49	-0.42	-0.04	-0.10	-0.11	-0.23	-0.08	0.15
NV	-0.05	-0.03	-0.12	-0.26	-0.44	-0.39	-0.94	-0.04	-0.13	-0.38	0.10	0.12
ID	0.33	0.17	0.07	-0.35	-0.36	-0.34	-0.51	-0.36	-0.29	-0.15	0.23	0.29
UT	0.09	0.13	-0.10	-0.43	-0.56	-0.53	-0.20	0.05	-0.24	-0.50	-0.08	-0.12
AZ	-0.11	0.03	-0.31	-0.27	-0.23	0.15	-0.47	-0.23	-0.09	-0.22	-0.16	-0.22
MT	-0.54	-0.50	-0.15	-0.47	-0.48	-0.59	-0.55	-0.54	-0.42	-0.55	-0.51	-0.45
WY	-0.31	-0.32	-0.26	-0.37	-0.52	-0.53	-0.33	-0.08	-0.42	-0.63	-0.39	-0.30
CO	-0.14	-0.31	-0.33	-0.36	-0.48	-0.48	-0.29	-0.05	-0.33	-0.50	-0.43	-0.37
NM	-0.12	-0.27	-0.33	-0.21	-0.12	-0.37	-0.68	-0.37	-0.24	-0.26	-0.22	-0.36
ND	-0.48	-0.25	0.11	-0.15	-0.10	-0.29	-0.20	-0.36	-0.31	-0.03	-0.15	-0.55
SD	-0.31	-0.11	0.07	-0.06	-0.13	-0.35	-0.45	-0.31	-0.41	-0.12	-0.17	-0.48
NE	-0.40	-0.17	-0.20	-0.21	-0.25	-0.50	-0.71	-0.54	-0.30	-0.20	-0.12	-0.17
KS	-0.25	-0.13	-0.16	-0.11	-0.22	-0.59	-0.73	-0.59	-0.27	-0.17	0.05	0.03

TABLE 4.1. (Continued)

State	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
OK	-0.01	-0.03	-0.06	-0.10	-0.17	-0.56	-0.64	-0.70	-0.36	-0.14	0.03	0.09
TX	-0.14	-0.18	-0.23	-0.24	-0.33	-0.61	-0.70	-0.71	-0.44	-0.14	-0.16	-0.13
IA	-0.15	0.07	0.01	-0.12	-0.07	-0.27	-0.46	-0.17	0.08	-0.05	0.22	0.10
MO	0.03	0.18	0.10	-0.14	-0.37	-0.54	-0.53	-0.49	0.04	-0.07	0.24	0.25
AR	0.15	0.24	0.07	-0.15	-0.32	-0.59	-0.56	-0.57	-0.09	0.04	0.14	0.26
LA	-0.04	-0.10	-0.11	-0.29	-0.06	-0.30	-0.48	-0.35	-0.06	0.23	0.01	0.17
MS	0.16	0.21	-0.04	-0.30	-0.41	-0.38	-0.42	-0.18	0.15	0.07	0.23	0.25
MN	-0.17	-0.06	0.02	-0.11	-0.10	-0.12	-0.22	-0.07	-0.21	0.02	0.03	-0.21
WI	-0.04	0.21	0.13	-0.04	-0.01	-0.20	-0.25	0.02	0.15	-0.18	0.23	0.20
MI	0.13	0.26	0.13	-0.10	-0.16	-0.22	-0.20	0.03	0.14	-0.26	0.21	0.25
IL	0.15	0.25	0.26	-0.13	-0.33	-0.48	-0.43	-0.22	0.20	-0.04	0.26	0.35
IN	0.30	0.20	0.34	-0.11	-0.29	-0.34	-0.36	-0.04	0.17	-0.01	0.17	0.41
OH	0.38	0.32	0.23	-0.02	-0.30	-0.33	-0.06	0.18	0.05	-0.05	0.11	0.39
KY	0.45	0.36	0.27	-0.09	-0.32	-0.31	0.31	-0.16	0.01	0.11	0.15	0.40
TN	0.41	0.46	0.14	-0.06	-0.23	-0.36	-0.32	-0.31	-0.08	0.11	0.22	0.36

TABLE 4.1. (Continued)

State	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
WV	0.47	0.33	0.18	-0.17	-0.32	-0.23	0.00	0.26	0.03	-0.06	0.13	0.26
VA	0.09	0.04	-0.05	-0.32	-0.26	-0.36	-0.14	0.13	-0.19	-0.10	0.04	-0.01
NC	0.05	0.05	-0.07	-0.35	-0.21	-0.30	-0.26	-0.15	-0.21	0.07	0.11	0.07
SC	-0.15	0.01	-0.22	-0.30	-0.28	-0.34	-0.47	-0.36	-0.16	0.04	-0.04	0.06
AL	-0.01	0.11	-0.07	-0.27	-0.24	-0.41	-0.41	-0.49	-0.28	0.09	0.03	0.21
GA	-0.12	-0.02	-0.22	-0.30	-0.24	-0.35	-0.45	-0.36	-0.23	0.09	-0.14	0.15
FL	-0.37	-0.38	-0.32	-0.13	-0.00	-0.38	-0.36	-0.48	-0.22	0.27	-0.10	-0.03
N.E. <sup>a</sup>	0.17	0.38	0.04	0.00	-0.31	-0.16	-0.10	0.03	-0.19	-0.20	0.25	0.33
NY	0.20	0.33	0.06	0.03	-0.28	-0.16	-0.13	0.11	-0.22	-0.22	0.09	0.20
PA+ <sup>b</sup>	0.19	0.16	-0.05	-0.10	-0.26	-0.38	-0.13	0.11	-0.22	-0.15	0.09	0.18

<sup>a</sup> New England states - Maine, Vermont, New Hampshire, Massachusetts, Connecticut and Rhode Island.

<sup>b</sup> Pennsylvania, New Jersey, Delaware and Maryland.

Note: An absolute correlation coefficient of 0.22 or larger is statistically significant at the 95% level.



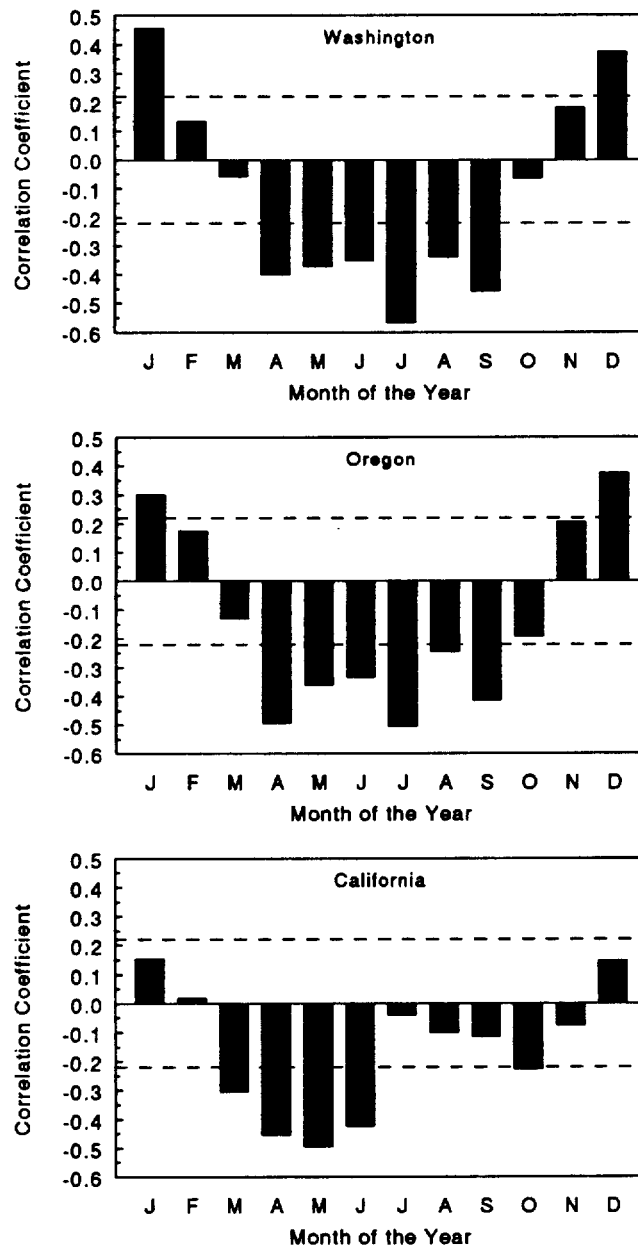


FIGURE 4.5. Correlation coefficients between monthly total precipitation and monthly mean temperature in each of the Pacific states: Washington, Oregon and California. Dashed lines indicate the 95% statistical significance level of correlation coefficient.

From April until September, the two states both have significant negative correlations between precipitation and temperature.

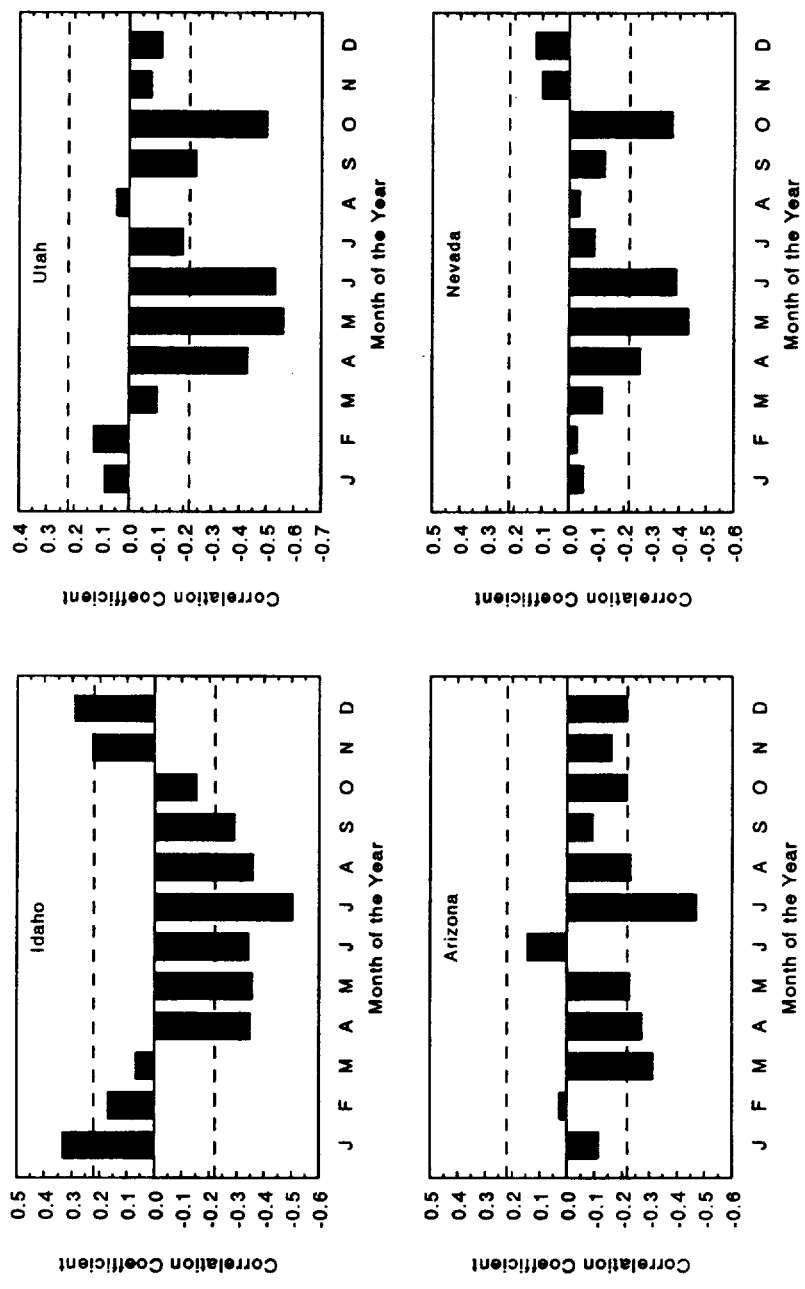
In California, winter months also have positive precipitation-temperature relationship but statistically insignificant. All spring months and also June show significant negative precipitation-temperature relationship, while later summer and autumn months do not show remarkable correlations.

b. Mountain states

All, or a larger part, of each of the following states are situated in the mountainous region of the Rocky Mountains: Nevada, Idaho, Utah, and Arizona on the west and Montana, Wyoming, Colorado, and New Mexico on the east. The precipitation-temperature relationship makes a broad distinction between the western states and eastern states in this region (Figure 4.6).

On the west, Idaho has the pattern of precipitation-temperature relationship similar to those of Washington and Oregon. December and January show the significant positive correlation; from April to September, correlations are negative and significant at 95% level and the correlation coefficient is less than -0.5 in July. Utah and Nevada have the similar patterns of precipitation-temperature relationship: the significant negative correlations were found from April to June as well as in October; and no notable significant correlations were observed in all other months. In Arizona, the remarkable correlation only occurred in July and the correlation coefficient is near -0.5; three spring months also show the significant but small correlation (correlation coefficients are about or larger than -0.3).

On the east, all four states exhibit the negative correlations between precipitation and temperature through the entire year. Particularly in Montana, the significant and strong



**FIGURE 4.6.** Correlation coefficients between monthly total precipitation and monthly mean temperature in each of the Rocky Mountains states: Idaho, Utah, Arizona, Nevada, Montana, Wyoming, Colorado, and New Mexico. Dashed lines indicate the 95% statistical significance level of correlation coefficient.

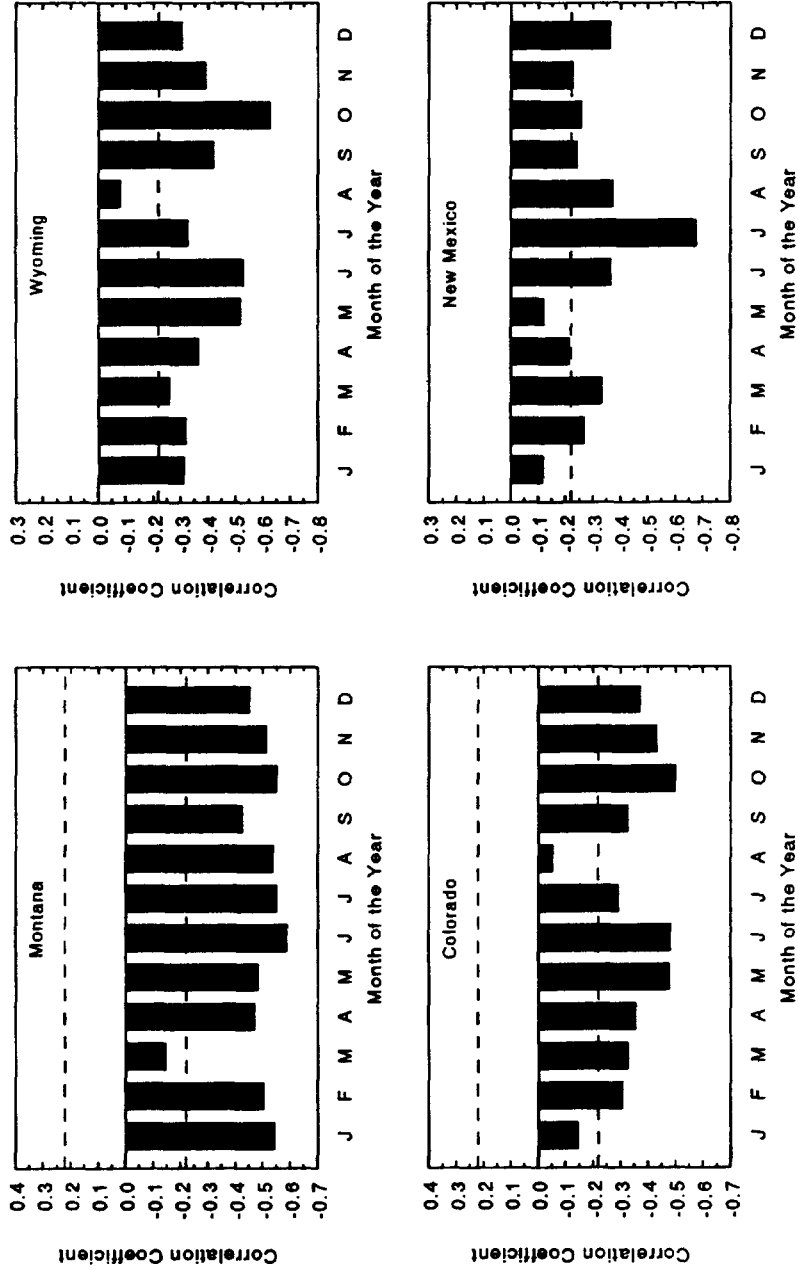


FIGURE 4.6. (Continued)

correlations were obtained for all months except March. Most months have the values of the correlation coefficients around -0.5. Montana is the only state in the United States that strong negative precipitation-temperature relationship persists through the year. In Wyoming, only in August, the correlation is insignificant at 95% level. The stronger correlations were found in May and June when the correlation coefficients are less than -0.5, and in October, the correlation coefficient can be below -0.6. In Colorado, correlations are not significant at 95% level in both January and August; the strongest correlations were found in May, June and October, but the correlation coefficients are above -0.5. New Mexico shows a somewhat different features of precipitation-temperature relationship from the other three states on the eastern side of the Mountains. Although the correlations are negative in all months, most are statistically insignificant or just over the significant level by a narrow margin. It is only in July that the remarkable correlation occurred in New Mexico and the correlation coefficient is near -0.7.

c. Plains states

Figure 4.7 shows the bar charts of the correlation coefficients between precipitation and temperature of six states in the Great Plains. These states are North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas.

