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Topographic and Seasonal Influences on Precipitation Variability in Southwest Saudi Arabia

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ABSTRACT. In southwest of Saudi Arabia, precipitation is characterized by variability in space and time. The 21 years records for sixty-three precipitation stations were examined for their relationship to elevation and geographic locations. These stations were selected for the best spatial coverage, and unique and well represent different climate conditions. The study shows that annual precipitation is moderately correlated with elevation and it does not always occur at high elevation. Topographic feature, distance from the source of moisture and seasonality are also important factors for precipitation occurrence at different location in different times within the study area. According to these factors the study area has been divided into three subregions named Tihamah, Plateau and Mountain. The study showed that it is very important to incorporate the geographical features and seasonal changes to understand the variability of precipitation with elevation due to interaction between different sources of moisture.

Introduction

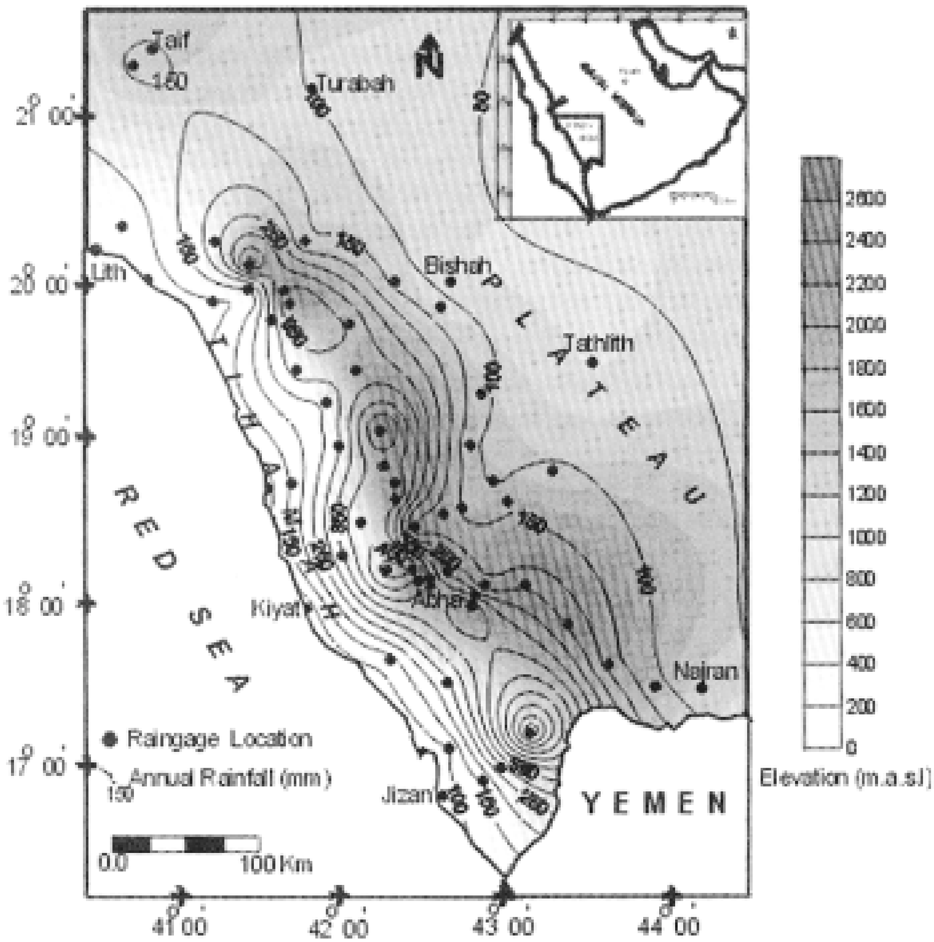
Precipitation is characterized by variability in space and time. This variability is due to the annual revolution of the earth around the sun, which produces the annual cycle in seasonal precipitation data. In addition to this external cause, there are many other factors that affect the magnitude and distribution of precipitation, such as altitude, various air mass movement, distance from the point of source moisture, temperature and pressure, and topography. The magnitude and distribution of precipitation vary from place to another and from time to time, even in small areas. Describing and predicting the precipitation variability in space and/or in time are fundamental requirements for a wide variety of human activities and water project design and budget.

