SYNOPTIC ORIGIN OF PRECIPITATION IN IRAN

By

Bohloul Alijani

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ABSTRACT

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By Bohloul Alijani

This research was undertaken to investigate the spatial and seasonal variations of precipitation mechanisms in Iran. For the period 1965 to 1969, uplift mechanisms associated with precipitation events at 40 different stations across Iran were determined from 12GMT surface and 500mb synoptic maps of the Northern Hemisphere. Importance of the uplift mechanisms was judged on the basis of their contribution to the number of each station's annual or seasonal precipitation days. Westerly disturbances, including both upper level and surface disturbances, were the most important uplift mechanism over the entire country throughout the year; their contribution to annual precipitation days was higher in the South and the Northeast but decreased to the north and northwest. Sea-effect was observed only on the southwest coast of the Caspian Sea in fall and early winter. The contribution by surface heating was low. Based on the patterns of contribution by westerly disturbances to annual precipitation days, the country was divided into six different regions. Representative stations of these regions were then used to analyze the

seasonal importance of the identified mechanisms as well as the moisture sources of the precipitation. Seasonally, upper level disturbances were the most frequent and important uplift mechanism during the transition seasons but were co-dominant with surface disturbances in winter, whereas summer was the season of greatest contribution by surface heating.

Important moisture sources of the country were determined for days with 10mm or more precipitation at the representative stations through the use of both surface and 700mb maps of the period July 1967 through December 1969. Although moisture from the Caspian Sea appeared to contribute the highest percentage to precipitation totals, moisture from the Mediterranean Sea affected a larger portion of the country. Persian Gulf moisture contributed the highest percentage of warm period precipitation days in the relatively dry South; the southeastern part of the country received most of its summer moisture from the Bay of Bengal.

To my wife Robab, who shared with me the difficulties
and gave me encouragement, and
to my children, Vajiheh and Taha.

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PREFACE

This research was undertaken in partial response to personal feelings I had toward my country, Iran. As a student of physical geography with particular interest in climatology, I had long wished to study aspects of the Iranian physical environment which had not been considered by others. Indeed, this goal was a major reason that led me to study abroad. After having been exposed to some physical geography courses at Michigan State University and becoming familiar with the literature about Iran, I realized that climatological studies of the country were mostly descriptive rather than explanatory in nature. As a geographer, I organized my program to permit me to better understand and explain the spatial pattern of weather elements in Iran, and elsewhere. Since the explanation of surface weather conditions is not possible without first understanding upper-level flow processes, I was particularly interested in the relationship between the surface weather patterns and upper level flow conditions, the field of "synoptic climatology".

In preparing this thesis I have tried my best to review the relevant literature and gather appropriate data, and I hope the product represents a contribution to the precipitation climatology of Iran. Its preparation by a writer whose primary language is not English may result in occasional ambiguity, and the author apologizes for any awkwardness or error in the style and structure of the text.

This thesis should be considered as only a preliminary work about the precipitation climatology of Iran which may be used as starting point for future research.

Bohloul Alijani
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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued. . .)

TABLE OF CONTENTS (Continued . . .)

LIST OF TABLES

LIST OF TABLES (Continued . . .)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED. . .)

Page

CHAPTER I

INTRODUCTION

The location of Iran between 25°N, and 39°N. latitudes places it under the climatic controls of both tropical and extratropical latitudes. During winter the cold Siberian anticyclone expands over the country while during the summer season the shallow heat low centered over west Pakistan and southern Iran is a dominant surface circulation feature. Another control of the climate of Iran is the shift of the mean position of the subtropical jet stream in the upper troposphere. In summer the region of its speed maximum shifts northward over Turkey (1). Since the subtropical jet stream is associated with subsidence to its south, Iran is affected by midtropospheric subsidence in summer (about 700mb above the surface heat low (2)). On the other hand, the westerly polar vortex and its accompanying cyclonic activity expand during winter, bringing the southern branch of the polar front jet stream over Iran. This occurs in association with heightened baroclinity. The regional climate, furthermore, is complicated by the configuration of the surface terrain. In the western and northern portions of the country the higher mountains add to the severity of winters and block the moisture flux to the interior parts of the country.

All of these variations in the circulation, as modified by the configuration of the terrain, bring different kinds of air masses to the country. For example, in winter continental polar air masses invade Iran from the north while modified Mediterranean air masses bring moisture-laden air from the west. In summer, continental tropical air originates over the country itself. As a result of these diverse climatic controls, Iran harbors a surprisingly complex climate.

According to the Koppen classification, Mediterranean climate is found in the north, northwest, and western highlands. Hot desert climates are found in the central areas east of the Zagros Mountains and in the coastal strip of the southern water bodies; the remaining areas are steppe climates. Based on the aridity index, Dehsara (3) classified the country into three broad regions of forest, steppe, and desert. The forest region covers the coastal areas of the Caspian Sea and northern parts of the Zagros Mountains. The steppe regions cover all the mountainous areas, while deserts cover the lowlands. Martonne (4) considers the southeasternmost part of the country to have a monsoon climate.

Regardless of the scheme, classifications convey the diversity of the climate of Iran. For example, mean annual precipitation ranges from very high values in Anzali on the southwest coast of the Caspian Sea to values below 50mm in the central deserts. In general, precipitation decreases from north to south and from west to east. Most of the country experiences a winter maximum while the Caspian coast is characterized by a fall maximum. A spring maximum exists on the sunny slopes of the northwestern highlands. Summer is the driest period over most of the country except in the coastal regions of the Caspian Sea. Ganji (5) was one of the first to recognize this diversity and divided the country into six precipitation provinces based mostly on mean annual precipitation and its degree of seasonality. Using the same subjective methods, Adl (6) organized the precipitation patterns into several subdivisions based on only the range of annual precipitation.

Why is there so much diversity in the Iranian precipitation pattern? What factors other than those discussed above generate this diversity? Since the occurrence of precipitation depends upon the coexistence of a lifting mechanism and moist air (7, 8, 9, 10), the explanation for this diversity lies in variations of both these components.

Uplift can be generated by several mechanisms (10, 11), yet all of them can be classified under two categories--dynamic and thermodynamic. Dynamic mechanisms include upper level divergence, surface cyclones, and surface convergence induced by terrain irregularities such as rough surfaces and mountain ranges. Among these mechanisms, upper level divergence produced by vorticity advection in the westerlies is by far the most important mechanism (12); indeed, surface cyclones are generated by this vorticity principle (13). Regions of positive vorticity advection exist to the east of upper level short-wave westerly troughs. Because of compensation, these

regions generate surface convergence and hence, ascending air (7). Within surface cyclones the areas of most important uplift are located along the frontal zones. At the warm front, the warm air glides over the cold air because of surface wind convergence and contrasting air mass densities. At the cold front the cold air subsides and undercuts the warm air forcing it to rise (7). Accordingly, frontal zones are often associated with the heaviest precipitation. In addition, another dynamic factor causing uplift is surface convergence created by such terrain irregularities as mountain ranges. For example, when an air stream approaches the Zagros Mountains from the west it is forced to ascend (14), resulting in condensation and possibly in precipitation at some point. Browning and Harroid (15) observed that such orographic uplift is an enhancing factor for already-existing precipitation areas; this effect usually occurs at more than 1000m above the mountain base, where uplift begins (16, 17, 18, 19).

Thermodynamic processes are induced directly or indirectly by vertical temperature differentiation in the atmosphere. Such processes as the warming of cold air by warm water surfaces, cold air advection, and extensive surface heating are included because they all lead to instability (20). Heating by an underlying water surface occurs when very cold air passes over a warm water body. In this process the air gains heat and moisture from the water and it may become destabilized. Cold advection occurs when cold air behind a surface cold front advances more rapidly in the lower troposphere than at the surface, leading to an increased lapse rate that maximizes beneath upper cold lows and short wave trough axes. Extensive surface heating, though not uncommon in the mid-latitudes, is most important as a destabilizing factor in equatorial lands (21). It is also a common uplift mechanism in hot coastal regions where moist air is brought in by sea breezes (21, 22, 23). In the mid-latitudes, intense surface heating may be a rain-inducing mechanism on the sunny slopes of the high mountains (24).

It is obvious that some, if not all, of these uplift mechanisms operate in Iran. Unfortunately, few studies have been published regarding the origin of precipitation in the country. Some references are available in general textbooks which relate most of the Iranian cold season precipitation to surface and upper level disturbances originating in the Mediterranean Sea region (25, 26). The fall precipitation maximum of the Caspian Sea (27), the spring maximum of the western highlands, and the summer precipitation over the entire country have been regarded (probably erroneously) as convectional in origin (5).

As mentioned earlier, availability of moist air is another important variable in the generation of precipitation (20, 24). Like the uplift mechanisms, moisture advection over Iran has been studied only in the context of regional or global patterns. According to Tuller (28), the amount of precipitable water is very high in the south and decreases northward. Bannon (29), in studying the moisture flux of the Northern

Hemisphere, found that the moisture flux is from the west to the east in the Middle East. Except for these general studies, no detailed research regarding the moisture patterns of the country is known to the author.

According to the literature presented here, it appears that no comprehensive study has been done regarding either uplift mechanisms or moist air as they contribute to Iranian precipitation patterns, in spite of their importance. Therefore, this study is undertaken to determine the spatial distribution of uplift mechanisms over Iran and to identify more precisely their contribution to overall precipitation. Also, an attempt is made to determine the major contributing moisture sources of the country.

The specific aims of the study are:

1) to determine the uplifting mechanisms operating over Iran,
2) to study the seasonal and spatial variations of these mechanisms,
3) to regionalize the country on the basis of dominant uplifting mechanisms,
4) to determine the most frequent and significant mechanism for the country and for each region on an annual and seasonal basis,
5) to study the moisture sources and trajectories contributing to regional precipitation, and

6) to study the triggering mechanisms, moisture sources, and relative contribution of heavy storms to regional precipitation.

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CHAPTER II

LITERATURE REVIEW

Introduction

Precipitation is produced when moist air and a lifting mechanism co-occur. The process of uplifting and the availability of moist air are governed by circulation both at the surface and aloft. Many surface pressure systems are generated and guided by atmospheric disturbances imbedded in the upper level flow; however, thermally-induced convectional lifting may develop independent from upper circulation. Day-to-day changes of the upper level flow pattern cause variations in the surface pressure pattern which, in turn, influence the distribution of such weather elements as precipitation.

Considerable spatial and temporal variation of precipitation exists in Iran. For example, the coastal areas of the Caspian Sea receive the most rain, with heaviest precipitation occurring in the fall. The southern parts of Iran, however, are almost rainless except for scattered and sporadic winter precipitation. In an area so large and topographically diverse, several mechanisms may operate on moist air derived from several possible sources. In the following sections I will summarize the factors involved in the generation of precipitation generally and then will review literature specifically concerned with the synoptic precipitation climatology of Iran.

Causes of Precipitation

The question of the origin of precipitation occupied meteorologists and climatologists beginning in earliest times and explanations varied widely. In his theory of rain formation presented in 1788, Hutton (1) stated that when moist air masses with different temperatures mix, supersaturation will occur resulting in condensation or rain. This theory stood as the primary explanation for the origin of rain for nearly a century and was supported by other studies (2). At the same time, Velschow (3) proposed that rain is produced by the descent of moist air, which removes the moisture through compression. This idea was rejected by Hazen because areas of atmospheric subsidence usually experience fair weather and clear skies. By the end of the nineteenth century Hutton's theory was abandoned when it became obvious through advances in the field that the amount of water which could be condensed in this way was too small. The process of air mass mixture may bring the temperature of warm air to the saturation point and produce fog, but the process will not produce significant amounts of rain. It was later understood that ascent of air would lead to adiabatic cooling which would then produce condensation in amounts adequate for precipitation. The necessary rate of ascent was determined to be 30 feet per minute for steady rain at fronts and up to one or two thousand feet per minute for heavy rains or thunderstorms (1).

Shaw (4) described a stable atmosphere as having successive layers of air which preserve their distinctive characteristics. He said that three physical processes could disturb this stability and could cause displacement: eddy motion caused from frictional or viscous forces, well organized air flow across the isobars resulting in upward motion in cyclones and descending motion in anticyclones, and thermal convection caused from surface heating.

A most significant contribution to the subject came from the Norwegian school through the development of frontal theory. The central theme of this theory was that the atmosphere consists of extensive bodies of fairly homogeneous air masses, separated by gently sloping frontal surfaces (5). According to this theory, wave cyclones develop when two contrasting air masses approach each other and wavey movements begin along the zone of contrast due to frictional forces. Within these cyclones the warm air glides over the cold air at the warm front, while at the cold front the cold air undercuts the warm air. At both regions upward motion occurs. In acknowledging the role of frontal uplift, V. Bjerknes (6) classified rainfall types as being orographic, frontal, and convectional. Following the same idea, Bjerknes and Solberg (7) classified the origin of rainfall over Norway as being caused by orographic uplift, instability, cyclonic uplift, warm front and cold front, or low level cooling. Douglas (8), on the

other hand, classified rain formation into two broad categories of dynamic ascent caused by wind shear of frontal zones, and thermodynamic ascent produced either by surface heating or by the passage of cold air over a warm surface.

Bjerknes and Solberg (7) defined orographic precipitation as that produced by air ascending a mountain slope when there is no cyclonic or instability precipitation in the vicinity. At other times such uplift may enhance the already existing precipitation (9, 10, 11). Druyan (11), Eliot and Shaffer (12) all concluded that orographic rain will be greater with the ascent of unstable air than with the ascent of stable air. Stable air tends to pass around the mountain (7) and, if forced to rise, will yield less precipitation or none at all.

Several studies have correlated precipitation with elevation. For example, Chuan and Luckwood (13) found a very high correlation between mean altitude and rainfall in the east Pennine region. Similar results were obtained by Schermerhorn (14). Lamb, et al. (15), in a study of the liquid content of orographic clouds for six storms over the Sierra Nevada, found that the highest values of precipitable water existed on the windward slope of the mountain. The strong buoyant region started from the height of 1000 meters (see also 7, 10). The high instability on the west side was thought to be caused by differential advection. Duckstein, et al. (16) attributed greater mean rainfall with greater elevation to an increase in the number of mountain slope showers and to the amount of precipitation per storm. In a study of orographic water balance for the Santa Ynez and Gabril ranges, California, Elliot and Hovind (17) found that orographic ascent could account for about 25 percent of the condensed water, an estimate increased for larger barriers. However, since atmospheric instability is very low in winter, small scale uplift (areas with 100km. in dimension or smaller) occurs only when the air is forced to ascend the mountain slope. Thus the mountains are more important when stability is greater, such as during the winter or at night, and when other lifting triggers operate (13).

Types of precipitation other than orographic are produced in the free atmosphere by surface convergence and resulting uplift. Bjerknes and Solberg (7) showed that these convergence regions are usually linear. In cyclones these regions are associated along lines of wind and temperature discontinuity, i.e., frontal surfaces (see also 18). Numerous studies have been done concerning the structure, mechanism, and efficiency of frontal or cyclonic precipitation (7, 9, 19, 20, 21, 22, 23). Bjerknes and Solberg (7) concluded that warm frontal precipitation results from the gliding of warm air over a gentle slope of cold air in a broad zone of 150 to 400 miles ahead of the surface front. Cold-front rain is produced when the cold air undercuts the warm air and uplifts it. Atkinson (22) found several types of large mesoscale precipitation areas within the warm frontal rain area, including linear cells, which originated in synoptic scale uplift. According to Browning and Harrold (21), cold front precipitation occupies a narrower area and results from a two phase convectional ascent. This includes near-vertical ascent up to 3km. over the front and then further ascent through a shallow slope up to 6km. behind the surface front. In studying the efficiency of the dynamics of cyclones in releasing atmospheric moisture, Robinson and Lutz (23) found that at the cold front the areal distribution of precipitation is narrow but its efficiency is very high. At the warm front, however, the areal distribution is broad and its efficiency is lower.

Browning and Harrold (9) found that the warm sector precipitation of cyclones was mostly affected by the instability of warm air and was organized as linear bands parallel to the warm sector wind flow. The instability showers grew more vigorous if the air being lifted contained abundant moisture. Curtis and Panofsky (24) found that in the presence of sufficient moisture no type of large scale vertical motion was related particularly well to daytime precipitation, since showers and thunderstorms can be produced by surface heating alone.

Nocturnal showers, on the other hand, showed significant correlation with large scale vertical motion. The nocturnal atmosphere is often more stable, and organized uplift is more necessary to promote precipitation. Oliver and Shaw (25) concluded that warm sector precipitation is highly related to the moisture content and instability of the air.

Instability showers are also common features of coastal regions as well as sunny mountain slopes. According to Bjerknes and Solberg (7), moist sea air invades coastal regions on hot summer days and with low level heating it rises and produces instability showers. Wexler (26) stated that sea breezes in mid-latitudes extend inland 30 to 40km. He also described the best condition for sea-breeze development as being hot, calm sunny days preferably with an off-shore flow. Flower (27) studied the sea breezes at Ismailia, Egypt, and concluded that they developed from a diurnal change of pressure and temperature and then moved overland as true cold fronts. In a study of the structure of these breezes, Simpson, et al.,(28) showed that the humidity of the air is higher at lower levels near the front and decreases toward the higher levels over the front due to high mixing rate at this level. The vertical velocity is highest near the leading edge of the sea breeze. Byers and Harriet (29) found that when there is no significant large scale vertical motion the convergence of two sea breeze fronts from the opposite sides of a peninsula stimulates surface convergence and hence thunderstorms. The same result was found by Harman and Hehr (30) for the eastern Upper Peninsula of Michigan.

Low-level heating may also lead to precipitation during the advection of cold air over a warm surface. For example, Bjerknes and Solberg (7) found that behind surface cold fronts heating from below occurs when polar air invades the relatively

warmer southern latitudes. Furthermore, if moisture is adequate in the cold air, instability showers develop. They found that the intensity of these cold advection showers depends on the moisture of the cold air. According to Stromman (31), when cold polar air passes over the warm surface of Lake Michigan it gains heat and moisture. By the time it reaches the lee shore it becomes unstable and may yield rain or snow showers. Druyan (11) found that when this air is not sufficiently unstable to produce showers on the coastal regions it may yield precipitation when it ascends mountain slopes near the coast. Douglas and Glasspool (10) concluded that over England the instability showers caused by surface heating (air mass showers) are important in summer and those of cold air advection are dominant in fall and winter. According to Harrold (20), squall-line precipitation is a good example of instability showers resulting from a cooling of the air column from above. However, in many instability showers the prime triggering factor of vertical motion is the large-scale uplift caused by the vorticity principle (22, 32, 33), and the vertical instability of air enhances the vertical motion or causes small scale variations (34).