In the northern Great Plains, North Dakota shows the strongly significant negative precipitation-temperature relationship during two winter months - December and January. The correlation coefficients are around -0.5. The significantly negative correlation also occurred in February, but the correlation coefficient is just over the 95% significance level. June, July, and September show significant but smaller negative correlations. Similarly, in South Dakota, significant negative correlations are also observed in December and January

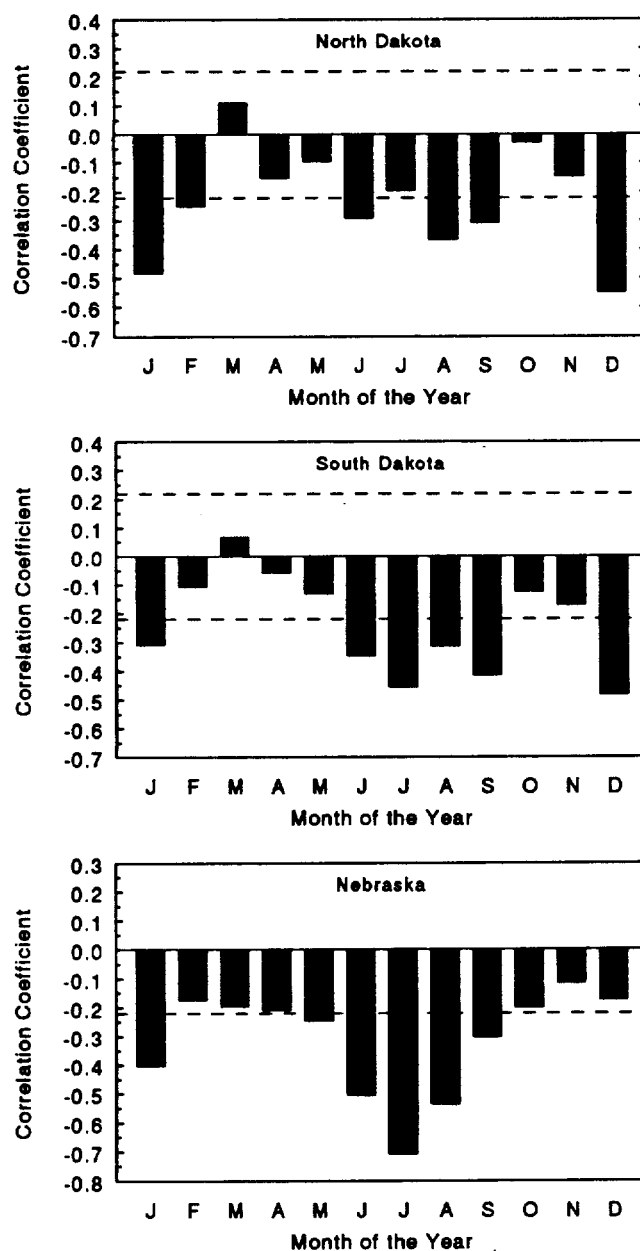


FIGURE 4.7. Correlation coefficients between monthly total precipitation and monthly mean temperature in each of the Great Plains states: North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas. Dashed lines indicate the 95% statistical significance level of correlation coefficient.

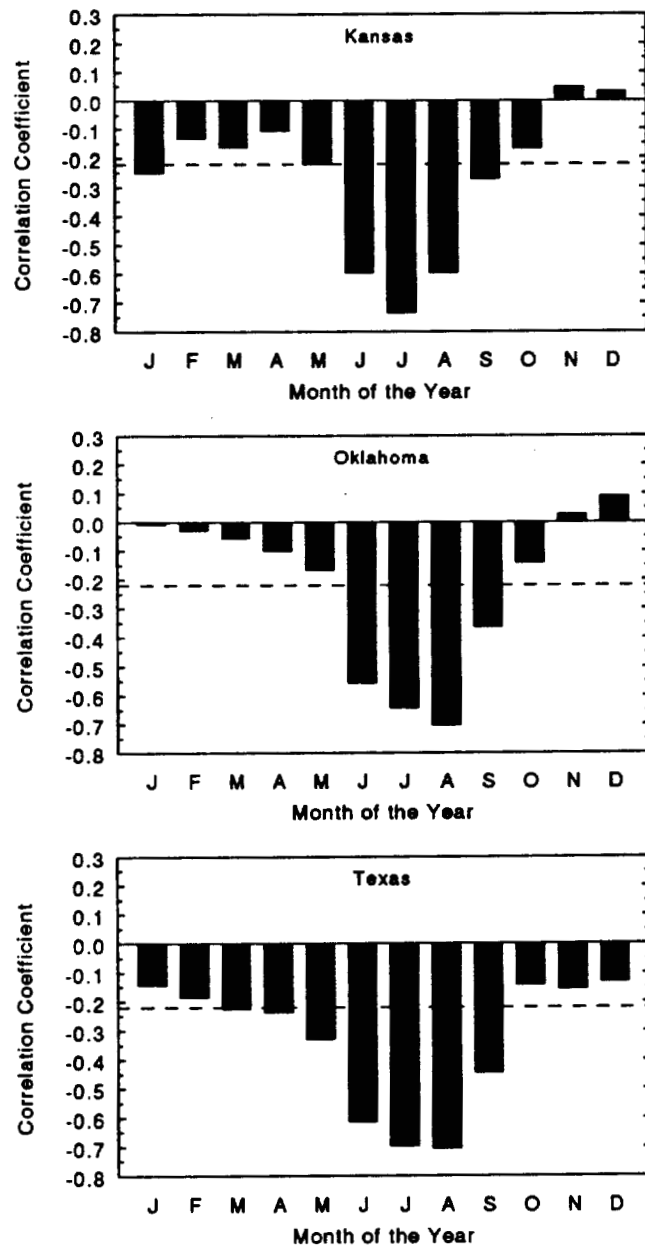


FIGURE 4.7. (Continued)

as well as from June to September.

In contrast with the two Dakotas, the other four states in the central and southern Great Plains have a distinguished feature of precipitation-temperature relationship in which the large negative correlations occurred during three summer months - the correlation coefficients are around -0.6 and even below -0.7. Significant negative correlations were obtained for September in these states but the correlations were relatively weak compared to summer months. No notable significant correlations were found for all other months in these states, except for January in Nebraska where significant negative correlations exist.

d. States on the western bank and delta area of the Mississippi River

In this area we have 5 states: Iowa, Missouri, Arkansas, Louisiana, and Mississippi. Figure 4.8 shows the correlation coefficients between precipitation and temperature in these states.

On the western side of the river, in Iowa, significant correlation was found only in July and the correlation coefficient is near -0.5; all other months do not show any significant correlation. In Missouri and Arkansas, the correlations show the feature similar to that in the central and southern Great Plains: the precipitation-temperature relationship is seen mainly during summer months with significant negative values of the correlation coefficients between -0.5 to -0.6; and all other months do not show notable significant correlations.

East of the Mississippi River and in the delta area, Louisiana and Mississippi also have significant negative correlations during summer months but the correlations are weaker than in Missouri and Arkansas. The correlation is also significant and negative for April in both states.



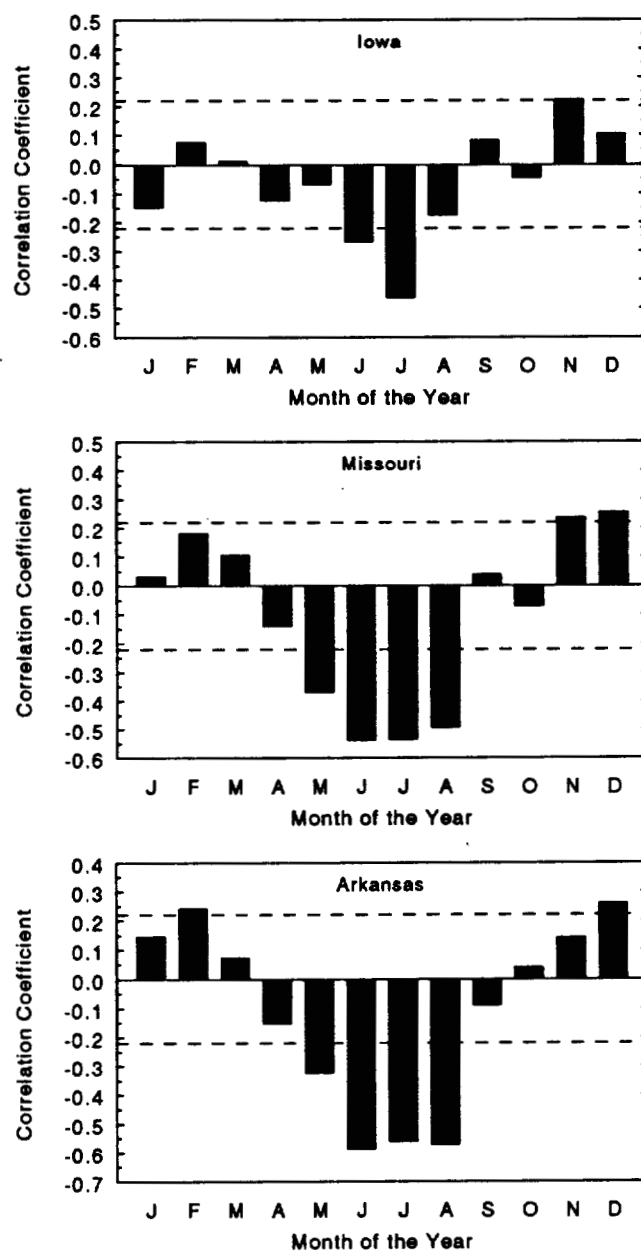


FIGURE 4.8. Correlation coefficients between monthly total precipitation and monthly mean temperature in each of the states in the western bank and the delta area of the Mississippi River: Iowa, Missouri, Arkansas, Louisiana, and Mississippi. Dashed lines indicate the 95% statistical significance level of correlation coefficient.

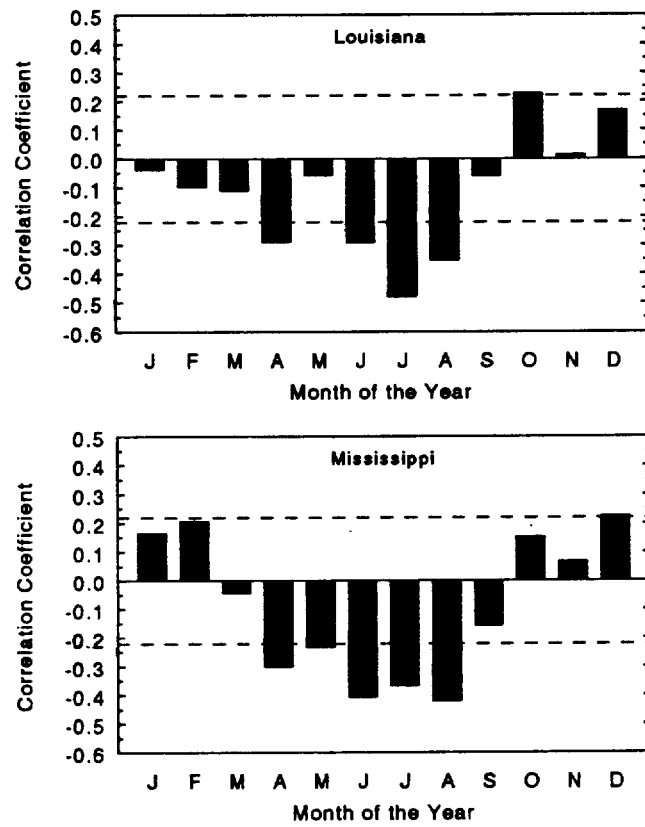


FIGURE 4.8. (Continued)

e. Lake states

On the west and east of the Great Lakes are three states: Minnesota, Wisconsin, and Michigan. None of these states show any remarkable correlation between precipitation and temperature during the entire year (Figure 4.9). Only in a very few months, the statistically significant correlations were found in the three states: July in Minnesota, July and November in Wisconsin, and February, June, October, and December in Michigan; however, the correlation coefficients are just over 95% significance level by a slim margin.

f. States south of the Great Lakes

South of the Great Lakes, the states Illinois, Indiana, Ohio, Kentucky, Tennessee, and West Virginia all show one distinguished feature: the remarkable positive correlation between precipitation and temperature during winter seasons (Figure 4.10). These states are the area where we have found that the significant positive correlations occurred in winter season. The positive correlations in Illinois for January and in Indiana for February are not significant, while early spring in March the correlation is also positive and significant in Illinois, Indiana, Ohio, and Kentucky.

g. Northeastern states

On the northeast of the United States, from Pennsylvania-Maryland northeastward to Maine, most months of the year do not exhibit strong relationship between precipitation and temperature (Figure 4.11). In early spring, later summer and all autumn months, the correlations are all below the significance level in these states, while in winter months correlations tend to be positive.

In the six New England states (Maine, New Hampshire, Vermont, Massachusetts,

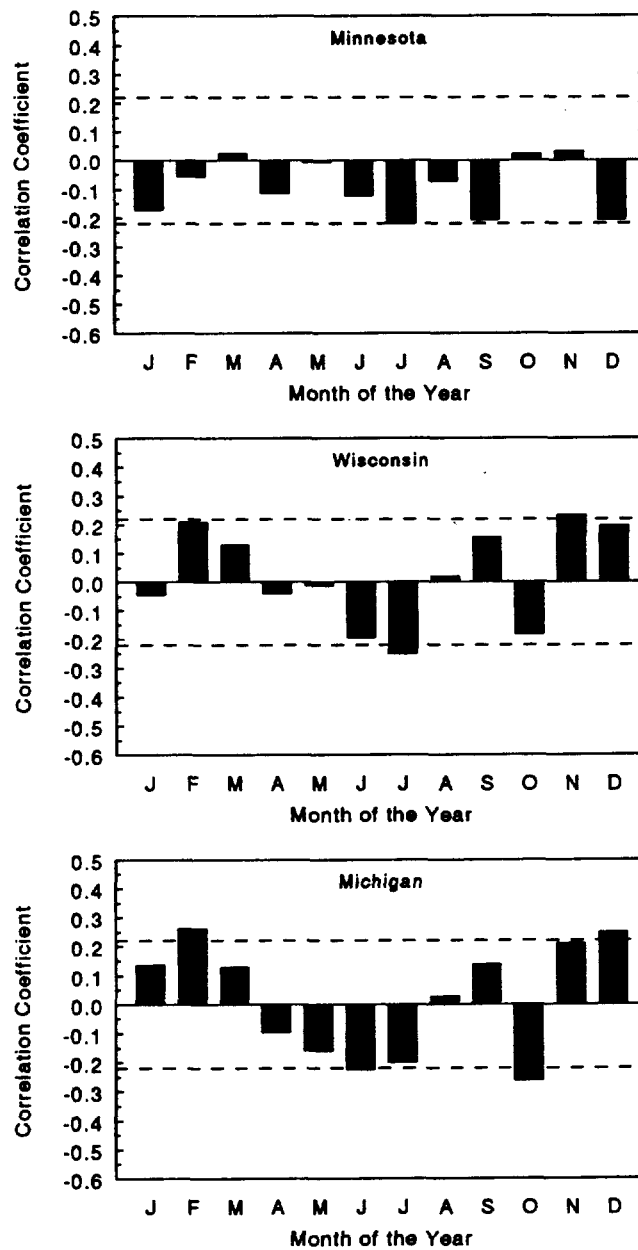


FIGURE 4.9. Correlation coefficients between monthly total precipitation and monthly mean temperature in each of the Great Lakes states: Minnesota, Wisconsin, and Michigan. Dashed lines indicate the 95% statistical significance level of correlation coefficient.

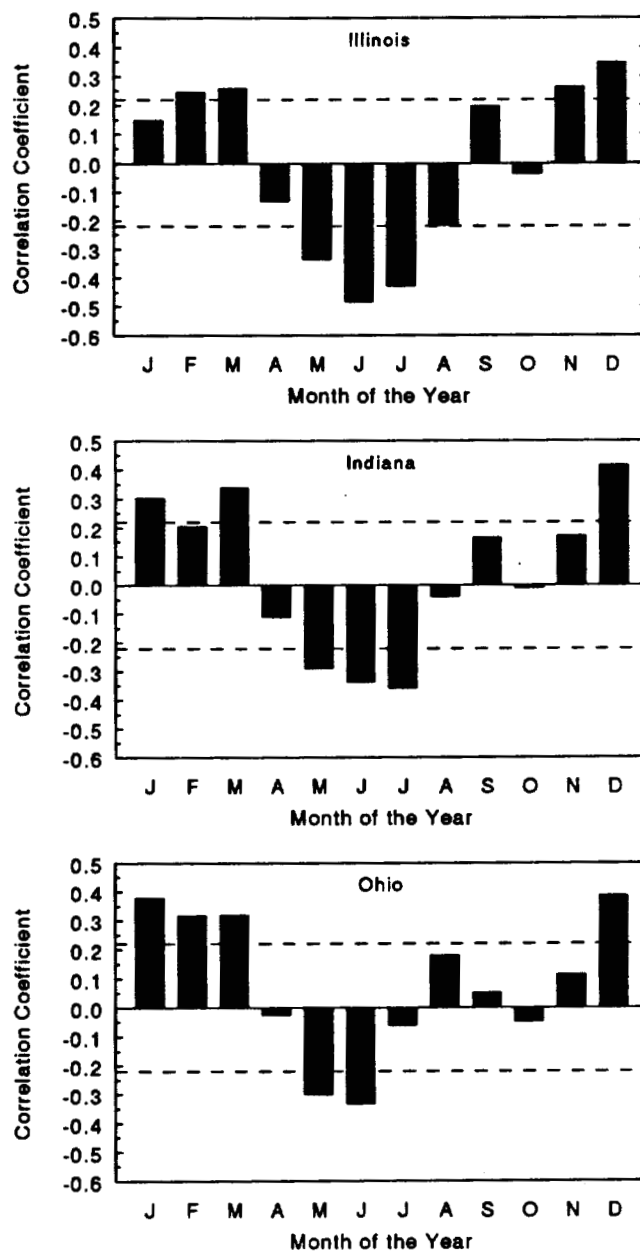


FIGURE 4.10. Correlation coefficients between monthly total precipitation and monthly mean temperature in each of the states north to the Great Lakes: Illinois, Indiana, Ohio, Kentucky, Tennessee, and West Virginia. Dashed lines indicate the 95% statistical significance level of correlation coefficient.

