PRECIPITATION DISTRIBUTION IN THE SOUTHWEST OF SAUDI ARABIA

by

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CHAPTER I

INTRODUCTION

The Southwest of Saudi Arabia is mostly mountainous. This region receives the highest amount of precipitation in the country with an average annual amount of about 400 mm. It is the most cultivated area in Saudi Arabia and supports both the largest rural population and rural population density. Extensive agricultural and urban development have been taking place in this area.

Information regarding the spatial and temporal nature of precipitation is essential for farmers, planners, and water managers. For example, knowledge of ongoing precipitation conditions is important to farmers making decisions about which crops to plant (Winkler, Murphy, and Katz 1983). Also, rainfall intensity during individual storms or over short periods is important hydrologists and water engineers who must forecast floods and provide flood warnings.

It is the concern of this dissertation to provide meaningful data and explanations regarding precipitation characteristics and distribution in the southwestern area of Saudi Arabia. Particular attention is given to the relationships between precipitation on the one hand and elevation and topography on the other. This includes the identification of the levels of maximum precipitation, spatial and temporal distributions, orientation of the mountains and distance from moisture sources. To understand the nature of these relationships, three main questions are proposed:

1) Is there a relationship between precipitation and elevation in the Southwest of Saudi Arabia? If so, how is that relationship expressed?

2) Do topographic factors such as elevation and orientation of the mountains affect the precipitation? If so, how?

3) How do the inter-relationships of topography and elevation influence the temporal and spatial patterns of precipitation in the Southwest of Saudi Arabia?

Some precipitation-elevation relationships are well established. Precipitation can be either enhanced or diminished with elevation. In general, precipitation increases with increased elevation up to a certain height. Beyond this point of maximum precipitation, an inverse relationship begins, and precipitation decreases with increased elevation. The elevation of maximum precipitation varies from one place to another and from time to time. The precipitation-elevation relationship is affected by atmospheric conditions, synoptic situation, storm types, seasonal patterns, wind speed and direction, slope, mountain orientation, leeward and windward position of the study area, and the distance from moisture sources.

To provide direction for the research, three hypotheses are stated:

1. Precipitation in the Southwest of Saudi Arabia increases with increased elevation up to a certain elevation. After this point of maximum precipitation an inverse relationship begins.

2. The elevation of maximum precipitation in the Southwest of Saudi Arabia varies from one season to another.

3. The north-south orientation of the Asir Mountains affects precipitation distribution in the study area. Therefore, stations lying on the southwest and west sides of the Asir Mountains receive more precipitation than stations lying on the other sides because the mountains are oriented perpendicular to the southwesterly flow.

Research Plan

The research herein utilized monthly precipitation records for a period of 10 years (1971-1980) for 104 stations. These were provided by the Department of Water Resource Development, Hydrology Division of the Ministry of Agriculture and Water, Kingdom of Saudi Arabia. These data were subjected to spatial and temporal analysis including the isohyetal method, Thiessen polygons, linear regression, and harmonic analysis.

The most significant results of this dissertation are:

1. the development of a detailed regional climatology in an area of the world for which little baseline climatic research has been accomplished,

2. the identification of spatial, annual and seasonal levels of maximum precipitation elevation which depart to a significant degree from the usual patterns described in the literature,

3. the explanation of these elevation-precipitation relationships are discussed in terms of the general circulation synoptic patterns, and

4. the identification of two discrete climatic regions which reflect the impressive impact of the 3000 m high Asir escarpment.

The remainder of this dissertation is organized as follows. Chapter II describes the study area including location, topography, and general climatic characteristics. Chapter III is a review of precipitation quality and quantity, its occurrence and measurement; a detailed literature review is provided. Chapter IV presents the statistical methods and techniques used in analysis of precipitation generally and of precipitation in southwestern Saudi Arabia specifically. Chapter V provides a description of the data analysis and associated results. Conclusions and recommendations are given in Chapter VI.

CHAPTER II

STUDY AREA

Location and Topography

The research was conducted in the Southwest of Saudi Arabia, which lies approximately between the country of North Yemen to the south and latitude $21^{o}N$ and between the Red Sea on the west and longitude $45^{o}00'E$ (Figure 1). The Southwest of Saudi Arabia is mostly mountainous. The topography of the region can be divided mainly into three zones: the Red Sea coastal plain (Tihama), the Scarp-Hijaz Mountains, and the Hijaz plateau (Figure 2).

The Red Sea coastal plain (Tihama) is a narrow coastal strip of land that extends from the Gulf of Aqaba south to the Yemen border. The northern part of Tihama is known as the Tihama Al-Hijaz and south as the Tihama Asir. Tihama width varies from 0 km in the north to 40 km in the south near Jizan.

The Scarp-Hijaz Mountains extend from north to south parallel to the Red Sea with a north-south orientation. The northern part of the mountains is known as the Hijaz mountains and the southern section is the Asir Mountains. This escarpment is one of the outstanding landscape features of Saudi Arabia, extending from Al-Taif in the north to the Yemen border. It ranges from 1600 to 3000 m in height and is especially precipitous as the Hijaz rim is approached. The mountains vary in width from about 30 km

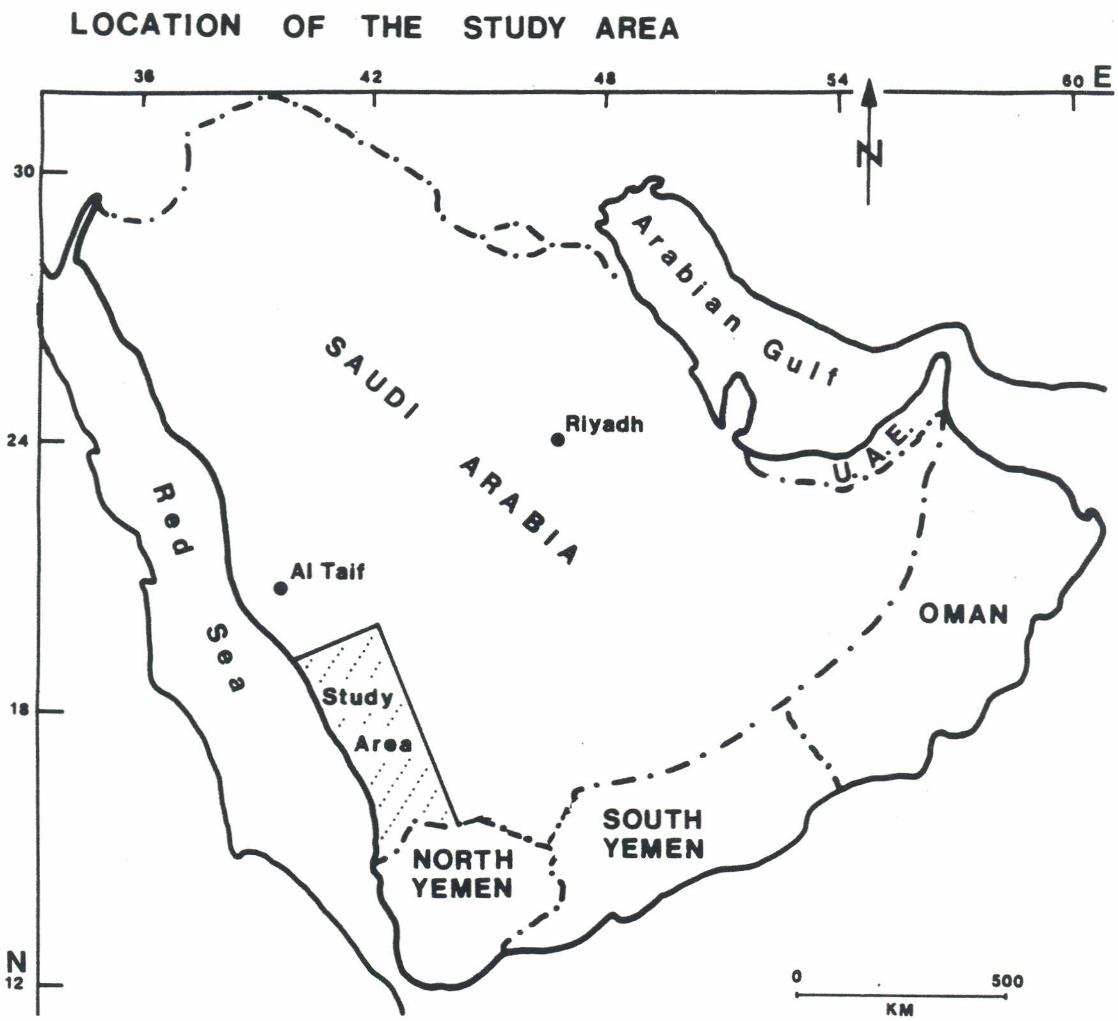


Figure 1. Location of the study area.

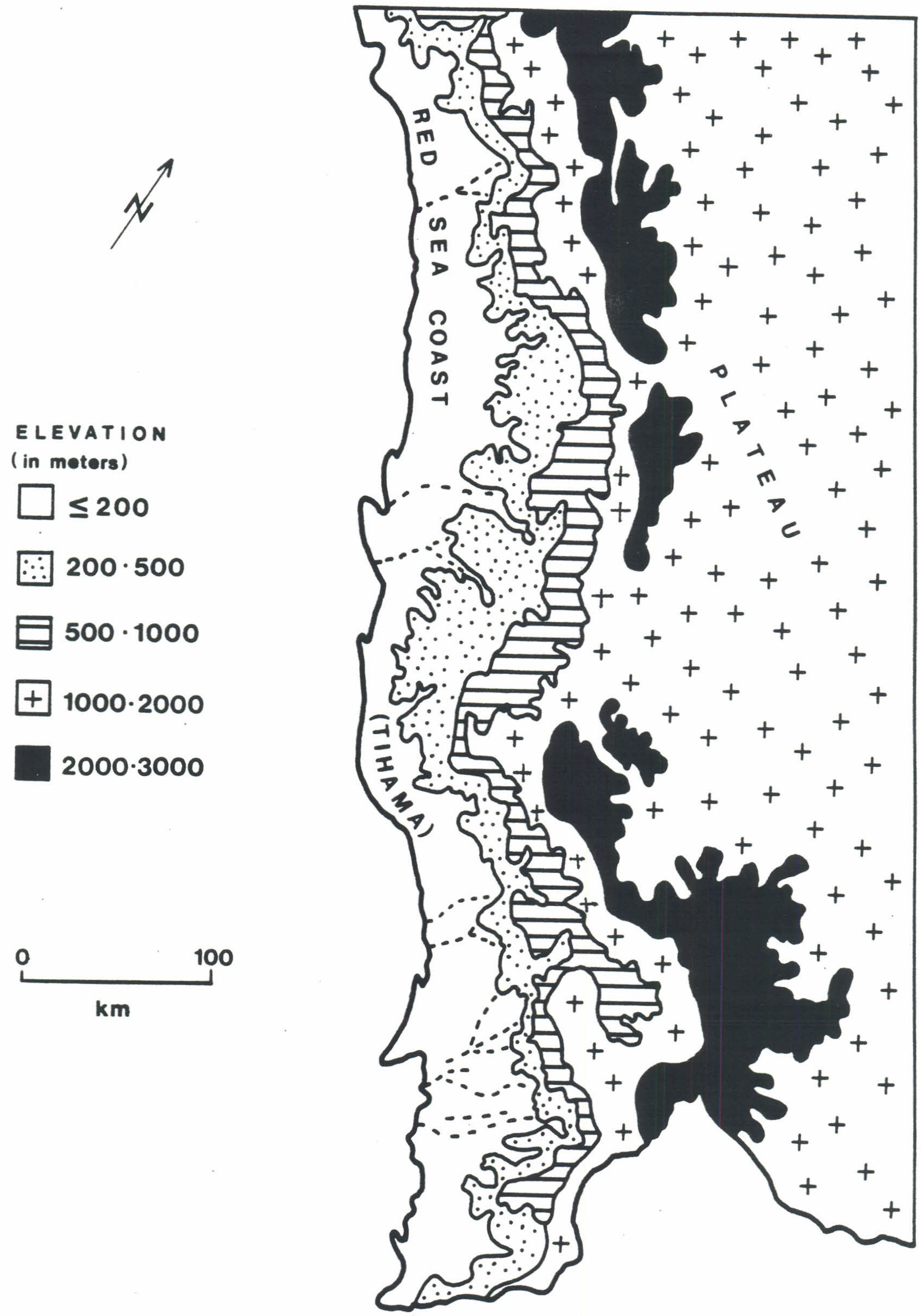


Figure 2. Topography of the Southwest of Saudi Arabia.

to a maximum of 140 km near the Yemen border. Most of the mountains lie above 1800 m with the highest point, Bani Shaib,. at 4260 m (El-Khatib 1980). Most of the Asir Mountains consist of exposed masses of ancient schists and granites.

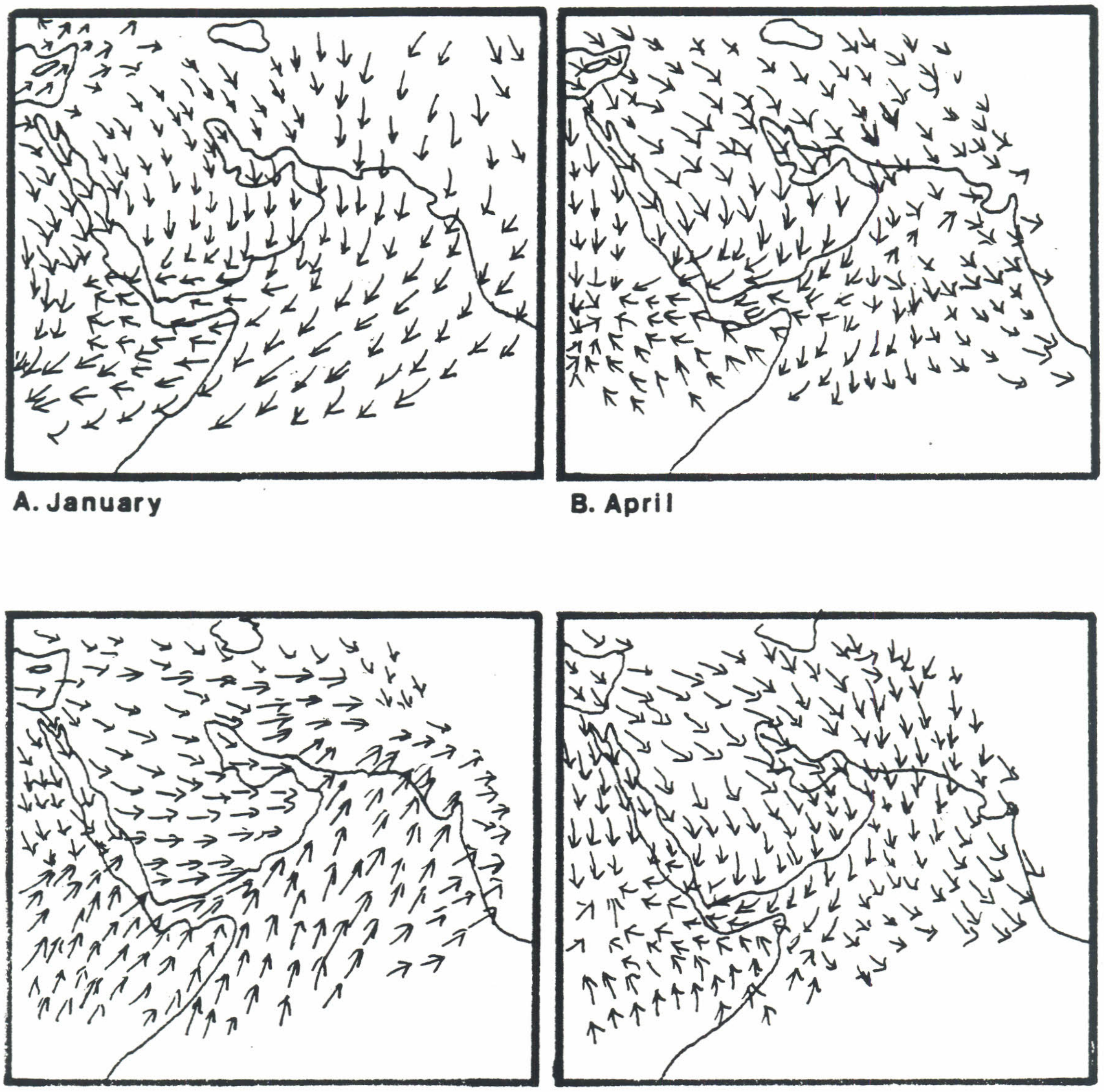
The Hijaz Plateau is divided into northern and southern portions. The Plateau is relatively flat, varies in elevation from 200 m to 1800 m, and is dissected by occasional wadis flowing to the east.

The Southwest of Saudi Arabia has a number of short distanced, but fast flowing streams for several months of the year. The upper courses of the streams are often entrenched in steep valleys which carry a dense vegetation of evergreen shrubs, thorns, and moderately sized palms. Near the valley bottoms vegetation changes to thick grassland with clumps of taller trees. In the west, at the junction of the uplands and a narrow coastal plain, the streams disappear in the sand. This area supports fields of millet and fruits. The upper slopes of the valleys have been cleared and terraced for the cultivation of bananas, dates, coffee, yams, vines, melons, millet, and wheat. The Southwest region is the most cultivated area of Saudi Arabia with the largest rural population and highest rural population density in the country.

Climate of the Region

The prevailing climate in the Southwest of Saudi Arabia according to Koppen classification can be divided into three climatic types: 1) the hot desert climatic type (Bwh) prevails in the Red Sea Coast (Tihama); 2) the hot steppe climatic type (Bsh) prevails in the plateau; and 3) the warm, temperate, rainy climatic type with a dry winter (CW) which prevails in the high elevations of the Asir Mountains (Taha et al. 1981, Al-Mawled 1982).

The climate of the Southwest of Saudi Arabia is an interaction of local circulation due to the topography of the region and the general circulation. Air flow over the Southwest of Saudi Arabia varies from one season to another. In winter, the winds are northerly to northeasterly; in summer, the winds are northwesterly to southwesterly. Spring and autumn are transition seasons (Figure 3). Average annual precipitation is about 400 mm but some parts of the region receive more than 500 mm. Average temperature in the region varies from one station to another (Appendix 1). For example, average temperature at Kiyat station (20 m) is 30.2^{o}C, at Al Heifa (1090 m) 25^{o}C, at Abha (2190 m) 18.3^{o}C, and at An nimas (2600 m) 15.8^{o}C. The average wind speed at Abha is 8.2 km/hr and at Kwash it is 6.2 km/hr (Appendix 2). The major winds blow from the southwest (Southwest Monsoon) and from the



A. January B. April

C. July D. October

Figure 3. Prevailing flow on the Arabian Peninsula (after Hastenrath, Hafz, Kaczmarczyk 1979).

southeast (Southeast Monsoon). The average relative humidity is 59.2% at Abha, 55.6%, at Biljurshi, and 43.3% at Bisha (Appendix 3); and average monthly evaporation is 264 mm at Abha and 308.3 mm at Bisha (Appendix 4). In addition to the influence of topography, the climate of the region is affected by different air mass systems (Figure 4) and general circulations: 1) the Polar Continental Air Mass, 2) the Tropical Continental Air Mass, 3) the Subtropical Jet Stream, 4) the Tropical Easterly Jet, 5) the Intertropical Convergence Zone, 6) the Red Sea Convergence Zone, and 7) the Mediterranean Depression. The influences of the air on the climate of the Arabian Peninsula vary from one season to another as a result of the variation in pressure gradient between the high and low pressure regions over and around the Arabian Peninsula (Figure 5). These influences will be indicated in the following discussion.

Polar Continental Air Mass

The polar continental air mass (CP) is found over central Asia during the winter season (Figure 5). The CP air mass is characterized by extremely cold and dry air and small amounts of clouds. However, the CP air mass is stable in the origin of its source, but it is modified when it passes over warmer surfaces such as the Caspian Sea or the Arabian Gulf. Therefore, the CP air mass brings cold

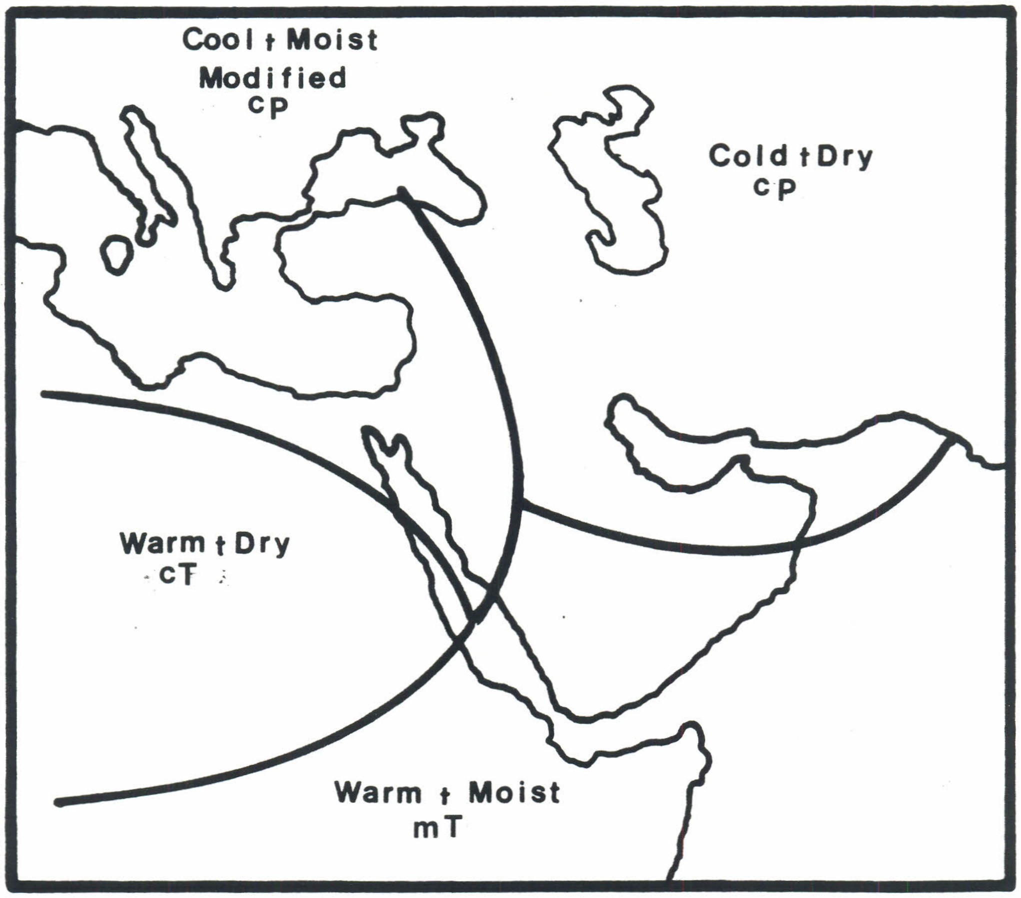


Figure 4. Air masses that affect the climate of the Arabian Peninsula (after Al-Qurashi 1981)

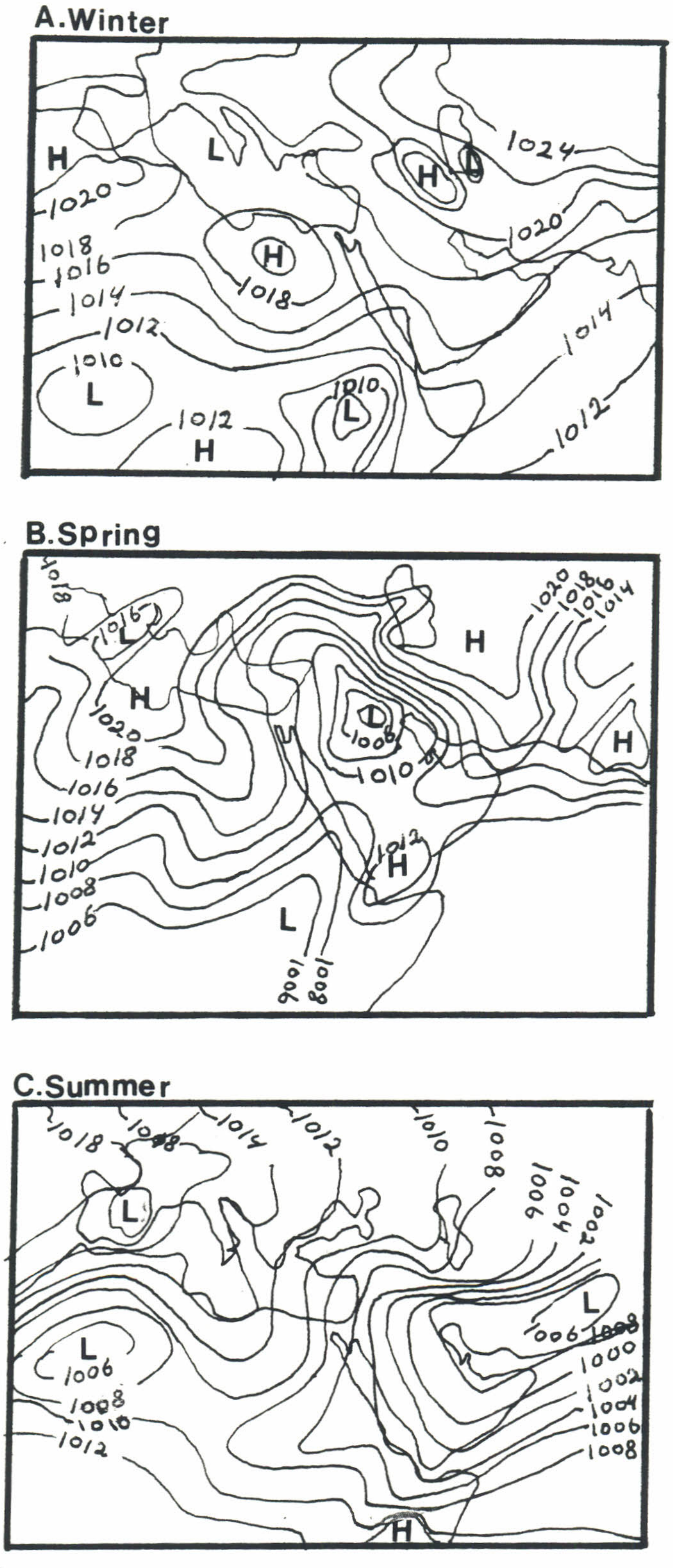


Figure 5. Mean sea pressure (after Al-Qurashi 1981).

and dry air to the Arabian peninsula during the winter season. But during summer, the CP air mass does not influence the weather of the Arabian peninsula because its source shifts further north.

