Al-Hegbani, Abdullah Abdulaziz (1993) *Physical and economic factors and their effects on development of solar energy in Saudi Arabia*. PhD thesis.

PHYSICAL AND ECONOMIC FACTORS AND THEIR EFFECTS ON DEVELOPMENT OF SOLAR ENERGY IN SAUDI ARABIA

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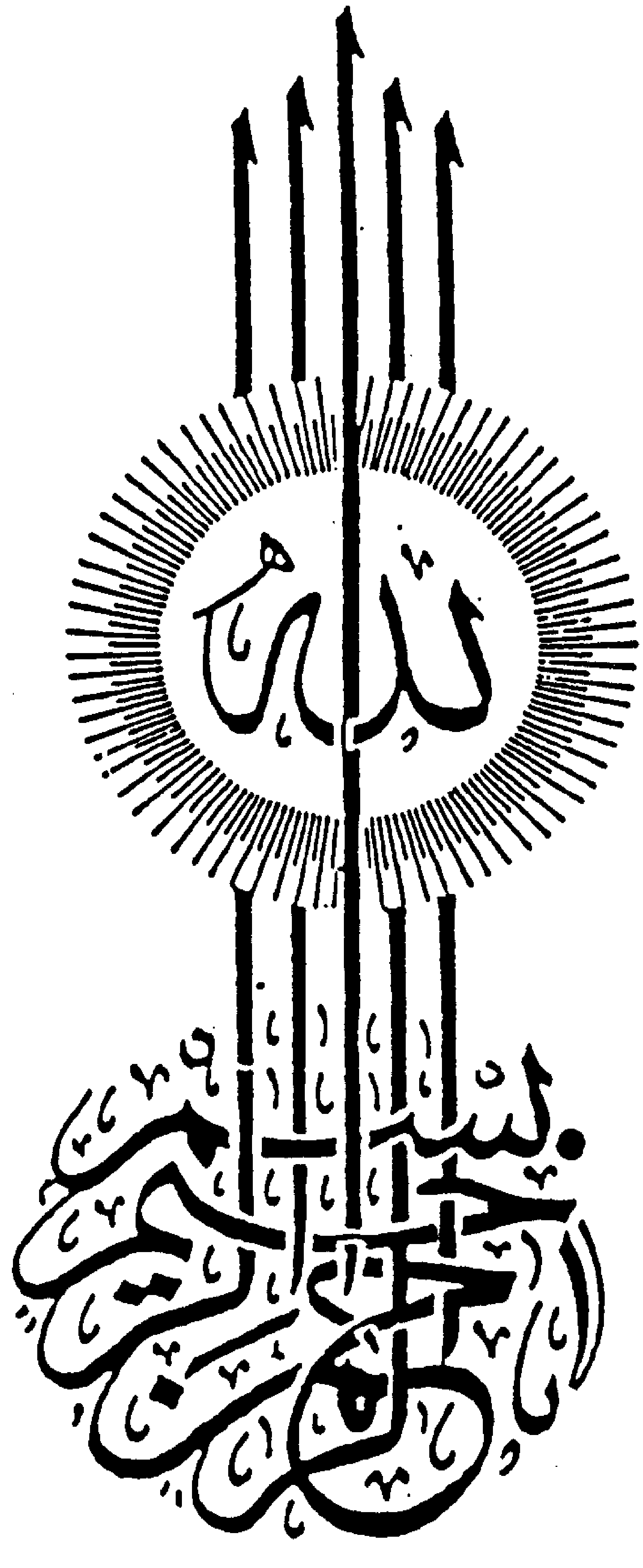
March, 1993



IN THE NAME OF ALLAH THE MERCIFUL
THE COMPASSIONATE

ACKNOWLEDGEMENTS

All praise belong to Allah and peace and blessings be upon the messenger of Allah. The completion of this thesis would not have been possible without the co-operation and great assistance of many helpful people. Although, much to my regret, it is impossible in this short note to mention all their names, I would like to extend my thanks to all of them.

I wish to express my deep appreciation and sincere gratitude to my advisors, Dr. Gordon Dickinson, and Prof. Arthur Morris for their guidance, help, and encouragement. Thanks are also extended to Dr. A. Morrison, and Dr. A. Findlay for their valuable comments and suggestions. Also, I would like to thank Prof. I. B. Thompson and Dr.J. Briggs for giving me a place in this department and for their assistance.

I must acknowledge the financial support that I received from the Imam University in Riyadh, Saudi Arabia. Also, I would like to thank the Department of Geography at the College of Social Sciences in Riyadh for the encouragement and assistance, particularly, Dr. A. Al-Khalaf and Dr. I. Al-Dousary.

I would like to thank Mr. U. Tarabulsi, the deputy minister of Petroleum and Mineral Resources in Riyadh, S. A. for his assistance in providing the data related to crude oil in Saudi Arabia. Special thanks to Mr. A. Heneady, the director of Meteorology and Environmental Protection Administration in Jeddah, S. A., and Mr. S. Al-Tubaishi, the director of Hydrology Division at the Ministry of Agricultural and Water in Riyadh, S. A., for providing the meteorological data related to the research.

Finally, I would like to express my appreciation to Mr. D. Evans for his assistance and comments regarding the solar radiation maps. Mr. H. Al-Shareedy, the director of Al-Uyaynah High School, for his hospitality and assistance during the fieldwork at Al-Uyaynah village. Last but not least, special thanks to my wife for her support, encouragement, and patience.

Abstract

The search for alternative energy resources began early in this century after the discovery of crude oil, but in 1973, when crude oil prices dramatically increased, the search for new energy sources intensified. The conservation of oil consumption, mainly in industrial countries has been more strictly applied, due to the limited quantities of fossil fuels, especially crude oil which is expected to be depleted within the next few decades. Moreover, the increasing level of air pollution and its severe consequences on human, animal, and plant life and climate, has forced the world to try to reduce air pollution emissions in the short-run, and to search for more reliable, renewal energy resources

Amongst renewable energy resources, solar energy has attracted much attention due to its unique characteristics, including its wide availability in huge quantities, particularly at the middle latitudes, its relatively simple harnessing compared with nuclear energy, and most importantly, its clean source which does not discharge any pollution emission.

The intensity of solar radiation in Saudi Arabia reaches an average of 290 wm^{-2}, one of the highest insolation values in the world. Here attention has been focused on solar energy as the main alternative source of power. However, there is a great variation in the distribution of incoming solar radiation within Saudi Arabia. This variation is attributed mainly to six major factors. They include the following :

1. Sunshine duration

2. Insolation index
3. Altitude of the station
4. Specific humidity
5. Cloud cover, and
6. Dust storms

In order to measure the effect of each factor mentioned above on the variation of incoming solar radiation, a multiple linear regression model is developed and used. This is the most appropriate method to explain the interrelationships between the determinants and their dependent variable.

In addition to the physical factors, the human factor is considered in this thesis as a result of the crucial effect of the perspectives and attitudes of people upon solar energy development. Therefore, a questionnaire was conducted at Al-Uyaynah Village, northwest of Riyadh, which has a solar-generated electricity in Saudi Arabia.

Location of future solar energy facilities is a very important issue for decision-makers as a result of the great variation of incoming solar radiation, not only from one site to another, but also from time to time. Appropriate locations should consider all six factors mentioned above in order to find the optimum intensity of solar radiation.

CONTENTS

Page No.

LIST OF TABLES

LIST OF FIGURES

Page No.

LIST OF PLATES

CHAPTER ONE

INTRODUCTION

1.1 The Energy Dilemma

The development of alternative energy resources gained a high momentum in the 1907s, particularly since 1973, following the dramatic increases in crude oil prices from $1.77 per barrel in September, 1973, to $ 5.17 in November of the same year. As a result of the increase in oil prices, many industrial countries, in North America and Western Europe, followed an energy conservation policy to reduce their heavy dependence on imported oil. Conservation policies led to a substantial decrease in oil consumption and an increase efficiency, particularly in vehicle engines.

Moreover, the instability in crude oil production, especially from OAPEC members as a result of regional conflicts, such as the Iraq-Irani war (1979-1989) and the Gulf Crisis in 1990-1991, has forced major industrial countries to expand the pace for alternative energy development.

The increasing level of air pollution, which is clearly noticed in cities with high population density such as New York, London, and Cairo, has led many countries to reduce the quantities of polluting emissions from industry, power plants, and vehicles, the major sources of air pollution. During the Gulf crisis more than 600 oil wells in Kuwait were burning, causing massive damage to human, animal, and plant life, not only in the Gulf region but also in areas located at more than 500 KM away. As a result of these pollution problems the search for alternative energy resources has became a dominant concern in many countries especially in oil importing countries.

Amongst energy alternatives, solar power has attracted much attention due to its unique features such as its clean source, widespread availability, and particularly, its undepletable source of energy. Therefore, research and experiments have focussed on the development of this source to make it economically competitive with other fossil fuels. These efforts resulted in a remarkable decrease in solar energy. Over the past two decades, the cost of photovoltaic electricity has fallen from US $ 30 per kilowatt / hour to just US $ 0.30 (Flavin and Lenssen, 1991). Nevertheless, the cost of solar energy production is still five to ten times more expensive than fossil fuel which makes it uncompetitive.

Like the other alternative energy sources, solar energy development is taking a long time to become technically viable and economically competitive with conventional energy sources. For each new source, the energy supplying capabilities must first be recognised, then the technologies developed and tested to transform the energy into usable forms, and finally the technologies must be made available to the users. For example, oil and natural gas only gradually achieved their major role in the energy market over a long period after their discovery even though these fuels were attractive from the beginning, due to their cost advantages, flexibility of use and convenience in transportation, storage and combustion (IEA, 1987). However, this thesis does not investigate the economic viability of solar energy versus crude oil. The production cost of solar energy will be discussed to some extent in Chapter Eight.

Due to the high intensity of solar radiation in Saudi Arabia, solar energy has become the main alternative source that has been promoted for development by universities and research institutes in the country since the 1970s. Despite its high intensity, the distribution of solar radiation over Saudi Arabia is not stable either in time or from one station to another. The variation of solar radiation in Saudi Arabia is a result of many factors that either increase its intensity, such as sunshine duration, altitude, and insolation index, or decrease it, such as specific humidity, cloud cover, and dust storms through scattering, reflection and absorption processes that attenuate the total amount of incoming solar radiation at the earth's surface. Therefore, the variation of incoming solar radiation over Saudi Arabia will be investigated based on these main six factors in Chapters Six and Seven.

The characteristics of the appropriate locations of solar energy plants need to be investigated since solar radiation is widely distributed over relatively large areas in Saudi Arabia. In addition to population density, many other important factors should be considered when choosing solar energy plants location such as, the intensity of solar radiation, cloud cover, dust storms, and humidity due to their influence on solar energy production. The location problem of solar energy plants is discussed fully in Chapter Eight.

In addition, human factors play a crucial role in solar energy development. The human perspective and attitude must be considered before introducing solar energy system, especially at remote villages where the education level is low compared with urban population. Thus, one of the main objectives of this thesis was to conduct a questionnaire at Al-Uyaynah Village, that had a solar powered generation, in addition to Al-Jubailah and Al-Hegrah villages, to investigate the perspectives and attitudes of people towards solar energy development.

1.2 Thesis Objectives

Solar energy development in Saudi Arabia has two dimensions, physical and human. The physical dimension involves the main meteorological factors affecting the intensity of incoming solar radiation and its spatial and temporal variations. The human dimension includes the economic factors influencing the appropriate location of solar energy plants in Saudi Arabia, and the awareness of the respondents about the potential of solar energy and their attitudes towards solar energy development. Due to their crucial role and influence on energy-policy makers, public attitudes should be considered when introducing a new source of energy to tackle any problem that may arise and to make a smooth transition to the new energy source. Therefore, particular attention has been given to the effect of age, education level, and the place of origin of the respondents on their attitudes to solar energy development, as the key factors shaping an individual's attitudes.

Thus, the following are the main integrated objectives of this thesis :

1. Saudi Arabia receives a very high amount of solar radiation that is capable to meet the energy requirement when fully developed not only in Saudi Arabia but also in other countries within the middle latitudes. Therefore, the first objective is to examine the potential role that solar energy may play in future energy development in Saudi Arabia. This will be discussed in Chapters Two and Three.

2. Despite the high intensity of solar radiation in Saudi Arabia, there is a noticable temporal and spatial variation, particularly in the central and northern regions of the country. Thus, the second objective is to determine

the temporal and spatial characteristics of the pattern of solar radiation distribution in Saudi Arabia based on the available meteorological data such as sunshine duration, altitude, insolation index, specific humidity, cloud cover, and dust storms, and by using a modified regression model of solar radiation. These will be discussed in Chapters Six and Seven.

3. Although the southwestern part of Saudi Arabia is the most appropriate location for solar energy development, there are some other locations that have high potential for solar energy development in this counrty, particularly in the western and central parts. Therefore, the third objective of this thesis is to examine the appropriate locations for solar energy plants in Saudi Arabia based on the available physical and human factors, particularly solar radiation intensity and population density. This will be discussed in Chapter Eight.

4. Solar energy development, as a new source of power, depends, to some extent, on the public perspectives and reaction. The satisfaction of the customers is very crucial for solar energy development, particualrly for private commercial sector. Therefore, the fourth objective is to investigate the human dimension of solar energy development through the people's attitudes towards solar energy development in Saudi Arabia. This will be discussed in Chapters Nine, Ten, and Eleven.

1.3 Study Scope

This thesis is divided into three main parts, as follows:

1. The first part focusses on the potential of solar energy in the light of

the current energy situation in Saudi Arabia, mainly crude oil and natural gas, and discusses the production, consumption, exports, and the life-span of these two sources of energy. It also examines the air pollution problem, caused by the emissions generated by fossil fuel consumption, and the need for an alternative clean source of energy.

2. The second part of this thesis investigates the temporal and spatial variations of incoming solar radiation in Saudi Arabia and determines the major factors influencing the intensity of incoming solar radiation in Saudi Arabia and their effect on the distribution and variation of incoming solar radiation over this country. A multiple linear regression is applied to estimate the effect of these major factors upon this variation. The spatial and temporal distribution patterns of incoming solar radiation are examined fully in this part.

3. The final part discusses the appropriate location of solar energy plants, and the effect of the meteorological and socio-economic factors that play a significant role in the final location decision with emphasis on the relationship between incoming solar radiation intensity and population density. It also evaluates some solar energy applications that are already in use in Saudi Arabia. This part also investigates the human dimension of solar energy development. This includes a survey which aims at analysing perspectives and attitudes of people at Al-Uyaynah Village. Public awareness of the potential of solar energy as a major alternative source of power in Saudi Arabia should be the cornerstone of its development. The public

must be convinced and satisfied before large-scale production of solar energy is intended, to make sure that there is a high demand for production. Therefore, this survey was conducted to measure the degree of their awareness, satisfaction, and attitude towards solar energy development.

1.4 Study Area

1.4.1 Location

Although the Al-Saud House has ruled most of the Arabian Peninsula, particularly the central part, for more than 300 years, the foundation of Saudi Arabia as a modern state began in 1932 when King Abdulaziz declared the unification of this country. The Kingdom of Saudi Arabia occupies most of the Arabian Peninsula. It is bounded in the north by Kuwait, Iraq, and Jordan, to the south and south-east by Yemen and Oman, to the west by the Red Sea, and to the east by the Arabian Gulf, Qatar, and United Arab Emirates. Saudi Arabia lies between 16^{o} and 32^{o} 12' north of the equator and 34^{o} 36' and 56^{o} east of Greenwich. Thus, Saudi Arabia is located at the middle latitudes with a very high average of solar radiation. The total area of Saudi Arabia is about 2.225 million km^2.

1.4.2 Climate of Saudi Arabia

The climate of Saudi Arabia is characterised by hot, dry and dusty summers with a noticeable increase of humidity in the coastal areas, and cold winters with small amounts of rain except in the south-western area, where rain tends to increase due to the higher altitude of this part. This is a distinctive kind of climatic feature which has a significant influence on the amount of incoming solar radiation in Saudi Arabia. Although the average intensity of solar radiation in this country is very high, there is a noticable temporal and spatial variation in the intensity of solar radiation. This variation is attributed mainly to the attenuating factors, particularly dust storms which reach as high as 13 days a month in the central region. Chapter Four discusses the climate and the physical characteristics of Saudi Arabia in some detail.

1.4.3 Population and Regional Elements

According to Al-Shareef (1987), the population of Saudi Arabia increased from 3.3 million inhabitants in 1962 to 6.7 million inhabitants in 1974. This figure did not include Saudi citizens who were out of the country at the time of the census. The latest census in 1992 indicated that the total population increased to 16.9 million inhabitants (Al-Eqtisadiah, 1992). In 1962, 76 per cent of the population were in the rural areas, while in 1974, it was 62 per cent. In the late 1970s, the percentage of rural population decreased to 40 per cent, due to urban migration. Although the population density increased from 1.5 per cent in 1961 to 3 per cent in 1974 (Al-Shareef, 1987), this is still a very low value due to the large area of Saudi Arabia.

Moreover, most of the population in the rural areas is widely distributed in isolated villages particularly in the southwestern part of Saudi Arabia. The connection of these isolated villages to the national electricity grid is very expensive particularly for villages located at a higher altitude. These remote villagaes can be served by isolated networks based on diesel generators, but finding staff to operate and maintain such systems and the regular supplies of fuel can often present real difficulties for the power utility. Therefore, solar energy offers a number of attractive advantages, in that it is modular, need no fuel, and the maintenance requirements are slight.

1.4.4 Economy

Like the Arabian Gulf States, the economy of Saudi Arabia depends highly on oil and natural gas revenues. According to Saudi Arabian Monetary Agency (1989), oil and natural gas revenues represented 70 per cent of the total budget in 1988 / 1989. In 1990 it increased to 73 per cent. This was due to the increase in oil prices as a result of the Gulf Crisis, when prices reached as much as $ 40 per barrel, compared with only $17 per barrel before the Gulf Crisis. Due to the instability of oil prices, the Government of Saudi Arabia decided in the mid 1970s to diversify its income revenues by encouraging the establishment of oil-related industries such as petrochemicals. In addition, the agricultural sector has significantly expanded helped by government loans with a high discount of up to 50 per cent to farmers.

Industrial and agricultural development depend largely on crude oil as the main source of fuel. However, the crude oil reserve is limited, despite its large quantity, and expected to be depleted within the next five to six decades. Therefore, it is urgent to consider the development of solar energy as the main alternative source of power as soon as possible especially with the current adequate finance of Saudi Arabia which enable it to support the research and development of solar energy.

In summary, the central research question is to investigate the potential role of solar radiation to meet the energy requirement in Saudi Arabia when fully developed, and to discusse the temporal and spatial variation of this resource as well as the appropriate locations for solar energy development and the physical and human factors affecting this potential. This investigation will be based on the availabe meteorological data influencing the intensity of solar radiation in Saudi Arabia, such as sunshine duration, insolation index, altitude, specific humidity, cloud cover, and dust storms. Furthermore, a questionnaire was conducted at Al-Uyaynah Village to see the attitudes and reaction of the respondents towards solar energy development in Saudi Arabia.

CHAPTER TWO

IMPLICATION OF RECENT TRENDS IN ENERGY USE IN SAUDI ARABIA

2.1 INTRODUCTION

The necessity of developing an alternative source or sources of energy stems from the fact that the fossil fuel reserves, mainly crude oil and natural gas, are limited and expected to be depleted over a relatively short time scale, despite their current large reserves. Moreover, the world's population, particularly in the third world, is steadily increasing and the per capita demand for energy is increasing substantially, especially in the transportation and electricity generation sectors. The majority of world population is now living in developing countries. In these countries, the level of energy demand tends to increase as the level of development increases and growth rates may be rapid. Fortunately, there are good opportunities for development of alternative sources of energy that can substitute for fossil fuels. Present reserves and rates of use of fossil fuels can supply the world with its energy requirements over the time needed to bring an alternative energy source on stream. Investment in renewable energy resources will allow the pace of the development to reach a stage when renewable energy resources can supply a large proportion of the world energy demand. This can occur before fossil fuels are exhausted.

Quraeshi (1984), addressed some basic questions in order to find an exit from the energy dilemma. He said....

> " In order to resolve this energy dilemma , all nations must address the same basic questions, which are: How can one increase the reliability of energy supply, ensure the gradual replacement of hydrocarbons, utilize the natural energy resources within one's own national boundaries to provide better protection of consumer, and to provide acceptable forms of energy to preserve the environment form pollution. "
>
> Quraeshi, 1984. p. 25.

The answer to these questions lies in increasing the pace of developing renewable energy resources, particularly solar energy, and decreasing the heavy dependence on conventional energy resources, such as crude oil, natural gas, and coal, the main sources of air pollution that have resulted in severe consequences to human, animal, and plant life. In other words, there must be a continuing shift from conventional energy resources towards renewable energy resources. Amongst renewable energy resources, solar energy is the main source that has the potential to supply energy needs, particularly for countries located in the middle latitudes where the intensity of solar radiation received at the earth's surface is high. Moreover, the technology of harnessing solar energy is relatively simple. This makes it more attractive to develop.

Thus, there are four reasons for doing this research. First, crude oil and natural gas reserves in Saudi Arabia are limited in quantity, despite the recent discoveries of additional oil reserves, and expected to be depleted within approximately the next five to six decades, particularly when crude oil reserves in some Western countries are depleted by the turn of this century, as predicted. Second, there is a worldwide concern about the increasing level of air pollution especially in the last few years which has resulted in remarkable changes in the climate system, due to the accumulation of fossil fuel emissions, which are clearly noticed at the beginning of the 1990s, though it is too early to say wether these changes are permanent or temporary. Third, there is a very high potential for solar energy development in Saudi Arabia due the high intensity of solar radiation and the low population density. Moreover, Solar energy is a clean source, widely distributed, and best of all it is a renewable energy. So, it is very important to expand the development of solar energy now, since it takes relatively a long time to be technically viable and econocially competitive with fossil fuels. Fourth, Saudi Arabia now has the oil income which enables her to finance the research and get solar energy started. Also, there is a logical continuity in this because Saudi Arabia is already energy porducer, and might try to continue to be so over time, so as to conserve her position.

Given that it is agreed there is a need for an alternative source of energy in Saudi Arabia, this requires an analytical review of the current energy resoureces. In particular, their reserves and the period that these reserves will meet the expected increase in energy demand. As the life-span of these reserves decreases, the necessity for an alternative energy source increases. Therefore, it is necessary to review the production and consumption patterns of current energy resources in Saudi Arabia to determine their reserves' life-span and the need for an alternative energy source.

2.2 THE PATTERNS OF CURRENT ENERGY USE IN SAUDI ARABIA

2.2.1 INTRODUCTION

In order to evaluate the potential for solar energy in Saudi Arabia, it is important to investigate its current situation of crude oil and natural gas. In Saudi Arabia, there is a large quantitiy of crude oil and natural gas reserves, and also a very high intesity of solar radiation received over its land. This may lead one to say that there is no great need to develop solar energy in Saudi Arabia at this time. Therefore, it is necessary to investigate this issue at the beginning of this thesis to justify the urgent need for solar energy development not only in Saudi Arabia but also in many countries that have high intensity of solar radiation.

2.2.2 CRUDE OIL AND NATURAL GAS PRODUCTION

Saudi Arabia was the third ranked oil producing country in the world in 1991, following the former Soviet Union and the United States, respectively. During that year, Saudi crude oil production averaged 8.580 million barrels a day, as seen in Table (2.1). According to Saudi Aramco (Undated), the number of commercial oil fields at the end of 1990 was 60. 14 of them offshore in the Arabian Gulf, 43 onshore and 3 (Berri, Qatif, and, Manifa) extending under both land and sea water, as shown in Fig. (2.1). The Ghawar oil field, 241 kilometres long and 40 kilometres at its greatest width, is the largest onshore field in the world. In fact, 50% of Saudi annual production comes from this field alone. Safaniya, which was the first offshore oil field discovered by Aramco, is the world's largest offshore oil field. According to Aramco (1989), the total number of oil producing wells in Saudi Arabia at the end of 1989 was 567.

A quick look at Fig. (2.2) reveals that there is a fluctuation in crude oil production from one year to another especially in the 1980s. Crude oil production has decreased by as much as 34% from the production of the proceeding year, as in 1982, and has increased by as much as 53% from the production of the proceeding year, as in 1986. This fluctuation in the crude oil production in Saudi Arabia is attributed to its distinctive role as a so called "swing producer" to prevent the world energy market from sudden disruptions in the crude oil prices which may damage the world economy.

Table (2.1)
TOP TEN PRODUCING COUNTRIES IN 1991
(in thousand barrels per day)

COUNTRY	CRUDE OIL PRODUCTION
EX-USSR	10430
U. S. A.	9025
SAUDI A.	8580
IRAN	3260
MEXICO	2970
CHINA	2810
VENEZUELA	2645
ABU DHABI	2130
CANADA	1975
Norway	1905
Total World	64230

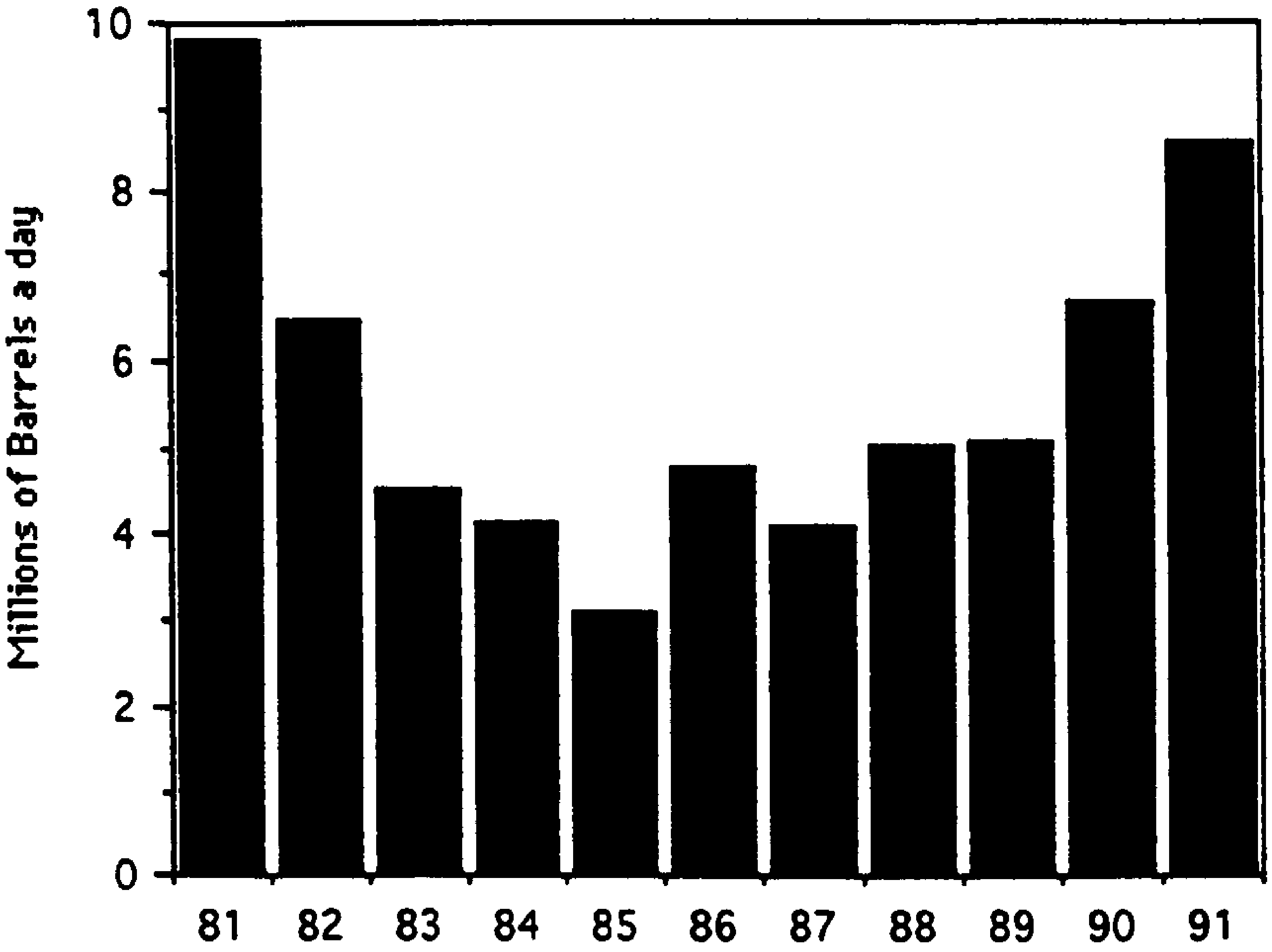
Source : BP Statistical Review of World Energy, June 1992.

Fig. (2.1)

Crude Oil Fields in Saudi Arabia

Source : Saudi Aramco, Undated.

Fig. (2.2)
Crude Oil Production in Saudi Arabia



Data Sources: Ministry of Petroleum and Mineral Resources (1983, 1989). BP Statistical Review of World Energy,1992.

Therefore, whenever there is a shortage in world crude oil supplies, Saudi Arabia increases its oil production to meet world oil demand and to prevent oil prices from increasing sharply. So, Saudi Arabia tends to increase its production not to take advantage of the profit but to prevent oil prices from sharp increases. Likewise, whenever there is an increase in world oil supplies, Saudi Arabia decreases its oil production to the level of the world demand, and hence prevents a decline in oil prices. The Saudi oil policy towards stabilizing world oil prices operates the same way as the world oil market. The oil market has a natural stabilization becuase as oil prices increase then production expands, and as oil prices decrease then oil production constracts and oil prices recover.

The production of natural gas in Saudi Arabia has been steadily increased since 1973 as the production of natural gas became economic due to the increase in energy prices in general and natural gas in particular. Also,the expansion of both the local consumption and the world demand for natural gas played a significant role in its gradual increase. However, as the real prices of crude oil and natural gas continued to increase to a high level in late 1970s and early 1980s, the demand for natural gas decreased as a result of conservation policies in the industrialised countries in particular. For example, the production of natural gas in Saudi Arabia in 1983 was only 124.57 thousand barrels a day compared with 159.73 thousand barrels a day in 1982, a decrease of 22 percent. Nevertheless, increase in production has resumed since 1989 and reached its highest level in 1991 with 171.06 thousand barrels a day.

2.2.3 CONSUMPTION OF REFINED PRODUCTS AND NATURAL GAS

Despite the large quantities of crude oil and natural gas production in Saudi Arabia, local consumption of refined products and natural gas represents a small fraction of the total production (approximately 8 per cent in 1989). However, the percentage of consumption is locally subject to change from year to year because of the significant variation in the total annual production. In fact, the local consumption of refined products and natural gas has increased since 1967 in both the domestic and industrial sectors, as a result of increase of the population, the number of housing units, vehicles, and the expansion of the industrial and commercial sectors. However, since 1984, local consumption of refined products has decreased slightly reaching 256.011 thousand barrels a day in 1989 compared with 301.355 thousand barrels a day in 1984, as a result of government policy. This has been aimed at conservation of energy consumption by raising the local prices of refined products. Unlike refined products, consumption of natural gas has been steadily increased reaching 156.016 thousand barrels a day in 1989 compared with 63.889 thousand barrels a day in 1980.

According to Elshayal and Al-Zakri (1981) the major consumers of refined products in Saudi Arabia are the transportation and utilities sectors with 32% and 29% of the total consumption in Saudi Arabia respectively. The oil industry and construction sectors come next with 15% and 14% of the total consumption in Saudi Arabia respectively.

The population growth rate has a lesser effect on the demand for crude oil, particularly in large population areas such as China and India, because the population growth rate has to be associated with a high level of economic activity to influence the level of energy demand. Most of the oil exporting countries are considered to be developing countries with a distinctively high population growth rate typically between 3-3.1 per cent. This is a function of decreasing death rate due to the improvement in the health conditions (United Nations, 1991). The increasing rate of population in the OPEC countries is reflected in the growing level of local consumption of energy, particularly natural gas, as a result of the high economic growth rate in these countries especially in Saudi Arabia. Consumption of refined products in OPEC members, which are the major suppliers of crude oil in the world, has been steadily increasing since 1967. The total consumption of refined products in OPEC members rose from 2.430 million barrels per day in 1980 to 3.219 million barrels per day in 1987, an increase of 32.5 per cent from 1980 consumption, OPEC (1988). Between now and the year 2000, the number of people aged twenty to forty will increase at about 2.6 percent a year in the developing countries (The World Bank, 1986). Based on this prediction, consumption of energy is also expected to increase in developing countries if the economic growth continues at its high level of 3-4 per cent.

The consumption of crude oil in the major OECD industrial nations decreased by over 15 per cent between 1973-1986 as a result of the gradual increases of crude oil prices especially after the so-called 'second oil shock' in 1978/79 (McCann, 1988). Moreover, economic recession has been an important factor in the depressed levels of world oil consumption in the early 1980s and 1990s in particular. World oil consumption was stagnant in 1991. Strong growth in the LDCs and moderate growth in the EC and Japan was largely offset by the lower demand in a recession that hit the industrialised countries in the early 1990s, (BP, 1992).

According to the Third Five-Year Plan, 1980-1985 of the Ministry of Planning (1980), total energy consumption in Saudi Arabia, mainly refined products and natural gas, is expected to reach 2.3 million barrels a day in the year 2000. Of this total consumption, the utilities sector consumption is estimated to increase to 38% by the year 2000. Moreover, according to OAPEC (1979), the total Arab crude oil consumption would reach 10 million barrels per day by the end of this century. This is equal to 58 per cent of the total Arab oil production in 1987. However, if this prediction is going to happend it would increase air pollution problems, particularly in the main urban areas, and also it would reduce the life-span of crude oil reserves in OAPEC members, particularly Saudi Arabia. In order to prevent this situation from being achieved, certian factors must be considered. First, energy conservation should be strictly implemented. Second, high standard of fuel efficiency should be regulated, especially in utility and transportation sectors. Third, alternative energy resources, particularly solar energy, must be taking more seriously and the development pace should be further accelerated. Fortunately, the expected high revenues of oil sales can be used partly to finance solar energy research and development especially in the utilities sector which requires high demand of fuels.

2.2.4 EXPORTS OF CRUDE OIL, REFINED PRODUCTS AND NATURAL GAS

Saudi Arabia is the leading exporter of crude oil in the world. In 1980, for example, total exports of crude oil were 9.790 million barrels a day. Since 1980, exports have followed a steady decline reaching as low as 2.150 million barrels a day in 1985. The cut in exports was to maintain the level of crude oil prices which had fallen as a result of the conservation policies of the major industrialised countries and the conflicts among OPEC members with respect to the ceiling production. By 1989, crude oil exports reached 3.22 million barrels a day.

Unlike crude oil, exports of Saudi refined products have steadily increased since 1983 as a result of the expansion in the number and capacity of crude oil refineries. By the end of 1989, there were 7 crude oil refineries in Saudi Arabia with a total output of 1.459 million barrels a day. Total exports of refined products reached 1.09 million barrels a day in 1989.

Since 1973, natural gas has acquired a considerable importance due to the increase in energy prices in general which make it of economic value. Most of the natural gas in Saudi Arabia is no longer burned, but is now gathered for both local consumption and exports. However, since 1981 there has been a fluctuation in the exports of Saudi natural gas liquids as a result of instability in world demand which in turn is highly sensitive to energy prices. Total exports of natural gas reached 417.2 thousand barrels a day in 1989.

2.2.5 CRUDE OIL AND NATURAL GAS RESERVES

Saudi Arabia is the first ranking country in the world in terms of quantity of crude oil reserves. Currently total proved crude oil reserves in Saudi Arabia is equal to 257.8 billion barrels. This represents 25.8 percent of the total crude oil reserves in the world estimated at 1000.9 billion barrels at the end of 1991. Moreover, geologists have already identified close to half a trillion barrels of "oil in place" in Saudi Arabia (Mc Hale, 1986). In fact, crude oil reserves have been steadily increasing since 1938, when oil was first discovered in the country, despite the large cumulative production of over 57.3 billion barrels since that time. In the last few years, there has been dramatic increases in crude oil reserves as a result of the expansion of the search for new fields, especially in the southeast province of Saudi Arabia. New crude oil fields were discovered in large quantities in late 1988 and early 1989 in Al-Hota and Al-kharj regions, raising the total crude oil reserves in Saudi Arabia from 169.5 billion barrels in 1987 to 254.9 billion barrels in 1988 and to 257.8 billion barrels in 1991.

In addition to crude oil reserves, Saudi Arabia has large natural gas reserves of 184 trillion cubic feet as of 1991. This quantity represents more than 4.2 percent of the total natural gas reserves in the world which reached 4378.1 trillion cubic feet in that year. Saudi Arabia ranks in the fourth place with respect to natural gas reserves.

An increase in the crude oil reserves obviously plays an important role in extending the life-span of a nation's crude oil reserves. However, the key factor that, specifically, determines the life-span of the crude oil reserves is the production level. In other words, as the production level increases, the life-span of the crude oil reserves decreases at the same rate, assuming other variables are constant. This relationship can be expressed by the so called "Reserve/Production ratio" (R/P) which can be obtained by dividing the total amount of crude oil reserves by the annual production of any particular year. The result is the period of time that those remaining reserves would last if the crude oil production were to continue at this level. For example, in the case of Saudi Arabia, if annual production of crude oil were to continue at the 1991 level (3.132 billion barrels), and there will be no additions to the total proved crude oil reserves of 1991, the remaining crude oil reserves would last for 82.3 years, assuming other variables constant.

By the turn of this century, many oil producing countries in Western Europe and North America, especially those with relatively small crude oil reserves, such as the United Kingdom and the United States, will be running out of crude oil. For example, the United Kingdom is depleting its crude oil reserves of 4.0 billion barrels at a high rate, due to its high level of oil production, 0.692 billion barrels per year in 1991. If this production level is going to continue, then the life-span of its current oil reserves will last for only 5.8 years. Therefore, the United Kingdom will depend heavily on oil imports by the end of this century. This may motivate OPEC countries, especially Saudi Arabia, to increase their oil production to meet the expected increase in the world oil demand which in turn will largely decrease the life-span of their oil reserves. However, such a decision to increase the oil production is subject to the overall energy policy of the oil producing countries, which includes considerations such as the capital needs and the energy needs of future generations, in addition to world oil demand.

As shown in Table (2.2), the life-span of crude oil reserves in Saudi Arabia is highly variable from one year to another and depends significantally on production level, which is subject to change according to its energy policy. A comparison between the life-span of crude oil reserves in 1990 and 1991 reveals that the life-span could be greatly decreased in a short period of time. Between 1990 and 1991, the life-span decreased by 23 years due to an increase in oil production in 1991. Therefore, solar energy, the main alternative source of energy in Saudi Arabia, should be further developed and the search for the different applications of solar energy should be largly financed especially with the current adequate financial situation due to the high revenues of crude oil, since it is proved to be economic at remote areas.

Table (2.2)
The Life-Span of Crude Oil Reserves in Saudi Arabia
(in Billion Barrels)

Product / Year	Crude Oil Reserves	Annual Production	Life-Span (in years)
1981	164.82	3.580	46.0
1982	168.32	2.366	71.1
1983	168.85	1.657	101.9
1984	171.71	1.511	113.6
1985	171.50	1.143	150.0
1986	169.20	1.752	96.6
1987	169.60	1.502	112.9
1988	255.00	1.841	138.5
1989	260.05	1.849	140.6
1990	257.50	2.446	105.3
1991	257.80	3.132	82.3
1995 *	257.50	2.920	88.1
2000 *	257.50	4.380	58.8

Sources of Data: Ministry of Petroleum and Mineral Resources (1983,1989).
BP Statistical Review of World Energy, 1992.
* Projected.

2.3 ENVIRONMENTAL POLLUTION

2.3.1 INTRODUCTION

One of the main reasons behind the search for a clean alternative source of energy is the increasing problem of air pollution. The severe consequences of air pollution on human, animal, and plant life, have intensified the pressure to find an energy source that is a pollution free which can substitue the current convetional energy sources. Therefore, the effort has been concentrated on the renewable energy resouces, particularly solar energy, due to its high potential which will be discussed later on in this Chapter.

Air pollution is a broad subject. There are a wide range of different causes and sources that have created and are still increasing pollution problems. Thus here we will discuss only some problems caused by the emission of polluting particles generated by the use of fossil fuels, particularly crude oil, coal, and natural gas. These types are the overwhelming energy sources for vehicles, power plants and industrial factories. The consequences of the concentration of these pollution particles is a further dimension of this problem.

At the outset, it is of importance to define the term " air pollution" in order to be able to specify the problem. According to Jones, Robertson, Forbes, and Hollier, 1990, air pollution means :

> " Any toxic or radioactive gases and PARTICULATE MATTER introduced into the atmosphere, principally as a result of human activity. Air pollution is usually associated with the emissions from car exhausts, power stations, factories, incineration plants and the domestic burning of FOSSIL FUELS in urban industrial areas. Pollutants may also originate in the countryside from pesticide sprays and the dust generated by mining and agricultural practices."
>
> Jones, Robertson, Forbes, and Hollier (1990), p. 19.

Here we will not consider natural sources of air pollution such as dust, forest fires and volcanic emissions, although they play an important role in increasing the air pollution level in the earth's atmosphere. The analysis will focus on man-caused sources of air pollution and in particular the emissions from the burning of fossil fuels.

2.3.2 THE MAJOR CAUSES OF AIR POLLUTION

The air pollution problem is a result of the huge quantities of pollution emissions generated form the heavy use of fossil fuels especially during the past few decades. The increase of air pollution gases, particularly carbon dioxide, carbon monoxide, and suphur dioxide, in the earth's atmosphere, has attracted the attention of many environmetalists. Their goal has been the search for the causes behind the increase in the intensity of air pollution, and the effects of air pollution on human, animal, and plant life.

According to Fells (1989), measurements of carbon dioxide concentrations in bubbles of air trapped in the Antarctica ice have shown that for 10 000 years it remained constant at 270 ppm. and only started to rise 100 years age. By 1957, it was 315 ppm. Current atmospheric carbon dioxide level is 365 ppm. which is 25 to 28 per cent higher than it was before the industrial revolution, and it is projected to double in the coming decades. Fossil fuel emissions and the clearing of forests are responsible for this increase. Ruoghly five billion tons of carbon dioxide are released into the air every year by the buring of oil, gas, and coal, (Kahn, 1990). In a study made by Khalil and Rasmussen (1984), measurements were provided for the past few years at Oregon, USA, which indicate that the background concentration of carbon monoxide is increasing at a rate of 6 per cent on the average per year. They also suggest that increased carbon monoxide may indirectly intensify global warming. By 2050, the carbon dioxide concentration increases by 37 per cent of the present value ; methane by 55 per cent ; nitrous oxide by 15 per cent ; and CFC by 74 per cenet, Kelly (1990). The effective carbon dioxide concentration reaches double the pre-indudstrial baseline during early 2030s, as shown in Fig. (2.3).