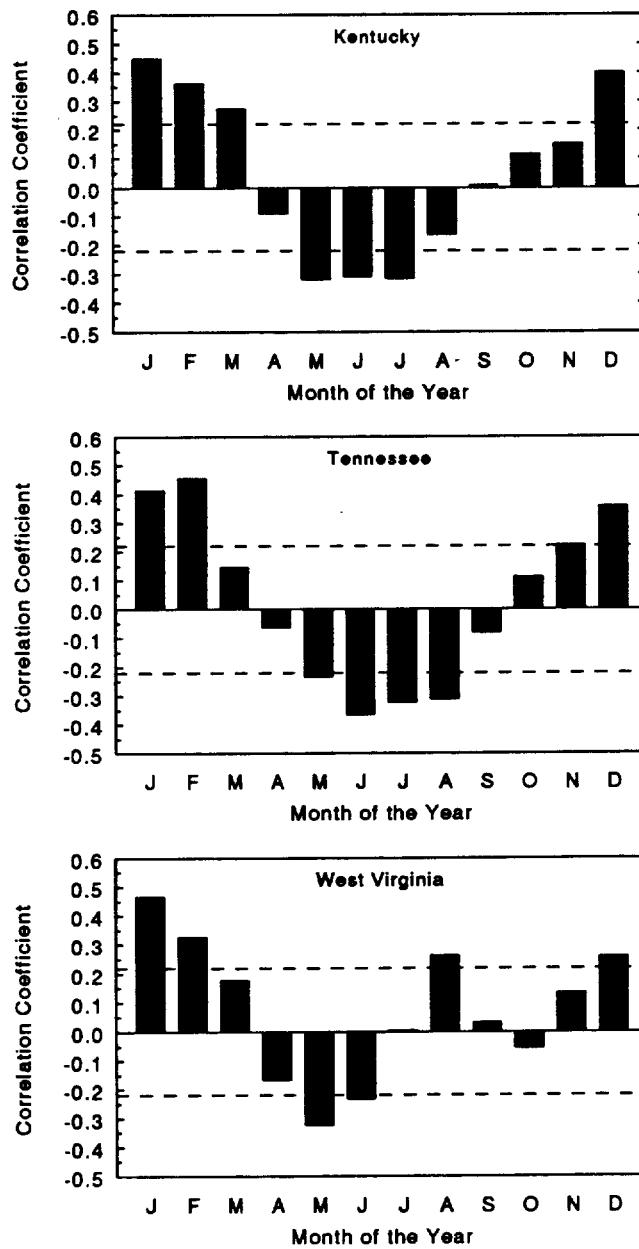


FIGURE 4.10. (Continued)

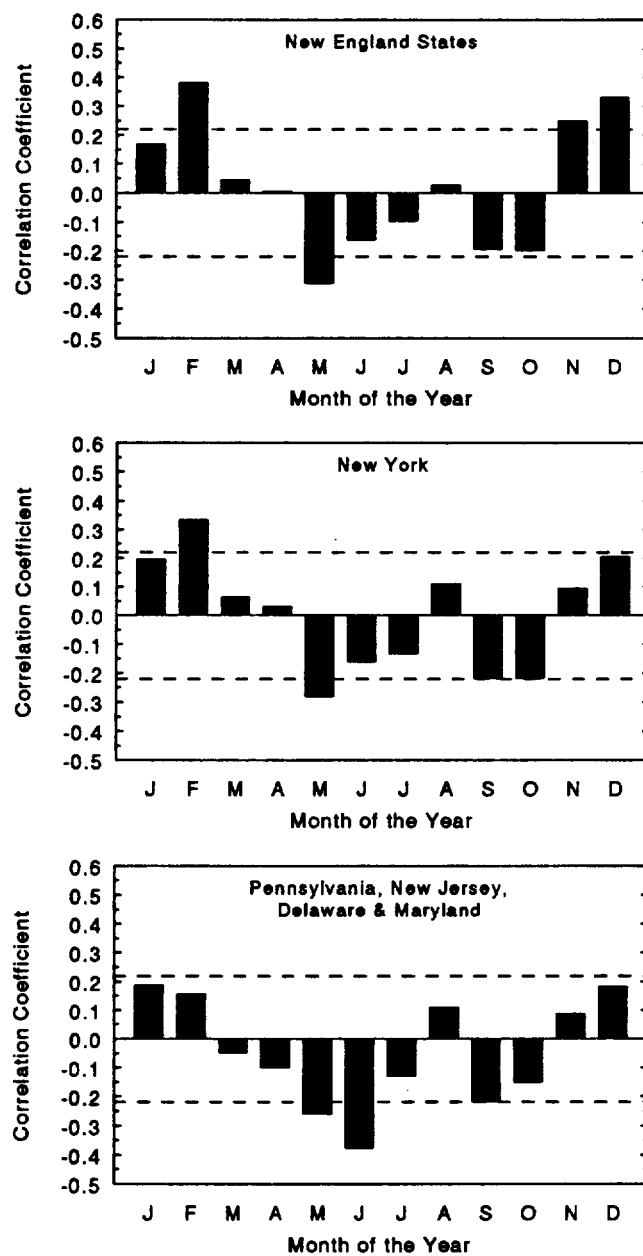


FIGURE 4.11. Correlation coefficients between monthly total precipitation and monthly mean temperature in each of the Northeastern states: New England States, New York, and the area including Pennsylvania, New Jersey, Delaware, and Maryland. Dashed lines indicate the 95% statistical significance level of correlation coefficient.

Connecticut and Rhode Island), on average, November, December, and February are the months that significant positive precipitation-temperature relationships were found and significant negative correlation was found only in May. In New York, only two months show the significant correlation between precipitation and temperature: positive correlation in February and negative correlation in May. For Pennsylvania and three other small states - New Jersey, Delaware, and Maryland, as a whole, significant correlations were found only in May and June; and in all other months, the correlations are below statistical significance level.

h. Atlantic states and southeastern states

Figure 4.12 shows the precipitation-temperature correlations for each month of the year in the states Virginia, North Carolina, South Carolina, Alabama, Georgia, and Florida. Most of these states do not show remarkable correlations in most months.

Significant but small negative correlations were obtained for the months from April to June in Virginia and for April, June and July in North Carolina; the correlations for all other months are below the 95% significance level. In South Carolina, Georgia, and Alabama, the notable significantly negative correlations mainly exist in summer months and the correlation coefficients are near -0.5 for July in South Carolina and Georgia and for August in Alabama; some months of spring and autumn also show the significant negative correlations but just above the significance level by a narrow margin; winter and later spring do not show any significant correlation in the three states. In contrast to the other states in this area, Florida has a different pattern of precipitation-temperature relationship: the significantly negative correlations were found not only in summer months but also in two winter months - January and February and one spring month - March. In October, a significant positive correlation between precipitation and temperature exists in Florida.



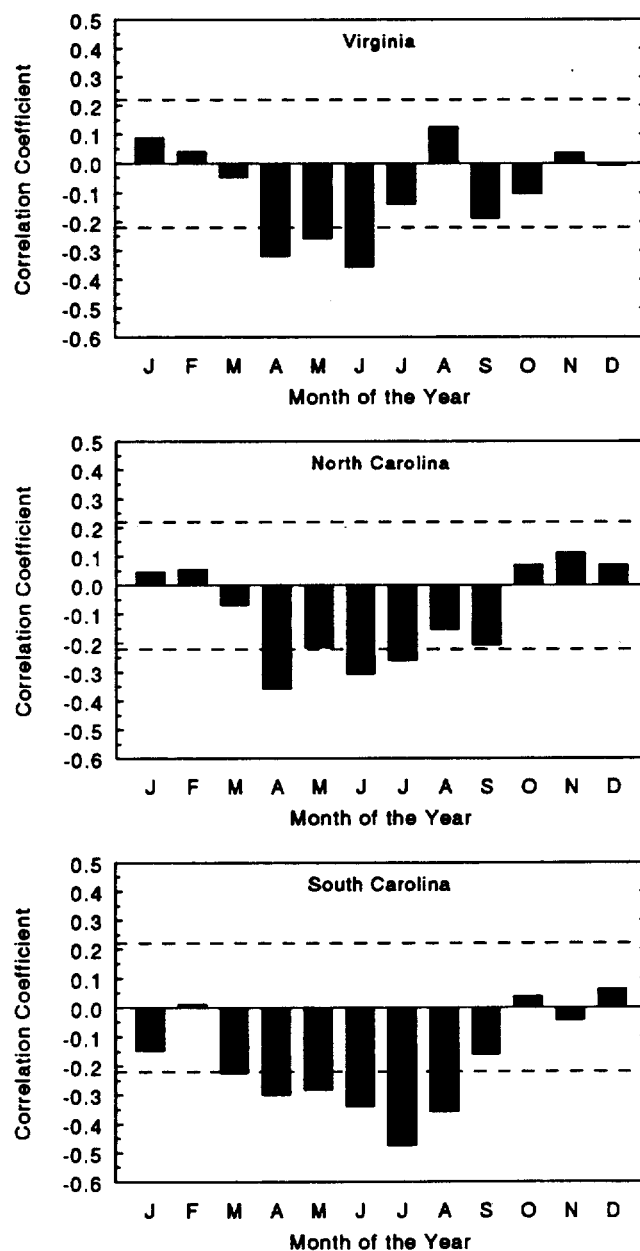


FIGURE 4.12. Correlation coefficients between monthly total precipitation and monthly mean temperature in each of the Atlantic and Southeastern states: Virginia, North Carolina, South Carolina, Alabama, Georgia, and Florida. Dashed lines indicate the 95% statistical significance level of correlation coefficient.

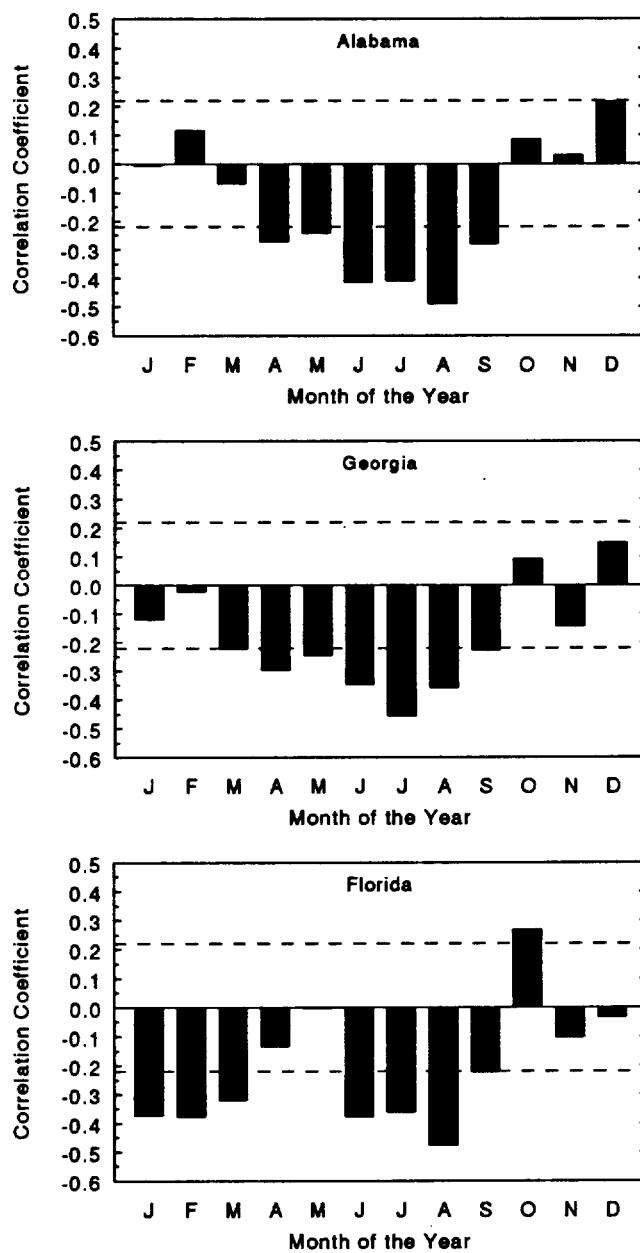


FIGURE 4.12. (Continued)

#### 4.1.3. For regional averages

The continental United States was divided into seven regions based on climatological and ecological considerations (Figure 2.4). The time series of regional averages of precipitation and temperature deviations were obtained for each region and were used to construct the relationship between precipitation and temperature for each region. The correlation coefficients between precipitation and temperature have been computed for regional mean deviations for each month. The results are listed in Table 4.2 and plotted as bar charts in Figure 4.13.

Differences in the precipitation-temperature relationship between the Pacific coast and the East coast areas is evident. Significant negative correlations exist in the Pacific coast area from April to September and the correlation coefficient drops below -0.5 in July; while in the East coast area, the significant negative correlation only appears in May and June and is weaker compared with that of the Pacific coast area. Positive correlations were observed in both areas, however the correlations are either insignificant or just over the significance level by a slim margin.

In the Rocky Mountains regions, on the west, the significant and negative correlations were mainly in summer months and some spring and autumn months; while on the east, the significant negative correlations persist through the entire year and the correlation coefficient can be lower than -0.6 in some months.

The agricultural areas show significant correlations during summer months; however, the correlations are much stronger in the western area than in the eastern area. And the positive correlations were found in the eastern area for December, February, and March, while the western area does not show any significant positive correlation through the year.

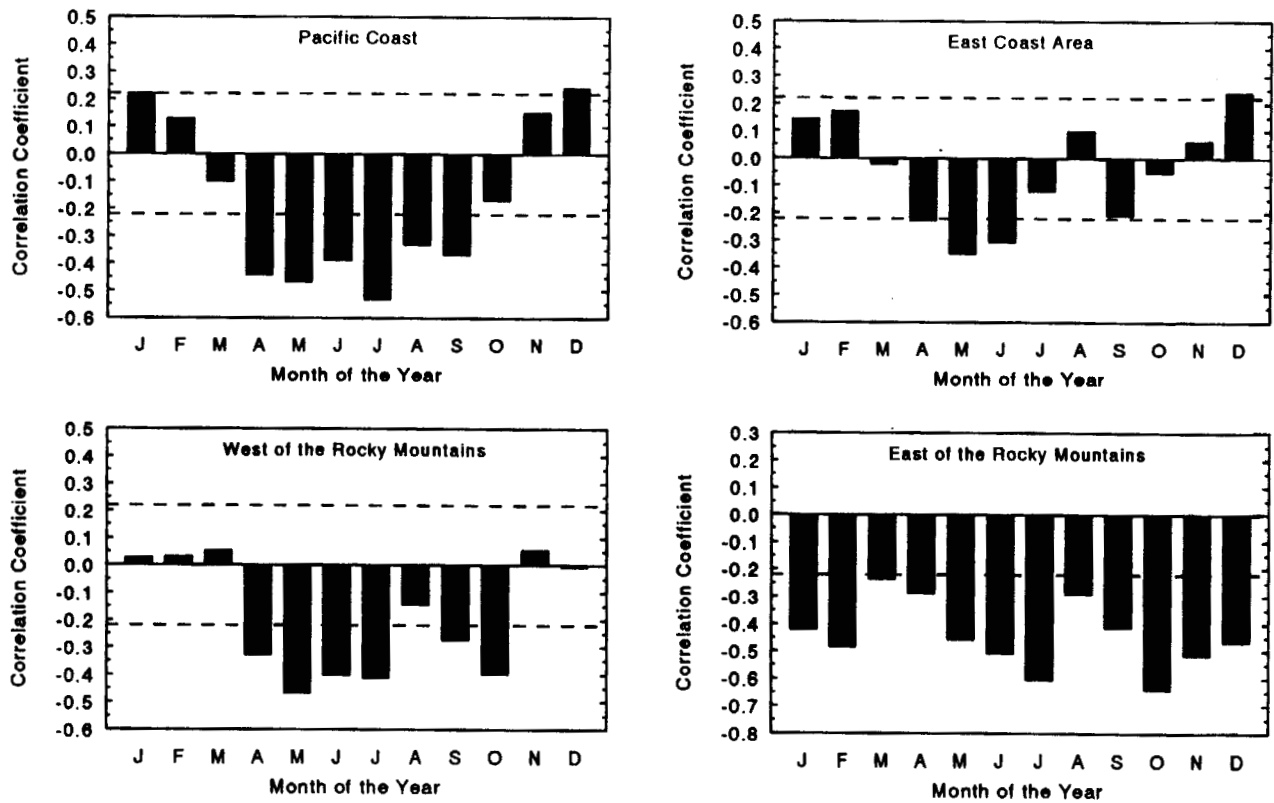
In the southern area, three summer months all have significant negative correlations,

**TABLE 4.2.** Correlation coefficients between monthly total precipitation and monthly mean temperature as regional and national-wide averages.

Region	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
PC	0.22	0.13	-0.10	-0.44	-0.47	-0.39	-0.53	-0.33	-0.37	-0.17	0.15	0.24
RW	0.03	0.03	0.05	-0.33	-0.47	-0.40	-0.41	-0.15	-0.27	-0.40	0.05	-0.01
RE	-0.42	-0.49	-0.24	-0.29	-0.46	-0.51	-0.61	-0.29	-0.41	-0.64	-0.52	-0.47
AW	-0.22	-0.03	0.01	-0.00	-0.12	-0.57	-0.74	-0.65	-0.31	-0.19	0.02	0.02
AE	0.14	0.25	0.28	-0.12	-0.28	-0.40	-0.43	-0.10	0.23	-0.10	0.23	0.35
SA	0.11	0.12	-0.05	-0.28	-0.18	-0.43	-0.41	-0.51	-0.15	0.14	0.04	0.20
EC	0.14	0.17	-0.02	-0.23	-0.35	-0.31	-0.12	0.10	-0.21	-0.05	0.06	0.24
US	-0.03	-0.00	-0.03	-0.38	-0.44	-0.52	-0.48	-0.32	-0.17	-0.16	0.05	0.12

Note: 1. PC - Pacific coast area; RW - west of the Rocky Mountains; RE - east of the Rocky Mountains; AW - western agricultural area; AE - eastern agricultural area; SA - southern area; EC - east coast area.

2. An absolute correlation coefficient of 0.22 or larger is statistically significant at the 95% level.



**FIGURE 4.13.** Correlation coefficients between monthly total precipitation and monthly mean temperature for regional averages in each region: Pacific Coast area, East Coast area, West and East of the Rocky Mountains, Western and eastern Agricultural areas, and southern area. Dashed lines indicate the 95% statistical significance level of correlation coefficient.