Tropical Continental Air Mass (CT)

The CT air mass originates over the Sahara of north Africa in the summer, late spring, and early autumn when surface heat is pronounced. This air mass is characterized by hot and dry air. CT air masses invade the northwest of the Arabian peninsula in advance of the transitory Khamsin or desert disturbances which occur in late spring or early autumn and move from west to east over the northern Red Sea (Taha et al. 1981).

The Subtropical Jet Stream (STJ)

The STJ is a belt of strong upper westerlies which pass across the Arabian peninsula around 23^{o}-27^{o}N at an altitude of 13 km with a maximum speed of 120 kt. The STJ covers more than 5^{o} and is subject to meridional oscillations in a range of 10^{o} latitude from summer to winter (Figure 6). The upper tropospheric divergence around the subtropical jet stream and lower convergence are important factors in the development of the convective activity observed in non-summer seasons. Moreover, the upper tropospheric divergence and lower convergence are

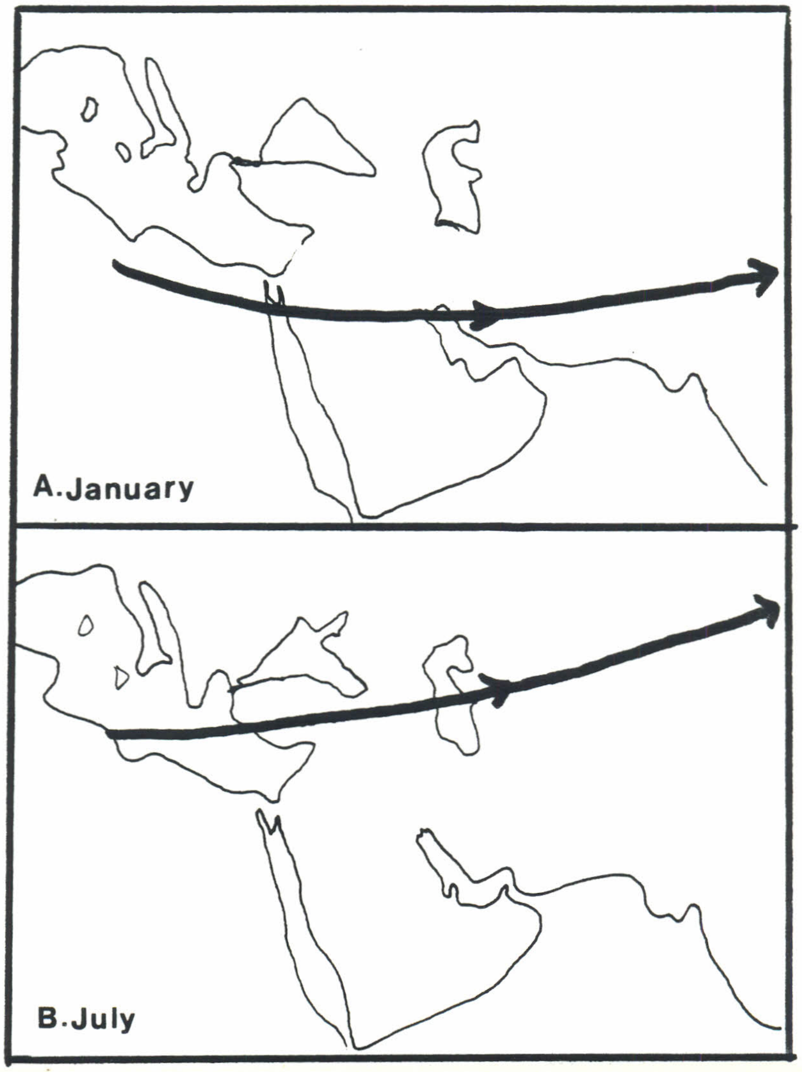


Figure 6. Mean position of the subtropical jet stream at 200 mb (after Beaumont, Blake, and Wagstaff 1976).

important factors for the permanence of small scale systems such as desert depressions (Taha et al. 1981). During winter, occasionally, the polar front jet moves farther south and combines with the STJ, and weather may be created from the associated cold fronts (Al-Qurashi 1981).

Tropical Easterly Jet (TEJ)

During summer, the TEJ forms in the upper troposphere over southern Asia about 15^{o} N at an altitude of 16 km with maximum speeds exceeding 100 kt. The TEJ is related to the thermal contrast between the cooler air to the south over the Arabian Sea and the Indian Ocean and the warm air to the north over the Asiatic land (Al-Qurashi 1981).

The TEJ is characterized by the location of the main belt of summer rainfall on the right, or northern side, of the axis, upstream of the wind maximum and on the left side downstream, except for the region where the orographic influence is predominant (Barry and Chorley 1982).

Intertropical Convergence Zone (ITCZ)

The ITCZ is a tropical feature where the trade winds meet. Its structure and characteristics vary from one area to another depending on such factors as topography and distribution of land and water surfaces.

The ITCZ moves north during summer up to latitude 20^{o}N. The time lag between the summer solstice and the time when the ITCZ reaches its highest latitude is 6 weeks (Solot 1950). The ITCZ movement is small over the ocean but is larger over the land surface (Ayoade 1983). Precipitation that connects with the ITCZ is not located at the boundary of the ITCZ but is located about 200 miles south (Solot 1950). During summer, the ITCZ influences the weather of Saudi Arabia and influences the precipitation amount, duration, and distribution.

The Red Sea Convergence Zone (RSCZ)

The RSCZ is a region of confluence between air stream flows from the northwest and stream flows from the southeast. These air streams meet over the Red Sea from October to May. The position of the Red Sea Convergence Zone varies from day to day. But the average position of the RSCZ during winter is about 20^{o}N; also, it moves southwards into the latitude of 15^{o}N. The RSCZ is characterized by calm or light and variable winds. During winter, the RCSZ produces a relatively wet region around the southern Red Sea (Pedgley 1966a, b).

The Mediterranean Depression

The Mediterranean climate is characterized by hot, dry summers and mild, wet winters. Precipitation over the Mediterranean is mainly due to the high sea surface temperatures during winter. For example, in January, the sea temperature is about $2^{o}C$ higher than the mean air temperature. The invasions of colder air into the Mediterranean cause the convective instability along the cold front producing frontal and orographic precipitation. The invasion of colder air gives rise to cumulus development and is critical in the formation of Mediterranean depressions. Some Atlantic depressions enter the western Mediterranean as surface lows due to the pressure gradient (Figure 5). The Atlantic depression (Saharan depressions) and the western Mediterranean depressions develop to the lee of the Alps and Pyrenees. The Sahara depressions and depressions from the western Mediterranean move eastward (Barry and Chorley 1982). The Mediterranean depression affects the Southwest of Saudi Arabia during winter and spring especially when it amalgamates with the Sudan low.

Seasonal Climate of the Southwest of Saudi Arabia

The seasonal climate of the study area is varied from season to season. This variation is due to the influence of different climatic regions.

In winter (December-February) the region is under the influence of northerly flows (Figure 3). The region is affected by westerly Mediterranean air associated with a depression that moves across northern Arabia. The Red Sea

Convergence is found over the south Red Sea. The westerly flow is channeled into the Red Sea trough, and, when turned toward the high mountains, precipitation falls.

In spring (March-May), the flow patterns are less distinct than in the winter season (Figure 3). The northeast monsoon over the Arabian Sea is less organized, and there is a strengthening of the southeasterly monsoon flow. The Red Sea Convergence Zone is still in existence over the south Red Sea. The southeasterly monsoon flow associated with the Red Sea Convergence Zone produces widespread precipitation over the southwest of Saudi Arabia.

During summer (June-August), the flow pattern is well defined. The Southwest monsoon flows from the equatorial region into the interior of southern Asia. Northwesterlies prevail over the north Arabian peninsula and merge with the southwest monsoon along an extended confluence zone over the Gulf of Aden and the southern portion of Arabia (Hastenrath, Hafez, and Kaczmarczyk 1979). The Westerly Jet Stream is shifted north and the Tropical Easterly Jet Stream is found at latitude 20^{o}N with a core around 150 mb. In summer, the area comes under the influence of a moist southwesterly air flow which brings precipitation to the southwest of Saudi Arabia.

In autumn (October-November), this season is transitional from summer to winter. The flow pattern is less distinct and weak. The northwesterly flow becomes more frequent, while the southwest monsoon flow begins to retreat.

Therefore, the climate of the Southwest of Saudi Arabia varies from one season to another as a result of the combination of local and general circulations.

CHAPTER III

PRECIPITATION: ITS OCCURRENCE AND MEASUREMENT

The literature of mountain climatology clearly supports relationships between precipitation and elevation. Up to a certain elevation this relationship is positive; in other words, increased precipitation is associated with increased elevation. Above this point of maximum precipitation an inverse relationship begins, and precipitation decreases with increased elevation. The level of maximum precipitation varies from place to place and from time to time. The precipitation-elevation relationship is further affected by atmospheric conditions, synoptic situation, storm types, seasonal patterns, wind speed and direction, slopes, mountain orientation, leeward and windward position of the study area, and the distance from the moisture sources.

This review is divided into five sections: (1) orographic precipitation and models; (2) a review of relevant literature on the precipitation-elevation relationship; (3) the factors that affect the elevation-precipitation relationship; (4) precipitation measurement and analysis; and (5) statistical methods.

Orographic Precipitation and Models

Precipitation generally occurs when air rises and is adiabatically cooled to and below the dew point. Of the three principal ways that air is forced aloft convectional, frontal, orographic the latter is most pertinent to this study. Orographic precipitation results from uplift and cooling of air along mountain barriers. Thus, windward slopes receive more precipitation than the leeward slopes. Mountains can also act as high heat sources on sunny days when convective clouds tend to form (Pedgley 1970). Explanation of orographic precipitation and its distribution requires knowledge of the following:

1. Large scale synoptic factors which determine the wind speed and direction, stability, and humidity of the air in mountains;

2. The microphysics of clouds and precipitation, especially as related to condensation and evaporation on the windward and leeward sides of the mountains; and

3. The dynamics of both local and broad scale air motion over and around the mountains (Sarker 1966).

Investigations to determine orographic effects on precipitation have been developed through time. These investigations have been based on a variety of parameters. For instance, early studies on orographic precipitation considered the influence of altitude on the annual precipitation (Lee 1911, Henry 1919). Later works examined seasonal aspects of orographic precipitation and the effect of physiographic variables on precipitation in the mountains and the importance of synoptic conditions in determining orographic effects (Donley and Mitchell 1939, Spreen 1947). Moreover, recent investigations include physical modeling, statistical modeling, and observation of the distribution of storm rainfall in mountainous areas (March and Wallace 1979).

Several theories and methods have been developed to explain and predict orographic precipitation. The development of modeling techniques and aircraft observation of orographic clouds has been important in this respect (Barry 1981). Pockels (1901), for example, developed a theory to explain the formation of precipitation on mountain slopes. He used dynamic equations to calculate vertical velocities and condensation which were due to adiabatic ascent over a slope. He concluded that the angle of slope is more important than the elevation in determining the amount of precipitation. Sarker (1966, 1967) developed a dynamic model for orographic precipitation over the western Ghats of India. The model assumes a saturated atmosphere with a pseudoadiabatic lapse rate based on linearized equations. The method accounts for a high percent of the observed maximum precipitation. Furthermore, Colton (1976) developed a meso-scale numerical model to simulate the orographic precipitation. He concluded that orographic precipitation processes can be simulated with sufficient accuracy to use numerical models to determine the spatial distribution in mountainous areas where orographic influences are dominant.

Relationships Between Elevation and Precipitation

The literature on precipitation in mountainous areas generally indicates that elevation is associated with both increases and decreases of annual precipitation over the globe (Bonacina 1945). It is believed to be one of the most important factors that affects the amount and distribution of precipitation (Lee 1911, Donley and Mitchell 1939, Bonacina 1945, Peck and Brown 1962, Chang 1973, and Wolfson 1975).

Bonacina (1945) indicated that when the mean annual precipitation is greater than about 5000 mm in the tropics and 2500 mm outside the tropics, elevation is a major factor. Generally, highlands receive more precipitation than lowlands (Peattie 1966, Brown and Coheme 1972, Ryden 1972, Pacl 1973), and the greatest annual precipitation totals in the world occur where mountain barriers lie across the paths of moisture bearing winds (Critchfield 1974). Moreover, there is much evidence for altitudinal influences (Barry 1981). Wolfson (1975) studied the topographical effects on standard normals of rainfall (SNOR) over Israel. He found that each rise of 100 m in station elevation accompanied an increase of 43 mm in the Carmel Mountains, 28 mm in the upper, western Galilee Mountains, and 26 mm in the upper, eastern and lower Galilee Mountains. In addition, Longley (1975) noted that precipitation decreases with depth into isolated valleys.

Investigations of the relationship of elevation to annual rainfall indicated that the amount of mean annual rainfall increases with increased altitude. Whitmore (1973) indicated that mean annual precipitation increases steadily by about 30 mm per 100 m increases in height. Balchin and Pye (1948) have also noted that the monthly totals show a close correlation with altitude. Peck and Brown (1962) found a good relationship between precipitation and elevation in Utah, for both the October-April and May-September periods. Outside the United States, Chuan and Lockwood (1974) found a good relationship between mean elevation and monthly precipitation in the central Pennines. Nieuwolt (1974) also found that annual rainfall totals increase with elevation in middle and high altitudes, except at very high elevations, where the depletion of atmospheric water may become a limiting factor.

The relationship between altitude and rainfall intensity is not clear. In a study of precipitation intensity and elevation in northern California, Linsley

(1958) found that there is a coefficient of correlation (r) of 0.88 and a standard error of 0.067 inch/hour between rainfall intensity and elevation. However, Cooper (1967) in a study in southern Idaho found there was no relationship between elevation and intensity of spring and summer rainfall in a 93 square mile area with a range of 3,500 ft. relief. Barry (1969) states that because the investigations in Idaho and coastal British Columbia indicate no relationship between intensity and elevation, there are exceptions to the general relationship between increased elevation and increased precipitation. Schermerhorn (1967) also noted that for western Oregon and Washington, station elevation alone does not explain much of the variation which predominantly occurs in winter. Dhar and Rakhecha (1981) found that there is no significant linear relationship between elevation and monsoon in the Himalayas and the correlation coefficient was r=0.188. However, in most cases it has been found that precipitation tends to increase with elevation (Smith 1979).

The amount of rainfall generally increases with increasing elevation, up to a certain level. This point of maximum precipitation is different from place to place and from time to time, but, in general, it is below 10,000 feet (Bonacina 1945). The argument is that the greatest amount of precipitation usually occurs immediately above the cloud base because most of the moisture is concentrated there.

A complete world study of vertical precipitation profiles was conducted by Lauscher in 1976 (Barry 1981, 195). He used data for 1300 long-term stations grouped into three major categories: (1) below 1 km, (2) 1-2 km, and (3) 2-3 km for 10^{o} latitude and 20^{o} longitude. Sectors were grouped between 35^{o}S and 55^{o}N and from 130^{o} westward to 110^{o}. He identified five general types of maximum precipitation (Figure 7). These are

> (1) 'tropical' (T) with a clear maximum at about 1 - 1.5 km; (2) 'equatorial' (E) where there is a general decrease with height above a maximum close to sea level; (3) 'transition' type (Tr) in the subtropics where there is either little height dependence or conditions vary considerably locally; (4) a 'mid-latitude' type (M) which shows a strong increase with height; and (5) a 'polar' type (P) where higher totals do occur near sea level, at least in the vicinity of open water.

The level of maximum precipitation is different from region to region as a result of local or regional factors. Generally, this level is higher in summer and lower in winter (Varney 1920). For instance, in East Africa, the elevation of maximum precipitation on both Mt. Kenya and Mt. Kilamanjaro is 1500 m; above that precipitation begins to decrease (Figure 8) (Flohn 1972).

Lauer (Barry 1981, 186) shows that the southern slopes of Mt. Cameroon, West Africa, have a maximum at their foot due to the monsoon regime, but on the northeast side, where trade wind influences are dominant, the maximum occurs at 1500 m (Figure 9).

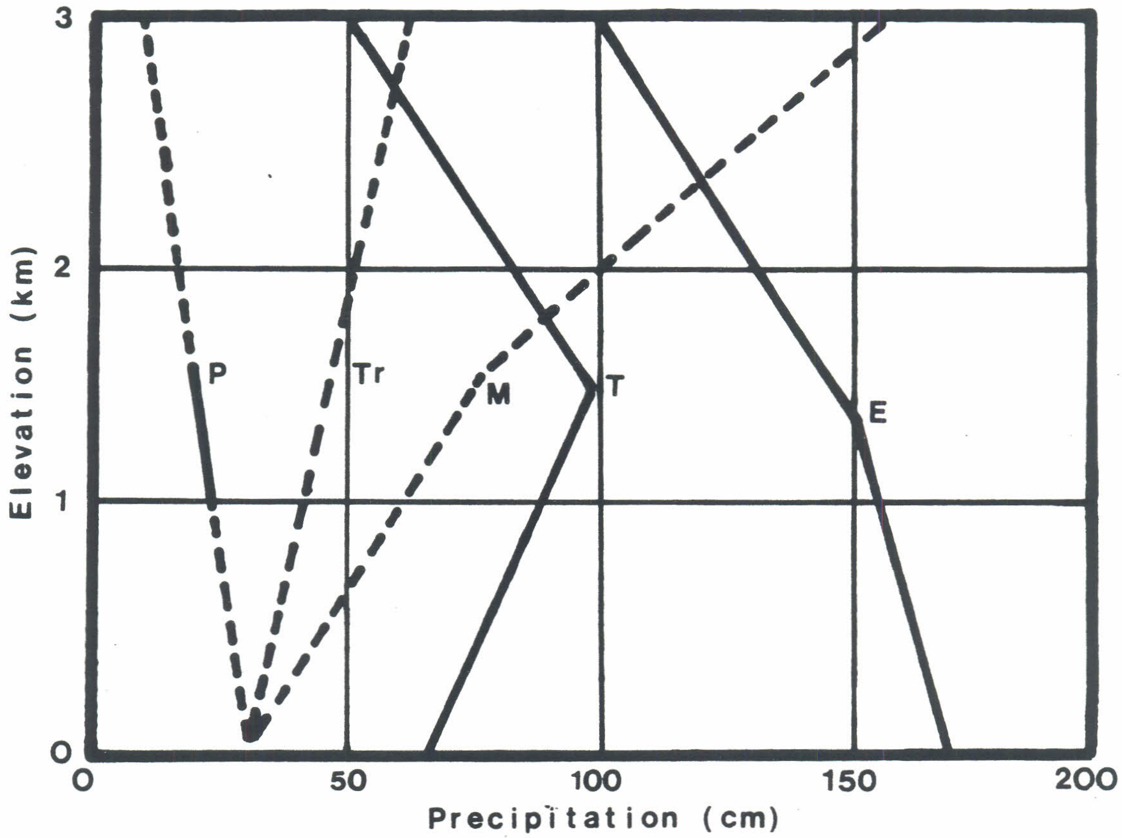


Figure 7. Mean annual precipitation in different altitudes in equatorial (E), tropical (T), middle latitudes (M), and polar region (P), (TR) a transitional pattern between latitude 30 and 40 (after Barry 1981).

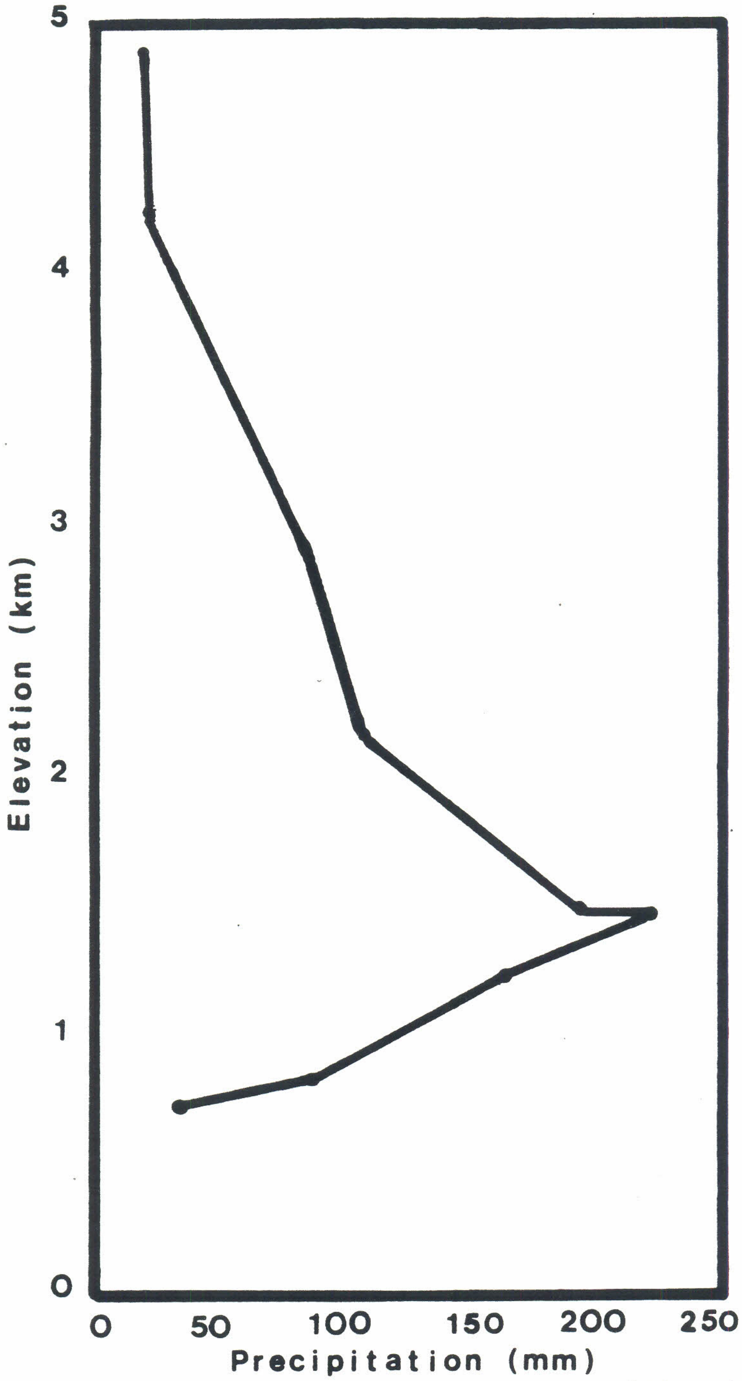


Figure 8. The maximum precipitation on Mt. Kilimanjaro (after Flohn 1972).

On the Caribbean slopes of the Mexican Meseta, the typical tropical maximum occurs between 600 and 1400 m, but there is a weak secondary maximum around 3000 m which results from convective heating over the basins. Lauer reports a similar phenomena in Ethiopia. The low-level, warm, moist monsoon air reaches the plateaus along the valleys where it enhances convective activity, causing maximum precipitation to occur between 2,000 and 2,500 m. Similar intense heating occurs over the subtropical deserts so that in the Sahara, for example, convection is set off within disturbances in the tropical easterlies and gives rise to a precipitation maximum at 2,500 m elevation in the Hoggar (Figure 9) (Barry 1981).