The vorticity principle was not well understood until just prior to World War II; important uplifting mechanisms previously were thought to be orographic, low-level convergence or upslope motions at frontal boundaries, and instability due to surface heating. After World War II, research at the

University of Chicago opened a new era in the field of synoptic meteorology. In one paper, surface weather patterns were related to the wind flow pattern in the mid to upper troposphere (35). In interpreting these principles, Harmon qualitatively described the connection between vorticity and associated vertical motion. Positive vorticity advection (upper level divergence) in the westerlies occurs where the upper level air streams undergo a vorticity decrease east of a trough line or the lee side of upper cold lows and cut-off lows. Less often this advection occurs under trough axes themselves and in the left exit of a jet stream maximum. The inflection point, the location where curvature vorticity changes sign, often lies near the center of the uplift region.

Several studies have related precipitation patterns to the upper flow pattern. Klein (37) presented a quantitative relationship between 700mb circulation patterns and surface precipitation at Knoxville, Tennessee. He studied the intensity of 5 day mean rainfall for each 5 degree longitude behind and ahead of trough and ridge lines. His computations showed that the heaviest rainfall occurred under southwesterly flow, i.e.,where positive vorticity advection and resulting vertical motion were the highest. This same relationship was described by O'Conner (38). Jenrette (32) showed that positive vorticity advection is associated with surface convergence and with decreasing atmospheric stability, resulting in high vertical motion.

As mentioned before, according to Harman (36), ascending motion is concentrated beneath the left exit region of the jet maxima. Starrett (39) studied the precipitation patterns in relation to jet maxima within 10 degrees latitude to the north and south of the quasi-linear jet axis. He found that the area of maximum precipitation occurs within a few degrees north of the jet axis. Others such as Johnson and Daniels (40) and Richter and Dahl (41) have done similar studies. In addition, Smith and Younkin (42) developed a forecasting model for jet streams associated with upper troughs. They found the precipitation maximum located in the area about 2.5 degrees longitude to the right side of the jet axis having a mean width of 3 degrees latitude and a length of 12 degrees longitude.

As a result of these and other studies, it has been established that by far the most important uplifting process in the baroclinic westerlies is associated with the vorticity principle. This relationship has become a tool for forecasting precipitation (43). However, this does not overshadow either the importance of the moisture content of the air mass or the degree of its stability in precipitation prediction. In addition, Oliver and Shaw (25) found that these variables played an important role in determining surface rainfall patterns.

With the development of a more thorough theoretical background in synoptic climatology (44), meteorologists and climatologists have attempted to classify precipitation according to the causative synoptic weather types (44, 45, 46, 47, 48, 49, 50, 66). In England and Wales, for instance, Lawrence (47) studied the rainfall averages for 27 surface flow categories such as cyclonic and anticyclonic. In a study of areal correlation of surface precipitation with upper level cold lows, Klein, et al., (51) found that the optimum precipitation occurs 2 degrees east of 850mb lows in the region of southwesterly flow, 3 degrees southeast of 700mb low, and 5 to 6 degrees east of 500mb and 300mb lows. The least amount of precipitation was observed to the northeast and west of the low centers. As a whole, the 850mb lows accounted for much of the precipitation. Williams, et al., (52) found that precipitation events associated with upper level low centers, those with at least one closed contour line, yielded heavier precipitation than those associated only with surface features such as frontal systems. They classified those associated with surface features according to whether the trigger was warm frontal, cold frontal, or attributed to other factors such as air mass showers, or occlusion. They observed that the cold frontal storms yielded the highest amount of precipitation among the classes. Others have studied precipitation types in relation to very specific synoptic situations (19, 53, 54, 55, 56, 57, 58, 59).

Precipitation Studies In Iran

Very little has been written about the origin of precipitation in Iran. Yet some references are available in general climatic textbooks. Trewartha (67) attributes the precipitation of the country to three synoptic origins. According to him, most of the cold-period rainfall over the country is caused by Mediterranean cyclones. He also noted that Siberian cold air becomes moist and unstable through passage over the Caspian Sea, resulting in "sea effect" precipitation on the lee shore. In the southeastern part of the country moist monsoon air provides moisture for summer season convectional rainfall.

Few synoptic studies have been done in Iran regarding the origin of precipitation. Gangi (65) classified the rain events over Iran according to whether the primary mechanism was cyclonic, convectional, or orographic. According to him, almost all of the cold period rain is of cyclonic origin whereas the summer rain is of convectional origin. The western highlands receive their maximum rainfall in spring because of convectional processes, while in the Caspian area northeasterly winds from central Asia cross the Caspian Sea to yield the fall rainfall maximum during orographic ascent on the lee shoreline. Recently, Khalili (64) related the origin of precipitation in the Caspian area to instability resulting from thermodynamic processes. These thermodynamic processes are produced by the passage of Siberian Polar air over the warm sea surface during the cold season. In describing the climate of Kerman, Becket and Gordon (60) stated that, apart from very rare monsoon rain, most of the rain in the area is caused by

Mediterranean disturbances. In summer southwesterly or southerly winds bring moist air from the Persian Gulf and permit convectional precipitation to develop over the area. To the author's knowledge, the first general explanatory study of rainfall dynamics in Iran was completed by Weickman (61). He concluded that the precipitation mechanisms affecting Tehran are similar to those over much of the rest of the country. The main control of precipitation over Tehran was found to be divergence associated with different wave types in the middle and upper atmosphere.

When studying an abnormal wet spell with flooding in Iran during July 1956, Ramaswamy (62) investigated the dynamic and physical interactions between middle and low latitude weather systems. During the wet spell, the monsoon air was deflected over Iran as far as the Caspian Sea coastal area because of a westward displacement of the Tibetan high. At the same time an upper level trough developed in the mid latitude westerlies over the Caspian Sea. As a result, the moist monsoon air was uplifted by upper level divergence yielding torrential rains over the area. Further to the west the physical interaction of warm, wet monsoon air with cool, continental air from the northwest caused frontal uplift aiding the intensity of the interaction of mid and low latitude atmospheric features. Except for this abnormal occurrence the author concluded that the moisture source for precipitation in Iran is normally provided by southwesterly and westerly winds from either the Mediterranean Sea or the Persian Gulf.

The effect of cyclonic uplift in Iran has been observed in areas as far south as the Persian Gulf. For example, Murray and Coulthard (63) attributed heavy thunderstorms in Sharjah to the instability associated with cyclonic circulation on the surface which was the result of an upper level trough over the area.

Most of these studies, however, have been concerned with restricted problems or areas, and no comprehensive study regarding the dynamics and moisture source of precipitation over Iran has been done. A study of the genetic climatology of precipitation in a comprehensive approach for the whole country is needed.

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CHAPTER III

PHYSICAL SETTING

Iran's physical geography has made it a region of diverse and complex climate (1). At least three factors cause this diversity. First, its latitudinal position brings it under the influence of both tropical and extra-tropical controls during the course of the year. Second, its location between Siberia and central Asia to the north, the Sahara and Arabia to the southwest, the Mediterranean Sea to the west, and the Indian region to the east makes it possible for weather from a variety of source areas to affect the country. The proximity of the country to these source areas results in little modification of the air masses before they reach it. Third, the location, configuration, and altitude of topographic features affect both the surface circulation and local climate elements such as temperature and precipitation. In this section I will describe some of the important topographic features of the country and then summarize other general controls of the climate of Iran.

Topography

Much of Iran is a plateau with high mountain belts forming its borders. These mountain belts consist of high continuous ranges on the North and West, but are made of broken, isolated ranges in the Northeast, East, and Southeast. The area enclosed by these belts is largely salty desert. Both the northern and western ranges converge in the northwest portion of the country and join in the extensive highlands of Turkey (Fig. 1).

The northern belt includes the west-east trending highlands of Azarbaijan, the north-south range near the west coast of the Caspian Sea, and the main Elburz Mountains. The mean elevation of the northern mountain belt is more than 2500m in Azarbaijan but increases to above 3000m in Elburz. To the southeast of the Caspian Sea the elevation drops to 900-1500m in the lowlands between the Elburz and the northeastern highlands. The northeastern highlands consist of parallel northeast-southwest ranges with lowlands between them.

The western belt runs southward parallel to the border between Iran and Turkey where it attains elevation above 2750m. To the south its elevation decreases to about 1500m in the lowlands between the northwestern highlands to the north and the main Zagros Mountains to the south. The Zagros Mountains run southeastward to a point north of Bandar Abbas and consist of several parallel ranges together more than 200km wide and 1000km long, attaining heights above 4500m (2). The Zagros Mountains separate the interior deserts from the Mesopotamian lowlands in the north and from the coastal areas of the Persian Gulf in the south. To the east of Bandar

FIGURE 1. Locational Map Of Iran With Selected Stations

Abbas, the mountain ranges attain relatively lower elevations and more closely approach the coast. Just to the east of and parallel with the Zagros lie a series of broken mountains with elevations of more than 2750m separating such fertile basins as the Esfahan from the deserts of central Iran. In contrast to the North and West where the mountains are very high, the eastern portion of the country consists of isolated upland massifs with elevations not exceeding 3000m.

The mountain ranges are very important to the climate of Iran. The Elburz Mountains block the influx of moisture from the Caspian Sea to the interior of the country just as the Zagros Mountains block the eastward movement of moist air from the Mediterranean Sea. As a result, regions to the north of the Elburz Mountains and the western slopes of the Zagros Mountains have a moist mild climate, while the interior is desert. On the other hand, the northeastern lowlands allow cold, dry Siberian air to enter the country, producing local temperatures below $0^{\circ}C$. The mountains exercise their influence very significantly during early spring when the relatively cold atmosphere warms in the lower layers because of increasing isolation on the mountain slopes. Therefore, in the presence of moist air, convectional mountain showers develop (3). This is clearly seen in the April maximum of Sanandaj (Fig.2).

Climate

Figure 2 shows the annual march of temperature and precipitation for selected stations. The country experiences

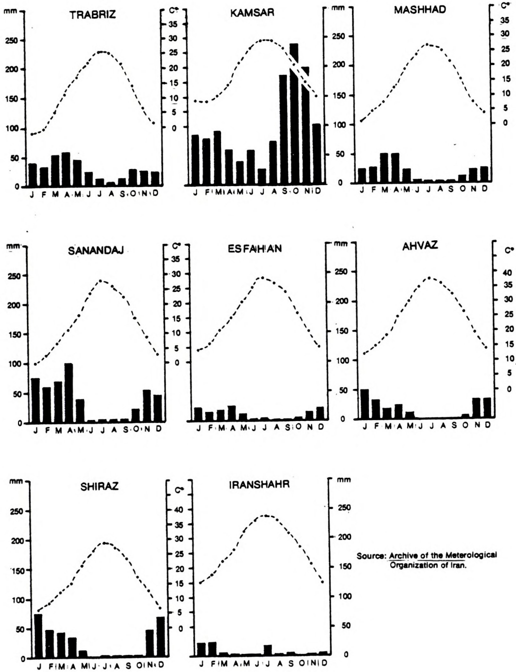

FIGURE 2. Mean Monthly Precipitation (in millimeter) and Temperature (in centigrad) at Selected Stations.

cold winters in the highlands and warm summers in the lowlands, particularly in the South. The highest mean monthly temperature ranges from 25°C. in such northern stations as Tabriz to as high as 39°C. at Iranshahr. In winter most of the highland stations record sub zero temperatures, as at Tabriz, while those with low elevation experience milder weather. Except in the narrow coastal regions, January is the coldest and July is the warmest month; in the coastal regions the influence of the water bodies postpones the coldest and warmest months to February and August, respectively.

In general, almost all of the country experiences a winter precipitation maximum, with little or no rain in summer. More than two thirds of the country receives more than 50% of its annual precipitation during winter (2). This percentage decreases with an increase in latitude and altitude, and the amount of precipitation decreases from northwest to southeast (Fig. 2). Most stations show only one winter precipitation maximum, whereas Ramsar on the Caspian Sea shows both a fall maximum and a secondary one in winter; Iranshahr, in the southeast, receives significant rain in July. The wettest part of the country throughout the year is the coastal region of the Caspian Sea. Even in winter, the wettest season, half of the country receives less than 10cm; two thirds of it receives less than 20cm annual precipitation. Therefore, most of the country falls under the desert or steppe climates and only the Caspian Sea region and western slopes of the Zagros Mountains

experience a kind of modified Mediterranean climate.

Within Iran the transitional seasons of spring and fall are short and winter and summer dominate. In most of the stations the transition period from summer to winter is sharper than is the transition from winter to summer (Fig. 2). Later in this section it will be shown that, even in terms of circulation patterns, spring and fall are not distinct seasons. Thus, I will review the circulation patterns for only winter and summer.

Winter

During winter the westerly vortex of the Northern Hemisphere expands, pushing the subtropical jet stream (STJ) southward over the Persian Gulf to about 29^{o} to 30^{o}N, at the 200mb level (13). At this time the maximum winds are over the Arabian peninsula, frequently placing Iran in the left exit region where uplifting may be common (5). At the same time, in the baroclinic westerlies, a deep mean trough develops over the eastern Mediterranean Sea, producing a mid-tropospheric southwesterly flow over Iran. As a result, the speed maxima and short wave troughs characteristic of the polar front jet streams pass over Iran to bring Mediterranean cyclones to the country (4).

On the surface, the very intense thermal anticyclone of central Asia (hereafter referred to as the Siberian anticyclone) develops from the extreme cooling of that large continent (6). This anticyclone extends over Iran and is indeed the dominant weather control over the country.

Because it is a cold system, it is confined mostly to the lower troposphere and drives very dry and cold polar air from Siberia into Iran, resulting in clear skies and light winds with very cold nights; daytime temperatures are relatively compensated by high solar radiation receipts. As this air moves south and southwestward it is modified by the terrain and gains sensible heat. When it descends the southwestern slopes of the Zagros Mountains, particularly, it is heated adiabatically and produces moderate temperatures over the region. Its main access to the interior of Iran is through the lowlands of the Northeast and it is accompanied by northerly or northeasterly winds over the country.

As was mentioned before, this air mass is very dry and produces very little, if any, precipitation except when it passes over a considerably warmer water body, gaining both heat and moisture in the lower layers. This modification occurs over the Caspian Sea in late fall or early winter when the water is much warmer than the overlying polar air, which crosses the Caspian Sea and is destabilized by the acquisition of heat and moisture. By the time it reaches the southwest coast of the Caspian Sea it is relatively moist and highly unstable, causing the fall rainfall maximum of this region.

Even though the Siberian anticyclone is a thermally-generated low level feature, its intensity, strength, and exact location are affected by upper level circulation patterns. For example, the superposition of upper level divergence over the anticyclone reduces it to several weak cells, and the westward movement of the Mediterranean cyclones forces it to retreat (7).

The Mediterranean cyclones begin invading Iran in late fall and continue until the end of spring, travelling toward Iran in two main tracks (4). The northern track crosses both the very northwestern part of the country and adjacent coastal areas of the Caspian Sea. Cyclones following this track appear in late fall and may be another reason for the fall rainfall maximum of the Caspian Sea region. The other track passes through the Kermanshah lowlands and north of the Persian Gulf. By January, cyclones affect all of the country. They yield maximum precipitation west of the Zagros Mountains and carry little rain eastward to the interior of the country (Fig. 2, Esfahan). Besides the Mediterranean cyclones, others develop inside Iran to the lee of the southern Zagros Mountains (4). These cyclones are shallow and develop in late winter when the polar front jet stream crosses over the Persian Gulf; the moisture source accessible to these cyclones is the Persian Gulf and adjoining parts of the Indian Ocean.

The Mediterranean cyclones bring modified air masses of both tropical and continental origin to Iran. The tropical air mass originates over north Africa and gains moisture when passing over the Mediterranean Sea or the Red Sea. Still, its moisture content is low and it may be associated with dust

storms over Arabia and occasionally over Iran. This air mass usually lacks the leading warm front at the surface. Often while passing over the Persian Gulf it gains moisture and thus brings hot and moist air to southern Iran (8). The most widespread air mass over Iran is the continental air mass which follows the cold fronts associated with Mediterranean cyclones (9). Many of these air masses originate over the Atlantic Ocean and release their moisture while crossing west Europe, but may acquire some additional moisture when passing over the Mediterranean Sea or Black Sea. These air masses enter Iran from the northwest and produce almost all of the cold-period precipitation. At first they have a distinct cold front, but as they move east or southeastward they become warmer and lose their initial characteristics so that when they reach southeastern Iran they are hardly distinguishable, and the associated cold front is seldom recognized (9).

The transition from the winter to summer circulation pattern takes place so sharply (13) that spring is very short and only April could be designated as a spring month, based on temperature (2). Spring is conspicuous, mainly in highland regions of the Zagros Mountains where a spring maximum in rainfall (Figure 2) can be recognized (Sanandaj). By May the summer pattern is established all over the country.

Summer

During summer the subtropical jet stream has moved northward over the Caspian Sea, placing Iran under the anticyclonic region to the south of the jet stream. Because of subsidence, the subtropical high pressure center develops, prohibiting major uplifting in the warm period of the year (10). This subsidence creates an inversion layer over Iran which in some places (such as the south) may be as low as 1000 feet above mean.sea level (9). The lower troposphere warms because of high solar radiation and a shallow surface low develops over west Pakistan and north of the Persian Gulf. At the same time a high pressure center develops over the Caspian Sea due to its colder temperatures. As a result, surface winds blow from the north or northwest toward the low center. One of these famous winds is the "120 Days" wind of Sistan which starts around May 21 and lasts for about four months. This particular wind is best developed in the eastern and southeastern parts of the country. To the west of the Zagros Mountains the winds flow toward the low center over the Persian Gulf and are channeled by the Iraq lowlands, locally they are called "Shamal" (northerly) winds (11). Sometimes these winds are interrupted by the southwesterly winds blowing toward the low center from Arabia. Through passage over the Persian Gulf, these winds from Arabia gain moisture and bring hot moist air to the Iranian coastal area, producing uncomfortable summer weather. These winds are thus called "Simum" (poison) (19). Although the moisture content of the air is high and surface temperatures are adequate to support some convection, instability is shallow because of the low level inversion and seldom results in significant rain.