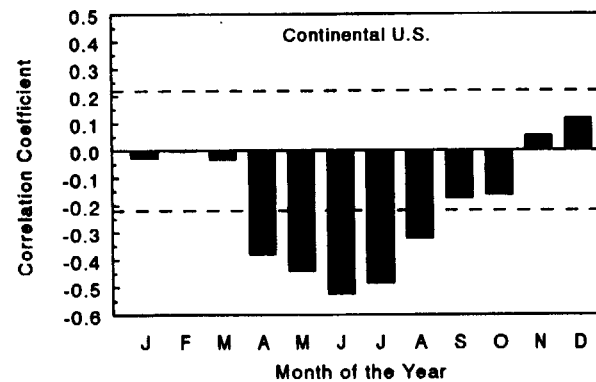
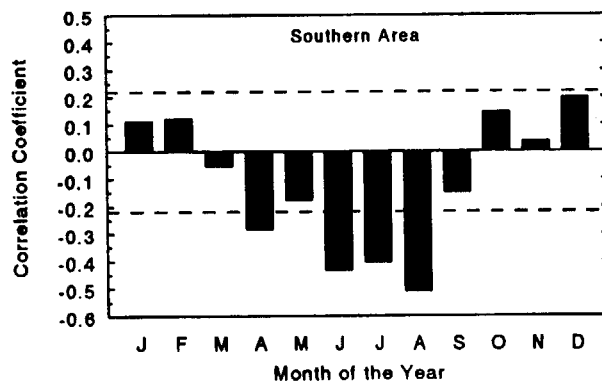
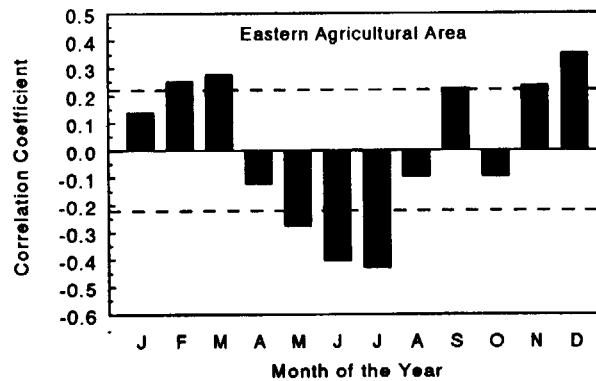
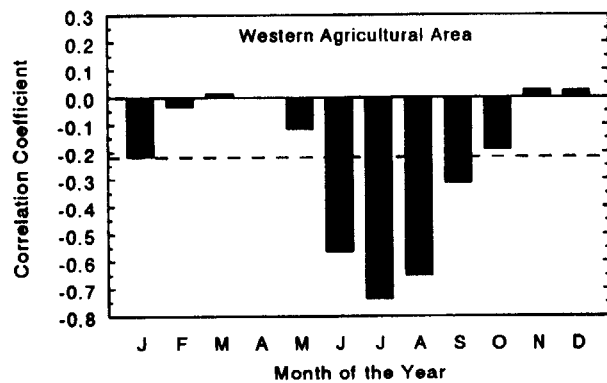


FIGURE 4.13. (Continued)

and all other months do not show any remarkable correlation.

The correlation coefficients between precipitation and temperature were also calculated for seasonal averages for each of the seven regions as well as for the continental average (Table 4.3 and Figure 4.14). The seasonal averages give results in which the month to month variations are smoothed out. The results for annual averages are also given in Table 4.3 and Figure 4.14.

Besides Pearson correlation coefficients, rank correlation coefficients were also calculated and listed in Table 4.3 (parenthetic data). The significance levels are same for both Pearson and ranking correlation coefficients. Two results do not differ very much and absolute values of rank correlation coefficients are larger than Pearson's in most cases. As a conservative choice, Pearson correlation coefficient is more preferable.

So far we have discussed the relationship between precipitation and temperature in the continental United States in terms of individual stations, state averages and regional averages. Some significant features of the precipitation-temperature relationship can be summarized as follows.

(1) Summer is the season that the precipitation-temperature correlation is most significant and has strong negative values for most of the United States. For continental averages only summer shows significant correlation. The lowest correlation coefficient is found in the central and southern Great Plains where the significant negative correlation persists through all summer months.

(2) The east of the Rocky Mountains is the area where the significant negative correlation occurs through the entire year. And for annual averages, only this area shows the

TABLE 4.3. Pearson correlation coefficients and rank correlation coefficients (parenthetic data) between monthly total precipitation and mean temperature as seasonal and annual averages in each region.

Region	winter	spring	summer	autumn	annual
Pacific Coast	0.21 ( 0.20)	-0.24 (-0.28)	-0.28 (-0.30)	-0.01 (-0.05)	0.13 ( 0.07)
Western Rockies	0.02 ( 0.01)	-0.30 (-0.32)	-0.39 (-0.47)	-0.29 (-0.41)	-0.15 (-0.22)
Eastern Rockies	-0.43 (-0.46)	-0.36 (-0.40)	-0.47 (-0.54)	-0.56 (-0.61)	-0.37 (-0.37)
Agricultural West	-0.05 (-0.09)	-0.15 (-0.18)	-0.72 (-0.69)	-0.20 (-0.26)	-0.25 (-0.30)
Agricultural East	0.25 ( 0.17)	0.12 ( 0.09)	-0.46 (-0.45)	0.01 (-0.06)	-0.09 (-0.14)
Eastern Coast	0.19 ( 0.16)	0.05 ( 0.00)	-0.13 (-0.16)	-0.10 (-0.04)	0.01 (-0.00)
Southern Area	0.25 ( 0.17)	0.04 ( 0.04)	-0.59 (-0.59)	-0.13 (-0.25)	-0.15 (-0.19)
U.S.	0.06 (-0.01)	-0.13 (-0.11)	-0.49 (-0.48)	-0.10 (-0.14)	-0.19 (-0.29)

Note: An absolute correlation coefficient of 0.22 or larger is statistically significant at the 95% level for both Pearson and ranking correlation coefficients.



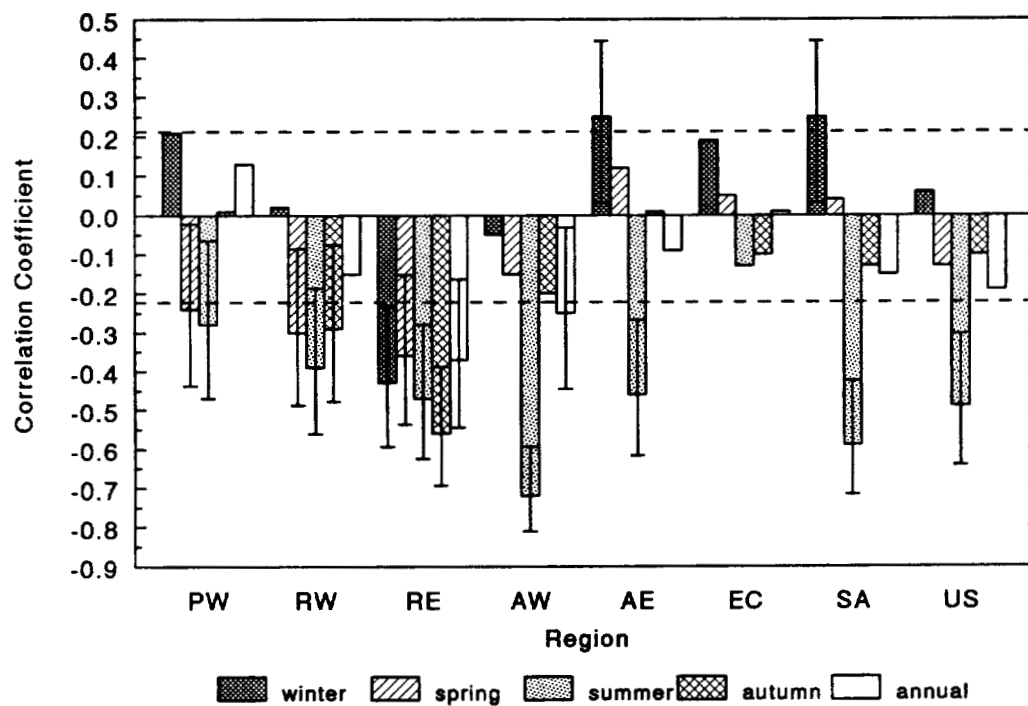


FIGURE 4.14. Correlation coefficients between monthly total precipitation and monthly mean temperature as seasonal and annual averages in each region (PW - the Pacific Coast area; RW - west of the Rocky Mountains; RE - east of the Rocky Mountains; AW - western agricultural area; AE - eastern agricultural area; EC - East Coast area; SA - southern area) and the continental U.S.. The dashed lines indicate the 95% significance level and error bars are 95% confidence intervals.

strong and significant negative correlation. Another significant, but relatively weaker, negative correlation for annual averages was found in the northern and central Great Plains, or the western agriculture area, however, this is mainly due to the tremendous negative correlation during summer in this area.

(3) The significant positive correlation was found only for winter season and only in the area south to the Great Lakes which covers most Indiana, part of Illinois, Ohio, Kentucky and Tennessee.

(4) Both the Pacific coast area and the East coast area do not display strong precipitation-temperature correlation through the entire year, particularly in the East coast area where most states only show significant correlation during summer months.

#### **4.2. Linear Regression of Precipitation on Temperature**

Regression analysis provides more information on the relationship of precipitation and temperature than correlation analysis alone. One of our interests in the relationship of precipitation and temperature is how much the precipitation will change when temperature changes a certain amount. Though the correlation coefficient between precipitation and temperature can indicate whether one of the two variables increases or decreases while the other increases, it merely measures the closeness between two variables, while the linear regression coefficient, specifically  $dP/dT$  (P and T denote precipitation and temperature respectively) in this case, measures the size of change in precipitation which can be predicted when a unit change is made in temperature.

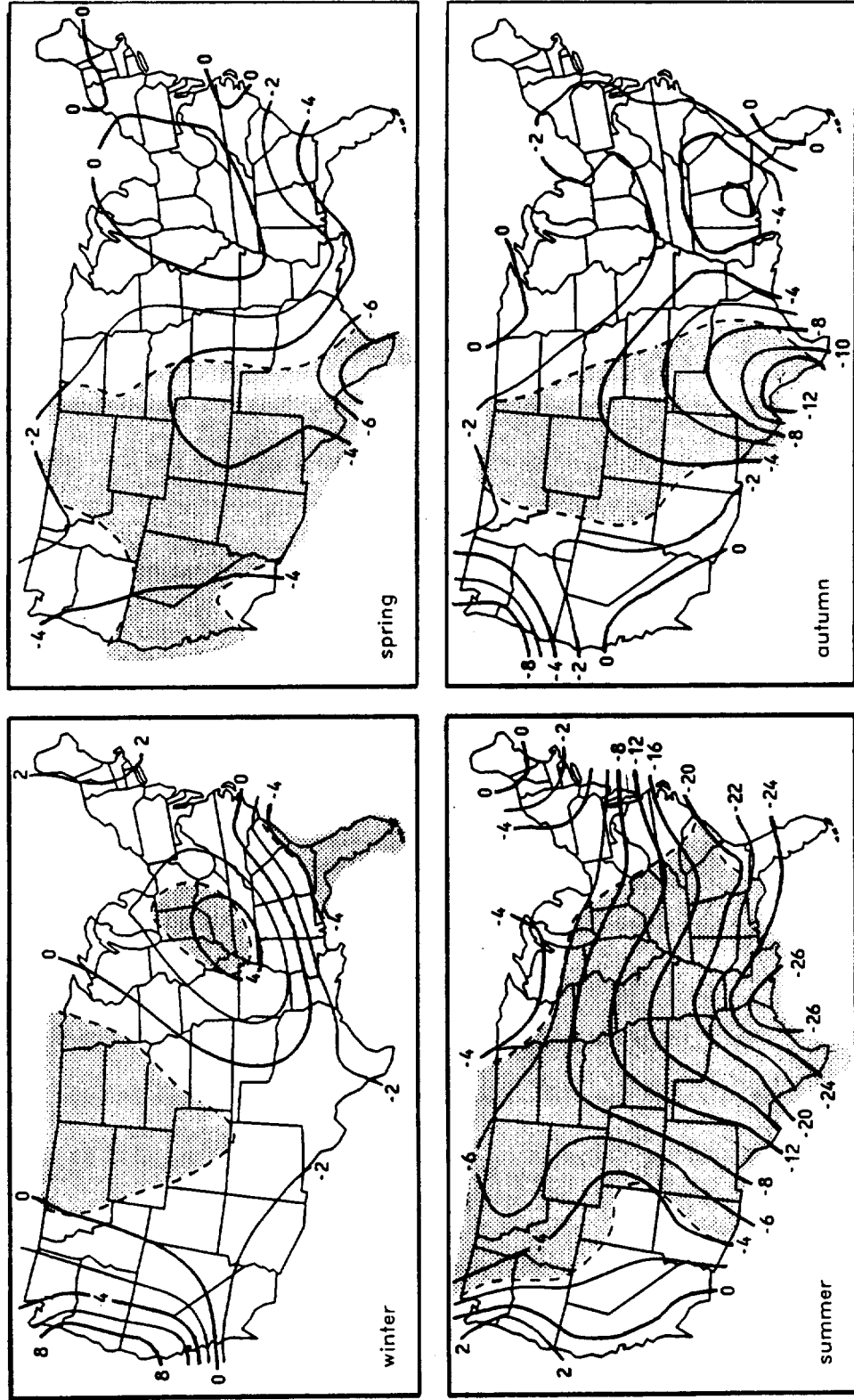
#### 4.2.1. Spatial distribution of regression coefficients

The linear regression of seasonal averages of monthly total precipitation on seasonal averages of monthly mean temperature is conducted for each station and for each season. Contours of the regression coefficients,  $dP/dT$ , are plotted in Figure 4.15. The maps show the change of monthly total precipitation in mm responding to  $1^{\circ}\text{C}$  increase of monthly mean temperature. The dashed lines indicate the 95% significance level of  $t$ -test for  $dP/dT$  ( $t_{95\%}=1.990$ ). The areas where  $dP/dT$  is significant at 95% level are shaded with small dots. Actually, the significant areas of  $dP/dT$  are the same as those of correlation coefficient, since the  $t$ -test for linear regression coefficient is identical to the significance test for correlation coefficient.

Generally, the change of precipitation predicted by its linear regression on temperature is small even within the significant areas. The regression coefficients are usually less than  $10\text{mm}/^{\circ}\text{C}$  for positive correlation and larger than  $-10\text{mm}/^{\circ}\text{C}$  for negative correlation. Therefore in most areas and most seasons, even though the correlation of precipitation and temperature is statistically significant, the change of monthly total precipitation is less than 10mm for  $1^{\circ}\text{C}$  change of monthly mean temperature. In winter season the larger significant negative correlation area of the northern and central Great Plains has less than 2mm precipitation change contributed by  $1^{\circ}\text{C}$  temperature change. Only during summer in the area where the strongest negative correlation between precipitation and temperature is found, the change of precipitation can be larger than 10mm for  $1^{\circ}\text{C}$  temperature change.

#### 4.2.2. For regional averages

The regional mean deviations of monthly total precipitation are plotted versus the regional mean deviations of monthly mean temperature for each region, defined in Chapter



**FIGURE 4.15.** Contours of linear regression coefficients (in mm/C) of monthly total precipitation on monthly mean temperature for each of the four seasons. The shaded areas are where the regression coefficients are statistically significant at 95% significance level.

1, (Figure 4.16-4.22) as well as for the continental United States (Figure 4.23). For every season and every region where precipitation-temperature correlation is statistically significant at 95% level, the linear regression of precipitation deviations on temperature deviations is conducted and displayed as dashed lines in the figures. Since the linear regression is applied on the deviations, the fitted line goes through the origin, or the regression constant is zero, which physically means that if temperature has no change precipitation does not change or vice versa. Table 4.4 lists the regression coefficients,  $dP/dT$ , together with their 95% confidence limits,  $t$ -values, and  $r^2$  - the percentage of precipitation variation explained by its linear regression on temperature. The 95% significant level of  $t$ -test with  $df=78$  or  $80$  data pairs is approximately 1.990.

The result for the regional averages confirms the feature of the linear regression of precipitation on temperature revealed in the last section. The change of precipitation predicted by its linear regression on temperature is limited and usually less than  $10\text{mm}/^\circ\text{C}$ ; only during summer in the middle of the United States it can be more than  $10\text{mm}/^\circ\text{C}$ , and up to about  $20\text{mm}/^\circ\text{C}$  for the Southern Area.

The percentage of variance of precipitation ( $r^2$ ) explained by its linear regression on temperature tells us that linear relationship between precipitation and temperature can explain less than 50% variation of precipitation and even less than 10% in some areas for some seasons. Only two regions - Agricultural West and Southern Area in summer - have values of  $r^2$  larger than 30%, showing a relative higher predictability. These two regions mainly cover the Great Plains where a strong negative correlation between precipitation and temperature was found for summer. Obviously temperature variability is not the only contributing factor that affects the precipitation, at least its effect on precipitation can not be fully explained by its linear relationship with precipitation. However, the result does show

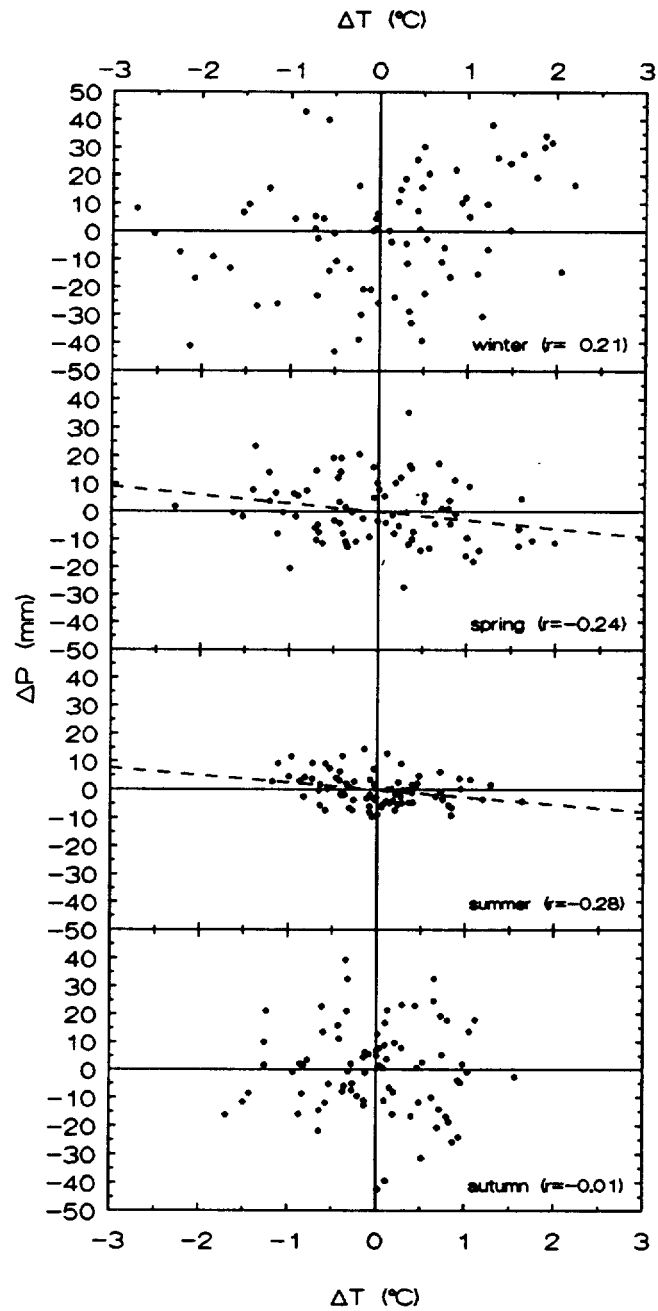


FIGURE 4.16. Deviations of monthly total precipitation versus deviations of monthly mean temperature for each season in the *Pacific Coast* area. Dashed lines are linear regression fitting of precipitation on temperature. The correlation coefficients ( $r$ ) between precipitation and temperature are also shown for each season.