The elevation of maximum precipitation is influenced by precipitation mechanisms and air mass characteristics. Controls include vertical profiles of moisture content and wind speed. The atmospheric profile's vapor content increases quite rapidly with height in the lower troposphere. Therefore, the amount of rainfall might be expected to decrease upward (Barry 1981). Price (1981, 103) stated that

> As the air lifts and cools further, the amount of precipitation will eventually decrease, because a substantial percentage of moisture has already been released on the lower slopes. In addition, the decreased temperature and pressure at higher elevations reduce the capacity of the air to hold moisture. The water vapour content at 3,000 m (10,000 ft) is only about one-third that at sea level.

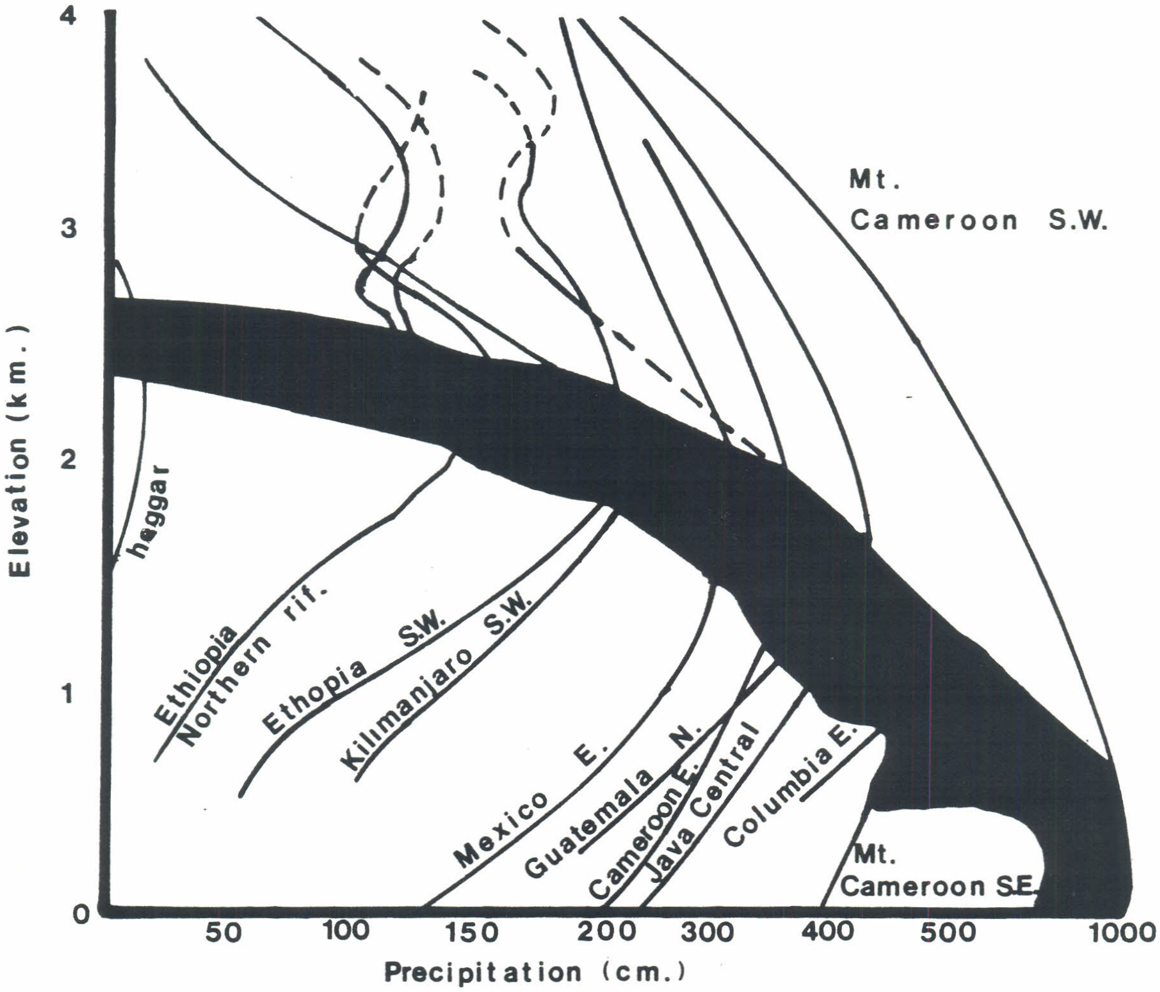


Figure 9. The zone of maximum precipitation in different altitudes (after Barry 1981).

Empirical studies have shown the reversal in the precipitation-altitude association. For example, Lee (1911) found that there is an increase of precipitation with altitude from the floor of the Great Valley up the western slope of the Sierra to about the 5000 ft (1500 m) level. The rate of increase is greatest in the lower foothills and steadily decreases with increases in elevation. Above 5000 ft, however, there is a moderate decrease in precipitation with increasing altitude.

Similarly, a study of Snake Mountain shows that the precipitation in the Tennessee River basin generally increases with elevation, but the relationship does not continue. At very high elevations, TVA's recording rain gauges on Snake Mountain, at an altitude of 5000 ft, consistently caught less than nearby valley stations over a 14-year period (Smallshaw 1953). Storr and Ferguson (1972) found that the maximum precipitation for Marmont Creek basin occurs at 2360 m which is 300 m below the summit of the area.

Herrmann (1972) indicates that precipitation in the northwestern Sierra Nevada de Santa Marta/Colombia increases from 350 mm at sea level to 2500 mm at an elevation of 1600 m, while the amount of precipitation at the elevation 4000 m is 1800 mm. In the Himalaya Mountains, the level of maximum rainfall during the monsoon generally occurs at or a little below 2000 m. Dhar and Rakhecha (1981) point out that in the Himalaya there are two maximum zones of rainfall; one is located just near the foot of the Himalaya at an elevation of 0.6 to 0.8 km and the other zone is at an elevation of 2.0 to 2.4 km.

In Africa, Nieuwolt (1974) mentioned that the level at which precipitation trends reverse is between 2600 and 3400 m. Also, he indicated that in other tropical mountain areas, the altitude above which rainfall decreases with height can be as low as about 1500 m. Moreover, Whitmore (1973) found that mean annual precipitation increases fairly steadily about 30 mm with each 100 m increase in height up to the elevation of 1300 m; above this point of height, the precipitation increases only slightly.

Factors that Affect the Elevation-Precipitation Relationship

There are several factors which affect the precipitation-elevation relationship. These include atmospheric condition, synoptic situation and storm types, seasonal patterns, wind force and speed, slope, mountain orientation, and distance from the moisture sources. Some of these factors have more influence than others on the relationship between precipitation and elevation. Succeeding sections will examine how these factors operate on the precipitation-altitude relationship.

Atmospheric Conditions

The condition of the atmosphere offsets orographic precipitation (Smallshaw 1953, Smith 1979, Price 1981, and Barry 1981). Mountains are sites of natural atmospheric instability and as such are ideal areas for artificial stimulation of precipitation (Price 1981). The stability conditions of the atmosphere have a marked effect upon the geographic distribution of rainfall. Also, the precipitation distribution patterns in mountains are usually very complicated, showing strong differences over short distances (Nieuwolt 1974, Colton 1976).

The orographic component of rainfall increases only when the approaching air mass is unstable. Under stable conditions, the mountains cause no significant orographic lifting and rainfall is from frontal lifting. Elliott and Shaffer's (1962) study of orographic precipitation over the western mountains of the United States indicated that large orographic precipitation rates are favored by an unstable atmosphere. The upper mountains apparently receive less rainfall than the lower zones under these conditions, because the shallow cloud development does not allow as much depth for falling precipitation particles to grow by collision and coalescence with cloud droplets before reaching the surface. In addition, local circulation systems between valley and upper slopes and rain shadow situations may result in valleys being considerably drier than the ridges. For example, in parts of the Hindu Kush, Karakoram, and Himalayas, many valleys are distinctly arid. These contrast sharply with the adjacent mountains, where large glaciers exist (Price, 1981). While Bonacina (1945) indicated the importance of convective instability for the generation of intense orographic rain, Douglas and Glasspoole (1947) noted that instability is not an important element in the warm sector of orographic rainfall.

Synoptic Situation and Storm Types

Synoptic patterns and storm types are important in orographic precipitation and can create a difference in the amount of the precipitation on a mountain area. For example, Williams and Peck (1962) show that in the Wasatch Mountains of Utah cold lows have a lower precipitation ratio than non-cold low storms (Figure 10). Thus, the lower elevations generally received greater amounts of precipitation than the higher stations when a "cold low" was observed in the upper air. Douglas and Glasspoole (1947) mention that orographic effects over Britain are strongest during the southwesterly flow ahead of a cold front where the atmosphere is typically moist and conditionally unstable.

Also, in the San Juan Mountains, Colorado, winter storms from the southeast and northwest are generally

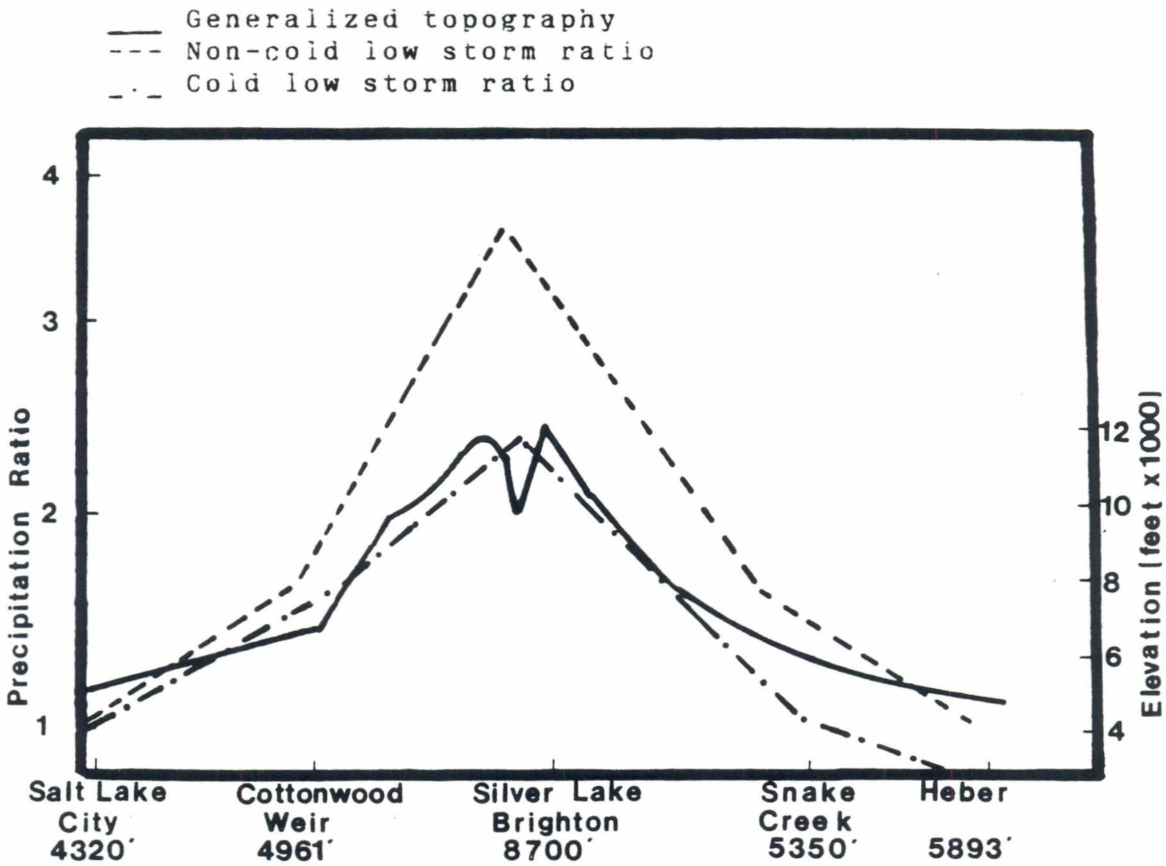


Figure 10. Topography and precipitation profiles across Wasatch Mountain near Salt Lake City (after Williams and Peck 1961).

associated with high precipitation, due to high upper air temperature, where storms from the west or the southwest generally give rise to more precipitation over the mountains (Barry 1981). Bonacina's (1945) study shows that orographic rain does not occur every time an air stream impinges on a mountain, but rather the air stream must have been affected by the prevailing weather situation. In addition, Sawyer (1956) states that warm sectors with strong wind and deep moist air are good conditions for heavy orographic rains. Moreover, Hanson (1982) concluded that the annual precipitation on a mountainous watershed in southwest Idaho varied not only with elevation, but also with location on the watershed, with the downwind locations receiving more precipitation than the upwind locations at equal heights. These differences occurred because most winter precipitation was due to large cyclonic storms that moved from the west and southwest into the watershed region.

Seasonal Patterns

Season "can determine the relative importance of stable versus convective rain" (Smith 1979). Seasonal effects appear to be related to the nature of the year (Merva, Stromman and Kidder 1976). Varney (1920) and Luil and Ellison (1950) indicated that the rate of increase of precipitation with altitude varies between periods and is at a minimum in the dry summer period.

Wind Force and Speed

Wind force or wind speed influences the elevation-precipitation relationship. For example, with calm conditions, precipitation falls with little variation over the region, but with high wind velocities the area of maximum precipitation was sometimes shifted leeward from the crest and to the leeward (Balchin and Pye 1948). Windward slopes exposed to high speed winds receive less precipitation than other areas because the wind increases the angle of inclination of the falling drops (Lee 1972, Sharon 1980).

Hovind's study (1965) indicated the difficulties in getting a good representative value of precipitation measurements around a windy mountain. In addition, the study showed that the precipitation catch on the windward side decreases to an apparent minimum near the crest, with an excess deposit of precipitation on the leeward side. These phenomena are related to the strength of the flow over the mountain; therefore, the wind force and wind speed should be determined in precipitation measurements and precipitation distribution.

Slope

The inclination of the slope of the mountain is important. The steeper and more exposed the slope, the more rapidly air can be forced to rise (Price 1981). The slope is also one of the local factors that influence the amount of precipitation received (Bonacina 1945, Nieuwolt 1974). Early investigators even suggested that the steeper the slope, the greater the precipitation (Henry 1919), and that the inclination of the slope is more important than absolute elevation for the precipitation on the windward slope of a mountain (Pockels 1901).

Mountain Orientation

The orientation of the mountains is another important factor in the relationship between precipitation and altitude. Along coastal mountains, the moisture-laden winds are predominantly from the ocean. They approach at low elevations, and the amount of precipitation is clearly a function of relief. Exceptions may occur in areas where the mountains are oriented parallel to the prevailing winds, and the frontal systems resist lifting. For example, in southern California, rainfall is heavier in the Los Angeles coastal lowlands than in the Santa Inez and San Gabriel Mountains (Price 1981) because of mountain orientation. Sneva and Calvin (1978) found a higher correlation coefficient for stations oriented in a SW-NE direction than for stations lying in a SE-NW direction. Moreover, valleys oriented parallel to the prevailing winds may receive as much or more precipitation than the mountains on the side, while valleys oriented perpendicular to the prevailing winds may be "dry holes" (Price 1981).

Leeward and Windward Position

The relief of an area is an important factor affecting precipitation distribution; windward sides of mountains generally receive more precipitation than the leeward slopes (Pockels 1901, Sims 1981). The degree of effect on precipitation varies with the direction and speed of the moist air flow, with height, and the regularity of the mountain barrier (World Meteorological Organization 1973). The rain shadow effect shows on the leeward side of minor as well as major relief features. Cases were also observed where, with strong winds, the point of maximum precipitation was displaced from near the crest of the windward slope to the leeward slope (Balchin and Pye 1948, Pacl 1973). This zone is known as a spillover zone. The spillover zone extends further beyond the ridge for snow than for rain (World Meteorological Organization 1973). For instance, Yoshino (1975) showed that in the Kirishina region mountains, Kyshu, Japan, the maximum precipitation occurs on the windward side of the mountain region, but in the case of typhoons, the maximum precipitation occurs slightly leeward because of the stronger wind.

In general, precipitation increases with increased elevation on windward slopes but rain shadow effects cause precipitation decreases on the lee side of the mountains; these effects may cause aridity in their lee (Peattie 1966). For example, the western Ghats, India, receive more than 5000 mm, but in their lee on the Deccan Plateau, the average amount of rainfall is only 380 mm (Price 1981). In northern Hawaii, windward sides of mountains receive more than 11,430 mm a year, while leeward slopes receive only about 558 mm (Peattie 1966). In addition, Pan (1972) found that the windward side of Tatunshan and Hsuch Mountains receive more precipitation than the leeward side of the mountains. In fact, increasing elevation almost always means increasing rainfall on the windward slope (Balchin and Pye 1948).

Distance from Moisture Sources

The distance from moisture resources is an important factor. Usually the amount of precipitation decreases with increased distance from the moisture source. Whitmore (1973) found that the distance from the sea is a secondary factor, after altitude, which affects the mean annual precipitation in south Africa. Wells (1922) mentioned that the distance from the sea is very important in the distribution of precipitation in Oregon.

Precipitation Measurement and Analysis

This section reviews the relevant literature on problems of precipitation measurement, consistency of precipitation records, estimating missing data, and statistical methods which have been applied to explain and predict precipitation distribution in a given area.

Precipitation Measurement

Precipitation is the prime element in the hydrological cycle. The accurate estimation of precipitation is very important for planning water resources projects, design of structures, seasonal runoff forecasting, and water supply (Gole, Kulkarni and Khatavkar 1972, Dunne and Leopold 1978). The accuracy of precipitation estimates depends on accurate measurement (Rechard 1972). Errors in precipitation measurement affect water supply, water resources studies, and runoff forecasting (Hamon 1971, Peck 1973).

Obtaining accurate measurements of precipitation in mountainous areas is difficult because of the differentiation in weather phenomena and processes which occur over short distances under the influence of changing elevation and topography (Colton 1976, Marcus 1974). The amount of information available on the precipitation distribution in high mountains is small because the greatest number of weather stations are located in low mountains, less in the medium-high mountains, and the least number of stations in high mountains (Vuglinski 1972).

Moreover, some high mountains are difficult to visit during certain months of the year and are not inhabited (Chang 1973).

Precipitation as measured by a standard rain gauge can never be considered to be an accurate measure of precipitation but can be used only as an "index" of the precipitation amount (Pierrehumbert 1976). There are several errors involved in precipitation measurement (Figure 11). These errors include; (1) natural conditions such as gauge location, wind speed and direction, and precipitation type; and (2) gauge configurations such as gauge type, shielded or unshielded, and height of the orifice.

Wind is the major cause of error in precipitation measurement (Popov 1972). It influences the local distribution of precipitation by changing the angle of inclination of falling particles (Lee 1972). Sharon (1980) concluded that a storm with a wind speed of 10 m/s causes rainfall inclination of 40-60^{o} and may reach 70^{o}. This error increases with the increased wind speed and is larger for solid than for liquid precipitation (Larson and Peck 1974, Popov 1972, Gray 1973); it may even reach 100 percent. (Sokolov and Chapman 1974). Moreover, Popov (1972) indicates that when wind speed in the Arctic exceeds a certain limit, the gauge will catch more snow that the true amount of precipitation. Decreased wind speed

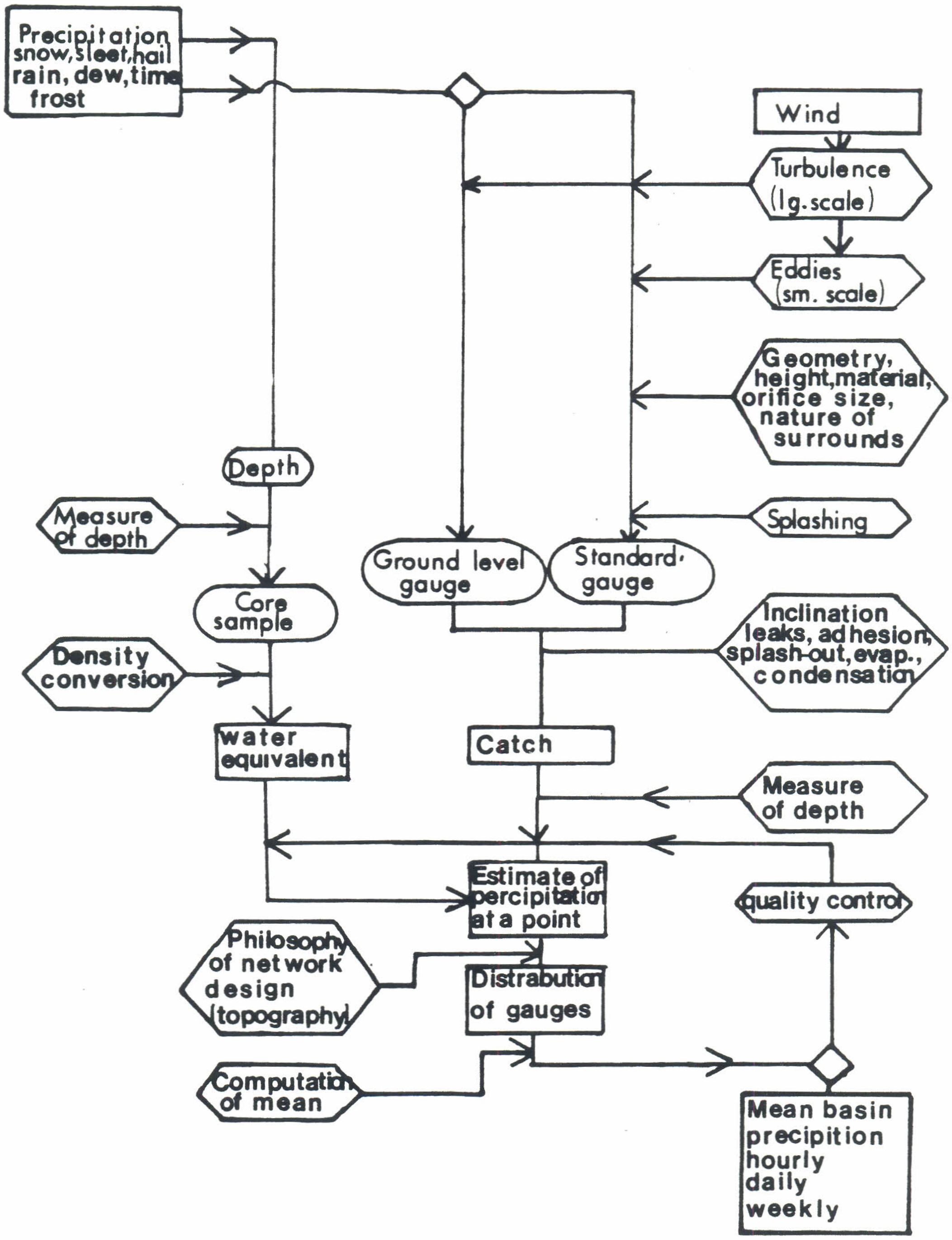


Figure 11. Sources of error involved in precipitation measurement (after Rodda, Downing, and Law (1962).

increases the amount of measured precipitation because the precipitation does not hit the mouth of the rain gauge under the influence of wind. Further, the higher the rain gauge, the greater the wind speed and turbulence above the exposed surface and less catch (Wang and Felton 1979). The magnitude of undercatch increases with elevation because of increasing exposure to strong winds (Sevruk 1974). Zhidikov and Levin (1972) state that the monthly precipitation sums during summer and winter are correlated with wind speed.

The precipitation undercatch problems of conventional gauges mounted with their rims above the ground have been well documented. Hamon (1971) argues that the weak correlation in precipitation-elevation relationships are attributable to the inability of the unshielded gauge to capture the falling precipitation, particularly snow, when exposed to light wind. Frequently, low-elevation gauge sites are in sheltered woodland areas, whereas higher elevation sites are in a treeless alpine zone (Sevruk 1974).

Various types of rain gauges and protection devices have been developed to reduce the effects of wind, but none are entirely acceptable under all conditions and for all types of precipitation (Weiss and Kresge 1962, Peattie 1966, Bochkov and Struzer 1972, Peck 1973, Larson and Peck

1974, Rodda, Downing, and Law 1976). Altershield has been developed to minimize the precipitation undercatch problems. Rechard (1972) indicates that precipitation gauges on polar mountains which have no altershield and no fence protection caught the least amount of precipitation. Gauges which have an altershield but no fence caught more precipitation than the previous gauges, but the gauge which is provided with an altershield and fence protection caught the highest amount of precipitation.

The other way to reduce the effect of wind on rain gauges is to install the gauges in a shallow pit with their rims level with the ground surface (Rodda, 1972). The pit gauge method is the most convenient method to collect accurate precipitation records (Neff 1977), but pit gauges require more space and maintenance than do the normal gauges. They are, therefore, not used as network instruments (Pierrehumbert 1976).