In semi-arid and arid regions, precipitation has a high variation in space as well as in time. In Saudi Arabia, precipitation can be described as being little and unpredictable as well as irregular, but very extensive during local storms. The southwest region of Saudi Arabia receives the highest amount of precipitation compared with the other regions, because of its mountainous nature and location within the subtropical zone. These dry conditions make it necessary to conserve every single drop of water in Saudi Arabia. Unfortunately, for most applications, precipitation is assumed to be rather uniform, both for simplicity and because of lack of data. In many cases, accurate data are available only in locations which are typically easily accessible (Johnson and Hanson, 1995). The importance of elevation in prescribing precipitation was highlighted in various statistical approaches (Smith, 1979; Smith, 1993; Hevesi *et al.* 1992a).

The mean annual and seasonal precipitation records in the study area were adapted from reports published by Al-Jerash (1989) and the Hydrology Division, Ministry of Agriculture and Water in Saudi Arabia (1995). Sixty-three meteorological stations for the period 1971 through 1990 have been selected from all parts of the study area (Fig. 1). These stations were chosen based on four criteria: 1) they represent the best spatial coverage of the region; 2) they maximize the same monthly precipitation records; 3) that have continuous monthly precipitation; and 4) they represent all different climate conditions. The large variations of annual and seasonal bases in precipitation, recorded in Appendix A, reflect the wide variety of environments within the study area from deserts to coastal mountain range. The main purpose of this study is to understand the precipitation variability in the Southwest region of Saudi Arabia. This understanding includes the relative importance of both topographic variability and temporal variability on annual and seasonal basis.

Geographical Setting of the Southwest Region

The study area is located in the southwest region of Saudi Arabia. This area is part of the Arabian Shield that covers one-third of the Arabian Peninsula. The southwest region lies between latitudes 17º:00′N and 22º:00′N and longitude 41º:00′E and 44º:00′E, and covers an area of 140×103 km^2. This region is mostly mountainous, and receives the highest amount of precipitation in the country. In this region, the average annual precipitation can reach more than 600 mm on the mountains, and it decreases to 120 mm on the coast side to the west and to 100 mm on the leeward side to the east. The southwest region is the most important area in the country in terms of renewable water resources due to



Fɪɢ. 1. Elevation contours (m) are shaded, with overlying isohyets of mean annual precipitation (mm) in Southwest of Saudi Arabia.

rainfall-runoff-recharge events. In addition, this region is the most highly cultivated and populated region in the country.

The topography of the region can be divided into three main zones: The Red Sea coastal plain (Tihamah), the Plateau (shadow area), and the Scarp-Hijaz-Asir Mountains.

The Red Sea coastal plain (Tihamah) is a flat strip of land bounded inland by the Scarp Mountains and seaward by the shelf area. The width varies from narrow beaches in the north to more than 40 km near Jizan in the south. The western portion of Tihama is a depositional surface, principally a coralline plain, while inland towards the foothills, it consists of Tertiary sedimentary beds or crystalline rocks locally covered by Quaternary deposits of sand, gravel, and alluvium (Alsayari and Zõtl, 1978). The elevation of Tihamah varies from sea level to 200 meters above sea level (Fig. 1). The drainage system in Tihamah, which starts from the Scarp and proceeds towards the Red Sea, is characterized by steep drainage gradients (Noory, 1983 Şorman *et al.* 1991).

The Plateau is a vast peneplain sloping slightly to the east of the Scarp Mountains. It consists mainly of Precambrian basement complex rocks. The elevation of the Plateau varies between 1000 and 1800 meters (Fig. 1). The major feature of the Plateau on the eastern side of the Scarp is that the drainage networks slope towards the east and disappear beneath the desert.