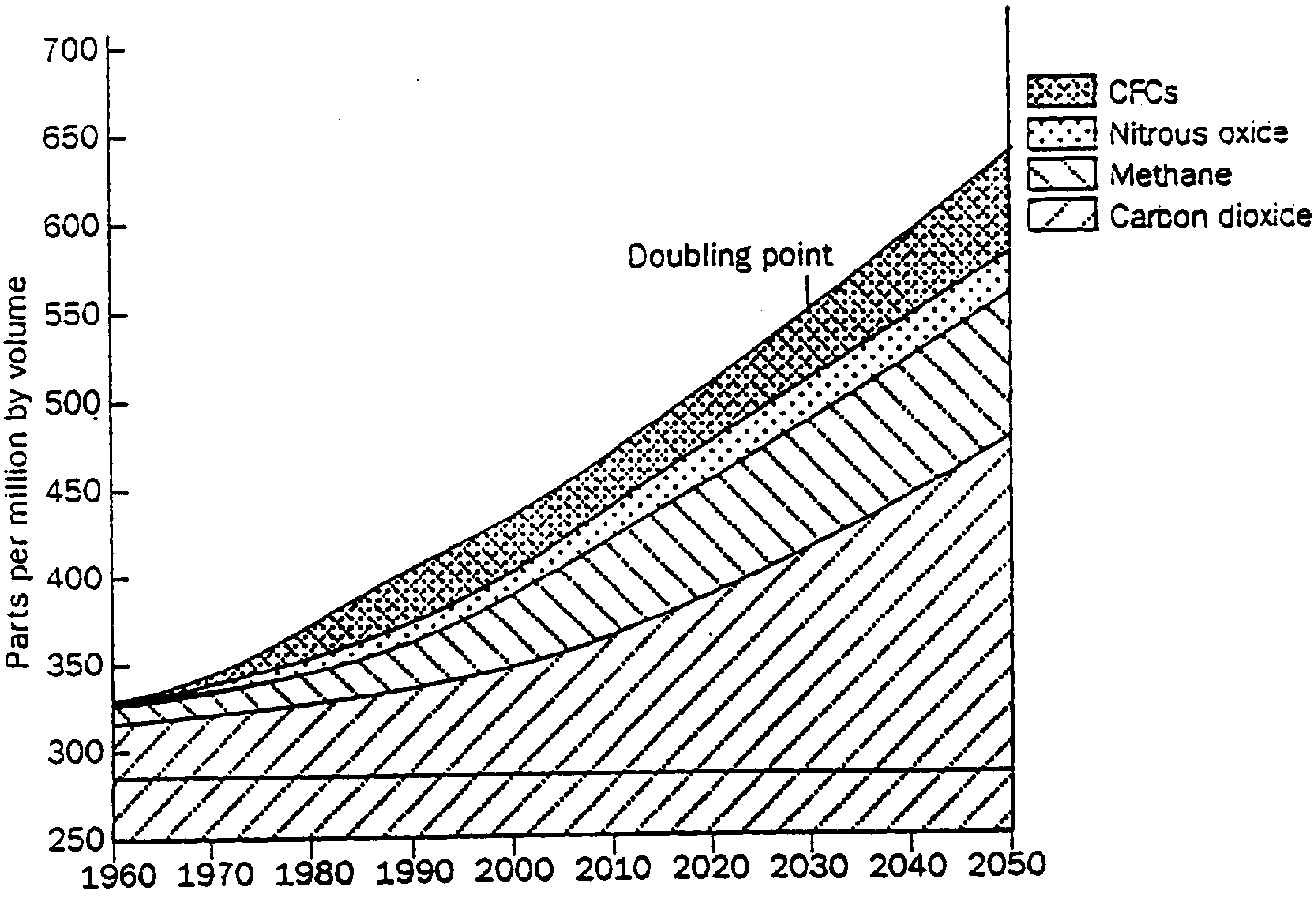


Fig.(2.3)

The concetrations of carbon dioxide and other pollution gases in the earth's atmosphere. The pre-industrial baseline is indicated by the horizontal bar.

Source: Kelly , M., 1990. **Fig (2.3)**

The use of the fossil fuels as the main energy sources led to other atmospheric consequences than the addition of heat: upon combustion, they creat a variety of effluents. Principal in their importance for causing atmospheric alterations are oxides of sulphur (SOx), oxide of nitrogen (NOx). These gases, through photochemical reactions induced by sunlight, cause the well-known "smog" (Landsberg, 1983). Figure (2.4) indicates the regions that have high susceptibility to photochemical smog in the world which include western and eastern United States, eastern Brazil, Argentina, southern Europe, India, China, south Africa, and southern Australia, as a result of the huge pollution emissions generated from the buring of fossil fuels, particularly coal, in these countries.

Air pollution is, in fact, a major problem that faces not only the advanced industrial countries, but also the developing and less developing countries as well, due to the movements of air pollution gases through the earth's atmosphere, by winds and production of greenhouse gases by the large population of some countries such as Eastern United States, China, India, and Eastern European countries. The issue of the movements of air pollution gases across the international borders has been raised since 1985 by environmental groups in Western European countries that are affected by the acid rain generated by United Kingdom power station emissions (Barnes, 1986).

The current Saudi Ambient Air Quality Standard (SAAQS) for carbon monoxide (CO) is 9 ppm. maximum for 8-hour average exposure, and 35 ppm. for 1-hour average exposure, which is also an international Satandard, (Rowe, Al-Dhowalia, and Mansour, 1989). In an investigation of traffic-generated carbon monoxide (CO) at heavily travelled arterials in Riyadh, Saudi Arabia, Koushki (1988) found that the one-hour and eight-hours carbon monoxide concentration in both 1985 and 1986 highly exceeded the permissible

Fig. (2.4)

Regions of high susceptibility to photochemical smog.

Source: Krupa, S and Kickert, R. 1989

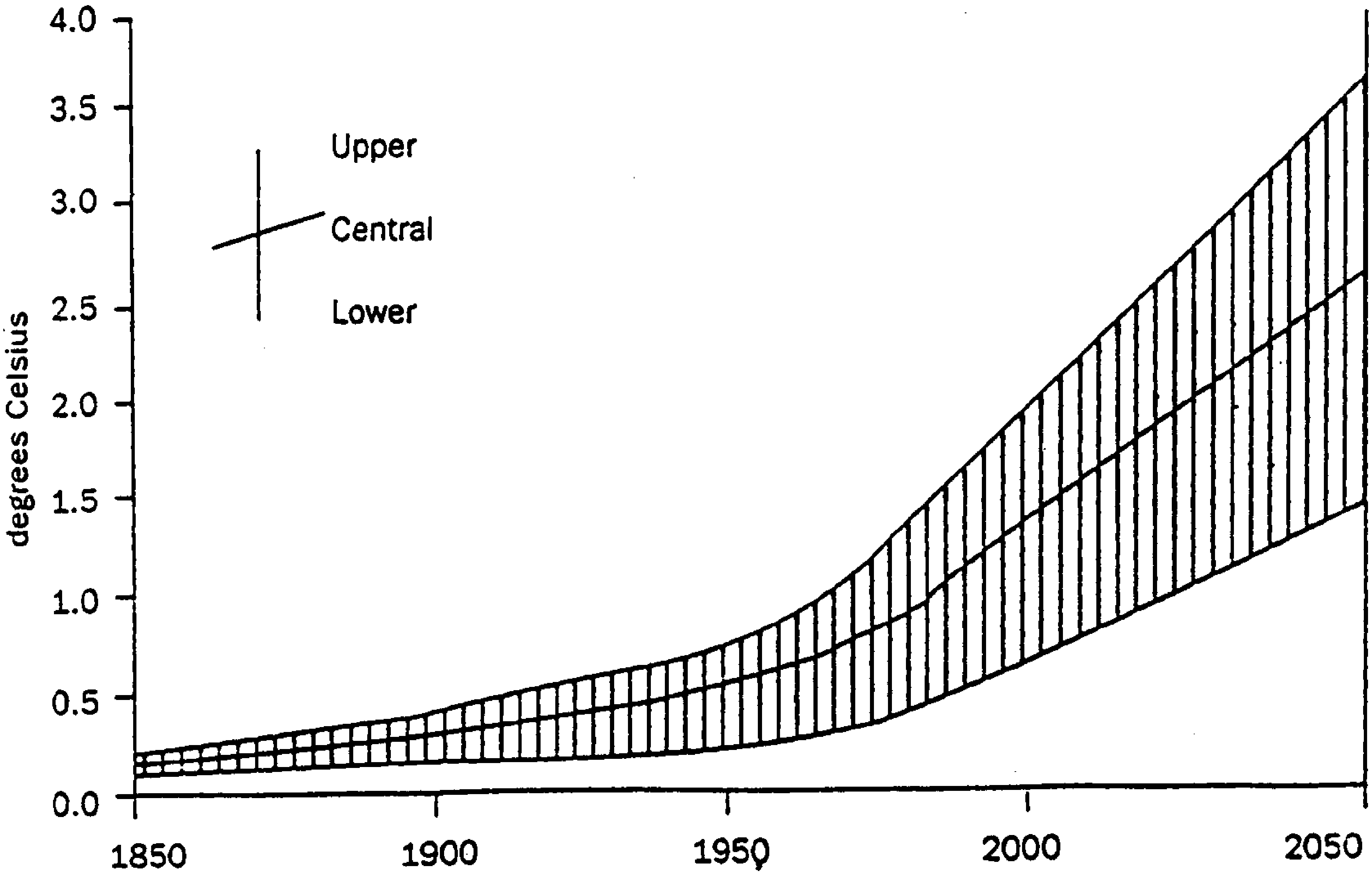


Fig. (2.5)

Projections of the trend in global surface air-temperature.

Source : Kelly, M , 1990.

international standards of 9 ppm. The one-hour mean CO levels at the centrelines of traffic lanes ranged from a low of 48 ppm at Al-Madina to a high of 62 ppm at Al-Matar during 1985. During 1986 concentrations varied from a low of 54.8 ppm at Al-washem to a high of 62 ppm at Al-matar. It was shown that CO levels increased significantly (at 0.05 level of significance) between 1985 and 1986. For example, eight-hours carbon monoxide level were 24 ppm at Al-Matar, 13 ppm at Al-Washem and 9 ppm at Al-Madina during 1985. During 1986, these levels were 23, 17, and 11 ppm at Al-Matar, Al-Washem, and Al-Madina, respectively.

Some of air pollution gases, particularly Carbon dioxide, are dissolved in the oceans, some are taken up by vegetation of all kinds including the biomass of the sea as well as plants and forests. Moreover, 20 thousand million tonnes of carbon dioxide produced each year makes its way into the upper atmosphere. There it traps the infra red radiation which would otherwise escape affecting the process that keeps the earth in equilibrium with the shorter wave length incident radiation it receives from the sun and causing a gradual global worming, (Fells, 1989).

2.3.3 THE MAJOR EFFECTS OF AIR POLLUTION

The greenhouse effect, induced in the atmosphere by the increase of air pollution gases, particularly carbon dioxide (CO_2), raises the atmospheric temperature and consequently leads to a sea level rise as well as a drastic climate change which affects human activities particualrly agriculatural production and transportation. Moreover, air pollution increases the amount of acid precipitation which rises the land acidification and damages forests and kills both land and water species including fish.

Global warming is the most serious effect of air pollution gases. According to Kelly (1990), the concentration of carbon dioxide in the earth's atmosphere, is likely to lead to an increase in the earth's surface temperature of between 1.5^{o} and 3.5^{o} C by the year 2050, as seen in fig. (2.5). The rise in the global mean temperature will increase the evapotranspiration processes and hence increases the chances for torrential rainfall in summer and heavy snow in winter. Moreover, the polar ice caps have started to melt ; their coastlines are shrinking and the oceans are rising at a rate between 1 to 1.5 cm per year (Veziroglu, 1984).

Acid rain is one of the most pronounced air pollution problems caused by the emissions of air pollution. Already, thousands of lakes in Canada, Norway, Sweden, Finland, Japan, and the United States have high levels of acidity from the fall of acid rains that they are no longer a suitable habitat for fish and aquatic plants (Veziroglu, 1984). In addition, acid rains are now contaminating drinking water sources in many parts of the world, particularly in the northern hemisphere.

Sulphur dioxide (SO2) is the major air pollutant that is generated from the coal combustion, electric generation, and industrial heat. Sulphur dioxide (SO2) causes widespread material damage to buildings and can destroy works of sculpture made of limestone, marble, or similar materials, and more important its sever effect on respiratory irritation. Moreovere, in high concentration, it can increase acute respiratory ailments and, where local concentrations are very high, it can lead to a significant number of deaths, (Cassedy and Grossman, 1990). According to Shea (1988), in the United States fossil fuel pollutants may cause as many as 50,000 premature deaths annually. Across the Atlantic, the air pollution caused by burning these fuels is implicated in damaging 31 million hectares of trees in central and northern Europe. Each year fossil fuel combustion emits some $4.8 * 10^{12}$ kg of carbon.

The increase of air pollution gases, mainly carbon dioxide, in the earth's atmosphere has been accompanied by a decrease in the quantity of ozone and, hence, reduction in the ozone layer of the earth's atmosphere. The ozone layer is an essential element in the earth's atmosphere because ozone absorbs solar ultraviolet radiation, thus warming the stratosphere and producing a steep temperature inversion between 15 and 50 km. which acts as a ceiling to vertical motion in the troposphere, where clouds are formed (Elson, 1987). The absorption of ozone by carbon dioxide, thus, will weaken the stratospheric inversion and affect the climate system. Moreover, the reduction of ozone would cause more ultraviolet visible light and infra-red radiation to reach the earth's surface not only increasing surface temperature but also endangering the health of human beings, through exposure of higher levels of u.v. radiation.

The depletion of the atmospheric ozone layer, caused by CFCs released during the production of insulation foams and the use of refrigerant fluids particualrly at the end of the equipment life, could have terrible effects on human and livestock health and on some life forms at the base of the sea food chain. According to Corbella (1989), the discovery of a hole in the ozone layer above the Antarctic suggests the possibility of a faster depletion rate than previously suspected, particularly if the level of thermal comfort in building now standing in developed countries is extended in the near future to developing countries (mostly warm and hot counrties) with the necessity of refrigeration and air conditioning that could be expanded several times which could lead to a catastrophic effect on the ozone layer.

The effect of the concentration of greenhouse gases will be to materially alter climate in different parts of the world in ways which are as yet unpredictable. There are already suggestions that the "weather machine" is becoming increasingly unstable and that the desertification of central Africa is already a result of the global worming (Fells, 1989). The intensive use of fossil fuels in the industrial sector, power stations and transportation has resulted in vast quantities of toxic gases being released into the earth's atmosphere, leading to dramatic changes in climate.

In the first half of 1992, there were remarkable changes in climatic system all over the world as a result of the increase in air pollution level, particularly from oil fires of the Gulf War that were burning for several months. According to Elmer-Dewitt (1992), in January, 1992, Middle East region experienced its coldest winter in 40 years with heavy snow that blanketed Amman, Damascus, and Jerusalem, as shown in Fig. (2.6). In February, torrential rain and heavy snow caused the worst flooding in southern California since 1938. In March, unusually low pressure together with winds from Africa causes the canals of Venice to overflow where water filled the Piazza San Marco to an ankle depth for several days. In April, Colorado experienced a dry and hot weather with record high temperatures. In May, in southern Brazil, for each of five days in May, it rained more than it usually rains in a month. Finally, a swath of Africa stretching from Cairo to Cape Town is suffering its worst drought in 50 years. These remarkable changes in climate that resulted from the concentration of air pollution gases in the earth's atmosphere will have severe consequences for irrigation systems, hydro-electric power, drought, structural designs, and agricultural land use.

Fig. (2.6)

Remarkable Changes in Climate System During 1992.

Source : Time, June 15, 1992.

These severe consequences of air pollution emissions are expected to increase rapidly, unless otherwise restrected measures to reduce the heavy reliance on fossil fuels and to control pollution emissions have been implemented. Expanded use of renewable energy resources, particularly solar energy, and a greater commitment to energy efficiency are the most cost-effective and environmentally sound approaches to mitigating many pollution problems. In fact, the most important factor in controlling air pollution problems can be found in encouraging the use of renewable energy resources, such as solar energy, wind energy, hydro-power, geothermal, wave energy, and tidal power, which are environmentally clean, widely available, and best of all, nondepletable.

2.4 THE POTENTIAL FOR SOLAR ENERGY IN SAUDI ARABIA

One of the main reasons for conducting this thesis is the high potential for solar energy to substitue fossil fuels and to meet energy demand when fully developed. The potential of renewable energy resources in general and for solar energy in particular has increased worldwide since early 1970s due to the dramatic increases in crude oil prices and the gradual decline in world crude oil reserves especially in the industrialized countries. The fear of a shortage in crude oil supplies forced the major consuming countries to search for alternative sources of energy to substitute for conventional energy resources. Among renewable energy resources, solar energy got a very large attention worldwide over the last two decades, due to its wide availability and the simple technology associated with harnessing it. This is especially the case for countries that receive a high intensity of solar radiation over most of the year.

Energy resources can be considered as renewable, questionable renewable, or non renewable. According to Shea (1988), an energy source is only renewable if, with proper management, its sustained use will not deplete supplies, such as wind, solar radiation, flowing water, plants, and forests. However, some energy resources, such as solar and wind energy, are always considered as renewable resources, regardless of the type of management. If there is an excessive consumption of a renewable source, such as fuelwood, it can no longer be thought of as renewable, but can be considered as questionable renewable energy source. The overcutting of the rain forests make it difficult to restore the lost species, the soil characteristics, and so on. Another energy source that may be considered as renewable and non renewable is hydro power. Water resources for hydro power depend on the amount of rain which is highly variable, particularly in arid and semi arid counrties. Moreover, the dams are usually affected by the accumulation of silt and sediments, particularly after a long period of time, which may reduce the capacity of hydro power generation. Any energy source is considered non-renewable if its sustained use will deplete its supplies regardless of the proper management, such as crude oil, coal, and natural gas. Therefore, energy resources can be divided into three main groups:

1- Renewable resources, such as solar energy, wind energy, wave energy, biomass energy, geothermal energy, and tidal energy.
2- Non-renewable resources, such as crude oil, natural gas, nuclear energy, and coal.
3- Questionable renewable resources, such as fuelwood and hydro power.

Sayigh (1983), suggested that more intensive and faster recourse to the use of non-oil sources of energy with a particular effort being made by the industrial countries to develop non- oil alternatives as well as intensive search for new oil sources in developed and developing countries, is the way to solve the problem of depleting oil reserves. What Sayigh said with respect to the development of non-oil alternatives is more important now because these alternatives, particularly renewable sources, have not been developed quickly enough to meet the expected increase in energy demand by the turn of this century. However, the search for new oil reserves is not the right approach to the depletion of current oil reserves due to the serious consequences of the pollution emissions generated from the use of these resources. The search for new oil reserves during the past 10 years has resulted in very minor discoveries, particularly in Sudan and Yemen, and wasted substantial amount of money that if it was used to develop non-oil resources, particularly renewable energies, it would increase the share of these resources towards total energy supply.

According to IEA (1987), renewable energy resources are now used in most of the industrial countries, and in some of them, these sources contribute significantly to the national energy supply. For example, renewable energy resources provide between 1 and 5% of the total primary energy requirements in Australia, Austria, Canada, Denemark, Sweden, and in Switzerland. In Portugal, biomass resources cover about 7 % of the energy requirements. Wind energy is expected to contribute between 8 to 10% of the total energy supply in the year 2000 in Denemark, Netherlands, Great Britain, Greece, and Spain. In the United States, the energy contribution from renewable energy resources amounts to about 64 million metric tons of oil equivalent per year, which is roughly equivalent to the total energy requirements of the Netherlands. However, the development of renewable energy resources is in its early stages and contributes no more than 10 per cent of the total demand. It is hoped that the development of the alternative energy resources will continue to solve not only the expected shortages in the energy supplies but also other problems associated with fossil fuels, particularly that of air pollution.

In late 1970s, Saudi Arabia became interested in developing solar energy as the main alternative source of energy for several reasons. According to Fendley, (1982), the main reason for developing solar energy in Saudi Arabia is the necessity to conserve its oil reserves. He also mentioned other reasons which can be summarised as follows:

(i) The yearly average of solar radiation received at the earth's surface in Saudi Arabia is 290 wm^{-2} one of the highest insolation values in the world and is over twice that received by a European country such as Holland.

(ii) Approximately half of the population in Saudi Arabia live in small, widely separated rural communities and the cost of providing reliable fuel transport and electric power transmission for these communities is high. Therefore, localized solar energy insolations tend to become cost-effective. Moreover, it could take up to 10 years for a power grid to reach some of the more inaccessible villages, but it is envisaged that complete electrification of these villages using solar powered generation could be carried out in some three years. In addition, 100% use of solar energy in rural communities, particularly remote villages, is the preferred strategy due to the high cost of electricity transmission, fuel transport, and maintenance of the power plants, while a mix of conventional and solar energy resources will be the most economic in urban areas as a result of the variability of incoming solar radiation, which may not meet the energy demand, particularly during peak hours.

(iii) Solar energy technology is in its early stages of development and is relatively unsophisticated compared to the other alternatives such as nuclear power. A country like Saudi Arabia with adequate finance, but lacking large numbers of technical personnel and a complex industrial base, can make good use of solar energy which has already utilised in many different applications.

(iv) Solar energy has no military potential and is non-polluting, therefore, its use will not creates a threat, either militarily or environmentally to neighbouring countries, (Fendley, 1984, p. 9).

These reasons mentioned by Fendley are actually crucial for solar energy development in Saudi Arabia. However, he did not mention the purpose of conserving crude oil reserves, wether it is for a longer porduction period, or as a raw material for petrochemical products. The current crude oil reserves in Saudi Arabia are large enough to meet energy demand for the next five or six decades which is a sufficient period to develop solar energy to supply a large proportion of energy requirements. Moreover, 100% use of solar energy in rural communities is very expensive at the current stage, except at the remote villages particularly in the southwestern part of Saudi Arabia which is a mountainous region. The production cost of solar energy is remarkably declining, but takes sometime to be competitive with fossil fuels, therefore, a gradual increase of solar energy use may be more plausible. Finally, the type of policy in which Saudi oil reserves where use at a puffer to stabilize world oil prices may no longer be viable in the world in which oil prices are much more floutly and certainly tend to increase over time.

In conclusion, crude oil reserves, the main source of energy, are limited and expected to be depleted within the next five to six decades. By the turn of this century, many industrial countries, such as the United States and the United Kingdom, are expected to depend heavily on OPEC oil, due to the expected depletion of their oil reserves. This will further decrease the life-span of oil reserves in OPEC members, due the large consumption level of the industrial countries, particularly the United States. Moreover, the accumulation of air pollution gases in the earth's atmosphere that generated from the burning of fossil fuels over the last decades has resulted in serious consequences to human, animal, and vegetation cover.

One set of reasons is worldwide there is a world coming shortage of crude oil that is absolute reasoning, therefore, there must be some other source of energy. Second, within Saudi Arabia, here is a country which has a very special interest in energy porduction, therefore, it is logical that for Saudi Arabia to convert that interest to a new energy resouce which is a logical continuation of interest, plus the physical strength of solar energy.

Therefore, it is very important to find an alternative source of energy before the depletion of world crude oil reserves, since it takes considerable time and effort for the new source to be technologically viable and economically competitive. Amongst the alternatives, solar energy is the most promising and reliable source to meet the energy demand, particularly in Saudi Arabia which has a high intensity of solar radiation and an adequate financial capabilitiy to develop this renewable source of energy.

CHAPTER THREE

LITERATURE REVIEW OF THE POTENTIAL AND MEASUREMENT OF SOLAR RADIATION

3.1 THE POTENTIAL AND APPLICATIONS OF SOLAR ENERGY

As a result of the gradual depletion of crude oil reserves, the main source of energy in the world, and the growing problem of air pollution and its severe consequences, the world has focused the attention on developing clean and renewable energy resources. Among these sources, solar energy received much attention due to its high potential and wide distribution particularly in the middle latitudes.

According to Joyce (1984), scientists calculate that the sun radiates a total equivalent of 38, 000 million million million kilowatts of uninterrupted power in all directions and that the slender beam of the sun's light that falls upon the earth generates about 170 million million kilowatts of power, thousands of times more than the world currently consumes. The highest intensity of solar radiation falls upon Saudi Arabia, as shown in Fig (3.1). Moreover, the solar energy that falls upon the Arabian Peninsula, where Saudi Arabia is located, in one year is greater than twice the world's known oil reserves (Joyce, 1984).

Since 1960s, OPEC members have investigated the possible use of solar energy as the main alternative source of energy. According to OPEC (1981), the interest that solar energy, regardless of its type - photovoltaic or solar thermal - evokes OPEC members is based on two major factors : first, its abundance of

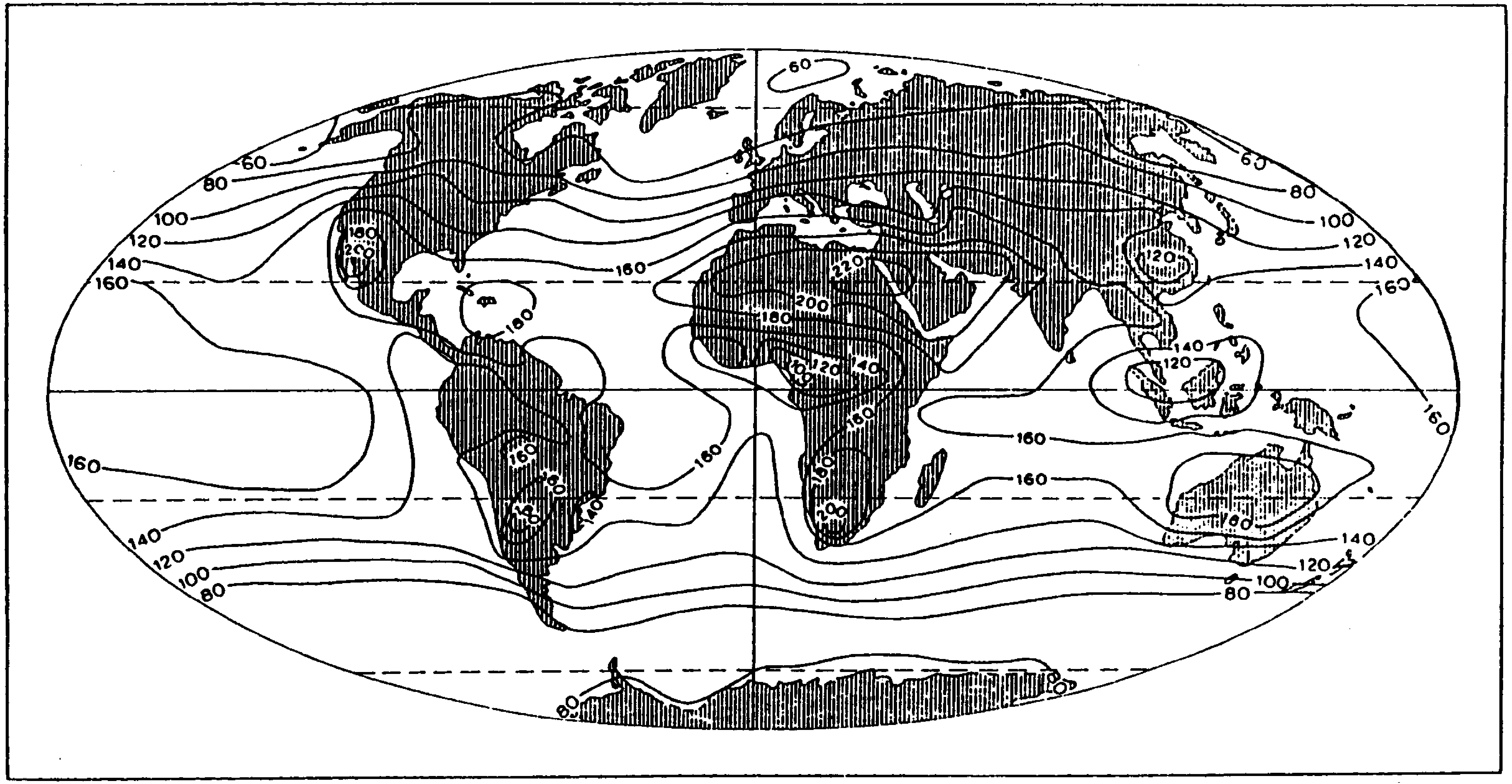


Fig.(3.1)

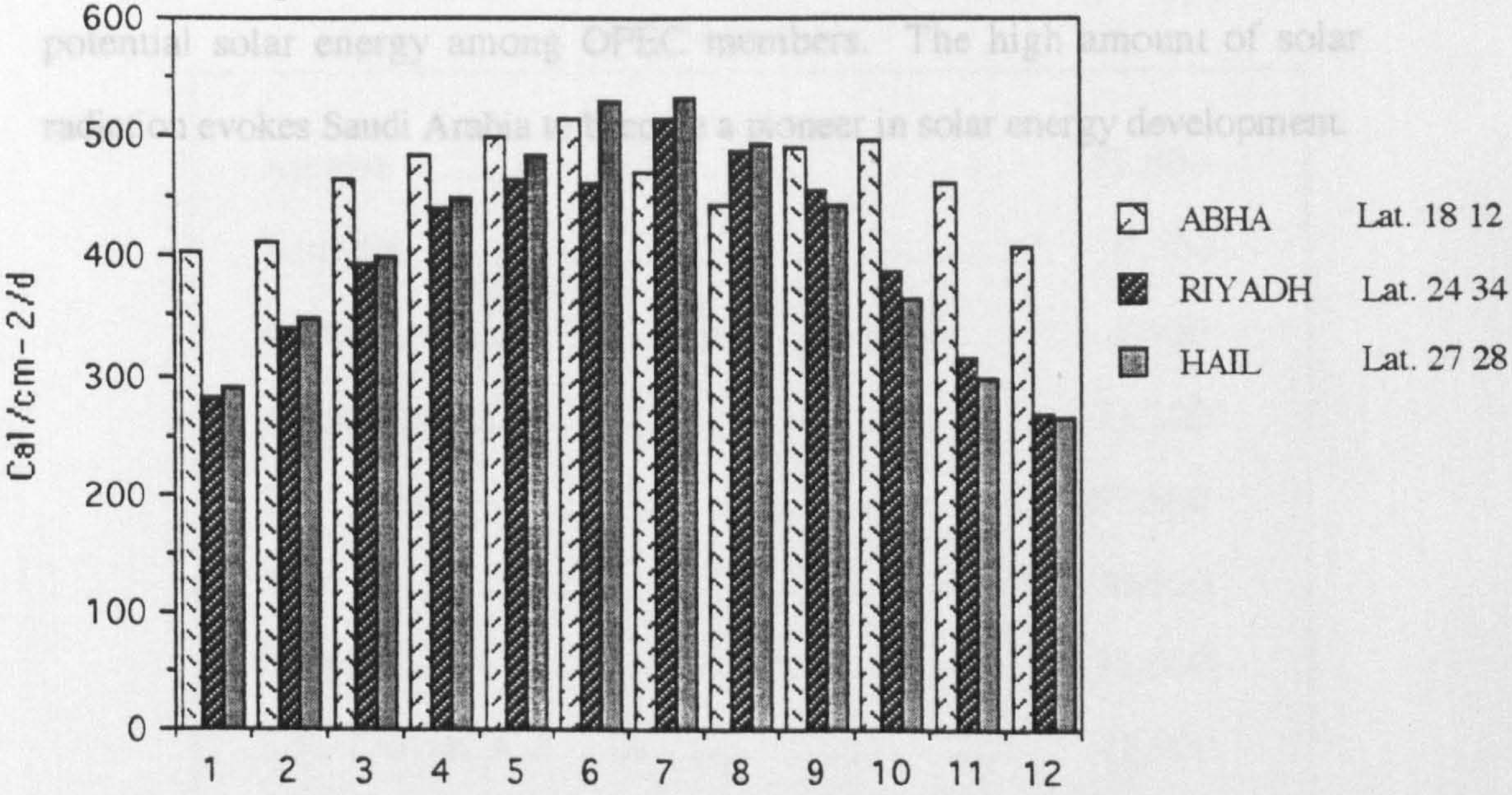
Average Annual Solar Radiation on a Horizontal Surface at Ground Level in $\text{Kcal cm}^{-2}\text{ yr}^{-1}$

Source: Barry, R G. and Chorley, R. J., 1982.

supply due to high average levels of solar radiation. Second, its flexibility in meeting small-scale needs, particularly in certain areas because it is decentralized in application, it needs little maintenance, and it is modular, and therefore adaptable in size.

Saudi Arabia, like most developing nations, lies in the sun belt area near the equator and thus, the intensity of solar radiation received is very high, as is shown in Figure (3.2). Therefore, the abundance and the continuous nature of solar energy makes it most suitable for power supplies for Saudi Arabia as well as for developing countries in general within the sun belt boundaries. This is particularly the case in the arid or semi-arid regions where the sun is rarely obscured by cloud, the main reflection factor of solar radiation.

Fig. (3.2)
Monthly Averages of Solar Radiation at Certain Cities in Saudi Arabia



MONTHS

Source of data: Ministry of Agriculture and Water (1980-1989).

In the year 2000, the potential of solar energy in Saudi Arabia has been estimated at 114,700 barrels of oil equivalent per day (boe/d), as shown in Table (3.1). By the year 2000, solar energy is projected to constitute between 2.4 and 6.9 per cent of total energy consumption as shown in Table (3.2). Table (3.2) indicates that Saudi Arabia is projected to have the highest share of potential solar energy among OPEC members. The high amount of solar radiation evokes Saudi Arabia to become a pioneer in solar energy development.

Table (3.1)

The Potential of Solar Energy in OPEC Countries in The Year 2000 (in boe/d)

Algeria	65,800
Ecuador	14,500
Gabon	4,300
Indonesia	73,200
I.R. Iran	167,500
Iraq	100,600
Kuwait	31,600
S.P. Libyan A.J.	45,900
Nigeria	63,100
Qatar	4,500
Saudi Arabia	114,700
U.A.E.	15,300
Venezuela	107,800
TOTAL	808,800

Source: OPEC Review (1981).

Table (3.2)
Share of Potential Solar Energy in OPEC Total Energy Consumption in the Year 2000 (per cent)

Algeria	4.27
Ecuador	5.49
Gabon	2.64
Indonesia	2.88
I.R. Iran	6.16
Iraq	6.65
Kuwait	6.12
S.P. Libyan A.J.	4.00
Nigeria	3.70
Qatar	2.42
Saudi Arabia	6.89
U.A.E.	2.66
Venezuela	5.89

Source: OPEC Review (1981).

Rural electrification projects that rely on photovoltaics are slowly spreading throughout the Third World particularly in middle latitudes. The greatest progress has been achieved in Saudi Arabia, the Dominican Republic, on islands in French Polynesia, and Greece. According to Shea (1988), more than 15,000 homes in the world receive their electricity from photovoltaic cells (PV). In Saudi Arabia alone, more than 1,000 homes rely completely on solar energy.

According to Flavin and Lenssen (1991), electricity from wind, solar-thermal and biomass technologies is likely to be cost-competitive in the late 1990s, while electricity from photovoltaics and liquid fuels from biomass should be so by the turn of this century. However, the pace of deployment will be determined by energy prices, particularly crude oil, and by government policies. As conventional energy prices increase, the pace of developing renewable energy sources in general and solar energy in particular increases because they become economically competitive with conventional energy sources.

Direct conversion of solar energy will likely be the cornerstone of sustainable world energy systems, not only because sunshine is available in great quantity but also because it is more widely distributed than any other energy source. According to Flavin and Lenssen (1991), in Cyprus, Japan, and Jordan, solar energy already heat between 25 and 65 percent of the water in homes. Moreover, a southern Californian company, Luz International, generates 354 megawatts of power from solar thermal collectors and has contracts to install an additional 320 megawatts. These collectors turn 22 percent of the incoming solar radiation into electricity. Spreading over 750 hectares, the solar collectors produce enough power for about 170,000 homes for as little as US $ 0.08 per kilowatt-hour, already competitive with generating costs in some regions, Flavin and Lenssen (1991). Rural areas are ideal for solar energy particularly photovoltaic as a result of low population density and simple applications required for rural development such as water pumping and lighting. For example, in India, more than 6,000 villages rely partly on solar energy, particularly for electricity generation.

Solar energy systems have been widely used in Saudi Arabia due to the high intensity of solar radiation particularly in summer. According to Khoshaim (1985), it is almost certain that the current state of solar electric technology would permit some solar applications at remote sites particularly small villages and highways. These applications include solar village, solar desalination plant, emergency telephone systems, and solar-powered devices for traffic control. The Solar Village is the largest solar energy application in Saudi Arabia. According to Rahman (1984), SOLERAS established a massive solar project at Al-Uyaynah Village to provide its 4,000 population with sufficient electric energy. This project is designed to produce 350 kilowatts of direct-current electricity during periods of intensive solar radiation, in addition to an energy storage system fitted with 1,100 kilowatt-hour lead acid batteries to provide the village with electricity during night and persistent clouds and dust storms periods.

In addition to the Solar Village, a water desalination pilot plant constructed in 1985 at Yanbu, on the western coast of Saudi Arabia. According to SOLERAS (undated), plant is designed to produce 6,000 cubic metres a day of potable water. This pilot system uses 18 point-focus collectors (80 square metres each) with dual axis tracking for solar collection. These two projects, the Solar Village and the water desalination pilot plant will be discussed more in Chapter Eight.

Moreover, solar energy has been utilized in many other applications especially for highway devices. According to Khoshaim (1985), many solar-powered highway devices have been designed and installed at different sites. These solar devices include overheight vehicle detection and diversion systems, solar power systems for permanent traffic counters, illuminated steep grade warning sign, sign lighting, and lighted warning signs for pedestrian crossing.

The highest intensity of solar radiation in the world is in the middle latitudes, particularly between 20 and 35^{o} N. Most of the Arab countries are located in this region. According to Sayigh (1987), the Arab countries receive 70% of the extraterrestrial radiation with an average of 500 w/m-2 a day. Due to this high potential of solar radiation, solar energy has been used in several applications such as solar heating and cooling, electricity generation, water desalination, irrigation, and traffic devices. Among these applications, solar heating is the most widely used in these countries. Moreover, countries such as Jordan, Saudi Arabia, Tunis, Egypt, Iraq, Syria, Lebanon, Morocco, and Libya have some manufacturing capability to produce solar water heaters. In Jordan, for example, 50,000 water heaters are in operation in Amman alone (Sayigh, 1987).

Since early 1960s, Egypt has been involved in solar energy development. The solar radiation intensity reaches an average 550 $\mathrm{Cal/cm^2/d}$. The Egyptian Solar Energy Laboratory has been involved in solar energy development since early 1960s. Among the various solar applications, the attention has been focused on certain types. According to Sakr (1987), these types include solar domestic water heating, solar collectors for industrial applications, solar desalination, and photovoltaics for remote applications. These applications were jointly conducted in a cooperation with both the United States and Germany.

As a result of the high potential of solar radiation in Iraq, the Iraqi Solar Energy Research Centre (SERC) has focused on three broad objectives which can be summarized as follows:

- To establish and develop a local scientific base and know-how in solar energy technologies.
- To develop systems utilizing solar energy which is suitable for Iraq.
- To establish a network of co-operation in this field between SERC and various institutions in Iraq and the world.

Among the several applications of solar energy in Iraq, the solar-cooled building of SERC is the largest single application of solar energy. According to Sakr (1987) this building was constructed in 1982 on the campus of the Iraqi Scientific Research Council in Baghdad. This building occupies an area of 3000 m^2 and contains 13 major laboratories, workshops, a lecture hall, a library, an administrative section, meeting rooms, a canteen, a machinery room and staff offices. The solar system utilizes 1017 pipe solar collectors covering the sloped front of the building and 560 collectors forming the roof of the car park area that is connected to the main building. This building acts as a laboratory for research on air conditioning and hot water supply.

Kuwait is located in the north-eastern part of the Arabian peninsula between 28^o 30' and 30^o 05' N and thus receives a high intensity of solar radiation which reaches an average of 280 w/ m^2 . As a result, the researches and studies have been concentrated on the development of this renewable source. According to Al-Marafie (1988), solar energy has been used for several applications, among them is the solar pond to provide thermal energy for a 150 MWe power plant, which is of standard size. The principal advantage of the solar pond is its capacity to store energy over long periods, thus eliminating the extra cost of storage tanks. The thickness of the heat storage zone, which absorbs and stores a substantial portion if the solar energy incident on the pond surface, depends on the use of the collected solar energy. The temperature in the storage zone may reach 100^{o} C. (Al-Marafie, 1988).

In Sudan, a typical semi-arid country , electricity grids do not exist in the rural areas and are not likely to exist in the near future due to the high prices of fossil fuels particularly crude oil. As a result, renewable energy resources in general and solar energy in particular have become increasingly important. Solar energy is abundant in Sudan particularly in the northern part where the intensity of solar radiation reaches an average of 500 $Cal / cm^2 / d$. Said (1989) made a comparative study of the economic competitiveness of photovoltaic powered irrigation in northern Sudan, when compared with other options for pumped irrigation (mainly diesel). The comparison shows a breakeven cost of solar photovoltaic module of US $ 4.14 per peak watt. He concluded that photovoltaic systems are economically viable and are the only alternative, provided that financial incentives, government subsidies and assistance are available to the farmers who would like to use this alternative.

Indonesia, the world's fifth most populous nation, has scheduled the installation of 2,000 solar energy systems as an integral part of efforts to provide electricity to its vast archipelago of 13,000 islands and over 66,000 villages. According to Sun World (1990) the first such installation, a photovoltaic solar panel system, was made in Sukatani, a remote village 113 km south of Jakarta, the Indonesian capital, and 457 m. a. s. l. on the slope of Mt. Salak. Like many villages throughout Indonesia, Sukatani is too remote to receive electricity from the state electricity company due to the high cost of fuel transport, maintenance, and electricity grid connection. The photovoltaic solar system allows for the decentralization of the electricity supply by harnessing solar energy directly at the local environment. Plans are also underway to develop solar electrification systems for cooking in a bid to reduce domestic use of fuel oil and wood, thus helping the country to preserve its oil reserves and forests (Sun World, 1990).

In 1986, the first utility-scale photovoltaic generating facility in Austin, Texas (USA) went into operation. According to Miskell (1988), this 300 KW power plant is capable of producing 628,000 KW h of electricity per year. That is sufficient to meet the needs of 150 typical households on a peak summer day. Moreover, this solar energy plant was completed in 5 months and the cost was only $ 2.7 million. Wolfe (1981), investigated costs of diesel generators vs thermoelectric generators. He found that for diesel generators, the initial capital cost is fairly high, particularly in remote areas. In order to capture the maximum possible intensity of solar radiation, the 154 panels of this solar plant are mounted on special sun-tracking structures.

Solar energy is also utilized to supply spacecrafts and airplanes with energy demand. The flight of photovoltaic powered airplane from California to North Carolina (USA) in summer of 1990 was a double millstone, making history in both aviation and photovoltaic. According to Piellisch (1991), this solar powered plane designed by E. Raymond and is essentially a glider with 8.2 square metres of amorphous PV cells from Sanyo powering its brushless DC Inland motor. Raymond set a new world record for solar powered airplane when he was able to logged 4060 kilometres (2,523 miles) during 125 hours in the air. Raymond's next plan is to fly around the world by a solar powered plane landing in as many technically advanced countries as possible with a higher speed than 90 km/h, the current possible speed that can be achieved.

In 1968, the Greek Military Government of the time opened the world's largest solar sea water distillation plant on the Island of Patmos. This island is 12 km x 5 km in area with no natural water catchment apart from a few wells to meet the growing water demand for its 2,500 population in addition to 5,000 peak tourist population plus day visitors. According to Twidell (1989), a flat low-laying area of land was chosen for the site of this project. The distillation used the sloping glass basin system. Essentially troughs of water were made of 40 m x 1.5 m lengths of black rubber placed directly over the levelled ground. This plant was operated well initially and was capable to produce 30 tonnes (m3) per day of potable water, but after 5 years of operation it was abandoned due to algae growth in the pipes and the costly management of the framework. According to Twidell (1989) cleaning is not per se a solar energy problem, but one of design engineering and implementation.

Regardless of the high potential of solar energy as the main alternative source of power, there are some constraints limiting the potential application of solar energy. According to OPEC (1981), there are three barriers that can be identified:

1 Technical - including storage of electricity and lack of standards (to meet national power standards).

2. Economic -the intially capital-intensive investment required and its economic viability.

3. Socio-economic traditional habits of some societies and the market penetration of existing types of generation, OPEC (1981) pp.89-91.

3.2 THE MEASUREMENT OF SOLAR RADIATION

During the last two decades, substantial research has been undertaken into the factors which influence the total amount of solar radiation received at the earth's surface. Research has analysed the variation of the incoming solar radiation at the earth's surface on the basis of climatological data such as sunshine duration, relative humidity, maximum temperature, and cloud cover.