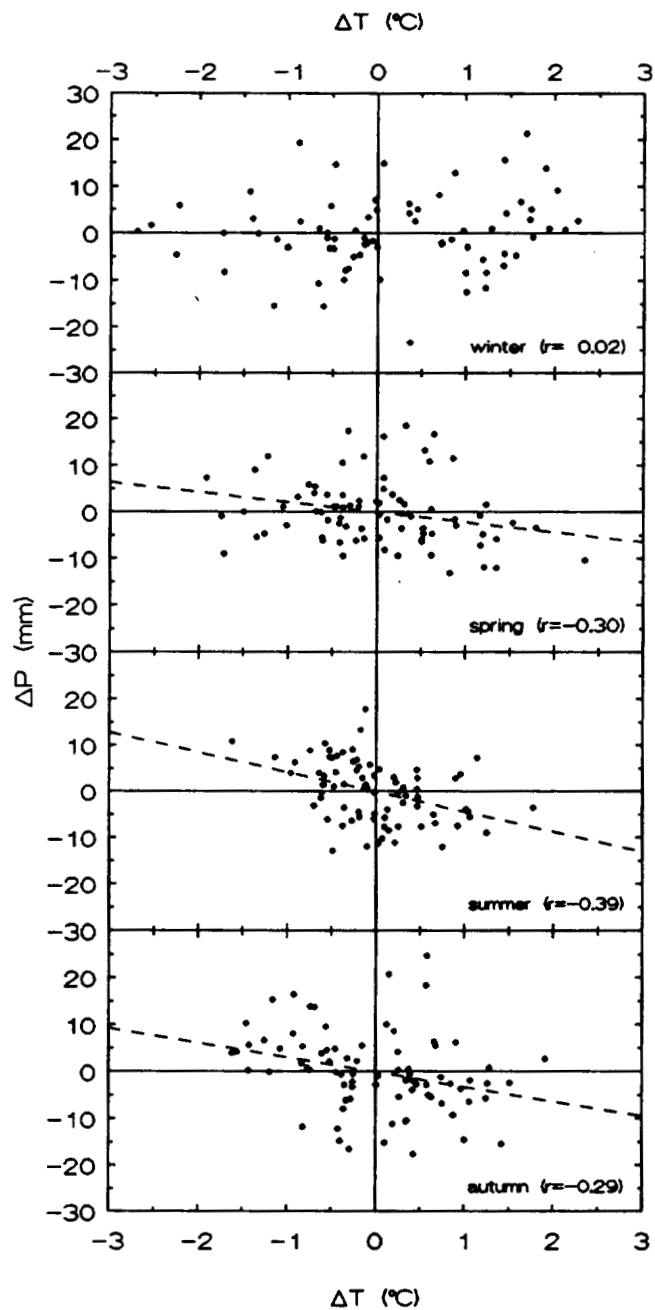


FIGURE 4.17. Deviations of monthly total precipitation versus deviations of monthly mean temperature for each season in *west of the Rocky Mountains*. Dashed lines are linear regression fitting of precipitation on temperature. The correlation coefficients ( $r$ ) between precipitation and temperature are also shown for each season.

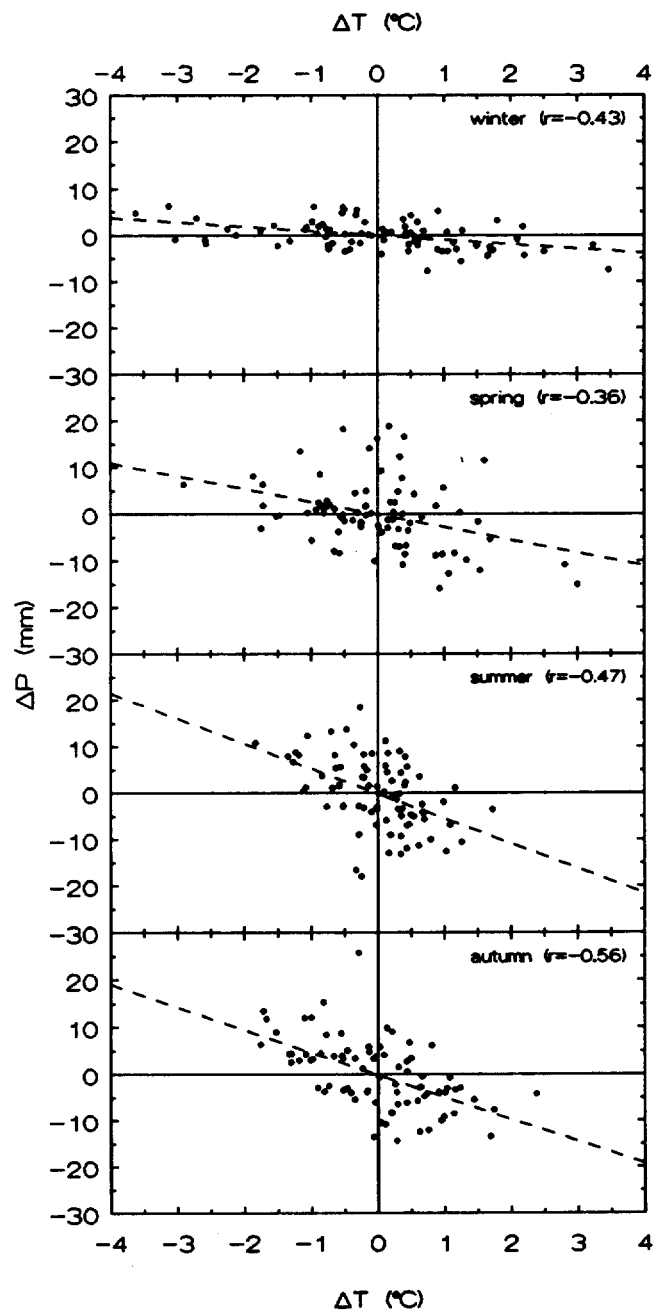


FIGURE 4.18. Deviations of monthly total precipitation versus deviations of monthly mean temperature for each season in *east of the Rocky Mountains*. Dashed lines are linear regression fitting of precipitation on temperature. The correlation coefficients ( $r$ ) between precipitation and temperature are also shown for each season.



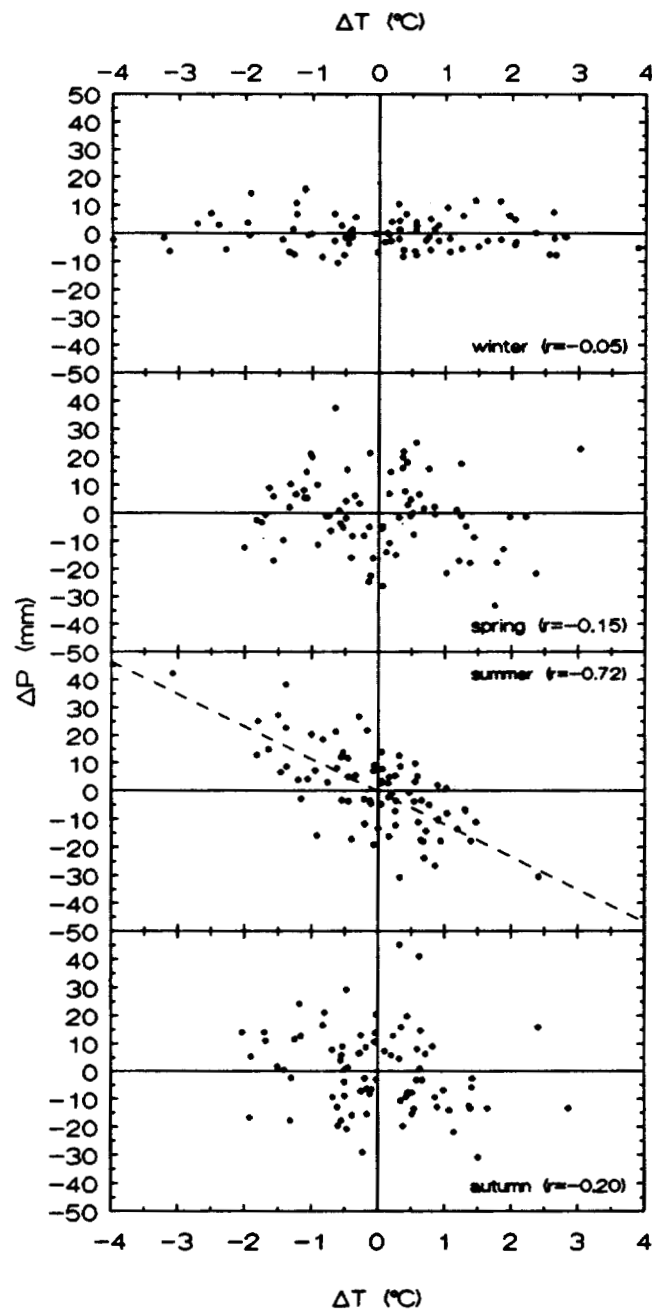


FIGURE 4.19. Deviations of monthly total precipitation versus deviations of monthly mean temperature for each season in the *western agricultural area*. Dashed lines are linear regression fitting of precipitation on temperature. The correlation coefficients ( $r$ ) between precipitation and temperature are also shown for each season.

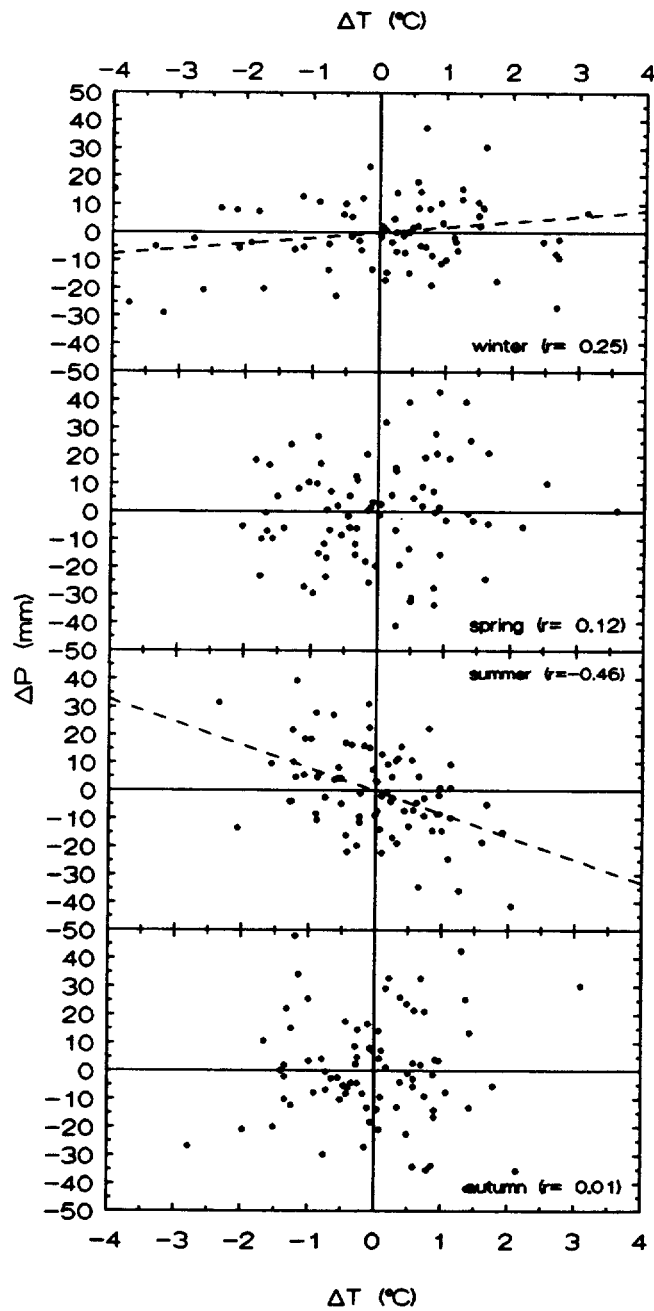


FIGURE 4.20. Deviations of monthly total precipitation versus deviations of monthly mean temperature for each season in the *eastern agricultural area*. Dashed lines are linear regression fitting of precipitation on temperature. The correlation coefficients ( $r$ ) between precipitation and temperature are also shown for each season.

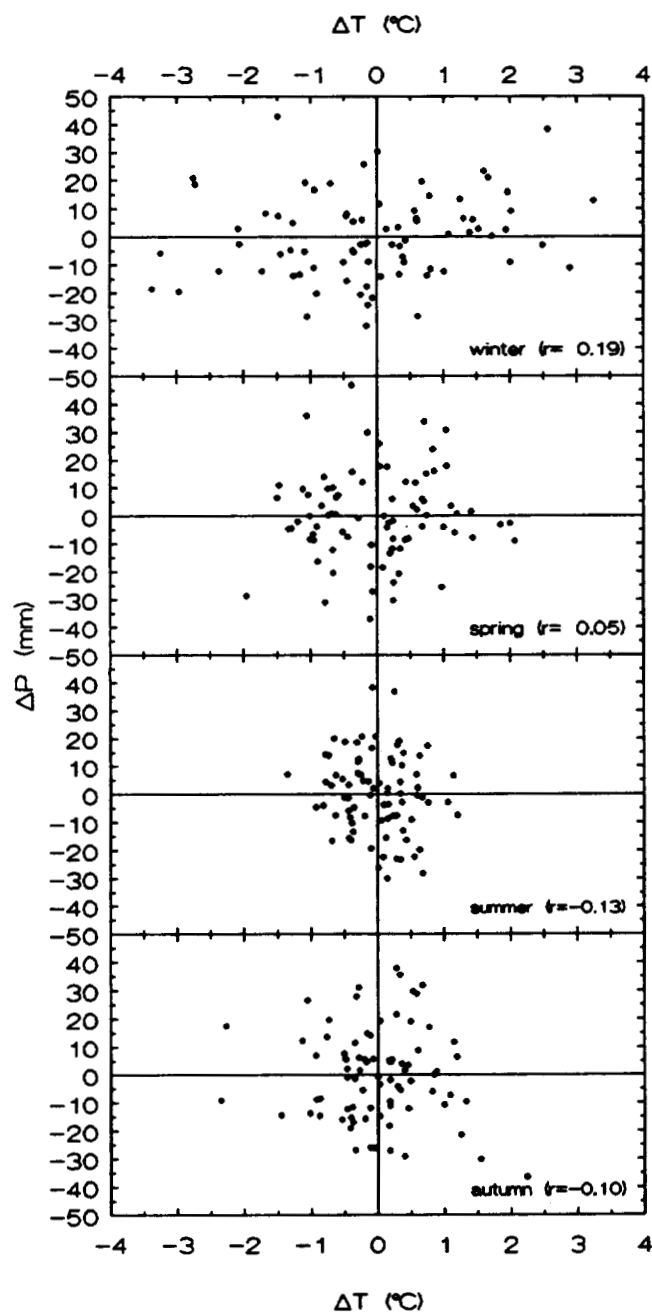


FIGURE 4.21. Deviations of monthly total precipitation versus deviations of monthly mean temperature for each season in the *East Coast* area. Dashed lines are linear regression fitting of precipitation on temperature. The correlation coefficients ( $r$ ) between precipitation and temperature are also shown for each season.

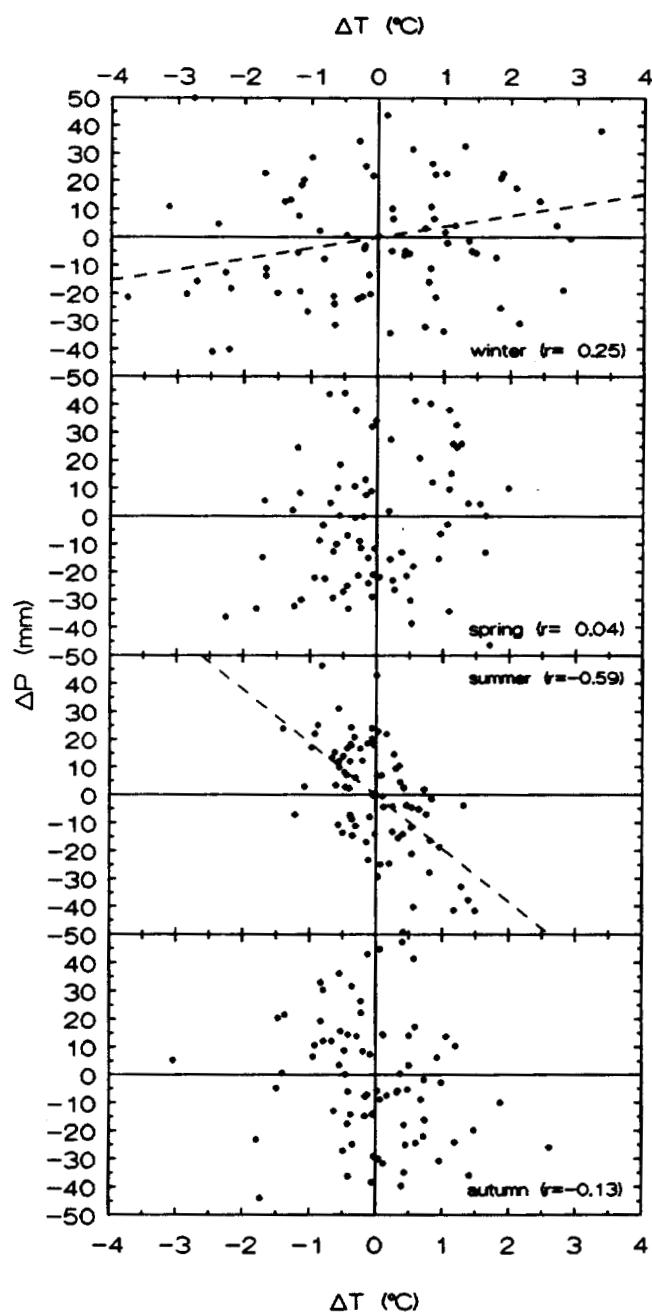


FIGURE 4.22. Deviations of monthly total precipitation versus deviations of monthly mean temperature for each season in the *Southern Area*. Dashed lines are linear regression fitting of precipitation on temperature. The correlation coefficients ( $r$ ) between precipitation and temperature are also shown for each season.