In general, during summer Iran is under the dry, hot continental tropical air mass which originates over the country itself. The aridity is widespread at this time except in the coastal areas of the Caspian Sea. The coastal areas are not completely under the subsidence, and consequently, occasional mid-latitude disturbances invade the area to produce precipitation. Thus, even in summer, this area is the wettest part of the country.

Besides the continental tropical air mass originating over the country itself, remnant monsoon air masses may affect portions of eastern and southeastern Iran. Through its circulation, surface low pressure located over southern Iran deflects the Southwest monsoon away from the Iranian coasts toward the west coast of India. This shallow, moist air circles the low center through the Indian peninsula, and by the time it reaches Iran from the east it has released its moisture over India and is a relatively dry air mass resulting in little rain. Even when this air is exceptionally moist, it will seldom produce rain because of the inversion layer aloft; only if a disturbance destroys the inversion will convectional systems develop and produce significant precipitation. The July precipitation of Iranshahr (Fig. 2) may be attributed to moisture brought by the monsoon air mass.

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CHAPTER 4

METHODS

Data Sources

As discussed in the preceding chapter, precipitation in Iran is variable both spatially and temporally. The objective of this study is to determine the origin of this precipitation in terms of both uplift mechanisms and moisture sources. To accomplish this objective, daily total precipitation records were obtained for forty stations for the period 1965-1969 from the Meteorological Organization of Iran; 1969 was the latest year used because it is the most recent year for which the synoptic weather charts were available. Since similar studies (1,2) have been carried out for five-year periods in other regions, this duration of record was thought to be adequate for this study as well. Also, the number of selected stations was limited by their availability from the Meteorological Organization of Iran. For the stations of Khoy, Kashan, and Bandar Lengeh, only four years of precipitation data were available, but since each day in this study is an observation, the one-year difference between samples is acceptable. All the selected stations are listed in Appendix 1 with their geographic coordinates, elevation, and mean annual surface pressure. The location of these stations is depicted in Figure 1.

Daily 12GMT (15:30 in Tehran) surface and 500mb synoptic maps of the Northern Hemisphere were obtained on microfilms for analysis from the National Climatic Center (3). Missing 500mb-level microfilm data for the period November 1967-December 1969 were replaced with data obtained from 12GMT 500mb synoptic charts available on microfilm from the Michigan Weather Service; the 700mb synoptic charts for moisture study were also obtained there. Both of these synoptic charts were published by the National Climatic Center.

Precipitation Mechanisms

For the purpose of this study any day with total precipitation of 0.1 millimeter or more was considered one precipitation day and included in the analysis. This low threshold was chosen because the initial objective was to determine the uplift mechanism of any precipitation regardless of the strength of that mechanism. Although more than one mechanism might combine to produce a precipitation day, only the mechanism detectable on the 12GMT synoptic maps was regarded as responsible for the day's total precipitation.

The mechanisms were classified according to the following scheme:

1) Upper level disturbances. This type included upper level short wave troughs embedded in the westerlies. Klein (4) demonstrated the relationship between these short wave troughs and the distribution of surface precipitation very well.

Precipitation days included in this type were those on which the station under consideration was located in one of the following situations:

a. Beneath the region of positive vorticity advection (upper level divergence). This region was defined in this study as the area between the trough axis and the next downstream ridge axis (5). The region of upper level divergence produces uplifting and surface convergence through atmospheric continuity (6).

b. Under an upper topospheric trough axis (4). In this case the uplifting is triggered mostly by the advection of cold air aloft which destabilizes the lower atmosphere.

c. Beneath upper cold lows, which most of the time combine the effects of both a and b above. Upper cold lows were defined as those having at least one closed contour line at the 500mb level. A precipitation day was considered in this category if the station under consideration was under a small, cold low and was difficult to classify into either category a or b.

2) Surface disturbances. This type included all eastward-moving surface cyclones regardless of their surface fronts, because most of the time these fronts are drawn subjectively. Any precipitation day was classified into this type if the station under consideration was located in one of the following situations:

a. Within an estimated 100 miles on either side of the surface cold front. At the cold front the cold air lifts the warm air, resulting in precipitation along a narrow strip (7, 8).

b. At or within about 400 miles ahead of the surface warm front. Here the warm air overruns the cold air, resulting in extensive precipitation over a broad area ahead of the surface front (7, 9, 10).

c. Days in which it was difficult to determine the precise frontal trigger were classified in a general cyclonic group.

d. Frontless cyclones. These were the cyclones surrounded by rather homogeneous air in which no fronts were recognized but were still associated with precipitation. Since surface disturbances are generated and guided by features of upper level circulation (5), this category could be combined with the first into one type. Nonetheless, the separation was maintained because, first, upper level disturbances may or may not stimulate surface cyclones, and second, I was interested in determining the contribution of surface disturbances regardless of their upper level support.

3) Sea effect. This mechanism occurs when very cold air crosses a warm water body. In this process, the air gains heat and moisture, and by the time it reaches the lee coast it is destabilized, thus leading to uplift. In this study, the conditions necessary for a precipitation event to be placed in this category were as follows:

a. The surface wind flow must cross over the water before reaching the station (the direction of the surface wind was estimated to be about 30^{o} to the right of the surface isobars (11).

b. Air temperature on the lee shore should be at least 15^{o}F. higher than the windward shore, evidence of modification from an overwater trajectory (sea temperatures were not available).

c. No other uplift mechanism should be apparent. Because sea effect does co-occur with other triggers on occasion, this last criterion probably led to an underestimation of its contribution near the Caspian Sea coast.

4) Surface heating. This type of uplift occurs when the air in the lower layers of the atmosphere has been heated from below to such a degree that autoconvection* develops. Those precipitation days were considered in this category when no other kind of uplift was evident and the temperature of the station or its surrounding area was either equal to or more than 80^{o}F., an arbitrary threshold. Only those days on which no other mechanism was apparent were placed in this category and, as in the case of sea effect, the days in this group are probably underrepresented, for this reason, since instability from air mass heating often assists other uplife mechanisms. Because the temperatures above 80^{o}F most often occur during very hot

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*When the lapse rate is more than 3.43C. per one hundred meters, the air parcel rises without any upper level trigger; this is called "autoconvection" (12).

summer days, all summer precipitation days with no other lifting trigger were included in this type.

5) Indeterminable. All precipitation days not falling into one of the above-mentioned types were considered indeterminable.

Orographic effects were not regarded as a separate uplift mechanism here because the micro-environments of the stations were not clearly known; most of the highland stations were located in valley bottoms or flat areas surrounded by mountain ranges; and above all, orographic effects are often enhancing and are seldom an independent lifting mechanism (10).

Procedure of Map Analysis

Pre-constructed tables were used to record the mechanism responsible for each precipitation day. Also, the date and the amount of precipitation of each day were recorded in these tables (Appendix 2). To determine the mechanism of each day on the maps, the following steps were taken in this order:

1) The 500mb maps were inspected to see whether the station under consideration was affected by any category of upper level disturbances. If so, the day was placed in this category.

2) The surface maps were then examined for the existence of surface disturbances, regardless of the existence of upper level disturbances. To determine whether the station fell within the pre-set range of frontal boundaries, the distance

between the front and station under consideration was estimated on the map by using the scale of the map.

3) If the event was still unclassified (in the absence of any kind of disturbance) and the station was coastal, the station was examined for sea effect.

4) Days in which none of the above mechanisms were evident and days with temperature above 80°F were classified into the surface heating type.

5) In the absence of all the above mechanisms the precipitation day of the station was considered indeterminable.

For each type the mean annual number of precipitation days falling into that type was computed and divided by the mean number of all precipitation days of the respective station. This ratio was then multiplied by 100 to get the percentage of annual contribution of a specific mechanism to the station's annual mean total of precipitation days. Because of the sequence of steps followed in the analysis, days in which a number of mechanisms co-occurred were automatically placed in the first appropriate category. Thus, days of multiple causation were placed in the upper level or surface disturbance category, a procedure that introduced some bias into the results but which was justified nevertheless because it was impossible to determine the relative influence of each mechanism during such situations from the data available. Also, this procedure was useful because days ultimately placed in the surface heating category included only those in which

other mechanisms had been discounted, providing an accurate assessment of the role of unassisted convection.

Regionalization

In order to regionalize the country on the basis of uplift mechanisms, Ward's method of hierarchical clustering analysis was adopted (13,14). In this method, clustering was based on the total sum of squared deviations of percentage contribution of each mechanism from the mean of the clustered stations. In other words, at each step only those individuals or clusters would be combined if their fusion resulted in the least increase of the total sum of squared deviations of percentage contribution. Ward named this term the "Error of Sum of Square" (ESS) which is computed from the equation:

$$ESS = \frac{\sum_{i=1}^{n} (D_i X)^2}{n} \qquad (1)$$

where D is the deviation of the value of an individual in cluster i from the cluster mean (X), and n is the number of members of cluster i. For cases with more than one variable this formula is repeated for each variable and the results are summed together. Since this study included five variables (mechanisms), standardized scores. (Z-scores) were computed from:

$$Z = \frac{X-\overline{X}}{Sd} \qquad (2)$$

where X is the value of each observation for each variable, $\overline{X}$ is the mean of observations for the same variable, and Sd is the standard deviation.

By applying Ward's method the maximum similarity between climatic stations was computed through the use of the computer software program CLUSTAN, written for use on Michigan State University's Cuber 750 computer. The input data were the Z-score values of the five variables for all stations. The variables were the percentage contribution to the mean annual precipitation days by upper level disturbances only; surface disturbances, with or without upper level support; surface heating; upper level and surface disturbances combined (westerly disturbances); and sea effect.

The output from program CLUSTAN included the within-cluster dissimilarity coefficients; the lower the coefficient the lower the total within-cluster ESS. The final clusters were determined on the basis of these coefficients.

Because of reasons described in the next chapter, the region-groups resulting from the multi-variable analysis were rejected and the classification procedure proceeded on the basis of a single variable, the predominant (most frequent) uplift mechanism which was determined according to the percentage contribution of each mechanism to the station's annual precipitation days. In this procedure regionalization was attempted through the use of the Z-scores of this one variable

for the stations. First, the spatial distribution and clustering of the single-variable Z-scores were observed on the map. Regional boundaries were then constructed using interpolated isolines selected to provide the greatest contrast between regions. The greatest contrast was defined as maximum slope on the surface. The resultant regions were tested by an Analysis of Variance test for their distinctiveness from each other (15) by using the following equation:

$$F = \frac{\text{Between-Group Mean Square of the Predominant Mechanism's Contribution}}{\text{Within-Group Mean Square of the Predominant Mechanism's Contribution}}$$

To study the regional and seasonal distribution of the precipitation mechanisms, one representative station was selected from each region using the following criteria. First, the percentage contribution of the most frequent mechanism to the annual precipitation days at the station had to be the highest in the region; and second, the station was located, as much as possible, in the geographic center of the region. Finally, based on the percentage contribution of the mechanisms, the regional and seasonal predominant mechanisms were determined. In addition, each year was divided into four seasons: winter (January-March), spring (April-June), summer (July-September), fall (October-December).

Importance of the Precipitation Mechanisms

The importance of the mechanisms was defined as their percentage contribution to the annual or seasonal precipitation total of the station. The higher the contribution, the more important the mechanism was assumed to be. The importance of the mechanisms was determined through the selection and analysis of representative stations within the regions. At each such station, the mean annual or seasonal precipitation which occurred during the days of each mechanism was totaled and then divided by the station's annual precipitation. By multiplying this ratio by 100, the percentage contribution of each mechanism was computed.

Moisture Sources

In the presence of atmospheric uplift mechanisms, the intensity of precipitation depends on the amount of available atmospheric moisture (16). The role of moisture in determining precipitation yield from various triggers is particularly important in an area such as Iran which is located far from larger bodies of water. The second objective of this study, after a determination of the precipitation mechanisms, was to identify the moisture sources and advective trajectories and their contribution to the country's precipitation. This objective involved analyzing all precipitation days with ten or more millimeters of precipitation at representative stations on 12 GMT surface and 700mb weather charts for the period July 1967-December 1969.

More than half of the atmospheric moisture exists below 850mb (17, 18), but since Iran is a plateau country, the mean surface pressure of most of the stations is about 850mb

(Appendix 1). Thus, the surface and 850mb level can be assumed to be roughly the same except in the narrow coastal areas. Therefore, most of the moisture flux must occur at levels about 850mb. For this reason the 700mb level, the next lowest available level, was selected in this study in agreement with other studies (19). In some situations, precipitation can be produced when a trigger acts on moist air left by a previous weather event. Because such precipitation is usually light, in this study only days with 10 millimeters or more were chosen to increase the likelihood that the precipitation was associated with a distinct influx of moisture. Since the 700mb weather charts were available for July 1967-December 1969, the moisture analysis was limited to this period at both the surface and the 700mb level.

Determining the Moisture Sources and Trajectories

On the surface maps the moisture trajectories and sources were determined according to the surface wind flow. In estimating trajectories, the mean surface wind direction was assumed to be about 35^{o} from the mean sea-level isobars (11). To further support the final decision, the surface dew point temperature gradient was checked to see whether the area of higher dew point temperatures was located upwind from the station. The moisture source was assumed to be the closest body of water in the upwind direction. In this study the term "water body" is applied only to water bodies not smaller than the Persian Gulf.

On the 700mb maps the moisture trajectory was assumed to be parallel to the height contours because at this level the wind flows generally parallel to the contour lines. The moisture trajectory of the station under consideration was determined as being parallel to the contour lines passing through station, and its source, as on the surface, was assumed to be the closest body of water in the upwind direction over which the contour lines pass.

The moisture source of the station for each study day was determined by combining the surface and 700mb level results. If the moisture sources indicated on the surface and 700mb on a given day were different, a combined category was recognized. If the source of one level was indeterminable, however, the source indicated at the other level was assumed to be the most important. Based on these computations, the moisture trajectories were constructed and shown on the maps. The moisture sources were classified on the basis of the precipitation days with identical sources both at the surface and 700mb level, and the days with combined sources were used as a supplementary aid. The sources with highest percentage of contribution were designated as the primary source and the sources with lower contribution were secondary. For example, a station having 20% of days with moisture influx from the Mediterranean Sea, 25% of days from the Persian Gulf, and 30% of days from both the Red Sea and the Persian Gulf was determined as having a primary source from the Persian Gulf and a secondary source from the Mediterranean Sea.

Because of a lack of adequate data, the magnitude of moisture influx was not measured, so the significance of the moisture sources was determined according to the areal average of the mean annual precipitation of the regions; the areal average was calculated by summing the annual mean precipitation of all stations and dividing by the number of stations included in the region. The areal averages of all regions were then added to yield the total of all the regional means, which was then used to calculate the percentage contribution of each region to the total of all the regions by the formula:

$$\frac{\text{Mean of each region}}{\text{Total of all means}} \times 100$$

The grand total of all regional means was assumed to be a measure of the total national precipitation provided by all regions. Therefore, a region with higher percentage contribution to the total provides a higher percentage of the country's total precipitation. Therefore, it can be assumed that the primary source of a region with higher contribution to the national total precipitation is more significant than the moisture source of the region with lower contribution to the national total precipitation. Based on this conclusion the relative importance of the moisture sources to the country's precipitation was qualititatively evaluated.

Heavy Storms

The heaviest ten per cent of precipitation days studied for moisture analysis were arbitrarily regarded as days with

heavy storms. For these days the uplift mechanisms and moisture sources were analyzed to indicate the dominant synoptic features associated with these heavy storms over Iran.

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CHAPTER V

RESULTS

Introduction

As was mentioned previously, the occurrence of precipitation depends upon the presence of an uplift mechanism and the availability of moist air. The uplift mechanisms affecting Iran recognized in this study included upper level disturbances,* surface disturbances, surface heating, and sea effect. Since daily 12 GMT weather maps were available for data analysis, each precipitation day at each station was attributed to at least one precipitation-forming mechanism. The first section of this chapter is devoted to a description of the spatial distribution of precipitation days over Iran. This is done to summarize the distribution of the precipitation days, and because the contribution of each mechanism was computed from these data.

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*The category "upper level disturbances" always designates upper level disturbances without any surface disturbance, unless otherwise specified.

However, since the main purpose of this study was to analyze the synoptic origin of the precipitation over the country and to determine its moisture sources, the other sections of this chapter presents 1) the percentage contribution of each type of uplift mechanism, 2) the regions derived from these frequency contributions, 3) seasonal distribution of uplift mechanisms within each region, 4) the efficiency of the uplift mechanisms in terms of their percentage contribution to the regions precipitation amounts, 5) the moisture source of each region, and 6) the synoptic conditions associated with the very heavy precipitation days within each region.

Annual Precipitation Days

The number of annual precipitation days for each station was averaged for the study period (Figure 3). This map provides a picture of the spatial distribution of all precipitation forming mechanisms over the country. The number was the highest on the coastal regions of the Caspian Sea, where the mean annual number was 133 days in Anzali but decreased to 101 days at Gorgan on the east coast. Outside the Caspian region the only comparable area was the Northwest, which is represented by Khoy with 101 days per annum. To the south, the number of precipitation days diminished but still remained above 80 days per year in the northwest and in the western slope of the northern Zagros Mountains.