In his study, Hay (1976) clearly shows that both variability at a single station and the discrepancies between stations can be reduced by excluding the effect of multiple reflection of shortwave radiation between the earth's surface and the overlying atmosphere. This is a function of both the surface albedo and the atmospheric back-scatter. In order to measure the solar radiation received at the earth's surface on a cloudless day, Suckling and Hay (1976) constructed a model which takes into account factors which deplete the incoming solar radiation, such as water vapor and dust. The model takes the following form :

$$S = Io \cos Z \; y_{wa} \; y_{da} \; y_{ws} \; y_{rs} \; y_{ds} \, , \qquad (3.1)$$

where :

Io : is the solar constant,

Z : is the solar zenith angle, and

y : are transmission function terms after water vapor absorption, aerosol or dust absorption, water vapor scattering, Rayleigh scattering, and aerosol or dust scattering respectively.

This model assumes that absorption of the solar radiation occurs before scattering, therefore, half of the aerosol or dust depletion was assumed to be due to absorptions. In their applications of this model on some Canadian cities, (Goose, NFld, Port Hardy, B.C., and Edmonton, Alta.). this model yielded errors of small absolute magnitude

As a development of the previous study, Suckling and Hay (1977) considered the effects of clouds on the total amount of solar radiation received at the earth's surface. In this study, cloud effects have been incorporated through the use of hourly values of cloud amount and type for up to four major layers, and hourly bright sunshine totals. The revised model or the cloud layer-sunshine (CLS), as they called it, provides a more accurate measure of the length of time the direct solar radiation is not attenuated by clouds. The analysis of the available solar radiation and meteorological data in Canada shows that the CLS model has a potential to almost triple the number of locations producing total solar radiation data and for many locations can extend the historical records of solar radiation backwards in time. However, the relative advantage, as well as the overall errors, will be diminished as the averaging period increases. Also, the CLS model has an additional advantage of calculating the separate direct and diffuse component fluxes of the total solar radiation.

An important study estimating the total solar radiation received at the earth's surface in Riyadh, Saudi Arabia, was carried out by Sabbagh, Sayigh, and El-Salam (1977). In their study, an empirical formula was obtained which relates the daily total solar radiation to the sunshine duration, relative humidity, maximum temperature and the latitude of the location. They found that water vapor absorbs a considerable amount of both direct and sky radiation, but they did not discuss the effect of elevation on the amount of solar radiation absorbed by water vapor.

Sayigh (1977) examined several factors that are considered to influence the amount of total solar radiation received at ground level in Riyadh, Saudi Arabia ; Kuwait city, Kuwait ; Bahtim, Egypt ; and Port Sudan, Sudan. These factors are : the amount of sunshine available per day ; the air temperature at ground level, including mean daily temperature, maximum and minimum temperature for each day ; the altitude and latitude of the station ; and relative humidity. He believes that these factors play a significant role in determining the total amount of incoming solar radiation received at ground level. Sayigh, however, did not use specific humidity as a precise factor to assess the influence of humidity upon the variation of incoming solar radiation. This limits the value of his approach because 17% of the incoming solar radiation is absorbed by the water vapor globally, and hence, it reduces the total amount of solar radiation received at the ground level (Abdelrahman, Elhadidy, 1986).

Daneshyar (1978) formulated a prediction method for the mean monthly solar radiation at different locations in Iran. This method depends on empirical relationships which use meteorological data, such as bright sunshine hours, the maximum air temperature and the relative humidity, to calculate the mean monthly solar radiation. The method is based on the assumption that direct and diffuse solar radiation are primarily functions of the solar zenith angle and cloud cover. He found that this method is suitable for the prediction of the mean monthly values of direct, diffuse and total solar radiation to a degree of accuracy similar to that of the experimental data. This method was used to compute tables of monthly mean solar radiation parameters at various locations in Iran. Moreover, the accuracy of the theoretical predictions indicates that for time scales of a month or more, large scale radiation monitoring stations are not necessary and theoretical models may be used in order to compute the radiation parameters.

In an attempt to describe the distribution of monthly averaged daily global solar radiation over Greece, Katsoulis et. al. (1978) used the relatively dense and uniform distribution of sunshine recording stations to estimate the radiation, using the following expressions :

$$Q = Qo\,[a + b]\,\left(\frac{s}{S}\right) \qquad (3.2)$$

where :

Q : is the global solar radiation,

Qo: is the global radiation above the atmosphere,

s : is the duration of bright sunshine,

S : is the maximum possible duration of sunshine, and

a and b : are constants.

In the case of Greece, the application of this method is difficult due to the lack of radiation data for different locations. In addition, the existence of mountainous regions causes substantial variations in cloudiness between locations which are separated by relatively short distances, and because topography and climate may change abruptly. Despite these problems, Katsoulis found that on clear days the turbidity (dust content) tends to increase from April onward. In addition, the higher water vapor content of the air contributes to the lowering of the solar radiation values, especially in the summer. Moreover, he found that the variation in the intensity of direct solar radiation cannot be assessed by instantaneous values alone, due to the fact that the sun's altitude varies greatly during the day and seasonally.

A radiation model has been constructed by Atwater and Ball (1978). The model takes into account the effects of Rayleigh scattering, absorption by the permanent gases, water vapor, clouds and pollutants, and scattering by clouds and pollutants. Due to the lack of any realistic data, pollutants were omitted in their trial application of the model. However, the radiation model has been applied to estimate the solar radiation from data collected at 10 radiation stations in the eastern region of the United States. The estimation of the solar radiation at these sites revealed a random variation in the distribution of solar radiation on a daily basis which was attributed to the natural progression of clouds across a given region. Moreover, they observed a decrease in the insolation from the coastline to inland areas. The reduced values of solar radiation inland are attributed to inland convective cloudiness and latitude difference. In addition, systematic intra-regional variations of solar radiation are clearly noticeable which, according to Atwater and Ball, result from latitudinal and elevation difference, frontal or air mass persistence, and cloud persistence. They concluded that in order to obtain a measure of the intraregional variations of solar radiation, these observations must be supplemented with mode-generated values at additional sites.

One of the simplest models which is used for the estimation of global solar radiation is the well-known Angstrom correlation (Khogali, Ramadan, Ali, and Fattah, 1983). This model takes the following form:

$$\bar{H}/H_O = a + b\ n/N \tag{3.3}$$

where :

$\bar{H}$: is the monthly average of the daily global solar radiation on a horizontal surface,

H_O: is the extraterrestrial solar radiation on the 15th of the month, n : is the monthly average of daily hours of sunshine,

N : is the maximum daily hours of sunshine, and

a and b : are regression constants.

The ratio n/N is the fraction of maximum possible number of bright sunshine hours. They found that a statistically significant correlation is usually obtained if long-term averages of H and n are available. However, this method requires knowledge of the number of sunshine hours as an input, beside the other parameters which depend on geographical position and day of the year, and thus require real data for each station.

Variations in the average daily, monthly and seasonal patterns of total solar radiation in Ibadan, Nigeria, were investigated by Bamiro (1982). He analyzed the variation of solar radiation with respect to basic climatological parameters such as relative humidity, sunshine hours, temperature, altitude, and latitude. The average monthly total radiation was predicted with reasonable accuracy, with r = (0.66), during the period October 16 - November 29 , and r = (0.49) during the peak of the rainy season between May 29 to August 31. This clearly reveals the effect of clouds in attenuating incoming solar radiation at the earth's surface.

Mani and Rangarajan (1982) computed the solar radiation component when no measured data were available, by using the well-known regression technique relating mean daily totals of global and diffuse solar radiation with the mean duration of sunshine. By using this method and taking into account the first order multiple reflections between the ground and the atmosphere, they obtained regression parameters from the monthly mean values of daily totals of global solar radiation and sunshine at a network of 16 stations in India. Mani and

Rangarajan also computed global and diffuse solar radiation from cloud observations, when no sunshine data were available by using the inverse relationship between sunshine and cloudiness.

Barra (1982) developed an empirical formula to estimate the solar radiation using various sets of climatological and geographical site data, such as cloudiness, the angle of declination of the sun, latitude and location of the site relative to the sea, relative humidity, air temperature, and sunshine duration. He linked the global daily solar radiation to the parameters mentioned above. This formula takes the following form :

$$Q = aK \exp [L (D - R^{1/3}/100 - 1/t)] \tag{3.4}$$

where:

L : is the latitude angle,
D : is the ratio of the bright sunshine hours relative to 12 hours,
R : is the relative humidity,
t : is the maximum air temperature in degrees centigrade,
K: is the latitude of the place, and
a : is a constant.

Nagaraja Rao and Bradley et.al. (1983) developed simple empirical relationships based on meteorological observations in Corvallis, Oregon, including the hours of sunshine, the daily temperature range, and relative humidity as important factors influencing daily global solar radiation. They found that the daily temperature range and the relative humidity explain more than 80% of the variability in the global radiation, but the usefulness of these two factors was somewhat limited by the fact that the near-surface temperature and relative humidity are influenced by the local climate. Moreover, when they compared the estimated values with the measured ones it was found that the correspondence between them was significantly high with R^2 equal to 0.91. In addition, they observed that the greater part of the variability in the daily incoming solar radiation at the earth's surface can be attributed to changes in the available solar radiation at the top of the atmosphere in the course of the year.

When considering proposed regions for the application of solar devices, Brinsfield (1984) found that very little information was available which gave details of hours of sunshine at Ely, Nevada. Because of this limitation, several investigators considered the possibility of correlating solar radiation with reported cloud cover, a variable for which data does exist. As a result, several empirical equations were developed which related the two variables. However, the applications of such models require detailed knowledge of local hourly sums of direct and diffuse radiation for clear skies as well as hourly cloud cover observations in various layers. Such data are not available for most locations.

In an investigation of the depleting factors of solar radiation over India, Rangarajan (1982), it was found that 15-25% of the total solar radiation is attenuated by dust through the scattering process which redistributes the solar radiation at the earth's atmosphere where a part of the solar radiation is scattered back to space. He also noticed that the total amount of solar radiation attenuated by dust scattering depends on the thickness of the dust layer. This layer is highly variable both in its contents and its size distribution.

In a study focused on the estimation of the solar radiation intensities under a cloudless and hazy atmosphere in Riyadh, in central Saudi Arabia, Mujahid,

(1983) found that dust storms have a significant effect on the intensity of total solar radiation received at the earth's surface, especially in this central region of the Kingdom. He also attributed the variations in turbidity of the atmosphere to the seasonal variations of wind speed, wind direction and precipitation.

Dust storms play an important role in reducing the total amount of incoming solar radiation received at the earth's surface. The overall reduction of solar radiation by dust storm depends on its thickness and duration. In a study carried out by Sashamanoglou and Bloutsos (1989), to measure the effect of dust on the total reduction of incoming solar radiation at the area of Thessalonika, Greece, it was shown that the intensity of solar radiation was reduced by 30%. This was due to dust storms originating in open areas and transferring to the atmosphere by wind turbulence. Reduction of solar radiation could be even higher during huge dust storms which last for several days in arid or semi-arid countries such as Saudi Arabia, which are surrounded by large desert areas,which act as source areas for large quantities of dust.

The effect of atmospheric dust on the intensity of incoming solar radiation was investigated by Al-Arury (1990). In his study, the total daily radiation measurements of six selected dusty days during 1986 and 1987 (3 dusty days were selected from each year with a visibility ranging between 4-5 km) were compared with the total daily radiation measurements recorded in a clear atmospheric dust-free days from the same month and year with visibility more than 20 km. The reduction in the received amounts of solar radiation due to the effect of atmospheric dust found to be 28%. He attrributed this result to the absorption by solid particles and to the known Rayleigh scattering. However, the effect of dust on the intensity of solar radiation can be made more accurate when longer period of solar radiation measurements is recorded and dusty days are compared with clear days.

Raja and Twidell (1990), constructed an insolation equation to estimate the global insolation for 37 observatories over Pakistan. The global insolation was computed from 'sunshine hours' using an Angstrom-type insolation-sunshine relation. The period of the sunshine records ranges from 13 to 37 years. The insolation equation takes the following model :

$$H/Ho = 0.335 + 0.367\, n/Nd \qquad (3.5)$$

where :

H : the global insolation (measured at only 5 observatories),
Ho : the extraterrestial global insolation,
n : sunshine period, and
Nd : day length

All parameters used here are monthly averages based on daily measurement. The effect of latitude was excluded from this equation because they believe that it is not relevant due to the more significant changes in height and cloudiness between stations. However, latitude is not an independent parameter but it depends on sun declination, as discussed in Chapter Five. Therefore, these two factors, latitude and sun declination, should be combined together as 'insolation index' and used in addition to the other parameters, such as cloud cover, altitude, dust, and humidity, to have a more precise estimate of global insolation, due to their significant role in the spatial variations of global insolation.

El Hadidy (1991), investigated the effect of sand storms, cloud cover, and rain fall on solar radiation at Dhahran, Saudi Arabia, based on monthly and yearly radiation data from 1985 to 1988. This investigation revealed that dust storms and cloud cover significantly decrease the intensity of solar radiation at the earth's surface. Moreover, he noticed a decrease in solar radiation during rainfall events. This is caused by large water droplets in the atmosphere, which scatter, reflect and absorb solar radiation.

Finally, Al-Riahi, Al-Hamdani, and Al-Saffar (1992), estimated the solar irradiance attenuated by the aerosols, clouds , gaseous and solid aerosols, using two equations. The first is used to calculate the attenuation for an atmosphere of normal condition, as follows :

$$Kt = H/Ho \tag{3.6}$$

where:

Kt : the attenuated irradiance under normal atmosphere,
H : monthly average of global radiation on a horizontal surface,
Ho: monthly average of the extraterrestrial radiation.

The second equation is used to calculate the attenuated irradiance for a clear atmosphere, as follows :

$$Ktc = Hc/Ho \tag{3.7}$$

where :

Ktc : the attenuated irradiance under a clear atmosphere,
Hc : potential radiation that corresponds to a completely cloudless sky, and
Ho : as defined before.

These two equations were applied for three different climatological zones in Iraq (Mosul, Baghdad, and Nasiriyah) when comparing the percentages of incoming global radiation that obtained at the three locations, they noticed a remarkable decrease at Nasiriyah at the southern part of Iraq. They attributed this decrease to dust storms invading this area during during summer.

In summary, solar energy has a high potential role to meet the energy requirements, particularly in countries located in the middel latitudes where the intensity of solar radiation is high. The production cost of solar energy is competitive with fossil fuels in the remote rural areas due the high cost of transmission and maintenance of electricity generated from fossil fuels.

The ivestigation of solar radiation measurement in different parts of the world indicates that there are several factors influencing the intensity of solar radiation, such as water vapour, dust storms, clouds, sunshine duration, latitude, and altitude. In addition, there are some other factors have not been included in the investigation, due to the lack of real meaurements, such as carbon dioxide, carbon monoxide, and other air pollutants, particularly in the urban areas where the intensity of air pollution gases is high. These factors play a significant role in attenuating solar radiation through absorption and scattering processes. The main factors influencing the intensity of solar radiation in Saudi Arabia will be discussed in Chapter Five.

CHAPTER FOUR

THE CLIMATOLOGICAL AND PHYSICAL ASPECTS OF SAUDI ARABIA

4.1 THE CLIMATOLOGICAL ASPECTS OF SAUDI ARABIA

The Kingdom of Saudi Arabia is located on the southwest of Asia between 16^{o} and 32^{o} north latitude. This means that it is located in the dry tropical desert area formed to the west of continents. It is located in the tropical high pressure zone in winter which is affected by dry trade winds and is under the control of the low pressure passing through South Asia in summer. Therefore, Saudi Arabia is exposed to dry continental winds, and hence, its climate is characterized by dryness throughout the year and high temperatures in summer especially in the central region of the Kingdom.

During the summer season (July , August, and September), most of Saudi Arabia is influenced by dry continental tropical air mass and meteorological conditions are stable with a noticable increase in temperatures in this season. Humidity is high especially at the coastal areas of the Kingdom. The exception is the Asir region in the southwestern part of the Kingdom which is characterized by a moderate temperature and a high level of rainfall caused by the moist tropical air-masses.

In winter (January, February, and March), the Kingdom is dominated by a cold dry continental air-mass extending from central Asia and Siberia, which increases the atmospheric pressure and decreases the temperature and makes the sky clear and dry. Also in this season, frost may occur in the early morning especially in the central and the northern regions of the Kingdom. At the end of this season, another air-mass from the Atlantic moves towards the middle and the northern parts, bringing some rainfall.

Seasonal changes are not distinct and are progressive. The dominating factors relate to the prevalence of the maritime polar air-masses and tropical continental air-masses. The spring and autumn seasons are characterized by moderate temperatures and a low level of precipitation with high winds especially during the spring season.

In this Chapter, the attention will be briefly focused on the climatological and physical factors influencing the intensity of incoming solar radiation in Saudi Arabia, such as sunshine duration, insolation index, altitude, cloud cover, specific humidity, and dust storms. The effect of these factors on the variation of solar radiation will be investigated to some extent in the next three Chapters. In addition, air temperature and rainfall will be mentioned here due to their effect on dust storms, particularly in the central region.

Sunshine duration plays a significant role in increasing the intensinty of solar radiation, particularly in the middle latitudes, where the sun is more perpendicular compared with the higher latitudes. Sunshine duration in Saudi Arabia is one of the highest values in the world. Table (4.1) reveals that sunshine duration reaches its maximum average in the central and northern regions during summer, while in the southwestern region, the highest sunshine duration is recorded in autumn. Therefore, the intensity of solar radiation is expected to be high in the central and northern regions during summer, while in the southwestern region, it is expected to reache its highest in autumn.

Table (4.1)
Monthly Averages of Sunshine Duration in Saudi Arabia

Month Station	1	2	3	4	5	6	7	8	9	10	11	12
1. Najran	9.1	8.2	8.1	8.8	9.5	9.5	9.0	8.2	9.6	10.1	9.9	10.0
2. Abha	7.7	8.1	8.2	8.5	8.7	8.5	7.1	6.6	8.5	8.7	8.5	7.8
3. Bishah	7.5	7.7	7.8	6.3	8.2	8.7	8.9	8.3	8.6	9.1	8.9	6.4
4. Sulyyel	8.9	8.4	8.3	9.2	9.1	9.8	8.3	9.3	10.1	10.2	9.8	9.1
5. Taif	9.0	8.3	8.3	8.7	8.8	10.1	10.2	8.2	8.7	8.1	8.9	8.5
6. Al-Aflaj	9.0	8.9	8.7	9.6	10.3	11.5	11.1	10.8	9.2	10.3	9.9	9.0
7. Dawadmi	6.9	9.2	7.0	7.2	6.6	9.0	9.7	9.2	8.8	7.8	7.7	6.9
8. Madinah	8.7	9.1	9.3	9.9	10.2	11.2	11.3	10.3	9.8	9.2	8.9	8.7
9. Riyadh	7.6	7.8	7.0	7.5	7.8	8.8	9.3	9.4	8.8	8.4	7.4	6.4
10. Al-Ahsa	8.0	7.6	7.1	8.0	9.8	10.1	10.3	10.1	8.9	9.5	8.5	7.7
11. Qassim	7.9	8.4	7.9	8.8	8.9	11.3	10.3	11.0	10.7	9.3	8.9	7.3
12. Dhahran	7.5	7.7	6.9	8.0	9.6	10.6	10.2	10.0	9.7	9.1	8.0	6.9
13. Hail	7.9	8.3	8.1	9.3	9.4	11.6	10.4	11.2	9.6	8.9	7.8	7.3
14. Tabuk	7.5	8.4	8.6	8.8	8.9	7.5	9.3	11.3	10.1	8.9	7.7	5.5
15. Jouf	6.4	6.9	7.8	7.7	8.4	10.0	9.9	9.6	8.8	7.5	6.8	6.4
16. Quryyat	7.2	7.6	7.9	8.5	8.9	10.8	10.2	10.4	9.2	8.2	7.3	6.9

Source: Ministry of Agriculture and Water (1980-1989).

The intensity of incoming solar radiation is highly influenced by insolation index (the percentage of solar radiation incidence), as the percentage of insolation index increases, the intensity of solar radiation tends to increase. Insolation index is very high in Saudi Arabia, particularly in the southwestern part, due to its location in the middle latitudes. Table (4.2) shows that insolation index tends to increase in the southwestern part of the country during spring, while in the central region, it reaches its maximum during summer. The northern part has the lowest insolation index values in the country, particularly during autumn due to the relatively higher latitude of this part (Quryyat 31^{o} 20' N) compared with the southwestern part (Najran 17^{o} 33' N). Therefore, the intensity of solar radiation is expected to be high in the southwestern part especially during autumn, while in the central and northern regions, it is expected to be high during summer where the sun is more perpendicular here in this time than the southwestern part of the country.

Cloud cover palys relatively significant role in attenuating the intensity of solar radiation in Saudi Arabia. The appearance of cloud cover is very low except in the southwestern region which is a mountainous area. The highes average of cloud cover in the country occurs during winter and early spring as a result of the effect of the north westerly winds. This air mass is characterized to be worm and moist which brings some rainfall particularly in the northern, western, and central regions of the country. The southwestern region is dominated by Monsoon winds, particularly during summer which increase the formation of cloud cover especially at the higher elevations. Therefore, the southwestern region records the highest average of cloud cover in Saudi Arabia, as shown in Table (4.3). As a result, cloud cover is expected to play relatively an important role in attenuating solar radiation in the southwestern region, particularly through reflection processes.

Table (4.2)
Monthly Averages of Insolation Index in Saudi Arabia

Month Station	1	2	3	4	5	6	7	8	9	10	11	12
1. Najran	0.784	0.858	0.941	0.990	0.999	0.995	0.998	0.998	0.962	0.902	0.815	0.763
2. Abha	0.776	0.851	0.936	0.986	0.999	0.996	0.998	0.998	0.967	0.897	0.807	0.754
3. Bishah	0.759	0.838	0.927	0.984	0.999	0.998	0.998	0.995	0.959	0.885	0.792	0.737
4. Sulyyel	0.752	0.831	0.922	0.982	0.999	0.998	0.999	0.994	0.956	0.879	0.784	0.729
5. Taif	0.739	0.821	0.915	0.978	0.998	0.999	0.999	0.992	0.951	0.870	0.773	0.716
6. Al-Aflaj	0.728	0.811	0.908	0.975	0.998	0.999	0.999	0.989	0.946	0.862	0.762	0.705
7. Dawadmi	0.701	0.788	0.892	0.965	0.994	0.999	0.999	0.984	0.932	0.842	0.733	0.677
8. Madinah	0.703	0.789	0.892	0.966	0.994	0.999	0.998	0.984	0.933	0.843	0.738	0.678
9. Riyadh	0.702	0.788	0.892	0.965	0.994	0.999	0.998	0.983	0.932	0.842	0.737	0.677
10. Al-Ahsa	0.688	0.777	0.883	0.960	0.999	0.997	0.980	0.925	0.832	0.724	0.724	0.663
11. Qassim	0.679	0.769	0.877	0.957	0.990	0.998	0.996	0.978	0.921	0.825	0.716	0.654
12. Dhahran	0.680	0.769	0.878	0.957	0.990	0.998	0.996	0.978	0.921	0.825	0.716	0.655
13. Hail	0.666	0.757	0.868	0.951	0.988	0.997	0.994	0.973	0.913	0.815	0.703	0.640
14. Tabuk	0.653	0.746	0.860	0.946	0.985	0.995	0.992	0.969	0.906	0.805	0.691	0.627
15. Jouf	0.636	0.731	0.848	0.939	0.981	0.993	0.990	0.964	0.897	0.792	0.675	0.610
16. Quryyat	0.610	0.708	0.830	0.926	0.974	0.989	0.984	0.954	0.882	0.770	0.649	0.583

Source of raw data: Ministry of Agriculture and Water (1980-1989).

Table (4.3)
Monthly Averages of Cloud Cover in Saudi Arabia

Month / Station	1	2	3	4	5	6	7	8	9	10	11	12
1. Najran	1.2	1.8	2	3.3	1.8	1.8	3.3	1.5	1.5	1	0.5	1.8
2. Abha	2	2.8	2.8	3	2.3	2.3	3.5	3.8	2.5	1.5	1.3	2
3. Bishah	1.3	1.8	2.3	2.8	2.3	1.5	2.5	2.8	1.5	1.5	1	2.3
4. Sulyyel	2	2	1.7	3.3	1	1	2.7	2	1	0.3	1	2.7
5. Taif	1	1.3	1.5	2.7	2.7	1.3	2	2.3	2	2.3	1.6	2.3
6. Al-Aflaj	1.8	2.2	2	3.2	1.3	0.5	1.8	1.5	0.5	0.3	1	2.5
7. Dawadmi	1.5	2.3	2.4	3	1.9	0	0.6	0.9	0.2	1.1	1.5	2.3
8. Madinah	1	1.8	1.3	2	2.8	0.5	1.3	1.3	1	1.5	1	2
9. Riyadh	1.5	2.3	2.3	3	1.5	0	0.8	1	0	0.3	1	2.3
10. Al-Ahsa	1.3	2.3	2	2.3	0.3	0	0.3	0	0	0.5	1	2
11. Qassim	1.5	2.3	2.5	3	2.3	0	0.3	0.8	0.3	1.8	2	2.3
12. Dhahran	1.8	2.5	2.5	3	1.5	0.3	0.5	0.5	0	0.5	1.8	2.5
13. Hail	1.3	2	2	2.5	3.5	0.5	0.5	1	0.8	1.3	2.5	2.5
14. Tabuk	1.8	2.3	2.3	2.3	1.5	0	0.3	0.3	0.3	1.5	1.8	2.3
15. Jouf	2	1.8	2.3	2	1.8	0.3	0	0.3	0	1.8	2	2.3
16. Quryyat	3.3	3.3	3.3	3	2.8	0.5	0	0	0.3	1.5	2.3	3.3

Source: Ministry of Defense and Aviation, 1980-1989.

In addition , the Kingdom is bordered by sea on two sides, the Red Sea in the west and the Arabian Gulf in the east. The effect of these two large bodies of seawater on the climate of the Kingdom is limited to the coastal regions. These extend for more than 2000 km along the Red Sea and for more than 500 km along the Arabian Gulf. The effects of the seas are restricted because of the Hijaz mountains in the west that protect the interior region from the effect of the Red Sea, and the northern winds that blow on the Arabian Gulf coast most of the year. Moreover, the interior regions are remote from the coastal areas and therefore atmospheric humidity decreases towards the interior. As a result, specific humidity palys its relatively major role in influencing the intensity of solar radiation at the coastal regions, particularly the eastern coast of the country.

Specific humidity has a maximum seasonal variation in the interior regions, while in the coastal regions it is high particularly during summer, due to the high evaporation in this season. In the summer, the average specific humidity in the internal regions (Riyadh) is about 8 gm/m^3 , while in the winter, the average specific humidity is about 6.5 gm/m^3 . In the coastal areas along the Arabian Gulf (Dhahran), average specific humidity in the summer is 18.7 gm/m^3 , which is the highest average in the country, while in the winter, the average is 10 gm/m^3 , as seen in Table (4.4). Therefore, specific humidity is expected to absorb a significant amount of solar radiation at the eastern region (Dhahran), particularly during summer.

Table (4.4)
Monthly Averages of Specific Humidity in Saudi Arabia
(in gm/m-3)

Month Station	1	2	3	4	5	6	7	8	9	10	11	12
1. Najran	5.01	5.96	5.51	8.23	7.12	5.46	5.74	6.26	5.35	5.30	5.48	5.38
2. Abha	7.00	7.45	7.38	8.86	9.51	9.28	8.49	9.28	8.47	7.44	7.63	7.23
3. Bishah	7.74	8.34	8.70	10.93	10.92	8.49	9.90	10.61	9.32	8.09	8.47	7.89
4. Sulyyel	4.51	4.57	6.68	8.48	5.11	3.89	4.29	5.20	5.11	4.89	6.16	5.76
5. Taif	6.76	6.76	7.57	8.30	8.81	5.65	4.66	5.18	5.12	6.34	7.44	7.16
6. Al-Aflaj	7.08	7.31	7.51	8.19	6.39	4.59	7.03	5.43	6.91	6.12	9.30	7.55
7. Dawadmi	6.63	6.10	8.01	8.55	9.50	7.02	6.38	6.71	6.67	7.44	7.68	5.58
8. Madinah	6.55	6.34	7.72	8.55	7.34	7.71	7.03	7.80	7.07	8.62	9.18	6.94
9. Riyadh	6.38	5.97	7.01	8.37	8.80	8.66	8.17	7.78	7.98	7.91	7.84	7.09
10. Al-Ahsa	7.26	6.76	9.18	10.70	11.83	10.75	13.0	13.08	14.05	11.79	10.27	7.83
11. Qassim	4.67	4.48	5.83	5.79	5.76	4.15	4.70	7.23	4.32	5.31	6.15	6.01
12. Dhahran	9.02	9.56	11.48	13.66	16.07	16.96	20.44	19.69	16.11	16.32	13.23	9.28
13. Hail	4.74	4.34	5.06	5.79	5.65	4.32	4.24	4.47	4.10	5.31	6.04	4.93
14. Tabuk	3.62	3.48	4.78	4.67	5.35	6.55	8.19	8.19	8.74	5.42	5.04	4.40
15. Jouf	6.12	4.77	6.33	7.51	6.88	7.28	8.06	7.98	7.20	7.31	7.03	5.87
16. Quryyat	3.99	4.09	4.38	5.17	6.17	6.99	7.64	8.63	8.81	6.35	5.48	4.34

Source of raw data: Ministry of Agriculture and Water (1980-1989).

The climate of Saudi Arabia is characterized by a high air temperatures during summer. These may reach as high as 49° C. especially in the central and eastern regions of the Kingdom. The average daytime air temperature in January, the coldest month of the year is 16° C. with occasional freezing at night especially in the northern region. The daily and seasonal variation in air temperature is more noticable in the interior regions than along the coastal regions either in the Red Sea coast or the Arabian Gulf in the east of the Kingdom. The mountainous region of Asir in the southwestern part is an exception. The climate of this region is characterised by its moderate temperatures and a high level of precipitation during summer.

In winter, there is a gradual decrease in air temperature from the southern part of the Kingdom towards the northern part. Air temperature in the north may fall below 0° C·, while in the south the average is around 7° C. The Red Sea coastal region in the west is warmer than the Arabian Gulf region in the eastern part because of the Hijaz mountains in the west. These protect this region from the northern cold winds coming from Siberia in this season. The average air temperature at the Red Sea coastal region during the winter season is 17° C., while in the coastal region of the Arabian Gulf it is only 12° C.

In the summer season, the maximum air temperature is usually recorded in the central and southern parts of the Kingdom with an average of 45° C. In the Arabian Gulf coastal region, the average air temperature is 44° C., while at the Red Sea coastal region, the average is only 37° C. The coolest air temperatures during the summer season are recorded at the Asir region in the southwestern part of the Kingdom with an average of 24° C. because of the higher altitude of this region above the sea level which exceeds 10,000 feet.

Rainfall is one of the most difficult parameter to predict, due to its inherent variability over most of the year and the Kingdom has suffered long periods of drought which forced the country to use desalinated seawater either for domestic, or for industrial and agricultural purposes. Rainfall is generally very low and occurs during winter and spring, except in Asir region in the far southwestern part of the country where rainfall occurs all year round and reaches the highest volume in the Kingdom, 600 mm. The high level of rainfall in the Asir region is attributed to the Monsoon effects during summer, and to the cold north westerly winds during winter.

In most cases the rainfall is highly intense, and of short duration, sometimes causing flooding and damage. This is especially so in the southwest. The average annual rainfall in the central and northern regions is 50-125 mm.. Table (4.5) shows that the southern (Sulayyel), the northern (Quryyat), and the northwestern regions (Tabuk) record the lowest average annual rainfall in the Kingdom. Annual rainfall might be the total of only one or two days rain, especially in the arid central regions which get very little rainfall.

Table (4.5)
Annual Averages of Rainfall in Saudi Arabia
(1980-1989 in mm)

1.	Najran	54
2.	Abha	384.6
3.	Bishah	63.9
4.	Sulyyel	43.1
5.	Taif	154.3
6.	Al-Aflaj	55.8
7.	Dawadmi	90
8.	Madinah	58.6
9.	Riyadh	84.4
10.	Al-Ahsa	88.4
11.	Qassim	121.2
12.	Dhahran	92.1
13.	Hail	84.5
14.	Tabuk	45.4
15.	Jouf	62.3
16.	Quryyat	50.4

Sources : Ministry of Agriculture and Water (1980-1989).

Ministry of Defense and Aviation (1980-1989).

As a result of the low amount of rainfall and the high temperature, particularly during summer, the spring vegetation cover usually disappears at the end spring, turning large areas to arid lands, as shown in plate (4.1). This increases the occurance of dust storms particularly in the southern, central, and northern regions of Saudi Arabia, as seen in Table (4.6). Therefore, the effect of dust storms in the intensity of solar radiation is expected to be significant at these regions, particularly through scattering processes.

Plate (4.1)

High temperature and low amount of rainfall play a significant role in the disappearance of spring vegetation cover.

Table (4.6)
Monthly Averages of Dust Storms in Saudi Arabia

Month Station	1	2	3	4	5	6	7	8	9	10	11	12
1. Najran	0	2	5.8	4.3	2.8	2.3	4	3.3	2	0.8	0	0.8
2. Abha	1	2.5	6.5	1	0.5	3.5	8	7	1	0	0	1
3. Bishah	3	6.3	10.3	6.3	4	2.8	6	3	5.3	2.8	0.3	2.3
4. Sulyyel	4.5	5	5	6.5	3	3.5	2.5	4.5	2.5	2	2	4
5. Taif	0	2.3	7	2	0.8	2.8	4.6	5	2	0.3	1	2
6. Al-Aflaj	3.8	4.5	9.2	6.9	5	5.9	3.8	6.2	3.4	2.2	2.4	4.2
7. Dawadmi	2	3.5	10.8	5.6	8.4	5.1	3	5.3	2.6	2.5	1.9	2.9
8. Madinah	1	2.5	2.5	2.3	1.5	0	0	0	2	1	4	1
9. Riyadh	3	4	13.3	7.3	10	8.3	5	7.8	4.3	2.3	2.8	4.8
10. Al-Ahsa	4	6	15	7.8	8.3	10.8	8	7	5.3	2	6	6.3
11. Qassim	1	3	8.3	3.8	6.8	1.8	1	2.8	0.8	2.7	1	1
12. Dhahran	1.8	2	5	4	2.8	7.3	4	4.3	2.8	0.3	2	2.8
13. Hail	10	1	4	1.3	2	1	0.3	1	0	1.7	0.3	1
14. Tabuk	1.7	3	7.8	5.3	5.7	3.7	2.3	5	3.3	3.7	2.8	3
15. Jouf	2.3	8.5	9.3	5	5.3	2.6	1.3	1.3	2	1.6	1.8	3
16. Quryyat	2.5	5	7	8	8.5	10.5	4.5	4	2	2.5	2.5	2.9

<u>**Source**</u>: Ministry of Defense and Aviation, 1980-1989.

4.2 THE PHYSIOGRAPHY OF SAUDI ARABIA

Saudi Arabia has relatively a large area (2.225 million square KM) and consists of 7 different physiographic provinces. According to the Ministry of Agriculture and Water (1988), Saudi Arabia can be divided to the following terrain regions :

4.2.1 THE COASTAL PLAINS :

These are further divided into the two following sub-regions:

A- The Tihamah Coast, also called the western coastal plain. This coast is located along the Red Sea in the western part of the Kingdom and extends for more than 1800 km. Its width increases to the south, where it reaches its maximum width of 45 km. at Jizan

B- The Eastern Coastal Plain of the Arabian Gulf in the east of the country. This coast is short, only 500 km long compared with the western coast, and extends from Ras Al-Khafji in the north to Dawhat Salwa in the south. Its width reaches 60 km. at its maximum as seen in Fig. (4.1).

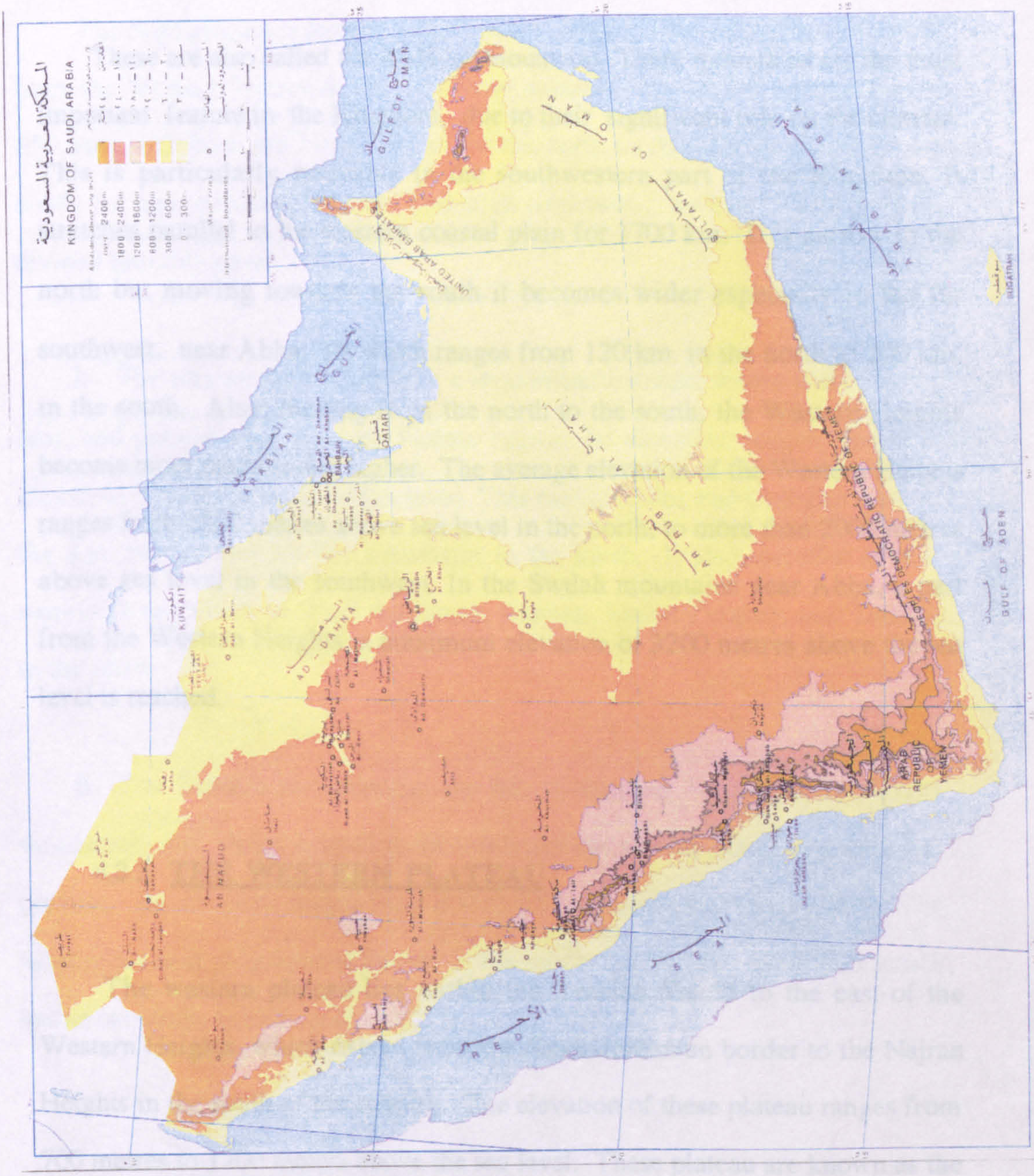


Fig. (4.1)

The Physical Aspects of Saudi Arabia

Source: The Saudi Arabian National Centre for Science and Technology, 1983.

4.2.2 THE WESTERN HEIGHTS :

These are also called the Al-Hijaz mountains. These mountains are the most important feature in the Kingdom, due to their significant role on the climate. This is particularly noticable in the southwestern part of the Kingdom. It stretches parallel to the western coastal plain for 1700 km. It is narrow in the north but moving towards the south it becomes wider especially in the far southwest, near Abha. Its width ranges from 120 km. in the north to 200 km. in the south. Also, moving from the north to the south, the Western Heights become more massive and higher. The average elevation of the Western Heights ranges from 1200 metres above sea level in the north, to more than 2000 metres above sea level in the southwest. In the Swdah mountains near Abha, a part from the Western Heights, a maximum elevation of 3200 metres above the sea level is reached.

4.2.3 THE WESTERN PLATEAU :

The western plateau lies within the Arabian Shield to the east of the Western Heights, which extend from the Saudi-Jordanian border to the Najran Heights in the south of the country. The elevation of these plateau ranges from 700 metres to 1700 meters above the sea level. These plateau are known as the Al-Hima plateau, Al- Hijaz plateau, Rakbah plateau , Asir plateau , and Najran plateau.

4.2.4 NAJD PLATEAU :

The Najd plateau is located in the middle region of the Kingdom. It extends from the Western Plateau to the Ad-Dahna desert in the east for approximately 650 km., and from the Great Nafud in the north to Ar-Rub' Al-Khali in the south, for approximately 800 km. Due to its large area , the Najd Plateau can be divided into two parts:

A- The western part which has a semi-circular shape, where it arcs to the east, and parallels the Western Plateau region. Its elevation ranges from 800 metres to 1200 metres above sea level. This part includes some heights such as the Aja, Salma, and An-Nir mountains in the north. It also includes several valleys (wadis) such as Wadi Ar-Rimah, Ranyah, Bisha, Turabah, and Tathlith to the south.

B- The Eastern part starts at the Saq mountains, Nafud As-Sir, Khuff mountains , and Nafud Addehi to the south and ends in the Ad- Dahna desert to the east. Its elevation ranges from 800 to 1096 metres above the sea level. The most prominent geographical feature in this part is the Tuwayq mountains which has an arc shape extending over 800 km.

4.2.5 THE EASTERN PLATEAU :

The Eastern Plateau extend from the Ad-Dahna sandy desert in the west to the coastal plain of the Arabian Gulf in the east, and from the Al-Batin valley (wadi) in the north of the Ar Rub' Al-Khali in the south. This area consists of the following plateau : Adibdibah plateau, As-Summan plateau, Al-Jafurah

Nifud, and Al-Hafat Al-Sakhriyah. The elevation of these plateau ranges from 170 to 40 metres above sea level.

4.2.6 THE NORTHERN PLATEAU :

The Northern Plateau are an extension of Badiyat Ash-Sham Plateau in the south of Jordan and Iraq. They include the northern-most portion of the Kingdom's territories, and extend from An-Nafud Al-Kabir in the south to the Jordanian, Iraqi, and Kuwaiti borders in the north. The most significant geographical features are the valleys (wadis) such as Wadi As-Surhan, Wadi Ar'Ar, Wadi Ar-Ruthiyah, Wadi Al-Mira, Wadi Al-Helali , and Wadi Fayahan.

4.2.7 THE SAND DESERTS :

Most of the Kingdom of Saudi Arabia is a sandy desert which includes the following deserts:

A- Ar-Rub' al-Khali desert which stretches as a low basin in the south of the country , from the east of the Western Heights of Saudi Arabia and Yemen in the west to the slopes of Oman Heights in the east , and from Najd Plateau in the north to the borders of Yemen and Oman in the south. The area of this desert is about 640,000 square km., therefore, it is one fourth of the Kingdom's area and it is the largest sandy desert in the world.

B- AN-Nafud Al-Kabir desert in the north. This desert is located in the northwestern part of the Kingdom. It has a triangular shape with an area of 56,320 square km. This desert is characterised by different forms of red coloured dunes.

C- Ad-Dahna desert. It lies on the northeast of the country and it takes the shape of an open crescent facing the west. It connects the An-Nafud Al-Kabir desert and Ar-Rub' Al-Khali for 1200 km. It is considered as a separator between the Najd plateau and the Eastern Plateau.