The Mountain belt of Scarp-Hijaz-Asir, as a part of Arabian Shield, extends the full length of the Arabian Peninsula, parallel to the Red Sea, from the Gulf of Aqaba in the north to Bab Almandab in the south (Fig. 1). It varies in width from 40 to 140 Km. The elevation increases from 1600 to 3000 meters (Fig. 3) within the study area from Taif vicinity in the north to the Yemen border in the south. Knife-edge ridges and deep canyons characterize the Scarps. Geologically, the mountains are a composite of mainly Precambrian complex of igneous and metamorphic rocks and relatively younger Tertiary and Quaternary volcanic rocks. The drainage paths of the Scarp, which flow towards the east and west sides, are controlled mainly by a series of faults at right-angles to the Scarp Mountains (Alshanti, 1993).

Climate in the Southwest Region

The southwest region is affected by the high pressure of the subtropical zone in addition to the local topography. Both the regional and local circulation have a dominant influence on the climate of the region. According to the world climate classification as established by Koppen (Glenn, 1954), the southwest region can be divided into three main climate types: 1) the hot desert climate prevails in the Red Sea coast, 2) the low latitude semi-arid climate prevails in the

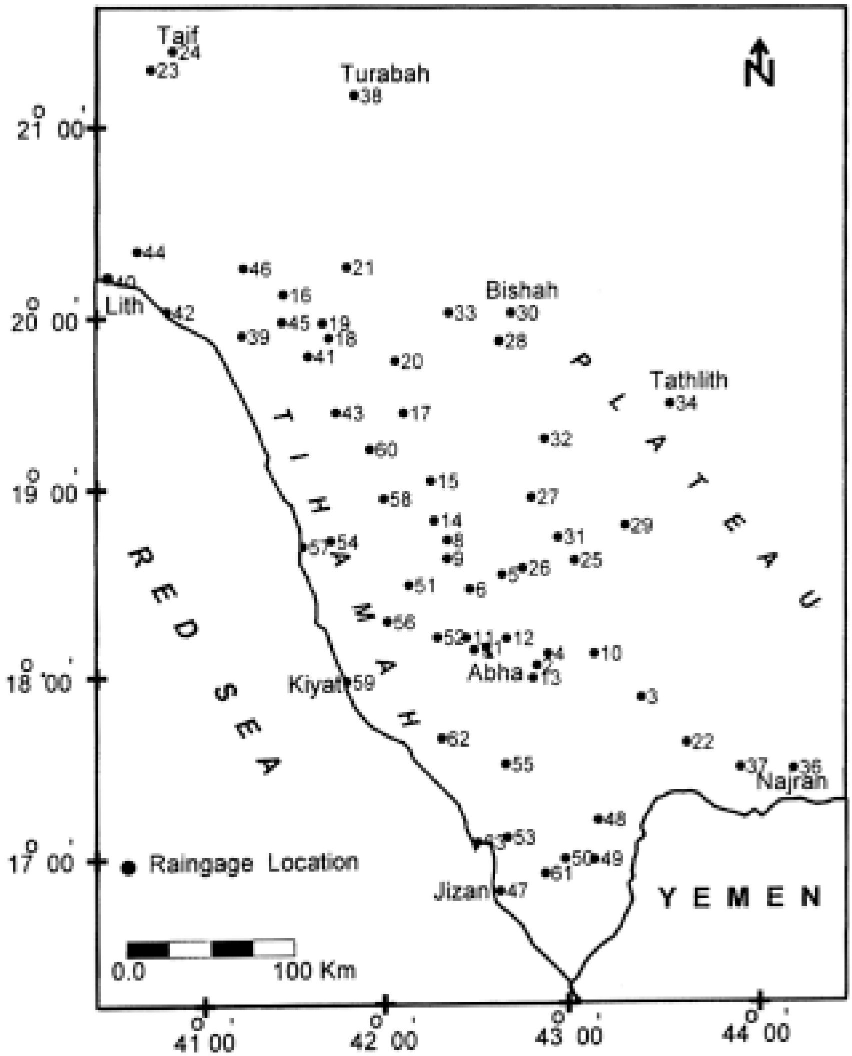


FIG. 2. Raingage locations in southwest of Saudi Arabia (see Appendix A for geographic names and locations).