The Zagros Mountains and the northeastern sections of the country, including the intervening foothills of the

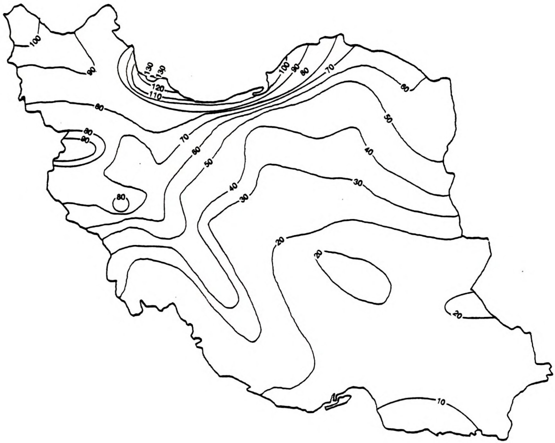

FIGURE 3. Mean annual precipitation days (1965-69)

SOURCE: Iranian Meteorological Organization

Elburz Mountains, all receive about the same range of annual precipitation days, varying from 38 days in Birjand to 65 days in Tehran. This portion of the country separates the highland regions to the north and west from the lowlying interior deserts. The deserts experienced fewer than 20 precipitation days annually; however, precipitation days increased again to the south (Figure 3).

In general, as is seen in this map, the annual number of precipitation days (precipitation mechanisms) decreased from north to south. A decreasing trend existed also in a west-to-east direction but with a lesser gradient, and it is marked by two outstanding patterns: the Caspian Sea showed an area of very high values, whereas, in the South, the central deserts developed a trough of relatively lower values.

Precipitation Mechanisms

Introduction

As was mentioned in the previous section, each precipitation day was regarded as the result of one precipitation mechanism depicted on the 12GMT surface and 500mb weather maps. The percentage of the mean annual precipitation days at each station, caused by each type, is shown in Figures 4, 5, 6 and 7. Upper level disturbances caused the highest percentage of annual precipitation days, followed by surface disturbances (Table 1). The sea effect was observed only in the coastal stations of the Caspian Sea (Figure 7). The percentage contribution by upper level disturbances showed the least degree of

Mechanisms	Contribution %	Coefficient of variation %
Upper level disturbances	55	15
Surface disturbances	18.5	28
Surface heating	7.5	68
Sea effect*	13	
Indeterminable	14	

*Only for Anzali and Ramsar

TABLE 1. Percentage contribution by mechanisms to mean annual precipitation days, averaged for all selected stations (1965-69).

spatial variation, while contribution by surface heating displayed the highest degree of spatial fluctuation (Table 1).

Upper Level Disturbances

This category included all upper level disturbances without any surface features. Eighty-one percent of upper level disturbances consisted of cases with upper level divergence (positive vorticity advection), whereas troughs aloft contributed 17% of the disturbances (Table 2). Uplift caused by upper cold lows was numerically least important. All three components of the upper level disturbance category decreased from north to south and from winter to summer. An important result is the complete absence of upper cold lows at Bandar Abbas and Iranshahr and their absence at all other stations in the second half of the year. Upper level divergence and trough axes aloft were most common in winter, whereas spring produced more upper cold lows, especially at Ramsar, which had the highest annual number of cold lows and total incidents of upper level divergence among all stations.

The annual contribution of upper level disturbances at each station was averaged for the study period. According to Figure 4, the percentage contribution of upper level disturbances decreased from south to north. For instance, in the south-central portions of the county, more than 80% of the precipitation days were caused by upper level disturbances, whereas in the southwest corner of the Caspian Sea this value fell below 40%. The maximum contribution was located in the

Station	Winter			Spring			Summer			Fall			Annual		
	Positive vorticity advection	Trough axis aloft	Upper cold lows	Positive vorticity advection	Trough axis aloft	Upper cold lows	Positive vorticity advection	Trough axis aloft	Upper cold lows	Positive vorticity advection	Trough axis aloft	Upper cold lows	Positive vorticity advection	Trough axis aloft	Upper cold lows
Iranshah	26	7		5	2					3			34	9	
Bandor Abbas	20	5		5	3					7	2		31	10	
Shahr Kord	36	8	1	26	5	3				30	10		92	23	4
Torbat Heydarieh	47	21	3	31	10	3	2	1		24	11		104	43	3
Zanjan	44	10	2	57	9	4	11	1		54	10		166	30	6
Ramsar	55	24	3	65	25	7	46	11		42	26		218	85	10
Mean	38	12	1	31	7	3	10	2	00	26	10	00	158	33	4
% of all disturbances													81	17	2

TABLE 2. Total number of precipitation days caused by different types of upper level disturbances at selected stations (1965-69).

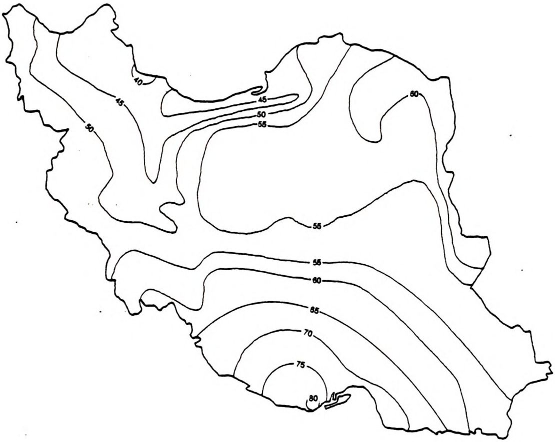

FIGURE 4. Percentage of mean annual precipitation days caused by upper level disturbances with no surface component.

South along the Persian Gulf coast with a secondary maximum in the northeastern part of the country. In the Northwest, the center of the lowest contribution was over the southwestern coast of the Caspian Sea and extended southward over the northern portions of the Zagros Mountains and eastward over the Elburz Mountains. Generally, along parallels the values decreased from east to west.

Surface Disturbances

This type included all mid-latitude cyclones with or without frontal systems. Table 3 shows the different constituents of the surface disturbances at selected stations. On the annual basis, cyclones with fronts outnumbered frontless lows over the entire country. On the whole, 64% of the days with surface disturbances during the study period experienced cyclonic activity with surface fronts, whereas in 35% of the days the disturbances had no surface front.

On a seasonal basis, summer lacked any cyclonic activity over the country and, during the transitional seasons of spring and fall, no surface disturbance migrated south of 32°N. Cyclonic activity maximized in winter but was high during fall also over the entire country. Although spring experienced less cyclonic activity than winter, it was the only season during which frontless lows outnumbered cyclones with fronts. These data reveal that surface disturbances were most frequent during the cold season over northern Iran while their occurrence in the southern region was restricted to only the winter.

Station	Winter		Spring		Summer		Fall		Annual	
	Cyclones and fronts	Frontless lows	Cyclones and fronts	Frontless lows	Cyclones and fronts	Frontless lows	Cyclones and fronts	Frontless lows	Cyclones and fronts	Frontless lows
Iranshahr	4	1					1		5	1
Bandar Abbas	8	3							8	3
Shahr Kord	42	6	4	5			4	4	50	15
Torbat Heydarieh	25	15	4	5			11	2	40	22
Zanjan	34	21	4	7			10	7	48	35
Ramsar	23	13	3	7	1		13	7	40	27
Mean	23	10	2	4	.1	00	6	3	32	17
% of all disturbances									65	35

TABLE 3. Total number of precipitation days caused by different types of surface disturbances at selected stations (1965-69).

Further breakdown of the cyclones with fronts (Table 4) revealed that 73% were cold fronts, whereas only 24% of them were cyclones with both frontal systems. Most of the cyclones affected the northern parts of the country, whereas to the south of 32°N only cold fronts were dominant, during winter only (Table 3).

The percentage contribution of surface disturbances of all kinds was averaged for the study period on an annual basis for each station (Figure 5). In contrast to upper level disturbances, the maximum contribution by surface disturbances occurred along the 32°N parallel. The highest contribution (30%) was observed at Shahr Kord. On Figure 5, three separate zones of more than 20% contribution are found to the north of 30°N latitude. These zones include the western highlands of Azarbaijan, the western slopes of the Zagros Mountains in the Southwest, and northeastern sections to the north of the central deserts. Both the northern and the southern parts of the country experienced relatively lower values, particularly in the Southeast, where the values fell below 10% (1% at Jask). The central trough of the isolines with values below 20% extended generally in a northwest-to-southeast direction. Comparison of this map with Figure 4 reveals that, in the South, the primary maximum of upper level disturbances coincided nearly with the minimum of surface disturbances, but in the northern parts both mechanisms showed low contributions.

Station	Cyclones with fronts	Cold front	Warm front	Occluded front	Stationary front
Iranshahr		5			
Bandar Abbas	1	7			
Shahr Kord	13	26		1	
Torbat Heydarieh	13	25		2	
Zanjan	4	39	1	2	1
Ramsar	12	28			
Mean	7	27		1	
% of all frontal disturbances	24	73		2	

TABLE 4. Total number of precipitation days caused by different types of surface frontal disturbances at selected stations (1965-69).

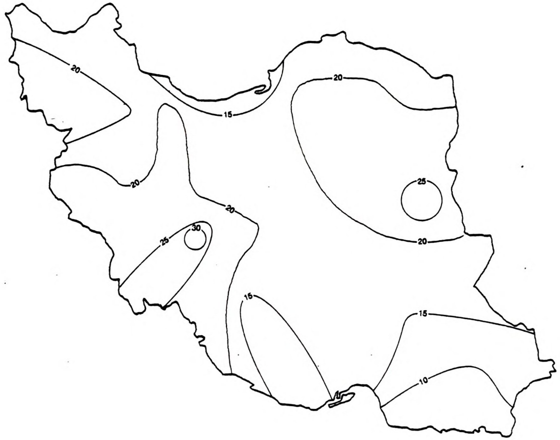

FIGURE 5. Percentage of mean annual precipitation days caused by surface disturbances.

<u>Surface Heating</u>

This type included those days when no other uplift mechanism was observed and the surface temperature remained over 80°F at or near the station. Since in some cases surface heating contributed to precipitation concurrently with upper level or surface disturbances and was therefore inadvertently included in those types, the surface heating category may underrepresent the number of qualified days. In this study this category includes the days when only surface heating appears to have been the primary cause of precipitation. This process occurs only when the air aloft is unstable, without interference from subsidence or temperature inversions. Therefore, occurrence of this type indirectly indicated the absence of atmospheric subsidence or an inversion which, otherwise, would not permit convection to proceed to the point of producing precipitation.

Figure 6 shows the spatial distribution of the percentage contribution of the surface heating process over the country. It is apparent from this map that the highest values were aligned in a northwest-southeast direction, with the primary maximum over the southeasternmost part of the country. In the North, the southeastern coast of the Caspian Sea comprised the secondary maximum. Areas of least contribution were located in the northeast and southwest extremes of the country where the contribution of upper level disturbances was at a maximum (Figure 4). For example, no convective precipitation was detected during the study period at Bushehr on the

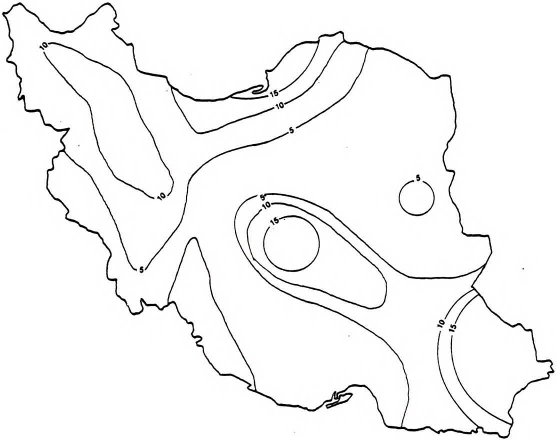

FIGURE 6. Percentage of mean annual precipitation days caused by surface heating.

Persian Gulf coast.

Sea Effect

This type was defined as those uplift processes which resulted from the passage of cold air over the warm water surfaces and, in this study, was found to be confined to the southern coast of the Caspian Sea (Figure 7). In this region, cold Siberian air gained heat and moisture through its passage over the Caspian Sea and by the time it reached the Iranian coast became unstable and caused precipitation. The maximum concentration of this activity occurred specifically on the southwestern coast of the Caspian Sea and decreased eastward. The weather charts of the days with sea effect type all showed an anticyclone centered to the north of the Caspian Sea, which caused the northerly, northeasterly, or easterly winds over the sea and carried moist, unstable air to the southwestern coast.

Regions of Precipitation Mechanisms

One of the objectives of this study was to regionalize the country on the basis of the dominant uplift mechanisms. A hierarchical clustering method was used with "ward's" least-squared distance algorithm as the measure of dissimilarity between observations. Five clusters were subjectively chosen to regionalize the country. This scheme ultimately was not found suitable for this study because the resulting regions were often fragmented and conveyed

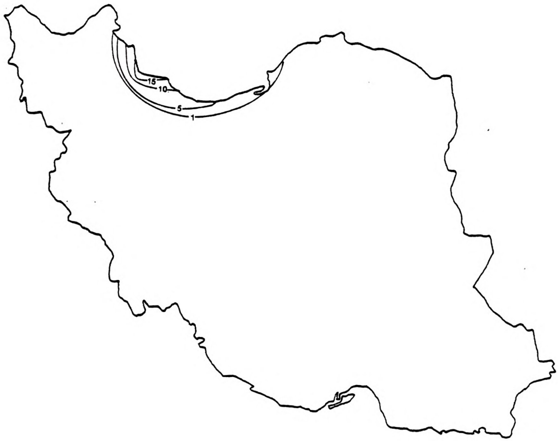

FIGURE 7. Percentage of mean annual precipitation days caused by sea effect.

confusing information. For example, cluster 5 (dominated by upper level disturbances) is interrupted by cluster 1 (dominated by surface disturbances); such a pattern is climatologically incoherent. Nonetheless, the clusterings are shown in Figure 8 and are presented statistically in Figure 9:

1) The stations on the northeastern and southwestern parts of the country were clustered together. This cluster is unique because of the relatively large contribution by surface disturbances; surface heating was the least important uplift mechanism to be recognized in this cluster.

2) The extreme northeastern and northwestern areas together with the south central parts of the country made up the second cluster; no single uplift mechanism accounted for most of the precipitation days.

3) The southeasternmost part of the country and the southeast Caspian coast, along with some other scattered areas, comprise the third cluster. This cluster is well distinguished because of a contribution by surface heating; westerly disturbances were least important in this cluster.

4) The fourth cluster is located mainly over the lands to the southwest of the Caspian Sea with a few outliers in the other areas. This cluster is characterized by the lowest contribution by upper level disturbances.

5) Only two stations in the South are included in the fifth cluster, which is distinguished by a strong contribution by upper level disturbances.

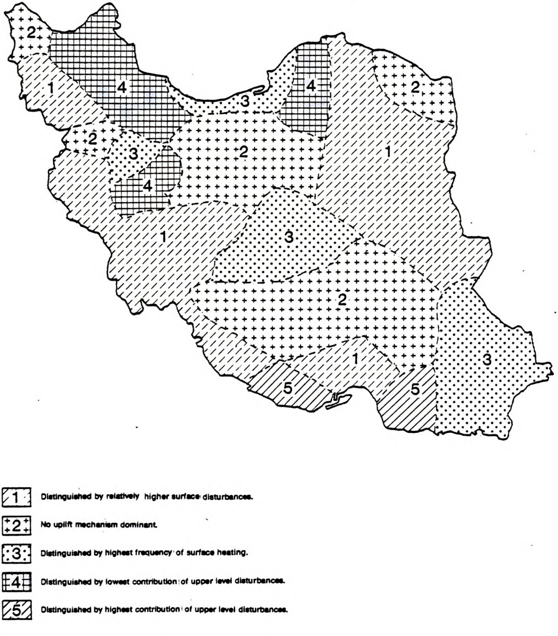

FIGURE 8. Regions of precipitation mechanisms based on cluster analysis and using all uplift mechanisms.

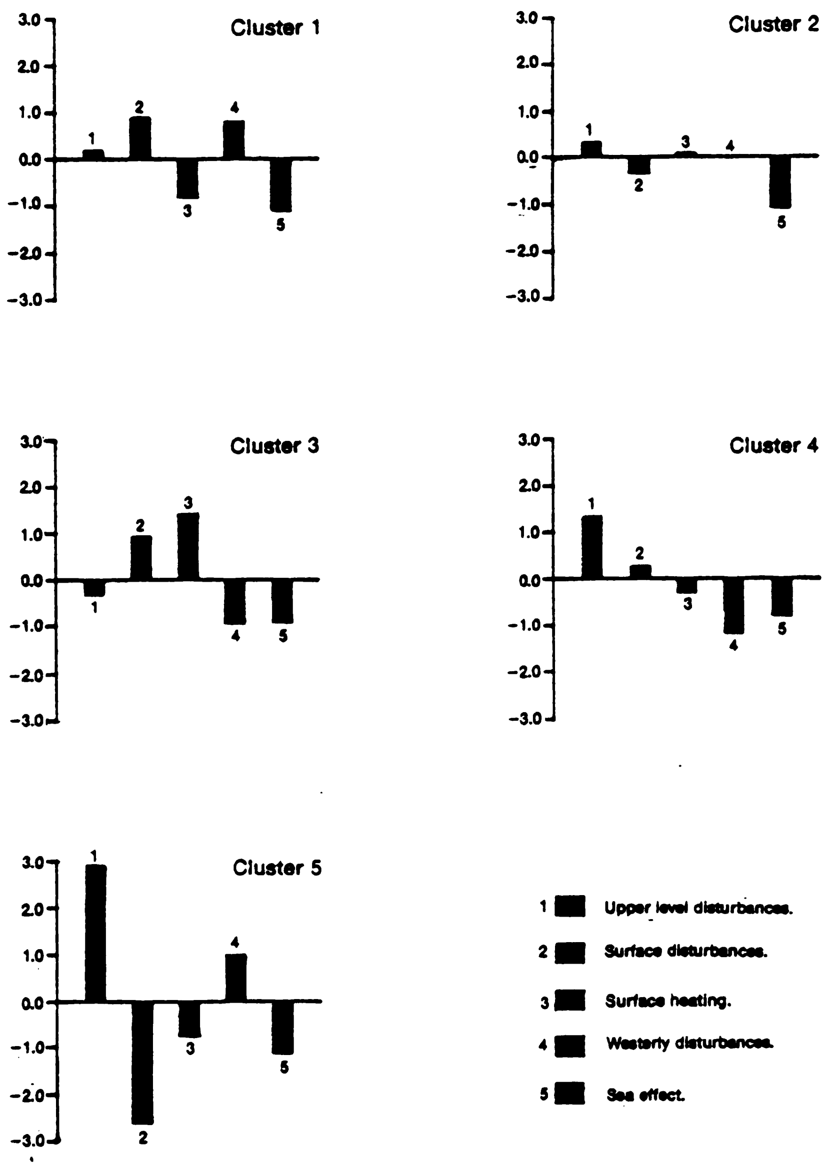

FIGURE 9. Mean Z-scores of the percentage contribution by uplift mechanisms to annual precipitation days for each cluster.