CHAPTER FIVE

THE MAJOR FACTORS INFLUENCING THE INTENSITY OF SOLAR RADIATION RECEIVED AT THE EARTH'S SURFACE IN SAUDI ARABIA

Introduction

Variations in the distribution of incoming solar radiation received at the earth's surface have been widely investigated from the standpoint of the importance of solar radiation as a major alternative source of energy. As stated earlier, variations have been attributed to several factors, such as sunshine duration, latitude, altitude, relative humidity and longitude. However, some variables, such as specific humidity, are either missing from most models of incoming solar radiation, or used in unappropriate way which do not explain the variation of incoming solar radiation, such as latitude. The key factors that determine the total intensity of incoming solar radiation received at the earth's surface in Saudi Arabia are sunshine duration, specific humidity, altitude, insolation index, cloud cover, and dust storms. Insolation index is a function of latitude and sun declination. The role of these major factors are analysed in detail in this Chapter. Each of these factors has a different effect upon the distribution of incoming solar radiation at the earth's surface in Saudi Arabia and, therefore, creates an overall detectable variation from one location to another.

5.1 Incoming Solar Radiation

Incoming solar radiation received at the earth's surface is the dependent variable in this research. It may be also termed insolation. As indicated earlier, the total solar radiation collected at the earth's surface is the sum of direct solar radiation and sky radiation. Solar radiation received at the earth's surface peaks in the short wavelengths between 0.4-0.7 micrometres (μ m). This is visible light and can be distinguished from long wave radiation (earth radiation) which is non-visible infra red radiation (between 9-14 μ m). Daily incoming solar radiation is recorded continuously on actinographs. The mean monthly solar radiation values that are used in this research are measured in calories per square centimetre per day (Cal / cm^2/d).

At a planetary scale, 17% of the incoming solar radiation is absorbed by certain atmospheric gases such as water vapor, clouds, and ozone, 30% is reflected back to the atmosphere by atmospheric particles and clouds, and 53% reaches the earth's surface, 31% of it as direct radiation and 22% as a diffuse radiation scattered back to the earth's surface by atmospheric particles such as aerosols, dust, and clouds (Sashamanoglou and Bloutsos, 1989). Therefore, attenuation of the incoming solar radiation accounts for 47% of the total solar radiation at the top of the earth's atmosphere.

To understand the effect of atmospheric particles upon the intensity of solar radiation received at the earth's surface, a detailed analysis of these particles must be conducted as well as for the other significant factors identified.

5.2 The Key Factors Influencing the Intensity of Incoming Solar Radiation in Saudi Arabia

In this thesis, I have attempted to analyse the overall effects of the major factors identified on the intensity of solar radiation at the earth's surface by using multiple linear regression, a precise statistical tool. This specifies the role of each identified factor upon the intensity of incoming solar radiation received at the earth's surface, irrespective of the other factors. This analysis is based on mean monthly values of these factors for ten years, from 1980 to 1989.

5.2.1 Insolation Index

Solar radiation rarely strikes the earth's surface perpendicularly, but rather reaches the earth's surface at an oblique angle which varies according to latitude of the location and the time of the year. Solar radiation is frequently closer to perpendicular at low latitudes than high latitudes because of the seasonal movement of the sun between the equator and latitude $23^{o}.5'$ south and north of the equator. Therefore, total intensity of incoming solar radiation depends on sun declination as well as the latitude of the site.

Many climatologists and solar energy scientists (e.g. Sayigh, 1977; Bamiro, 1982; Barra, 1982) have not considered sun declination as an important factor in determining the amount of solar radiation received at the earth's surface, but have used latitude of the location instead. In fact, the latitude of the location is not independent in itself, but depends on the sun's declination. The sun declination angle may be determined as follows :

$$\delta = 23.5 \cos \frac{[(2\pi(d-172)]}{365} \qquad (5.1)$$

where:

δ : angle of solar declination,

d : day of the year.

(Rosenberg, Blad and Verma, 1983).

Solar declination (δ) may be estimated by using the following equation :

$$\delta = 23.5 \sin n^{o} \qquad (5.2)$$

where:

δ: solar declination.

n: the number of days before (-) or after (+) the nearestequinox.

(Lee, 1978).

Therefore, these two variables, latitude and sun declination, should be combined as one independent variable by using Lambert's Law, as follows :

$$\cos \alpha = \cos (\phi - \delta) = I/I_O \qquad (5.3)$$

where:

α: angle of incidence of direct insolation.

ϕ: latitude of location.

δ: sun declination.

I : actual direct insolation received at the latitude of the location, and

I_O: direct insolation on a surface perpendicular to the suns'rays.

So, Cos α is the portion of insolation available at the point of the sun's declination that is actually received at the location.

The latitudes of the study area, Saudi Arabia, range from 17° 33' N (Najran) to 31° 20' N (Quryyat). This relatively large range has an important effect on the spatial variation of incoming solar radiation through months of the year and seasons. Using equation (5.3), it is found that the intensity of incoming solar radiation received at the earth's surface increases when the sun's declination is perpendicular at the latitude of the location. In other words, as the difference between the latitude and sun declination increases, the intensity of insolation received at the earth's surface decreases.

5.2.2 Specific Humidity

According to Rangarajan (1982), the most important gas in the earth's atmosphere which influences to the total *absorption* of solar radiation is water vapour, particularly at the coastal areas. He found that fluctuations in the mean water vapour content in the earth's atmosphere from year to year are rather small. This was based on measurements over 5-year period (1971-1975) in 19 stations in India. This work shows that there is only a small effect, due to variations in atmospheric water vapour, on the yearly intensity of solar radiation received at the earth's surface. The truth of the importance of the derivation of specific humidity has a universal applicability. The derivation of specific humidity would have applicability to Saudi Arabia due the wide range of variation in humidity both in time and space, particularly between inland and coastal areas.

Most of Saudi Arabia is arid land, bounded by two large bodies of water, the Red Sea to the west and the Arabian Gulf to the east, as a result, high humidity is expected to be found in coastal areas especially in summer when the evaporation rate is very high. For example, in Dhahran, on the eastern coast of Saudi Arabia, the amount of solar radiation absorbed by water vapour may be as high as 26% of the total received at the earth's surface (Abdelrahman, Elhadidy, 1986). This is particularly so in the summer months when humidity is very high, as seen in plate (5.1). As the amount of water vapor in the earth's atmosphere increases, the amount of absorbed solar radiation increases too, and, as a result, the amount of solar radiation received at the earth's surface decreases. Water vapour comprises up to 4% of the earth's atmosphere by volume near the surface, but it is almost absent above 10 to 12 km. (Barry and Chorley, 1982). The total amount of water vapour in the earth's atmosphere depends on the actual evapotranspiration.

Plate (5.1)

High humidity at the eastern coast of Saudi Arabia, where incoming solar radiation is significantly absorbed by water vapour.

The amount of water vapour in the earth's atmosphere can be expressed by different measures, including relative humidity, absolute humidity, mixing ratio, and specific humidity. Of these measures, relative humidity has been used in the majority of relevant studies as an indicator of the amount of moisture in the earth's atmosphere which can absorb solar radiation. Such studies include those by Sabbagh, Sayigh, El-Salam (1977); Sayigh (1977) and Daneshyar (1978). However, relative humidity does not give a precise estimate of water vapour content in the earth's atmosphere because it depends on temperature. As temperature increases, relative humidity decreases given the same amount of the moisture in the air. Therefore, relative humidity is not an absolute measure of atmospheric water vapour content. Specific humidity can be used to estimate precisely moisture content in the earth's atmosphere and, hence, give an accurate estimate of the portion of solar radiation absorbed by water vapor content. Specific humidity is defined as the ratio of the mass of water vapor to the total mass of the air and is expressed as grammes of water vapor per kilogramme of air (g/Kg). Since relative humidity is the only published measure of water vapour content in the air for weather stations in Saudi Arabia, it was necessary to derive specific humidity from the relative humidity and ambient surface temperature using the following equation : (5.4)

$$Wat = RH \times (4.7923 + 0.3647\ T + 0.0055 \times T^2 + 0.0003 \times T^3)$$

where :

Wat : the atmospheric water vapour content per unit volume of air (or specific humidity).

RH : the relative humidity.

T : the ambient temperature in C^{o}.

(Hussain, 1984).

This empirically-derived equation is adequate to obtain climatological values of Wat with a high level of confidence, especially with monthly averaged data over a relatively short period.

5.2.3 Sunshine Duration

Length of sunshine duration is a major factor which influences the total amount of incoming solar radiation received at the earth's surface in any latitude. The longer the daytime during which the sun is shining the greater is the intensity of solar radiation that is received at any latitude. Daylength varies with respect to latitude of the location and the season of the year. For example, at the equator, day-length is close to 12 hours throughout the year, while at the north and south poles it varies between 0 and 24 hours between winter to summer respectively.

Therefore, sunshine duration is a key factor in determining the amount of incoming solar radiation received at the earth's surface. Many solar scientists and climatologists have used sunshine duration as the main factor to be used in estimating the total amount of incoming solar radiation received at the earth's surface. Angstrom (1924), perhaps the best known of this group, used a regression model which depends only on the sunshine duration as follows :

$$\frac{\bar{H}}{Ho} = a + b\,(\,\bar{n}/N) \qquad (5.5)$$

where:

$\bar{H}$: is the monthly mean daily global radiation received on the earth's surface,

Ho: is mean monthly daily radiation at the earth's surface in the absence of any atmosphere,

$\bar{n}$: is mean monthly daily sunshine hours,

N : is mean monthly daily sunshine hours for a given month between sunrise and sunset, and

a and b: are determined regression coefficients.

(Ibrahim, 1985).

However, $\bar{n}/N$ gives only the percentage of possible sunshine duration. This varies from location to location according to the latitude of that location. Thus, it is more accurate to use actual sunshine hours measured directly by recording instruments, such as the Campbell-Stokes (CS) recorder, or the Foster sunshine switch. These can give a precise measure of sunshine duration hours in any location.

Sunshine duration decreases with increasing latitude in winter, especially in higher latitudes. There are, however, two regions that receive the maximum sunshine duration; these are located between 20° – 30° south and north of the equator. Saudi Arabia is located between 17° - 33° N , falling largely into one of the maximum zones, and receives a high sunshine duration by world standards with a daily average of 12 hours (Ministry of Agriculture and Water, 1988). The Hydrology Division of the Ministry of Agriculture and Water of Saudi Arabia publishes mean monthly values for sunshine hours based on direct measurements. This data is used in this research project.

5.2.4 Altitude

Elevation is a major determinent of the total intensity of incoming solar radiation received at the earth's surface. The greatest variation of incoming solar radiation compared with sea level projected values is usually recorded at mountainous stations. For example the average amount of solar radiation at Abha in the southwest of Saudi Arabia at an altitude of 2200 metres a. s. l. is 500 Cal / cm^2/d. while at nearby Bisha, at an altitude of 1020 metres a. s. l., the average amount of solar radiation is only 350 Cal / cm^2 /d.

The physical map of Saudi Arabia, fig. (4.1), reveals significant differences in elevation of the recording stations used in this research. Their elevation varies from 2400 metres a. s. l. (Biljurashi) in the southwestern part of Saudi Arabia to only five metres a. s. l. (Dhahran) in the eastern coast of Saudi Arabia.

Altitude of the location plays an important role in the spatial variation of incoming solar radiation received at the earth's surface. Garrison (1984), found that the intensity of incoming solar radiation increases as the altitude of the location investigated increases. Pasquale (1987), also concluded that incoming solar radiation tends to increase with increasing altitude. There are two reasons for this. First, the thickness of the earth's atmosphere becomes smaller with increasing altitude and, hence, the portion of incoming solar radiation attenuated by the atmospheric particles decreases. Secondly, there are decreasing amounts of water vapour as altitude increases. Barry and Chorley (1982), stated that the intensity of incoming solar radiation in middle latitudes increases by 5% to 15% for each 1000 m increase in elevation in the lower troposphere. The variation of incoming solar radiation is strongly affected by aspect at micro and meso climatology. However, at the regional and national scale, the effect of aspect is not significant, and therefore can not be included in the radiation model. The effect of aspect is further discussed in Chapter Eight.

5.2.5 Cloud Cover

Cloud cover plays a minor role in attenuating incoming solar radiation in Saudi Arabia, except in the Asir region in the southwestern part of the country. Cloud cover attenuates incoming solar radiation through three processes: reflection, absorption, and scattering. Furthermore, the amount of reflected, absorbed and scattered solar radiation by clouds depends on the type of clouds as well as their thickness. The amount of cloud is normally measured as a regular part of the observation programme at most of the meteorological stations in Saudi Arabia. Cloud cover is reported in Oktas (eighth) of the sky covered by clouds.

Types of clouds are distinguished by their heights (low, middle and high). Their vertical structure is also recorded. Horizontal layers are termed stratus, whilst clouds with a vertical extension, or puffy clouds, are termed cumulus. High clouds are classified as cirrus. Therefore, the amount of solar radiation attenuated by cloud depends on both the thickness and the height of the clouds. As the cloud becomes thicker and lower, the amount of solar radiation blocked by cloud tends to increase. However, the average amount of solar radiation attenuated by clouds in Saudi Arabia is very low, due to the low occurrence of clouds. Nationally, this is estimated to be 5 days a month. Also the typically high altitude of clouds, especially during summer and autumn seasons decreases their effect. The exception to this is in the mountainous region of Asir in the south-west of the Kingdom, where there is a high frequency of cloud cover all around the year in general, and in summer and winter in particular. In this region, therefore, there are great variations in the intensity of solar radiation received.

The proportion of solar radiation that is reflected by cloud is termed albedo. The amount of the reflected solar radiation depends on the type and thickness of the clouds, as seen in plate (5.2). Measurements from aircraft show that the albedo of a complete overcast ranges from 44 to 50% for cirrostratus to 90% for cumulonumbus (Barry and Chorley, 1982). Some of the reflected solar radiation can be reflected back to the earth's surface by cloud. This is called multiple reflection and usually happens with cumulus cloud when the sky is not fully covered by cloud. This type of solar radiation received through multiple reflection is called diffuse radiation.

Plate (5.2)

Cloud cover plays a significant role in attenuating the intensity of incoming solar radiation, particularly through reflection processes.

Clouds also play an important role in scattering solar radiation in the earth's atmosphere. This is termed Mie scattering and is effective whenever the scattering particles are of a similar size to the wavelength of the solar radiation. The amount and direction of scattering is thus a function of both the particle size and the wavelength of the solar radiation (Sellers and Robinson, 1986).

Absorption of solar radiation by cloud is relatively small and is usually considerably less important than scattering. The total amount of solar radiation absorbed by cloud in the earth's atmosphere accounts for 2%.

Diffuse radiation is more affected by clouds appearance and might be eliminated if dark clouds intervened. Lestrade, Acock, and Trent (1990), found that totally dark, absorbing clouds decrease the level of diffuse radiation in direct proportion to the fraction of sky covered by clouds. Moreover, they found that totally overcast skies resulted in zero diffuse radiation at the ground. The sharp decrease in diffuse radiation is attributed to the fact that diffuse radiation is attenuated through the reflection processes in clouds and by atmospheric aerosols, and therefore cannot penetrate the lower cloud layer in a totally overcast sky. Although cloud attenuates solar radiation by reflection, scattering and absorption, these occur simultaneously, and each process is separate and has different consequences.

Saudi Arabia is an arid country with a general lack of cloudiness. As stated earlier, on the average, there are more than 300 days of direct sunshine per year which means that there are less than five cloudy days per month (Abdulrazzak and Masoud, 1985). However, the number of cloudy days varies spatially and with season. Though of low occurance, it is necessary to include the cloud cover factor in the regression model of the variation of incoming solar radiation to explain some of the variation, especially in the mountain areas of southwestern Saudi Arabia.

5.2.6 Dust Storms

Dust storms are the major factor which attenuate solar radiation received at the earth's surface in Saudi Arabia, paricularly through the *scattering* processes in the inland areas. The accumulation of dust particles on solar radiation collectors reduces the total solar radiation, sometimes to very low amounts. This necessitates both periodic cleaning and maintainence of the solar collectors. Dust storms affect the intensity of solar radiation through two distinctive processes, absorption and scattering. The total effect of these two phenomena in attenuating solar radiation depends on the total concentration of dust and its size distribution.

Drier and less mountainous areas have many dust storms. These occur particularly over the Arabian peninsula where dust storms are strong enough to cause severe visibility problems. A dust storm is defined as an occasion when visibility is reduced by the presence of dust, to less than 1000 m. (Goudie, 1978). Idso (1976), specified five major regions where dust storms originate: the Sahara, the southern coast of the Mediterranean Sea, north-east Sudan, the Arabian Peninsula, and the lower Volga and North Caucasus in U.S.S.R.

There are many factors which control dust storm generation. The main factors, according to Mohammad (1989), are the nature of the surface (alluvial surfaces, playas, sabkhas, etc.), the velocity of the wind and the quantity of precipitation. Arid and semi-arid surfaces produce the environmental condition from which dust storms can be generated. As wind speed increases, the quantity of dust in the storm tends to increase, and the distance travelled by the dust storm tends to increase. Precipitation level is the main factor controlling the development of vegetation cover, and the moisture characteristics of the soil in dust storm generating areas. The presence of vegetation cover during the rainfall period in winter and spring plays a crucial role in reducing the occurence of dust storms. This vegetation cover usually disappears within a short time due to overgrazing or to high summer temperatures.

When small particles of fine dust appear in the atmosphere, the colour of the sky begins to change from blue to milky white. But when the quantity of dust increases further, especially during the summer season, the sky may become yellow. Although dust particles are small, they are large enough to scatter all wavelengths of visible radiation in all directions. The scattering of solar radiation by dust and other particles in the earth's atmosphere can be clearly visible whenever there is a break in clouds layers. These make the solar radiation appear bright and are especially noticeable towards sunset due the longer path that solar radiation takes through the earth's atmosphere.

Since the sky is clear most of the year in Saudi Arabia, dust storms are the dominant factor that reduce the intensity of solar radiation received at the earth's surface through scattering and absorption processes in the earth's atmosphere, as seen in plate (5.3). The effect of dust on the intensity of solar radiation varies with according to the thickness of the dust in the atmosphere and the time of the day. The amount of solar radiation attenuated by dust tends to increase during the early and late hours because solar radiation is inclined and thus takes a longer path through a thick earth's atmosphere, while at noon-time it is nearly perpendicular, as shown in plate (5.4). Oblique angle of incidence also increases reflection from top layers of dust storm. A comparison between plate (5.4) and plate (5.5) clearly shows the effect of dust storms in attenuating solar radiation.

Plate (5.3)

Dust storms significantly reduce the intensity of incoming solar radiation, particularly through scattering processes.

Plate (5.4)

The capital Riyadh during a dust storm.

Plate (5.5)

The capital Riyadh during a clear day.

5.3 Characteristics of the Data Used in the Research

This analysis of the variations in the intensity of incoming solar radiation at the earth's surface in Saudi Arabia requires accurate data for the major factors identified which affect the pattern of variation. These data should be based on daily measurements rather than estimations, to give precise results.

Primary data required for analysis were obtained from the Hydrology Division of the Department of Water Resources Development of the Ministry of Agriculture and Water in Riyadh, S.A.; The King Abdulaziz City for Science and Technology (KACST); and The Meterology and Environmental Protection Administration (MEPA) of the Ministry of Defense and Aviation in Jeddah, S.A.

All data used in this analysis are monthly means based on daily measurements for the period 1980 to 1989, and are for 16 stations distributed throughout the Kingdom of Saudi Arabia. These are fairly representative all the topographic and climatological conditions in the Kingdom, though not of the whole spatial area.

The data units used in this research are as follows; incoming Solar Radiation in Cal / cm^2/d ; sunshine duration as the actual observed number of sunshine duration hours per day ; altitude in metres above mean sea level ; cloud cover as the fraction of sky covered by clouds measured in eighth parts (oktas). The insolation index is derived from the latitude of the location and the solar declination for that location for the time of the year. This gives the portion of insolation that actually is received at the location under investigation. Specific Humidity is derived from both relative humidity and ambient temperature (C^o), and measured in gm / m^3. Dust storms is measured as the average monthly number of occurences. The derivation and calculation of these factors has been discussed earlier in this chapter.

5.4 Theoretical Bases and analytical Procedures

In this thesis, the analysis of the variation of incoming solar radiation is based on the theoretical premise that there is a relationship between the incoming solar radiation received at the earth's surface, the dependent variable, and the major independent variables, sunshine duration, insolation index, altitude, specific humidity, cloud, and dust storms. This give the general hypothetical base for this part of the research.

More particularly, the analysis of the factors influencing the intensity of incoming solar radiation is based on the following specific hypotheses: (i) the intensity of incoming solar radiation received at the earth's surface is affected positively by the duration of sunshine hours; (ii) the insolation index, which is a function of the latitude of the location and sun declination, has a positive effect on the intensity of solar radiation received at the earth's surface; (iii) the altitude of the location positively affects the intensity of solar radiation received at that location; (iv) solar radiation received at the earth's surface is negatively affected by water vapour, measured by specific humidity. The negative effect of water vapor upon the intensity of solar radiation received at the earth's surface is expected to be significant, especially in coastal regions where water vapour content is high compared with inland regions and mountain areas where water vapour content tends to decrease as altitude increases; (v) the cloud cover of the location negatively affects the total amount of incoming solar radiation received; and (vi) dust storms negatively affect the intensity of incoming solar radiation.

To test these hypotheses, T-tests and F-tests have been used. The T-test examines the significance of the effect of each independent variable between locations. The F-test examines the significance of the effect of the overall regression model; that is, the significance of the effect of all the independent variables on the variation of incoming solar radiation at the earth's surface.

5.5 The Radiation Model

An important step in analysing the variation of incoming solar radiation is the selection of statistical model to reveal the effects of the related factors upon overall variations. In explaining the complex variations in the intensity of incoming solar radiation in Saudi Arabia, a multiple linear regression model has been chosen as the most appropriate method to explain the interrelationships between determinants and their dependent variable, incoming solar radiation. The model used has been specifically adapted and developed for this research project. The value of using this multiple linear regression model in the research, stems from the fact that the effect of each independent factor upon the intensity of incoming solar radiation can be made more certain (Lewis-Beck,1980). Moreover, it measures the unexplained variation effected by the other variables, not explicity included in the regression equation.

The proposed model, the multiple linear regression, is stated thus :

$$ISR_i = \beta_0 + \beta_1 SD_i + \beta_2 IN_i + \beta_3 ALT_i + \beta_4 SH_i + \beta_5 CC_i + \beta_6 DT_i + E_i$$

where:

ISR_i: incoming solar radiation received at the earth's surface in calories per square centimetre per day (Cal / cm^2 / d) of location i, where i = 1, 2, ... 16

β_0 : the intercept, which is the average effect on Y (ISR) of all variables omitted from the model.

SD_i: sunshine duration of location i in hours per day

IN_i: insolation index, the actual percentage of insolation available for the value of solar declination received at location i and is measured as follows :

$$IN = \cos \alpha = \cos (\phi - \delta) = I/Io$$

where :

IN : as defined above,

α : angle of incidence of direct insolation,

ϕ : latitude of the location,

δ : sun's declination,

I : actual direct insolation received at the latitude of the location, and

Io : the direct insolation to a surface perpendicular to sun's radiation.

ALT_i : the altitude of location i in metres above sea level.

SH_i : specific humidity of location i in grams of water vapour per cubic metre of air (gm/m^3) derived from relative humidity (%)

and ambient temperature (C^o) (see equation 5.4).

CC_i : cloud cover, which measured by the monthly average fraction of cloud cover expressed in oktas.

DTi : Dust storms, measured by the monthly average number of dust storm days.

E_i: the error term, which is the components of unexplained variation in incoming solar radiation received at the earth's surface.

The main factors mentioned above, sunshine duration, insolation index, altitude, specific humidity, cloud cover, and dust storms are expected to explain the majority of variation in the intensity of incoming solar radiation in Saudi Arabia. The results of this approach are evaluated in the next Chapter.

CHAPTER SIX

TEMPORAL VARIATIONS IN THE RECEIPT OF SOLAR RADIATION IN SAUDI ARABIA

There are quite large temporal variations in the intensity of incoming solar radiation received at the earth's surface in Saudi Arabia despite the apparently limitless sunshine hours. These variations can be attributed to the physical and meteorological characteristics of the stations investigated. In this thesis, the investigation of variations of incoming solar radiation will be based on six main factors. These factors are, sunshine duration, insolation index, altitude, specific humidity, cloud cover, and dust. The derivation of these factors has been discussed in detail in Chapter Five.

The investigation is based on records from sixteen stations distributed throughout the Kingdom. These represent the physical and meteorological range within the study area, which extends from Najran (17° 37' N) at the southwest of Saudi Arabia to Qurryat (31° 25' N) at the northern part of the country and from Taif (40° 09' E) in the west to Dhahran (50° 09' E) at the eastern coast of Saudi Arabia as seen in fig. (6.1).

Incoming solar radiation received at the earth's surface in Saudi Arabia as well as its major determining factors are analysed using the multiple linear regression model described in the previous chapter. This is the appropriate statistical method to reveal the effect of each factor on the intensity of incoming solar radiation. Multiple linear regression parameters and their corresponding T- and F- ratios as well as R^2, the coefficient of determination, are shown in Tables 6.1 - 6.6, respectively, in which Table 6.1 represents the months of January and February and Table 6.2 represents the months of March and April and so on.

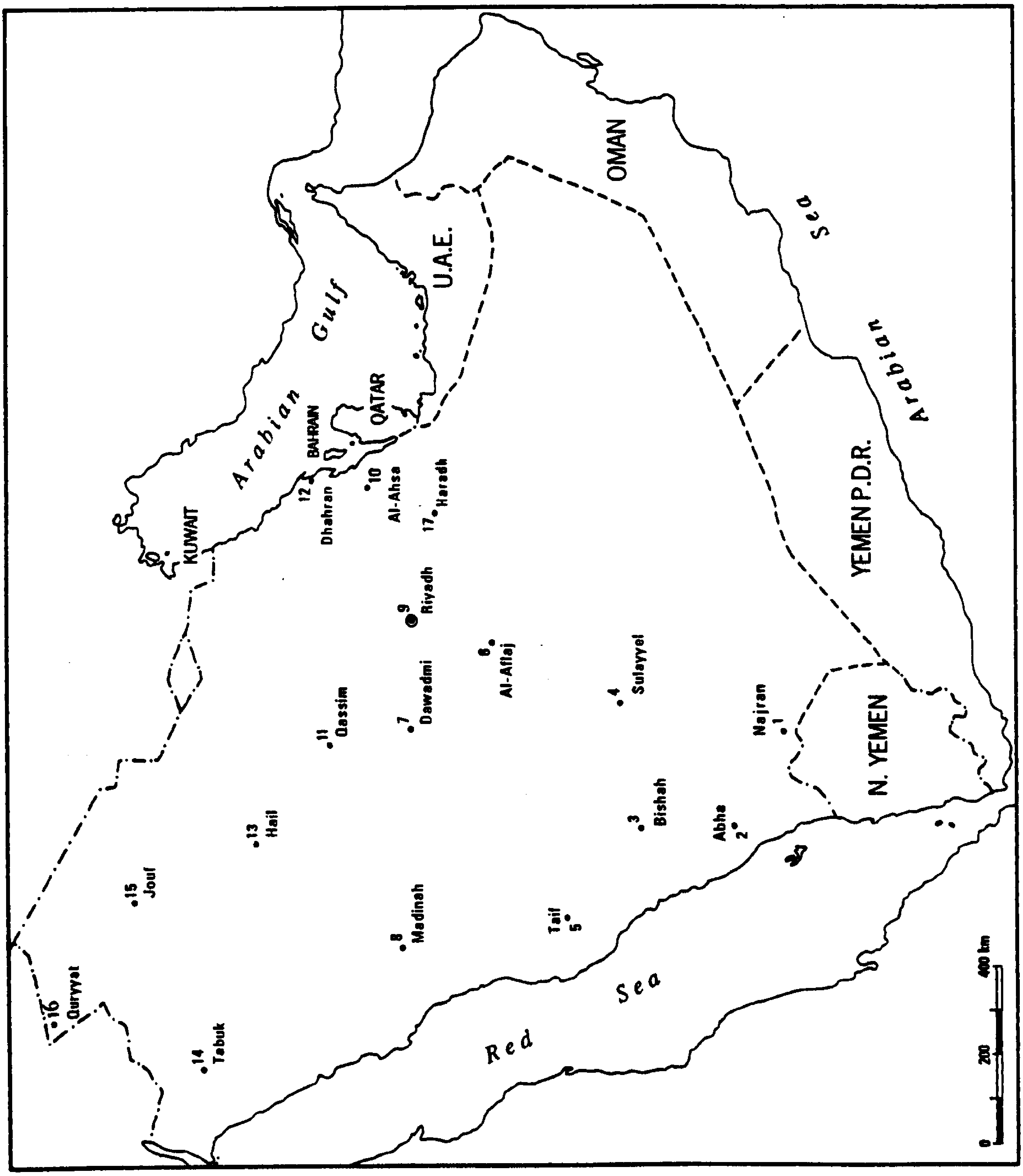


Fig. (6.1)

Stations included in the investigation of the Variation of Solar Radiation in Saudi Arabia

During the month of January, there is a noticeable low value decrease in the intensity of incoming solar radiation received at the earth's surface in Saudi Arabia particularly in the northern part of this country. This relatively low value for incoming solar radiation is associated with both low sunshine duration and insolation index because the sun is in the southern hemisphere in this time of the year. For example, at Quryyat (Station 16), the total intensity of incoming solar radiation in this month is only 226 Cal/cm^{-2}/d compared with 403 Cal/cm^{-2}/d recorded at Abha (station 2), 78 percent higher.

The most important factor that determines the intensity of incoming solar radiation in the month of January is altitude of the location as shown in Table (6.1). As the altitude of the location increases, the intensity of incoming solar radiation tends to increase too. For example, at Tife , station 5 (1454 m a. s. l.) , the total intensity of incoming solar radiation received at this station is 366 Cal/cm^{-2}/d, while at Sulyyel, Station 4 (616 m), it is only 232 Cal/cm^{-2}/d. Altitude of the location plays a significant role in determining the intensity of incoming solar radiation at the earth's surface in Saudi Arabia during the month of January. The analysis shows that as the altitude of the location increases one unit (one metre), the intensity of incoming solar radiation increases 0.06 units (Cal/cm^{-2}/d) as shown in Table (6.1). Finally, the attenuating variables of incoming solar radiation in Saudi Arabia, specific humidity, cloud cover, and dust storms, have no significant effect in decreasing the amount of incoming solar radiation due to their low values and occurrence in the month of January.

TABLE (6.1)

RESULTS OF MULTIPLE LINEAR REGRESSION ANALYSIS FOR JAN AND FEB

MONTH	VARIABLE	ESTIMATED PARAMETER	T-RATIO	F-TEST	R-sq
JAN	Intercept	233.1	1.29	8.45*	91.0%
	Sunshine Duration	12.02	0.66		
	Insolation Index	256.7	0.73		
	Altitude	0.0615	2.17 *		
	Specific Humidity	-0.447	-0.06		
	Cloud Cover	-36.81	-1.62		
	Dust	-9.21	-0.93		
FEB	Intercept	-126.7	-0.55	10.56*	94.1%
	Sunshine Duration	73.88	4.14 *		
	Insolation Index	211.6	0.74		
	Altitude	0.0531	3.03 *		
	Specific Humidity	-2.988	-0.58		
	Cloud Cover	-14.88	-1.03		
	Dust	-8.382	-1.87		

* Represents significance at the 0.05 level.

In February, there is a gradual increase in sunshine duration in Saudi Arabia, particularly in the south-western part. For example, at Station 2 (Abha), sunshine duration in this month is 8.1 hours compared with 7.7 hours in January. As sunshine duration increases, the intensity of incoming solar radiation tends to increase too. Statistically speaking, as sunshine duration increases by one unit (one hour), the intensity of incoming solar radiation at the earth's surface in Saudi Arabia increases by 73.9 units ($Cal/cm^{-2}/d$) as shown in Table (6.1). As noticed in the month of January, altitude of the location continues to play a significant role in increasing the intensity of incoming solar radiation. For instance, the monthly average of incoming solar radiation received at Station 5 (Taif, 1454 m) is 425 $Cal/cm^{-2}/d$ while at Station 9 (Riyadh, 611 m) it is only 340 $Cal/cm^{-2}/d$. As altitude of the location increases one unit (one metre), the amount of incoming solar radiation tends to increase 0.053 units, holding the other variables constant, as is shown in Table (6.1).

Dust storms begin to have an important effect, although not highly significant, in decreasing the amount of incoming solar radiation , for example, at Station 4 (Sulyyel), the intensity of incoming solar radiation is only 280 $Cal/cm^{-2}/d$ despite the high duration of sunshine hours, which reaches 8.4. This low amount of incoming solar radiation at Station 4 (Sulyyel) can be attributed to the occurrence of dust storms of this station on average 5 days in this month.

In March, there is a noticeable increase in sunshine duration particularly in the northern part of Saudi Arabia. For example, at Stations 15 (Jouf) and 16 (Quryyat), sunshine duration in this month is 7.8 and 7.9 hours respectively, compared with 6.9 and 7.6 hours respectively recorded at these two stations in the previous month of February. This increase in sunshine duration in the northern part of the country has a positive effect on the intensity of incoming solar radiation received. For example, the amount of incoming solar radiation recorded at stations 15 (Jouf) and 16 (Quryyat) was 390 and 357 Cal/cm^{-2}/d, respectively, compared with 329 and 287 Cal/cm^{-2}/d respectively, recorded at these two stations in the previous month of February, an increase of 19 and 24 percent, respectively, from that month.

Altitude of the location continues to have a significant effect in increasing the intensity of incoming solar radiation for the third consecutive month. Stations 2 (Abha, 2200 metres), 5 (Taif, 1454. metres) and 8 (Medinah, 636 metres) located at the Western Heights of Hejaz demonstrate this. The higher altitude of these stations results in a higher intensity of incoming solar radiation reading 465, 481 and 447 cal/cm^{-2}/d respectively. The statistical analysis of the relationship between incoming solar radiation received at the earth's surface in March and altitude of the location revealed that as altitude of the location increases by one unit (one metre), the incoming solar radiation increases by 0.087 units (cal/cm^{-2}/d), when other explanatory variables are constant, as shown in table (6.2).

Moreover, in March, cloud cover begins to play a significant role in attenuating the incoming solar radiation before it reaches the earth's surface, through absorption, reflection, and scattering processes which occur simultaneously in the earth's atmosphere, as shown in fig. (6.2). The increase of cloud cover is generated by the humid Western winds coming from the Atlantic Ocean at this time of the year which reach the northern and middle parts of Saudi Arabia. As cloud cover increases by one unit (one cloudy day), the amount of incoming solar radiation received at the earth's surface decreases by 46.79 units (as shown in table (6.2).

In April, for the second consecutive month, cloud cover continues to play a significant negative effect on the intensity of incoming solar radiation received particularly in the mountainous areas in the south-western part of Saudi Arabia. in this area. Here there is a noticeable increase in the monthly average of cloud cover caused by the Monsoonal winds coming from the Indian Ocean, which commence in early summer and continue during the summer season in this area. For example, at Najran (station 1), the monthly average of cloud cover in this month is 3.3 days compared with only 2 days in the previous month. This is the highest average value for cloud cover recorded in Saudi Arabia in April. Table (6.2) reveals that as cloud cover increases by one unit (one cloudy day), the amount of incoming solar radiation received at the earth's surface tends to decrease by 112 units (Cal/cm^{-2}/d).

TABLE (6.2)

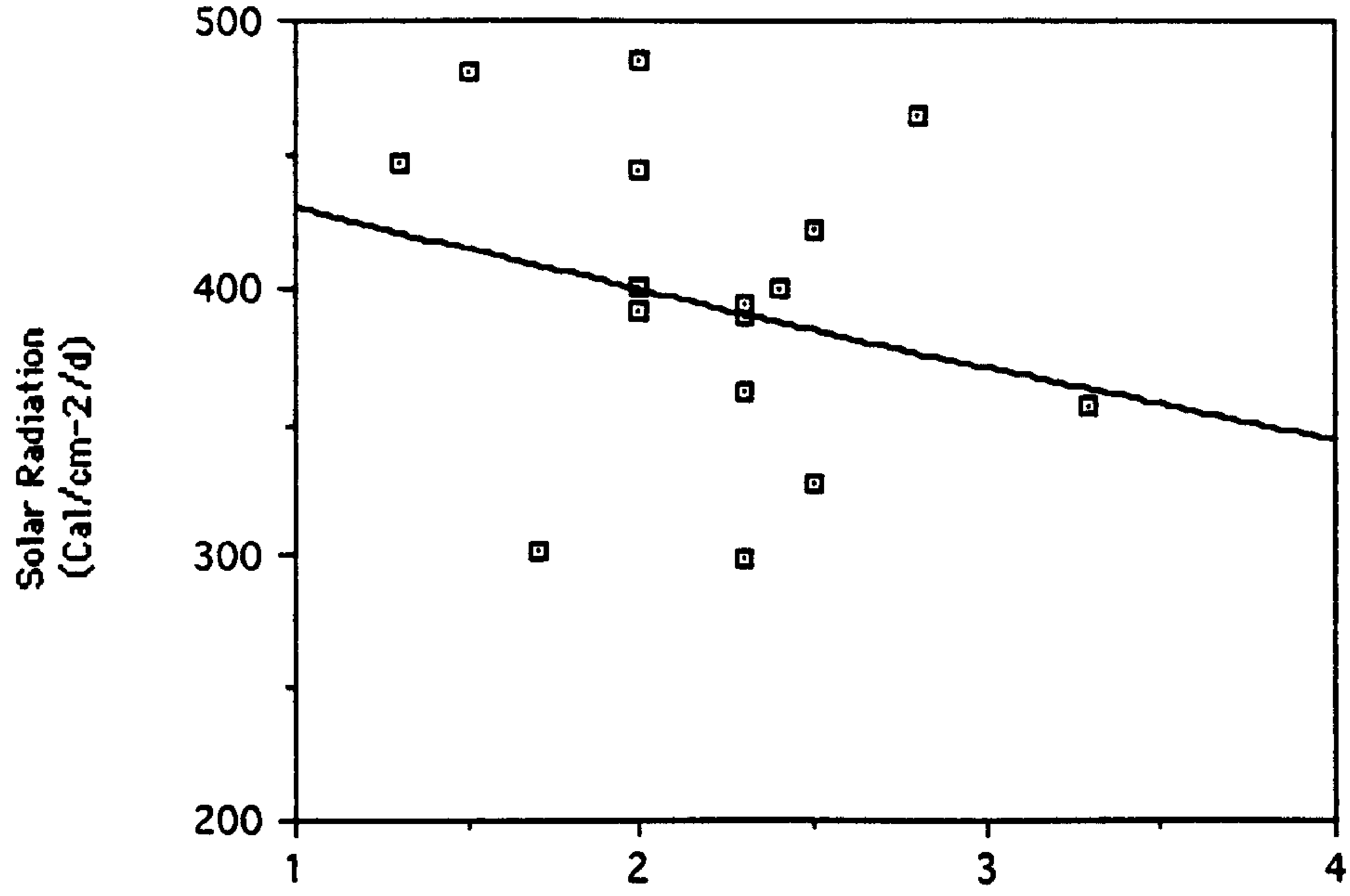
RESULTS OF MULTIPLE LINEAR REGRESSION ANALYSIS FOR MAR AND APR

MONTH	VARIABLE	ESTIMATED PARAMETER	T-RATIO	F-TEST	R-sq
MAR	Intercept	704.2	2.19	8.28 *	96.1%
	Sunshine Duration	26.03	1.17		
	Insolation Index	680.2	2.01		
	Altitude	0.0868	4.36 *		
	Specific Humidity	-11.45	-1.94		
	Cloud Cover	-46.79	-2.60 *		
	Dust	-5.78	-1.58		
APR	Intercept	3385	2.68	2.77	84.7%
	Sunshine Duration	16.98	0.65		
	Insolation Index	3678	2.23		
	Altitude	0.0451	1.15		
	Specific Humidity	-41.72	-2.30 *		
	Cloud Cover	-112.06	-2.46 *		
	Dust	-25.10	-2.54 *		

* Represents significance at the 0.05 level.

Fig (6.2)

The Relationship between Solar Radiation and Cloud Cover



Data Source: Ministry of Defense and Aviation (1980-1989).

At the month of April, the air temperature begins to rise, particularly in the middle and eastern parts of Saudi Arabia. As air temperature rises, humidity tends to increase especially along the eastern coast. For example, the specific humidity measured at Station 12 (Dhahran), located at the coast of the Arabian Gulf, was 13.66 gm/m^{-3}, (equivalent to 62% relative humidity), compared with only 5.79 gm/m^{-3}, (equivalent to 31% relative humidity), recorded at Station 11 (Qassim). The water vapour (expressed in specific humidity) is the main *absorption* factor of incoming solar radiation received at the earth's surface in Saudi Arabia, particulary at the coastal areas.

The increase of humidity in the earth's atmosphere led to a noticeable decrease in the amount of incoming solar radiation received. For example, at Station 12 (Dhahran), the amount of incoming solar radiation measured at this station in the month of April was 402 $Cal/cm^{-2}/d$ while at Station 11 (Qassim) it was 490 $Cal/cm^{-2}/d$. The increase in the intensity of incoming solar radiation at Station 11 (Qassim) is attributed, partly, to the low of specific humidity at this station. As the amount of specific humidity increases by one unit (one gm/m^{-3}), the intensity of incoming solar radiation decreases by 41.7 units, when the other explanatory variables are kept constant.

In addition , in April, dust storms start to affect the intensity of incoming solar radiation, particularly at the stations located at the edge of the deserts of Ar-Rub' Al-Khali in the south-east, Ad-Dahna in the east, and An-Nafud in the north of Saudi Arabia. These dust storms are generated by severe surface winds which are caused by the presence of tropical continental air masses which dominate the Arabian Peninsula areas in the spring and autumn seasons. Cold downdraughts form along the leading edge of a thunderstorm which then lift dust or sand into a huge dark cloud that may extend over 150 km (Ahrens, 1988). As the amount of dust increases, the amount of incoming solar radiation scattered by the dust storms increases, and the intensity of incoming solar radiation decreases, as seen in fig. (6.3). Statistically, as dust storms increase by one unit (one day), intensity of incoming solar radiation decreases by 25.1 units, with the other explanatory variables constant, as shown in table (6.2). Thus, both specific humidity and dust storms are important factors in attinuating incoming solar radiation but in different ways and at different areas. Dust storms attenuate solar radiation, prticualrly throuth scattering processes mainly in the inland areas, while specific humidity attenuates solar radiation through absorption processes mainly at the coastal areas.

As the sun continues its apparent movement northwards, duration of sunshine hours increases and the percentage of insolation index also increases. For example, in May, the sunshine duration at Station 8 (Medinah) is 10.2 hours and the percentage of insolation index measured at this station is 99%, because the sun is close to perpendicular in the sky. The increase in both sunshine duration and insolation index leads to an increase in the amount of incoming solar radiation at this station to 518 cal/cm^{-2}/d, an increase of 5 percent form April. Statistically, as sunshine duration increases by one unit, the intensity of incoming solar radiation increases by 99 units. Meanwhile, as the percentage of insolation index increases by one unit, the intensity of incoming solar radiation increases 6739 units, when other explanatory variables are constant, as shown in table (6.3). Unlike the other factors, the variation in the altitude of the stations investigated is high which range from 2200 metres a. s. l. at Abha in the southwestern part to only 5 metres a. s. l. at Dhahran in the eastern part of the country, therefore, this high difference in altitude between the stations is expected to play a significant role in the variation of solar radiation in Saudi Arabia, particularly at the mountainous areas. in May, altitude of the station plays a relatively significant role in increasing the intensity of incoming solar radiation. Table (6.3) reveals that as the altitude of the location increases by one unit (one metre), the intensity of incoming solar radiation tends to increase by 0.08 unit (cal/cm^{-2}/d). This relatively small value is attributed to the high variations between stations with respect to altitude which range between 17 - 2200 m a. s. l., therefore, the effect of altitude on the intensity of solar radiation at Abha (2200 x 0.08) is more significant than its effect at Dhahran (17 x 0.08).