Plateau, and 3) the warm temperate rainy climate with dry winters prevails in the Scarp Mountains (Taha *et al.* 1981).

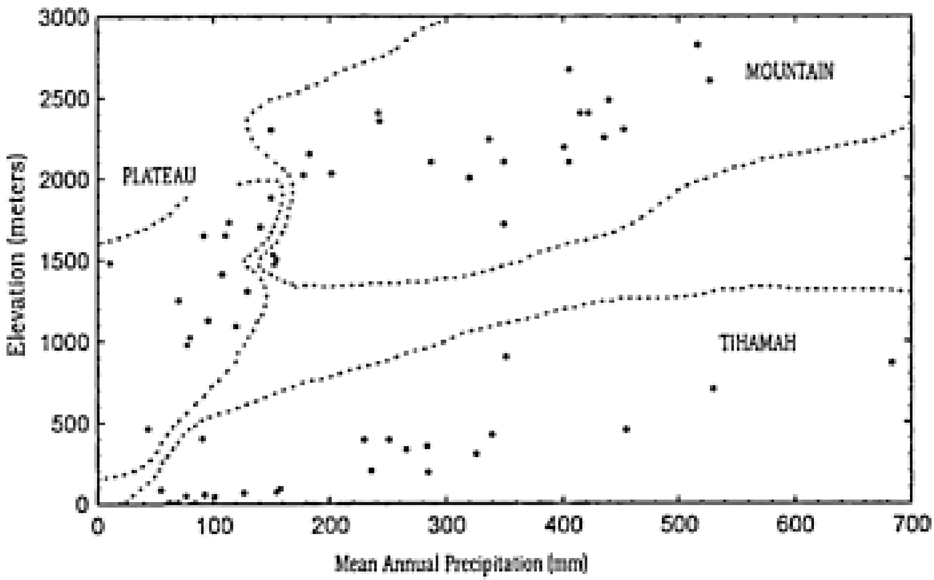


FIG. 3. Scattered plot of mean annual precipitation-elevation in the southwest of Saudi Arabia.

On the Red Sea coast, there are two basic types of climate: cool to warm and stable air originating from the Mediterranean Sea during the winter period, and warm and moist air due to monsoons coming from the Indian Ocean during summer. From the temperature records in the Red Sea coast stations, the mean monthly maximum temperature is 38ºC and the mean monthly minimum temperature is 20ºC. The highest recorded temperature in July is 49ºC and the lowest in January is 12ºC. The relative humidity varies from 55% in summer to 70% in winter.

The climate of the Plateau is generally characterized as mild with some rain in winter and spring, and hot and dry in summer and fall. The mean monthly maximum temperature is 30ºC and the mean monthly minimum temperature is 15o C. The highest temperature recorded in July is 38ºC and the lowest in January is 8ºC. The relative humidity ranges from below 20% in summer to 45% in winter.

The Scarp Mountains, which are characterized by high altitude, tend to have a lower annual range of temperature than the surrounding low areas. The mean minimum temperature is as low as 0ºC in scattered locations, especially in high peaks in winter. The mean monthly maximum temperature is 25ºC in summer. The relative humidity ranges from 35% in summer to 65% in winter.

Precipitation Mechanism in the Southwest Region

Precipitation generally occurs when an air mass rises up and cools. Besides the orographic conditions, air streams are the main centers making the moisture air rise and thus producing precipitation. As mentioned earlier, the southwest region is located under the influence of subtropical and orographic conditions. The precipitation in different seasons is due to different mechanisms.