In order to produce contiguous and more understandable regions, further regionalization was based on analysis of the predominant uplift mechanisms. According to Table 1, the highest percentage of annual precipitation days was caused by upper level disturbances (55%), and surface disturbances (18%) were second in importance. Since any traveling surface disturbance is associated with an upper level disturbance, both the surface and upper level disturbances were combined into one group. As a result, this combined type (westerly disturbances) was by far the most predominant uplift mechanism, reflecting the dominance of westerly disturbances, and contributing 73% to the country's annual precipitation days (Table 1). For the purpose of regionalization the Z-scores of the percentage contribution of this combined category for the stations were computed and are shown in Figure 10 (their numerical percentages are listed in Appendix 1); the Z-scores best demonstrated the spatial variation of percentage contribution of this combined category among the stations. Spatial clustering can be interpreted from the isoline patterns, with the highest positive deviation from the mean percentage contribution by the predominant mechanism on the coastal areas of the Persian Gulf and the highest negative deviation on the southwest corner of the Caspian Sea. The isoline +1 in the South and the isoline -1.5 in the North were arbitrarily chosen to distinguish these extremes from their surroundings. In the northern parts of the country all the northwestern highlands and their continuation eastward, including the eastern half

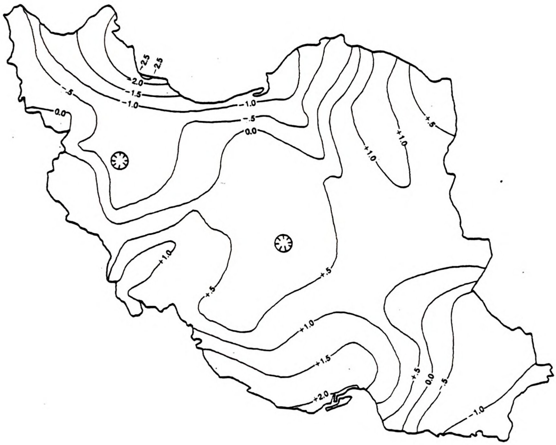

FIGURE 10. Z-score values of percentage contribution made by upper level disturbances, with or without surface disturbances, to the mean annual precipitation days.

of the Caspian Sea coastal region, are separated by the isoline 0.00 from those areas to the south. In the central portions of the country there are two secondary maxima in the Northeast and Southwest. Values decrease toward central Iran from these maxima. A zone of lower values passing through Kashan, Yazd, and Bam separates these two maxima from each other. The final regions are shown in Figure 11 and are as follows:

1) Caspian region. This region encompasses the coastal areas of the western Caspian Sea. It led all other regions in terms of the annual precipitation days (Table 5), with precipitation occurring on approximately a third of the days. Upper level disturbances were the dominant mechanism in the region with 45% contribution (Table 5). Nevertheless, this value was the lowest among the regions. Sea effect was second to upper level disturbances in causing the precipitation days (13%), whereas surface heating (9%) was the least important mechanism.

2) Northwestern region. This region covers all the northwestern highlands, the Elburz Mountains with their southern foothills, and the eastern half of the Caspian Sea coast. It was second to the Caspian region in terms of annual precipitation days (Table 5) and 49% of its precipitation days were attributed to upper level disturbances, whereas surface disturbances accounted for 20%. Surface disturbances affected both northern and southern parts of the region more than the central part (Figure 5), whereas the central areas

FIGURE 11. Regions of precipitation mechanism based on the percentage contribution of the predominant uplift mechanism to the mean annual precipitation days.

had a greater contribution from surface heating.

3) Southwestern region. This region consists of almost all the Zagros Mountains and the lowlands to their west except the coastal areas of the Persian Gulf. Mean annual precipitation days were less than in either the Caspian region or the northwestern region (Table 5). Upper level disturbances were associated with the highest percentage of the precipitation days (57%), and surface disturbances were more important here than elsewhere, too. Contribution by surface heating was very low (4%).

4) Northeastern region. This region includes the lands to the south of the Elburz Mountains and east of the Zagros Mountains up to the border of Afghanistan. The region includes all the central deserts of Iran. The highest percentage of the precipitation days was caused by upper level disturbances (Table 5). The 20% contribution by surface disturbances was second only to the southwestern region. Like the latter region, surface heating contributed a very low percentage of days.

5) Southern region. The coastal lowlands of the Persian Gulf and the western half of the Gulf of Oman make up this region. Upper level disturbances accounted for a higher percentage (70%) of days here than in any other region, but the contribution by surface disturbances was very low (2%). Despite its very southerly location, surface disturbances contributed 16% to the region's annual precipitation days.

Region	Regional Mean				
	Number of annual precipitation days	% of precipitation days caused by			
		Upper level disturbances	Surface disturbances	Surface heating	Sea effect
Southeastern	16	60	10	11	
Southern	18	72	16	2	
Southwestern	48	57	27	4	
Northeastern	34	59	20	4.5	
Northwestern	78	49	20	9.5	
Caspian	126	45	12.5	9	13

TABLE 5. Mean regional number of annual precipitation days and the percentage contribution by each mechanism (1965-69).

6) Southeastern region. The southeasternmost part of the country, with the lowest number of precipitation days (15 days), is included in this region. It was the leading region in the percentage contribution made by surface heating (14%), but, at the same time, surface disturbances contributed the least to its annual precipitation days compared with all other regions (Table 5). Still, like other regions, upper level disturbances were the most frequent trigger among the various mechanisms.

Seasonal Variation of Precipitation Mechanisms

To study the seasonal variation of precipitation mechanisms, one representative station was selected for each region (see Table 6). Among all seasons, winter had the highest number of precipitation days (Figure 12). The percentage contribution of this season to annual totals was highest in the southern and southeastern regions but decreased northward until it fell to 29% in the Caspian region. Summer was almost rainless in the southern, southwestern, and northeastern regions. The highest number of summer precipitation days was observed in the Caspian region where the seasonal range in the number of such days was lowest. Autumn contributed the lowest percentage to annual totals in the southeastern and southern regions, where the seasonal value fell as low as 7%. In other regions, fall contributed about one-third of the annual precipitation days. Greatest contribution was in the western highlands (the northwestern and southwestern regions). Like fall, spring contributed lower

Region	Representative Station
Southeastern	Iranshahr
Southern	Bandar Abbas
Southwestern	Shahr Kord
Northeastern	Torbat Heydarieh
Northwestern	Zanjan
Caspian	Ramsar

TABLE 6. Representative stations of the regions.

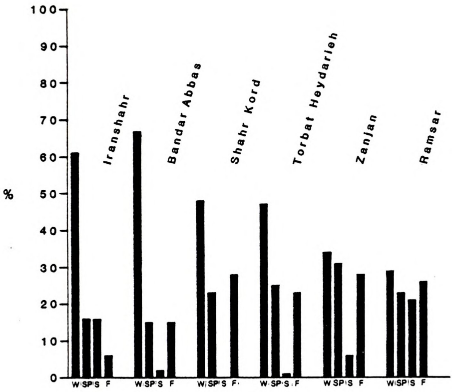

FIGURE 12. Percentage contribution by season to mean annual precipitation days at selected stations.

percentages to the South and the North. The spring contribution to the annual precipitation days was greatest in the northwestern region. Figure 13 depicts the seasonal importance of the mechanisms by region.

Winter

The predominant cause of precipitation throughout the country, except in the northwestern and southwestern regions, was upper level disturbances, although this predominance decreased from south to north. For instance, this mechanism accounted for more than 70% at Iranshahr and Bandar Abbas but only 46% at Ramsar. In these regions, surface disturbances were of second greatest importance; indeed, their role in the southeastern region was substantial (69%). In the northwestern and southwestern regions the contribution by surface disturbances was equal to, or higher than, that by upper level disturbances. No contribution by surface heating was observed in this season except in the southeastern region where it accounted for 14% of the precipitation days at Iranshahr. In general, during the winter season upper level disturbances were predominant in the Caspian and southeastern regions, but in the remaining parts of the country surface disturbances were the leading mechanism.

Spring

In contrast to winter, the most frequent uplift mechanism in spring in all regions was upper level disturbances (Figure 13); their dominance ranged from 89% at Bandar Abbas

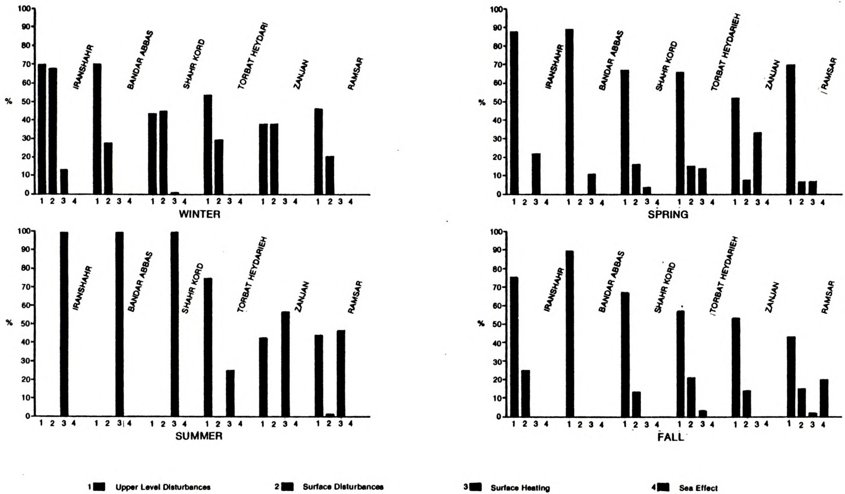

FIGURE 13. Percentage contribution by mechanisms to seasonal precipitation days.

to 51% at Zanjan in the northwest. Surface disturbances were absent in the southern and southeastern regions and played a secondary role in the southeastern and northeastern regions , with 18% contribution at Shahr Kord and 13% at Torbat Heydarieh. They made even less contribution in the northwestern and Caspian regions, with 8% at Zanjan and 7% at Ramsar. The northwestern region was unique in that surface heating accounted for up to 33% of precipitation days. This region was followed by the southeastern region (22% at Iranshahr). In other regions, the contribution by surface heating was generally low and, in some places such as Shahr Kord, was negligible.

Summer

Surface disturbances were unimportant over much of the country, and upper level disturbances were the most frequent only in the northeastern region. Over the rest of the country surface heating was the most frequent mechanism (Figure 13); however, the difference between the contributions of upper level disturbances and surface heating was not significant in the Caspian and northwestern regions.

Fall

Upper level disturbances were the predominant mechanism over the entire country, as they were in spring. Their contribution was as high as 89% at Bandar Abbas in the southern region but fell to 43% at Ramsar on the Caspian coast. Except for the southern region, all the country was affected by some surface disturbances. The highest contribution was 25% at Iranshahr in the southeastern region followed by 21% at Torbat Heydarieh in the Northeast.

In this season, the Caspian region benefitted also from sea effect. This process accounted for 20% of the region's fall precipitation days (Ramsar, Figure 13). Surface heating was not important anywhere in the country.

Summary

The predominant seasonal precipitation mechanisms of the regions, based on their contribution to the annual number of precipitation days, are shown in Table 7. The most frequent uplift mechanism in the transitional seasons of spring and fall over the entire country was upper level disturbances. During the summer, surface heating was important except in the northeastern region where upper level disturbances were significant. In winter, upper level disturbances predominated in the southern, northeastern, southeastern, and Caspian regions, but surface disturbances were dominant in the southwestern region. The northwestern region was equally affected by both surface and upper level disturbances.

Importance Of Precipitation Mechanisms

Introduction

The importance of a precipitation mechanism is assessed according to its contribution to a station's annual or seasonal precipitation total, rather than frequency, and

	Mechanisms			
Region	Winter	Spring	Summer	Fall
Southeastern	upper level disturbances	upper level disturbances	surface heating	upper level disturbances
Southern	" "	" "	" "	" "
Southwestern	surface disturbances	" "	" "	" "
Northeastern	upper level disturbances	" "	upper level disturbances	" "
Northwestern	surface disturbances	" "	surface heating	" "
Caspian	upper level disturbances	" "	" "	" "

TABLE 7. Predominant (most frequent) precipitation mechanisms of the regions, by seasons.

these results will be described in detail later. However, before moving into this discussion I will describe the spatial variation of the annual precipitation amounts over the country to give the reader a general understanding of the precipitation pattern.

Annual Precipitation

Mean annual precipitation for the study period is shown in Figure 14, which depicts a highly diverse pattern across the country. For instance, the southwestern coast of the Caspian Sea, the region of highest precipitation, received more than 1700mm annual precipitation, whereas the central deserts of the country were driest with annual precipitation of less than 100mm. The northern slopes of the Elburz Mountains received annual mean precipitation as much as four times that of the southern slopes. The northwestern highlands of the country received mean totals between 300mm and 600mm, whereas the highlands of the northeastern portion of the country had values below 300mm. The overall precipitation pattern of the country can be portrayed as follows: Caspian Sea area, 600mm to 1800mm; northwestern parts, 300mm to 600mm; northeastern section, 200mm to 300mm; southern coastal strip, 100mm to 200mm; and central deserts, below 100mm.

Annual Importance of Precipitation Mechanisms

The annual contribution of each mechanism to the total precipitation of the representative stations was determined

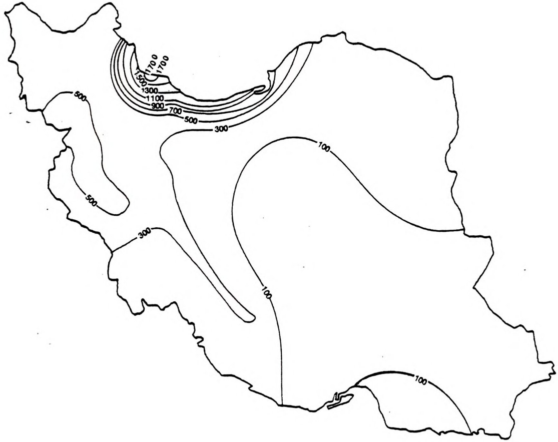

FIGURE 14. Mean Annual precipitation in millimeters (1965-69)
SOURCE: Iranian Meteorological Organization.

(Figure 15). Upper level disturbances contributed the highest percentage to the annual precipitation (Figure 15), with values ranging from 46% at Shahr Kord in the southwestern region to 67% at Bandar Abbas in the southern region. Surface disturbances were the second most important mechanism overall except in the southern region where surface heating was second. The highest contribution by surface disturbances was at Shahr Kard (40%), whereas Ramsar received the lowest contribution (11%). Surface heating was almost inconsequential in the southern, southwestern, and northeastern regions, but contributed up to 18% in the southeastern region. Contribution by sea effect was observed only at Ramsar (13%). The mean contribution to the country's annual precipitation by each mechanism was computed from the representative stations as follows: upper level disturbances 57%, surface disturbances 26%, and surface heating 7%.

Seasonal Importance of Precipitation Mechanisms

To assess the seasonal importance of the precipitation mechanisms, the percentage of annual precipitation contributed by each season was computed for the representative stations (Figure 16). Winter provided more than half of the country's annual precipitation, except in the northwestern and Caspian regions. Winter precipitation constituted 84% of the annual precipitation at Bandar Abbas in the southern region but only 24% at Ramsar in the Caspian region.

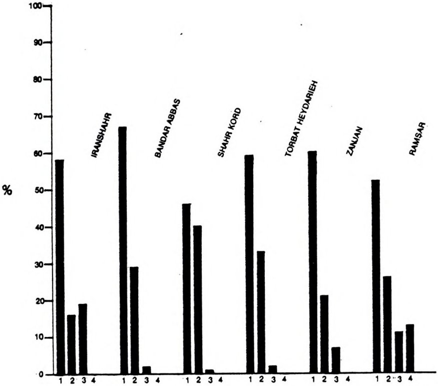

FIGURE 15. Percentage contribution by mechanisms to mean annual precipitation at selected stations. Columns are as follows: 1. Upper level disturbance, 2. Surface disturbances, 3. Surface heating, 4. Sea effect.

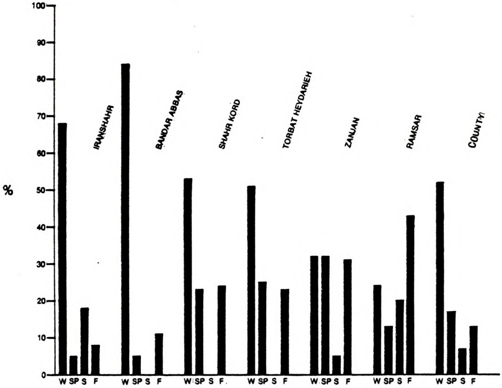

FIGURE 16. Percentage contribution by season to mean annual precipitation at selected stations.

Spring was the driest season in the southeastern and Caspian regions (5% of the annual in the former and 15% in the latter). Spring contributed less than did winter in the northeastern region but equalled winter in the northwestern region (31% for both at Zanjan).

Summer saw almost no rain in the southern, southwestern, and northeastern regions. Greatest summer precipitation was observed in the Caspian region where about 20% of the region's annual precipitation occurred. This region was followed by the southeastern region where summer accounted for 19% of the annual precipitation, but only 6% in the northwestern region.

Autumn accounted for much of the annual precipitation in the Caspian region (43% at Ramsar), but only 8% at Iranshahr in the southeastern region.

For the country as a whole, winter accounted for more than half of the annual precipitation. This season was followed by fall, with summer providing the least precipitation over the entire country.