Clearly, it is necessary to consider the distribution of the rain gauge network and gauge undercatch when establishing true rainfall-elevation relationships, and precipitation distribution.

The Consistency of the Precipitation Data

The quality level of precipitation data is very important to the researchers. This quality level depends on the purpose of the research and on the data available.

A variety of ways have been developed to check the homogeneity of the data and to estimate the missing data from the records.

Climatic data should be checked to make sure data along the period of record is homogeneous. Several things cause non-homogeneity of record such as relocation of a rain gauge, changes in the hydrologic ecosystem, growth of trees close to a gauge site, changes in the method of observation and the use of shields which may reduce the wind effect. The changes due to meteorological causes presumably would not affect homogeneity because all stations would be similarly affected (Linsley, Kohler and Paulhus 1982). Stations used to adjust non-homogeneous situations should be close to the station to be adjusted. The effectiveness of the adjustment depends on the correlation between the stations, and it should be in the same environment and not be farther than 80 km from the station to be adjusted according to Thom (1971).

Double mass analysis was employed by Marriam (1937) to test the consistency of the record at a station by comparing its accumulated annual or seasonal precipitation with the accumulated values of mean precipitation for a group of surrounding stations. The homogeneity of record for each of these latter stations should be examined before any test is made. Stations with non-homogeneous records should be dropped (Linsley, Kohler and Paulhus 1982). A check of the gauge history also should be made to confirm any changes indicated in double mass analysis (Dunne and Leopold 1978). A criticism of the double mass technique is that the record of the stations used in the adjustment may also contain errors. This may be especially true is only a few stations are used in the solution (Schulz 1974).

Estimating Missing Data

Some missing data in precipitation records is normal. This is due to a variety of reasons such as closing down of the rain gauge, improperly functioning gauges, or absence of the observer. These and other factors create gaps in the records. This problem should be estimated before using the data.

Several methods have been developed and employed to estimate gaps in precipitation records. Generally speaking, applying a method depends on the percentage value missing from the record. For example, if the normal annual precipitation at each index station is within 10% of that for the station with the missing record, an arithmetic average of the precipitation at the index stations provides the estimated amount (Linsley, Kohler and Paulhus 1982). But, if it is greater than 10%, the regression and correlation technique could be used to estimate the missing data. Also, the missing data at a given station can be estimated by using the surrounding stations. For example, a gap in records at station A can be estimated from three or four surrounding stations by applying this method:

$$P_A = \frac{1}{3}\left(\frac{N_A}{N_B} P_B + \frac{N_A}{N_C} P_C + \frac{N_A}{N_D} P_D\right),$$

where P_B, P_C, and P_D are precipitation recorded at the three surrounding stations A and N_A, N_B, N_C, and N_D are the long-term normal precipitation at the four surrounding stations (Dunne and Leopold 1978).

Another method, used by the U.S. National Weather Service and explained by Linsley, Kohler and Paulhus (1982), estimates precipitation at a point as the weighted average of fourstations, one in each of the quadrants delineated by north-south and east-west lines through the point. Each station is the nearest in its quadrant to the point for which precipitation is being estimated. The weight applicable to each station is equal to the reciprocal of the square of the distance between the point and the station. Multiplying the precipitation at each station by its weight factor, adding the four weighted amounts, and dividing by the sum of the weight yields the estimated precipitation for the point.

In general, all of the methods described above give good results in wide spread cyclonic rainfall over areas of fairly uniform topography (Dunne and Leopold 1978). Under other conditions such as highly variable precipitation, non-uniform topography, incomplete networks, and for particular storms, the isohyetal map method yields a better estimation than the previously described techniques (Gray 1973, Hjelmfelt and Cassidy 1975, Dunne and Leopold 1978).

CHAPTER IV

STATISTICAL METHODS AND TECHNIQUES IN PRECIPITATION ANALYSIS

A number of statistical methods and techniques have been developed to determine precipitation distribution. These techniques have been used to find the relationship between precipitation and elevation and other topographic factors. Several techniques such as harmonic analysis have been employed to describe and map temporal and spatial distribution of precipitation. Also, various methods have been developed to estimate the depth of precipitation in a given area. These methods will be discussed in the following review.

Precipitation-Elevation Relationship

Several statistical techniques have been developed and applied to examine the relationship between precipitation and topography. Donley and Mitchell (1939) applied the straight-line equation which was developed by J. Lippincott in 1899 to find the elevation-rainfall relationship. The equation used was:

$$R = R + K (A/100),$$

where R and R are the average annual rainfall in inches at the higher and lower points. A is the difference in altitude in feet, and K is a constant for each zone.

Spreen (1947) used a graphical correlation technique for mean precipitation (for an 11-year period, 1920-1930) in western Colorado. He tested precipitation against elevation and precipitation against topographic parameters of elevation, maximum slope of the land, and orientation. The result obtained by the application of the orographical correlation method was high. Linsley (1958) applied a technique called the coaxial method of graphical correlation to determine the correlation between two years' one-hour rainfall intensity at 126 recording rainfall stations in northern California and related topographic and climatic parameters. He examined precipitation intensity as the dependent variable against the topographic and climatic factors as independent variables. These were land slope, elevation, orientation, barrier, and zone of environment. The result of applying the coaxial method shows that the relationship has a coefficient of correlation of 0.88 and standard error of 0.067 inch/hour.

Unwin (1969) applied trend surface analysis to find precipitation distribution. This technique uses least squares criterion to fit polynomials of higher order to areal distribution data:

for a Linear Surface:

$$X_n = b_0 + b_1U + b_2V,$$

for a Quadratic Surface:

$$X_n = C_0 + C_1U + C_2V + C_4UV + C_5V^2,$$

for a Cubic Surface:

$$X_n = d_0 + d_1U \quad d_2V + d_3U^2 + d_6U^3$$
$$+ d_7U_2 + d_8U^2V + d_9V^3,$$

where X_n is the value of the areal distribution variables and U and V are the geographic coordinates.

The result of applying the trend surface method shows that the technique gave results higher relationships than conventional regression methods. This is shown in the following statistical summary:

Method	% Reduction In Sum of Squares
Multiple linear regression	79.30
Quadratic trend surface	82.51
Cubic trend surface	84.89

Unwin (1969) concluded that the trend method can be used in areas; it gives a better result than the conventional regression methods because the trend method uses polynomials rather than the planes fitted by conventional regression.

Wolfson (1975) employed a standard stepwise regression technique to evaluate the effect of topographical parameters on standard normals of rainfall (SNOR) over Israel. He divided the study area into eleven rainfall regions. For each region, the standard stepwise regression was employed to determine the relationship between SNOR for the period 1931-1961 and the topographic parameters (station elevation, station distance from the Mediterranean Sea, and station distance from 33°20'N). The result shows that using the standard stepwise regression technique gives a good estimation of SNOR, and the estimated values obtained from this technique deviate from the observed values usually between 5% to 10%.

Taylor (1980) applied the multiple regression analysis to explain the areal variation in average annual precipitation totals in California. He used precipitation as the dependent variable and altitude, latitude, and distance from the coast as the independent variables. The regression analysis produced a high coefficient which was 0.9392. Taylor mentions that multiple regression analysis produces high levels of explanation and relatively accurate prediction. Molnau et al (1980) also used regression analysis to find the percentage of variation in annual precipitation in mountainous areas that is accounted for by any one or more combinations of the following variables: elevation, slope, aspect, cover class corresponding to vegetation, and the hydrological soil classification.

Precipitation was tested against each variable alone and combinations of two, three, four, and five variables. The r^2 value is shown in the following summary:

Variable	r^2
Hydrologic soil class	0.016
Aspect	0.021
Slope	0.122
Elevation	0.498
Cover class	0.509
Elevation and cover class	0.637
Elevation, cover class, and aspect	0.648
Elevation, cover class, aspect, and slope	0.656
Elevation, cover class, aspect, slope and hydrologic soil class	0.657

The result shows that for both elevation and cover class, r^2 was 0.637, while for all five variables r^2 was 0.657, and the correlation coefficient was 0.881.

Dhar and Rakhecha (1981) studied the relationship between rainfall and elevation in the central Himalayas. Dhar and Rakhecha employed the technique of orthogonal polynomial regression analysis. Polynomials of different degrees were tested by the student "t" test to derive the best-fit polynomial. They found that rainfall and elevation parameters can be related by a polynomial of the fourth degree at a 95% level of significance. The relation between rainfall (Y) and mean elevation (X) in the central Himalayas was produced from the following equation:

$$R = 21.81 - 40.58X + 40.12\,X^2 - 12.40X^3 + 1.06X^4.$$

Another method employed by Dhar and Rakhecha for the central Himalayas was the ratio method. A curvilinear relation was derived between the rainfall ratios and the elevation. The relation between rainfall ratios, R, and mean elevation, X (in km), is:

$$R = 1.43 - 1.98X + 1.46X^2 - 0.03X^3 - 0.09X^4.$$

Employing both orthogonal polynomial analysis using rainfall-elevation data and the ratio method gave similar results.

Several methods have been developed to explain precipitation distribution in mountainous areas. Many investigations have related variation in precipitation distribution to elevation alone, but some researchers added more topographic and climatic variables to the elevation factor. It is apparent from the literature that no perfect technique can explain precipitation distribution in all mountainous areas, because each region has its own special topographic and climatic characteristics.

Harmonic Analysis

Harmonic analysis is a unique technique which can be applied to the periodic variation of the climatological parameters. It helps in the physical understanding of the regular fluctuations (Panofsky and Brier 1958). Harmonic analysis can be used to obtain an objective description and mapping of the temporal and spatial distribution of precipitation (Horn and Bryson 1960, Sabbagh and Bryson 1962, Shulman and Leblang 1974, and Barry and Perry 1973).

The aim of harmonic analysis is to permit any irregular or complex curve to be expressed mathematically as the algebraic sum of a series of curves (Horn and Bryson 1960). The curve can be represented as the sum of a series of different sine curves (Scott and Shulman 1979). Horn and Bryson (1960, 159) state that the best fit can be defined as the

> best least squares fit. The sine curve is fitted to the observed curve so that the sum of the squares of the difference between the sine curve and the observed curve is a minimum.

For instance, the monthly mean precipitation (12-month value) can be described by six harmonics. The best fit to the curve of original data is obtained by adjusting the amplitude (ordinate), which is a measure of half the difference between the maximum and minimum of the sine curve and by shifting the phase angle (abscissa) which determines the time of the year at which maximum and minimum occurs (Sabbagh and Bryson 1962). Since the length of the months is not equal, it is necessary to adjust it to the length of 30.44 days, one-twelfth of a year (Horn and Bryson 1960). Isolines of the phase angle for a given harmonic are known as isochrones and describe the distribution of the approximate dates of the maximum values for that harmonic. The isolines of the amplitude describe the importance of the harmonic. The convergence of isochrones to a line (nodal line) or to a point (nodal point) indicate regions of rapid transitions of one rainfall type to another (Shulman and Leblang 1974), and the amplitude of that harmonic is zero; therefore, the phase angle could have any value (Horn and Bryson 1960).

The first harmonic is a curve with one maximum and one minimum. It describes the tendency towards an annual variation in the observed precipitation. This curve is adjusted to give the best mathematical description of the annual tendency. The amplitude provides a measure of difference in rainfall between the annual maximum and minimum. For example, if a station has a rainfall curve which has a strong annual variation, the amplitude of the first harmonic will be large, while if there is little annual variation the amplitude will be small. The second harmonic, which consists of a sine curve with two maxima and two minima, describes the semiannual tendency of the observed curve. If the curve has two maxima of rainfall six months apart, the second harmonic will be relatively large while the amplitudes of the other harmonics will be small. The third, fourth, fifth, and sixth harmonics describe the four-month, three-month, two- and four-tenths month, and two-month variations in the observed rainfall curve (Horn and Bryson, 1960). In general, harmonics which best fit the observed curve will have the largest amplitude, while those which fit poorly will have small amplitudes. If a harmonic is a good fit, the amplitude of the other harmonic will be zero (Shulman and Leblang 1974, Scott and Shulman 1979).

The six harmonics are uncorrelated; therefore, each harmonic can be treated as an independent, and no two harmonics can explain the same part of the variance. The variances explained by the different harmonics can be added to each other. For example, the first harmonic accounts for 30%, the second for 50%, and the third for 15% of the variance; the three harmonics together explain 95% of the total variance, so additional harmonics are not necessary (Panofsky and Brier 1958). But some rainfall curves require the use of all six harmonics to best describe the observed curve. Horn and Bryson (1960, 160) state that

> a station with a strong annual tendency in precipitation will have a first harmonic of large amplitude, but it may also have a second harmonic although of small amplitude. The fact that a second harmonic exists does not mean that the observed curve has two maxima, but that the curve cannot be completely described by the first harmonic alone. The second -- and probably the other harmonics -- complete the description of the curve. If an observed curve could be completely described by a sine curve of frequency one, all the other amplitudes would be zero. However, such simple precipitation curves are rarely, if ever, found.

been chosen as the 15th of December; the twelve months can be indicated every 30^o. For example, January (30^o) is indicated by 1, 15 February (60^o) as 2, 15 March (90^o) as 3, and so on (Scott and Shulman 1979). The variance reduced by the ith harmonic, except the last, is equal to half the amplitude squared ($C_i^2/2$), and the variance for the last harmonic is equal to the amplitude squared ($C_i/2$) (Panofsky and Brier 1958).

Several studies have applied the harmonic techniques to describe the temporal and spatial distribution of precipitation. Horn and Bryson (1960) used harmonic analysis to determine the temporal precipitation pattern in the United States. They used adjusted mean precipitation for the period 1921-1950. They state that the method of harmonic analysis is

> distinctly advantageous in that it permits an objective areal analysis of the temporal features of the precipitation. The manner of transition from one rainfall type to another is often clearly presented. This is especially valuable in genetic analysis.

The disadvantages of harmonic analysis are

> the absolute precipitation amounts are not clearly presented and that one needs to view several charts to obtain the desired information. However, if one uses the method as a tool in climatological investigations rather than as an end in itself, the method can be of considerable value.

A harmonic analysis was carried out by Sabbagh and Bryson (1962) to investigate the regional characteristics of the march of precipitation over Canada. They found that

The general form of the harmonic analysis for the annual cycle is as follows (Panofsky and Brier 1958):

$$X = \bar{X} + \sum_{i=1}^{N/2} [A_i \sin(\frac{360}{P}it) + B_i \cos(\frac{360}{P}it)],$$

where $\bar{X}$ is the annual mean, N is the number of observations, i is the number of the harmonic, P is the fundamental period of the data (for the annual cycle the period is 12 months), t is the phase angle, and A and B are coefficients. The formulae for the coefficients are:

$$A_i = \frac{2}{N} \sum [X \sin(\frac{360}{P}it)],$$

$$B_i = \frac{2}{N} \sum [X \cos(\frac{360}{P}it)].$$

The sine and cosine can be combined into a single term:

$$C_i \cos(\frac{360}{P}i(t-t_i)),$$

where C_i is given by $(A_i^2 + B_i^2)^{1/2}$ and t_i by $(P/360)\arctan(A_i/B_i)$, where C_i is the amplitude of the ith harmonic, and t_i is the time at which the ith harmonic has a maximum.

The phase angle is obtained in degrees; also it can be indicated by the time of year. The origin ($0 = 0^o$) has the first two harmonics explain a large portion of the variance of the annual precipitation curve. Thus the first and second harmonics suffice to show the main outlines of precipitation variance over Canada. Sabbagh and Bryson (1962) concluded that the method of harmonic analysis has proved to be a useful tool in studying precipitation climatology.

Shulman and Leblang (1974) applied harmonic analysis to the mean precipitation of 30 years (1931-1960) for 36 stations in New Jersey and 17 stations in the adjacent states of Delaware, Pennsylvania, and New York. The study shows that the first harmonic is most significant in the interior and northwestern parts of New Jersey and diminishes in significance toward the coast. They state that

> the harmonic analysis of monthly mean precipitation provides a unique view of the areal and temporal precipitation of New Jersey.

Another study was carried out by Scott and Shulman (1979). They used harmonic analysis to examine precipitation seasonality in the northeastern United States and its changes through time. Harmonic analysis is applied to the monthly precipitation normal for 200 stations in the northeastern United States for a period of 30 years (1941-1970). The results show that the first, second, and third harmonics account for most of the variance in the study area.

In addition to the previously mentioned studies, several studies were done outside the United States. These studies used harmonic analysis to examine precipitation distribution. Barry and Perry (1973) mentioned some of them such as "Fourier analysis of Indian rainfall" by Lettau and White (1964), "Harmonic analysis of the rainfall over South Africa" by McGee and Hastenrath (1966), and "Analysis of normal monthly precipitation over Alaska and western Canada" by Walker (1964).

Estimating Precipitation Depth

Mapping the annual and monthly precipitation over the earth is important for the purpose of the world water balance. It is essential to estimate the average precipitation and annual time distribution over a region (Popov, 1972). The accurate estimation of precipitation depth over a region depends on accurate measurement (Rechard 1972).

A good estimation of precipitation depends on the density of the network and the size and type of storm event. For example, in a desert region where precipitation originates from local thunderstorms, it is more difficult than in a region where precipitation originates mainly from general cyclonic storms. Also, it is more difficult to estimate the average of precipitation and its spatial distribution in mountainous regions because of the differentiation in weather phenomena and processes which occur over short distances under the influence of changing elevation and topography (Dunne and Leopold 1978). Moreover, estimating the average precipitation in mountainous areas is difficult because the amount of information available on precipitation distribution is little because the greatest number of weather stations are located in low mountainous areas (Vuglinski 1972).

Several methods have been proposed to compute the depth of precipitation over a given area. Three common methods to calculate the depth of precipitation are the arithmetic method, the Thiessen method, and the isohyetal method. These common methods (arithmetic, Thiessen and isohyetal) have their advantages and disadvantages. Each of these methods is discussed in more detail.

Arithmetic Method

This method computes the areal average of precipitation as arithmetic means or weighted means. The arithmetic method can be calculated as follows:

$$P_a = \frac{1}{n} \left(\sum_{s=1}^{n} P_s \right),$$

where P_s is station precipitation and n is the total number of stations (Lee 1980). The advantages of the Arithmetic Method are that it is the simplest method to obtain the average depth of precipitation in a given area (Linsley, Kohler and Paulhus 1982), and it gives good results where the gauge network is dense and representative and the topography of the area is uniform (Gray 1973, Dunne and Leopold 1978, Lee 1980, and Linsley, Kohler and Paulhus 1982). Disadvantages are that the method yields poor estimates where precipitation and topography in an area are not uniform and gauge sites are not representative. This problem can be overcome partially if elevation influences and areal representatives are taken into account in the selection of rain gauge locations (Linsley, Kohler and Paulhus 1982).

Thiessen Method

This method was proposed by Alfred Thiessen in 1911. The purpose of the Thiessen polygons is to divide the given area into sub-areas of influence that may be attributed to a number of rain measuring stations inside or in the vicinity of the area (Diskin 1969); and it is assumed that the precipitation at any point is equal to the precipitation at the nearest station (Butler 1957). It also assumes a linear variation between stations (Sneva and Calvin 1978, Gray 1973, and Linsley, Kohler and Paulhus 1982). The Thiesen mean (P_i) is:

$$P_i = \frac{1}{A}\left(\sum_{s=P_s A_s}^{n}\right).$$

The Thiessen Method has been improved and redeveloped several times. For instance, Diskin (1969) proposed a method of computation and a digital computer program for the determination of Thiessen weights. The method is based on a Monte Carlo procedure. Also, Diskin (1970) developed another program for the computation of the Thiessen weights based on the systematic and uniform coverage of the rectangle that circumscribes the watershed boundaries. Lastly, in 1978, an improved Thiessen grid for eastern Oregon was developed by Sneva and Calvin.

The advantages of the Thiessen method are that (1) it adjusts for the non-uniform distribution of rain gauges (Gray 1973) and is a better measure where the distribution of gauges is not uniform and where precipitation gradients are strong (Dunne and Leopold 1978); and (2) the results are usually more accurate than those obtained by the arithmethic method (Linsley, Kohler and Paulhus 1982). The method's disadvantages are (1) the method does not allow for the effect of storm patterns (Sneva and Calvin 1978); (2) the Thiessen diagram is required every time there is a change in the gauge network (Linsley, Kohler and Paulhus 1982); (3) the method does not allow for orographic influences (Sneva and Calvin 1978, Dunne and Leopold 1978, Lee 1980, Linsley, Kohler and Paulhus 1982); and (4) it is time-consuming and yields answers close to the arithmetic average unless the spatial distribution of the gauges is not uniform (Dunne and Leopold 1978).

Isohyetal Method

The Isohyetal Method is the third common method to estimate the amount of precipitation over a given area. The method can be presented as follows:

$$P_i = \frac{1}{A} \left(\sum_{c=1}^{n} P_c A_c \right),$$

where n is the number of partial areas, P_i is the Isohyetal mean, and P_c is taken as the arithmetic mean of bounding isohyets. Better accuracy is achieved by computing a weighted mean based on the length of the individual isohyets (Lee 1980).

The Isohyetal technique is the most common method of computing the average areal precipitation. The isohyetal line is equal to the mean of the precipitation at the isohyetal lines. It depends on the skill of the analyst. Kwan, Riley and Amisial (1968) proposed a digital computer program to plot isohyetal maps and calculate volumes of precipitation.

The advantages of the Isohyetal Method are (1) it takes into account strong precipitation gradients caused by topography or by thunderstorm cells (Dunne and Leopold, 1978); (2) it is the most accurate in estimation of areal precipitation (Johnstone and Cross 1949, Gray 1973, Lee 1980, and Linsley, Kohler and Paulhus 1982); and (3) it takes into account a number of factors, such as relief, aspect, and direction of storm movement (Ward 1975). A depth-area curve can be drawn only from isohyetal results (Schultz 1974). Its disadvantages are that (1) the accuracy of the Isohyetal Method depends on the skill of the user (Lee 1980, Linsley, Kohler and Paulhus 1982); and (2) the method is time-consuming and gives results similar to the arithmetic method unless the spatial distribution of rain gauge network is not uniform (Dunne and Leopold 1978).

Therefore, each method of the three common methods has its advantages and disadvantages. The application of these methods depends on various factors such as precipitation type, topography of the region, the level of the accuracy desired, skill of the users, and time and money available to the user.

CHAPTER V

ANALYSIS OF THE PRECIPITATION IN THE SOUTHWEST OF SAUDI ARABIA

Precipitation Data

Mean monthly and annual precipitation records for the period of 10 years (1971-1980) for 104 stations were used (Figure 12, Appendices 5 and 6). The data are published by the Department of Water Resources Development, Hydrology Division, of the Ministry of Agriculture and Water in the Kingdom of Saudi Arabia. The percentage of missing data from the record is small. Therefore, the missing data is estimated by the arithmetic average of the surrounding stations or estimated from precipitation maps.

Precipitation Analysis

Several methods and techniques were employed to find the relationship between precipitation and elevation, and to describe the temporal and spatial distribution of precipitation in the Southwest of Saudi Arabia. These methods and techniques are RSQUARE Procedure (SAS), isohyetal analysis, and harmonic analysis.