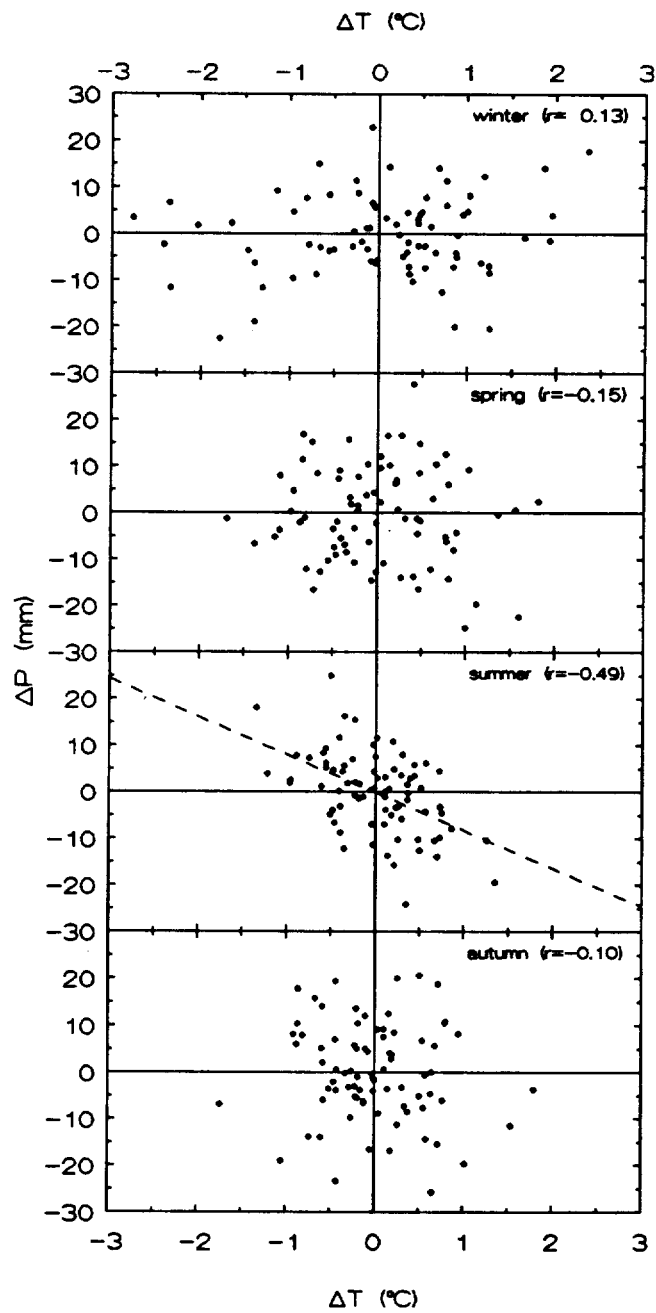


FIGURE 4.23. Deviations of monthly total precipitation versus deviations of monthly mean temperature for each season in the *continental U.S.*. Dashed lines are linear regression fitting of precipitation on temperature. The correlation coefficients ( $r$ ) between precipitation and temperature are also shown for each season.

TABLE 4.4. Linear regression coefficient ( $dP/dT$ ) between precipitation and temperature for each season and each region where the precipitation-temperature correlation is statistically significant at 95% level. Listed are also the means and standard deviations of temperature and precipitation.

	Season	$dP/dT$ (mm/°C)	$t$ -value <sup>a</sup>	$r^2$ (%)	Temp. (°C)		Precipi. (mm)	
					Mean	S.D. <sup>b</sup>	Mean	S.D. <sup>b</sup>
Pacific Coast	spring	-3.0 ( $\pm 2.7$ ) <sup>c</sup>	-2.209	5.8	11.07	0.92	37.7	11.5
	summer	-2.6 ( $\pm 2.0$ )	-2.564	7.8	19.93	0.59	11.6	5.5
Western Rockies	spring	-2.1 ( $\pm 1.6$ )	-2.727	9.0	8.33	1.00	23.4	7.3
	summer	-4.3 ( $\pm 2.3$ )	-3.735	15.2	19.78	0.59	21.8	6.5
	autumn	-3.1 ( $\pm 2.3$ )	-2.707	8.4	9.58	0.80	23.9	8.5
Eastern Rockies	winter	-0.9 ( $\pm 0.4$ )	-4.230	18.5	-3.06	1.42	12.4	3.1
	spring	-2.7 ( $\pm 1.6$ )	-3.448	13.0	6.77	0.99	26.7	7.4
	summer	-5.4 ( $\pm 2.3$ )	-4.684	22.1	18.91	0.66	32.7	7.6
	autumn	-4.8 ( $\pm 1.6$ )	-5.924	31.4	8.43	0.87	20.2	7.4
Agricultural West	summer	-11.6 ( $\pm 2.5$ )	-9.197	51.8	23.02	0.97	62.3	15.7
Agricultural East	winter	1.9 ( $\pm 1.4$ )	2.238	6.3	-3.53	1.78	39.4	14.0
	summer	-8.2 ( $\pm 3.5$ )	-4.633	21.2	21.80	0.89	71.4	15.7
Southern Area	winter	3.8 ( $\pm 3.3$ )	2.299	6.3	8.50	1.58	80.5	24.0
	summer	-19.0 ( $\pm 5.9$ )	-6.454	34.8	26.72	0.61	76.5	19.6
U.S.	summer	-8.1 ( $\pm 3.2$ )	-5.028	24.0	22.22	0.52	61.4	8.6

<sup>a</sup> The 95% statistical significance level of  $t$ -value for  $dP/dT$  is  $\pm 1.990$ .

<sup>b</sup> S.D. - Standard Deviation

<sup>c</sup> Parenthetic data are 95% confidence limits of  $dP/dT$ .

that the tendency that increasing temperature is associated with precipitation increase in some areas while in other areas increasing temperature is associated with precipitation decrease.

#### **4.3. Correlation Contributions from Various Time-scale Variations**

We have demonstrated that the areas of both significant positive and negative correlations between precipitation and temperature are found in the continental United States. However, the question is - do the correlations between precipitation and temperature reflect a relationship that is common to variations at all frequencies or, is one favored in a limited frequency band? To answer this question, the contribution from various time-scale variations of precipitation and temperature to their total correlation should be determined.

Here we look at the precipitation-temperature relationship in three different time-scales: cycles shorter than 5 years (high frequency), between 5 and 15 years (medium frequency), and longer than 15 years (low frequency). The time series of monthly total precipitation and monthly mean temperature were first partitioned into these three cycle bands by use of the moving-average filters for each of individual station and for each season; and then the correlation coefficients between precipitation and temperature were computed. The contours of the correlation coefficients are plotted in Figure 4.24 for the short-cycle band, Figure 4.25 for the medium-cycle band, and Figure 4.26 for the long-cycle band. Since the number of data points of each time series is reduced by moving-average filtering, the significance level of correlation coefficient will change for filtered time series. For short-cycle partition, the 95% significance level of correlation coefficient is about  $\pm 0.23$  ( $df=74$ ); and for medium- and long-cycle partitions, the 95% significance level is about  $\pm 0.24$  ( $df=64$ ).

The notable areas of both positive and negative correlations were found for all three

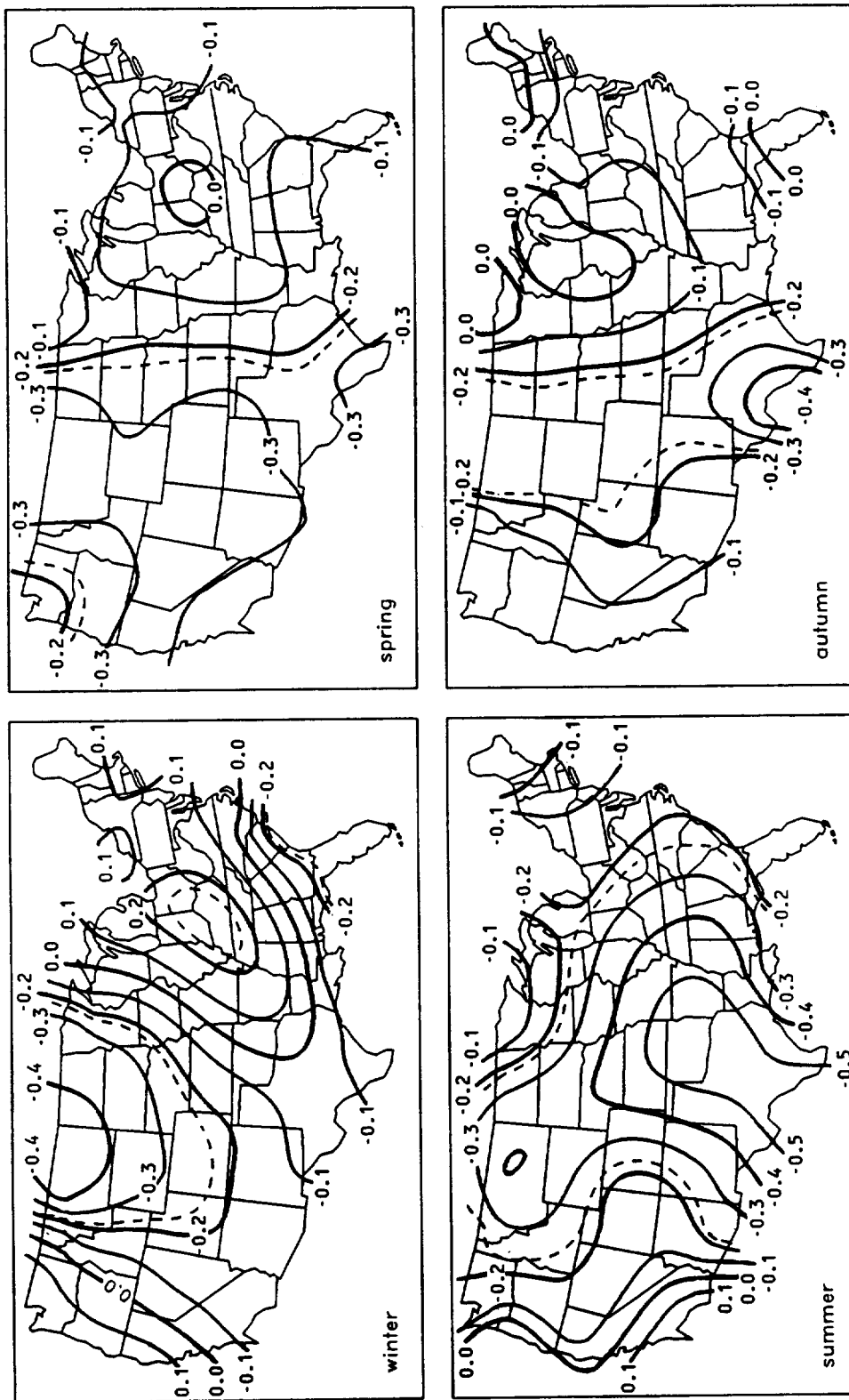
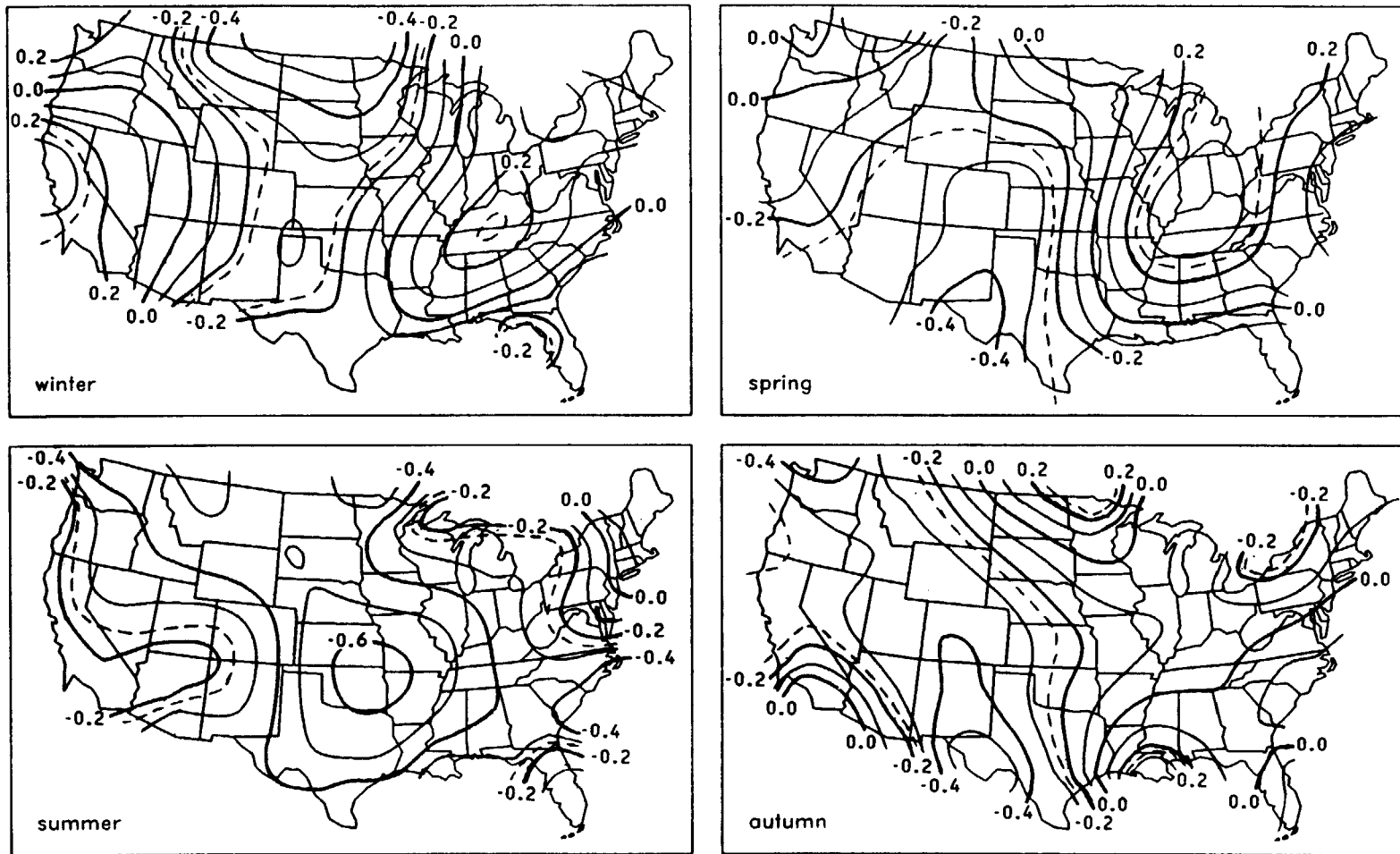
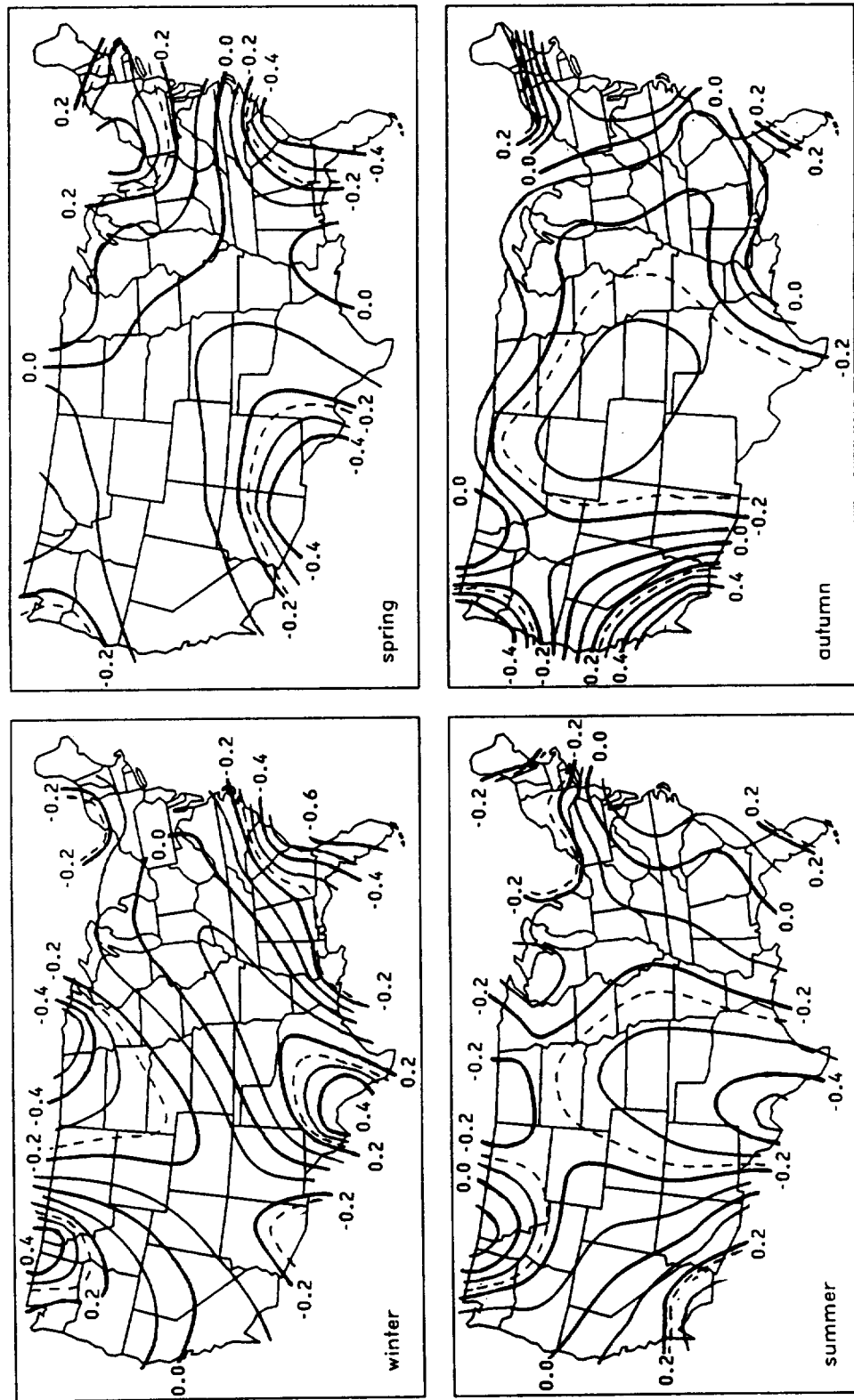


FIGURE 4.24. Contours of correlation coefficients between precipitation and temperature for the variations of cycles shorter than 5 years. Dashed lines indicate the 95% statistical significance level of correlation coefficient.