Winter:

Surface disturbances provided the highest proportion of the season's precipitation in the northwestern and southwestern regions (55% at Shahr Kord and 47% at Zanjan). Yet, in the other parts of the country, upper level disturbances were the most important mechanisms (Figure 17). These disturbances contributed 59% of the seasonal precipitation at

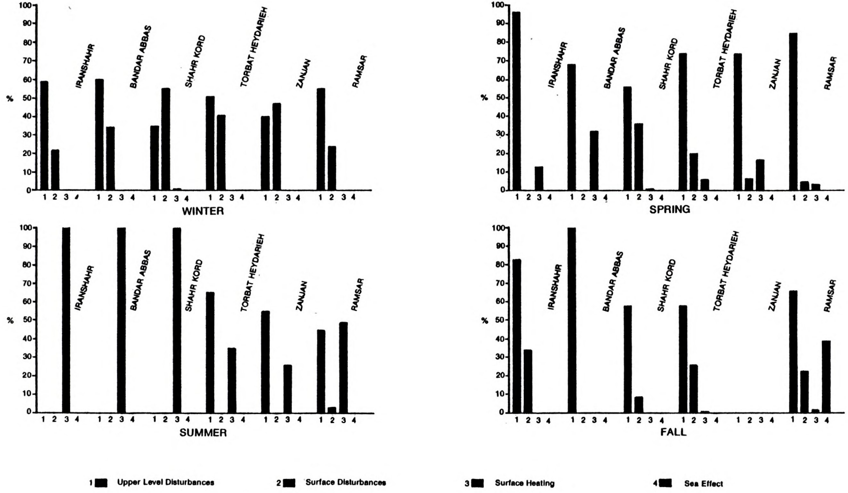

FIGURE 17. Percentage contribution by mechanisms to seasonal total precipitation.

Iranshahr. The contribution by surface heating was not important over any part of the country.

Spring:

The most important uplift mechanism was upper level disturbances (Figure 17). They contributed the highest percentage in the southeastern region (87%), with 56% in the southwestern region. The contribution by surface disturbances was highest at Shahr Kord (36%), but they were absent in the southern and southeastern regions. In other regions their contribution was not significant. Surface heating produced relatively high amounts of seasonal precipitation in the southern regions (36% at Bandar Abbas), and also in the northwestern region (17% at Zanjan), This contribution was very low in the remaining regions.

Summer:

During this season, the southern half of Iran received all of its seasonal precipitation, if any, from surface heating (see Bandar Abbas, Iranshahr, and Shahr Kord in Figure 17). In the northern half of the country, with the exception of the Caspian region, upper level disturbances produced more than half of the season's precipitation (65% at Torbat Heydarieh and 55% at Zanjan); the remainder of the precipitation in the North was the result of either surface heating or other mechanisms undetermined by this study. Both upper level disturbances and surface heating produced almost equal amounts of precipitation in the Caspian region, 45% and 49% respectively. Only this region received a measurable percentage (3%) of its precipitation from surface disturbances, which were completely absent from the rest of the country.

Fall:

Fall was the season of upper level disturbances over all the country. Their contribution to the season's precipitation varied from 100% at Iranshahr to 41% at Ramsar (Figure 17). Surface disturbances ranked second to upper level disturbances outside the Caspian region and achieved their highest percentage in the southeastern region. In the Caspian region, the mechanism second in importance to upper level disturbances was sea effect, which accounted for 29% of the region's autumn precipitation. The contribution by surface heating was slight over the entire country.

Summary

Seasonally important uplift mechanisms of the regions are listed in Table 8. Upper level disturbances were the most important mechanism during the transitional seasons over all the country. In winter, except in the northwestern and southwestern regions where surface disturbances were the most important, upper level disturbances accounted for over half of the seasonal precipitation. Summer was the only season when surface heating was the most important mechanism, except in the northeastern region where upper level disturbances continued to be the most important.

Region	Mechanisms Winter	Spring	Summer	Fall
Southeastern	upper level disturb- ances	upper level disturb- ances	surface heating	upper level disturb- ances
Southern	" "	" "	" "	" "
Southwestern	surface disturb- ances	" "	" "	" "
Northeastern	upper level disturb- ances	" "	upper level disturb- ances	" "
Northwestern	surface disturb- ances	" "	" "	" "
Caspian	upper level disturb- ances	" "	surface heating	" "

TABLE 8. Most important precipitation producing mechanisms, by season.

Regional and Seasonal Summary

I have presented the findings of this study regarding the contribution of the mechanisms to the annual and seasonal precipitation over Iran. In this section, I will summarize the importance of these mechanisms in each region by seasons (Table 9).

Caspian Region:

This region received maximum precipitation during fall, while the remainder of the precipitation is distributed rather equally among other seasons. During the colder half of the year, upper level disturbances were the most important and frequent mechanism, but, in the warmer period of the year, surface disturbances were most frequent.

Northwestern Region:

Most of the annual precipitation occurred during the winter and spring seasons. Summer was the driest season of the year. Surface disturbances were the most frequent and important uplift mechanism in winter, but upper level disturbances prevailed through the other seasons.

Northeastern Region:

In this region summer precipitation was negligible and winter was the rainiest season. The most frequent and important mechanism was upper level disturbances throughout the year.

	Winter				Spring				Summer				Fall				Annual	
	% of annual				% of annual				% of annual				% of annual					
Region	PD	P	MFM	MIM	PD	P	MFM	MIM	PD	P	MFM	MIM	PD	P	MFM	MIM	MFM	MIM
South-eastern	61	68	U	U	16	5	U	U	16	19	H	H	7	8	U	U	U	U
Southern	67	84	U	U	15	5	U	U	2	00	H	H	7	11	U	U	U	U
South-western	48	53	S	S	23	23	U	U	00	00	-	H	28	24	U	U	S	S
North-eastern	47.5	51	U	U	25	25	U	U	1	00	U	U	23	23	U	U	U	U
North-western	34	32	U&S	S	31	32	U	U	6	6	H	U	28	31	U	U	U	U
Caspian	29	24	U	U	23	13	U	U	21	20	H	H	26	43	U	U	U	U
Mean (country)	48	52	U	U	22	16	U	U	9	9	H	H&U	19	23	U	U	U	U

Abbreviations = PD, Precipitation Days; P, Precipitation; MFM, Most Frequent Mechanism; MIM, Most Important Mechanism.

TABLE 9. Regional and seasonal summary of precipitation mechanisms in Iran.
Symbols: U, upper level disturbances; S, surface disturbances; H, surface heating.

Southwestern Region:

Surface disturbances were the most frequent and important mechanism in winter. The transitional seasons were characterized by upper level disturbances. Summer was almost rainless.

Southern Region:

Winter was the rainiest season of the year and summer was the driest and nearly rainless season. Precipitation in the summer, if any, was caused by surface heating. In other seasons, upper level disturbances were the most frequent and important mechanisms.

Southeastern Region:

The rainiest season of the year was winter, whereas autumn was the driest season. The most frequent and important precipitation mechanism was upper level disturbances through the cold period of the year and surface heating through the summer.

Moisture Sources

As mentioned earlier, the two important factors responsible for precipitation are an uplift mechanism and an adequate amount of moist air. In previous sections of this chapter, mechanisms contributing to Iran's precipitation were described. In this section, I identify the principal moisture trajectories and sources of moist air involved in this precipication. For this purpose, precipitation days with amounts of 10mm or more at the representative stations were analyzed using data from both the surface and 700mb level for the period July 1967 to December 1969. The relative annual contribution of the moisture sources is listed in Table 10 and illustrated in Figure 18. These results show that the country received moisture from nearby water bodies such as the Persian Gulf, the Black Sea, the Red Sea, the Gulf of Oman, the Caspian Sea, the Mediterranean Sea, and as far as the Bay of Bengal. Among these sources, the most important were the Persian Gulf, the Caspian Sea, and the Mediterranean Sea (Table 10, bottom row).

The Caspian Sea moisture reached only the nearby coastal areas and was the predominant moisture source of this region (Figure 18). This moisture invaded the area in association with different synoptic patterns. The major pattern involved anticyclones traveling north of the Caspian Sea under the northern branch of the European Polar Front jet stream; these anticyclones were common throughout the year. When these anticyclones were to the west of the Caspian Sea, northerly winds on their east side crossed the sea and carried moisture to nearly all the adjacent southern coastal areas. When they were to the north or northeast of the Caspian Sea, however, the northeasterly or easterly winds affected mostly the southwestern coast. A variant of this pattern developed when the thermally-reinforced Siberian anticyclone was located to the east or northeast of the Caspian Sea. Moisture acquired by the resulting wind flow from this very cold anticyclone affected the southwestern coast. During the warm season, moist

Regions	PG or GO	MS	RS	PG & MS	PG & RS	RS & MS	CS	MS & CS	BS	BS & PG	RS & BS	M & BS	RS & CS	BS & CS	BB
Southern	100														
Southeastern	66														33
Southwestern	61	3	6	6	21	3									
Northeastern	37	19	-	25			12	6							
Northwestern	4	26	15	18	26	4				4	4				
Caspian		7				2	68	13	2		1		6	1	
Mean	45	9	3	8	8	1	13	.3	.3	.6	.6	1	.1	1	5

TABLE 10. Annual percentage contribution by moisture trajectories to regional precipitation days (10 millimeter or more), (July 1967-December 1969).

Abbreviations = PG or GO, Persian Gulf or Gulf of Oman; MS, Mediterrean Sea; RS, Red Sea; PG & MS, Persian Gulf and Mediterranean Sea; PG and RS, Persian Gulf and Red Sea; RS and MS, Red Sea and Mediterranean Sea; CS, Caspian Sea; MS and CS, Mediterranean Sea and Caspian Sea; BS, Black Sea; BS and PG, Black Sea and Persian Gulf; RS and BS, Red Sea and Black Sea; MS and BS, Mediterranean Sea and Black Sea; RS and CS, Red Sea and Caspian Sea; BS and CS, Black Sea and Caspian Sea; BB, Bay of Bengal.

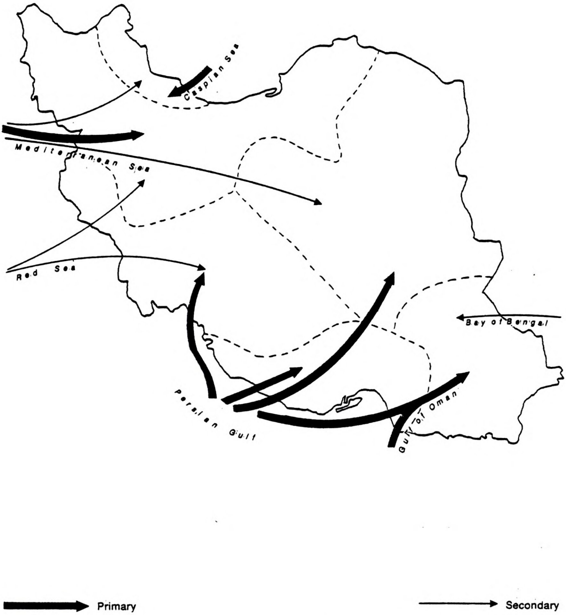

FIGURE 18. Annual moisture trajectories.

air from the Caspian Sea affected the coastal strip through the establishment of sea breezes.

Moisture from the Mediterranean Sea reached all the northern half of the country (Table 10) but it was the primary source only in the northwestern region (Figure 18). This moist air often invaded the country with anticyclones steered eastward by the southern branch of the Polar Front jet stream behind surface cold fronts. These anticyclones originated over southern or western Europe and gained moisture from the Black and Mediterranean Seas, yielding precipitation over Iran. Moisture from these sources was also brought by the upper level flow pattern, as when a trough at 700mb developed over the Mediterranean Sea, resulting a moist southwesterly flow into the country. This mild Mediterranean air mass was uplifted over Iran by one or more of four different synoptic processes;

1) Cold front uplift.

2) Warm occlusion. In some cases, especially in winter, the western extremity of a very cold Siberian anticyclone occupied Iran. This cold air forced the mild Mediterranean air mass over it, which yielded precipitation.

3) Uplift by upper level disturbances. Following the passage of cold fronts the Mediterranean air mass remained over the country and was uplifted by passing upper level disturbances.

4) Slope instability. Air over the slopes of the western mountains became warmer than the ambient air because of differential heating. This lapse rate increase resulted in

convectional uplifting of the Mediterranean air mass; however, this process was affected by orographic influences as well.

Persian Gulf moisture together with that from the Gulf of Oman affected the southern half of the country (Figure 18). Moist air from these water bodies invaded the country with several synoptic patterns. First, as Mediterranean cyclones invaded Iran, the wind flow ahead of these systems drew moisture northward from these water bodies and yielded precipitation over the country, especially in the northeastern section. Second, especially in the transitional seasons, either the Mediterranean cyclones became stationary or inverted troughs developed over Iraq. These cyclones or troughs drew in moisture from the Persian Gulf on their eastern flank to the western slopes of the Zagros Mountains. Third, during the summer, moisture was drawn in from these sources by the establishment of sea breezes in the lower atmosphere. Fourth, development of an upper level (700mb) trough over Arabia generated southwesterly flow from the Persian Gulf. This circulation was the only one responsible for transporting moisture from the Red Sea and it arose when the trough was located over northwestern Africa.

The Bay of Bengal was the farthest water body to affect the southeastern region and was important only in summer (Figures 18, 19). During this season, the establishment of the Indian low in the lower atmosphere drew moist air from the Bay of Bengal across the Indian subcontinent into Iran around the northern flank of this low.

Seasonal Distribution of Moisture Sources

Winter

This season was most similar to the annual pattern of moisture flux (Figure 19). In the Caspian region, the primary source was the Caspian Sea, accounting for 47% of total seasonal frequencies of moisture trajectories (Table 11). The Mediterranean Sea*, accounting for 35% of the total, was the second most important source of moist air. The primary source in the northwestern region was the Mediterranean Sea (12% of the total), whereas the Red Sea was the secondary source. Moisture from the Persian Gulf often combined with these sources, but in the eastern and southeastern regions the Persian Gulf was the primary source, and the Mediterranean Sea was the secondary source. Both southern and southeastern regions received all their moisture from the southern water bodies.

Spring

The moisture influx in the Caspian, northeastern, and southwestern regions was similar to the winter pattern (Figure 19). No moisture source was identified in the southern and southeastern regions because these areas did not receive any precipitation values of 10mm or more per day (Table 12). The primary sources for the northwestern region were the Mediterranean and the Red Seas.

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*Days with moisture trajectories from both Mediterranean Sea and Red Sea concurrently were classified into a combined group and included in the category of the Mediterranean Sea.

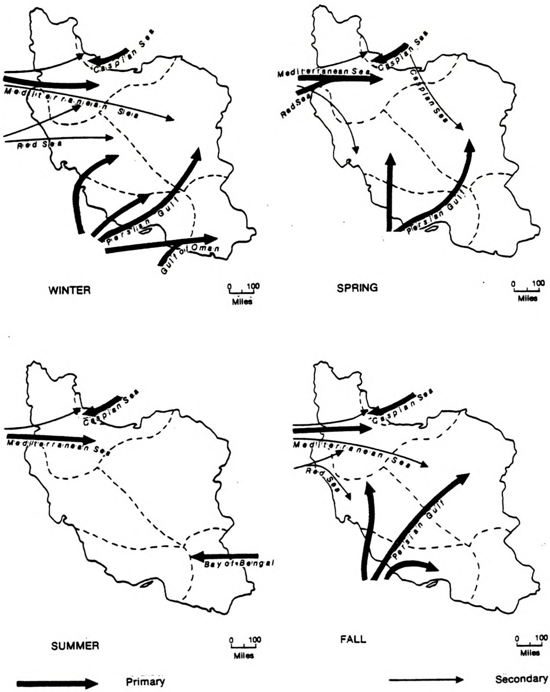

FIGURE 19. Relative importance of seasonal moisture trajectories.

Regions	PG or GO	MS	RS	PG & MS	PG & RS	RS & MS	CS	MS & CS	BS	BS & PG	RS & BS	MS & BS	RS & CS	BS & CS	BB
Southern	100														
Southeastern	100														
Southwestern	61		7	7	15	7									
Northeastern	30	17		50											
Northwestern		12		12	37	25	12								
Caspian		29				6	47	12				6			

TABLE 11. Same as Table 10 except for winter.

Abbreviations: Same as Table 10.

Regions	PG or GO	MS	RS	PG & MS	PG & RS	RS & MS	CS	MS & CS	BS	BS & PG	RS & BS	MS & BS	RS & CS	BS & CS	BB
Southern															
Southeastern															
Southwestern	55	11			33										
Northeastern	33			33			33								
Northwestern	11	22	22							11	11				
Caspian							73	20					9		

TABLE 12. Same as Table 10 except for Spring.

Abbreviations: Same as Table 10.

Summer

During this season, the southwestern, northeastern, and southern regions did not receive precipitation values of 10mm or more per day. The northwestern region received all of its precipitation from the Mediterranean Sea and the southeastern region from the Bay of Bengal (Table 13). The Caspian region had the same pattern as the previous seasons but with an increase in contribution by the Caspian Sea (Table 13).

Fall

Fall was the driest season in the southeastern region (Figure 19). The southern, southwestern, and northeastern regions received most of their moisture from the Persian Gulf. In the northwestern region, in contrast to spring, the Red Sea was the second most important source after the Mediterranean Sea. The Caspian region experienced the same pattern as in the other seasons but with the addition of a very low contribution from the Mediterranean Sea (Table 14).

Importance of Moisture Sources

According to Table 10, the moisture sources contributing the greatest amount of precipitation over all the country were the southern water bodies, with the Mediterranean Sea ranking third after the Caspian Sea. To determine their regional importance, the percentage contribution of each regional mean to the national mean (computed from regional

Regions	PG or GO	MS	RS	PG & MS	PG & RS	RS & MS	CS	MS & CS	BS	BS & PG	RS & BS	MS & BS	RS & CS	BS & CS	BB
Southern															
Southeastern															100
Southwestern															
Northeastern															
Northwestern		100													
Caspian							87	13							

TABLE 13. Same as Table 10 except for Summer.

Abbreviations: Same as Table 10.

Regions	PG or GO	MS	RS	PG & MS	PG & RS	RS & MS	CS	MS & CS	BS	BS & PG	RS & BS	MS & BS	RS & CS	BS & CS	BB
Southern	100														
Southeastern															
Southwestern	70		10	10	10										
Northeastern	43	28					14	14							
Northwestern	33	11	22	33											
Caspian		2				2	66	10	4				10	2	

TABLE 14. Same as Table 10 except for Fall.