Correlation and regression analysis were used to determine the nature of the relationship between precipitation and elevation in the Southwest of Saudi Arabia. The RSQUARE Procedure (SAS User's Guide 1982) was employed using the Arizona State University computer

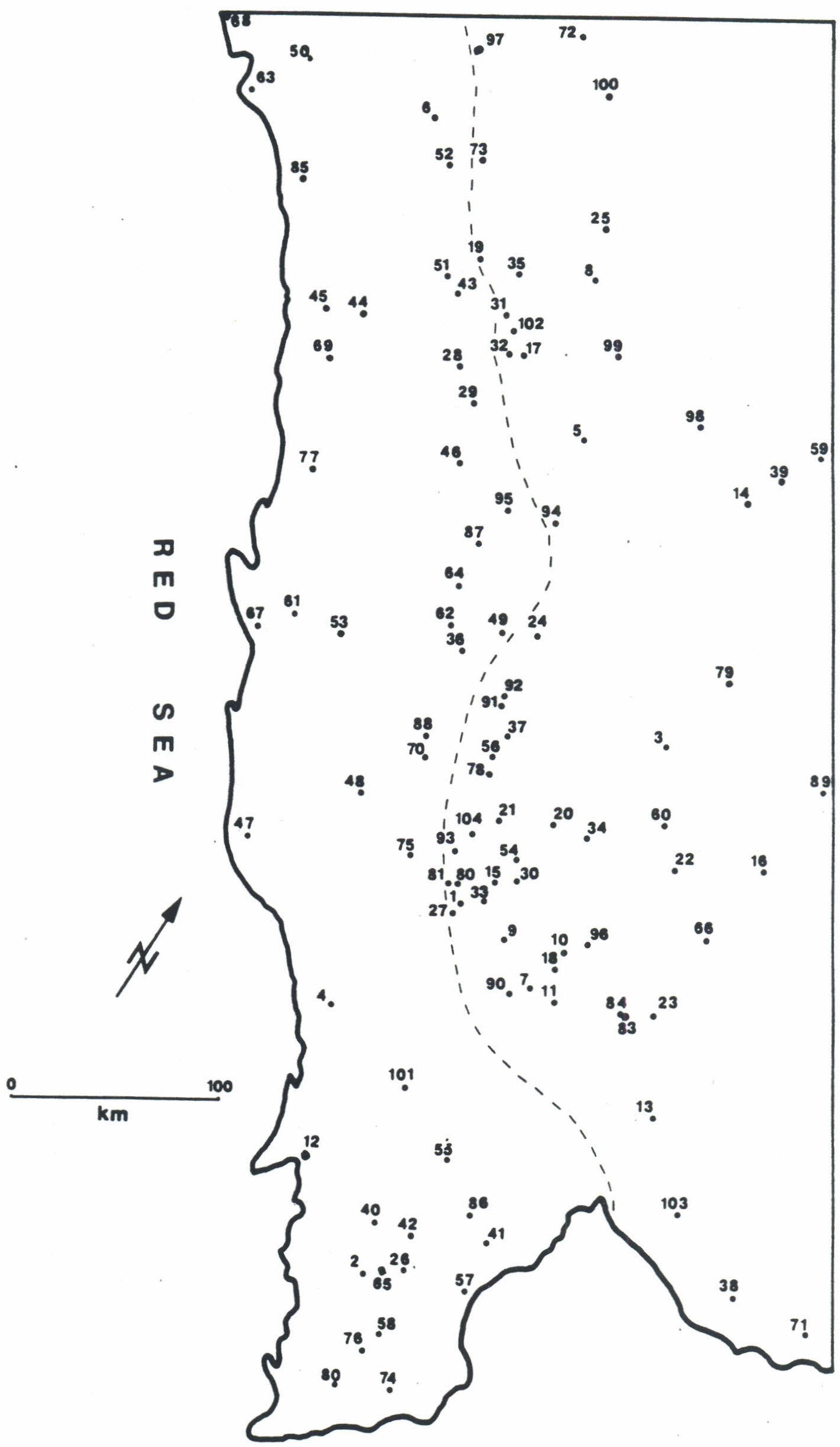


Figure 12. Rain gauge locations.

system. Mean monthly, seasonal, and annual precipitation are employed as dependent variables and elevation is used as the independent variable. Appendix 7 shows the relation graphically between precipitation and elevation for the whole region on a monthly basis. The west slope stations are differentiated from the east slope sites.

Isohyetal Method

Isohyetal and Thiessen techniques were employed to determine precipitation depth and distribution in the area between the Red Sea and Sawdah. Twenty-three non uniformly distributed stations were used. Station elevations ranged between 20 m at the Red Sea (Qahmah station) to 2820 m at the top of the Asir Mountains. The results of the test show that the isohyetal method gives a better description of the precipitation than the Thiessen method. Because of the complexity of the topography of the Southwest of Saudi Arabia and the random distribution of stations, the isohyetal method was used to map the mean and median of precipitation in the study area.

Harmonic Analysis

Harmonic techniques are employed to describe the temporal and spatial precipitation distribution in the Southwest of Saudi Arabia. The harmonic program used in this study was written by Dr. Robert Balling, Jr., May, 1982 (see Appendix 8).

Mean and Median Precipitation

Mean and median monthly, seasonal, and annual precipitation in the Southwest of Saudi Arabia were mapped. The maps of the mean and median precipitation were analyzed and discussed.

Precipitation Distribution

Precipitation distribution over the Southwest of Saudi Arabia is not uniform. This is due to several combined topographic and climatic factors. The topographic factors are station location, elevation, slope, mountain orientation, leeward and windward, and the distance from the moisture sources. The climatic factors influencing precipitation distribution are atmospheric conditions, synoptic situation, storm types, seasonal patterns, wind speed and direction, and temperature. Therefore, the amount of precipitation received depends on the position of the station and the time of the year. The mean and median of the seasonal and annual precipitation were used to obtain a better understanding of the distribution of precipitation in the Southwest of Saudi Arabia (Appendices 9, 10,11, and 12). These two statistics were used because the study area is characterized as arid and semi-arid climate with fluctuations in the amount of precipitation.

Figures 13-22 demonstrate the degree of difference between the mean and median precipitation patterns. Generally, values are higher on the maps displaying the mean values. The exact degree of difference, however, varies spatially and with the seasons.

Winter Precipitation

During the winter season (December-January), the Southwest of Saudi Arabia is influenced by the Mediterranean depression and the Sudan lows and the Red Sea trough. The region is affected by the westerly Mediterranean flow associated with a depression that moves across the northern area and reaches to the Southwest region. The Red Sea Convergence Zone is predominant almost throughout winter over the Red Sea. Frequently, the Mediterranean depressions affect the weather of the Southwest and bring rainfall to the area, especially when the Mediterranean depression is amalgamated with the Sudan low.

During winter, precipitation is spread through the Southwest of Saudi Arabia. Figures 13 and 14 demonstrate that the largest amounts of precipitation occur along the northern section of the Asir Mountains. On the eastern slope of the mountains, the higher stations receive more precipitation than stations in the lower elevations. Also, Figures 13 and 14 show that precipitation west of the

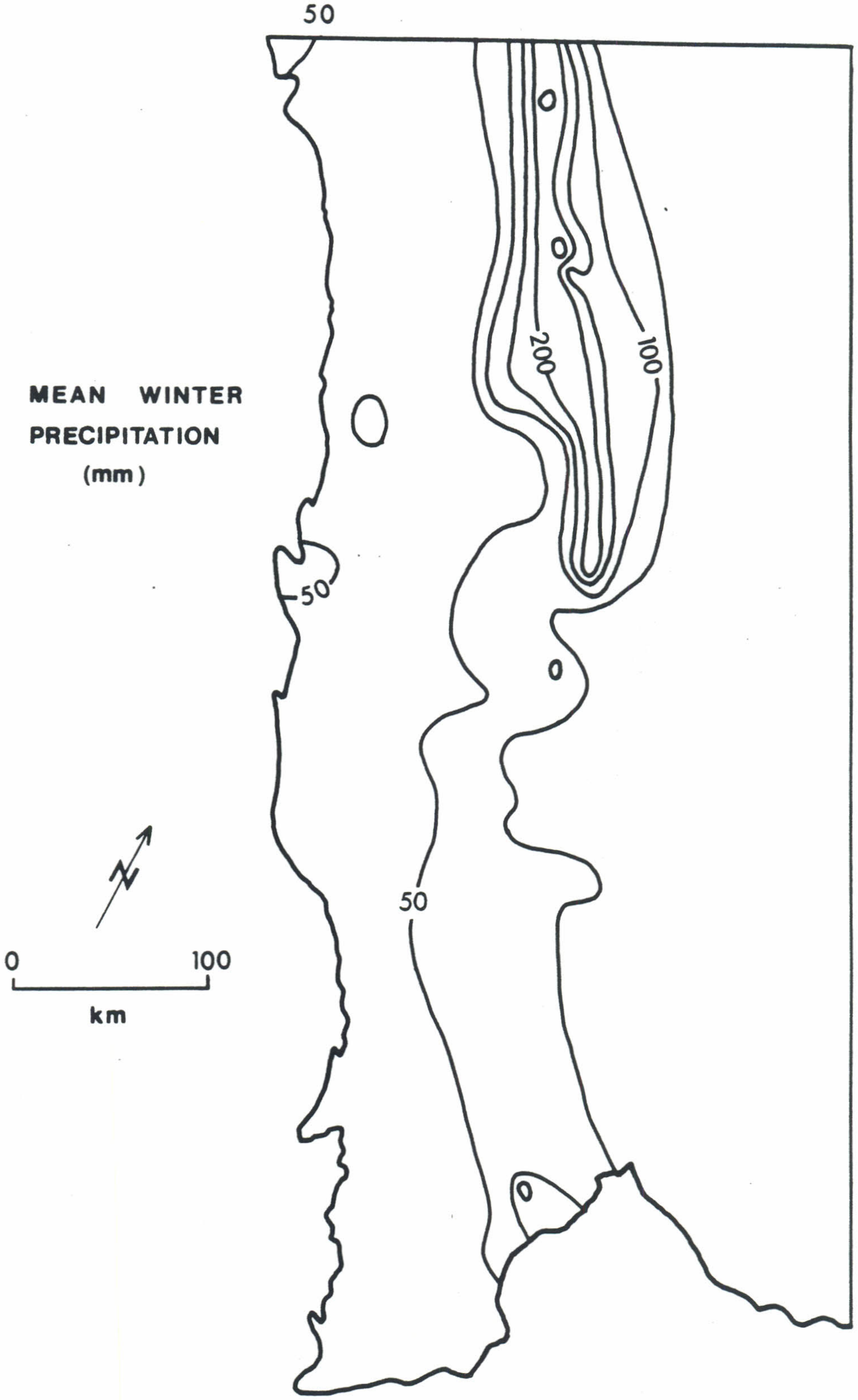


Figure 13. Mean winter precipitation (mm).

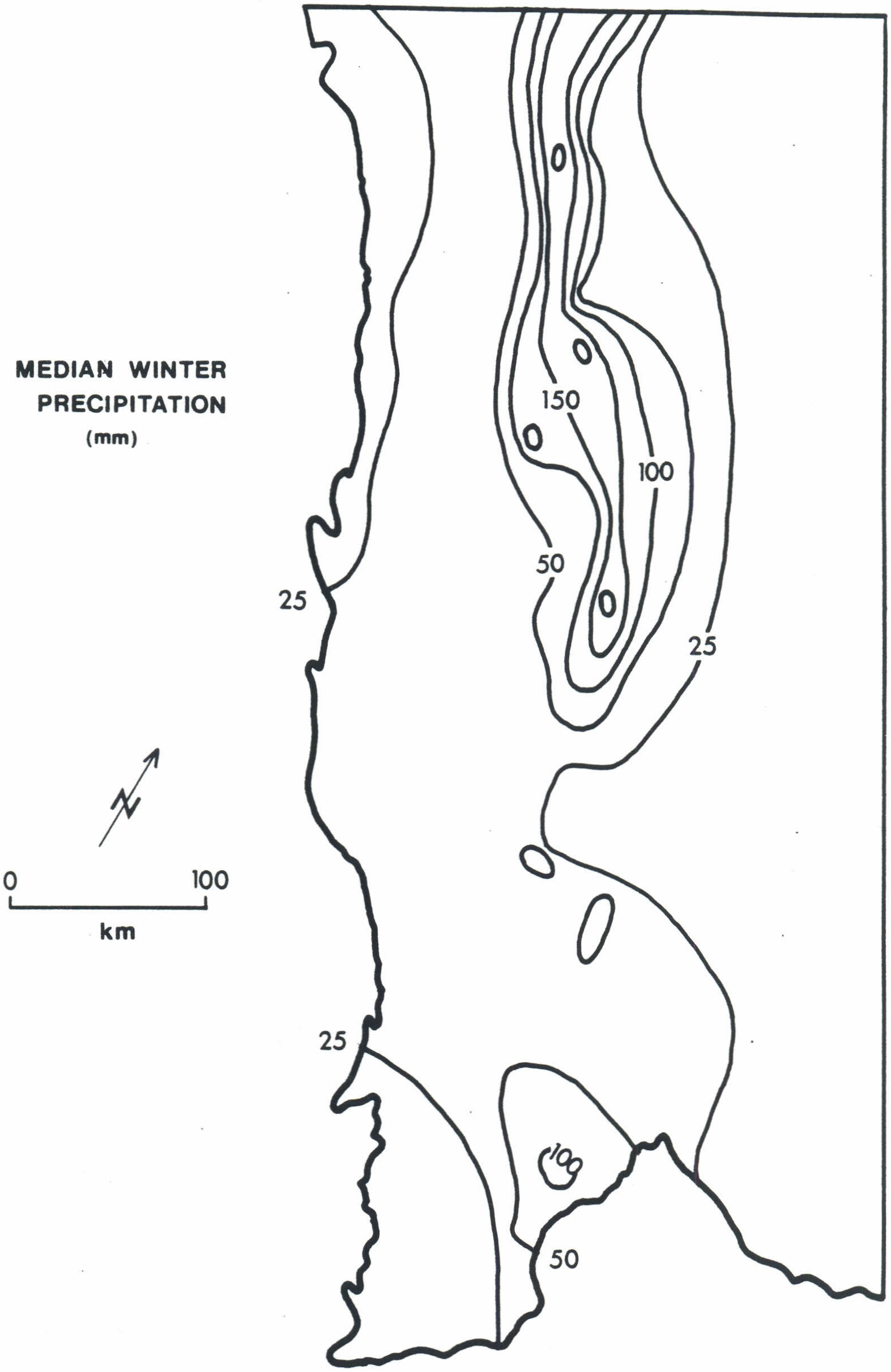


Figure 14. Median winter precipitation (mm).

mountains increases with increased elevation. And the foothills receive quite an amount of precipitaton. The highest ten years of winter mean and median precipitation (Tables 1 and 2) are situated in the higher elevations of the northern section of the southwest mountains and in the foothills. The highest amount of winter mean and median precipitation are recorded at Baha (2110 m) with a mean and median of 253 mm and 244 mm respectively (Tables 1 and 2). The highest precipitation amount falls at Baha station (2110 m) during winter because it is exposed to the northwesterly air flow.

During winter, precipitation over the Southwest of Saudi Arabia is affected by the Mediterranean depression, Sudan lows, and the Red Sea Convergence Zone. These factors are responsible for winter precipitation over the Southwest of Saudi Arabia. The Mediterranean depressions reach the Southwest of the region when associated with Sudan lows.

Spring Precipitation

Precipitation during spring is spread through the Southwest of Saudi Arabia (Figures 15 and 16). Figures 15 and 16 show that the precipitation increases gradually from the Red Sea until the peak and the escarpment of the mountains where the highest amount of precipitation falls. Precipitation, generally, increases with increasing

TABLE 1

MEAN OF THE HIGHEST 10 VALUES
IN THE RECORD DURING THE WINTER SEASON

STATION NAME	STATION NUMBER	ELEVATION (m)	PRECIPITATION (mm)
Baha	TA 343	2110	253
A Bani Malik	TA 229	1820	213
Annimas	B 002	2600	178
Al Mindak	B 001	2400	169
Baljurshi	B 003	2400	167
Al Ajaeda	B 101	--	162
Az Zandi	J 127	440	145
Hasan Abs	J 137	398	145
Tirra Thaqif	TA 228	1820	143
Th. Bani Amer	B 216	2000	140
Fajah	J 131	370	140
J. Fayfa	SA 110	860	136
Tenamah	A 120	2100	135

TABLE 2

MEDIAN OF THE HIGHEST 10 VALUES
IN THE RECORD DURING THE WINTER SEASON

STATION NAME	STATION NUMBER	ELEVATION (m)	PRECIPITATION (mm)
Baha	TA 343	2110	244
Q.A. Bani Malik	TA 229	1980	200
Annimas	B 002	2600	178
Al Mindak	B 001	2400	176
Baljurshi	B 003	2400	168
Fayjah	J 131	370	141
Th. Bani Amer	B 216	2000	140
J. Fayfa	SA 110	860	136
Al Ajaeda	B 101	--	136
W. Fig	B 212	2240	136
Tirra Thaqif	TA 228	1820	131
Tenomah	A 211	2100	127

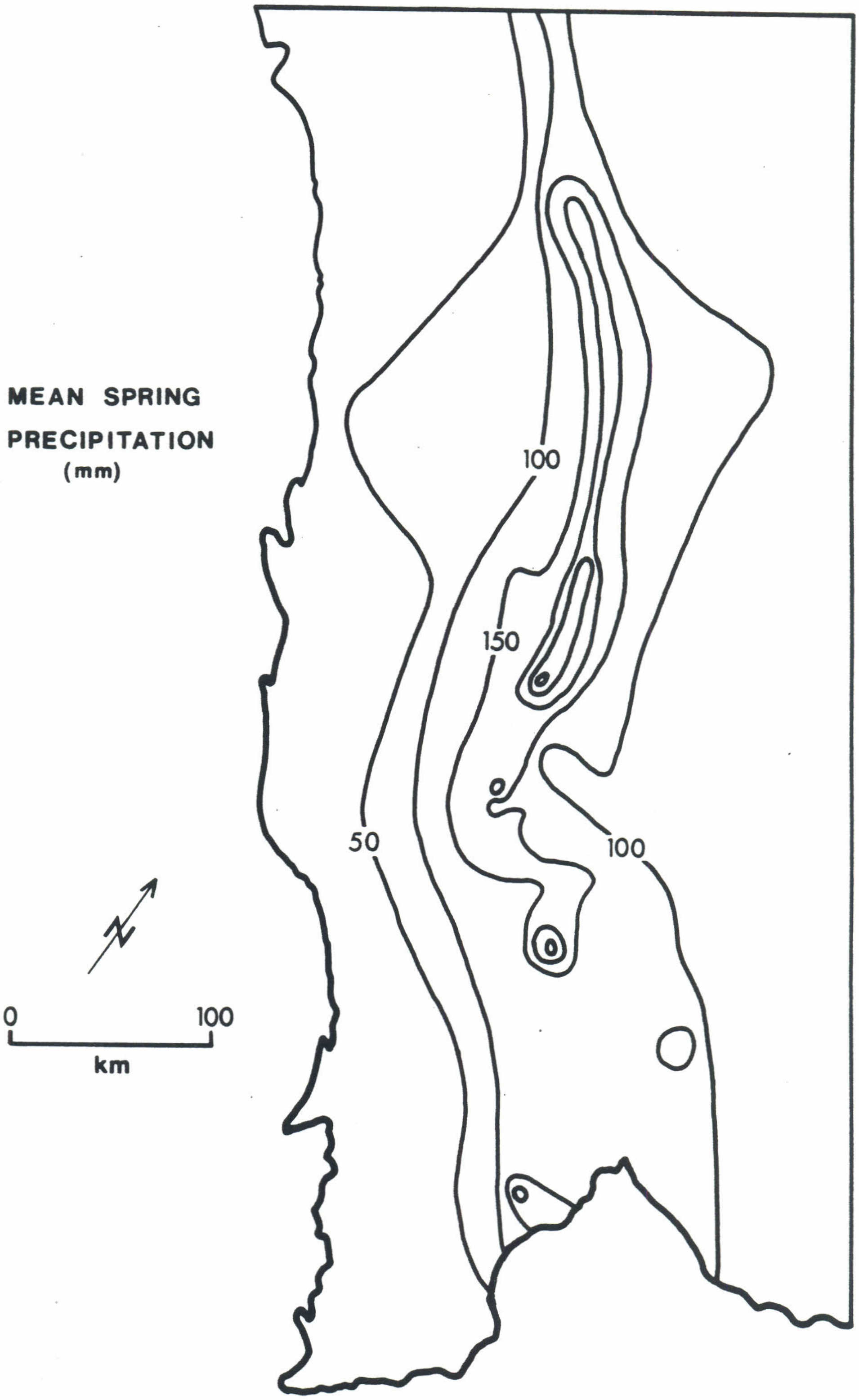


Figure 15. Mean spring precipitation (mm)

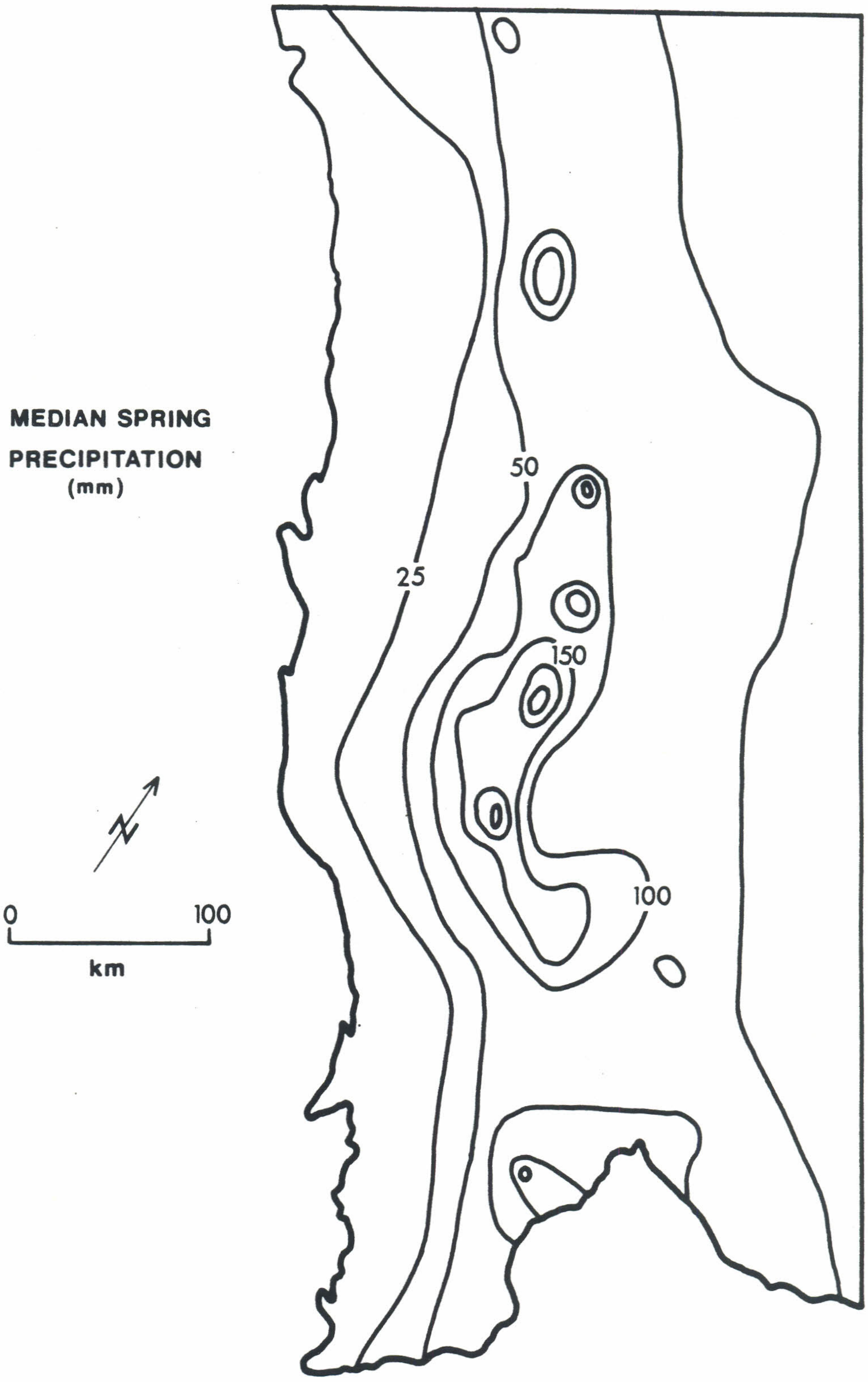


Figure 16. Median spring precipitation (mm).

elevation. East of the escarpment the precipitation decreases with decreasing elevation. In general, in the spring season, the high land of the mountains and the plateau receive more precipitation than the lower lands west of the mountains and along the Red Sea coast.

Spring mean and median precipitation for ten years of record, (Appendices 9 and 10 and Tables 3 and 4), show that the highest amounts of precipitation fall at the higher elevation stations along the southwest mountains of Saudi Arabia. Also, they indicate that the highest ten in the record are located at an elevation of 2000 m and higher. The eastern slope and the plateau receive more precipitation than the western slope of the mountains and the Red Sea coast region because the east slope stations are exposed to the southeasterly monsoon and westerly flows which reach the region from the Mediterranean depression. Tables 3 and 4 indicate that the maximum amount of precipitation for the spring season occurs at Ibalah (2480 m) with a mean and a median of 264 mm and 247 mm, respectively.

The high land of the Asir Mountains and plateau receive the largest amount of precipitation in the spring season. This is from the influence of several combined effects. First, the daily temperature contrast between the land and the sea surface creates local circulation between

TABLE 3

MEAN OF THE HIGHEST 10 VALUES
IN THE RECORD DURING THE SPRING SEASON

STATION NAME	STATION NUMBER	ELEVATION (m)	PRECIPITATION (mm)
Ibalah	A 206	2480	264
Belesmer	A 127	2250	234
Sawdah	A 118	2820	232
Annimas	B 002	2600	225
Sawdah	A 203	2820	222
Teyhan	A 312	2440	218
Timniyah	A 121	2300	212
Tenomah	A 120	2100	210
Th. Bani Amer	B 216	2000	198
Tinomah	A 211	2100	195

TABLE 4

MEDIAN OF THE HIGHEST 10 VALUES
IN THE RECORD DURING THE SPRING SEASON

STATION NAME	STATION NUMBER	ELEVATION (m)	PRECIPITATION (mm)
Ibalah	A 206	2480	247
Belesmer	A 127	2250	240
Teyhan	A 312	2440	228
Sawdah	A 203	2820	223
Annimas	B 002	2600	221
Sawdah	A 118	2820	220
Th. Bani Amer	B 210	2000	198
Al Kam	A 106	2200	198
Abha	A 001	2190	184
Temniyah	A 121	2300	183
Al Firra	A 306	2490	182

land and sea. This local circulation brings afternoon rainfall to the area.