During winter, (December-February), precipitation is associated usually with weak influxes of moist cold air of westerly Mediterranean origin which is coupled with the local effects of the Red Sea and Scarp, where the rainfall occurs orographically. During spring (March-May), the intertropical front starts to move northwards, and the region comes under the influence of a relatively moist southeasterly air stream monsoon flow and the Red Sea convergence zone, which give rise to rainfall along the leeward side of the mountains and the Red Sea coast. During summer (June-August), monsoon condition, the creation of thunderstorms along the escarpment and the southern part of the Red Sea coast, is predominant. During fall (September-November), the southeasterly air stream weakens as a result of increasing outbreaks of northwesterly air stream. This phenomenon sometimes causes a strong convergence and gives way to tropical winter conditions and widespread rainfall. Finally, rainfall occurs over the escarpment and the Red Sea coast (Şen 1983; Alehaideb, 1985; Nouh, 1987; Wheater *et al.* 1991a-b).

In general, precipitation in the southwest region occurs in every season of the year. Fall rainfall is related to local diurnal circulation, summer rainfalls to the monsoons, and winter and spring rainfalls to the African-Mediterranean interaction. The mean annual precipitation distribution map is presented in Fig. 1, showing the spatial variation of precipitation. This figure also reflects the topographic variations and shows how the annual rainfall generally increases with elevation.

Mean Annual Precipitation-Elevation Relation in the Southwest Subregions

The variation of annual precipitation with elevation was investigated in the study area. Figure 3 shows the plotting of the mean annual precipitation of the available stations versus the elevation in the study area. This figure does not illustrate clearly this relationship. Some low elevation stations receive high amounts of precipitation while some other high elevation stations receive low amounts. A linear correlation coefficient (Pearson) with a value of $r = 0.45$ for all region (Table 1), was obtained for this relationship. This moderately but significant correlation is due to the variation of precipitation for the years in the study area.

TABLE 1. Pearson correlation between annual precipitation and elevation.

Subregion	Range of elevation (m)	Number of stations	Pearson corr. coeff. (α = 0.05)	Significant
Tihama	3 - 900	25	0.86	Yes
Plateau	600 - 1880	14	0.76	Yes
Mountain	1470 - 2820	24	0.68	Yes
Whole area	3 - 2820	63	0.45	Yes

The heterogeneity of the precipitation complicates the study of this area as one region. It is preferable to divide the area into subregions in order to delineate areas which are possibly homogeneous in terms of topographic and geographic features, and analyze them on the basis of the mean annual precipitation. Hence, the southwest region of Saudi Arabia was divided into three subregions, following the topographic features named Tihama, the Plateau and the Mountain subregions (Subyani, 1997).

The Tihamah subregion, or the Red Sea coastal plain, is a flat strip of land bounded by the Scarp Mountains and the Red Sea. The elevation of precipitation stations in this area ranged from 3 to 900 meters (Fig. 3). The correlation coefficient between the mean annual precipitation and elevation is about r = 0.86. This value gives a good indication of the high association between these two variables. Some stations, however, received more than 400 mm/year even though they are located at a low elevation, such as Jabal Fayfa (860 m), Rejal Alma (700 m), and Muhayil (450 m) (Fig. 2 and Appendix A). These three stations are located in the south of Tihama and are influenced mainly by the summer monsoon precipitation. They are located directly in the foothills near the sharp edge of the Scarp, which represents another significant factor. On the other hand, the northern stations in Tihamah received less precipitation mainly in winter, and had no influence of summer monsoons.

The Plateau is a vast peneplain sloping slightly to the east of the Scarp Mountains (Fig. 1). This area is also called the shadow or leeward side of the mountains. The elevation of precipitation stations in this area ranged from 600 to 1880 meters. The correlation coefficient between annual precipitation and elevation is about r = 0.76 which is lower than what has been derived in Tihama area. However, some stations located at high elevations received a low amount of precipitation (less than 150 mm/year), such as Alyara (1880 m), Abu Jinneyah

(1650 m), Smakh (1480 m), and Bani Sar (1700 m) (Fig. 2 and Appendix A). These stations are located east of the high elevation mountains and far from the moisture sources of the Indian Ocean or the Red Sea and the Mediterranean Sea.