**FIGURE 4.25.** Contours of correlation coefficients between precipitation and temperature for the variations of cycles between 5 and 15 years. Dashed lines indicate the 95% statistical significance level of correlation coefficient.



**FIGURE 4.26.** Contours of correlation coefficients between precipitation and temperature for the variations of cycles longer than 15 years. Dashed lines indicate the 95% statistical significance level of correlation coefficient.

frequency bands. Generally, the spatial patterns of the correlation coefficients for the short-cycle band are almost identical with the patterns of the total correlations for all four seasons (Figure 4.24); on the other hand, for the medium- and long-cycle bands, though the patterns display features similar to that of the total correlations, the difference is evident (Figure 4.25 and 4.26). This characteristic indicates that the patterns of the total correlations mostly reflect the high frequency or short cycle variations of precipitation and temperature.

a. Winter season

For winter season, the region south to the Great Lakes, where the significant positive correlation was found, retains its significance for the short-cycle variations (Figure 4.24), but loses the significance for the medium- and long-cycle variations (Figure 4.25 and 4.26). For the medium-cycle band, only a tiny area around Kentucky-Tennessee border is still significant in this region; and for long-cycle band, this region displays positive but statistically insignificant correlations, instead the significant positive correlation area appears in Texas. The northern and central Great Plains is the region that was found to have the significant negative correlation during winter season. This feature still exists for short-cycle variations (Figure 4.24) and extends southward to western New Mexico and northern Texas for the medium-cycle variations (Figure 4.25), but for long-cycle band, only North Dakota, South Dakota, and most Minnesota retain the significance (Figure 4.26). Florida shows the significant negative correlation for short- and long-cycle bands but not for medium-cycle band.

b. Summer season

For the high and medium-cycle variations, most of the continental United States exhibits the significant negative correlations and the strongest correlation is located around

Oklahoma (Figure 4.24 and 4.25). However, for the long-cycle variations, the significant negative correlation mainly occurs in the central and southern Great Plains and the area of the strongest correlation moves to middle Texas; while other areas, such as eastern Washington, northern Idaho and most of Montana, and part of Northeast also show significant negative correlations (Figure 4.26). And the southern end of California and southern reach of Florida show the significant but small positive correlation.

c. Spring and autumn seasons

The difference of the spatial patterns of precipitation-temperature relationship among the different cycle bands are more notable for spring and autumn seasons. Except the identical patterns for short-cycle variations with the patterns of the total correlations in these two seasons, the patterns for medium- and long-cycle bands are much different.

In spring season, the area extending from southern Wyoming and west Nebraska southward to the southern U.S. border bounded on west by Nevada-southern California and on east by the middle Great Plains show the significant negative correlations for medium-cycle variations (Figure 4.25); in contrast, for the low frequency band, the significant negative correlations were found in three smaller areas: the area including southern Arizona, southern New Mexico and western reach of Texas, the narrow band along the Washington and Oregon coast, and an area in the Southeast (Figure 4.26). One unique feature for spring season is that the area south of the Great Lakes, where the significant positive correlations were found for winter season, also exhibits the significant positive correlations for medium-cycle variations. In the previous sections, we have demonstrated that the insignificant positive values of the total correlations occurs in this area for spring season (Figure 4.2) and some states within this area show the significant positive correlations in some spring months (Figure 4.10); this

feature could be primarily contributed by the medium-cycle variations. For long-cycle band, the significant positive correlations were found in New York and Pennsylvania and surrounding areas.

In autumn season, the significant negative correlations occur in most of the western portion of the continent for medium-cycle variations (Figure 4.25) and in the large area of the central U.S. for long-cycle variations (Figure 4.26). Significant positive correlations also appear in some small areas - southern California, northern New England, and southern end of Florida - for long-cycle band.

Figure 4.27 illustrates the areas where the significant correlations were found for all three cycle bands. Those areas are shaded in the maps. For winter, only the northern Great Plains show significant correlations which are contributed by the variations of all three time scales; in summer, the area covers mainly the central and southern Great Plains.

#### **4.4. Two Special Regions**

In this section, we will discuss the relationship between precipitation and temperature in two special regions: (1) the central Great Plains where a remarkable negative correlation was found for summer; (2) the area south to the Great Lakes where the significant positive correlation exists in winter.

##### **4.4.1. The central Great Plains in summer**

The middle United States is the area where the statistically significant negative precipitation-temperature relationship occurs in summer season. Particularly in the central and

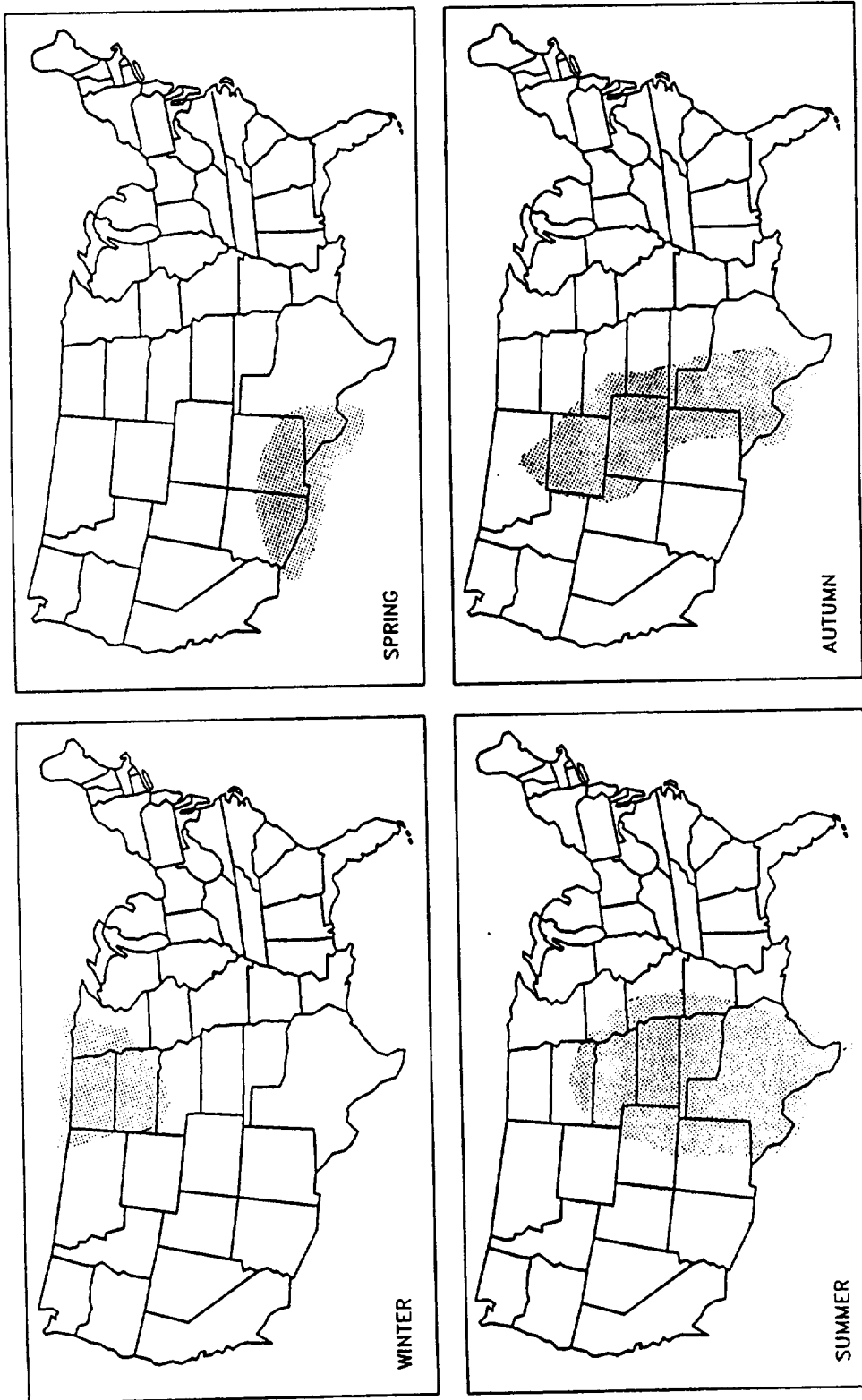


FIGURE 4.27. The shaded areas are where the correlations between precipitation and temperature are statistically significant at 95% level for all three cycle bands.

southern Great Plains, the negative correlation is very strong. Here we will discuss the precipitation-temperature relationship in the central Great Plains, the area where is the one of the main agricultural productivity regions in the United States. We chose the stations within the 95°W-105°W longitude and 32°N-42°N latitude (including Kansas, Oklahoma, most of Nebraska, eastern reach of Colorado and New Mexico, and northern Texas) and calculated the regional mean deviations of summer precipitation and temperature by averaging the deviations of summer monthly total precipitation and monthly mean temperature, respectively, over 116 stations within this area.

The time series of precipitation and temperature deviations were plotted as histograms in Figure 4.28. Out of 80 years of the record, 28 years show the warmer-than-average summers were abnormally dryer and 29 years had abnormally colder and wetter summers - that is, 71% of years show the inverse relationship between precipitation and temperature. Table 4.5 lists the temperature and precipitation deviations in the years when the temperatures were different by more than 1°C from the 80-year average. The 10 warmest years all had precipitation below the long-term average; and all 9 coldest years had precipitation above the long-term average. The correlation coefficient between precipitation and temperature is approximately 0.75. The linear regression between precipitation and temperature indicates that with a 1°C increase of monthly mean temperature, the monthly total precipitation decreases nearly 14mm (Figure 4.29). Since the value of  $r^2$  is about 0.56, the variation of precipitation that can be explained by its linear relationship with temperature is nearly 60%.

Besides the total correlation between summer precipitation and temperature in this area, we also looked at the relationships in the three cycle bands - cycles shorter than 5 years, between 5 and 15 years, and longer than 15 years. The filtered time series of precipitation and

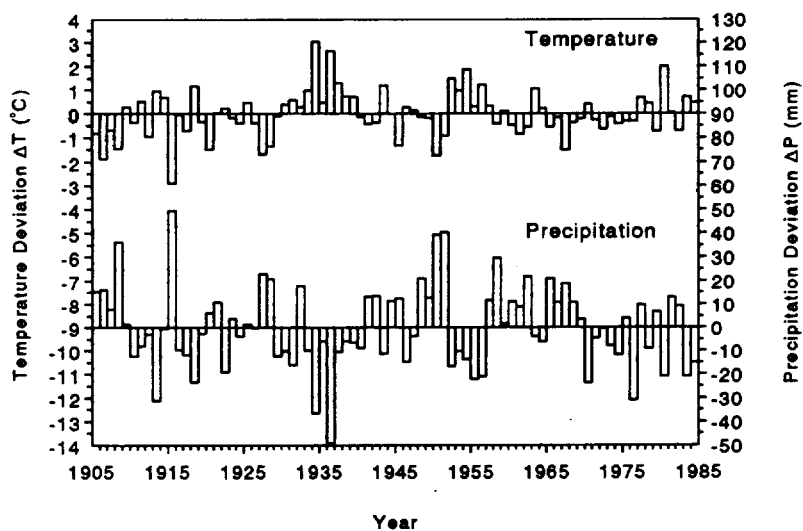


FIGURE 4.28. Time series of monthly mean temperature and monthly total precipitation as the deviations from long-term averages for the central Great Plains in summer season.

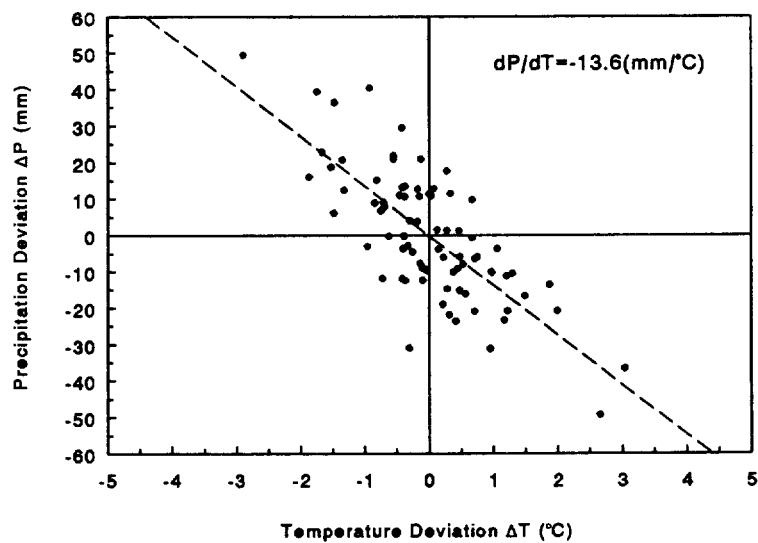


FIGURE 4.29. Deviations of monthly total precipitation versus deviations of monthly mean temperature for the central Great Plains in summer season. Dashed line is the linear regression fitting.  $dP/dT$  is the regression coefficient.



TABLE 4.5. Deviations of monthly mean temperature and monthly total precipitation for the years when temperatures were more than 1°C different from the long-term average in the central Great Plains in summer.

Warmer Summers			Colder Summers		
Year	Temperature $\Delta T$ (°C)	Precipitation $\Delta P$ (mm)	Year	Temperature $\Delta T$ (°C)	Precipitation $\Delta P$ (mm)
1934	3.04	-36.6	1915	-2.89	49.5
1936	2.66	-49.3	1906	-1.87	16.1
1980	2.00	-20.8	1950	-1.75	39.4
1954	1.88	-13.6	1927	-1.67	22.9
1952	1.49	-16.7	1967	-1.53	18.8
1937	1.30	-10.5	1920	-1.48	6.2
1956	1.23	-20.9	1908	-1.47	36.4
1943	1.21	-11.2	1928	-1.35	20.8
1918	1.17	-23.4	1945	-1.33	12.5
1963	1.06	-3.7			

temperature in these three cycle bands were plotted in Figure 4.30. The correlation coefficients between precipitation and temperature are respectively -0.75 for short cycles, -0.72 for medium cycles, and -0.48 for long cycles. Although the correlations between precipitation and temperature are statistically significant for all three cycle bands, the fact that the correlation for long cycles is much weaker than the correlations for short- and medium-cycles demonstrates that the contribution from long-cycle variations of precipitation and temperature are less than the contributions from short- and medium- cycle variations.

#### **4.4.2. The area south of the Great Lakes in winter**

The area south of the Great Lakes, including Indiana, western Ohio, southeastern Illinois, most of Kentucky, and part of Tennessee, is the only area where a significant positive correlation between winter precipitation and temperature was found in the United States. The area, located within 80°W-92°W longitude and 33°N-43°N latitude, covers the eastern portion of the U.S. Corn Belt. The regional mean deviations of winter precipitation and temperature were obtained by averaging deviations of monthly total precipitation and monthly mean temperature over 148 stations within this area.

Figure 4.31 show the histograms of deviations of winter precipitation and temperature in this area, and Table 4.6 lists the deviations of temperature and precipitation in the years when the temperature departed from the 80-year average by more than 1°C. Precipitation and temperature were synchronously above or below the long-term average in more than half of the 80-year record. Among 23 warmest winters, in which the temperatures were 1°C or more above the long-term average, 17 winters were wetter than average; and, 15 out of 20 coldest winters, in which the temperatures were 1°C or more below the long-term average, were abnormally dryer. The correlation coefficient between winter precipitation and temperature

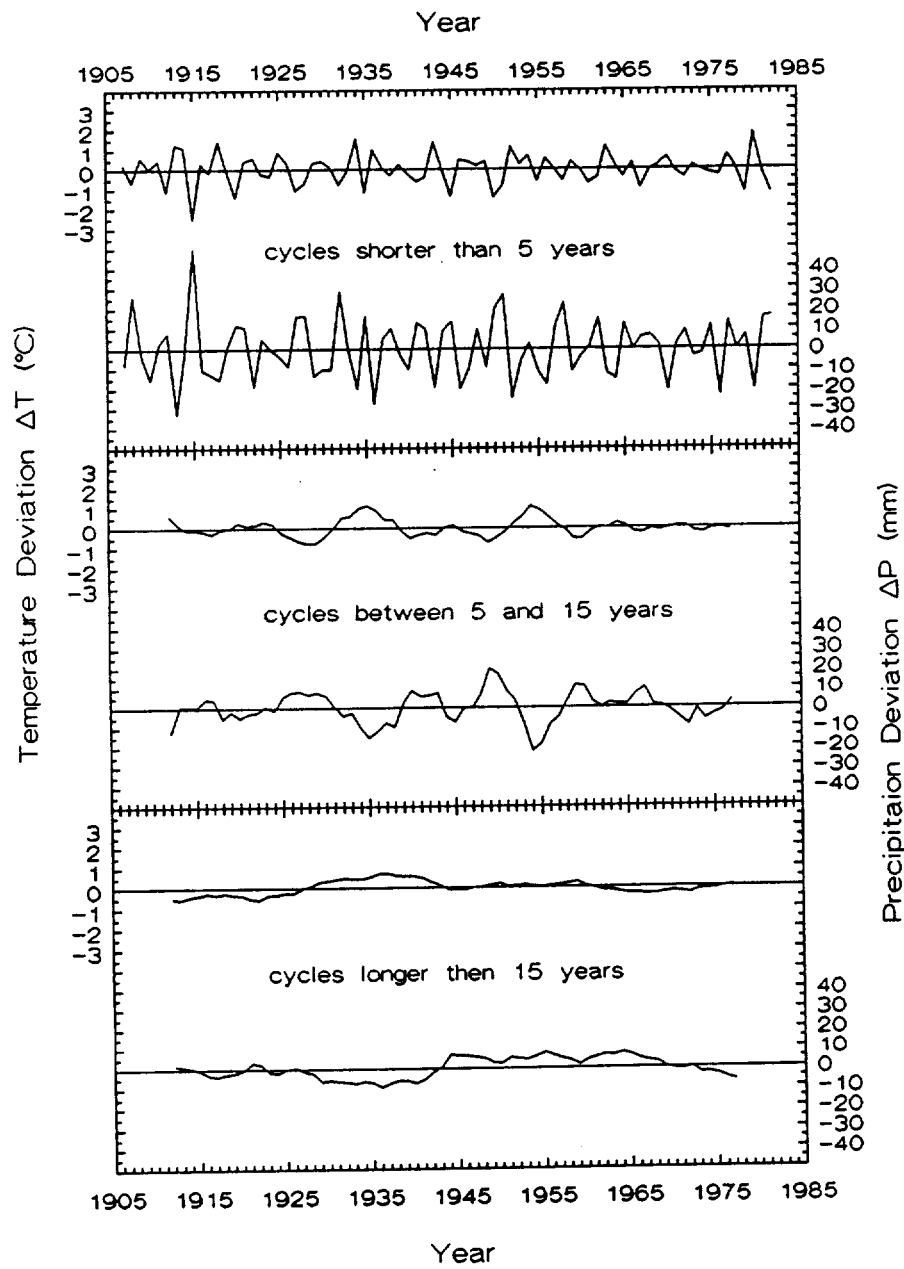


FIGURE 4.30. Deviations of monthly mean temperature and monthly total precipitation in three cycle bands for the central Great Plains in summer season.