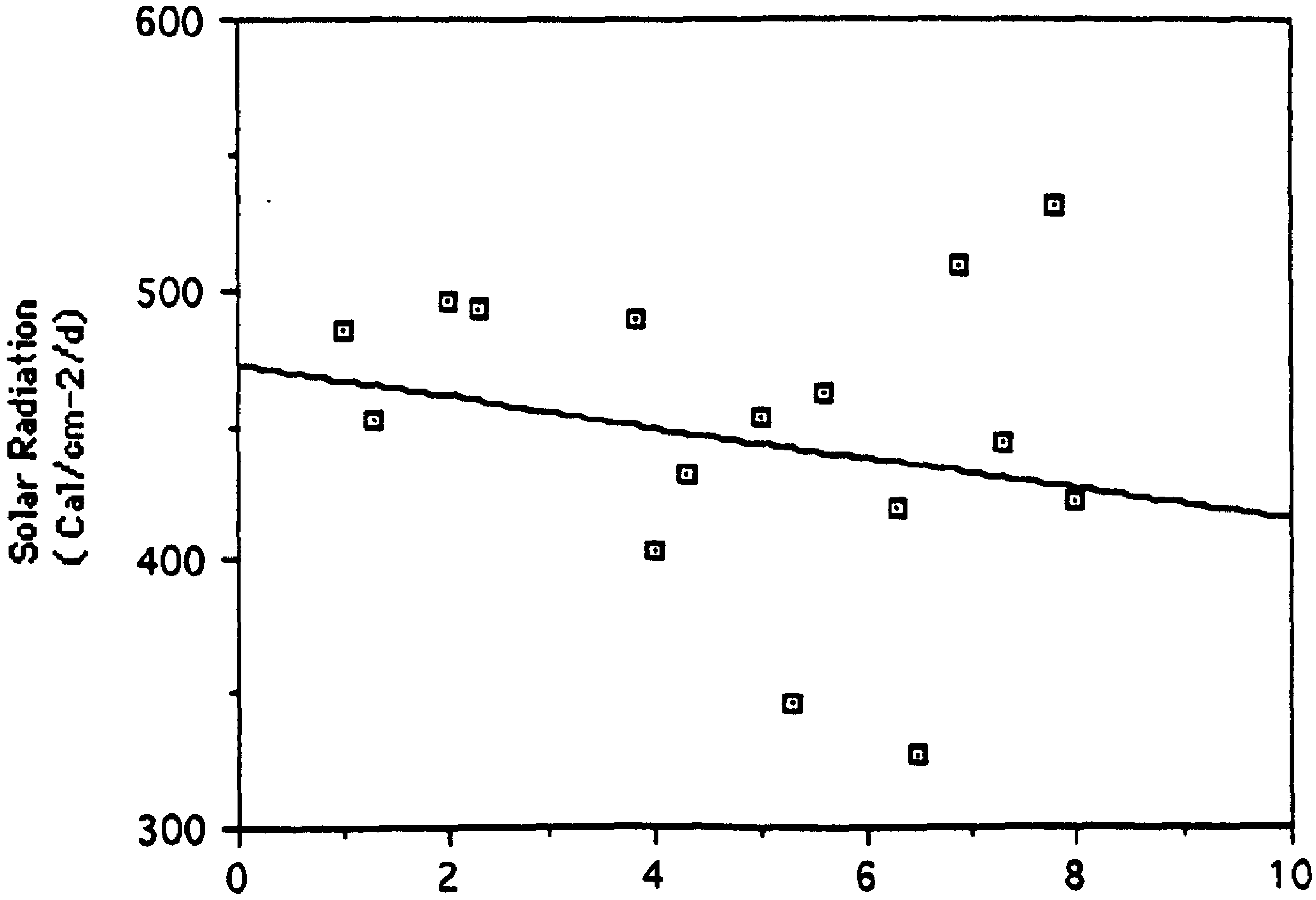
The air temperature is already high in May. For example, at Station 8 (Medinah) the average air temperature is 32^{o} C. The increase of air temperature results in an increase in atmospheric water vapour especially in the coastal areas. As the amount of atmospheric water vapour increases in the earth's atmosphere, the proportion of incoming solar radiation absorbed by atmospheric water vapour increases. For instance, the intensity of incoming solar radiation received at Station 12 (Dhahran) is only 430 Cal/cm^{-2}/d compared with 561 Cal/cm^{-2}/d recorded at Station 10 (Al-Ahsa). The decrease in the amount of incoming solar radiation received at Station 12 (Dhahran) is attributed mainly to an increase in specific humidity which reached 16.07 gm/m^{-3}, (equivalent to 53% relative humidity), compared with only 11.83 gm/m^{-3}, (equivalent to 39% relative humidity), measured at Station 10 (Al-Ahsa). In table (6.3), the analysis of data for May, reveals that an increase in specific humidity of one unit, results in a decrease in incoming solar radiation of 12.4 units, with other variables constant.

Despite its low occurrences, cloud cover also plays a significant role in attenuating the intensity of incoming solar radiation in the earth's atmosphere, despite its low occurrences. For example, the average number of cloud cover recorded at Station 13 (Hail) in the month of May is 3.5 days, the highest in

Saudi Arabia for this month. This cloud cover is the partial cause of the decrease in the intensity of incoming solar radiation at Station 13 (Hail) to 485 Cal/cm^{-2}/d. An increase in average of cloud cover of one unit, results in an increase in the proportion of incoming solar radiation absorbed, reflected, and scattered by cloud cover by 90 units, as seen in table (6.3).

Dust storms reach their maximum occurences during the spring and summer. For example at Station 9 (Riyadh), the capital of Saudi Arabia, there are on average 10 dust storm days in May, the highest recorded figure in Saudi Arabia in this month. As the number of dust storms increases, the intensity of incoming solar radiation received at the earth's surface decreases as a result of scattering processes, as shown in Fig (6.3). Table (6.3) indicates that as the average number of dust storms increases by one unit, the intensity of incoming solar radiation decreases by 33.4 units, when the other explanatory variables are constant.

Fig (6.3)
The Relationship between Solar Radiation and Dust Storms



Monthly Averages of Dust Storms

Data Source: Ministry of Defense and Aviation (1980-1989).

TABLE (6.3)

RESULTS OF MULTIPLE LINEAR REGRESSION ANALYSIS FOR MAY AND JUN

MONTH	VARIABLE	ESTIMATED PARAMETER	T-RATIO	F-TEST	R-sq
MAY	Intercept	-7627	-3.03	4.29*	81.1%
	Sunshine Duration	99.26	3.58 *		
	Insolation index	6739	2.76 *		
	Altitude	0.0820	2.20 *		
	Specific Humidity	-12.42	-2.82 *		
	Cloud Cover	-90.04	-3.90 *		
	Dust	-33.45	-4.31 *		
JUN	Intercept	1060	0.20	3.00	78.3%
	Sunshine Duartion	31.58	1.58		
	Insolation Index	972	0.18		
	Altitude	0.144	3.17 *		
	Specific Humidity	-7.12	-1.56		
	Cloud Cover	-82.77	-2.26 *		
	Dust	-5.96	-0.85		

* Represents significance at the 0.05 level.

In June, the effect of Westerly winds, which generate the cloud cover in the northern and middle parts of Saudi Arabia, starts to diminish, while in the southwestern part of the country the wet Monsoon winds that come from the Indian Ocean start to dominate and continue throughout the summer. Therefore, there is a noticeable decrease in the intensity of incoming solar radiation received in the southwestern part of the Kingdom. For example, at Station 2 (Abha), the intensity of incoming solar radiation is 515 Cal/cm^{-2}/d compared with 600 Cal/cm^{-2}/d recorded at Station 11 (Qassim). This relatively low intensity at Abha resulted partly from cloud cover which occurred on 2.3 days compared with 0 cloud cover at Qassim. As cloud cover increases by one unit, the intensity of incoming solar radiation decreases by 82.77 units, with the other explanatory variables constant, as seen in table (6.3).

In addition to cloud cover, altitude of the station has a significant effect on the intensity of incoming solar radiation in June. At Station 13 (Hail, 1013 meters), the intensity of incoming solar radiation is 530 Cal/cm^{-2}/d compared with only 409 Cal/cm^{-2}/d received at Station 14 (Tabuk, 776 meters). Table (6.3) reveals that as altitude of the station increases by one unit, the intensity of incoming solar radiation increases by 0.14 units, with other explanatory variables are constant.

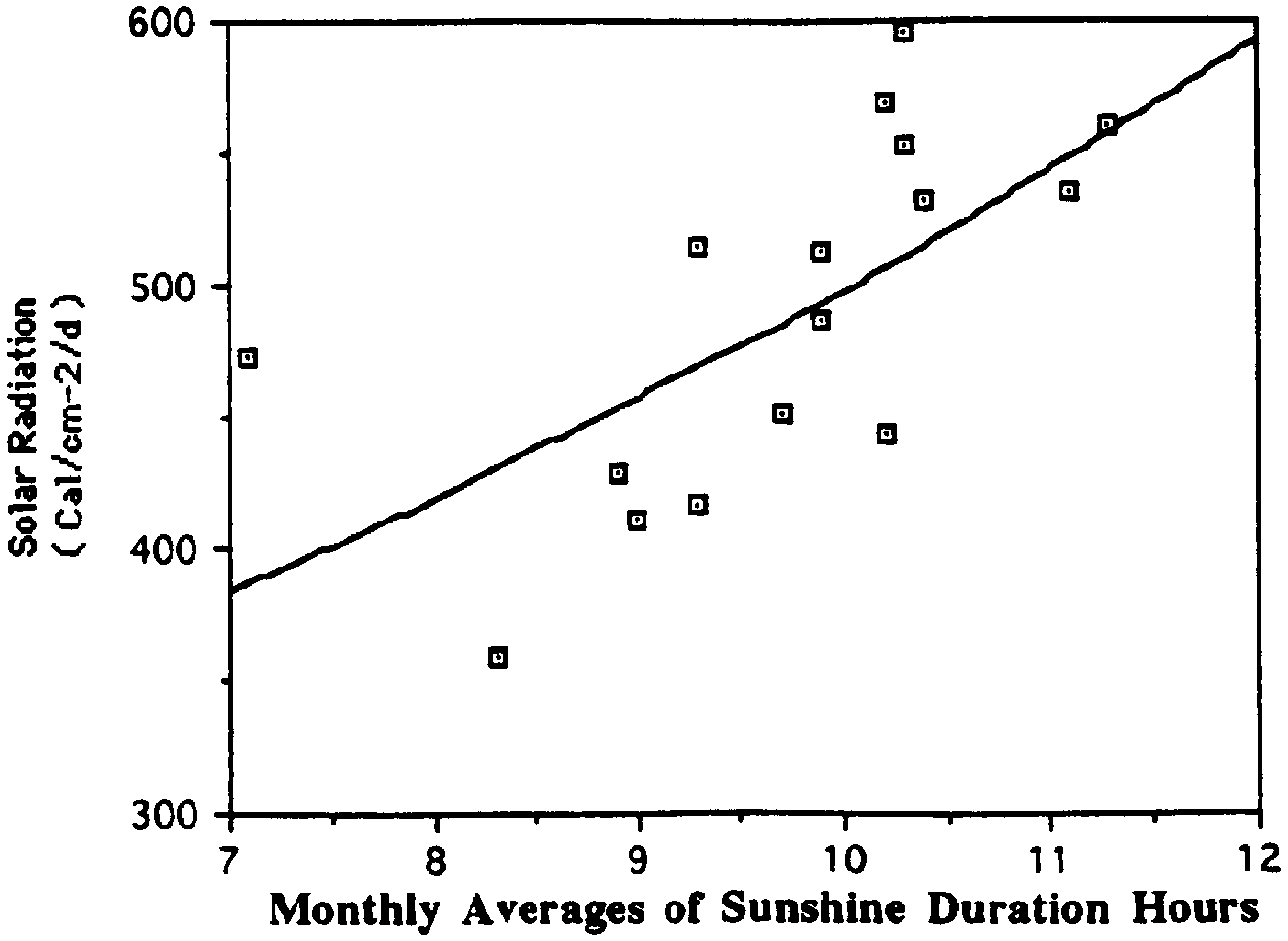
During July, sunshine duration reaches its maximum particularly in the middle and northern parts of Saudi Arabia, whilst the insolation index is highest in the middle zone where the sun is perpendicular at this time of the year. Therefore, the highest intensity of incoming solar radiation is recorded at the middle part of the country. At Station 11 (Qassim), the intensity of incoming solar radiation reached 595 Cal/cm^{-2}/d compared with 569 Cal/cm^{-2}/d recorded at Taif (station 5), an increase of 5% from the second highest value. This high intensity is attributed to both long sunshine duration, which reached an average

10.3 hours, as seen in fig. (6.4), and the high insolation index which measured 99%. Table (6.4) reveals that as sunshine duration increases by one unit, the intensity of incoming solar radiation increases by 33.3 units, and as the insolation index increases by one unit, the intensity of incoming solar radiation increases by 9559 units, whilst the other explanatory variables are constant.

The altitude of the station continues to have a significant impact on the total amount of incoming solar radiation received.A comparison between Station 5 (Taif) and 4 (Sulyyel) reveals this. At Station 5 (Taif) the intensity of incoming solar radiation received at this station in the month of July was 569 Cal/cm^{-2}/d while at Station 4 (Sulyyal) it was only 358 Cal/cm^{-2}/d. The high intensity of incoming solar radiation received at Taif is attributed mainly to its high altitude 1454 meters a.s.l., compared with only 616 meters for Sulyyel. As the altitude increases by one unit, the intensity of incoming solar radiation increases by 0.117 units as seen in Table (6.4).

Cloud cover has a significant negative effect on the intensity of incoming solar radiation received in the southwestern part of Saudi Arabia during the month of July. This cloud cover is caused by the wet Monsoon Winds that come from the Indian Ocean and which dominates in this part of the country during summer. As a result , there is a noticeable decrease in the intensity of incoming solar radiation received here as is shown in the example of Station 1 (Najran) where the total incoming solar radiation received was only 410 Cal/cm^{-2}/d, a decrease of 14 percent from the last month. This low amount of incoming solar radiation is related to cloud cover which occurs on average for 3.3 days. As cloud cover increases by one unit, the intensity of incoming solar radiation decreases by 68.31 units, as shown in table (6.4).

Fig (6.4)
The Relationship between Solar Radiaition and Sunshine Duration



Data Source: Ministry of Agriculture and Water (1980-1989).

TABLE (6.4)

RESULTS OF MULTIPLE LINEAR REGRESSION ANALYSIS FOR JUL AND AUG

MONTH	VARIABLE	ESTIMATED PARAMETER	T-RATIO	F-TEST	R-sq
JUL	Intercept	-9347	-3.12	9.86 *	92.2%
	Sunshine Duration	33.30	2.24 *		
	Insolation Index	9559	3.13 *		
	Altitude	0.117	3.80 *		
	Specific Humidity	-2.35	-0.76		
	Cloud Cover	-68.3	-4.26 *		
	Dust	-3.39	-0.45		
AUG	Intercept	3452	4.60 *	5.56*	87%
	Sunshine Duration	8.36	0.66		
	Insolation Index	2752	3.75 *		
	Altitude	0.214	4.49 *		
	Specific Humidity	-16.1	-4.39 *		
	Cloud Cover	-117	-4.83 *		
	Dust	-4.10	-0.90		

* Represents significance at the 0.05 level.

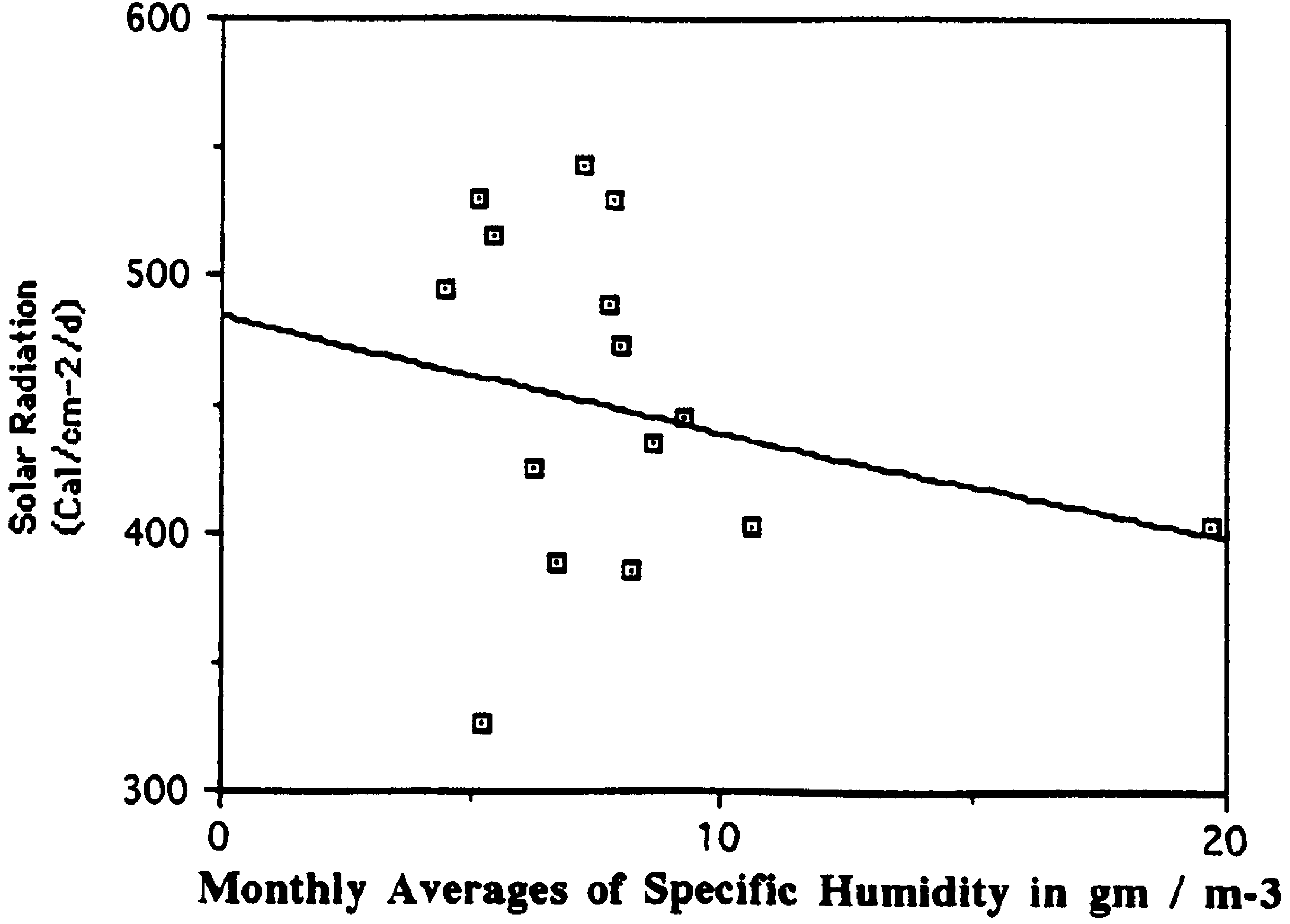
In the month of August, the insolation index, altitude of the station, and cloud cover continue to have significant influences on the total amount of incoming solar radiation received as shown in table (6.4). Moreover, specific humidity plays a significant role in reducing the total amount of incoming solar radiation received, especially near the coastal areas. The increase in humidity in the month of July is generated by the high air temperature which reaches an average of 35^0 C in eastern parts of Saudi Arabia. Therefore, as specific humidity increases, the intensity of incoming solar radiation received at the earth's surface decreases as in the example of Station 12 (Dhahran) where the intensity of incoming solar radiation was only 402 $Cal/cm^{-2/d.}$ This is associated with a high specific humidity that reaches 19.69 gm/m^{-3}, (equivalent to 53% relative humidity), as shown in fig. (6.5). Table (6.4) reveals that as specific humidity increases by one unit, the intensity of incoming solar radiation decreases by 16.1 units, when the other explanatory variables are held constant.

In September, humidity continues to have a significant effect on the intensity of incoming solar radiation despite the decrease in the average specific humidity in this month compared with the previous month of August. The decrease in humidity is attributed to a decrease in sunshine duration hours as the sun continues to move, in its apparent journey, to the southern hemisphere. Therefore, as specific humidity increases one unit, the incoming solar radiation received at the earth's surface decreases 9.66 units compared with 16.1 units for the month of August, as seen in Table (6.5).

In addition to specific humidity, the insolation index has a significant effect on the intensity of incoming solar radiation received at the earth's surface in the month of September, particularly in the southwestern part of Saudi Arabia, because the insolation index is higher here than in the other parts of the country, as seen in fig. (6.6). For example at stations 1 (Najran) and 2 (Abha), the intensity of incoming solar radiation received was 506 and 491 Cal/cm^{-2}/d respectively, compared with only 378 Cal/cm^{-2}/d at Station 16 (Quryyat). The increase of incoming solar radiation received at Stations 1 and 2 can be attributed to a high insolation index at these two stations which reaches 96% compared with only 88% at Station (16). Table (6.5) reveals that as insolation index increases by one unit, the intensity of incoming solar radiation increases by 238 units.

Fig (6.5)

The Relationship between Solar Radiation and Specific Humidity



Data Source: Ministry of Agriculture and Water (1980-1989).

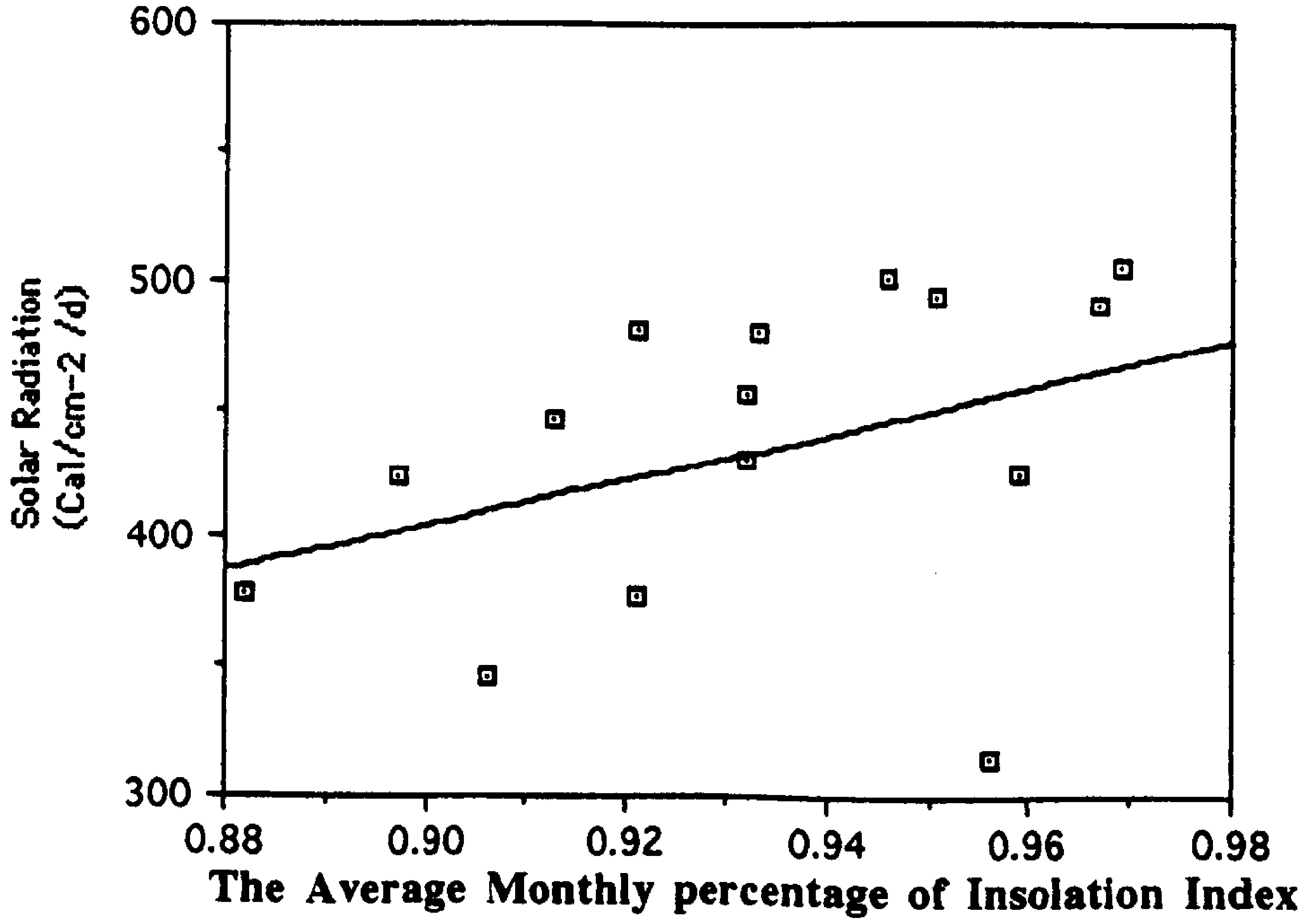
TABLE (6.5)

RESULTS OF MULTIPLE LINEAR REGRESSION ANALYSIS FOR SEP AND OCT

MONTH	VARIABLE	ESTIMATED PARAMETER	T-RATIO	F-TEST	R-sq
SEP	Intercept	-1261	-2.26	6.62 *	90.9%
	Sunshine Duration	34.30	1.70		
	Insolation Index	238	3.57 *		
	Altitude	0.0582	1.34		
	Specific Humidity	-9.66	-3.13 *		
	Cloud Cover	-15.7	-0.52		
	Dust	-22.4	-2.64 *		
OCT	Intercept	554	1.84	4.70 *	82.5%
	Sunshine Duration	95.4	3.55 *		
	Insolation Index	1406	2.91 *		
	Altitude	0.119	2.47 *		
	Specific Humidity	-2.67	- 0.65		
	Cloud Cover	- 74.70	- 2.06		
	Dust	-47.70	- 3.00 *		

* Represents significance at the 0.05 level.

Fig (6.6)
The Relationship between Solar Radiation and Insolation Index



Source of raw Data: Ministry of Agriculture and Water (1980-1989)

In September, dust storms have a significant impact on the intensity of incoming solar radiation, particularly at stations located near sand deserts. For example at station 3 (Bishah), the intensity of incoming solar radiation 425 Cal/cm^{-2}/d compared with 494 at Station 5 (Taif). The low intensity of incoming solar radiation at Station 3 is caused by the occurrences of dust storms which reached 5.3 days during this month compared with only 2 days for Station 5. This high average of dust storms plays a significant role in attenuating solar radiation through reflection and scattering processes by sand and dust particles. As the number of dust storms increase by one unit, the intensity of incoming solar radiation decreases by 22.4 units, as seen in Table (6.5).

Dust storms continue to be a significant factor in decreasing the intensity of incoming solar radiation received at the earth's surface during the month of October. Station 14 (Tabuk) is a clear example of the effect of dust storms where the total intensity of incoming solar radiation received is only 265 Cal/cm^{-2}/d compared with 337 Cal/cm^{-2}/d received at Station 15 (Jouf). The decrease of incoming solar radiation at Station 14 is mainly caused by the occurrence of dust storms at this station during the month of October which reached 3.7 days compared with only 1.6 days at Station 15. As dust storms increase by one unit, the intensity of incoming solar radiation decreases by 32.8 units, with the other explanatory variables constant as shown in Table (6.5).

In addition to dust storms, sunshine duration and insolation index are shown to be significant, particularly in the southern part of Saudi Arabia where sunshine duration and the insolation index are greater than the north. For example, at Station 1 (Najran), sunshine duration reached 10.1 hours and insolation index measured 90%. The increase in both sunshine duration and insolation index at Station 1 led to an increase in the intensity of incoming solar radiation which reached a total of 485 Cal/cm^{-2}/d, compared with only 266 Cal/cm^{-2}/d received at Station 16 (Quryyat). This low intensity of incoming solar radiation at Station 16 is attributed to a decrease in both sunshine duration and insolation index to 8.2 hours and 77% respectively. As sunshine duration increases by one unit, the amount of incoming solar radiation increases by 95.4 units. Meanwhile, as insolation index increases by one unit, the amount of incoming solar radiation increases by 1405.7 units holding other explanatory variables constant, as seen in Table (6.5).

In October, altitude of the station has a significant effect in increasing the intensity of incoming solar radiation received at the earth's surface, especially at the mountain areas in the south-western part and along the Western Heights of Saudi Arabia. The highest intensity of incoming solar radiation was measured at Station 2 (Abha) with 497 Cal/cm^{-2}/d which can be attributed to its high altitude of 2200 meters above the sea level. This is also the highest altitude in Saudi Arabia. Table (6.5) shows that as altitude of the station increases by one unit, the intensity of incoming solar radiation increases by 0.119 units.

During the month of November, there is a noticeable decrease in sunshine duration, insolation index, cloud cover, and dust storms all over the country compared with the previous month. The only variable that has a significant effect on the intensity of incoming solar radiation at the earth's surface is altitude as seen in Table (6.6). As altitude of the station increases, the intensity of incoming solar radiation increases, as shown in fig. (6.7). The highest intensity of incoming solar radiation is recorded along the Western Heights and in the south-western part of Saudi Arabia. Table (6.6) indicates that as altitude of the location increases by one unit, the intensity of incoming solar radiation tends to increase by 0.145 unit, holding the other explanatory variables constant.

Finally, in the month of December, altitude of the location continues to have a significant effect in increasing the intensity of incoming solar radiation received at the earth's surface as discussed above. Table (6.6) shows that as altitude of the location increases by one unit, the intensity of incoming solar radiation received increases by 0.110 unit, with the other explanatory variables constant.

TABLE (6.6)

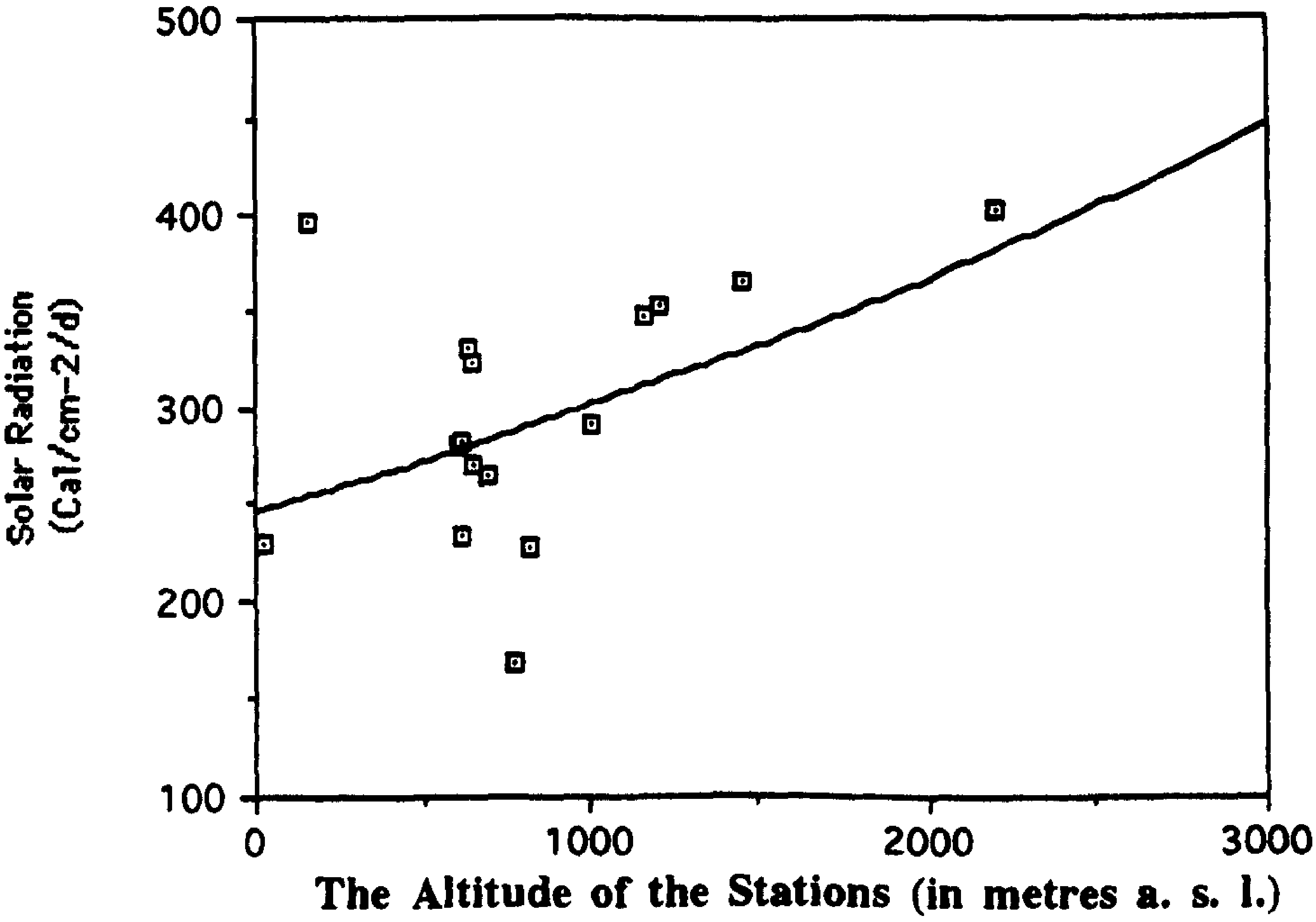
RESULTS Of MULTIPLE LINEAR REGRESSION ANALYSIS FOR NOV. AND DEC.

MONTH	VARIABLE	ESTIMATED PARAMETER	T-RATIO	F-TEST	R-sq
NOV	Intercept	851	0.83	4.41 *	81.5%
	Sunshine Duration	33.7	0.92		
	Insolation Index	1303	0.79		
	Altitude	0.154	2.56 *		
	Specific Humidity	-18.0	-1.81		
	Cloud Cover	-72.5	-0.93		
	Dust	-14.8	-0.69		
DEC	Intercept	235	0.88	4.88 *	80.7%
	Sunshien Duration	26.8	1.38		
	Insolation Index	449	0.87		
	Altitude	0.110	2.69 *		
	Specific Humidity	-27.8	-2.04		
	Cloud Cover	-68.9	-1.59		
	Dust	-10.7	-1.08		

* Represents significance at the 0.05 level.

Fig (6.7)

The Relationship between Solar Radiation and the Altitude of the Sation



Data Source: Ministry of Agriculture and Water (1980-1989)

In summary, the statistical analysis indicates that all the six factors play a significant role in the variations of the intensity of incoming solar radiation in Saudi Arabia. The intercept, which is the average effect of all other factors not included in the radiation model due to the lack of real measurement, has a slight effect on the variation of incoming solar radiation with an average of 13 per cent of the total variation as indicated by the R^2 (the coefficient of determination). However, the significancy level of these six factors is not constant with respect to time, but rather it varies from month to another. Altitude is the most significant factor influencing the intensity of solar radiation in Saudi Arabia. particularly, at the mountain areas in the western and southwestern regions of the Kingdom. Sunshine duration and insolation index can also be considered to be a major factors explaining the variations in solar radiation, particularly during spring and summer seasons when their values are relatively high. The other factors such as cloud cover, humidity, and dust, seem to have a significant influence at certain regions at particular times. For example, cloud cover has its highest effect at the northern and southwestern parts of Saudi Arabia, while, dust has its maximum influence at the northern and southeastern parts where the major deserts are located. Likewise, humidity has its dominant role during the summer season at the coastal areas, particularly, the coast of Arabian Gulf. The spatial pattern revealed by this analysis is discussed fully in the next chapter.

CHAPTER SEVEN

THE SPATIAL DISTRIBUTION OF INCOMING SOLAR RADIATION IN SAUDI ARABIA

7.1 INTRODUCTION

As was discussed in the previous chapter, the distribution of incoming solar radiation is based on monthly averaged data for ten years, between 1980 and 1989 for 16 stations distributed throughout the Kingdom of Saudi Arabia. However, it was necessary to include another meteorological station (Haradh) due to the lack of data related to Ar Rub' Al-Khali desert which was influenced by the high solar radiation at station 10 (Al-Ahsa). The location of these stations is broadly representative of the various of climates in the country. In addition to monthly maps of incoming solar radiation, seasonal maps have been included to show the pattern of change in incoming solar radiation. The seasonal maps are required because monthly changes may not give a clear picture of variations, due to the short term variations of climate especially in the inland areas of the Kingdom.

I had a problem, and the problem is that I was using a certain number of meteorological stations which were distributed across Saudi Arabia in a rather irregular manner related to the patterns of solar radiation. From this set of data, I wanted to construct a series of maps which reveal the pattern of solar radiation. The method ought to be interpolating on monthly basis, but giving the range of values and the scatter of points, this presented certain technical diffeculties.

Any map-drawing programme must have a reliable method of estimating Z values (on the nodes of a grid) from the original set of irregular data. This is a particularly important issue in the case of the data for Saudi Arabia. Each estimated value will depend in some way on its neighbors, but this dependency diminishes with increasing distance. The method should also be able to deal with discontinuities in the data, if they occur.

Several methods of map production were investigated. These interpolation methods included a straightforward hand-drawing interpolation, Trend Surface Analysis, and UNIMAP. However, neither of hand-drawing interpolation nor Trend Surface Analysis led to a satisfactory results because they introduced distortion. They did not give a very clear general statement of the way in which the pattern of solar radiation changes over time. Unlike the other two methods, UNIMAP appeared the most promising because it is an interactive mapping and modelling system which can be used to draw contour plots and perspective views of surfaces. It is particularly useful because it would allow interpolation from this rather difficult set of data and depict patterns in a generalized way which enable the reader to pick up the general trends of the variation of solar radiation in Saudi Arabia. It is one of the four interactive graphic programs in the UNIRAS suite of software.

According to UNIRAS (1990), UNIMAP offers seven different interpolation methods. Each method has its own characteristics and deals with specific kind of input data. The same set of data (for January) is used for each method to demonstrate and evaluate the difference more clearly. These interpolation methods are as follows:

1- BILINEAR method.

2- POLYNOMIAL method.

3- FAULT method.

4- MIN CURVATURE method.

5- KRIGING method.

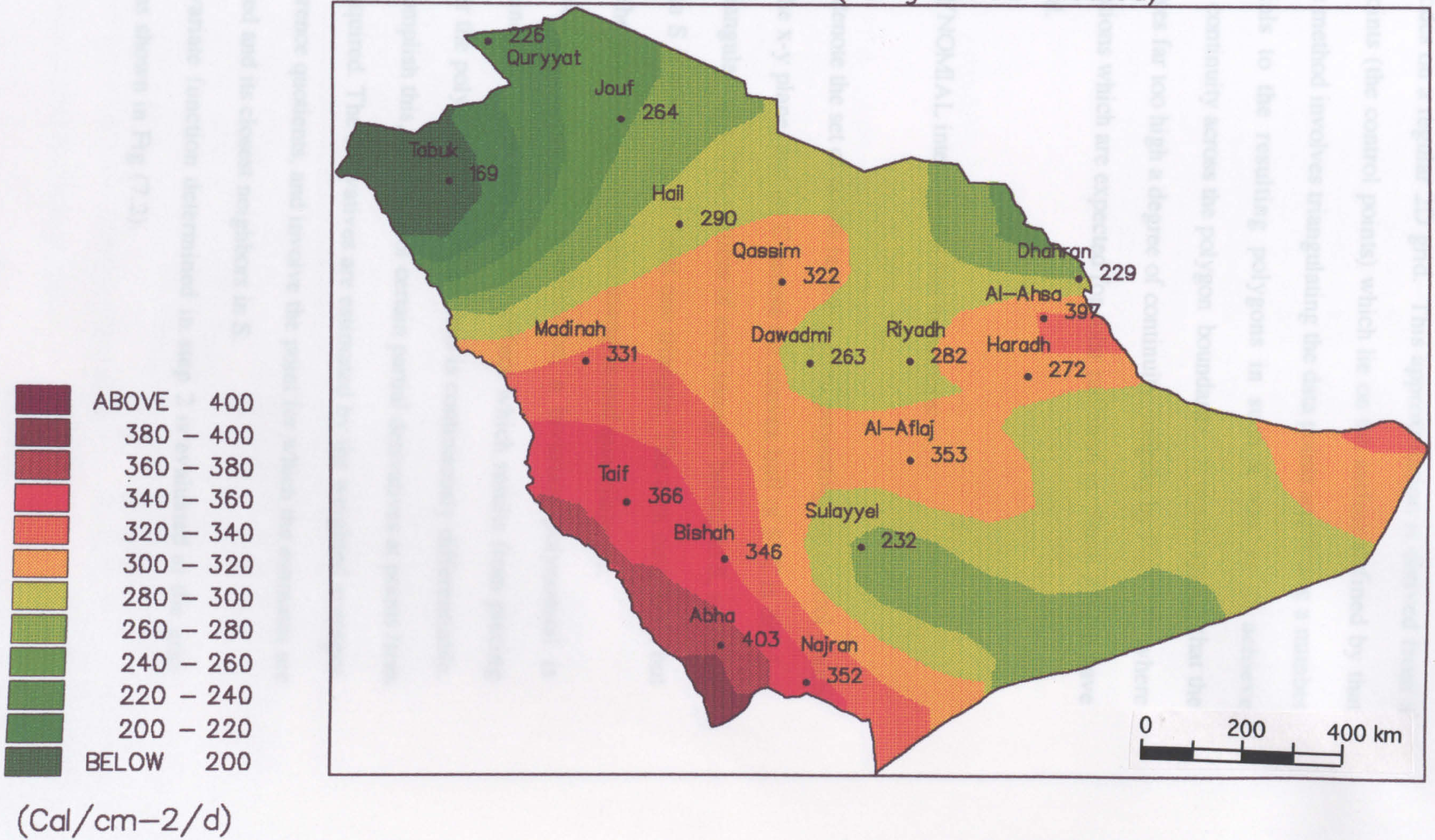
6- USER method.

7- BICUBIC method.

The BILINEAR method approximates the value of a bivariate function at the grid nodes on a regular 2D grid. This approximation is derived from a number of points- the control points- which lie on the surface to be defined by the Bilinear function. The function is approximated only at grid nodes inside the active regions, and a control point (x, y, z) contrtibutes to the approximation only if (x, y) is inside the active regions. For the purposes of the solar radiation maps of Saudi Arabia, there was a single active region defined by the (x,y) co-ordinates of the country boundries. The BILINEAR interpolation has four steps :

1. Let S denote the set of points resulting from projecting the control points onto the x-y plane. For each point in S, the closest grid node is located, and the function value at the node is set equal to the z coordiate of the corresponding control point. If several control points are assigned to the same grid node, the node value is set equal to the average of the z-coordinates of the control points.
2. For each grid node which has not been assigned a value in the frist step, neighboring grid nodes are used to generate the function value at the node. Double linear interpolation formula is used to estimate the value the bivariat function at an arbitrary point (x0, y0).
3. The grid is smoothed by quadratic interpolation which is a nonlinear filtering operation that tends to amplify local exterema.
4. Each grid node value is replaced by a weighted average of the values at some of the neighboring nodes, as shown in Fig (7.1).