The Scarp Mountains extend parallel to the Red Sea with a north-south orientation. This area is characterized by knife-edge ridges and deep canyons. The elevation of precipitation stations ranged from 1470 to 2880 meters (Fig. 1). The correlation coefficient between annual precipitation and elevation gives the value of $r = 0.68$, which is not strong as compared with the Tihamah region. However, some stations are situated on the top of the mountain edge and received more than 500 mm/year, such as Alnamas (2600 m) and Sawdah (2880 m) (Fig. 2 and Appendix A). The main source of precipitation during winter and spring seasons is the Red Sea and the Mediterranean Sea. This precipitation is not as heavy as the monsoon which is more dominant in the south of the Tihama region.

Generally, in these three regions, the maximum amount of annual precipitation does not always occur at the highest elevation. This indicates that the elevation is not the only factor in precipitation distribution. Other geographic factors, such as distance from the source moisture, temperature and pressure, and topography are also important. Another main factor has been found in this analysis is the time factor (*i.e.* seasonality). Hence, the precipitation distribution is not uniform in time or in space, and it should be treated and analyzed as spatiotemporal phenomena, which will be discussed in next section.

Mean Seasonal Precipitation-Elevation Relation in the Southwest Subregions

As mentioned above, precipitation in the study area occurs with different mechanism. Winter and spring precipitation is related to the African-Mediterranean interaction, fall precipitation is related to local diurnal circulation, and summer precipitation is related to the monsoons. In addition, the topographic feature is a significant factor to divide the region into three main subregions called, Tihamah, Plateau and Mountain. So it important to detect the topographic influence on seasonal precipitation for the whole are and each subregion.

During winter, precipitation in the whole area occurs with low significant correlation with elevation (*i.e.* $r = 0.34$). That is due the Mediterranean and Red Sea local effect. Tihamah area received a moderate amount of precipitation (Appendix A). Precipitation in this area also has moderate significant correlation with elevation (Table 2) due to the convergence zone or Red Sea. This zone or streams have little chance for climbing the high mountain walls. The precipitation in the Plateau area, which lies in the shadow side and is coming under the monsoon effect has highly significant correlation with elevation ($r = 0.7$). The Mountain area precipitation has low and insignificant correlation, but some stations in the northern part of the study area with very high altitude (more than 2200 meters) received very high amount of precipitation such as Al-Namas, Buljurashi, and Tanomah as shown in Fig. 2 and Appendix A.

TABLE 2. Pearson correlation coefficients between elevation and seasonal precipitation.

Subregion / Season	Tihamah	Plateau	Mountain	Whole area
Winter	0.64	0.7	0.39*	0.34
Spring	0.82	0.58	0.6	0.77
Summer	0.8	0.8	0.5	0.15*
Fall	0.68	0.03*	0.5	0.18*

*Not significant at $\alpha = 0.05$.

During spring, the whole area precipitation occurs with highly significant correlation with elevation (r = 0.77). This is due to the monsoon and Red Sea convergence zone. The Tihamah area received a moderate amount of precipitation correlated highly significantly with elevation. The Plateau area precipitation also has significant correlation with elevation (r = 0.58). On the other side, the Mountain area, precipitation has also significant correlation with elevation (r = 0.6). This means, in general, that the precipitation in the whole area is in the form of orographic effect including the Tihamah region (r = 0.82) (Table 2).

During summer, the whole area precipitation occurs with no influence of elevation (r = 0.15). This is due to the predominancy of monsoon precipitation. However, the three subareas show highly significant correlation between summer precipitation and elevation (Table 2). This means that the heavy monsoon has more effect than that of the elevation, especially in the southern part of the study area near the Yemen boarder.

During fall, the whole area precipitation also occurs with no effect with no influence of elevation (r = 0.18). This season is a transitional period between summer monsoon and winter Mediterranean. The amount of precipitation is low as compared with the other seasons. The Tihamah area has highly significant correlation between precipitation and elevation (r = 0.68), and received high amount of precipitation as compared with the other subregions, especially in south of Tihamah due to monsoon effect. The Plateau area has no effect of elevation (r = 0.03), with very low precipitation. In the Mountain area, correlation is moderately significant (r = 0.5) where the northern part of mountain is orographic and the southern part is coming under monsoon effect (Table 2).