The second effect is the topography of the area. The existence of high mountains in the Southwest of Saudi Arabia forces the air to rise and precipitate along the slope of the mountains. Also, the existence of the irregular topography of the mountains intensifies differential heating and surface instability. These combined factors account for higher rainfall.

The third effect which brings rainfall to the high lands of the Southwest of Saudi Arabia is the southeast monsoon which blows from the Arabian Sea toward the Asir Mountains and the high lands. When the southeast monsoon reaches the high lands, it is forced to ascend and precipitate large amounts of precipitation over the plateau and over the eastern slope of the mountains.

The fourth effect is the influence of Mediterranean depressions. The Mediterranean depressions effect the Southwest of Saudi Arabia during the spring season especially when amalgamated with the Sudan low.

Due to the irregular topography of the mountains, the weak stability in the lower atmospheric layers, daytime temperature contrast between the land and the sea, the flow of southeast monsoon over the area, the effect of the Mediterranean depressions, and the advancement of the Sudan low to the west and southwest of Saudi Arabia, the mountains and the high lands of the Southwest of Saudi Arabia receive the largest amounts of precipitation in the spring season.

Summer Precipitation

During summer (June-August), the flow patterns are pronounced. The subtropical high pressure and the westerly jet stream shift further north. Therefore, they do not affect the weather of the Southwest of Saudi Arabia. In the summer, a trough of low pressure (thermal monsoon trough) is established over the area and extends from India and Pakistan across Arabia with southwesterlies blowing over the southern section of the Arabian peninsula. This flow is conditionally unstable, and its potential for precipitation production depends on the nature of the topography and the underlying surface (Taha et al. 1981).

Another feature of the summer season is the Intertropical Convergence Zone (ITCZ). The ITCZ is the confluence zone between the northwesterly wind, which is characterized by moist and cool air. The ITCZ shifts north as far as latitude $21^{o}30'$N (Al Qurashi, 1981). The Tropical Easterly Jet (only during summer) can be identified over Arabia at latitude 20^{o}N with a core around 150 mb (Hastenrath, Hafez and Kaczmarczyk 1979).

Summer precipitation over the Southwest of Saudi Arabia is brought mainly by the Southwest monsoon flow. It is characterized by moist and cool air. The winds over the southwest form a west to southwest direction and may extend north to Jeddah especially when the monsoon trough is accentuated due to interaction with the Sudan low (Meteorology and Environmental Protection Administration 1978, 1979). Southwest monsoon winds bring great amounts of moisture from the Indian Ocean and Arabian Sea through the Red Sea. When the moist monsoon winds reach the Southwest of Saudi Arabia, they are forced to rise and precipitate.

Summer precipitation is spread through the study area but it is not uniform (Figures 17 and 18). The foothill stations receive more precipitation than other stations. This variation is due mainly to the nature of the topography of the area. The mountains of the southwest extend in a north to south direction. Therefore, they are oriented perpendicular to the southwesterly flow. Figures 15 and 16 indicate that, in general, the precipitation increases with increasing elevation. In addition, the foothills and the western slope of the escarpment receive more precipitation than the eastern slope because the monsoon winds precipitate most of their moisture on the peak and along the western slope. Thus, precipitation decreases east into the Asir Mountains.

During summer, precipitation decreases from south to

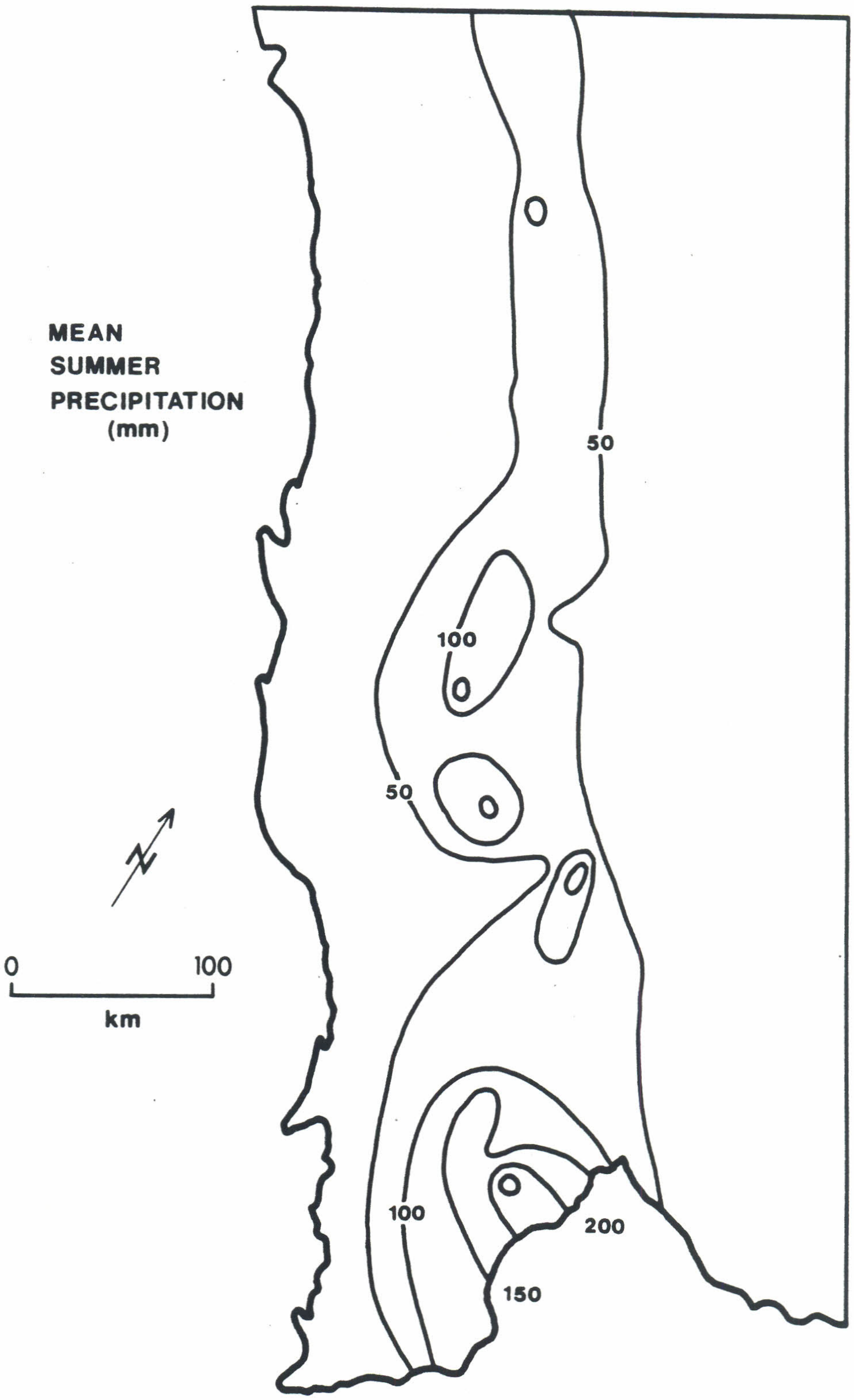


Figure 17. Mean summer precipitation (mm).

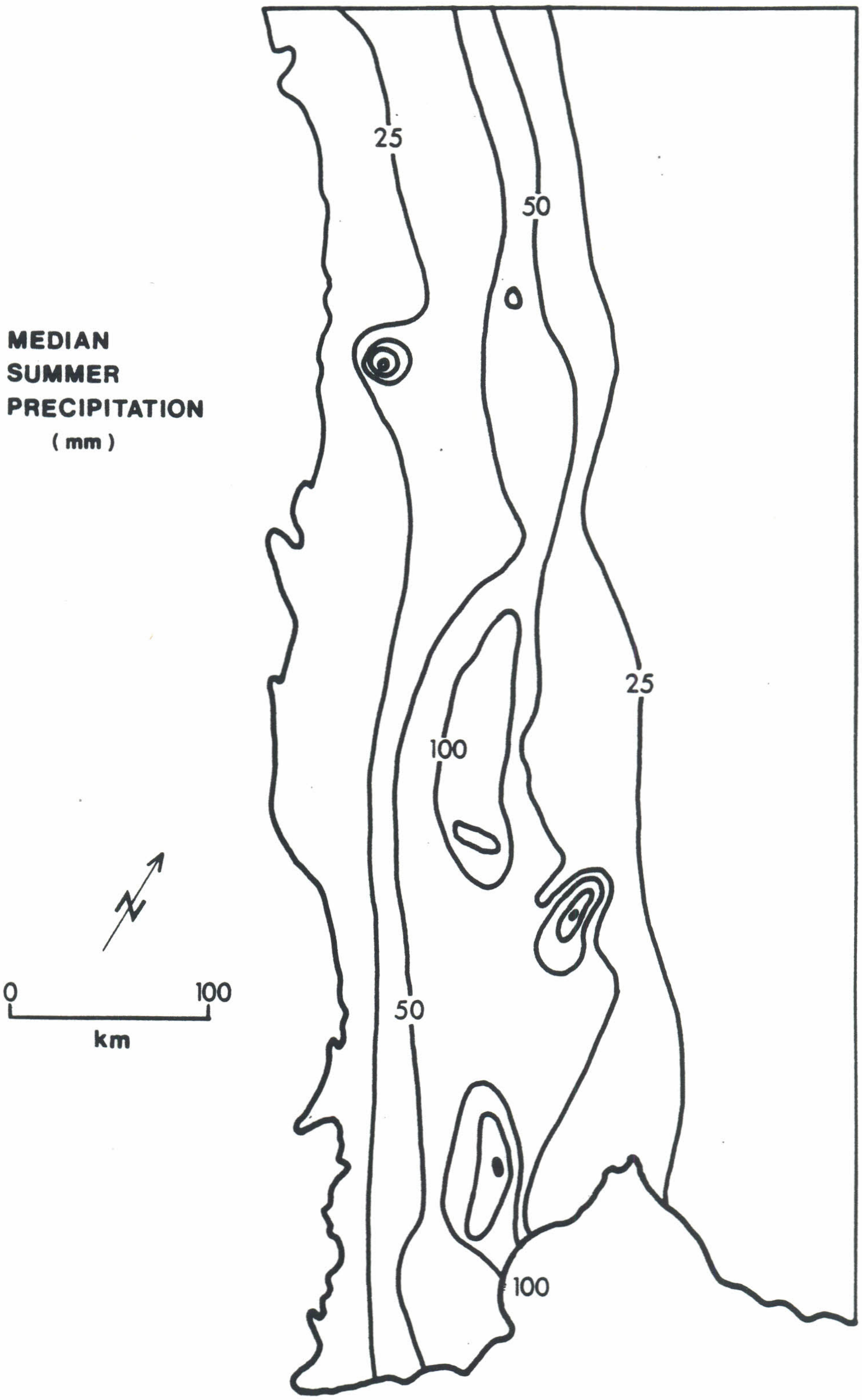


Figure 18. Median summer precipitation (mm).

north. The southern foothills receive more precipitation during summer than the peak and its adjacent land (Appendices 9 and 10 and Tables 5 and 6). Tables 5 and 6 show that the maximum amount of the summer mean over the Southwest of Saudi Arabia is 224 mm which occurs at Jabal Fayfa at an altitude of 860 m, while the maximum amount of summer median precipitation falls at Ardah at an altitude of 223 m. However, the summer maximum amount of precipitation is received at the lower elevations, not at the higher elevation. This is because the southern foothills are perpendicular to the southwestern monsoon and also are located further south. Therefore, the southwestern flow does not travel as far inland as it does to reach the peak. The nature of the relationship between precipitation distribution and altitude will be discussed later in more detail.

During the summer season, precipitation over the Southwest of Saudi Arabia is produced mainly by the monsoon flows. The advance of the monsoon winds farther north over Arabia is effected by the ITCZ position (Al-Qurashi, 1981). The coastal and western slope of the Asir Mountain stations may receive daily afternoon precipitation. This is due to the daily temperature contrast between the Red Sea and the land surface.

TABLE 5

MEAN OF THE HIGHEST 10 VALUES
IN THE RECORD DURING THE SUMMER SEASON

STATION NAME	STATION NUMBER	ELEVATION (m)	PRECIPITATION (mm)
Jabal Fayfa	SA 110	860	224
Al Firra	A 306	2490	176
Al Kam	A 106	2200	164
Ardah	SA 104	223	164
W. Damad	SA 129	150	163
Harub	A 126	540	160
J. Sala	SA 111	900	156
Muhyil	SA 113	450	156
Rejal Alma	SA 116	700	161
Sawdah	A 203	2820	149
Sawdah	A 118	2820	147
Suq Ayban	SA 140	305	148

TABLE 6

MEDIAN OF THE HIGHEST 10 VALUES
IN THE RECORD DURING THE SUMMER SEASON

STATION NAME	STATION NUMBER	ELEVATION (m)	PRECIPITATION (mm)
Ardah	SA 104	223	178
Al Firra	A 306	2490	173
J. Fayfa	SA 110	860	168
Harub	A 126	540	168
Suq Ayban	SA 140	148	168
Al Kam	A 106	2000	160
Sawdah	A 203	2820	156
Rejal Alma	SA 116	700	155
Sawdah	A 118	2820	151
Ash Shaaf	A 210	2620	140
Malaki	SA 001	190	134
Muhyil	SA 113	450	130

Autumn Precipitation

Autumn season (September-November) provides a transition period from summer to winter season. The flow pattern is less distinct and weak. The influence of the Mediterannean depression begins while the westerly monsoon begins to retreat. In early autumn (September), the area continues to be under the influence of the monsoon trough and the Sudan low which accentuated the Red Sea trough (Meteorology and Environmental Protection Administration 1978, 1979). By mid and late autumn, the area comes under the influence of the Red Sea trough and the Mediterranean depression. These combined factors cause precipitation in the Southwest of Saudi Arabia.

Autumn precipitation is spread through the Southwest of Saudi Arabia (Figures 19 and 20), but the precipitation amount falling over the area, in general, is less than the amount which occurs in the spring, summer or winter seasons. Figures 19 and 20 show that the foothill stations receive more precipitation than the higher stations do. The highest ten autumn means and medians are recorded at foothillstations (Appendices 9 and 10 and Tables 7 and 8). Tables 7 and 8 show that the maximum amount of precipitation for the autumn period occurs at Harub (540 m) with a mean and median of 178 mm and 153 mm, respectively. Also, the foothill stations receive more precipitation than

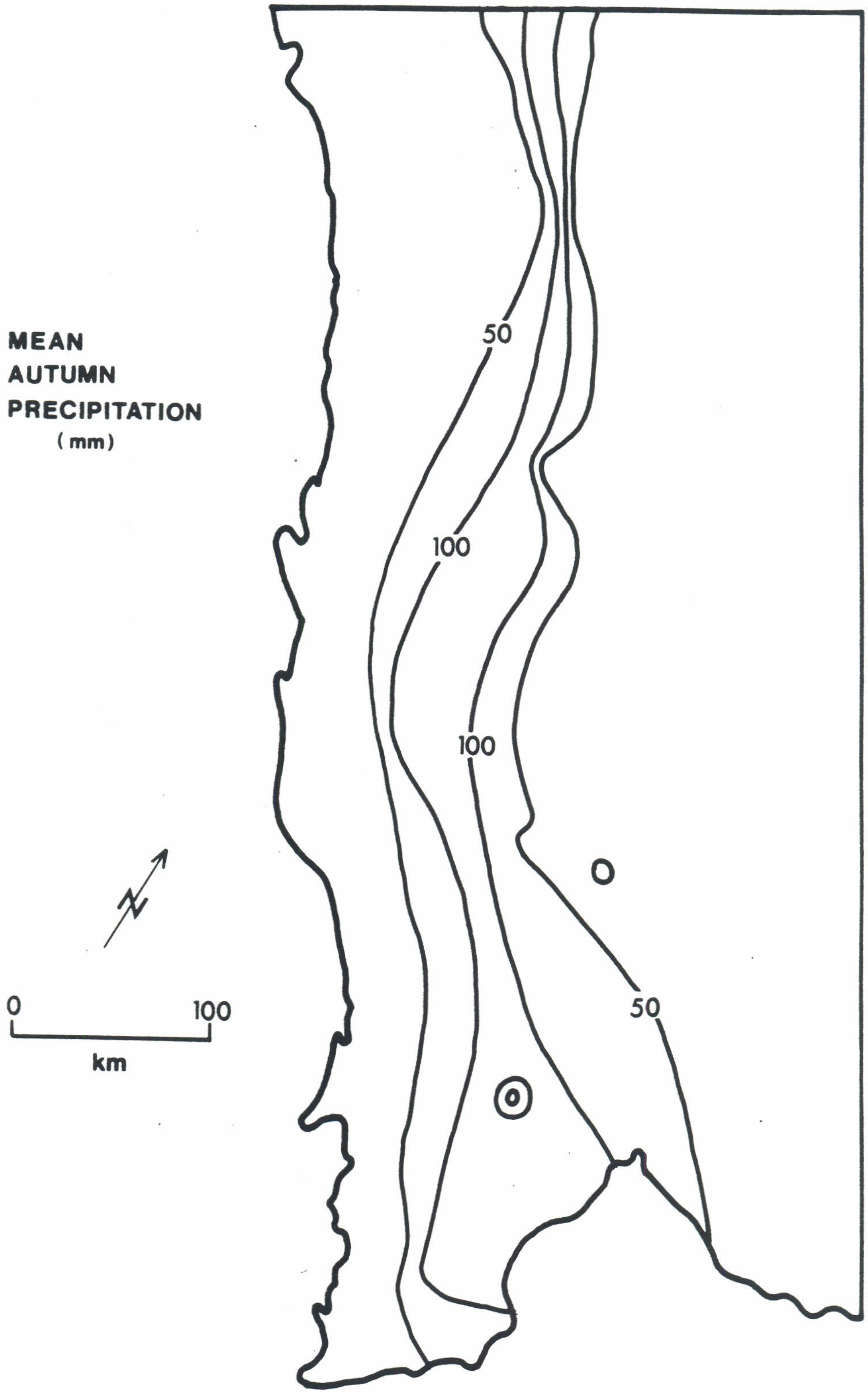


Figure 19. Mean autumn precipitation (mm).

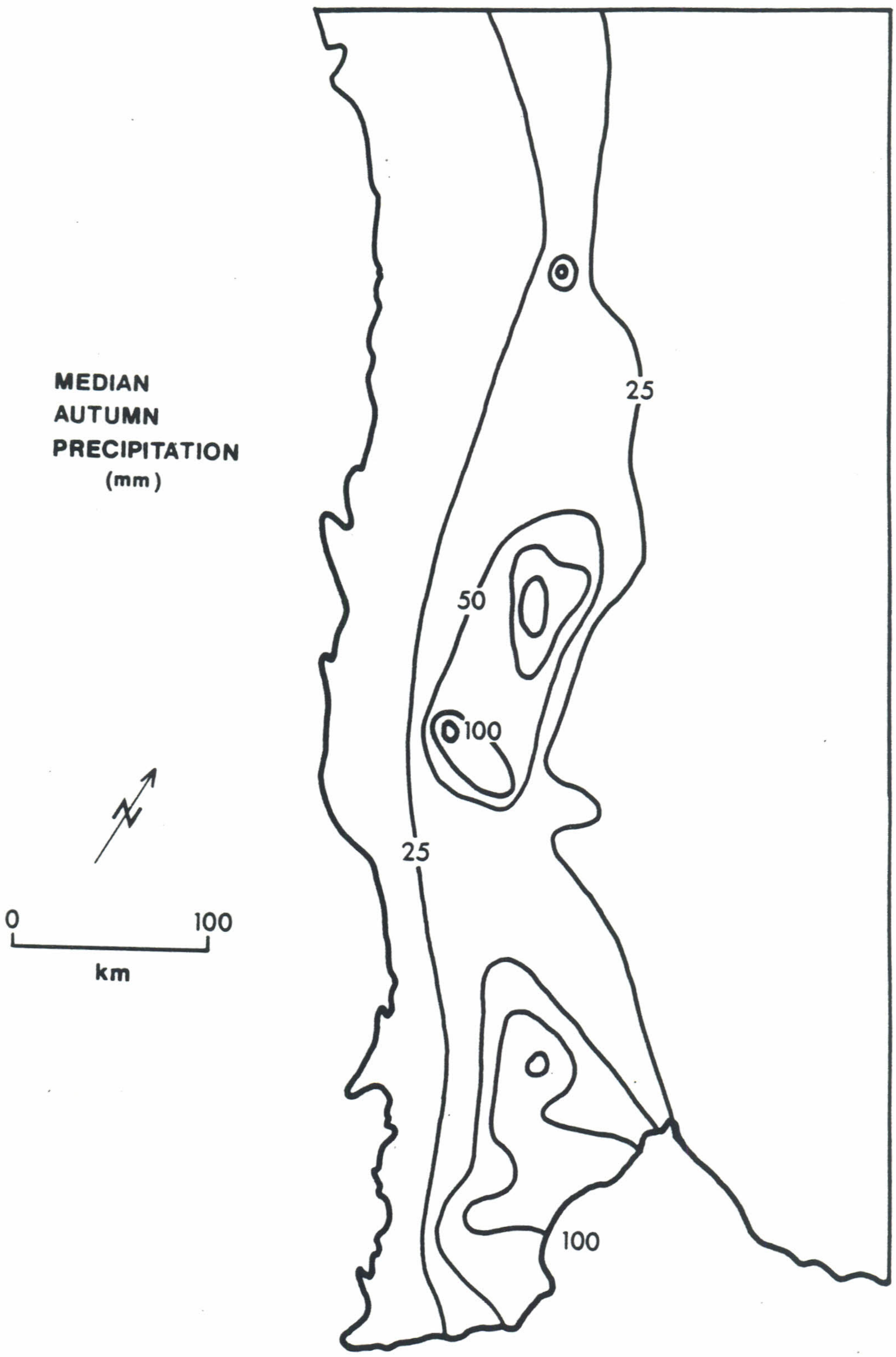


Figure 20. Median autumn precipitation (mm).

TABLE 7

MEAN OF THE HIGHEST 10 VALUES
IN THE RECORD DURING THE AUTUMN SEASON

STATION NAME	STATION NUMBER	ELEVATION (m)	PRECIPITATION (mm)
Harub	A 126	540	178
Garn Albahr	SA 108	420	152
Ardah	SA 164	223	130
Malaki	SA 001	190	128
W. Damad	SA 129	150	127
Suq Ayban	SA 140	305	115
Barik	SA 105	390	114
Jadiyah	SA 133	80	109
J. Sala	SA 111	900	107
Rejal Alma	SA 116	700	105

TABLE 8

MEDIAN OF THE HIGHEST 10 VALUES
IN THE RECORD DURING THE AUTUMN SEASON

STATION NAME	STATION NUMBER	ELEVATION (m)	PRECIPITATION (mm)
Harub	A 126	540	153
Garn Albahr	SA 108	420	146
Ardah	SA 104	223	127
W. Damad	SA 129	150	121
Hasan Alabs	T 137	398	117
J. Sala	SA 111	900	111
Barik	SA 105	390	110
Rejal Alma	SA 116	700	107
Tarqush	SA 138	570	106
Ghat	SA 139	450	106
J. Fayfa	SA 110	860	106
Kwash	SA 003	350	103

the higher stations located at the peak or on the eastern slope of the mountains because the foothill stations are exposed to the southwesterly monsoon, especially in early autumn. In addition to the monsoon trough, the Southwest is influenced by the Red Sea trough and the Mediterranean depression. These factors cause precipitation in the Southwest of Saudi Arabia during the autumn season.

Annual Precipitation

The mean and median of annual precipitation in the Southwest of Saudi Arabia were mapped (Figures 21 and 22) and tabulated (Appendices 11 and 12). Figures 21 and 22 show that the amount of precipitation is varied from one station to another, but, generally, increases with increasing elevation. Some Stations located in the foothills of the western slopes of the mountains receive more precipitation than other stations, even those at higher elevations. This is because the southwest mountains are oriented north-south, perpendicular to the southwest air flows and act as a barrier to the flow of air and force the air to ascend then precipitate. Also, Figures 21 and 22 indicate that values of precipitation decrease as one goes farther east of the escarpment. This area is known as leeward or the rain shadow because most of the precipitation falls on the western slope of the mountain (windward).