Fig (7.1) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (Using Bilinear Method)

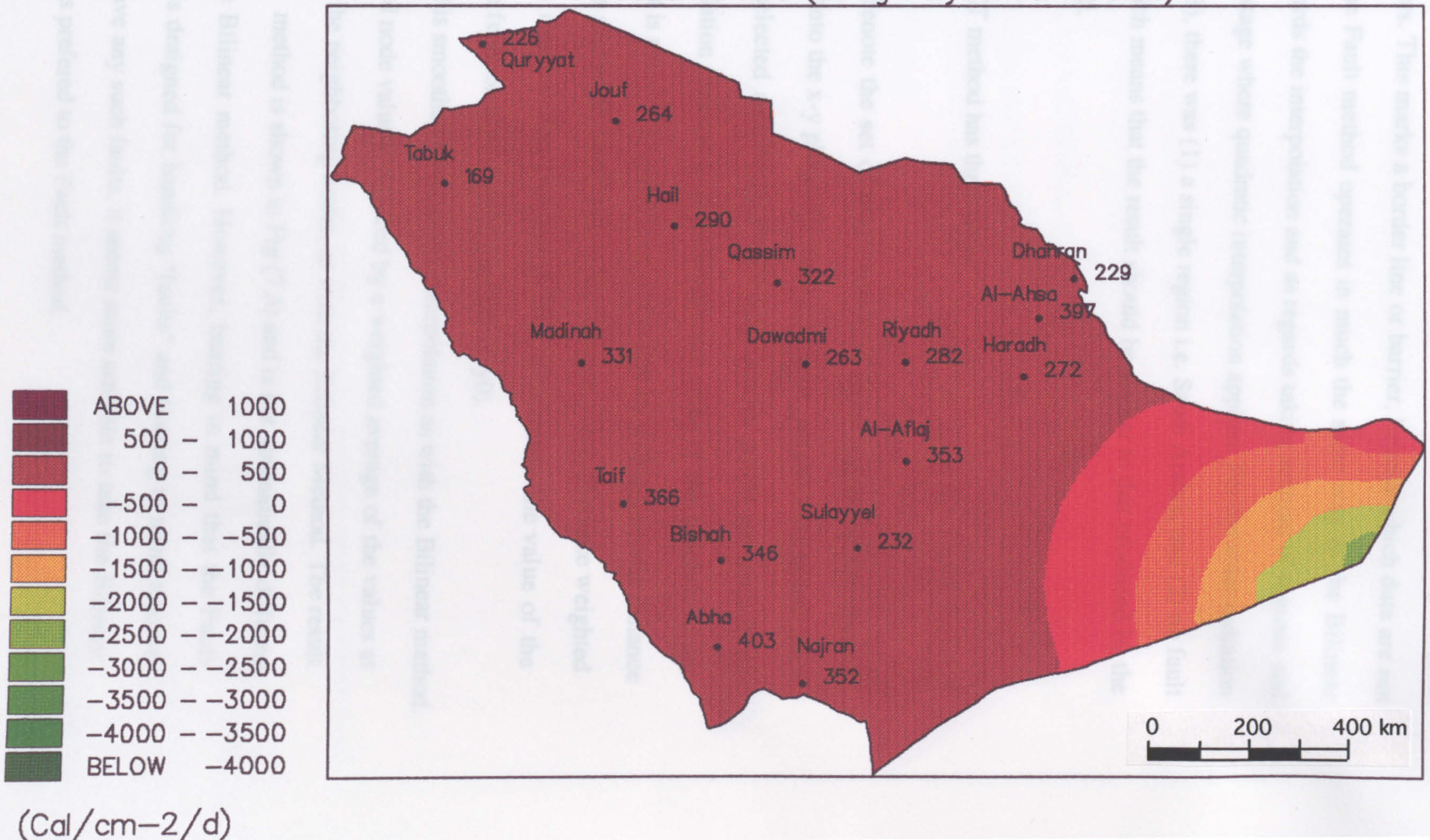


The POLYNOMIAL method approximates the value of a bivariate function at the grid nodes on a regular 2D grid. This approximation is derived from a number of points (the control points) which lie on the surface defined by that function. The method involves triangulating the data points and fitting a number of polynomials to the resulting polygons in such a way as to achieve mathematical continuity across the polygon boundaries. It would appear that the method achieves far too high a degree of continuity, judging by Fig (7.2), where the local variations which are expected for solar radiation in Saudi Arabia have been smoothed.

The POLYNOMIAL interpolation has three steps:

1. Let S denote the set of points resulting from projecting the control points onto the x-y plane, and let C denote the convex hull of S. C is divided into triangular cells. The vertices of each triangle belong to S, and each point in S is a vertex of at least one triangle. The area outside C, but inside the grid, is subdivided into triangles and quadrilaterals.
2. For each polygon in the subdivision, a bivariate polynomial is determined in such a way that the surface which results from piecing together the polynomial surface patches is continuously differentiable. To accomplish this, estimates of certain partial derivatives at points from S are required. The derivatives are estimated by the weighted averages of difference quotients, and involve the point for which the estimates are computed and its closest neighbors in S.
3. The bivariate function determined in step 2 is evaluated at the grid nodes, as shown in Fig (7.2).

Fig (7.2) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (Using Polynomial Method)

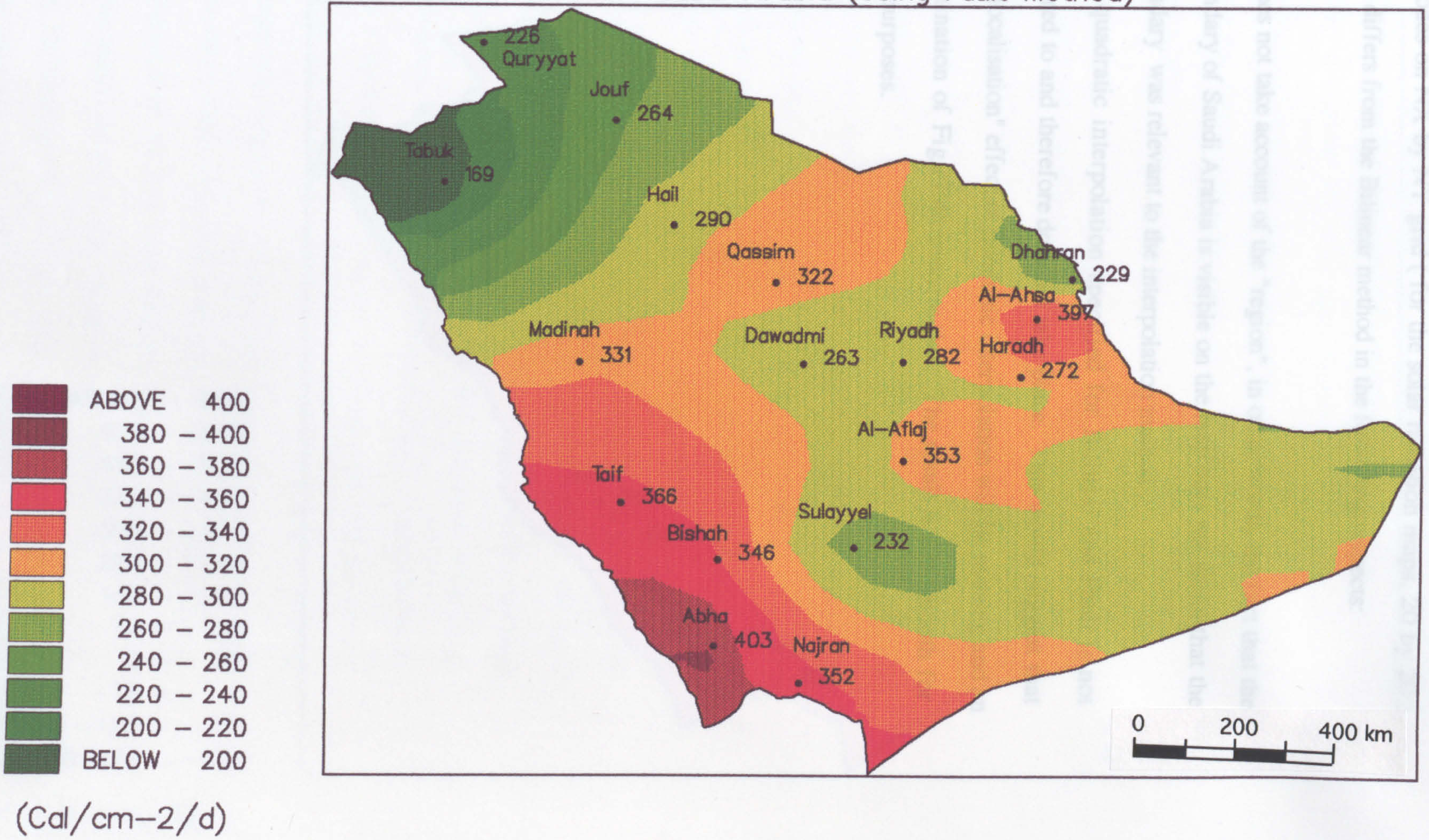


The FAULT method is a variation of Bilinear method. It is used to input a list of X-Y coordinates that define one or more fault lines, such as geological faults and rivers. This marks a border line or barrier, beyond which data are not correlated. The Fault method operates in much the same way as the Bilinear method as regards the interpolation and as regards taking account of regions and as regards the stage where quadratic interpolation applied. For the solar radiation map in Fig (7.3), there was (1) a single region i.e. Saudi Arabia, and (2) no fault lines at all, which means that the result should be similar to that produced by the Bilinear method.

The FAULT method has three steps:

1. Let S denote the set of points resulting from projecting the control points onto the x-y plane. For each grid node, neighboring points from S are selected and the corresponding control points are used in an interpolation formula to approximate the value of the function at the node. It is possible to make only points that lie within a certain distance from the grid node, contribute to the function value. Distance weighted average interpolation fromula is used to estimate the value of the bivariate function at an arbitrary point (x0, y0).
2. The grid is smoothed by quadratic interpolation as with the Bilinear method.
3. Each grid node value is replaced by a weighted average of the values at some of the neighboring nodes, as with the Bilinear Method. The result of Fault method is shown in Fig (7.3) and is not dramatically different from the Bilinear method. However, bearing in mind that the Fault method is designed for handling "faults" and bearing in mind that we do not have any such faults, it seems more sensible to take the Bilinear method as prefered to the Fault method.

Fig (7.3) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (Using Fault Method)

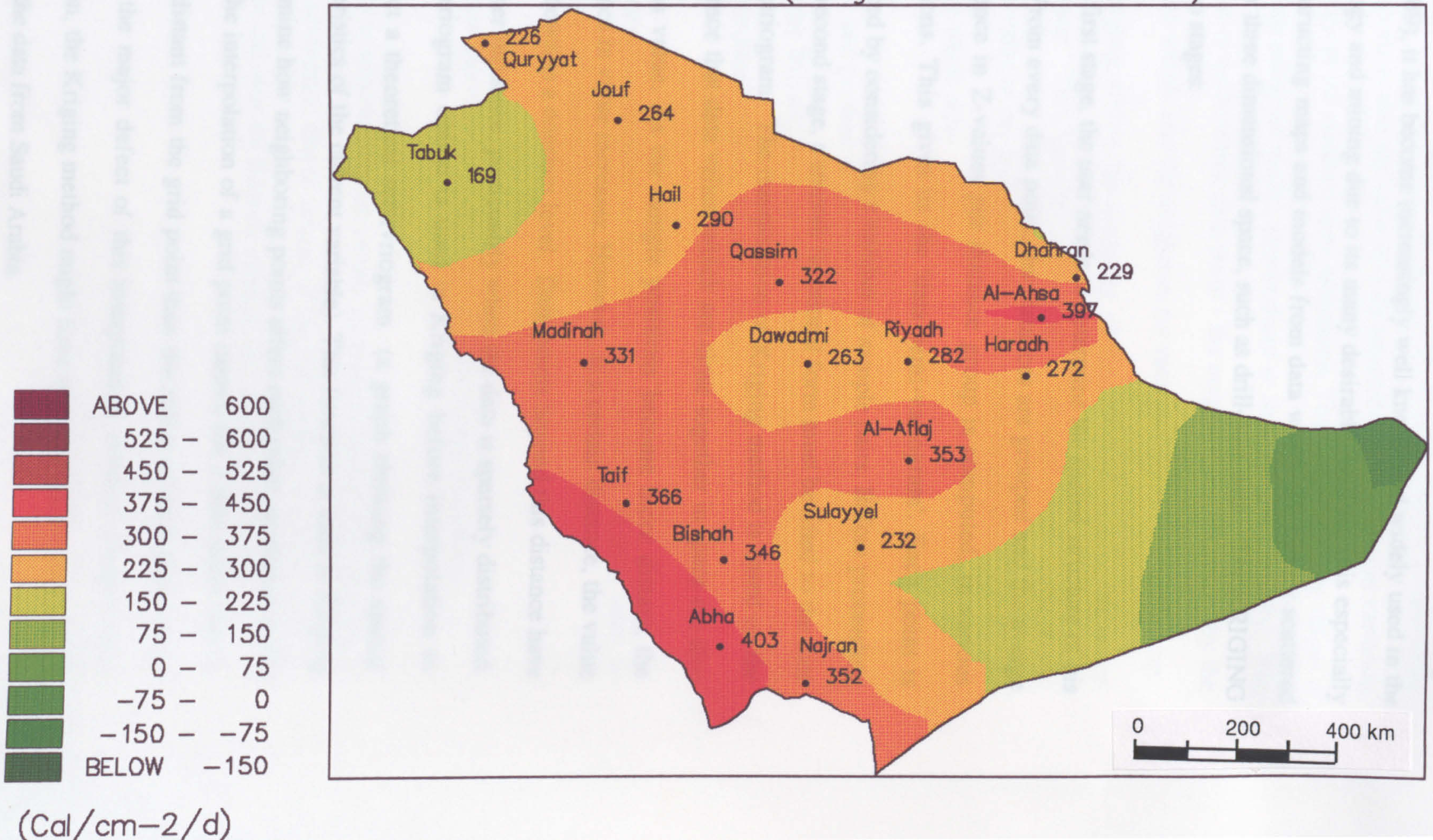


The MIN CURVATURE method estimates the value of a bivariate function at all grid nodes on NX by NY grid (for the solar radiation maps, 20 by 20). This method differs from the Bilinear method in the following respects:

1- It does not take account of the "region", in other words, the fact that the boundary of Saudi Arabia is visible on the map does not mean that the boundary was relevant to the interpolation method.

2- The quadratic interpolation specified for Bilinear and Fault is not referred to and therefore does not take place. This would suggest that the "localisation" effect of quadratic interpolation will be missing and an examination of Fig (7.4) confirm this. The result is too smooth for our purposes.

Fig (7.4) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (Using Min Curvature Method)



The KRIGING method is a special geostatistical interpolation. According to UNIRAS (1989), it has become increasingly well known and widely used in the fields of geology and mining due to its many desirable features. It is especially useful in constructing maps and models from data which are widely scattered through two or three dimensional space, such as drill-hole data. The KRIGING method has two stages:

1. In the first stage, the user needs to determine the spatial structure of his data. From every data point, the distances are grouped and the averge difference in Z-values per distance group is computed, in various directions. This gives us the 'data semi-variogram'. Each point is produced by considering a number of sample pairs. Before proceeding to the second stage, a smooth functional form must be fitted to the data semi-variogram. The interpolation of Kriging method is based on the experience that data values which are close together in space are also close in value. As the sample positions become more distant, the difference in value increases. However, at a certain distance, the value settles down to a constant level. Data points beyond this distance have no further influence, particualrly when the data is sparsely distributed. The Variogram option is used in Kriging before interpolation to construct a theoretical semivriogram (a graph showing the spatial characteristics of the current variable). This function is used in Kriging to determine how neighboring points affect each other, as shown in Fig (7.5). The interpolation of a grid point cannot use a data point that is further distant from the grid point than the radius of each grid node. This is the major defect of this interpolation method. Despite this limitation, the Kriging method might have been a siutable method for treating the data from Saudi Arabia.

2. The second stage of the Kriging process is the interpolation itself. When estimating the Z-value of the grid node, kriging chooses neighboring data points so that the value chosen minimizes the estimation variance, which gives the standard error estimation. The weights are the values of the semivariogram model, standardized so that their sum is unity. The Z-value of each chosen data point - the neighbor - is multiplied by the standard weight and the neighbors for each grid point are summed up. So, Kriging allows the mapping of the 'error surface' or 'standard error map'. This 'standard error map' is not dependent on the actual sample value at any specified point, but rather on the average behavior over the whole area.

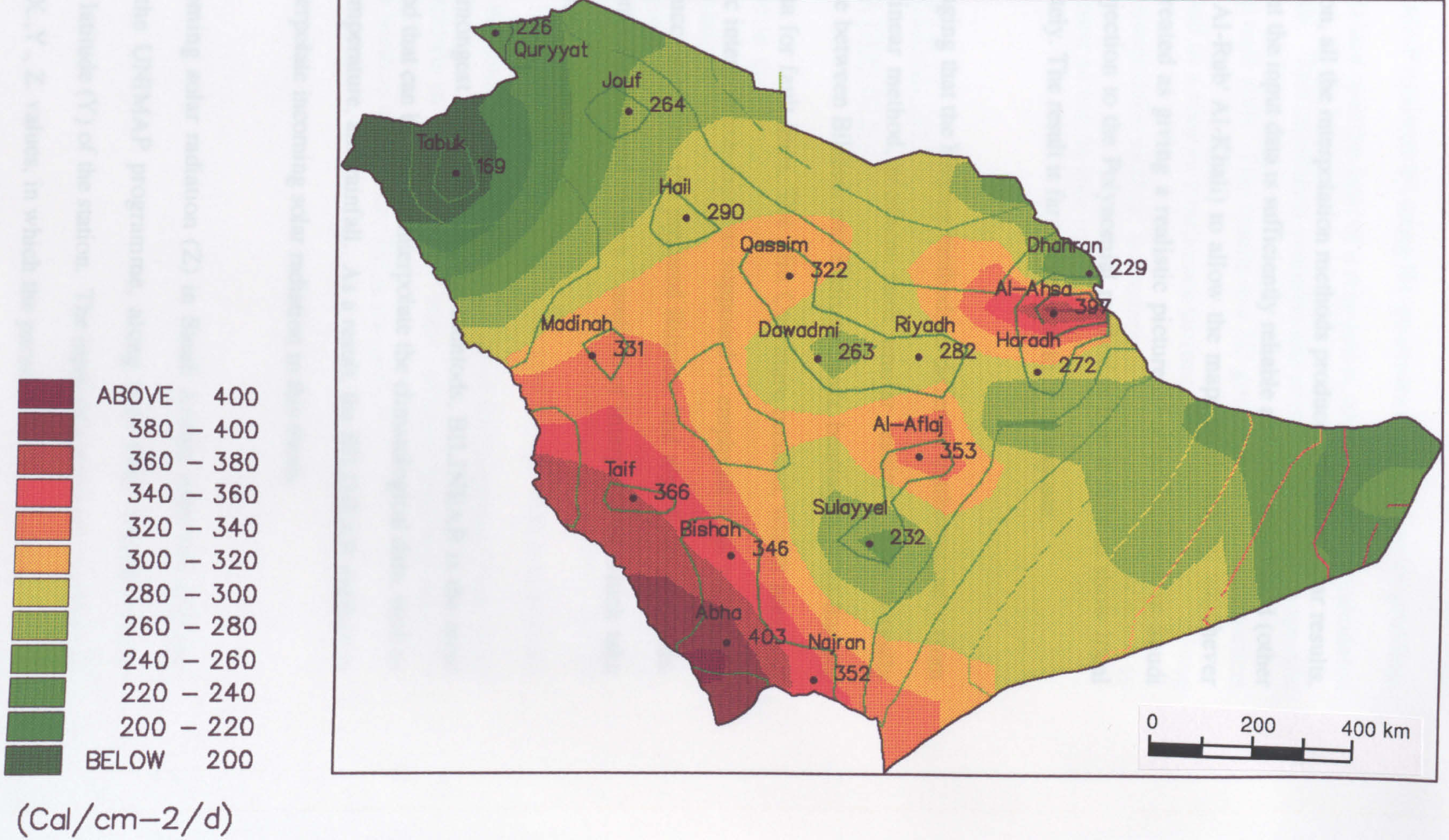
The end product of the Kriging method, as shown in Fig (7.5), is very similar to the Bilinear method but the method has the following specific options, when compared with the Bilinear method:

1- The method is designed to deal with specific kinds of data, such as geological and mining data.

2- The data is expected to include a lot of adjacent data recordings.

3- The need to experiment with certain parameters during stage one is not seen as advantage. But of course, if the end product was obviously an important one over the Bilinear method, that would be different.

Fig (7.5) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (Using Kriging Method)



The last two interpolation methods, USER and BICUBIC have currently no application.

In conclusion, all the interpolation methods produce broadly similar results. This suggests that the input data is sufficiently reliable and well distributed (other than that in the Al-Rub' Al-Khali) to allow the maps produced, by whichever method, to be treated as giving a realistic picture of solar radiation in Saudi Arabia. The objection to the Polynomial method is that it fails to show local variation adequately. The result is far too general to be of any use.

It is encouraging that the Kriging method, so different mathematically from the prefered Bilinear method, produces such similar results. There is really nothing to choose between Bilinear and Fault methods, bearing in mind that we don not have data for fault lines. The Min Curvature method, which seems to lack the quadratic interpolation that was supposed to emphysis local variations, is slightly less successful than the prefered Bilinear and also Fault methods. This seems to confirme the need to have a method of interpolation which take account of local variations.

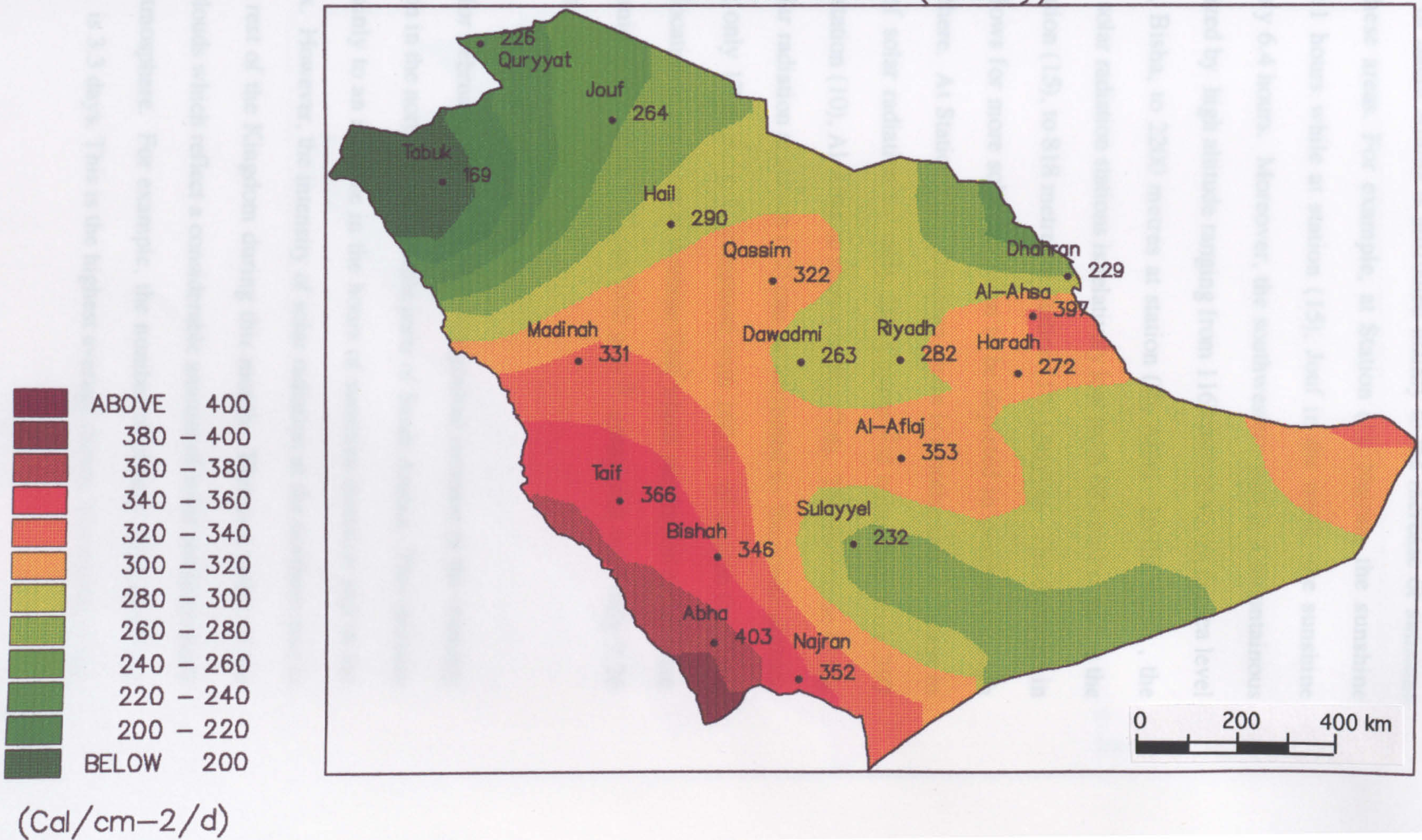
Therefore, amongest these interpolation mehtods, BILINEAR is the most appropriate method that can be used to interpolate the climatological data, such as solar radiation, temperature, and rainfall. As a result, the BILINEAR method is chosen here to interpolate incoming solar radiation in this thesis.

Data of incoming solar radiation (Z) in Saudi Arabia were fed into the computer using the UNIMAP programme, along with their correspondent longitude (X) and latitude (Y) of the station. The input data normally consists of points with three X.,Y., Z. values, in which the parameter Z is a function of the parameters X and Y. The X.,Y. coordinates represent the 2D location of a point, and the Z. coordinate represents the factor to be visualized (the solar radiation). UNIMAP operates by using the processes of a rectangular gridding, in which a grid is laid over the field of a data points, and a Z value is calculated for each grid node. This calculation evaluates and averages the data in a specific area surrounding each node. This results in a 3D grid or surface reconstruction that can be plotted as a smooth continuous surface (UNIRAS, 1990). Using the BILINEAR interpolation method, the pattern of variation of solar radiation in space is made clearer as will be seen in this Chapter.

7.2 THE SPATIAL DISTRIBUTION OF INCOMING SOLAR RADIATION IN SAUDI ARABIA

As discussed in the previous chapter, the distribution of incoming solar radiation is a result of a combination of several factors such as, sunshine duration, insolation index, altitude of the site, specific humidity, cloud cover, and dust. The first map, Figure (7.6), depicts the situation in January. In this month, sunshine duration is at its lowest in the year though with a noticeable increase towards the south and south-western parts of the Kingdom. Thus, there is a southward increase in the intensity of solar radiation from less than 250 Cal/cm^{-2}/d in the north to 400 Cal/cm^{-2}/d in the south.

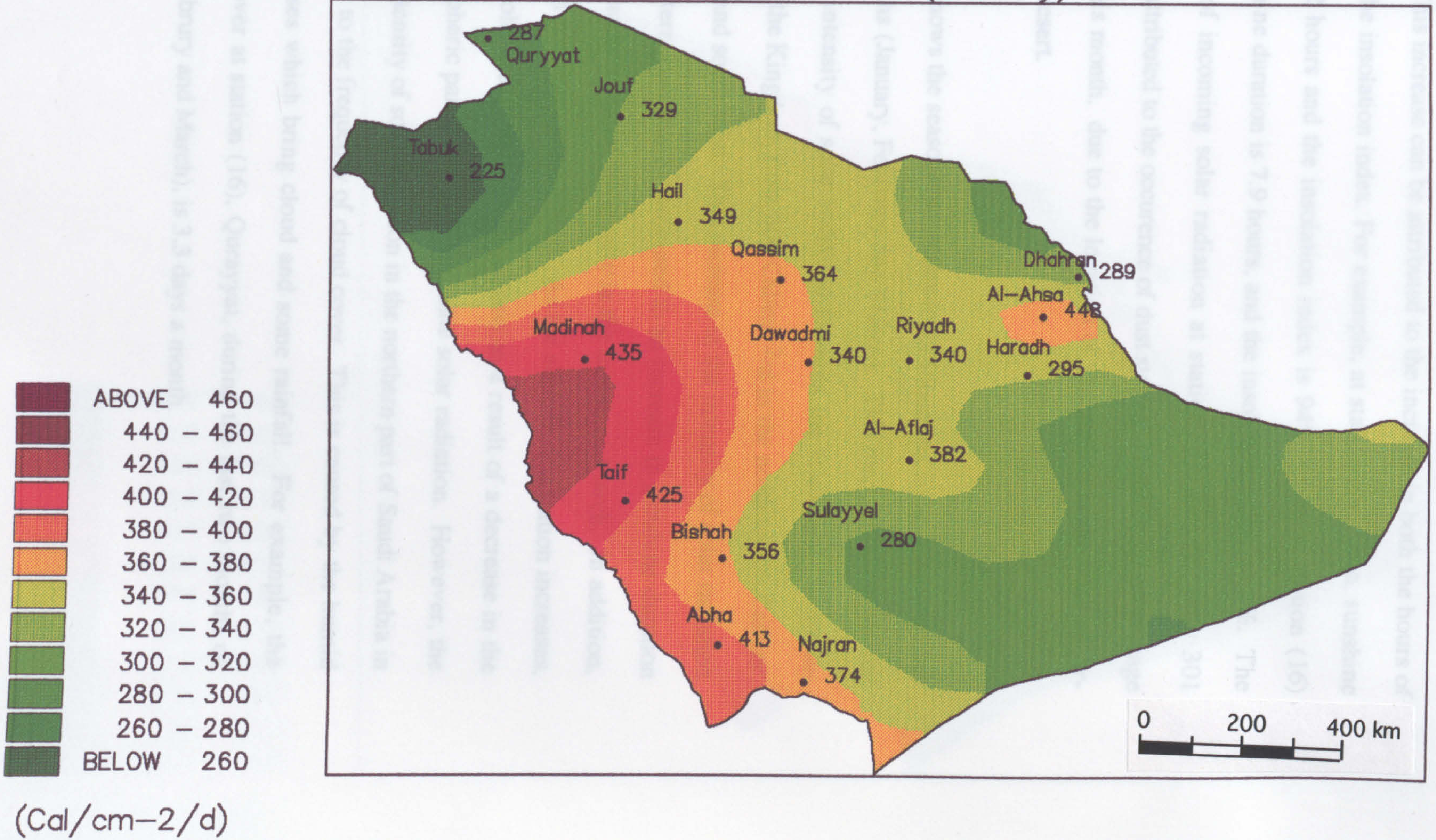
Fig (7.6) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (January)



The increase in the intensity of solar radiation in the south and southwestern parts of Saudi Arabia is attributed mainly to the increase of sunshine duration in these areas. For example, at Station (1), Najran, the sunshine duration is 9.1 hours while at station (15), Jouf in the north, the sunshine duration is only 6.4 hours. Moreover, the southwestern part is a mountainous area characterized by high altitude ranging from 1163 metres above the sea level at station (3), Bisha, to 2200 metres at station (2), Abha. In the north , the altitude of the solar radiation stations is relatively low from 689 metres above the sea level at station (15), to 818 metres at Station (16) Quryyat. The decrease in the altitude allows for more solar radiation to be depleted in passage through earth's atmosphere. At Station (12), Dhahran, there is a noticeable decrease in the intensity of solar radiation to only 229 Cal/cm^{-2}/d compared with 397 Cal/cm^{-2}/d at station (10), Al-Ahsa as shown in Fig.(7.6). The reduction in the intensity of solar radiation at station (12) can be attributed to the lower altitude of this station, only 17 m a. s. l., compared with 160 m of station (10), and also due to its location at the coast of Arabian Gulf which resulted in an increase in specific humidity at station (12), to 9.02 g/m^{-3} compared with only 7.26 g/m^{-3} at station (10), Al-Ahsa.

The map for February, Fig. (7.7), reveals a gradual increase in the intensity of solar radiation in the northern and middle parts of Saudi Arabia. This increase is attributed mainly to an increase in the hours of sunshine duration and in the insolation index. However, the intensity of solar radiation at the northern part is lower than the rest of the Kingdom during this month. This is a result of the appearance of clouds which reflect a considerable amount of solar radiation back to the earth's atmosphere. For example, the number of cloudy days at station (16), Qurayyat, is 3.3 days. This is the highest average during this month in the Kingdom.

Fig (7.7) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (February)



In the month of March, Fig. (7.8), there is a noticeable increase in the intensity of incoming solar radiation at the southern and southwestern parts of the country. This increase can be attributed to the increase in both the hours of sunshine and the insolation index. For example, at station (2), Abha, sunshine duration is 8.2 hours and the insolation index is 94%, while at station (16) Quryyat, sunshine duration is 7.9 hours, and the insolation index is 83%. The low intensity of incoming solar radiation at station (4), Sulyyel, only 301 Cal/cm^{-2}/d, is attributed to the occurence of dust storms. These occur on average for 5 days in this month, due to the location of this station at the edge of Ar-Rub' Al-Khali desert.

Fig. (7.9) shows the seasonal distribution of incoming solar radiation over the winter months (January, February and March). This map reveals a gradual increase in the intensity of solar radiation towards the south and the south-western parts of the Kingdom, from 300 Cal/cm^{-2}/d in the north to 400 Cal/cm^{-2}/d in the south and south-west. This increase in the intensity of solar radiation in the south-western parts can be attributed to an increase in sunshine duration hours and the insolation index, especially in the month of March. In addition, the south-western parts are mountainous. As the altitude of a station increases, the intensity of solar radiation tends to increase as a result of a decrease in the density of atmospheric particles which attenuate solar radiation. However, the decrease in the intensity of solar radiation in the northern part of Saudi Arabia in this season is due to the frequency of cloud cover. This is caused by the humid Atlantic air masses which bring cloud and some rainfall. For example, the average cloud cover at station (16), Qurayyat, during the last two months of winter season (Februry and March), is 3.3 days a month.

Fig (7.8) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (March)

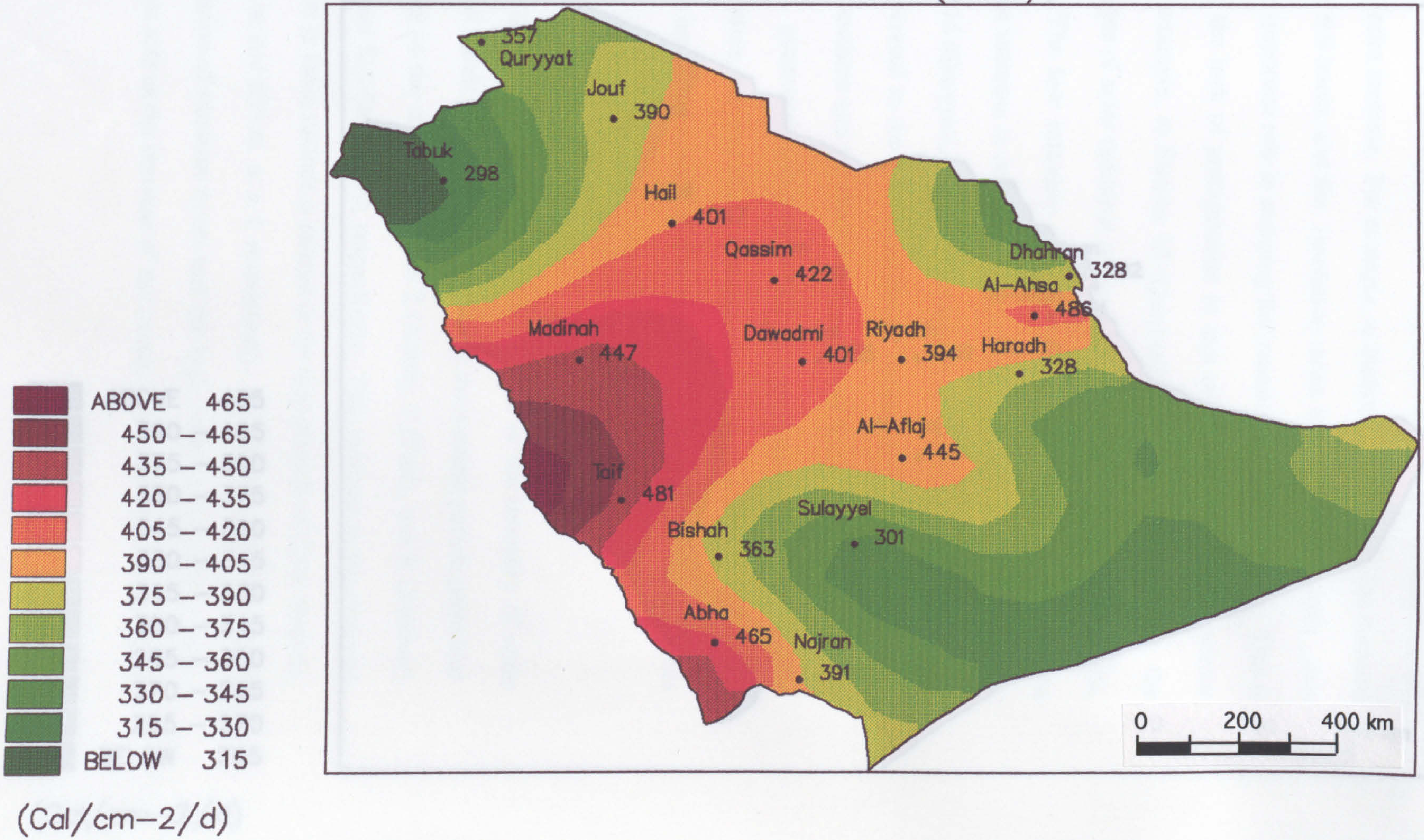
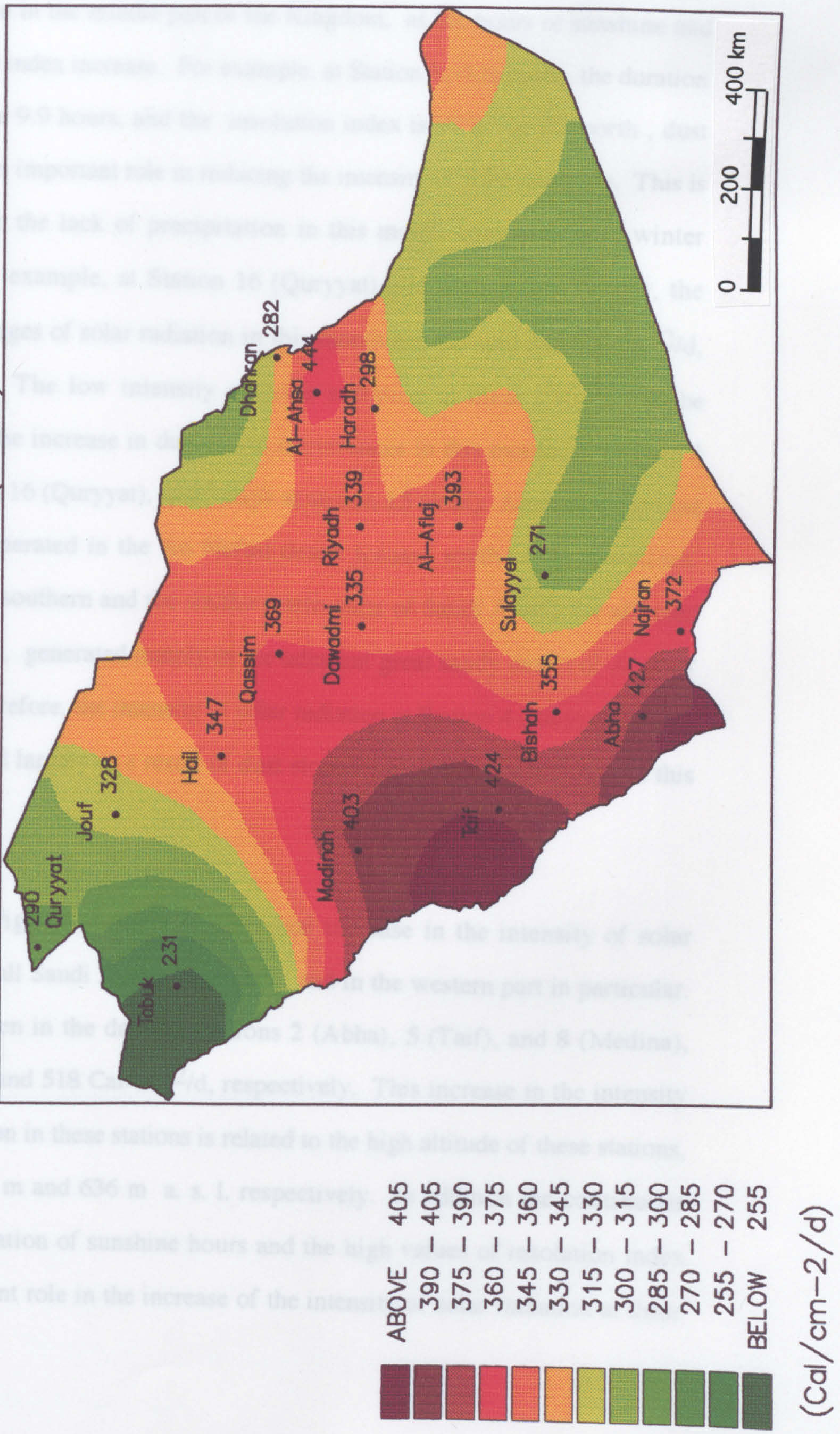


Fig (7.9) Seasonal Distribution of Incoming Solar Radiation in Saudi Arabia (Winter)



During April, Fig. (7.10), there is a noticeable increase in the intensity of solar radiation in the middle part of the Kingdom, as the hours of sunshine and the insolation index increase. For example, at Station 8, (Madinah), the duration of sunshine is 9.9 hours, and the insolation index is 97%. In the north , dust storms play an important role in reducing the intensity of solar radiation. This is in part due to the lack of precipitation in this month compared with winter months. For example, at Station 16 (Quryyat) and Station 14 (Tabuk), the monthly averages of solar radiation in this month are 422 and 346 Cal/cm^{-2}/d, respectively. The low intensity of solar radiation at these stations can be attributed to the increase in dust storm occurrences in this month, averaging 8 days at station 16 (Quryyat), and 5 days at station 15 (Jouf). Most of these dust storms are generated in the An Nafud desert located south of these stations. Similarly, the southern and the southwestern parts of Saudi Arabia are affected by dust storms, generated mainly in the adjacent great sandy desert of Ar Rub' Al-Khali. Therefore, the intensity of solar radiation at Station 4 (Sulyyel) is only 327 Cal/cm^{-2}/d largely as a result of dust storms which average 6.5 days in this month.

In May, Fig.(7.11), there is a gradual increase in the intensity of solar radiation over all Saudi Arabia in general, and in the western part in particular. This can be seen in the data for stations 2 (Abha), 5 (Taif), and 8 (Medina), with 501, 526 and 518 Cal/cm^{-2}/d, respectively. This increase in the intensity of solar radiation in these stations is related to the high altitude of these stations, 2200 m, 1454 m and 636 m a. s. l. respectively. In addition the continuous increase in duration of sunshine hours and the high values of insolation index play a significant role in the increase of the intensity of solar radiation at these stations.