Conclusion

Precipitation in the southwest region of Saudi Arabia is characterized by variability in space as well as in time. There are many factors affecting the magnitude and distribution of precipitation in this area. The preliminary analysis of precipitation mechanism showed that the maximum amount of annual precipitation does not necessarily occurs at high elevation due to different sources of moisture, topography, and seasonality. However, These factors support an idea that the study area should be divided into three subregions named, Tihamah (coastal plain), Mountain (Hijaz-Asir Scarp), and Plateau (shadow area). The results showed that the study area is located under different precipitation patterns such as African-Mediterranean, Red Sea convergence zone, and monsoon. The analysis of correlation between seasonal precipitation and elevation for the whole area and subregions showed that these patterns are not completely clear for every season. In addition, further studies are needed to understand the precipitation mechanism in small scale in space as well as in time.

Acknowledgement

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Appendix A

Geographic locations, names, altitude, and mean annual precipitation of weather stations in the southwest region of Saudi Arabia

Station code	St. no.	Station name	Longitude (E)	Latitude (N)	Altitude (m)	Mean ann. pre. (mm)
A001	1	Abha	42 29 00	18 12 00	2190	401
A103	2	Al Amir	42 47 00	18 06 00	2100	350
A104	3	Alharaja	43 22 00	17 56 00	2350	243
A213	4	Almala	42 50 00	18 10 00	2030	202
A107	5	Almowyn	42 34 00	18 36 00	2150	183
A108	6	Altajer	42 23 00	18 31 00	2300	150
A210	7	Ash Shaaf	42 25 00	18 11 00	2670	405
A127	8	Beleasmar	42 15 00	18 47 00	2250	436
A206	9	Ibalah	42 15 00	18 41 00	2480	440
A207	10	Sarat Abidah	43 06 00	18 10 00	2400	242
A118	11	Sawdah	42 22 00	18 15 00	2820	517
A006	12	Sir Lasan	42 36 00	18 15 00	2100	287
A121	13	Tamniyah	42 45 00	18 02 00	2300	453
A120	14	Tanomah	42 10 00	18 53 00	2100	405
B002	15	Al Namas	42 09 00	19 06 00	2600	527
B001	16	Al Mandaq	41 17 00	20 06 00	2400	415
B216	17	Bani Amer	41 59 00	19 28 00	2000	320
B003	18	Buljurashi	41 33 00	19 52 00	2400	422
B212	19	Wadi Fig	41 31 00	19 57 00	2240	337
B217	20	Adimah	41 56 00	19 45 00	1715	350
B220	21	Al Aqiq	41 39 00	20 15 00	1470	153
N103	22	Zah. Aljanob	43 38 00	17 41 00	2020	178
TA002	23	Hema Saysad	40 30 00	21 18 00	1500	155

Appendix A. (Continued).