Abbreviations: Same as Table 10.

means) was determined (Table 15). The Caspian region received more than half of the country's precipitation (51%), whereas the southeastern region received only 4% of the precipitation. Because the primary source of moisture in the southern, southwestern, northeastern, and southeastern regions was from southern water bodies (Figure 18), I conclude that these water bodies were of limited total importance. The Mediterranean Sea was the primary source in the northwestern region and the secondary source in the northeastern region. Consequently, the most important moisture sources for the country as a whole were the Caspian Sea and the Mediterranean Sea (Table 15). The influence of the Caspian Sea was limited to a very small area on its coast, whereas the Mediterranean Sea moisture flux affected most of the country.

Heavy Storms

The heaviest ten percent of precipitation days (those used in moisture analysis) in which 10mm or more occurred per day was defined as days with heavy storms. The mean intensity of these heavy storms was computed for the representative stations and ranged from 23mm in the northeastern region to 74mm in the Caspian region (Table 16). Their contribution to the regions' precipitation was very high in the southern region (58%),but decreased to 14% in the northwestern and northeastern regions. Thus, most of the annual precipitation in the southern region came in the form of heavy storms, but heavy rainfalls

Region	Mean annual rainfall (mm)	Contribution to total mean (%)
Southeastern	86	4
Southern	133	6
Southwestern	312	13
Northeastern	252.6	11
Northwestern	358	15
Caspian	1204	51

TABLE 15. Mean regional rainfall and percentage contribution to the total mean precipitation of all regions.

were less common in the northwestern and northeastern regions. Positive vorticity advection (upper level divergence) was the main uplift mechanism associated with these events in all regions, except in the Caspian region where sea effect often caused the heavy storms. The main moisture source was the Caspian Sea in the Caspian region, the Mediterranean Sea in the northwestern and northeastern regions, and the southern water bodies in the remaining regions (Table 16).

Region	Mean intensity (mm)	Predominant mechanism	Primary moisture trajectory	Contribution to the region's annual precipitation (%)
Southeastern	25	Positive vorticity advection	Persian Gulf	37
Southern	50	" "	" "	58
Southwestern	44.3	" "	" "	25
Northeastern	23.24	" "	Mediterranean Sea	14
Northwestern	27	" "	" "	14
Caspian	74	Sea effect	Caspian Sea	35

TABLE 16. Primary mechanisms and moisture trajectories of heavy storms (heaviest 10% of precipitation days with 10 millimeter or more) and their percentage contribution to regional mean annual precipitation.

CHAPTER VI

DISCUSSION

The results of this study have shown the following patterns. First, despite their higher absolute frequency in the North, upper level disturbances were responsible for a higher percentage of the annual precipitation in the South, and they were the most frequent and significant mechanism across the country throughout the year; their spatial distribution showed a form of regionality. Second, surface disturbances were most frequent and made the greatest contribution to annual precipitation totals in the central parts of the country, although their regional importance was similar to upper level disturbances in winter. Third, despite the higher average dew points on the southern coastal areas, surface heating contributed a higher percentage of summertime precipitation days in the non-coastal areas of the Southeast and Northwest. Fourth, over the entire country, only the southwestern coast of the Caspian Sea received sea effect precipitation. Fifth, although the Caspian Sea provided the highest percentage of the national mean precipitation, moisture from the Mediterranean Sea was more widespread over the country. Sixth, the occurrence of precipitation was sporadic and was in the form of heavy single events more in the South than in the North.

In the following sections these patterns will be discussed in more detail. In addition, the final sections are devoted to a discussion of the validity of the findings and the methods of study, including their application and limitations.

Sea Effect

Although the country is bordered by bodies of water on the north and south, sea effect was significant only along the coastal regions bordering the Caspian Sea (Figure 7). The required conditions for this process occurred during fall and winter, and the contribution by this mechanism was highest along the southwest portion of the coast. The establishment of an anticyclone to the northwest, north, or northeast of the Caspian Sea produced northerly or northeasterly winds which seldom affected the southeastern coasts. The lack of sea effect in the other seasons was explained by the lessening or even reversing temperature difference between sea and overlying air which is required for atmospheric destabilization. During fall and early winter the sea was much warmer than was the air, but it became cooler as the season progressed until, in spring and summer, the land and overlying air masses became warmer than the sea.

Although the findings of this study are in agreement with those of Khalili (1), in contrast to his conclusion this study did not show the establishment of a frontal zone between the Caspian air mass and the interior continental air mass. He had suggested that this front is the main cause for the precipitation maximum of the region. This suggestion was not supported by this study because Anzali, located on the coast, received the highest precipitation of any station in the country, north of the suggested front; if the Caspian air mass yielded precipitation because of frontal uplift, the region of maximum precipitation should have also shifted farther south than Anzali, which was not the case in this study. The occurrence of sea effect in Anzali indicated that the destabilization by the sea surface alone was adequate for lifting the air and hence yielding precipitation. However, this study did not have data from areas inland from the coastal zone to determine the exact extent of sea effect.

The southern coastal areas did not experience this process because, as a result of their southerly location, the air-water temperature difference was never adequate and most of the cold period winds were off-shore.

Surface Heating

This mechanism contributed the lowest percentage of annual precipitation days and showed the highest spatial variation among all mechanisms (Table 1). Despite the high dew points over the coastal regions, an important precondition for precipitation-stimulating convection, this mechanism occurred most frequently in the northwestern highlands and in the

Southeast. As was mentioned earlier, these patterns apparently reflect the dynamically-induced stability of the atmosphere, as the lower contribution in the southern coastal areas suggests that the atmosphere was normally too stable to be overturned by surface heating alone.

The spatially irregular contribution by the surface heating mechanism could be explained differently for different parts of the country. In the Northwest, where moisture from the Mediterranean Sea was present much of the time, convectional showers occurred in spring when high insolation on the mountain slopes appeared to increase the lapse rate, as suggested by Scorer (2). But in the hot weather of the Southeast, surface heating gave rise to showers only when modified monsoon air was drawn in from the east (Figure 19).

Despite the widespread and intense surface heating of summer, it caused significant precipitation only in the Caspian region; in the others summer precipitation was inconsequential (Figure 16). The suppression of summer precipitation in these regions might be related to the northward shift of the subtropical jet stream in summer. As was suggested by other researchers (3, 4), during summer the subtropical jet stream shifts northward over Turkey and northern Iran, most frequently placing the greater part of the country under subsiding conditions. Under these circumstances only occasional well-developed short waves invade Iran, particularly the northern parts, resulting in uplift. This stable condition may also be disturbed by very intense heating of modified monsoon air in the Southeast, as evident by the summer precipitation at Iranshahr (Figure 16).

Surface Disturbances

Surface disturbances were particularly frequent across the middle portions of the country, extending from Ahwaz in the West to Birjand in the East (Figure 5). Along each parallel, these disturbances contributed less in central Iran than along the east and west parts of the country. This pattern developed apparently because, first, some of the disturbances dissipated as they moved eastward from western Iran, and second, the eastern parts of the country received disturbances from both the northwest and southwest. Thus, both the western and eastern portions were affected by more surface disturbances than were the central parts. This spatial distribution is in agreement with the findings of Alijani (5), who found that the main cyclonic track crossed Iran north of the Persian Gulf (see also Table 3).

The seasonal fluctuations in the extent to which Iran is affected by surface disturbances are consistant with the variation in size of the Northern Hemisphere westerly vortex as it envelopes the northern half of the country during fall and expands to include all of Iran by late winter, bringing strong short waves into even southern Iran. By summer the westerlies have shifted northward, leaving the country under

the influence of the subtropical highs and beyond the reach of mid-latitude cyclones. As a result, cyclonic activity begins in fall, reaches its spatial maximum during winter, retreats in spring, and is completely absent in summer (Table 3). Therefore, the results of this study confirm the findings of earlier workers (5, 6) that the surface disturbances were frequent in, and caused much precipitation during, the colder period of the year.

Another interesting aspect of the surface disturbance pattern is the number of cyclones without fronts during spring. In this season, "frontless" lows were more frequent than were cyclones with fronts (Table 3). This may indicate that, in spring, solar heating of the earth's surface modifies the air masses to such an extent that they lose their surface identities, particularly at the warm front, and thus the fronts disappear (7). This process often occurred as the cyclones invaded Iran and the associated warm fronts dissipated (Table 4); during spring the frontless lows outnumbered the depressions with frontal systems (Table 3).

Upper Level Disturbances

These disturbances contributed more precipitation days than did any other mechanism over the country. The opposing trend of occurrence and contribution along the north-south direction deserves comment. Their highest absolute frequency was in the Caspian region (Table 2), where they contributed

the lowest percentage to the mean number of annual precipitation days (Figure 4); the opposite pattern developed in the South along the Persian Gulf coast. This pattern appears to be related to the number of uplift mechanisms which occurred over the different parts of the country, in that in the Caspian region almost all of the identified uplift mechanisms were present. In the southern region, however, some of them, like sea effect, were absent, or they contributed a lower percentage, such as surface disturbances and surface heating (Table 5). Consequently, in the North the precipitation days were divided between more uplift mechanisms than they were in the South, resulting in a higher contribution by upper level disturbances in the latter region. The absence of sea effect in the South was discussed earlier in this chapter; the lower contribution by surface disturbances and surface heating is related to the seasonal expansion and contraction of the westerly vortex. As is apparent from Table 2, the northern parts of the country experienced more upper level disturbances than did the southern parts throughout the year, with fewer strong upper level disturbances and, hence, surface disturbances in the South. On the other hand, since the southern limit of the mid-latitude westerly vortex is marked by the position of subtropical high centers, the northward shift of the westerlies in summer brings the southern parts under the subsidence associated with the subtropical anticyclone. This subsidence prohibits most convectional uplift, and only occasional upper level disturbances can invade the area which result in uplift and possible precipitation, as indicated earlier.

The importance of upper level disturbances in the northeastern region (Figure 4), the only region where upper level disturbances were frequent and important through all seasons (Tables 7, 8), is explained by the influence of the Siberian anticyclone and the continental situation of the area. During much of the winter the Siberian anticyclone dominated this region and, consequently, diverted surface disturbances along a more southerly track; in the warmer season because of the continental situation of the region, convection probably occurred with inadequate low-level moisture to produce significant amounts of precipitation. As a result, only upper level disturbances disrupted the stable conditions caused by the Siberian high in winter and were responsible for importing moist air from distant sources which led to precipitation in both seasons.

One important winter characteristic of upper level disturbances was the strength of their contribution in the northwestern, southwestern, and southeastern regions. This, once again, indicates that in winter strong upper level disturbances affected nearly all the country in association with surface disturbances.

In all regions, upper level disturbances produced very high precipitation amounts because they were frequent. But in the northwestern region they yielded the most total summertime precipitation even though surface heating was the most frequent mechanism (Figures 13, 17). An explanation of this pattern lies in the moisture availability for the uplift mechanisms. Convectional uplift operates on local moisture, whereas upper level disturbances bring moist air from outside sources as well. Consequently, because of the continental situation of the northwestern region, upper level disturbances imported more moisture and generated more precipitation than did surface heating.

Most Frequent Uplift Mechanism

During the year as a whole, upper level disturbances, with or without surface disturbances, accounted for the greatest percentage of precipitation days. However, during summer, surface heating became the predominant mechanism, but, since summer precipitation was very light in regions other than the Caspian region, surface heating contributed a small absolute amount of moisture to annual totals (Figure 16). This leads to the conclusion that, at least in terms of precipitation, Iran is under the influence of mid-latitude climate controls. During the study period no type of tropical uplift mechanism (tropical cyclones, monsoon depressions, easterly waves, or the Inter-Tropical Convergence Zone) was detected, a finding in agreement with the conclusions of Snead (7) and Tanaka (8). Although whatever summer precipitation occurred was usually

of convective origin, the uplift mechanism most common in the tropics, I conclude that the country cannot be regarded as being under the influence of tropical controls because the contribution by convection was small in comparison to uplift mechanisms associated with the baroclinic westerlies. Also, the moisture influx through the monsoon low affected only a small part of the country and accounted for low precipitation amounts.

Regions of Precipitation Mechanisms

The cluster analysis, based on all uplift mechanisms, did not result in distinctive contiguous regions. This was true because, first, the mechanisms were interrelated and increases in the percentage contribution of one mechanism resulted in decreases in the others. Second, resulting regions made little spatial sense: region types were scattered across the map with no apparent spatial logic; and many regions were based on fewer than three stations.

However, the regions identified according to the single variable, predominant (most frequent) uplift mechanisms were significantly different from each other and, in addition, showed distinctive characteristics through the subsequent analysis of different uplift mechanisms.

Furthermore, the spatial distribution of the most frequent mechanism displayed regional concentrations with sharp gradient zones between them (Figure 10). The following unique attributes were possessed by each region:

1) The southern region showed the highest contribution by upper level disturbances, but the lowest contribution by surface heating (Table 5). In all seasons except summer, upper level disturbances were the most frequent and important mechanisms; summer precipitation was unimportant.

2) The southeastern region experienced the greatest frequency contribution by surface heating and the minimum frequency contribution by surface disturbances. Also, it had the lowest annual number of precipitation days. This region was the only one that benefitted from Indian monsoon air in summer (Figure 19).

3) The southwestern region received the highest frequency contribution from surface disturbances among all regions. It is the only region where surface disturbances were the most frequent uplift mechanism and yielded much precipitation during the cold period of the year.

4) The northwestern region was distinguished from others because it had a spring maximum of precipitation apparently associated with surface heating.

5) The northeastern region was second to the southern region in percentage contribution by upper level disturbances (Figure 4). It was the only region where, even in summer, upper level disturbances were the most frequent mechanism and gave more precipitation. This region was affected by the

Siberian high through much of the winter, also.

6) The Caspian region was the only region characterized by fall precipitation resulting from sea effect. It was also the region with the highest annual number of precipitation days and lowest frequency contribution by upper level disturbances.

Moisture Sources

Although the Caspian Sea was the moist air source accounting for the highest percentage of combined regional precipitation over the country (Table 16) and the Persian Gulf was frequently the moisture source in the South, moist air from the Mediterranean Sea was most widely involved in precipitation falling over Iran. The effect of the Caspian Sea was limited to a narrow coastal strip north of the Elburz Mountains. Therefore, despite its high contribution, it did not play an important role in the precipitation production over most of the country. The southern and southeastern regions, where southern water bodies are the primary sources but mean precipitation is low, also did not contribute significant amounts to the national mean (Table 15). The Mediterranean Sea was found to be the most frequent source in the northwestern region and a secondary source in the Caspian and northeastern regions. Because these regions occupy a large portion of the country and are heavily agricultural the Mediterranean Sea emerges as the most important water source for the country as a whole.

The Climatology of Heavy Storms

Precipitation in southern Iran was more sporadic and in the form of heavier storms than it was in the North. Westerly disturbances infrequently invaded the South because of its lower latitude and the influence of the stable atmosphere. Thus, most of the time the region experienced dry weather. However, the occasional strong westerly disturbances lifted the moist air supplied by local sources, as indicated by the high dew points, and produced heav ier rains (9,10,11). In the North, with the exception of the Caspian region, both the intensity and percentage contribution of the heavy storms were less. For example, in the northwestern region their mean intensity was 27mm per day and they contributed only 14% of the region's annual precipitation (Table 16). They were less important because, first, the moisture source is located far from the region and therefore the air masses release some of their moisture before reaching Iran, and, second, these areas are usually affected only by uplift mechanisms associated with westerly disturbances, leading to a pattern of frequent precipitation of moderate intensity. Only very rarely do these disturbances have access to very moist and produce torrential precipitation. In the Caspian region, the contribution of heavy storms to regional precipitation was not very high although the intensity of the storms averaged higher than elsewhere over the country. This results because, first, the air is always moist and, second, the uplift mechanisms have similar strength so that the total precipitation is distributed rather evenly between all precipitation events; abnormal, strong mechanisms are very rare.

In conclusion, proximity to water bodies seems to affect the intensity of the precipitation events. That is, uplift mechanisms produced heavier precipitation on coastal regions because of the presence of moist air. This conclusion is in complete agreement with other studies (12).

Original Contributions

The major contribution of this study is the clarification of some aspects of the precipitation climatology of Iran. Specific contributions are listed below:

1) In the past some authors have referred to the climate of Iran as being very complex (13), and this assumption was the main impetus for this research. As was mentioned early in this work, Iran's subtropical location places it in a transitional zone between the Mediterranean climate to the west and the monsoon climate to the east, the Siberian anticyclone to the north and the subtropical highs to the south. The irregular spatial distribution of precipitation (Figure 14) further suggests a complexity of causes. However, this research has demonstrated that in spite of this spatial complexity the precipitation dynamics in Iran can be explained

in terms of a relatively small number of repetitive precipitation mechanisms.

2) A high percentage of precipitation days was caused by westerly disturbances. This percentage increased progressively from north to south.

3) Seasonally, the invasion of Iran by westerly disturbances began first in the North in fall, expanded to include much of the country in winter, and receded in spring, so that by summer the country was almost free of these disturbances.

4) The precipitation mechanisms in Iran showed regional differences.

5) Precipitation events were heavier and more sporadic in the South than in the North; most often, upper level disturbances with no surface disturbances were responsible for these heavy storms.

6) Sea-effect precipitation in the Caspian region resulted not only from the thermally-induced Siberian anticyclone, but also from eastward-moving dynamic ones.

Research Design

The overall appropriateness of the research design is reflected to some degree by the fact that only 14% of the annual precipitation days remained unclassified, whereas 86% were assigned to at least one mechanism (Table 1). Certain research design decisions made during the course of the study deserve comment here.

1) At the beginning of the study, the general category of upper level disturbances was divided into three sub-classes which included upper level divergence, trough axes aloft, and upper cold lows. Subsequently, it became apparent that the percentage contribution by trough axes aloft and upper cold lows was very low (Table 2). Therefore, in the later stages they were recombined into a single class of upper level disturbances. This combination was justified because all three mechanisms were types of uplift generated by vorticity relationships, and the distinction seemed artificial.