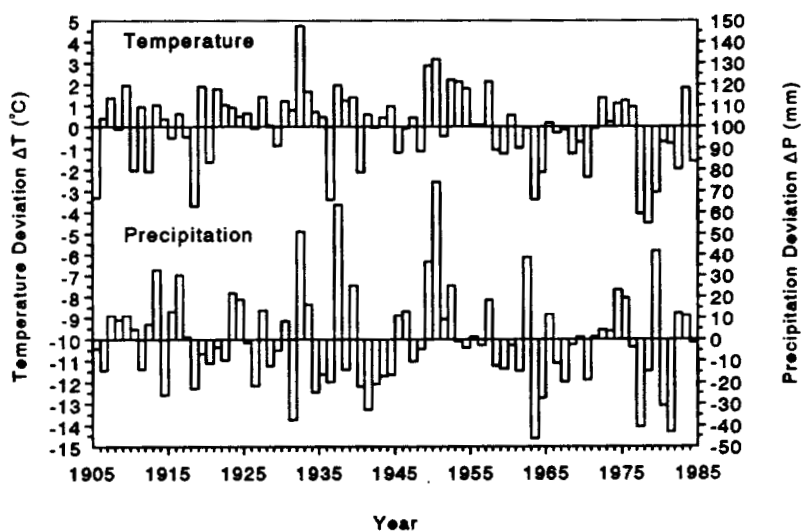


FIGURE 4.31. Time series of monthly mean temperature and monthly total precipitation as deviations from the long-term averages for the area south of the Great Lakes in winter season.

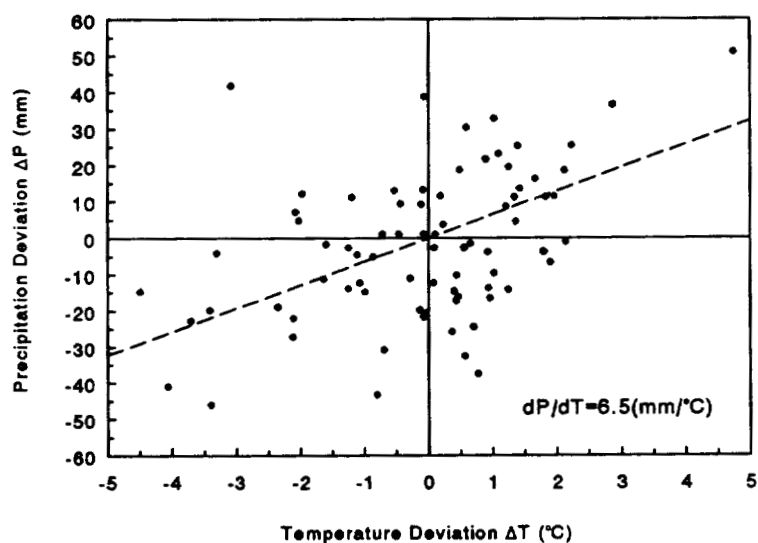


FIGURE 4.32. Deviations of monthly total precipitation versus deviations of monthly mean temperature for the area south of the Great Lakes in winter season. Dashed line is the linear regression fitting.  $dP/dT$  is the regression coefficient.

TABLE 4.6. Deviations of monthly mean temperature and monthly total precipitation for the years when temperatures were more than 1°C different from the long-term average in the area south of the Great Lakes in winter.

Warmer Winters			Colder Winters		
Year	Temperature $\Delta T$ (°C)	Precipitation $\Delta P$ (mm)	Year	Temperature $\Delta T$ (°C)	Precipitation $\Delta P$ (mm)
1932	4.74	51.0	1978	-4.50	-14.7
1950	3.20	74.3	1977	-4.06	-40.8
1949	2.88	36.6	1918	3.70	-22.7
1952	2.23	25.5	1936	-3.41	-19.8
1953	2.14	-0.9	1963	-3.39	-46.0
1957	2.12	18.6	1905	-3.30	-4.1
1909	1.96	11.4	1979	-3.08	41.8
1937	1.96	63.8	1970	-2.35	-18.9
1919	1.90	-6.6	1964	-2.11	-27.2
1983	1.83	11.2	1940	-2.11	-22.0
1954	1.81	-3.8	1912	-2.08	7.3
1921	1.79	-3.6	1910	-2.02	4.9
1933	1.67	16.3	1982	-1.97	12.1
1927	1.43	13.5	1920	-1.64	-11.2
1939	1.40	25.3	1984	-1.60	-1.6
1972	1.36	4.6	1959	-1.25	-13.9
1907	1.34	11.2	1968	-1.25	-2.6
1975	1.25	19.5	1945	-1.20	11.2
1938	1.25	-14.1	1948	-1.11	-4.5
1930	1.21	8.7	1958	-1.07	-12.3
1974	1.10	23.2			
1913	1.03	32.9			
1922	1.02	-9.6			

in this area is about 0.49. Figure 4.32 is the plot of precipitation deviations versus temperature deviations and the linear regression of precipitation on temperature is shown as a dashed line in the figure. About 6mm increase of monthly total precipitation can be predicted by 1°C increase of monthly mean temperature based on the linear relationship between two variables. The linear regression between precipitation and temperature can only explain 23% of precipitation variation ( $r^2=0.23$ ).

Figure 4.33 shows the time series of winter precipitation and temperature deviations of the area in the three cycle bands. The correlation coefficient between precipitation and temperature for short cycles is about 0.43; while the values for medium and long cycles are respectively 0.24 and 0.22 - just at or below the 95% significance level. The extremely low correlations in medium and long cycles indicate that the correlation between precipitation and temperature in this area for winter season is mainly contributed by short-cycle (less than 5 years) or high-frequency variations of precipitation and temperature.

The existence of significant positive correlation between precipitation and temperature is probably the influence of evaporation and water balance of the Great Lakes on this area. The Great Lakes provide an important influence during winter months by raising average daily minimum temperatures at surrounding areas by some 2°-4°C above those inland locations (*Barry and Chorley, 1978*). The open water contributes larger amount of moisture to northwesterly cold and dry air streams from Arctic and Canadian continents. The Appalachian Mountains prevents the air mass moving over to its eastern side.

These two regions represent the two opposite relationships between precipitation and temperature in the continental United States. However, the negative correlation in the central Great Plains in summer is much stronger than the positive correlation in the area south of

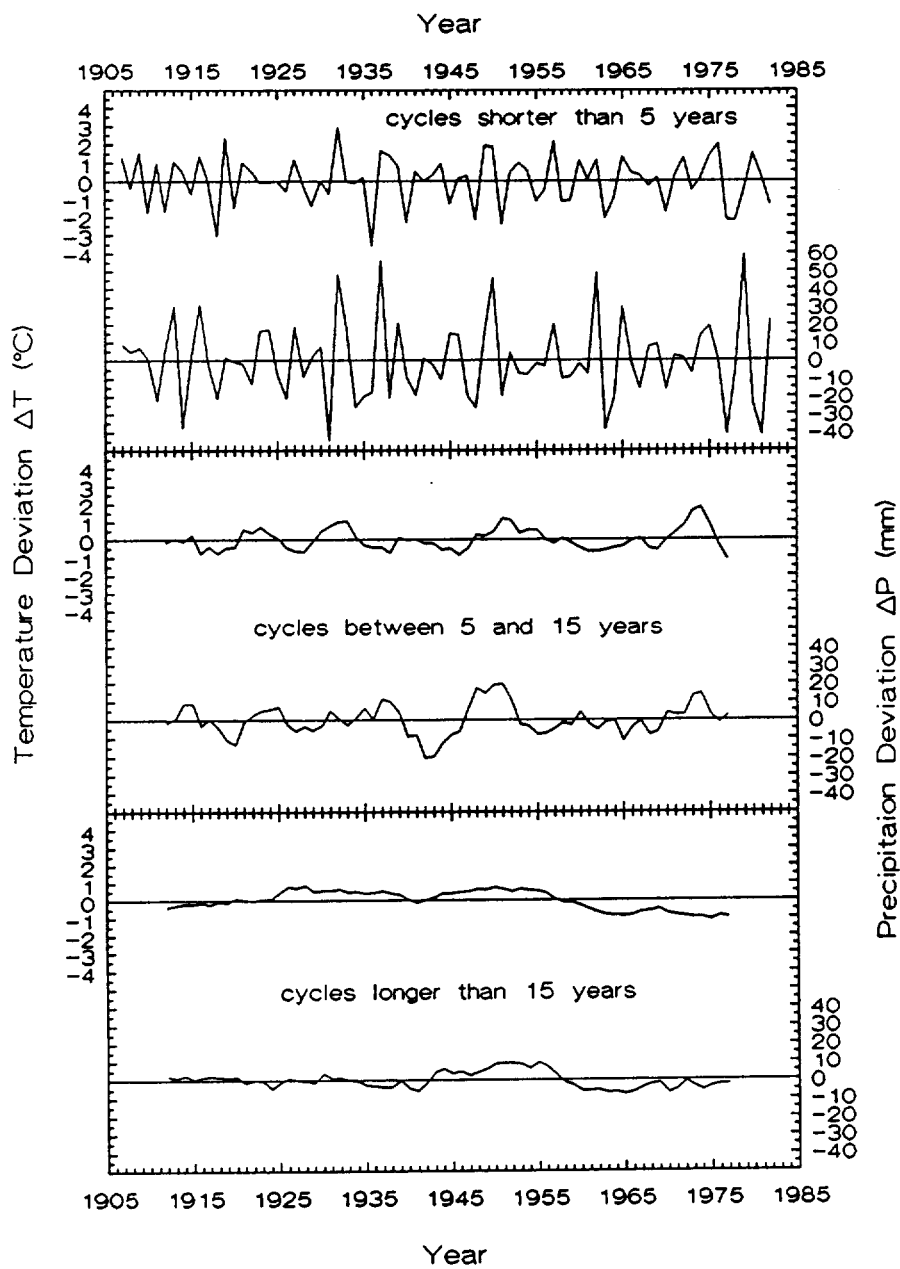


FIGURE 4.33. Deviations of monthly mean temperature and monthly total precipitation in three cycle bands for the area south of the Great Lakes in winter season.

the Great Lakes in winter. Furthermore, the correlation in the central Great Plains seems to persist in the variations of all time-scales, even though weaker in long cycles; while the correlation in the area south of the Great Lakes is caused mainly by the short cycles. The correlation coefficients between precipitation and temperature of these two areas for all time-scales and the three cycle bands are listed in Table 4.7 and plotted as a bar chart in Figure 4.34, for convenience of comparison.



TABLE 4.7. Correlation coefficients between precipitation and temperature from variations of different time-scales in the central Great Plains for summer and in the area south of the Great Lakes for winter.

Time-scale (Cycle Band)	Correlation coefficient	
	Central Great Plains (32°N-42°N; 95°W-105°W)	South of Great Lakes (33°N-43°N; 80°W-92°W)
All cycles	-0.75 (-0.22)	0.49 (0.22)
Cycles shorter than 5 years	-0.75 (-0.23)	0.43 (0.23)
Cycles between 5 and 15 years	-0.72 (-0.24)	0.24 (0.24)
Cycles longer than 15 years	-0.48 (-0.24)	0.22 (0.24)

Note: Parenthetic data are the 95% significance levels of correlation coefficient.

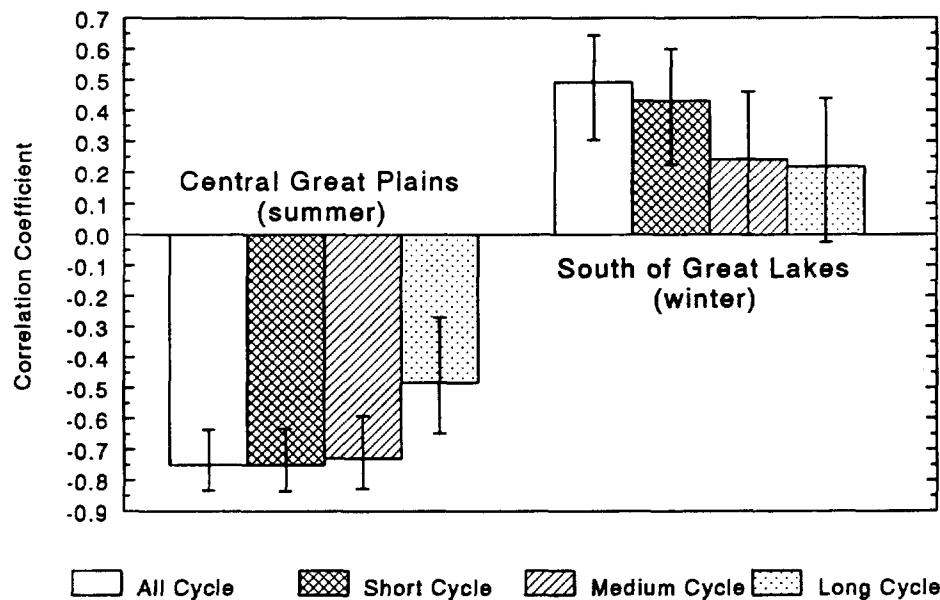


FIGURE 4.34. Correlation coefficients between monthly total precipitation and monthly mean temperature from variations of different time-scales in the two areas. Error bars are the 95% confidence intervals.

## CHAPTER 5. SUMMARY AND CONCLUSIONS

This study has examined the relationship between precipitation and temperature within the continental United States based on the monthly precipitation and temperature data set from the Historical Climatology Network. The patterns of precipitation-temperature relationship revealed in this study cannot be used by themselves to predict the climate change that would occur due to the increase of the greenhouse gases in the atmosphere. The results might be useful, however, as an illustration of the nature of the sensitivity of the climate system and, also, for comparisons with the results of numerical modeling and paleoclimatological analogues.

The correlation analysis has been conducted on the 80-year (1905-1984) time series of monthly total precipitation and monthly mean temperature of individual stations, state averages, and regional averages for each month and each season. The significant features of precipitation-temperature relationship are: 1) over most areas of the United States summer precipitation and temperature tend to be negatively correlated, and greatest negative correlation exists in the central United States; 2) the significant positive correlations mainly occur for winter season in the area south of the Great Lakes including most of Indiana, part of Illinois, Ohio, Kentucky and Tennessee; 3) the significant negative correlation persists through the entire year in the eastern Rocky Mountains area; 4) both the Pacific and East coasts do not display strong precipitation-temperature correlations through the entire year, particularly in the east coast.

The linear regression between precipitation and temperature has also been applied

to the regional average data for each season. Generally, the change of precipitation predicted by the linear relationship between precipitation and temperature is limited, and less than 50% of variability of precipitation can be explained by their linear relationship.

The contribution to the total correlation on the variations of short (shorter than 5 years), medium (between 5 and 15 years), and long (longer than 15 years) cycles has been calculated by means of moving-average filtering. The results have shown that, in general, both negative and positive correlations occurs on all time-scales; however, for most areas, the correlation tends to occur on the variations of short and medium cycles. Specifically, in the central Great Plains, the significant negative correlation is much stronger on short- and medium-cycle variations than on long-cycle variations; and in the area south of the Great Lakes, the significant positive correlation mainly exists on short- cycle variations.

It is suggested that one should be cautious of using the results of this type of study to predict regional patterns of future climate change. The fact that negative or positive relationship between precipitation and temperature existed during past 100-year period or so does not guarantee that the same conditions will recur in the future if the earth is warmed by the greenhouse effect. There are going to be many boundary conditions that are different, such as the distribution of snow and ice, sea surface temperature, and patterns of vegetation and deserts. The differences will influence the large-scale atmospheric circulations that determine regional precipitation and temperature. Reliable predictions of the potential impact of greenhouse effect on the climate will only be made when a better understanding of the mechanisms of climate change is achieved. Much of this understanding should come from investigations of recent changes in the atmospheric circulation and related variability of climatic variables in addition to precipitation and surface temperature on the land.

On the issue of future climate change, all different approaches - numerical modeling,

paleoclimatological analogue, and recent climate variability - should play important roles and are given equal priority. And it is reasonable to assign a higher probability to the specified climate change occurring in the regions where the different investigation approaches are in agreement. For example, in the central United States, paleoclimatological analogue (e.g., *Kellogg, 1977; Butzer, 1980*), Patterns of recent climate (e.g., *Williams, 1980; Wigley et al., 1980; this study*), and climate models (e.g., *Kellogg and Zhao, 1988*) all show that negative relationship between precipitation and temperature or warm and dry climate pattern occurs during summer season. It might also be pointed out that no matter how sophisticated numerical climate models become there will always be the need to analyze climate data, not only because it is the way to investigate the mechanism of climate variability, but also because it serves to check whether the models behave like the real world.

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