Fig (7.10) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (April)

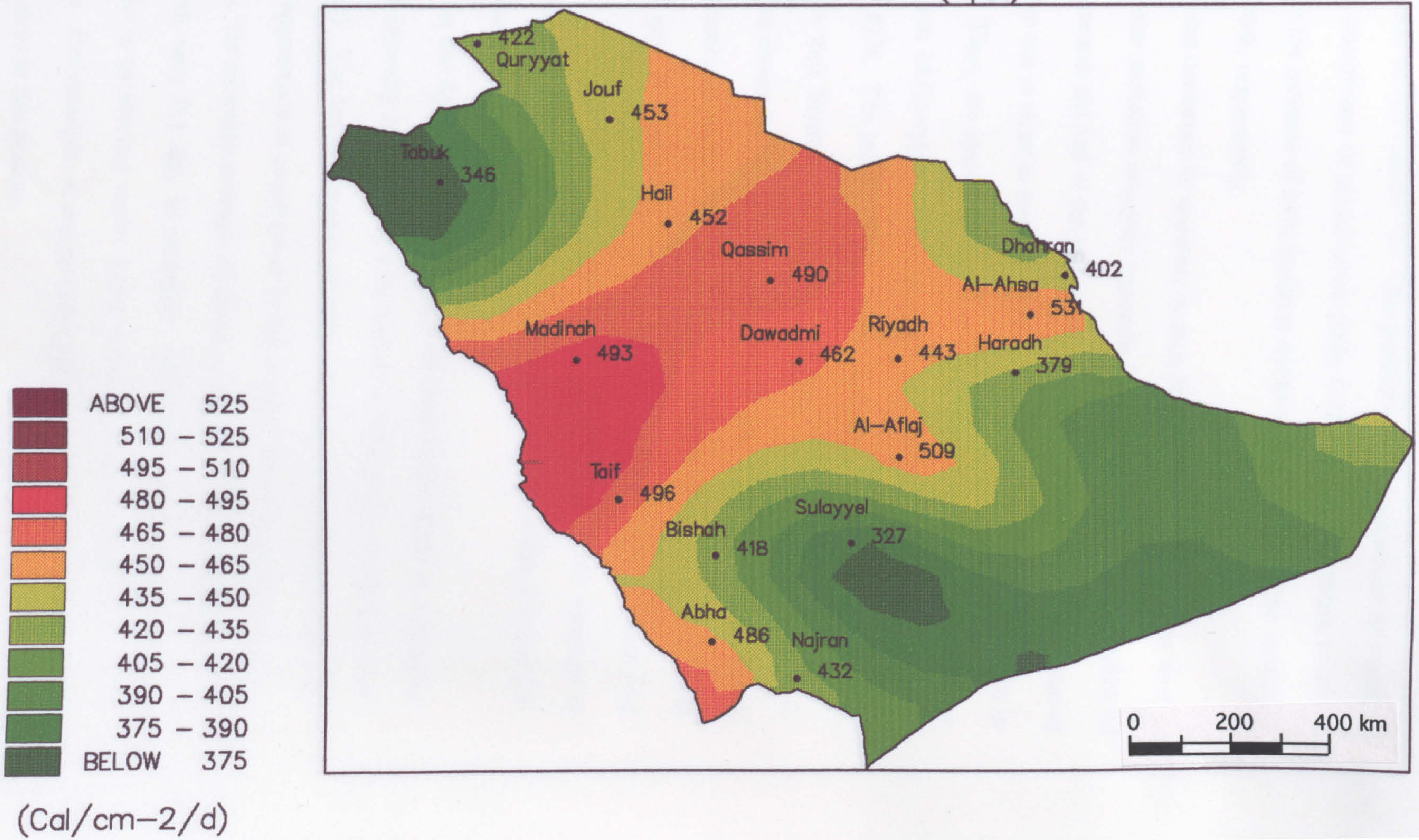
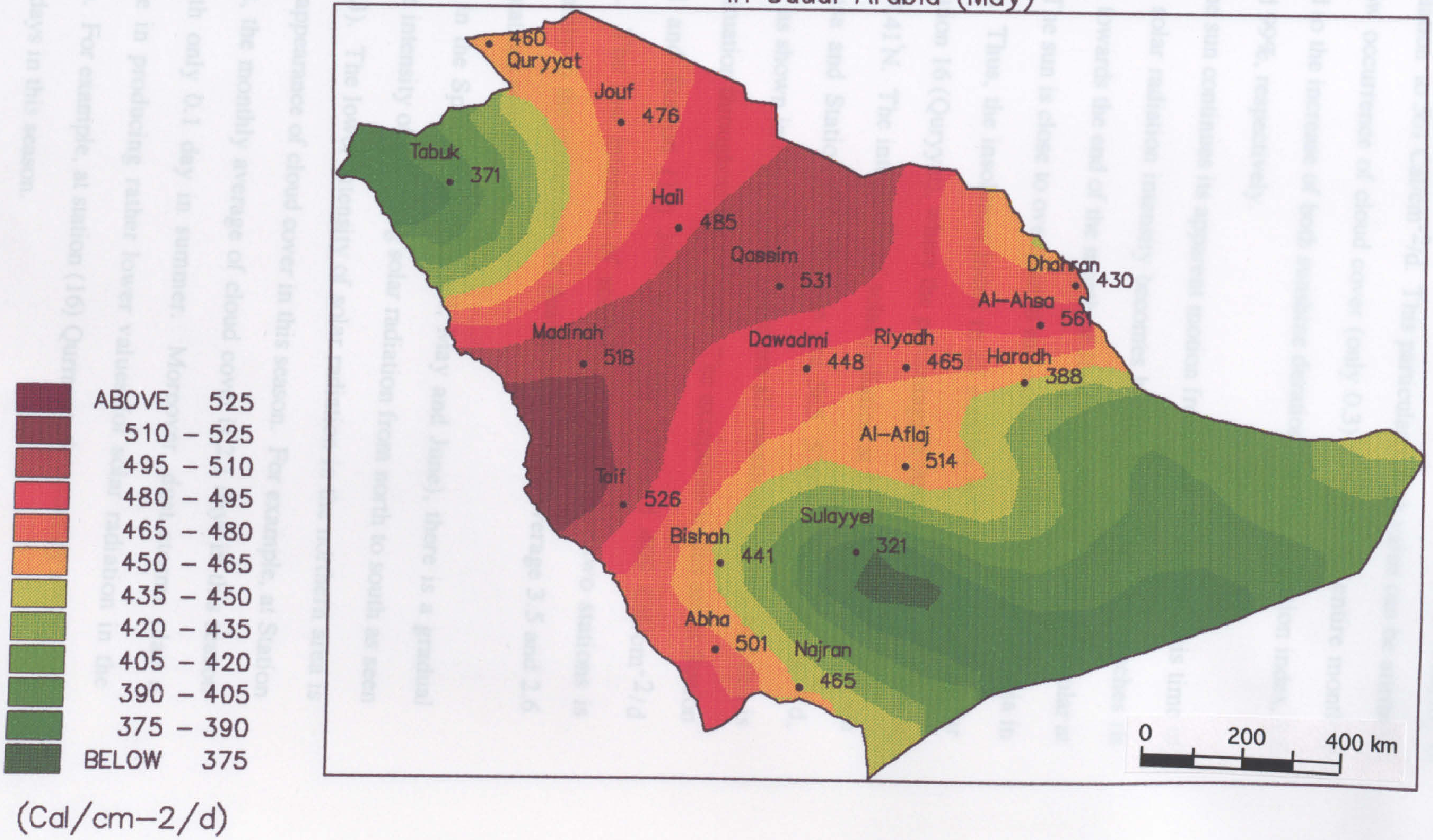


Fig (7.11) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (May)



At station 10 (Al-Ahsa), there is a remarkable increase in the intensity of solar radiation to 561 Cal/cm^{-2}/d. This particularly high value can be attributed to the low occurrence of cloud cover (only 0.3) days for the entire month of May, and to the increase of both sunshine duration and the insolation index, 9.8 hours and 99%, respectively.

As the sun continues its apparent motion from south to north at this time of the year, solar radiation intensity becomes higher and higher, and reaches its maximum towards the end of the month of June when the sun is perpendicular at $23^{o}.5'$ N. The sun is close to overhead at most of the stations in Saudi Arabia in this month. Thus, the insolation index in all stations is 99% except at the far north at Station 16 (Quryyat), where the percentage is 98% due to its location at latitude $31^{o}.41'$N. The intensities of solar radiation at Station (5) Taif, Station (10) Al-Ahsa and Station (11) Qassim are 565, 570 and 600 Cal/cm^{-2}/d, respectively as shown in Fig. (7.12). These are all maximum values, and this is the normal situation throughout the country. The exceptions to this are at Station (4) Sulyyel and Station (15) Jouf with only 376 and 409 Cal/cm^{-2}/d respectively. The low intensity of solar radiation at these two stations is attributed mainly to the occurrence of dust storms, which average 3.5 and 2.6 days at both stations respectively.

Overall, in the Spring season (April, May and June), there is a gradual increase in the intensity of incoming solar radiation from north to south as seen in Figure (7.13). The lower intensity of solar radiation in the northern area is caused by the appearance of cloud cover in this season. For example, at Station (16), Qurrayat, the monthly average of cloud cover is 2.1 days in this season compared with only 0.1 day in summer. Moreover, dust storms play a significant role in producing rather lower values for solar radiation in the northern region. For example, at station (16) Qurrayat, the monthly average of dust storm is 9 days in this season.

Fig (7.12) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (June)

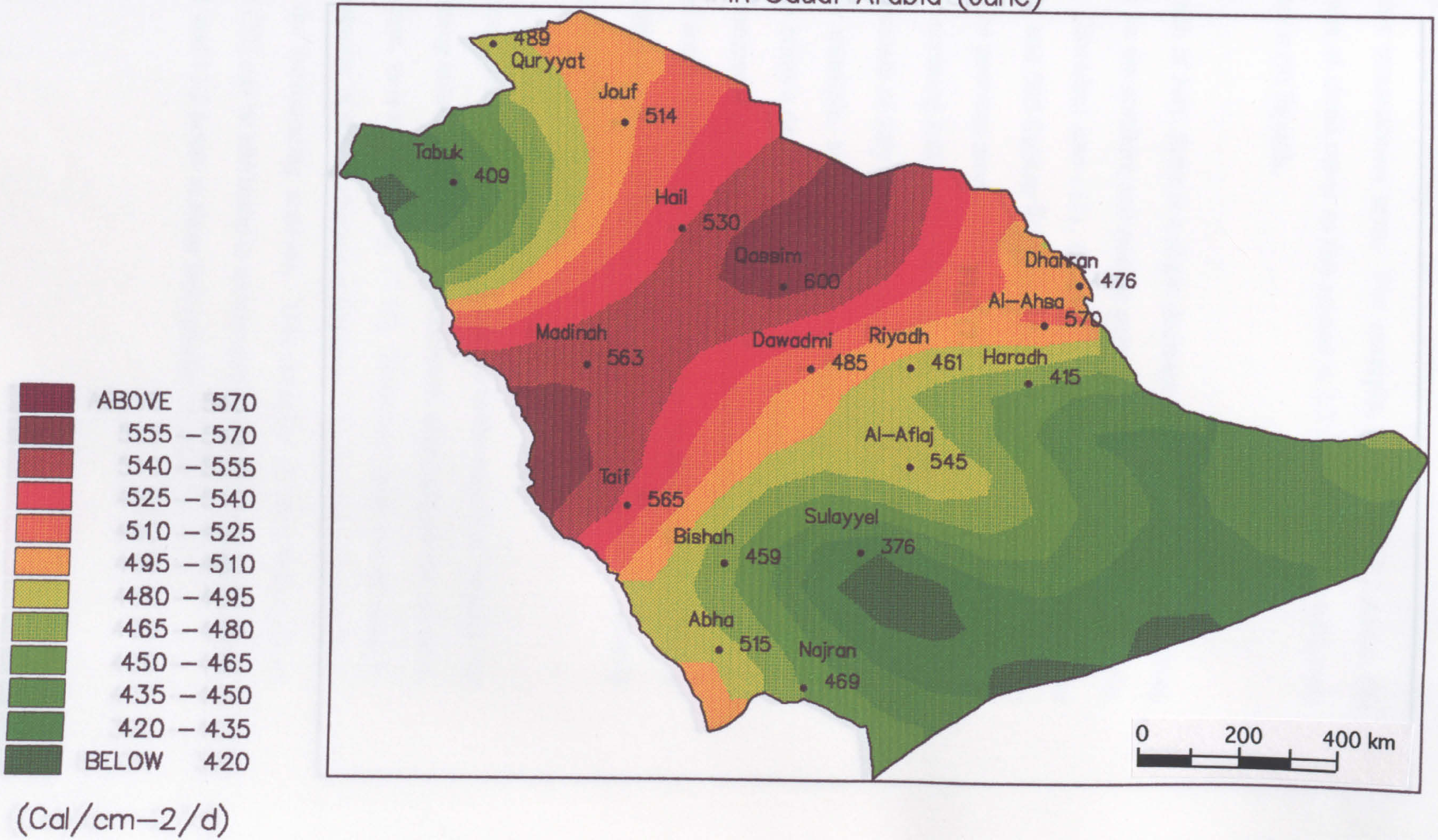


Fig (7.13) Seasonal Distribution of Incoming Solar Radiation in Saudi Arabia (Spring)

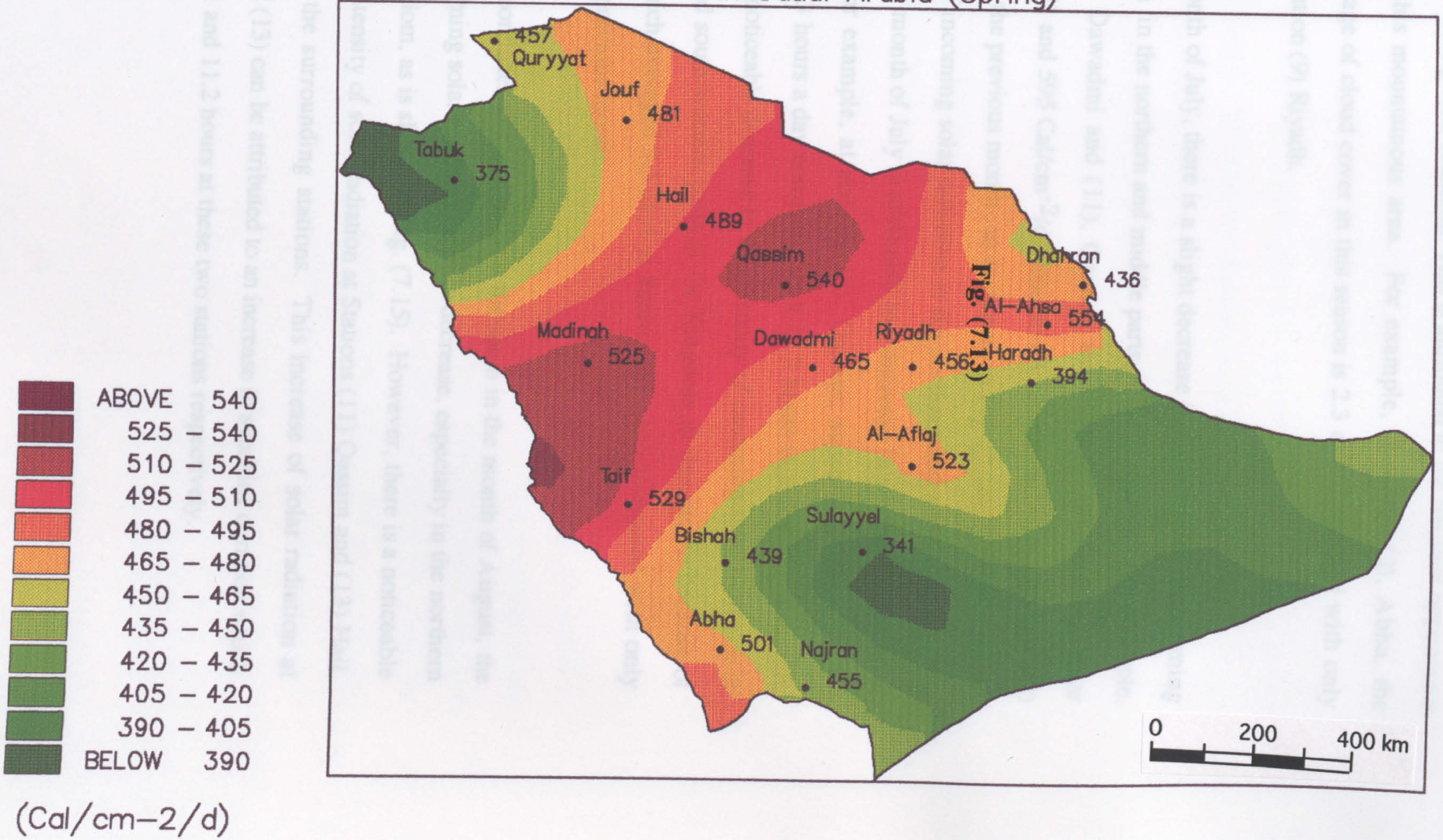


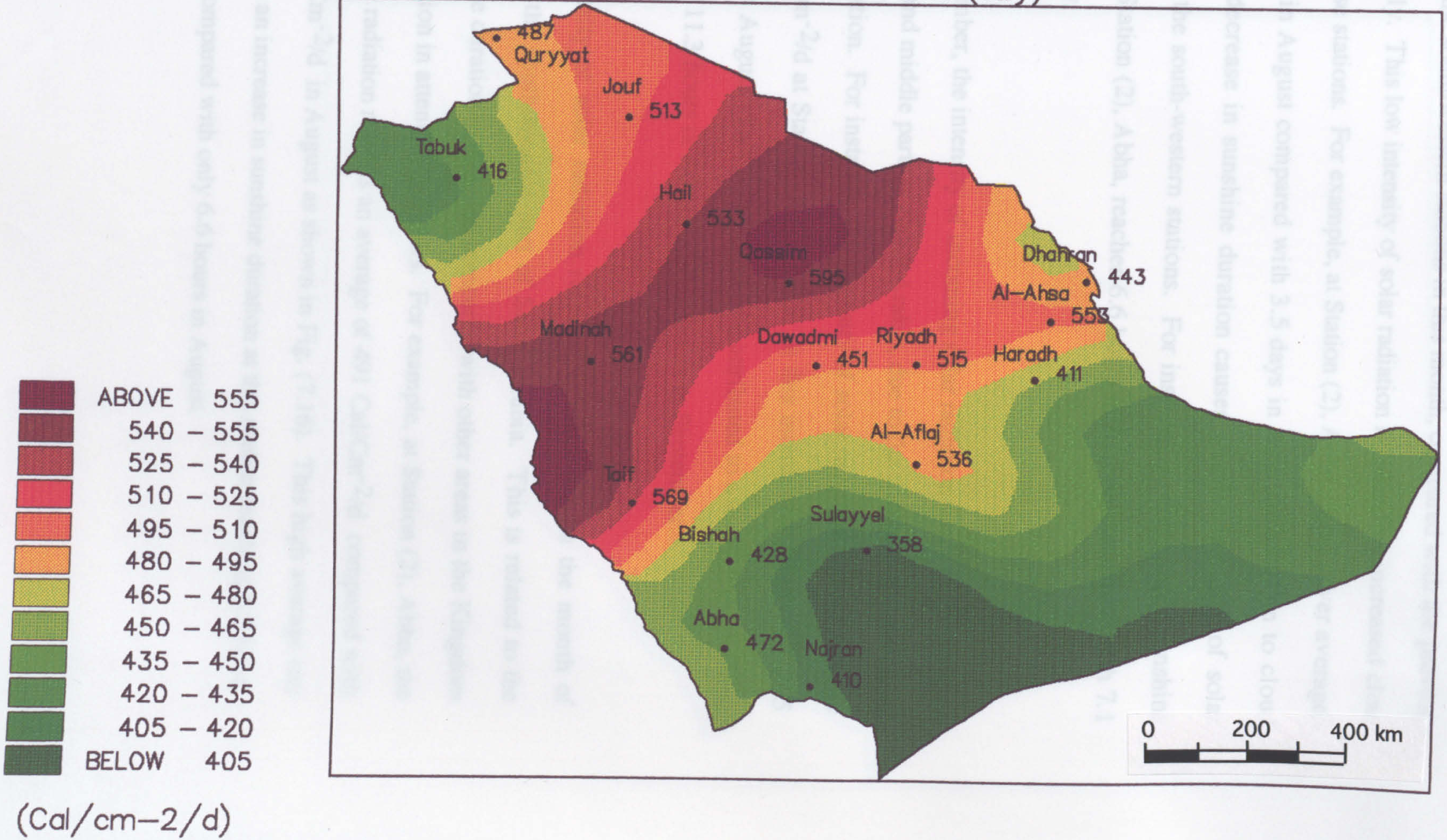
Fig. (7.13)

In the southwestern part of the kingdom, there is a noticeable decrease in the intensity of incoming solar radiation. This is attributed to the frequent appearance of cloud in this mountainous area. For example, at station (2), Abha, the monthly average of cloud cover in this season is 2.3 days compared with only 1.5 days at station (9) Riyadh.

In the month of July, there is a slight decrease in the intensity of incoming solar radiation in the northern and middle parts of the Kingdom. For example, at station (7) Dawadmi and (11), Qassim, the intensity of incoming solar radiation is 451 and 595 Cal/cm^{-2}/d respectively, compared with 485 and 600 Cal/cm^{-2}/d in the previous month , as is shown in Fig. (7.14). The decrease in the intensity of incoming solar radiation in the northern and middle parts of the kingdom in the month of July is attributed to a decrease in sunshine duration at these parts. For example, at station (11), Qassim, sunshine is recorded on average for 10.3 hours a day compared with 11.3 hours in the previous month. There is also a noticeable decrease in the intensity of incoming solar radiation in the southern and south-western parts of the Kingdom in this month because of cloud cover which averaged 3.5 days at Station (2) Abha compared with only 2.3 days in the previous month.

As the sun continues to move towards the south in the month of August, the intensity of incoming solar radiation tends to decrease, especially in the northern part of the Kingdom, as is shown in Fig. (7.15). However, there is a noticeable increase in the intensity of solar radiation at Stations (11) Qassim and (13) Hail, compared with the surrounding stations. This increase of solar radiation at Stations (11) and (13) can be attributed to an increase in sunshine duration which is measured at 11 and 11.2 hours at these two stations respectively.

Fig (7.14) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (July)



Moreover, there is a decrease in the intensity of incoming solar radiation received at the south-western stations in this month, compared with the previous month of July. This low intensity of solar radiation is caused by increased cloud cover at these stations. For example, at Station (2), Abha, cloud cover averaged at 3.8 days in August compared with 3.5 days in July. In addition to cloud cover, the decrease in sunshine duration causes a lower intensity of solar radiation at the south-western stations. For instance, average daily sunshine duration at Station (2), Abha, reaches 6.6 hours in August, compared with 7.1 hours in July.

In September, the intensity of incoming solar radiation tends to decrease in the northern and middle parts of Saudi Arabia, due to the continuing decrease in sunshine duration. For instance, the intensity of solar radiation has an average of 346 Cal/Cm^{-2}/d at Station (14), Tabuk, in this month compared with 385 Cal/Cm^{-2}/d in August. This decrease can be attributed to a decline in sunshine duration from 11.3 hours in August to 10.1 hours in September.

The intensity of solar radiation reaches its maximum in the month of September in the south-western part of Saudi Arabia. This is related to the longer sunshine duration in this area compared with other areas in the Kingdom and to a reduction in attenuating factors. For example, at Station (2), Abha, the incoming solar radiation reaches an average of 491 Cal/Cm^{-2}/d compared with only 445 Cal/Cm^{-2}/d in August as shown in Fig. (7.16). This high average can be attributed to an increase in sunshine duration at this station reaching 8.5 hours in this month compared with only 6.6 hours in August.

Fig (7.15) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (August)

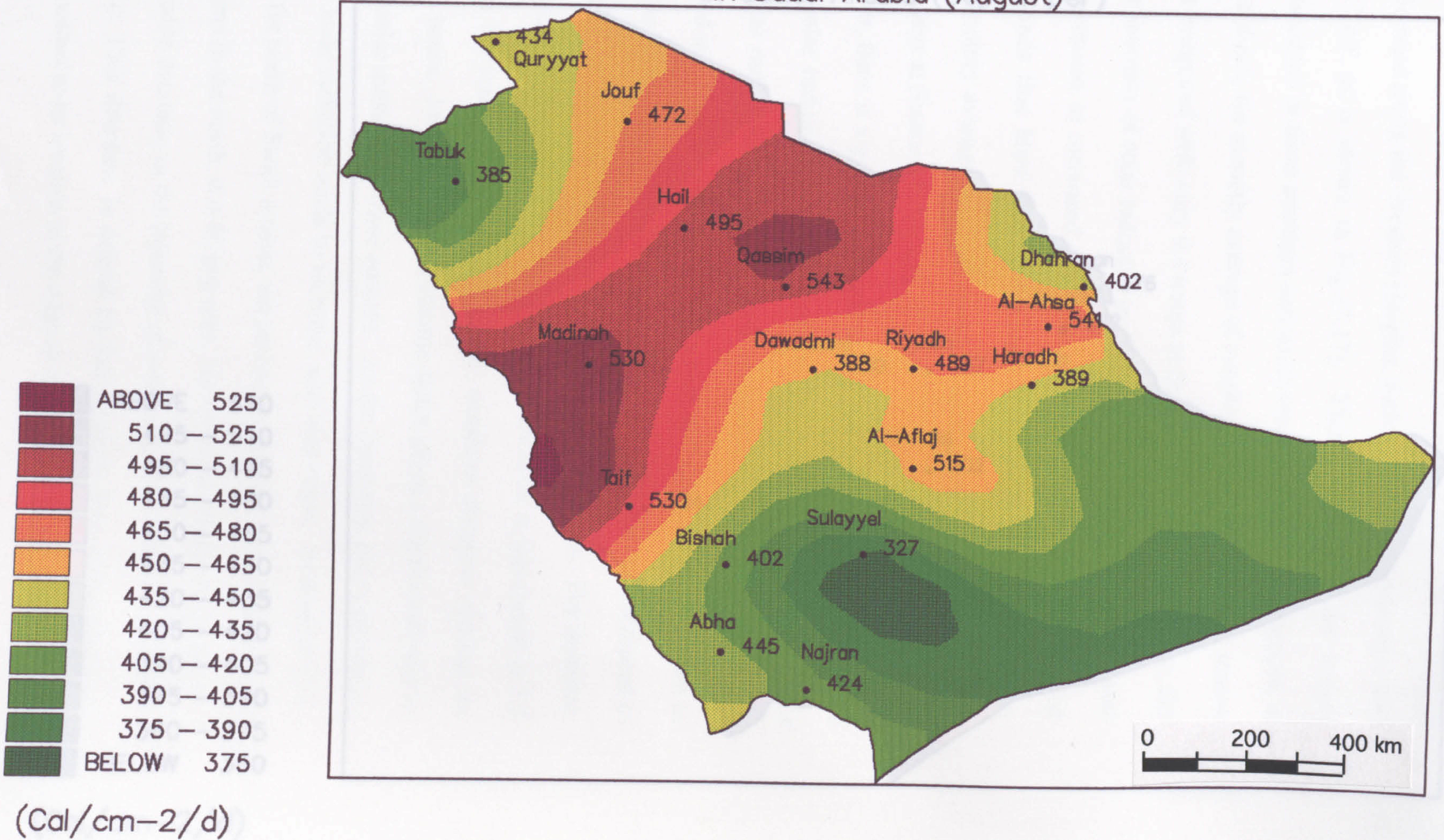
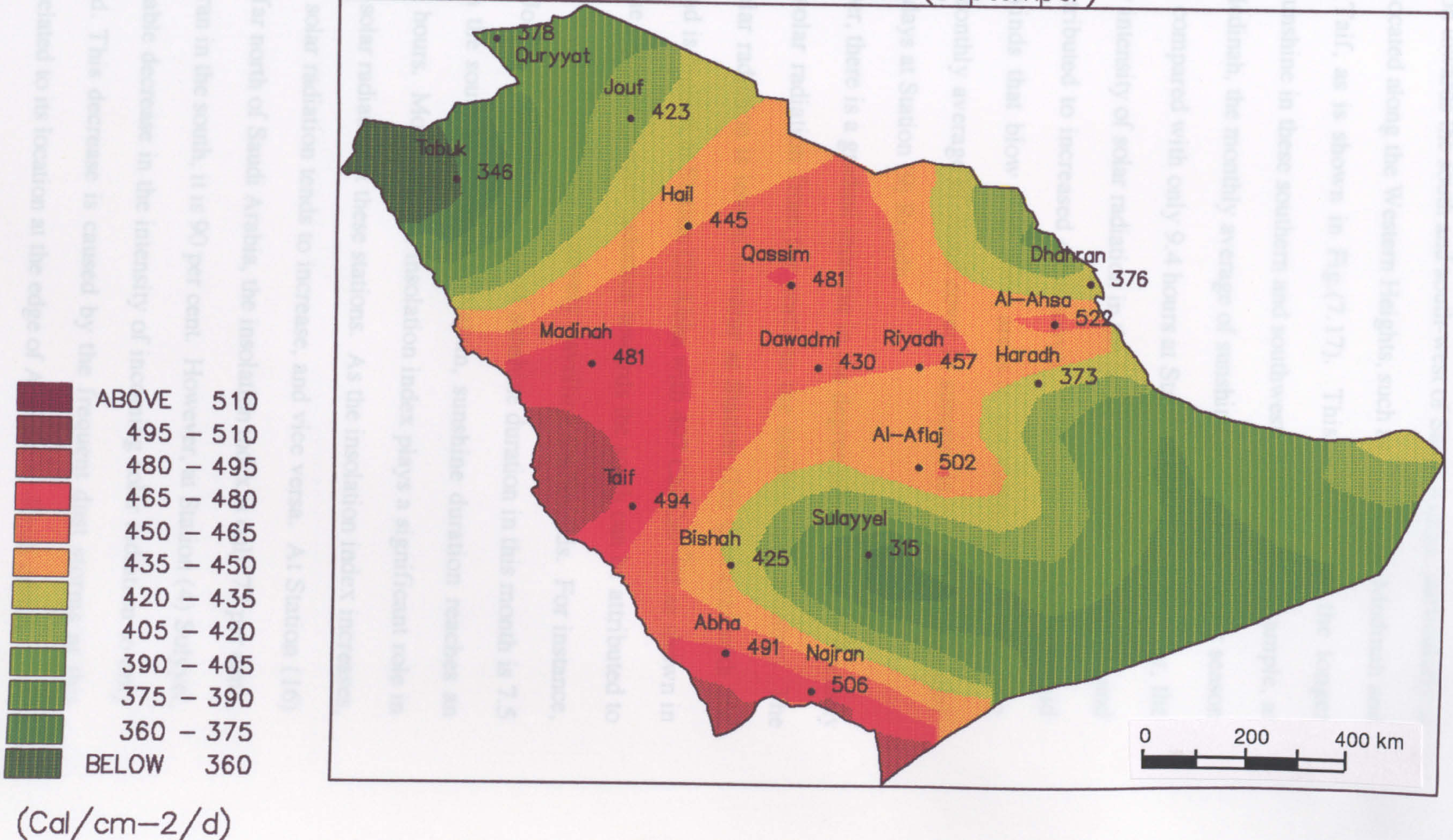


Fig (7.16) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (Septemper)



Thus, in summer, there is a gradual increase in the intensity of incoming solar radiation towards the south and south-west of Saudi Arabia, particularly at the stations located along the Western Heights, such as Station (8) Medinah and Station (5) Taif, as is shown in Fig.(7.17). This is caused by the longer duration of sunshine in these southern and southwestern areas. For example, at Station (8) Medinah, the monthly average of sunshine during the summer season is 10.5 hours compared with only 9.4 hours at Station (15) Jouf. However, the relatively low intensity of solar radiation in the far south-western stations (1) and (2) can be attributed to increased cloud cover. This is related to the humid Monsoonal winds that blow over these areas in the summer. At Station 2 (Abha), the monthly average of cloud cover in summer is 3.3 days compared with only 0.6 days at Station (9) Riyadh.

. In October, there is a gradual increase in the degree of variation of intensity of incoming solar radiation from the north to the south of the country. The intensity of solar radiation is lowest in value at Station (16) Qurrayat with 266 Cal/Cm^{-2}/d, and is highest at Station (2) Abha with 497 Cal/Cm^{-2}/d as shown in Fig. (7.18). The increase in solar radiation towards the south can be attributed to sunshine duration which increases relatively travelling southwards. For instance, at Station (15) Jouf, the monthly average of sunshine duration in this month is 7.5 hours, while in the south at Station (1) Najran, sunshine duration reaches an average of 10.1 hours. Moreover, the insolation index plays a significant role in the variation of solar radiation at these stations. As the insolation index increases, the intensity of solar radiation tends to increase, and vice versa. At Station (16) Qurrayat in the far north of Saudi Arabia, the insolation index is only 77 per cent, while at (1) Najran in the south, it is 90 per cent. However, at Station (4) Sulyyel, there is a noticeable decrease in the intensity of incoming solar radiation to only 274 Cal/Cm^{-2}/d. This decrease is caused by the frequent dust storms at this station. This is related to its location at the edge of Ar-Rub' Al-Khali desert.

Fig (7.17) Seasonal Distribution of Incoming Solar Radiation In Saudi Arabia (Summer)

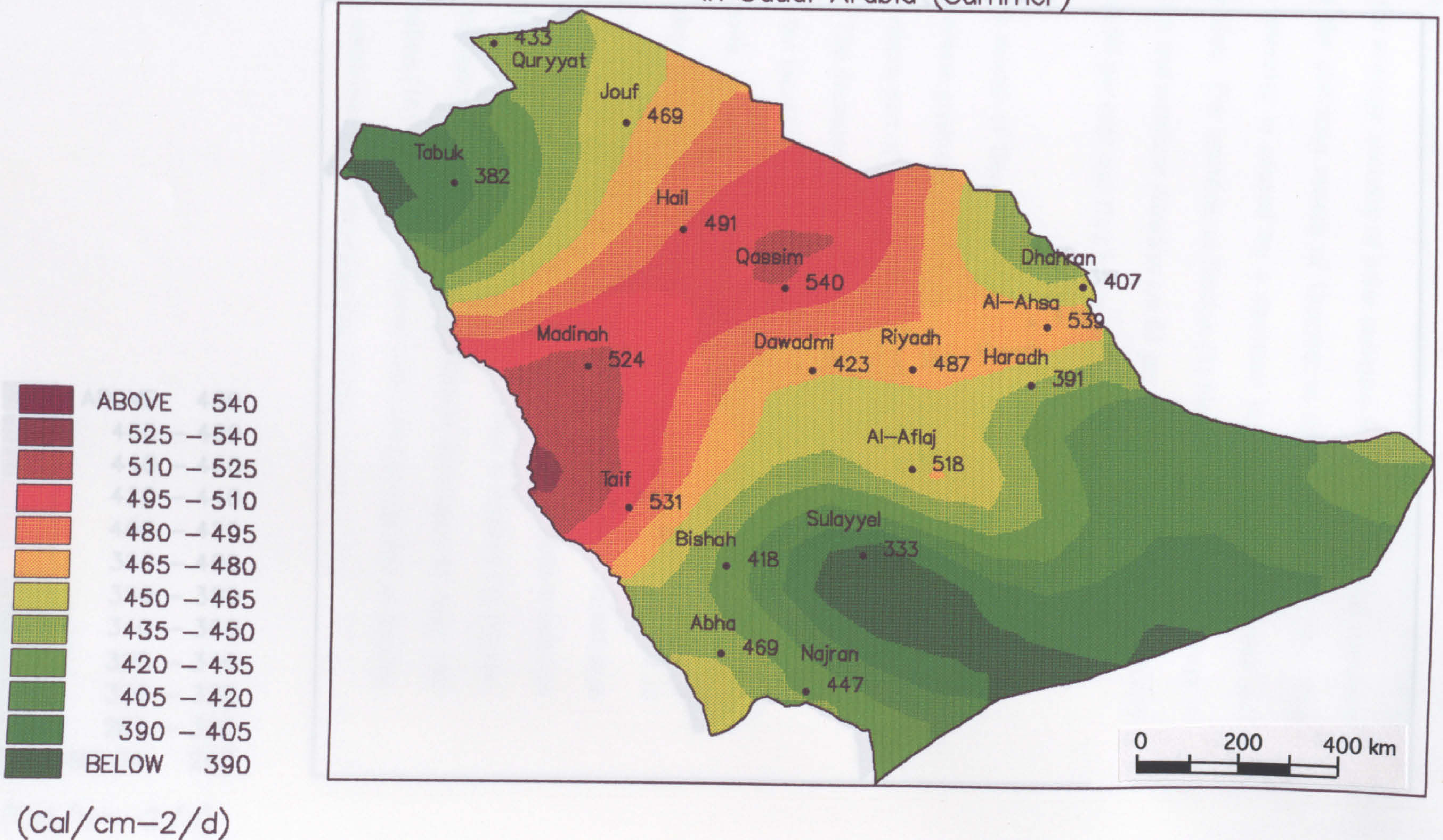
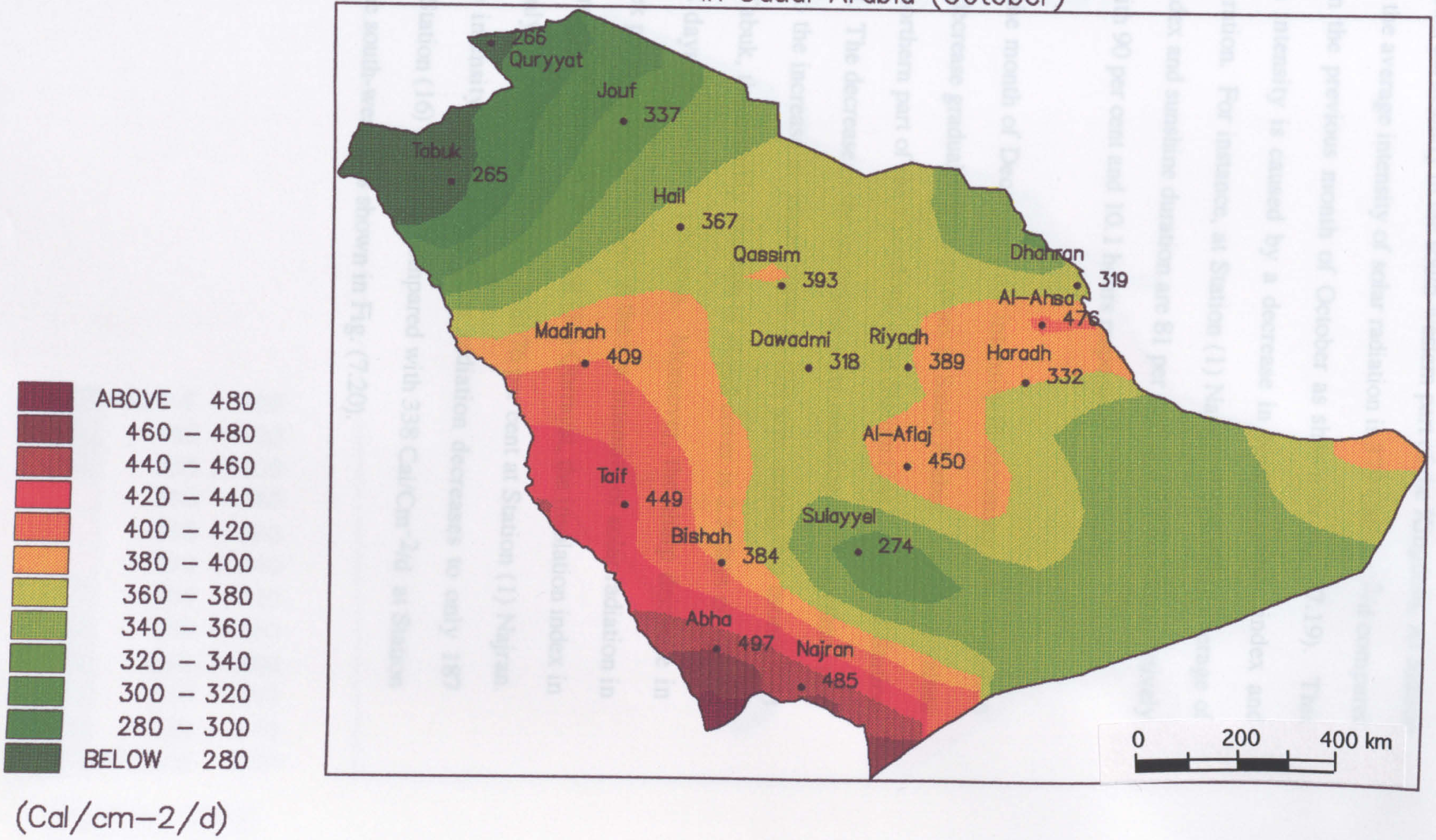


Fig (7.18) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (October)



In November, there is a noticeable decrease in the intensity of incoming solar radiation, particularly in the south-western part of the Kingdom. At Station (1) Najran, the average intensity of solar radiation is 379 Cal/Cm^{-2}/d compared with 485 in the previous month of October as shown in Fig. (7.19). This decrease in intensity is caused by a decrease in both insolation index and sunshine duration. For instance, at Station (1) Najran, the monthly average of insolation index and sunshine duration are 81 per cent and 9.9 hours respectively compared with 90 per cent and 10.1 hours respectively, in October.

During the month of December, the intensity of incoming solar radiation continues to decrease gradually at all stations in Saudi Arabia. Minimum values occur in the northern part of the Kingdom, as at Station (14) Tabuk and Station (16) Qurrayat. The decrease in the incoming solar radiation at the northern part is attributed to the increase in cloud cover in this area during this month. At Station (14) Tabuk, the monthly average of cloud cover is 2.3 days compared with only 1.8 days at Station (1) Najran. Moreover, the sharp decrease in insolation index plays an important role in the low intensity of solar radiation in this northern area. For example, at Station (16) Qurrayat, the insolation index in December is only 58 per cent compared with 76 per cent at Station (1) Najran. Therefore, the intensity of incoming solar radiation decreases to only 187 Cal/Cm^{-2}/d at Station (16) Qurayyat compared with 338 Cal/Cm^{-2}/d at Station (1) Najran in the south-west as is shown in Fig. (7.20).