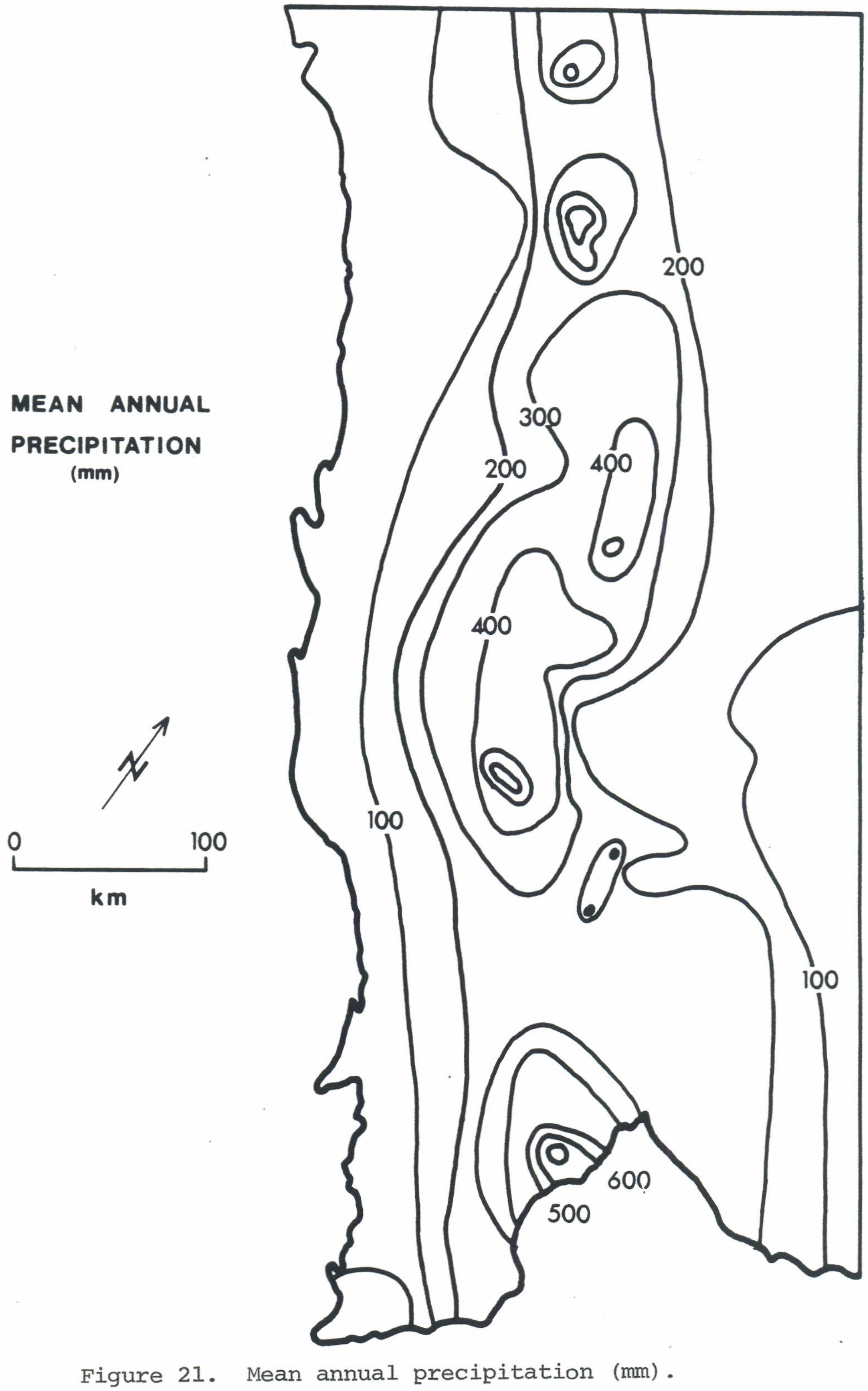


Figure 21. Mean annual precipitation (mm).

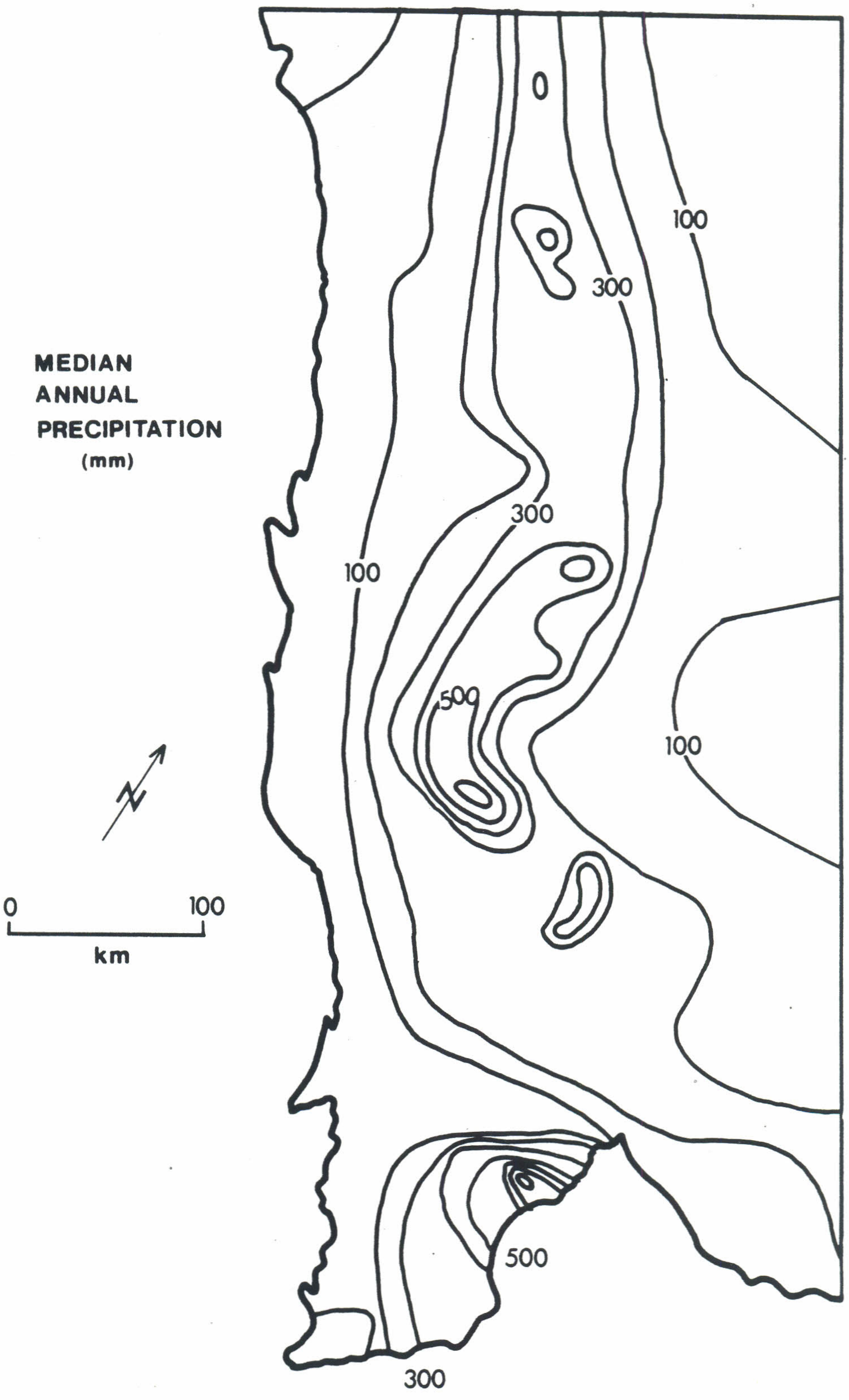


Figure 22. Median annual precipitation (mm).

TABLE 9

MEAN OF THE HIGHEST 10 VALUES
IN THE ANNUAL RECORD

STATION NAME	STATION NUMBER	ELEVATION (m)	PRECIPITATION (mm)
Jabal Fayfa	SA 110	860	655
Baha	TA 343	2110	547
Sawdah	A 118	2820	516
Rejal Alma	SA 116	700	507
Annimas	B 002	2600	505
Al Firra	A 306	2490	497
Harub	A 126	540	496
Q.A. Bani Malik	TA 229	1820	483
Al Mindak	B 001	2400	466
Muhayil	SA 113	450	455

TABLE 10

MEDIAN OF THE HIGHEST 10 VALUES
IN THE ANNUAL RECORD

STATION NAME	STATION NUMBER	ELEVATION (m)	PRECIPITATION (mm)
J. Fayfa	SA 110	860	691
Annimas	B 002	2600	560
Rejal Alma	SA 116	700	548
Baha	TA 343	2110	537
Sawdah	A 118	2820	524
Harub	A 126	540	523
Sawdah	A 203	2820	513
Muhyil	SA 113	450	506
Al Firra	A 306	2490	489
Q.A. Bani Malik	TA 229	1820	469

The maximum amount of precipitation falls at Jabal Fayfa (860 m) which receives an annual mean and median of 655 mm and 691 mm respectively (Tables 9 and 10). Tables 9 and 10 show the highest ten values of precipitation and their elevation. Tables 9 and 10 indicate that the highest value does not fall at the highest elevation but occurs at Jabal Fayfa with an elevation of 860 m. Also, Table 9 and Table 10 show the high values of precipitation occur at lower elevations as well as higher elevations. This means that the maximum amount of precipitation does not always occur at the highest elevation in the area, and that elevation is not the major factor in precipitation distribution. Moreover, Tables 9 and 10 depicts that four of the ten top precipitation values recorded in the Southwest of Saudi Arabia are located at lower elevations. These four stations are Jabal Fayfa (860 m), Rejal Alma (700 m), Harub (540 m), and Muhayil (450 m), situated in the foothills of the western slopes of the southwest mountains and exposed to the prevailing winds. The other six stations are Baha (2110 m), Sawdah (2820 m),An nimas (2600 m), Al-Firra (2490 m), Q.A. Banimalik (1820 m), and Al Mindak (2400 m). These stations are situated at higher elevations, and they are exposed to the moist winds.

The annual value of precipitation obtained for each station is varied by using the mean and median statistics

(Tables 9 and 10). For example, the annual mean at Jabal Fayfa is 655 mm while the annual median is 691 mm. So, a station may have the second top value of precipitation received in the area by using the mean and it may have a lower or higher record by using the median. For example, Baha receives the second top of the annual mean while it obtained the fourth highest annual median. The variation in the annual value by applying the mean and median statistics is due to the extreme variance in the annual precipitation received by a station from one year to another.

Temporal and Spatial Precipitation Distribution by Employing the Harmonic Analysis

Harmonic analysis is a technique which can be employed to obtain objective description and mapping of the temporal and spatial distribution of precipitation. It consists of uncorrelated six harmonics. Thus, each harmonic can be treated as an independent, and no two harmonics can explain the same part of the variance. The variances explained by the different harmonics can be added to each other. The first harmonic is a curve with one maximum and one minimum. It describes the tendency toward an annual variation in the observed precipitation. This curve is adjusted to give the best mathematical description of the annual tendency. The second harmonic, which consists of a sine curve with two maxima and two minima, describes the semi-annual tendency of the observed curve. The third, fourth, fifth, and sixth harmonics describe the four-month, three-month, and two and four-tenths month and two-month variance in the observed precipitation curve. Harmonics which best fit the observed curve have the largest amplitude, while those which fit poorly have small amplitudes. The phase angle of the harmonic represents the time of year when the maximum of precipitation occurs.

Temporal and spatial precipitation distribution in the Southwest of Saudi Arabia was analyzed by applying harmonic analysis. Variances explained by the six harmonics and the phase angles of the six harmonics will be discussed in general; variances and the phase angles of the first, second, and the third harmonics will be discussed in more detail because the first three harmonics account for 80% of the total variance reduced by the six harmonics.

Variance Reduced by the Six Harmonics

Variances reduced by the six harmonics vary from one harmonic to another as indicated in Appendix 13. Variances reduced by the first harmonic accounted for 46% of the total variance. The second harmonic accounts for 13%, the third harmonic accounts for 6%, and the sixth harmonic accounts for only 5% of the total variance.

The first three harmonics account for 80% of the total variance while the last three harmonics account for 20% of the total variance. The first three harmonics explain most of the physical factors responsible for the observed patterns (Figure 23). The importance of the harmonic varies from one harmonic to another (Figure 23). Reviewing Figure 24 it is found that the first harmonic is important and it reduces the highest value of variance for 78 stations. These stations are distributed throughout the study area. The other stations which have low variances are found mainly along the Asir Mountains, Red Sea coast, and the foothills (Figure 24).

Six stations with low values of variance in the first harmonic have higher variance values in the second harmonic. These stations are Najran ($17^{o}33$'N, $44^{o}14$'E), Ghat $19^{o}03$'N, $42^{o}02$'E), Mudayfil ($19^{o}32$'N, $41^{o}03$'E), Ushaylah $19^{o}41$'N, $19^{o}41$'E), and W. Doqah ($19^{o}44$'N, $41^{o}02$'E). Seventeen stations have the highest values reduced by the third harmonic. These stations extend mainly along the Asir Mountains and its foothills. Also, some stations are located on the Red Sea coast such as Ad-Darb, Lith, and Ghomeqa (Figure 24).

The higher three harmonics reduce low variances for all stations except Al Gooz station. The highest value of variance for Al Gooz station is reduced by the sixth harmonic. For example, the variance for Al Gooz reduced by

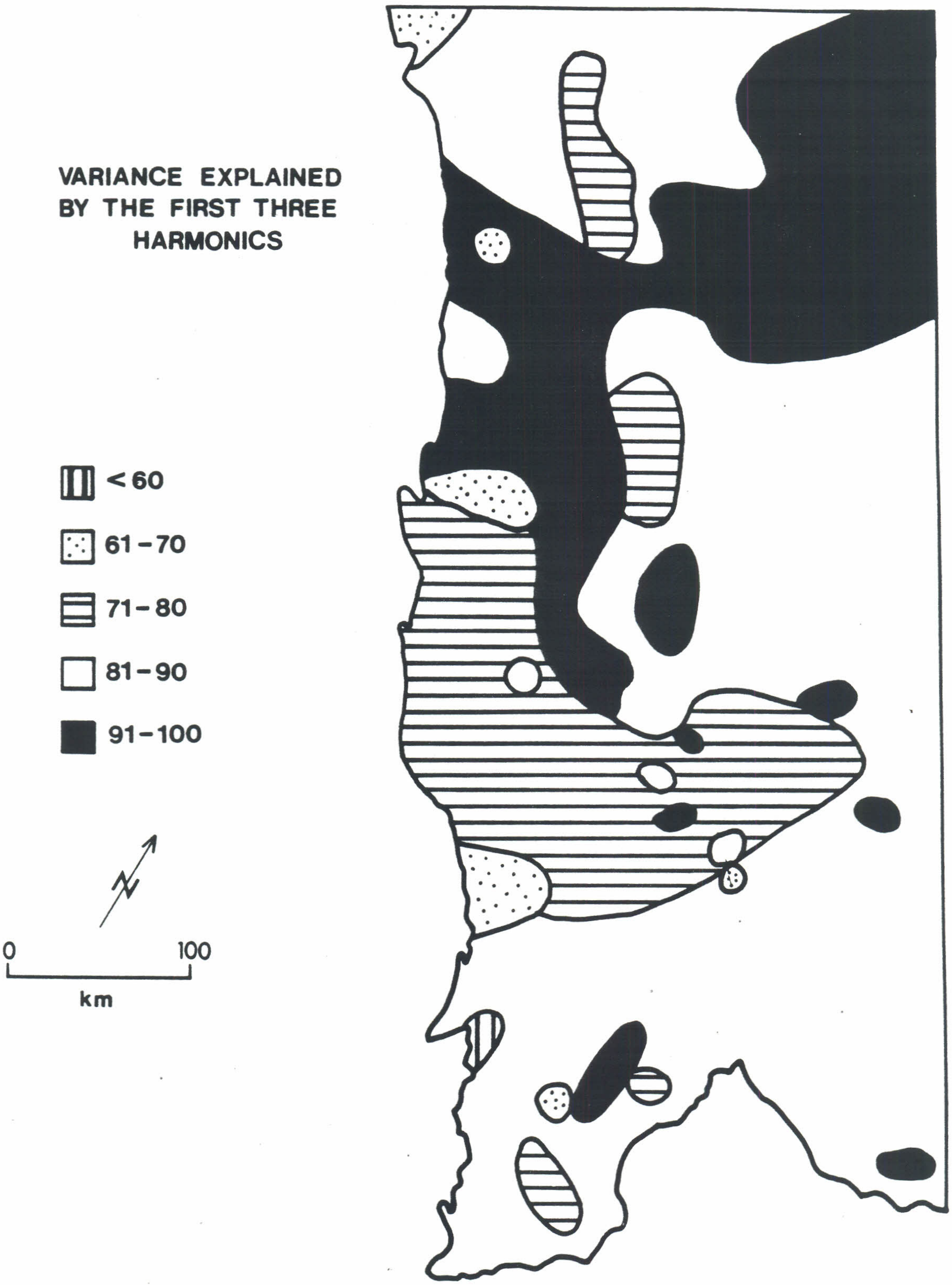


Figure 23. Variance explained by the first three harmonics.

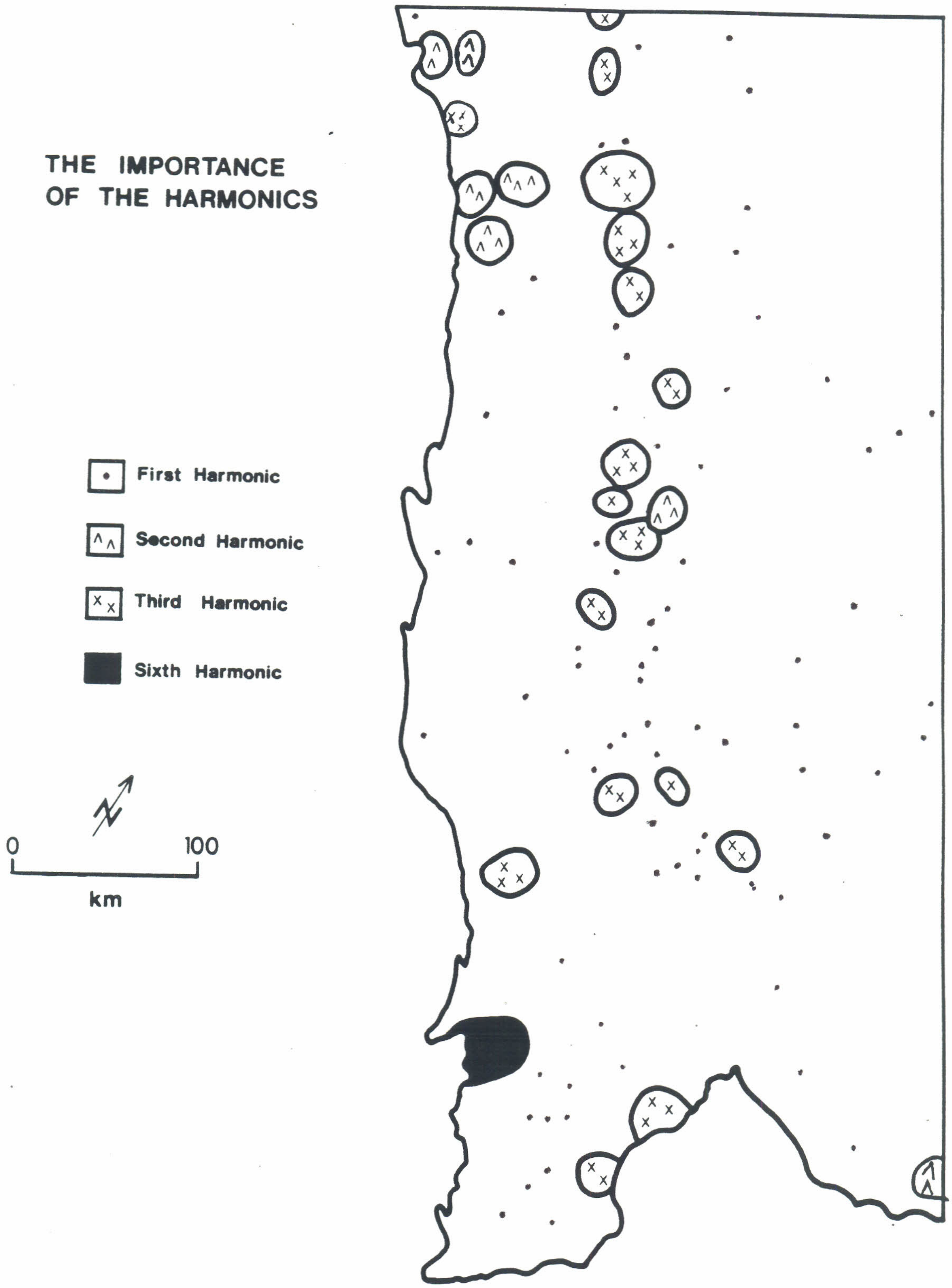


Figure 24. The importance of the harmonics.

the first harmonic is 17%, second harmonic is 1%, third harmonic 5%, fourth harmonic 18%, fifth harmonic 36%, and sixth harmonic 43%.

Phase Angle of the Six Harmonics

The date of maximum precipitation in the Southwest of Saudi Arabia varies from one station to another. This variation indicates that the precipitation in the Southwest of Saudi Arabia is influenced by more than one climatic regime.

Amplitudes and variances reduced by the six harmonics show that no one harmonic perfectly fit the observed curve and described the precipitation distribution in the Southwest of Saudi Arabia. This is due to two reasons: the influences of more than one climatic regime and the physical nature of the study area. Figure 24 depicts that the first harmonic is the most important harmonic and the third harmonic is second, then the second harmonic. Amplitudes and variances obtained from the six harmonics indicate that 78 stations have the tendency toward an annual variation in the observed precipitation curves with one maxima and one minima (Appendix 13), six stations have a tendency toward semiannual variation with two maxima and two minima, 19 stations have 4-month variation in the observed precipitation curve, and there is one station with a 2-month variation in the observed precipitation curve

(Appendix 13 and Figure 24).

Stations with annual tendency are distributed throughout the Southwest of Saudi Arabia and have different times of maximum precipitation.

Variance of the First Harmonic

The first harmonic is a curve with one maxima and one minima. It describes the tendency toward an annual variation in the observed rainfall. Variances reduced by the first harmonic range from .08 to 82% of the total variance (Appendix 13 and Figure 25). Figure 25 shows that the Harub station (17°27'N, 42°50'E) has the highest variance reduced by the first harmonic (82%) while the least variance reduced by the first harmonic is found at Hasan AlHabs station (19°58'N, 41°20'E). The value of variance reduced by the first harmonic varies from one station to another. Figure 25 indicates that there are six areas of dominance. These areas are indicated in percentages as follows: 0-15, 16-30, 31-45, 46-60, 61-75, and 76-85. The area with the highest value of variance reduced by first harmonic (76-85%) dominates only three station. These stations are Harub (82%), W. Damand (77%), and Bir Asker (77%). The second area of high value of variance reduces by first harmonic range from 61-75% of variance. This area occupies two areas. The first area as illustrated in Figure 25 is a strip extending along the

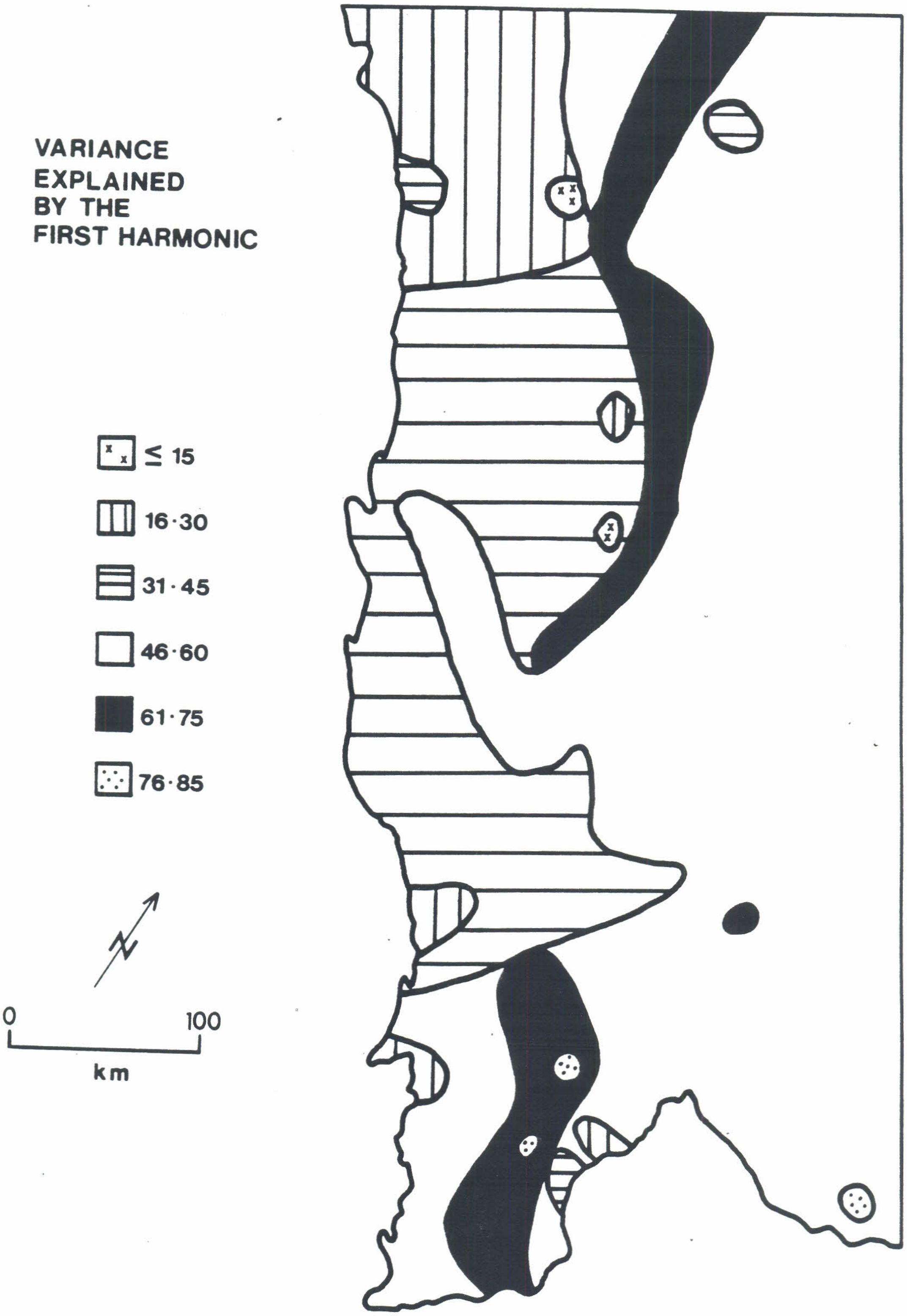


Figure 25. Variance explained by the first harmonic.