2) Similarly, surface disturbances were first divided into sub-classes of cyclones, frontless lows, and frontal systems alone but later were combined into a single category of surface disturbances. The combination was made because, first, most surface disturbances were cold fronts (Table 4), and second, all of them in fact are constituents of one major type of synoptic-scale system in which uplift is concentrated largely along the frontal zones (14).

3) In order to regionalize the country, I relied heavily on the patterns of westerly disturbances because traveling synoptic-scale surface disturbances seldom exist without the support of upper level triggers; both are interrelated through the vorticity principle. Thus, since most of the precipitation in Iran was generated by both upper level and surface disturbances, all related through the vorticity principle, the results of this study convey the idea that the

long-term precipitation pattern in Iran is related to the strength, frequency, and spatial distribution of upper level vorticity centers in the baroclinic westerlies.

4) The designation of mechanisms accounting for each precipitation day proceeded on an assumed order. In other words, evidence was first sought for the presence of upper level disturbances, followed by surface disturbances. On the coastal regions, in the absence of either mechanism, sea effect was deduced if the required conditions existed. Surface heating was then invoked if an event was still unexplained and the predetermined criteria were met. This approach gave generally acceptable results. Further, this procedure lowered the probability of overlap between the mechanism so that no precipitation day was counted more than once in the case of multiple causation.

5) Another important point about the research methods used in this study concerns the scale and coverage of the synoptic weather maps. Although it is likely that the 24-hour map interval and smaller scale obscured some short lived or mesoscale mechanisms, they were useful, nonetheless, in identifying at least one mechanism for each precipitation day 86% of the time throughout this study. This fact underscores their usefulness, especially for areas where local meteorological data are not available. Since over at least part of the world local meteorological networks are not extensively developed, large-scale synoptic maps with short intervals are not available, or there are very few local soundings, these

maps have important utility in the explanation and understanding of precipitation mechanisms. This study has shown that maps of this kind can be used in a remote part of the world to yield useful results.

Limitations of the Study

During this research some limitations inherent in the methods were recognized, but they are not considered to be factors affecting the validity of the results. They are mentioned here as areas for future improvements. One potential source of error was the lack of synchrony between the timing of the precipitation observations and the time of the synoptic maps. In this study 12GMT synoptic weather maps were used to investigate the synoptic origin of daily precipitation. It is possible that occasionally during each 24-hour interval other mechanisms in addition to the one(s) depicted on the map were responsible for that day's precipitation, or that none of the responsible mechanisms were present at the map time over the respective station. Because of this imperfect synchrony and the smaller scale of the maps, this study was not able to demonstrate the effect of mountain ranges on precipitation despite the mountainous nature of the country. Unfortunately, these maps were the only current data sources available, and the high percentage of explained precipitation events confirms their value as a research tool nonetheless. Also, the brevity of the study period (5 years)

did not constitute a serious limitation because each day was treated as a separate observation, and it is likely that all important synoptic precipitation-inducing situations were encountered during the period.

The method used for assigning precipitation mechanisms contained a few minor weaknesses. First, it underestimated the contribution by surface heating because, as noted earlier, even warm summer days were classified into a dynamic uplift mechanism category when evidence so indicated, in spite of possible assistance by surface heating. Second, the 80^{o}F minimum threshold designated for surface heating was not appropriate because during most summer days the temperature was above this level. A similar subjective method was used for determining sea effect, in that the minimum threshold was a 15^{o}F difference between windward and lee shore dew point temperatures in the Caspian region. Although the general research method would give the same overall results regardless of the order of steps used to assign each day to a mechanism, it was not able to determine the relative influence of each mechanism during days when precipitation resulted from multiple causes.

In other studies of this type which are concerned with determining the relative influence of precipitation mechanisms in Iran, the following modifications are recommended:

1) Synoptic maps of shorter interval and larger scale should be used to facilitate more detailed studies.

2) The degree of uplift associated with westerly disturbances should be measured according to the amount of vorticity advection.

3) The thermal instability of the atmosphere should be measured through the use of local soundings.

4) The amount of daily precipitation should be statistically related to the degree of vorticity advection, atmospheric instability, and the amount of moisture in the atmosphere.

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CHAPTER VII

SUMMARY AND CONCLUSIONS

The synoptic origin of precipitation in Iran was investigated by utilizing daily precipitation totals of 40 stations distributed over the country, obtained from the Meteorological Organization of Iran for the period 1963 to 69. Responsible uplift mechanisms for each precipitation event at each station were determined from 12GMT surface and 500mb synoptic maps of the Northern Hemisphere. Importance of uplift mechanisms was judged on the basis of their contribution to the number of each station's annual or seasonal precipitation days.

The results of this research strongly suggest that upper level disturbances, alone, were the most frequent and important uplift mechanism in Iran throughout the year; although surface heating produced a high percentage of summer precipitation, its overall importance to annual totals was low because summer precipitation is normally light. Second to upper level disturbances in contribution to both precipitation days and precipitation totals were surface disturbances, which caused most of the cold-period precipitation over the western highlands of the country. Sea effect contributed to

fall and early winter precipitation along the southwestern coast of the Caspian Sea. The combined category of upper level and surface disturbances (traveling westerly disturbances) accounted for the highest percentage of the country's precipitation totals. The results of the study led to the conclusion that, first, Iran is under mid-latitude climate controls in terms of precipitation climatology and, second, a well-developed westerly flow pattern, strong enough to generate surface disturbances, develops seasonally over the northern parts of the country and only occasionally extends over the southern portions of Iran.

The country was regionalized according to the spatial variance of the Z-score values of the percentage contribution by the predominant uplift mechanism (westerly disturbances) to the stations' annual precipitation days. The resultant regions were statistically distinct from each other and had unique climatological characteristics, as follows:

1) The southern region experienced the greatest frequency contribution by upper level disturbances among all regions in all seasons except summer.

2) The southeastern region received the greatest percentage of its precipitation days from surface heating but the lowest percentage from surface disturbances among the regions.

3) Among all regions, surface disturbances caused the greatest percentage of precipitation days in the southwestern region.

4) Surface heating accounted for a greater percentage of spring time precipitation days in the northwestern region than in any other northern region of the country.

5) The northeastern region was unique in that, even in summer, upper level disturbances were the most frequent and important mechanism.

6) The Caspian region had the lowest total contribution from upper level disturbances among all regions and was the only region with a significant contribution from sea effect.

Important sources of atmospheric moisture were determined for days with 10mm or more precipitation at representative stations through the use of both surface and 700mb level data. The results suggest that southern water bodies (the Persian Gulf and the Gulf of Oman) were the most frequent source for the southern, southeastern, and northeastern regions, but that the Mediterranean Sea contributed the greatest amount of moisture in the northwestern region. The Caspian Sea contributed the highest percentage of moisture in the Caspian region; during summer the Bay of Bengal was the most frequent moisture source in the southeastern region. In terms of moisture contribution to the country as a whole, the Caspian Sea led all sources, but its influence was limited to a narrow coastal strip, whereas the Mediterranean Sea, though with a lower percentage contribution, provided the moisture for a larger portion of the country, particularly the agricultural areas.

The nature of precipitation was very sporadic and heavy in the South compared to the North. In the South most of precipitation was produced from very heavy storms, whereas in the North storms with moderate intensity were most often responsible for the region's precipitation.

The results of this study suggest additional questions regarding the precipitation climatology of Iran. Some of these are summarized below.

1) A high percentage of precipitation in Iran was caused by westerly disturbances. These disturbances travel eastward along the configuration of the upper-level mean flow pattern. What is the relationship between the spatial distribution of precipitation mechanisms in Iran and the position of upper-level mean long wave troughs over the country and adjacent regions?

2) The contribution by westerly disturbance was concentrated over the southern and northeastern parts of the country, where subtropical highs and the Siberian anticyclone, respectively, most often occur. A relationship may exist between the presence of these controls and the relative importance of westerly disturbances compared to other mechanisms. To what degree do these anticyclones relate to the occurrence and spatial concentration of precipitation mechanisms?

3) An assessment of the influence of mountain ranges was not sought at the outset of this study because it was

assumed that the mountain ranges only enhance existing uplift mechanisms. However, the concentration of precipitation days along the mountains does suggest a possible influence by the mountains themselves. Do these mountain ranges exercise their influence because they interfere with the influx of moisture, enhance the already-existing uplift mechanisms, or generate additional uplift?

4) It was suggested that the prevalence of the surface heating mechanism in the northwestern region was caused by differential heating on the mountain slopes. Under what synoptic circumstances does this process occur?

5) There was no tropical effect detected in this study. Is it likely that a longer study period would demonstrate that uplift mechanisms of tropical origins affect the country?

6) Under what specific synoptic situations does the moisture influx from each moisture source affect Iran?

7) The frequent occurrence of heavy storms in the South was attributed to the abundance of moist air in the region. To what degree is moisture, rather than the relative strength of uplift mechanisms, actually responsible for this more intense precipitation?

This research was a preliminary and exploratory study regarding the synoptic origin of precipitation in Iran. Although it provided only a general image of the spatial and seasonal variations of both the dynamics and moisture sources of precipitation over the country, this study may be used for both a basic information source and for planning more detailed studies on the subject.

APPENDIX I

SELECTED STATIONS WITH THEIR GEOGRAPHIC COORDINATES, ELEVATION, AND CLIMATIC DATA (1965-69)

Station	Latitude	Longitude	Elevation (m)	Mean surface pressure (mb)	Mean annual precipitation (mm)	Mean annual precipitation days	Percentage of precipitation days caused by: Upper level disturbances	Surface disturbances	Surface disturbances plus upper level disturbances	Surface heating	Sea effect	Indeterminate
Abadan	30:22	48:15	11	1018.5	129.6	30	57	25	82	2		16
Ahvaz	31:20	48:40	18	1018.6	212	22	58	25	83	5		12
Anzali	37:28	49:28	-16	1023.9	1723.4	133	39	14	53	7	18	22
Arak	34:06	53:41	1383	867.3	378.7	64	45	22	67	11		22
Bam	29:06	58:24	1067	898.8	44.1	17	60	15	75	9		16
Bandar Abbas	27:13	56:22	10	1016.2	103.5	12	71	19	90	3		7
Bandar Lengeh	26:35	54:50	14	1015.5	60	14	81	9	90	2		8
Birjand	32:52	59:12	1455	*	152	38	54	27	81	6		13

APPENDIX I (Continued . . .)

Station	Latitude	Longitude	Elevation (m)	Mean surface pressure (mb)	Mean annual precipitation (mm)	Mean annual precipitation days	Percentage of precipitation days caused by					
							Upper level disturbances	Surface disturbances	Surface disturbances plus upper level disturbances	Surface heating	Sea effect	Indeterminate
Bushehr	28:59	50:50	4	1038.4	202.5	29	64	21	85	00		15
Chahbahar	25:25	60:45	6	*	92	10	59	8	67	8		25
Dezful	32:24	48:23	143	1005.1	340.5	45	53	23	76	6		18
Esfahan	32:37	51:40	159	844.9	95	29	55	22	77	3		20
Gorgan	36:51	54:28	105	1003.9	684.7	101	47	15	62	16	1	21
Hamadan	35:12	48:43	1644	825.1	312.6	66	49	16	65	13		22
Iranshahr	27:12	62:42	566	458.8	72.2	12	57	10	67	19		14
Jask	25:38	57:46	4	1016.3	164.5	8	73	1	74	5		21
Kashan	33:59	51:27	955	913.3	138.6	44	57	15	72	4		24
Kerman	30:15	56:58	1749	828.3	86.5	25	60	19	79	11		10
KermanShah	34:19	47:07	1322	871.2	567.4	75	52	24	76	5		19
Khorram Abad	33:29	48:22	1160	885.3	537.7	81	47	21	68	7		25
Khoy	38:33	44:58	1157	891.2	368.3	101	52	20	72	8		20

APPENDIX I (Continued . . .)

Station	Latitude	Longitude	Elevation (m)	Mean surface pressure (mb)	Mean annual precipitation (mm)	Mean annual precipitation days	Percentage of precipitation days caused by					
							Upper level disturbances	Surface disturbances	Surface disturbances plus upper level disturbances	Surface heating	Sea effect	Indeterminate
Mashad	36:16	59:38	985	910.5	221.1	59.4	60	17	77	5		18
Qazvin	36:15	50:00	1302	*	317.9	86	45	22	67	7		
Ramsar	36:54	50:41	-20	1022.7	120.4	120.2	50	11	61	11	8	20
Sabzevar	36:13	57:40	944	914.6	151.7	44	63	22	85	2		13
Sanandaj	35:14	47:00	1373	854.9	531.1	95	52	17	69	9		22
Saqez	36:15	46:16	1476	855.1	573.7	71	51	23	74	6		20
Semnan	35:33	53:23	1138	890.8	109.7	39	59	15	74	8		18
Shahr Kord	32:19	50:51	2066	797.9	312	46	51	30	81	1		18
Shahroud	36:25	55:02	1366	868.9	151.3	51	45	21	66	10		24
Shiraz	29:36	52:32	1505	851.7	317	39	66	14	80	2		18
Tabriz	38:08	46:15	1349	864.7	387.9	97	44	20	64	12		24
Tabas	33:36	56:54	691	941.6	66	29	57	22	79	3		18
Tehran	35:41	51:19	1204	*	217.6	65	54	17	71	10		19

APPENDIX I (Continued . . .)

Station	Latitude	Longitude	Elevation (m)	Mean surface pressure (mb)	Mean annual precipitation (mm)	Mean annual precipitation days	Percentage of precipitation days caused by					
							Upper level disturbances	Surface disturbances	Surface disturbances plus upper level disturbances	Surface heating	Sea effect	Indeterminate
Torbat Heydarieh	35:16	59:13	1333	868.6	252.6	53	58	23	81	3		16
Urmia	37:40	45:04	1297	*	439.6	87	50	22	72	6		22
Yazd	31:54	54:24	1230	881.5	54.1	19	54	19	73	18		9
Zabol	31:02	61:29	487	963.4	42.2	15	63	18	81	1		18
Zahedan	29:28	60:53	1370	866.9	90	23	51	16	67	16		17
Zanjan	36:41	48:29	1663	837.3	351.9	86	45	20	65	14		21
$\overline{X}$					306.4	52	55.45	18.55	73.55	7.42		
Sd					322.95	33.22	8.28	5.23	8.1	5.06		
CV					105	64	15	28	68			

SOURCE: First six columns were obtained from the Meteorological Organization of Iran; the author contributed the data in the last six columns.

*Not available.

APPENDICES

APPENDIX 2

FORM OF MAP ANALYSIS

		Uplift Mechanisms							
		Upper Level Disturbances			Surface Disturbances				
Date	Amount of precipitation (mm)	Positive vorticity advection	Trough axis aloft	Upper cold lows	Cyclones fronts	Cyclones without fronts	Sea Effect	Surface heating	Undetermined

APPENDIX 3

Stations included in the cluster analysis with their Z-scores for the uplift mechanisms

Cluster	Station	Upper Level disturb-ances (only)	Surface disturb-ances	Surface heating	Upper Level & surface disturb-ances	Sea effect
1	Abadan	.19	1.23	-1	1.04	-1.1
	Ahwaz	.3	1.23	-.47	1.17	-1.1
	Bandar Abbas	1.88	.09	-.86	2.03	-1.1
	Birjand	-.15	1.61	-.27	.92	-1.1
	Bushehr	1.05	.57	-2.51	1.41	-1.1
	Dezful	-.27	.85	-.27	.3	-1.1
	Esfahan	-.05	.66	-.85	.42	-1.1
	KermanShah	-.39	1.04	-.47	.3	-1.1
	Sabzewar	.91	.66	-1	1.41	-1.1
	Saqez	-.51	.85	-.27	.05	-1.1
	Shahr Kord	-.54	2.10	-1.2	.92	-1.1
	Tabas	.21	.66	-.86	.67	-1.1
	Torbat Heydarieh	.3	.85	-.86	.8	-1.1
	Urmia	-.66	.66	-.26	-.19	-1.1
	Zabol	.93	-.1	-1.2	.92	-1.1
	Mean	.21	.86	-.82	.81	-1.1
2	Bam	.55	-.68	.31	.18	-1.1
	Kashan	.19	-.68	-.66	-.19	-1.1
	Kerman	.55	.09	.7	.67	-1.1
	Khoy	-.39	.28	.12	-.19	-1.1
	Mashhad	.55	-.3	-.47	.42	-1.1
	Sanandaj	-.39	-.3	.31	-.56	-1.1
	Semnan	.45	-.68	.12	.05	-1.1
	Shiraz	1.29	-.87	-1	.18	-1.1
	Tehran	-.15	.3	.51	-.31	-1.1
	Mean	.29	-.31	-.00	.02	-1.1

APPENDIX 3 (Continued . . .)

Cluster	Station	Upper level disturb-ances (only)	Surface disturb-ances	Surface heating	Upper level & surface disturb-ances	Sea effect
3	Chahbahar	.45	-2.02	.12	-1.3	-1.1
	Gorgan	-1.02	-.68	1.69	-1.42	-.94
	Hamadan	-.78	-.49	1.1	-1	-1.1
	Iranshahr	.19	-1.6	2.27	-.8	-1.1
	Ramsar	-.65	-1.4	.7	-1.5	-.12
	Yazd	-.17	-.09	2.1	-.07	-1.1
	Zahedan	-.51	-.49	1.69	-.81	-1.1
	Mean	-.25	-.96	1.38	-.98	-.93
4	Anzali	-1.98	-.87	-.1	-2.54	1.1
	Arak	-1.2	.66	.7	-.81	-1.1
	Khorramabad	-1.02	.47	-1	-.69	-1.1
	Qazvin	-1.2	.66	-.1	-.81	-1.1
	Shahroud	-1.2	.47	.51	-.93	-1.1
	Tabriz	-1.38	.28	.9	-1.18	-1.1
	Zanjan	-1.26	.28	1.29	-1	-1.1
	Mean	-1.32	.27	.31	-1.13	-.78
5	Bandar Lengeh	3.08	-1.8	-1	2.08	-1.1
	Jask	2.14	-3.35	-.47	.05	-1.1
	Mean	2.97	-2.57	-.73	1.04	-1.1

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