Station code	St. no.	Station name	Longitude (E)	Latitude (N)	Altitude (m)	Mean ann. pre. (mm)
TA001	24	Taif	40 37 00	21 24 00	1530	152
A110	25	Alyara	42 59 00	18 41 00	1880	150
A113	26	Bani Sar	42 41 00	18 38 00	1700	141
B208	27	Abu Jinneyah	42 44 00	19 01 00	1650	111
B005	28	Alhaifa	42 32 00	19 52 00	1090	120
B209	29	Almadha	43 16 00	18 52 00	1410	108
B004	30	Bishah	42 36 00	20 01 00	1020	80
B110	31	Khaybor	42 53 00	18 48 00	1650	92
B219	32	Smakh	42 48 00	19 20 00	1480	111
B114	33	Tubalah	42 14 00	20 01 00	1305	130
B113	34	Tathlith	43 31 00	19 32 00	975	78
SU001	35	Alselayel	45 34 00	20 28 00	600	44
N001	36	Najran	44 14 00	17 33 00	1250	71
N308	37	Bir Askar	43 56 00	17 33 00	1730	114
TA005	38	Turabah	41 40 00	21 11 00	1126	96
J001	39	Mudaylif	41 03 00	19 52 00	53	93
J108	40	Lith	40 17 00	20 09 00	6	63
J126	41	Makhwa	41 26 00	19 46 00	330	266
J120	42	Showaq	40 37 00	19 59 00	46	77
J131	43	Fajah	41 36 00	19 28 00	300	326
J107	44	Ghomeqa	40 27 00	20 19 00	84	55
J124	45	Guiloua	41 17 00	19 57 00	400	91
J121	46	Hajrah	41 03 00	20 14 00	390	230
M405	47	Jizan	42 35 00	16 52 00	3	85
SA110	48	Jabal Fayfa	43 08 00	17 16 00	860	684
SA111	49	Jabal Sala	43 07 00	17 03 00	900	352
SA001	50	Malaki	42 57 00	17 03 00	190	285
SA113	51	Muhayil	42 02 00	18 32 00	450	455
SA116	52	Rejal Alma	42 12 00	18 15 00	700	530
SA002	53	Sabya	42 37 00	17 10 00	40	101
SA142	54	Hali Station	41 35 00	18 46 00	90	158
SA204	55	W. Beysh	42 36 00	17 34 00	200	236
SA108	56	Karn Albahr	41 55 00	18 20 00	420	340
SA004	57	Kiyat	41 24 00	18 44 00	30	78
SA003	58	Kwash	41 53 00	19 00 00	350	284
SA115	59	Qamah	41 40 00	18 00 00	20	63
SA121	60	Suq Thaluth	41 48 00	19 16 00	390	251
SA101	61	Abu Arish	42 50 00	16 58 00	69	155
SA102	62	Ad Darb	42 14 00	17 42 00	65	127
SA125	63	Algooz	42 27 00	17 08 00	5	70

تأثير التغير الفصلي والطبوغرافي على هطول الأمطار في جنوب غرب المملكة العربية السعودية

علي بن محمد الصبياني

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المستخلص . يتميز هطول الأمطار على الجزء الجنوبي الغربي من المملكة العربية السعودية بتغير في قيمته في بعدي الزمان والمكان . وهناك عدة عوامل تؤثر على كمية وتوزيع الأمطار في هذه المنطقة ، منها مثلاً طبوغرافية المنطقة وبعد الموقع عن مصادر السحب واختلاف مصادر السحب بين البحر الأبيض المتوسط والبحر الأحمر والمحيط الهندي بالإضافة إلى اختلاف المواسم . وقد اختيرت ثلاث وستون محطة لقياس الأمطار ولمدة إحدى وعشرون سنة (١٩٧١م-١٩٩٠م) بحيث تعطي هذه المحطات أفضل توزيع مكاني يغطي منطقة الدراسة وذات تمثيل زمني جيد نظراً لاختلاف المواسم .

وبتطبيق الفرضية القائلة بأن كمية الأمطار تتناسب طردياً مع الارتفاع ، فقد لوحظ أن هذه العلاقة لم تكن واضحة مع معدل الأمطار السنوي باعتماد المقياس الإحصائي للارتباط (بيرسون) ، ولذلك تم تقسيم المنطقة إلى ثلاثة أجزاء حسب بيئتها الجغرافية وهي المنطقة الساحلية (تهامة) والمنطقة الجبلية (جبال الحجاز - عسير) ومنطقة الظل شرق المنطقة الجبلية (الهضبة) وتم دراسة كمية الأمطار في كل موسم وعلاقتها بالارتفاع في كل منطقة على حدة .

وقد أوضحت الدراسة أن هذه المناطق الثلاث تستقبل كميات مختلفة من الأمطار في مواسم ومواقع مختلفة . واستنتجت الدراسة أن المنطقة بشكل عام تقع تحت عوامل مطرية مختلفة مثل أمطار البحر الأبيض المتوسط والأمطار الموسمية من المحيط الهندي والتأثير المحلي للبحر الأحمر .