Asir Mountain. The second area dominates the southwest foothills of the Asir Mountains.

The third area of dominance has a value of 46-60%. This area of variance reduces by first harmonic occupies the largest part as portrayed by Figure 23. This area extends from northeast to southwest. The fourth area of dominance has variances ranging from 31-45%. This area is occupied mainly in the middle of the Red Sea coast and east of the plateau. In addition to these main areas, there are three small areas of dominance such as J. Fayfa, Aqiq Rd, and Tiraa Thaqif which have percentage values of 33, 44, and 41, respectively.

The fifth area of dominance reduces by the first harmonic has a value range from 16 to 30%. This area relatively dominates northwest of the Red Sea coast. Also, it dominates small areas as Thurayban (28%), AdDarb (19%), Al Gooz (17%), and J. Sala (28%). The last area of dominance reduces by the first harmonic has a value ranging from 0 to 15%. This area dominates only fourstations: Hasan Al Habs (8%), Najran (9%), Ghat (14%), and Guiloua (14%).

Phase Angle of the First Harmonic

The phase angle of the first harmonic indicates when maximum precipitation falls. The phase angle of the first harmonic (annual tendency with maximum and one minimum) is complicated (Appendix 13 and Figure 26). This may be due to the physical nature of the area. For the purpose of discussion, the area can be approximately divided into four main regions: the Red Sea coast, foothills, Asir Mountains, and the Plateau.

Red Sea coast

Along the coast and its adjacent land, the phase angles vary from September to February. Along the Red Sea coast the maximum precipitation occurs in the autumn and winter seasons. The date of maximum precipitation of the first harmonic along the coast varies from one station to another and also from stations located near the Red Sea to stations located a little farther inland. For example, the date of maximum precipitation at Al Gooz (17°8'N, 42°27'E) is approximately on November 21st, while at Qahmah (18°0'N, 41°40'E) the date of maximum precipitation is January 13th. The date of maximum precipitation at Meykoush (18°38'N, 41°19'E), Kiyat 18°44'N, 41°24'E, and Showaq 19°59'N, 40°37'E) is December (Figure 26). In the northern part of the Red Sea coast, the time of maximum precipitation at Lith (20°9'N, 40°17'E) and Mojermah is January.

In addition to the variation in the date of maximum precipitation near the Red Sea, the date also varies as from the Red Sea coast to the east. For example, the date

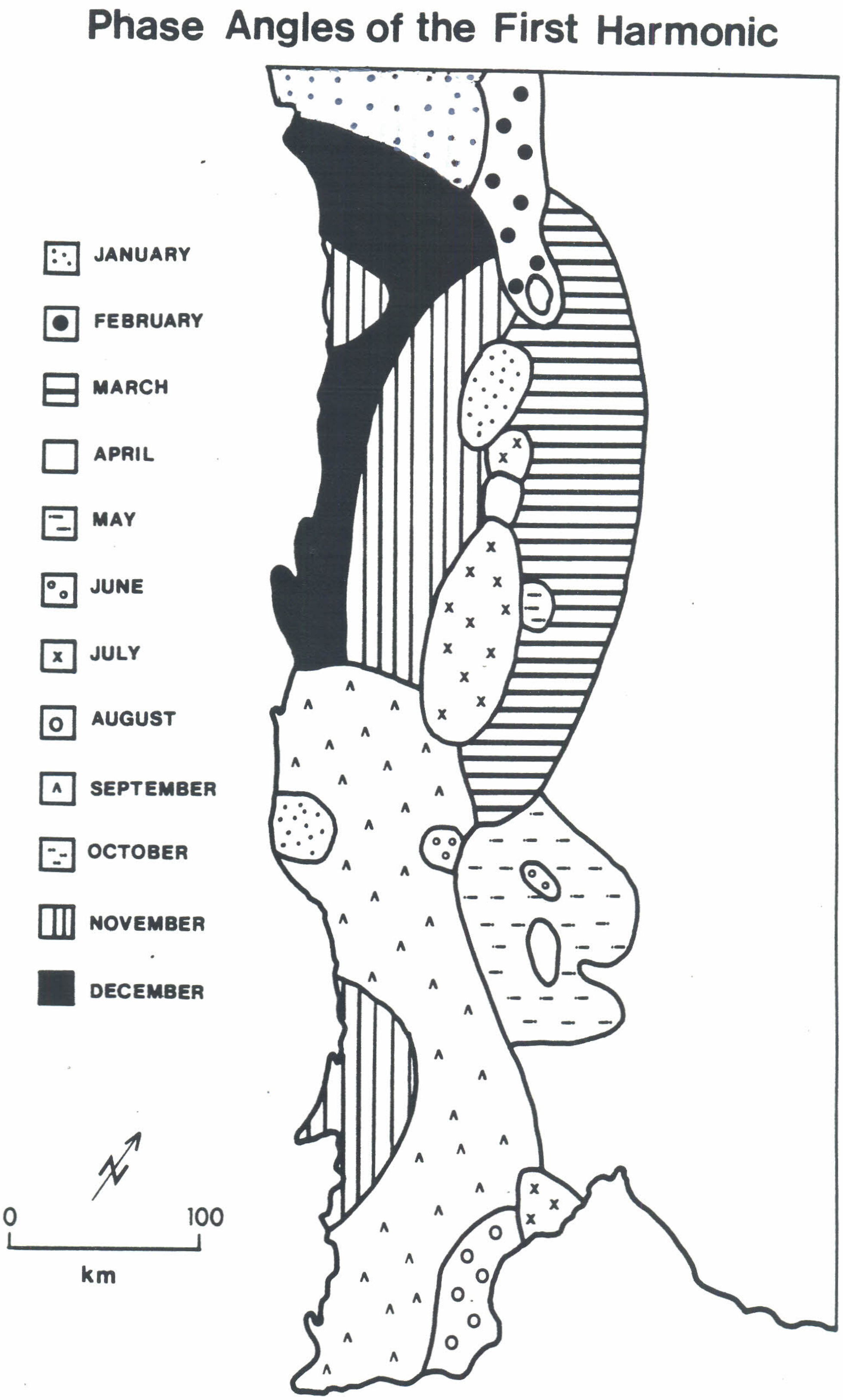


Figure 26. Phase angles of the first harmonic.

of maximum precipitation at Suq Ayban ($17^{o}19$'N, $43^{o}2$'E) is November, for W. Doqah is December. As we go further east, the date of maximum precipitation approximately occurs in September and November (Figure 26).

Foothills

The phase angle of maximum precipitation along the foothills of the Asir Mountains varies from one station to another (Figure 26). In the northern part of the foothills, the date of maximum precipitation occurs in the autumn and winter seasons, similar to the coast region. For example, the date of maximum precipitation at Adham ($20^{o}27$'N, $40^{o}54$'E) is October,Hajrah ($20^{o}14$'N, $41^{o}3$') is November, Al Mindak ($20^{o}6$'N, $41^{o}17$'E) is February, and at Az zandi ($19^{o}40$'N, $41^{o}32$'E) and Fayjah ($19^{o}28$'N, $41^{o}36$'E) is approximately January.

In the middle of the foothills, the date of maximum precipitation approximately occurs in the summer season (June-August). For example, the date of maximum precipitation at Thurayban ($19^{o}26$'N, $41^{o}50$'E), Majrada ($19^{o}0$'N, $41^{o}50$'E), Kawsh $19^{o}0$'N, $41^{o}53$'E), Barik ($18^{o}0$'N, $41^{o}58$'E), Tarqush ($18^{o}38$'N, $42^{o}4$'E), and Muhayil ($18^{o}32$'N, $42^{o}2$'E) is July. Figure 26 depicts that all the stations located in the middle foothills have maximum precipitation in July except Suq Thuluth station ($19^{o}16$', $41^{o}48$'N) which has maximum precipitation in April. In the southern foothills, the date of maximum precipitation is July and August. But stations which lie on the western edge of the hills have maximum precipitation in September (Figure 26).

Asir Mountains

The date of maximum precipitation in the Asir Mountains varies from the north to the south of the mountains (Figure 26). In the northern part of the mountains, the date of maximum precipitation is in late January and early February. For example, Tiraa Thaqif ($20^{o}45'$N, $40^{o}51'$E) and Q. Bani Malik have maximum precipitation in February.

In the middle of the Asir Mountains, the phase angle of maximum precipitation is March. This is depicted in Figure 26 as a strip line extending along the mountains. In the southern part of the Asir Mountains, the dates of maximum precipitation are April and May. East of the Asir Mountains on the Plateau the maximum precipitation occurs in April (Figure 26).

Comparing the dates of the maximum precipitation obtained from the first harmonic with times of the observed maximum precipitation in the Southwest of Saudi Arabia indicates that the phase angles of the first harmonic for 50 stations are the same as the times of the observed maximum precipitation (Table 11), and the phase angles of the first harmonic for 36 stations are not much different

TABLE 11

PHASE ANGLES OF THE FIRST HARMONIC ARE THE SAME AS THE DATES OF OBSERVED MAXIMUM PRECIPITATION

NAME	NUMBER	TIME OF MAXIMUM PRECIPITATION
Abu-Jinneyah	B 208	April
Al-Qiq	B 220	April
Al-Azazah	A 311	April
Al-Gharrah	A 303	May
Al-Haraja	A 104	April
Al-Heifa	B 005	April
Al-Madha	B 209	April
Al-Tajer	A 108	April
Al-Yaara	A 110	April
Al-Jawf	A 105	April
Aqiq Rd	TA 340	April
Ardah	SA 104	August
Az-zandi	J 127	January
Bani Malik	A 112	May
Bani Sar	A 113	April
Bir Asker	N 308	April
Bishah	B 004	April
W. Damad	SA 129	August
W. Doqah	J 139	December
Fayjah	J 131	January
Qahmah	SA 115	January
Ghat	SA 139	May
Guiloua	J 124	December
Hani	A 201	May
Harb	SA 126	September
Ibalah	A 206	April
J. Sala	SA 111	August
Khaybor	B 110	April
Mashrafa	A 326	April
Meykonsh	Sa 117	December
Mojermah	J 122	December
Najran	N 001	April
Qufl	SA 136	August
S. Alahad B.Z.	J 129	December
Sabah	A 117	April
Smakh	B 219	April
Smatah	SA 137	August
Sawdah	A 118	May
Sawdah	A 203	May
Sereat Abid	A 119	April
S. Thuluth	SA 121	April
Tathulith	B 113	March

TABLE 11 cont.

NAME	NUMBER	TIME OF MAXIMUM PRECIPITATION
Temniyah	A 121	April
Tenomah	A 120	March
Teyhan	A 123	May
Tindahah	A 123	May
Tubalah	B 114	April
Upper Ranyah	B 222	April
Zahran Al J.	N 103	April

from the actual dates of observed maximum precipitation. These variations range from ± 1 to 27 days, and the variations for 16 of the 36 stations range from ± 1 to 10 days, and the variations for 19 stations range from ± 11 to 27 days (Table 12). Also, the results show that the dates of maximum precipitation obtained from the first harmonic for 18 stations vary from the observed dates of maximum precipitation. These variations range from ± 1 to 2 months (Table 13).

Variance of the Second Harmonic

The second harmonic with two maxima and two minima describe the semiannual tendency of the observed curve. The variances reduced by the second harmonic range from 0.0 to 49% as depicted in Appendix 13. The second harmonic accounts for much less of the total variance than the first harmonic. The variances of the stations reduced by the second harmonic, except 11 stations, are less than the variances reduced by the first harmonic. In some small areas, the second harmonic is more important than the first harmonic. For example, the variance for Hasan Al'Habs reduced by the second harmonic is 39% while the variance reduced by the first harmonic is only 8%. Variance for Najran station reduced by the second harmonic is 42%, while the value of variance obtained by the first harmonic for the same station is only 9%. Also, in the second harmonic,

TABLE 12

PHASE ANGLES OF THE FIRST HARMONIC ARE VARIED FROM THE DATES OF THE OBSERVED MAXIMUM PRECIPITATION

STATION NAME	STATION NUMBER	NUMBER OF DAYS
Adham	J 119	+12
Al-Kam	A 106	+ 7
Al-Ajaeda	B 101	+ 2
Al-Mala	A 213	+ 3
Al-Mindak	B 001	+12
Al-Mowayn	A 107	- 3
Ash Shaaf	A 210	+27
Makhwa	J 126	-15
Ashran	A 216	+ 4
Baha	TA 343	+16
Baljurshi	B 003	+ 8
Barik	SA 105	-12
Belesmer	A 127	- 6
J. Fayfa	SA 110	-20
Hasan Al Habs	J 137	-20
Garn Al Bahr	SA 108	-15
Ghomeqa	J 107	+19
Hali Station	Sa 142	+11
Kiyat	SA 004	- 9
Lith	J 108	+ 2
Malaki	SA 001	+ 2
Mudayilf	J 001	-15
Muhayil	SA 113	-27
Q.B. Harith	TA 238	- 3
S. Alahad M.	SA 118	+ 7
Sereat Abid	A 207	+11
Showaq	J 120	- 5
S. Ayban	SA 140	- 7
Tarqush	SA 138	-20
Tenomah	A 211	-19
Thurayban	SA 120	+ 1
T. Thaqif	TA 228	+20
W. Turaba	TA 215	-20
W. Beysh	SA 204	+24
Zahara	A 124	- 4

TABLE 13

PHASE ANGLES OF THE FIRST HARMONIC ARE VARIED FROM THE DATES OF THE OBSERVED MAXIMUM PRECIPITATION

NAME	NUMBER	NUMBER OF MONTHS
Abha	A 001	+ 2
Abu-Arish	SA 101	+ 1
Ad Darb	SA 102	- 2
Ademah	B 217	- 1
Al-Amir	A 103	- 2
Al-Firra	A 306	- 2
Al-Gooz	SA 125	- 2
An nimas	B 002	- 1
Bani Sar	TA 219	- 2
Damad	SA 107	+ 1
Ushaylah	J 308	- 1
Hajrah	J 121	- 1
Jadiyah	SA 133	- 1
Kawsh	SA 003	- 1
Majarda	SA 122	- 1
Rejal Alma	SA 116	- 1
Th. Bani Amer	B 216	- 1
W. Fig	B 212	+ 1

the Ghat station has a variance value of 39% while in the first harmonic the station has only 14%.

The variances reduced by the second harmonic are divided into four levels, 0-15, 16-30, 31-45, and 46-60% (Figure 27). Figure 27 reveals that the area with the highest value (46-60%) dominates only one station (Showaq) which has a variance value of 49%. The second area which has variances ranging from 31-45% dominates mainly the area which is located in the middle of the Red Sea coast. The third area with values ranging from 16-30% of the variances dominates the eastern part of the Plateau and Red Sea coast and small areas in the south. The fourth area of dominance reduced by the second harmonic has a value range from 0-15%. This area extends from north to south. It dominates the foothills, the Asir Mountains, and the western part of the plateau.

Phase Angle of the Second Harmonic

The phase angle of the second harmonic represents the time of year when the maximum occurs. The second harmonic has two maxima and minima and describes any semiannual variation in the original curve. The phase angles of the second harmonic are complicated as depicted by information in Appendix 14 and Figure 28. For the purpose of discussion, the area can be divided into four regions. These regions are the Red Sea coast, foothills, Asir

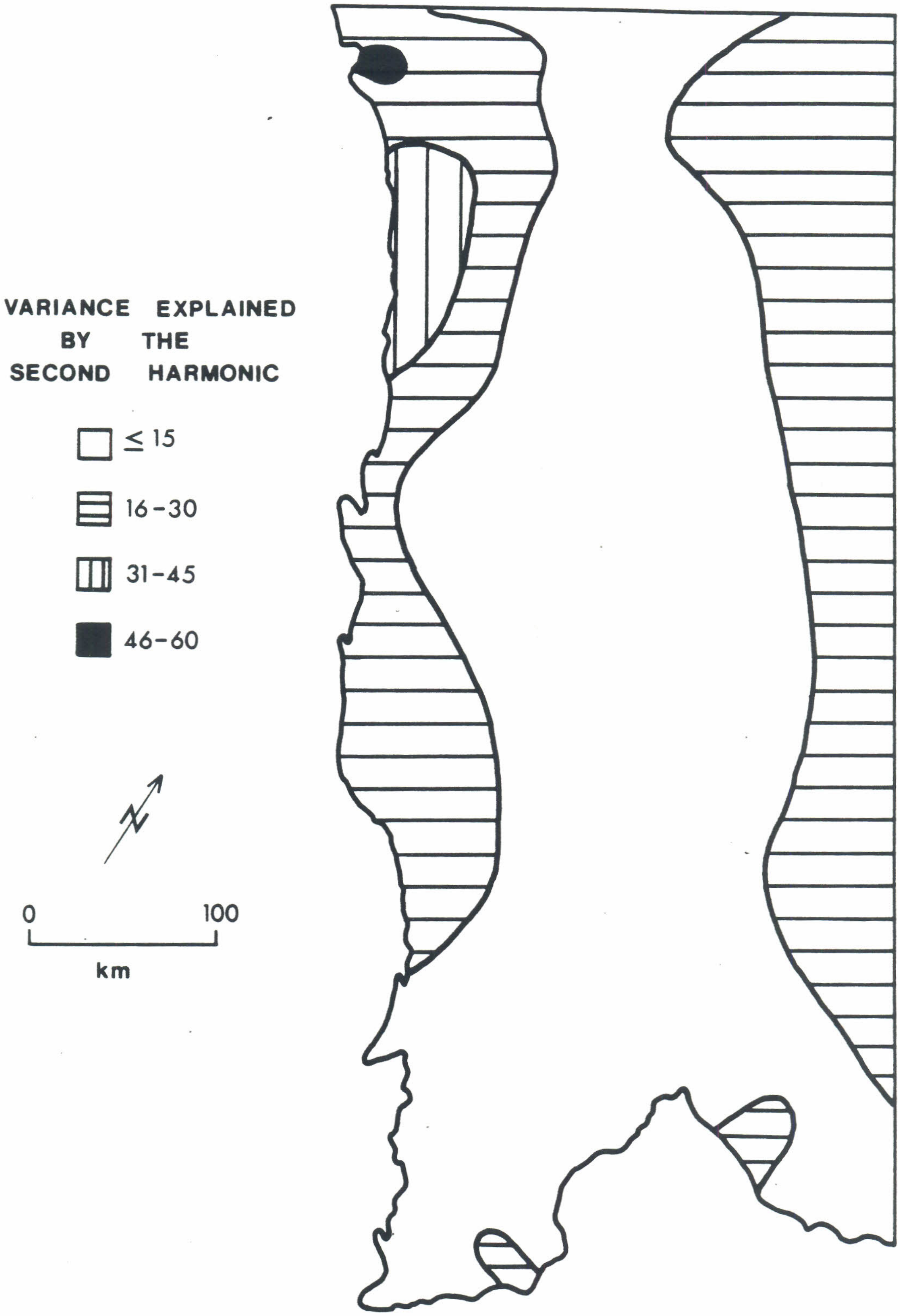


Figure 27. Variance explained by the second harmonic.

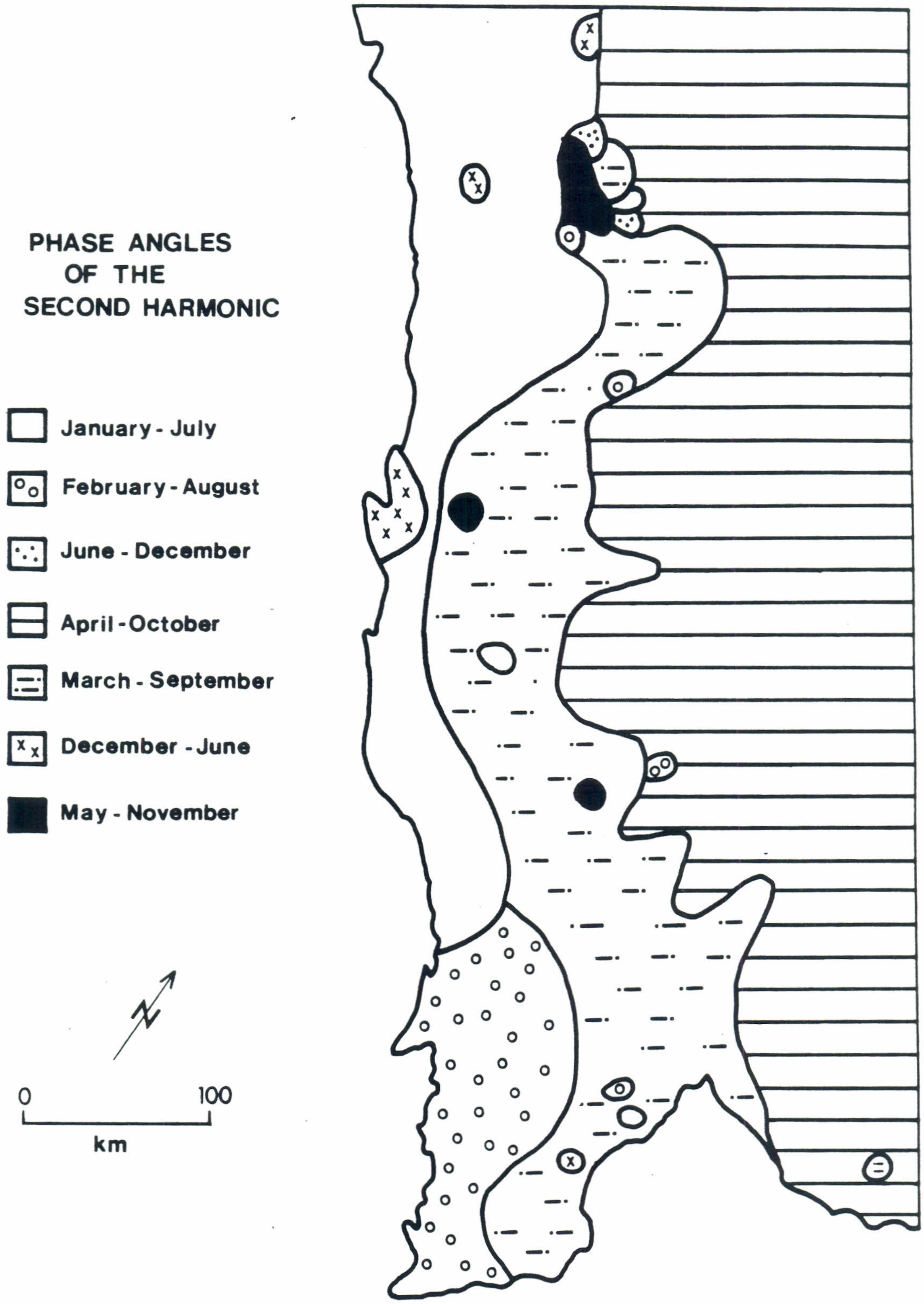


Figure 28. Phase angles of the second harmonic.