Fig (7.19) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (November)

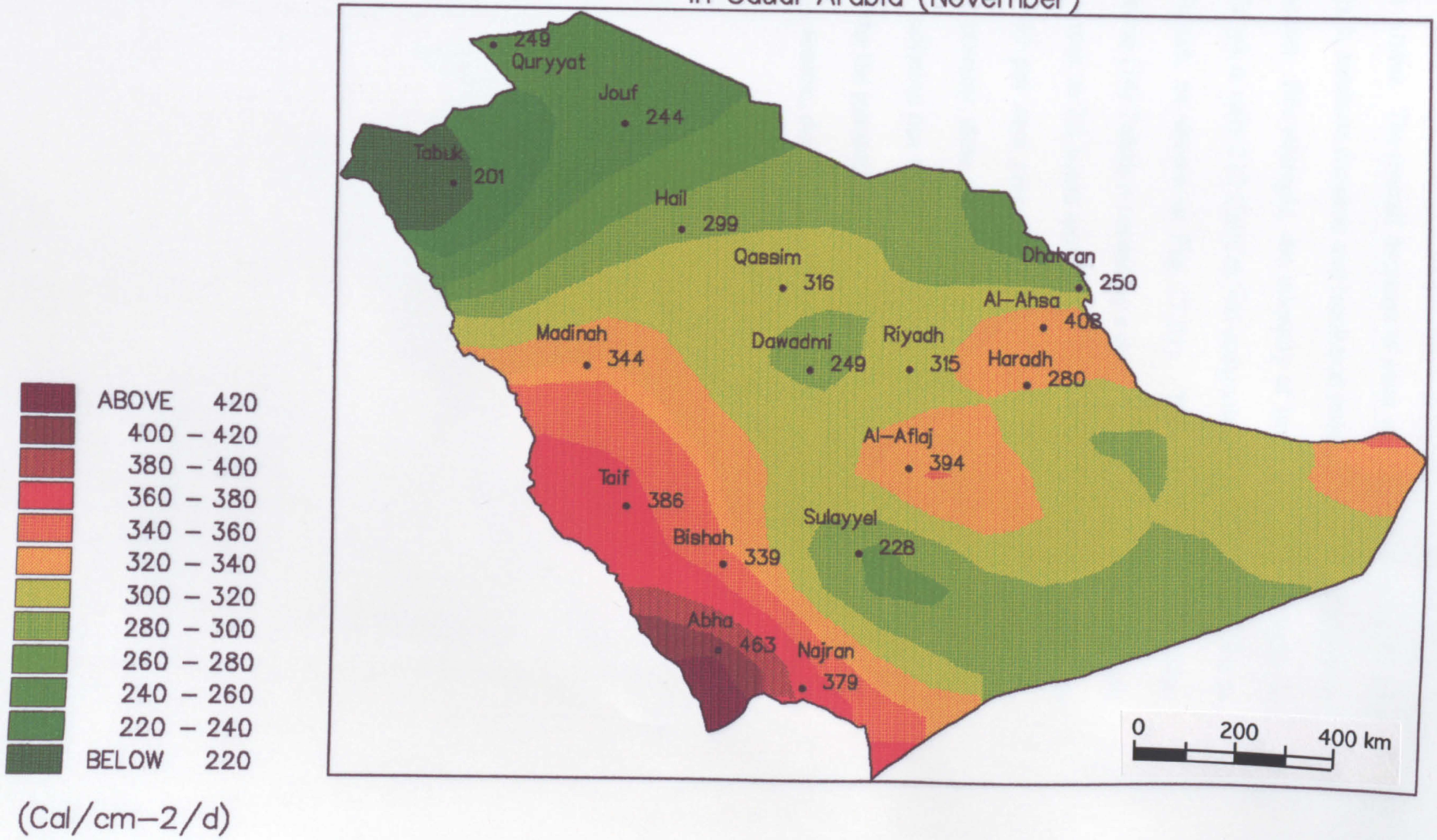
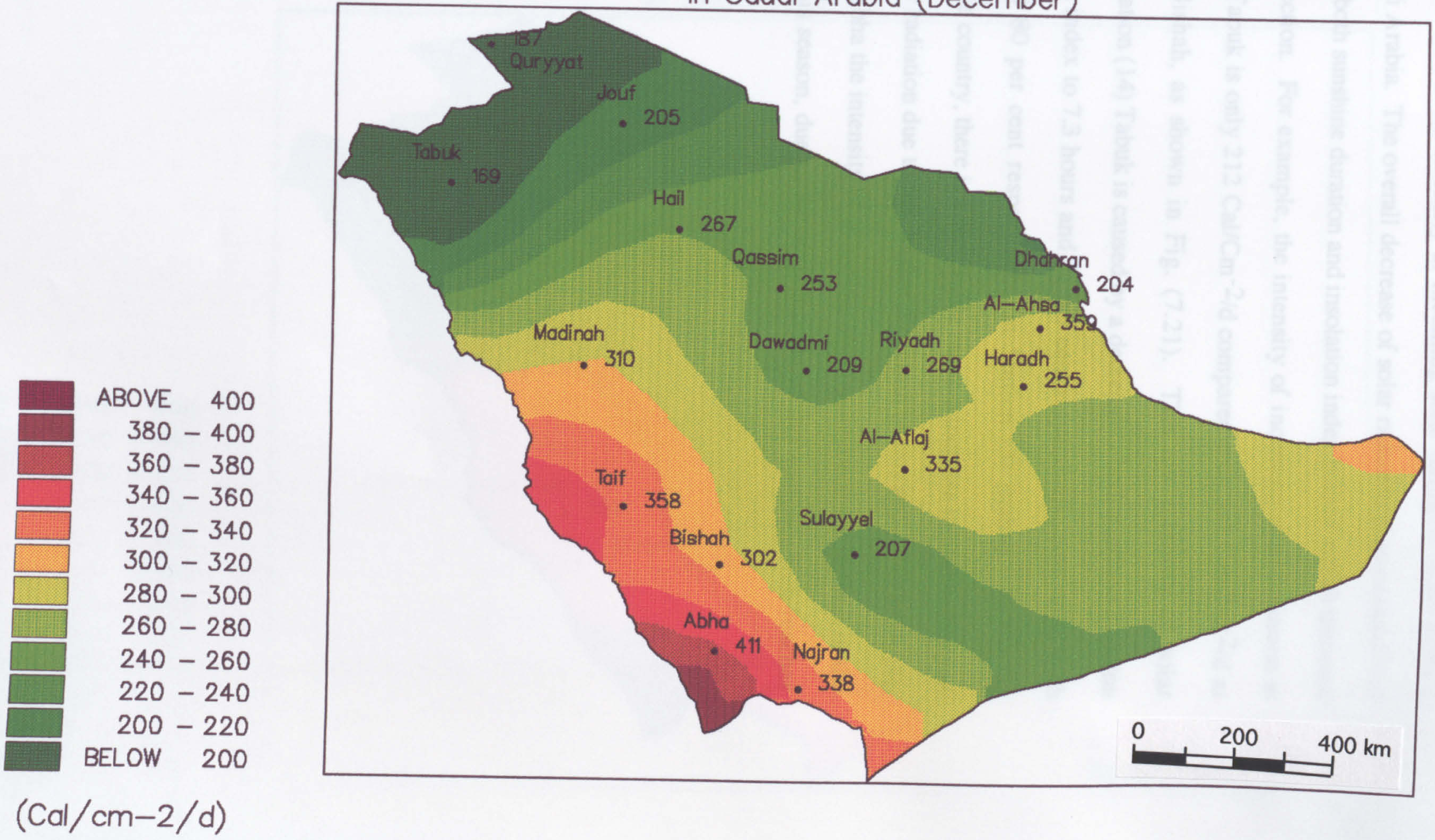
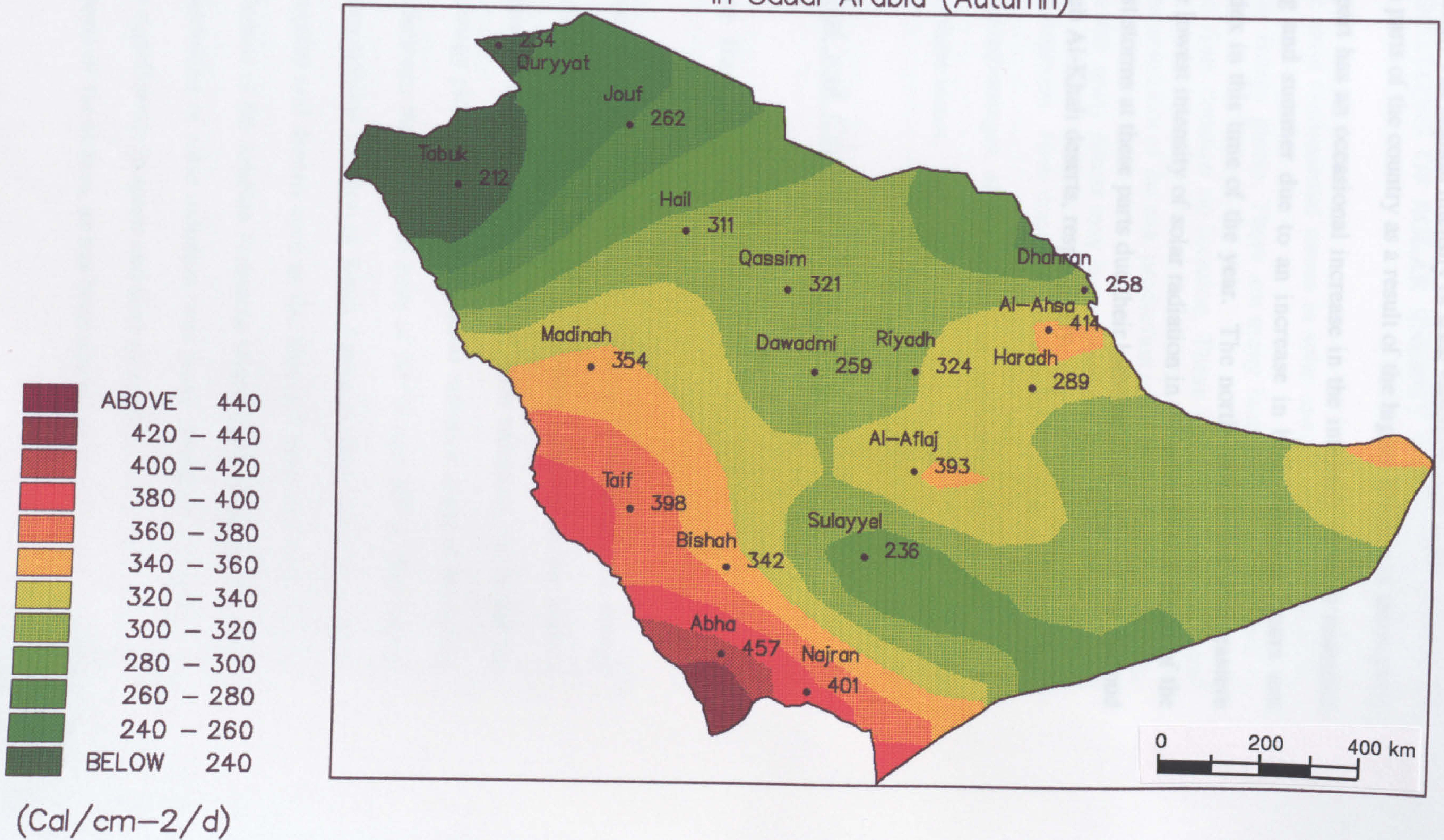


Fig (7.20) Monthly Distribution of Incoming Solar Radiation in Saudi Arabia (December)



Thus, in the autumn months (October, November and December), there is a significant decrease in the intensity of incoming solar radiation from south to north in Saudi Arabia. The overall decrease of solar radiation is associated with a decrease in both sunshine duration and insolation index,both of which decrease the same direction. For example, the intensity of incoming solar radiation at Station (14) Tabuk is only 212 Cal/Cm^{-2}/d compared with 342 Cal/Cm^{-2}/d at Station (3) Bishah, as shown in Fig. (7.21). This low intensity of solar radiation at Station (14) Tabuk is caused by a decrease in both sunshine duration and insolation index to 7.3 hours and 71 per cent respectively, compared with 8.1 hours and 80 per cent respectively, at Station (3) Bishah. In the far southwest of the country, there is a noticeable relative increase in the intensity of incoming solar radiation due to the higher elevation of this area. For example, at Station (2) Abha the intensity of incoming solar radiation is the highest in the Kingdom in this season, due to the high altitude of this station which reaches 2200 m a.s.l.

Fig (7.21) Seasonal Distribution of Incoming Solar Radiation in Saudi Arabia (Autumn)



In summary, there is quite a variation in the intensity of solar radiation over Saudi Arabia, both temporally and spatially as a result of the six major factors mentioned earlier. The highest intensity of solar radiation falls at the western and southwestern parts of the country as a result of the higher altitude of these parts. The middle part has an occasional increase in the intensity of solar radiation during spring and summer due to an increase in both sunshine hours and insolation index in this time of the year. The northwestern and southeastern parts have the lowest intensity of solar radiation in the country as a result of the prevailing dust storms at these parts due their location at the edge of the Nafoud and the Ar' Rub Al-Khali deserts, respectively.

CHAPTER EIGHT

THE LOCATIONS OF SOLAR ENERGY FACILITIES

One of the most fundamental issues in solar energy development is the location of solar energy plants. There are many factors to be considered in determining the final decision on location. These include the physical and climatoligical characteristics of the site, production costs, and population density. The difficulty is that many places may have specific locational advantages for solar energy development. How does one evaluate these places and all of their advantages and disadvanteges, and decide on an appropriate location ?. This chapter examines these issues.

8.1 The Physical and Climatological Factors

8.1.1 Solar Radiation Intensity

One of the main factors that determine the optimum location for solar energy plants is the intensity and duration of solar radiation received at the earth's surface. The higher the intensity and duration of solar radiation, the better the location of solar energy plants. Since the best solar radiation areas of the world are those located between the latitudinal belts of 30° N and 30° S, this means that the general geographical location of Saudi Arabia is ideal. However, most of these areas comprise arid deserts such as the Sahara Desert of North Africa and the Arabian Deserts of the Arabian Peninsula where Saudi Arabia is located. Moreover, the distribution of solar radiation over Saudi Arabia is significantly variable. It varies significantly in space and time as a result of the physical and climatological aspects of the station, as has been discussed in Chapters Six and

Seven. Thus there are distinct advantages for certain areas in the Kingdom in radiation terms, in spite of the overall favourable conditions in Saudi Arabia.

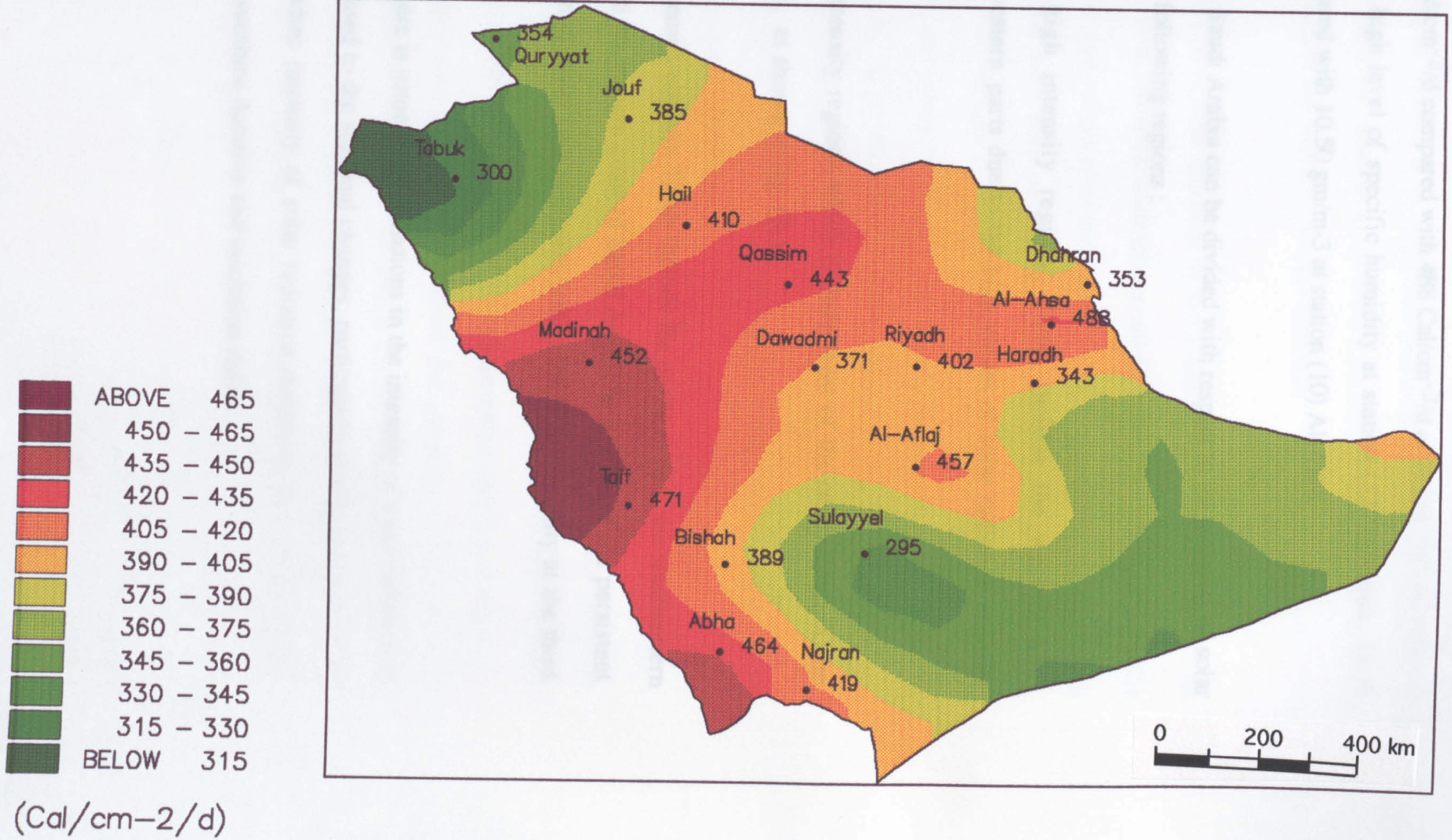
The variation in the intensity of incoming solar radiation makes it difficult for decision makers to determine the aptimum location for solar energy plants. However, the best approach to this problem is to consider the annual and seasonal distribution of incoming solar radiation. The annual distribution will determine the overall income of solar radiation and allows to make comparisons between sites, while the seasonal distribution will determine energy efficiency and whether it meets the energy demand of that period. For example, in Saudi Arabia, energy demand reaches its peak in summer when energy consumption, for air conditioning and refrigeration, is higher. Thus, in the case of Saudi Arabia, seasonal distribution pattern is a key factor in determining the appropriate location of a solar energy plant. Moreover, any shortage in the intensity of solar radiation could be met by installing large-scale storage of energy through batteries. These may be used either at night, or during the periods when the intensity of solar radiation is low as a result of the attinuating factors such as dust storms and cloud cover. According to Advisory Committee on Technology Innovation (1981), if year-round operation without a back-up generating system is required, the battery system may be designed for as much as one month of operation at the average load without recharging. However, capacity depends on how the battery is used. Capacity is defined in terms of the number of hours or days of service the battery will provide when fully charged. In Saudi Arabia, the current energy storage at the Solar Village is furnished with 1100 KWH lead acid batteries that designed to provide electrical load power during night hours and inclement weather (Saudi Arabian National Centre for Science and Technology, Undated).

Figure (8.1) shows the annual distribution of incoming solar radiation over Saudi Arabia. As shown in Fig (8.1), the highest intensity of solar radiation comes in the western and southwestern areas of Saudi Arabia. This map also indicates that there is a gradual increase in the total amount of incoming solar radiation from the north to the southwest, as a result of the increase in both sunshine duration and insolation index (the portion of insolation available from the sun's declination that is actually received at the earth's surface). For example, at Station 1 (Najran) in the far south, the intensity of solar radiation reaches 419 Cal/cm^{-2}/d, compared with only 354 Cal/cm^{-2}/d at Station 16 (Quryyat) in the far north. The increase in the intensity of solar radiation at Station 1 (Najran) can be attributed to an increase in both sunshine duration and insolation index at this station which reaches 9.2 hours and 91% respectively compared with 8.6 hours and 81% respectively recorded at station 16 (Qurayyat).

However, in the southeast part of Saudi Arabia, there is a noticeable decrease in the intensity of incoming solar radiation caused by the frequent occurrence of dust storms generated in the Ar Rub Al-Khali desert. For example at Station 4 (Sulyyel) the intensity of incoming solar radiation declines to an average of 295 Cal/cm^{-2}/d due to the effect of dust storms in this area which occur on 3.8 days a month on average.

At Station 2 (Abha), there is an increase in the intensity of incoming solar radiation due to its high altitude. Incoming solar radiation reaches an average of 464 Cal/cm^{-2}/d at this station compared with only 389 Cal/cm^{-2}/d at Station 3 (Bishah). The increase in the intensity of incoming solar radiation at Station 2 (Abha) is attributed mainly to its high altitude, 2200 m a. s. l. compared with only 1163 m for Station 3 (Bishah).

Fig (8.1) Annual Distribution of Incoming Solar Radiation in Saudi Arabia



Finally, at station (12), Dhahran, the intensity of incoming solar radiation tends to decrease due to the effect of humidity. The intensity of solar radiation reaches 353 Cal/cm^{-2}/d compared with 488 Cal/cm^{-2}/d at station (10) Al-Ahsa as a result of the high level of specific humidity at station (12) Dhahran, 14.60 gm/m-3 compared with 10.50 gm/m-3 at station (10) Al-Ahsa.

Therefore, Saudi Arabia can be divided with respect to the intensity of solar radiation to the following regions :

1. Very high intensity regions. These include the western and southwestern parts due to the high values of solar radiation at these areas.

2. High intensity regions which include most of the central part of the country, as shown in fig. (8.1).

3. Low intensity regions. These include the northern part, the southeastern part, and the eastern coast of Saudi Arabia as a result of the persistent dust storms at the first two parts, and to the high humidity at the third part.

However, there is some slight variations in the intensity of solar radiation at these regions related to the seasonal changes, particularly during autumn in the central region when intensity of solar radiation decreases as a result of the decrease in both sunshine duration and insolation index.

8.1.2 The Altitude of the Location

The altitude of the site is an important factor influencing the intensity of incoming solar radiation received at the earth's surface. The higher the altitude of the site, the greater the intensity of solar radiation.

The distribution of solar radiation in Saudi Arabia confirms this pattern. As one gets higher, solar radiation tends to increase because there is less atmosphere to absorb, scatter and reflect solar radiation. In the southwestern part of Saudi Arabia, a mountain area, solar radiation is higher compared with the other parts of the country. For example at Station 2 (Abha) which locates at an altitude of 2200 m a. s. l., the intensity of solar radiation is higher as compared with Station 3 (Bishah), at an altitude of 1163 m. However, the variation of solar radiation at the mountainous areas, particularly in the southwestern part of Saudi Arabia, in significantaly affected by aspects which reflect large proportion of solar radiation, especially in winter.

Moreover, in Saudi Arabia increasing altitude together with irregular topography increases the possibility of cloud formation, as shown in plate (8.1). Thus, large proportions of solar radiation are attenuated through absorption, reflection, and scattering processes. Therefore, the optimum location of solar energy plants should be chosen in a flat area at altitude below the condensation level where the possibility of cloud formation is low. Persistent cloud cover which extends over a significant area is an important barrier limiting the optimum location of solar energy plants.

Plate (8.1)

Cloud cover is formed at the condensation level. Therefore, a solar energy plant should be located below this level.

8.1.3 Dust Storms

Dust storms play a crucial factor that should be considered when selecting the appropriate site for solar energy plants. As the occurrence of dust storms increase, the intensity of solar radiation decreases due to reflection, scattering and absorption processes. The Ar' Rub Al-Khali desert in the southeast and the Nafud desert in the north of the country are the main generating areas of dust storms in Saudi Arabia. Therefore, the site of solar energy plant should be located away from such areas where the potential of dust storms occurrence is high. In certain areas of the Kingdom dust storms may reach an average of 13 days a month, as shown in Figure (8.2). This significantly reduces the intensity of solar radiation.

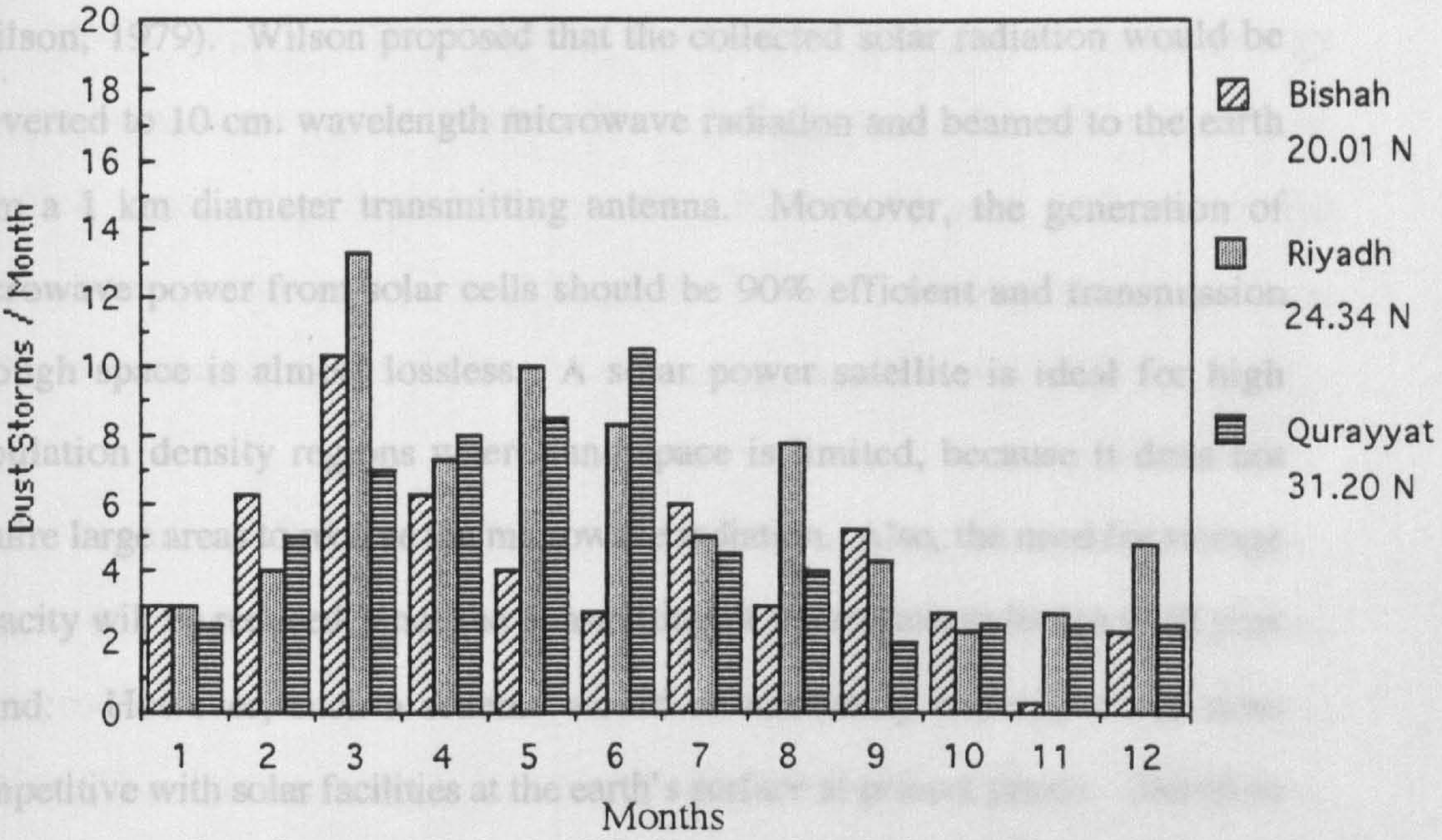
According to Holbeck and Ireland (1979), dust storms have an impact on solar energy plants in two ways; first, particle impact alone may damage the solar energy equipment, particularly the solar panels; secondly, dust or sand particles carried by storms may be capable of etching the solar energy panels' surfaces thus reducing the collection capability of these panels. However, these two impacts of dust storms are very similar. The most important impact of dust storms is the accumulation of dust on the surfaces of the solar panels which significantally reduces the efficiency of their energy production, as shwon in plate (8.2). Therefore, solar energy plants should be protected from the effects of dust storms by topography or by vegetation shields. These do not prevent incoming solar radiation reaching the solar panels but help to minimise dust impact. Extreme meteorological events, such as high winds, long periods of rainfall, will adversely affect the physical and economic bases of solar energy plant facilities, especially the solar panels. Therefore, an appropriate site is one where the occurrence of such extreme meteorological events is low. More importantly, equipment must be designed to withstand such events, within acceptable, calculated levels of risk.

Plate (8.2)

Dust storms significantly reduce the efficiency of solar panels in Saudi Arabia

Fig (8.2)

Monthly Averages of Dust Storms at Certain Cities in Saudi Arabia



Data Source: Ministry of Defense and Aviation (1980-1989).

A future way of overcoming the problem of solar radiation attenuation by factors such as cloud, dust or atmospheric gases, is through solar power satellites. These would transmit solar radiation to any specific station on the earth as microwave radiation. One of the promising solar power satellite projects is proposed by P.E. Glasery (in Wilson, 1979). This involves fixing a large array of cells in geostationary orbit, 22, 300 miles above the earth. These will be exposed to the sun all year, apart from brief periods of eclipse at the equinoxes (Wilson, 1979). Wilson proposed that the collected solar radiation would be converted to 10 cm. wavelength microwave radiation and beamed to the earth from a 1 km diameter transmitting antenna. Moreover, the generation of microwave power from solar cells should be 90% efficient and transmission through space is almost lossless. A solar power satellite is ideal for high population density regions where land space is limited, because it does not require large areas to receive the microwave radiation. Also, the need for storage capacity will be reduced, since the transmitting of microwave radiation is all year round. However, such a scheme would be extremely expensive and non-competitive with solar facilities at the earth's surface at present prices. Therefore whilst such a scheme could be used in any country, the inherent national advantages of Saudi Arabia, and the low use of installations promotes more conventional schemes and approaches.

8.2 The Land Requirements of Solar Energy Plants

One of the major problems associating with solar energy development is whether the space demand for solar energy production on a large scale could be met without causing major spatial demand problems. This problem stems from the fact that solar energy plants require about 10 times the area of a conventional power plant, because of the deployment of a large number of solar radiation collectors (Palz, 1978). This problem is much worse in areas of high population where the land is limited and thus more expensive. For example, the United Kingdom would need to devote about 10% of its total land area to solar systems, assuming a conversion efficiency of 10% (Palz, 1978). However, this problem could be reduced by using the land simultaneously for other activities such as arable farming, forestry, and livestock.

With respect to Saudi Arabia, the land requirement for solar energy application is not a great problem due to its large area (2.2 million Km^2) of which desert areas represent more than 50% of the total. Moreover, the population density is very low (3.11 per km^2) and 40 per cent of the population live in rural areas, the ideal place for solar energy applications.

Singer and Roberts (1976), estimated the land requirements for various types of energy sources needed to produce 50 per cent of the projected increase in production of electrical energy in the United States from 1970 to the year 2000. This was estimated to be $5.302 * 10^9$ MWh. As shown in Fig. (8.3), the total land required for solar energy to produce this projected increase in electricity was estimated to be 12,700 square miles. For relatively small-scale electricity production (i.e. 1000 MWh), the estimated value of the area needed for solar plant ranges from 8.3 to 20.8 square miles. This variation results from the spacing of the heliostats (reflectors) and total storage capacity (Singer and Roberts, 1976). Lower insolation intensity areas require more collectors and larger areas of land to produce sufficient quantities of electricity for various uses.

The collecting area of solar radiation is a main determining factor in solar energy production. Reddy (1987), noticed that most solar energy systems follow the law of diminishing returns which implies that increasing the size of the solar collector area results in a less than proportional increase in the yearly total of solar radiation. He also found that the variation of the annual incident of solar radiation is a major problem in determining the size of collecting area, due to the high cost of solar devices. The land required for collecting solar radiation can be reduced by using on-site systems. These can range from small systems mounted on residential roofs to much larger devices on larger industrial and commercial sites. The on-site applications have some savings associated with use of roofs for system support, but inapproppriate orientation would reduce this advantage, in addition to its relatively higher costs resulting from small scale application (Ahmad, 1981).

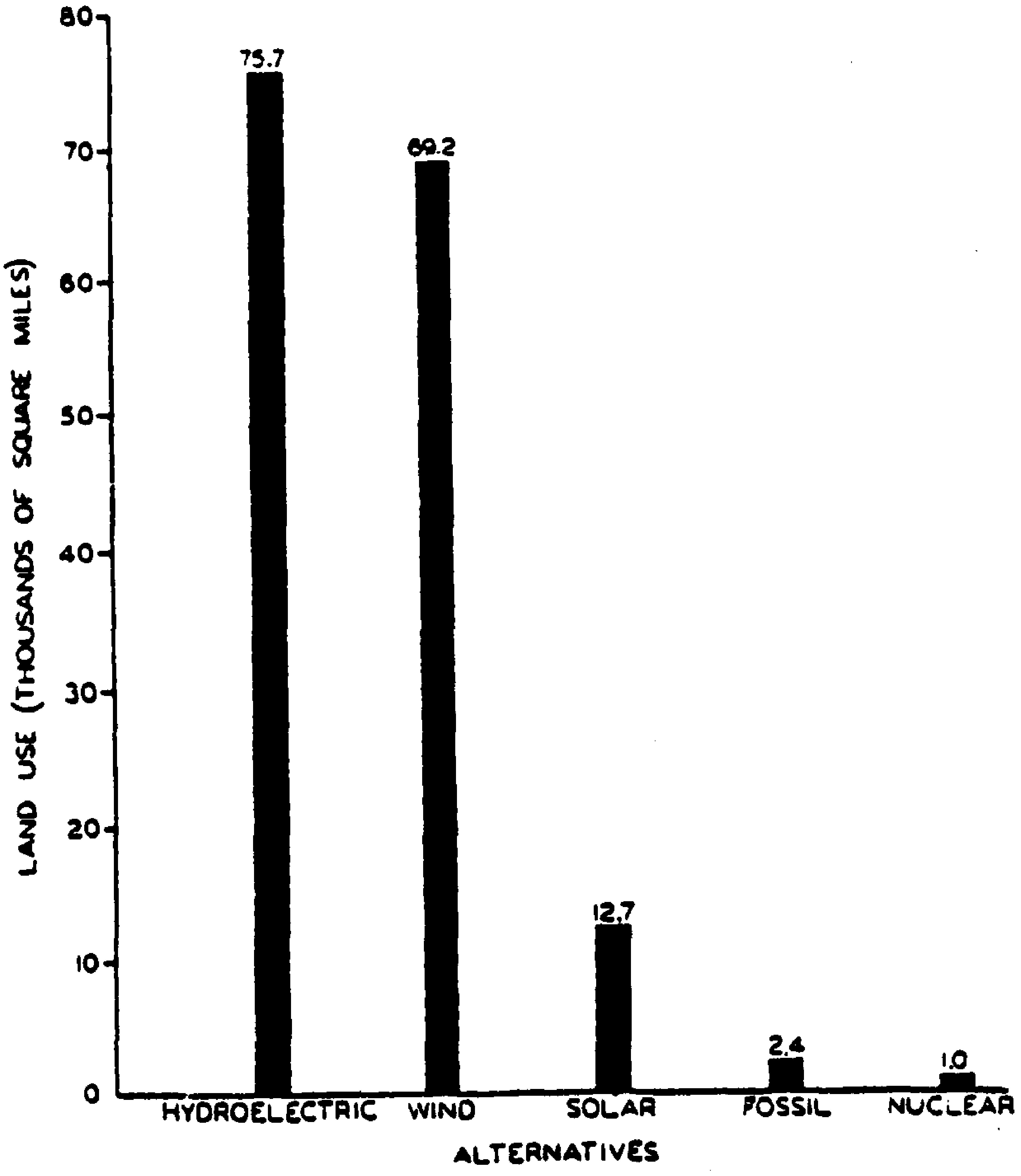


Fig. (8.3)

Land Required to Produce 50% of Projected Increase in Electrical Energy (1970-2000).

Source : Singer and Roberts, 1976.

Although a centralised solar system appear to be cheaper initially, the small stand- alone system for each house is to be preferred especially in areas with a high population density. According to Starr (1985), there are several reasons for this. First, they can be roof mounted, and thus need not take up valuable land near the village. Second, they do not require a distribution system to take energy to each house, an expensive item if the houses are widely separated. Third, no metering system is needed, thereby avoiding the associated administrative costs for meter reading and bill computations. Fourth, with no distribution system, the problem associated with unauthorised connections and theft of electricity are avoided. Finally, a centralised system may soon prove to be unreliable, due to problems resulting from unauthorised connections. Failure of a centralised system affects all users, whereas failure of a household system affects only one consumer.

The effect of shading caused by the relative position of the solar energy collectors with respect to each other must be taken into account. According to Elsayed and Al-Turki (1991), shading can be eliminated when collectors are widely spaced, but this is at the expense of the ground area. They said that the designer in many cases is faced by the fact that a limited area must be utilized for the installation of a number of solar collectors. By doing so, the spacing between collectors could be reduced to a limit at which shading causes a sizeable reduction in the amount of the collected solar energy.

To achieve maximum efficiency, each collector in a field should be orientated to collect the optimum amount of solar radiation. Thus, shading from the collectors themselves and from surrounding terrain should be minimized. The south facing slopes are much more useful than north facing slopes. On flat terrain, shading can be overcome by spacing the collectors, though enough flat terrain may not always be available to do this to best effect (Holbeck and Ireland, 1979).

The most appropriate location of a solar energy plant is on a top of a flat hill. This will reduce the amount of solar radiation attenuated in the earth's atmosphere. If there are no available adjacent hills, then the height of structures on nearby land is very important. These should not interrupt incoming solar radiation to the site of proposed solar energy plant. The site should have an uninterrupted view to the south down to an angle of 10 degrees above the horizon, extending from the local southeast to southwest direction (Holbeck and Ireland, 1979).

8.3 The Production Cost of Solar Energy

The cost of solar energy system is high compared with conventional systems, except at remote villages, where solar systems are competitive due to the high cost of fuel transportation and maintenance for conventional systems. The high cost of the solar systems can be attributed to the high prices of solar cells, though there has been a remarkable decrease in their prices in the last two decades. Further, sharp decrease in the price of solar cells is expected when they are produced in large-scale quantities and when there are widespread applications of solar systems.

According to Twidell (1988), renewable energy resources in general and solar energy in particular, can only be judged 'economic' when six conditions are met. These are; their capital costs decrease; a lifetime operation of at least 20 years is proven; accountancy procedures such as ' 2 year payback ' and '

Treasury 5% rate of return ' are discounted; environmental and social benefits are credited in explicit monetary terms for each renewable energy installation; self sufficiency sustainability, diversity and local autonomy are all credited as benefits; and unfair barriers, such as local taxation rates, are removed.

Cost reduction has been given especially high priority. According to IEA (1987), three basic strategies have been employed to address this issue. The first is the development since the mid-fifties of inexpensive, automated methods of manufacturing crystalline silicon cells, the primary material technology. The second is to develop alternative cell materials that are cheaper to produce. The third approach is to design systems that concentrate sunlight on cells, thereby lowering the unit cost of the electricity produced even when using more expensive cell materials.

Energy from the first photovoltaic systems was about one hundred times more expensive than that generated by conventional energy sources. Today, such energy is only five to ten times as expensive, and costs continue to decrease (IEA, 1987). In addition, the efficiency of cells has steadily improved, and new materials and fabrication processes are being developed which are believed to have great promise with respect to cost and performance.

From 1974 to 1984, the capital cost of solar cells fell from approximately $ US 100 per peak watt of generating capacity to about $ 4 per peak watt. This is competitive with electricity from diesel generators in remote areas where fuel supply and maintenance costs may be large (Twidell and Weir, 1986).

Research and development activities, particularly in the industrialized countries which have directed their efforts towards photovoltaic devices, have increased dramatically. Further, manufacturers of these devices realise that the production volumes needed to continue the trend of declining manufacturing cost must result from an increased demand. The price of photovoltaic devices must go down in order to stimulate demand.

To achieve the cost reduction for solar powered generation, cells production will have to be automated, and produced on a large-scale, continuous basis. Some experts think that a minimum annual plant production of 100 MW capacity would be required to produce a manufacturing cost which would allow competition with conventional electricity generation costs (IEA, 1987). The cost of solar powered generation is expected to stay somewhat more expensive at least for the coming decade. To further reduce the cost of solar energy production, particularly for large population centres, solar energy stations should be distributed around the population centre to reduce the cost of distribution systems and maintenance. Wilson (1979), in discussing this point, said that it is not possible to say if solar power stations on the scale of current conventional stations will be realistic, and felt that solar power is more suited to a distributed network of generators than to a central power station and grid system.

Significant cost reductions can be expected when a photovoltaic power system is integrated in a house. In this case no extra area or site preparation is necessary, the support structures of the building itself can be used and electrical distribution losses do not occur, because energy is produced and consumed at the same location (Schmid, 1984).

The cost of solar powered generation is expected to decline over time compared with the other conventional fuels. Figure (8.4) clearly shows that all the fossil fuel plants have levelized costs (real) that rise over time because these are scarce resources in decreasing supply, while the real cost of solar powered generation will fall over time and will eventually be the lowest cost alternative in the long term (Wright, 1985).

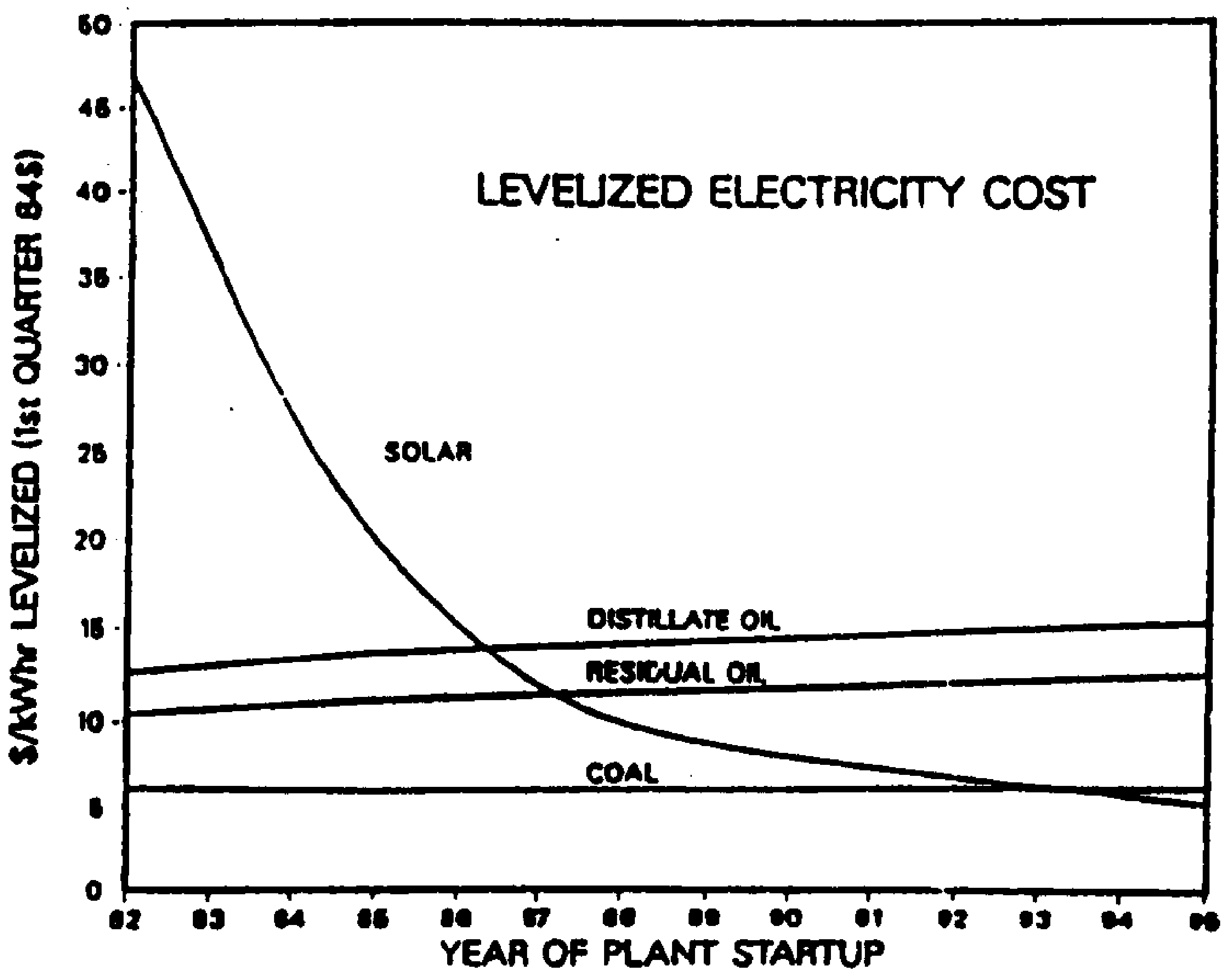


Fig. (8.4)

The levelized Electricity Cost for the Various Power Generation Technologies.

Source : Wright, 1985.

Since there is a relatively small variation in the intensity of incoming solar radiation in each specific region, except in the mountain areas where there is a great variation due to differences in altitude of sites, transmission cost of electricity is a key factor in determining the ultimate site of solar energy plants. In order to minimise the cost of electricity transmission, solar energy plants should be located near population centres, particularly remoter villages that are not connected to the national electricity network.

Electricity consumption in Saudi Arabia has sharply increased since 1975, as shown in Fig. (8.5). The total electricity consumption in 1989 reached 55.2 million MW/hour compared with 3.8 million MW/hour in 1975 (Ministry of Industry and Electricity, undated). This increase is attributed to an increase in population, the number of villages and settlements connected to the electricity network, particularly in the southwestern part of the country and to the greater industrial demand for electricity. According to the Ministry of Industry and Electricity, (undated), industrial consumption of electricity has increased from 2.17 million MW/hour in 1975 to 15.52 million MW/hour in 1989, as shown in Fig. (8.5). This now represents 28 per cent of the total electricity consumption in Saudi Arabia. However, if solar powered generation is used in the industrial sector, not only will total fossil fuel powered generation be reduced, but more importantly, air pollution levels, related to industrial and power plant emissions, will be noticeably decreased.

The number of cities, villages and settlements connected to the electricity network in Saudi Arabia was 5148 at the end of 1989. Most of these, particularly villages, are concentrating in the southwestern part of the country (Ministry of Industry and Electricity, undated). The cost of connecting electricity grids to these mountain villages is extremely high and require regular maintenance and fuel supplies. Solar powered generation is already competitive with fossil fuels at these isolated villages.

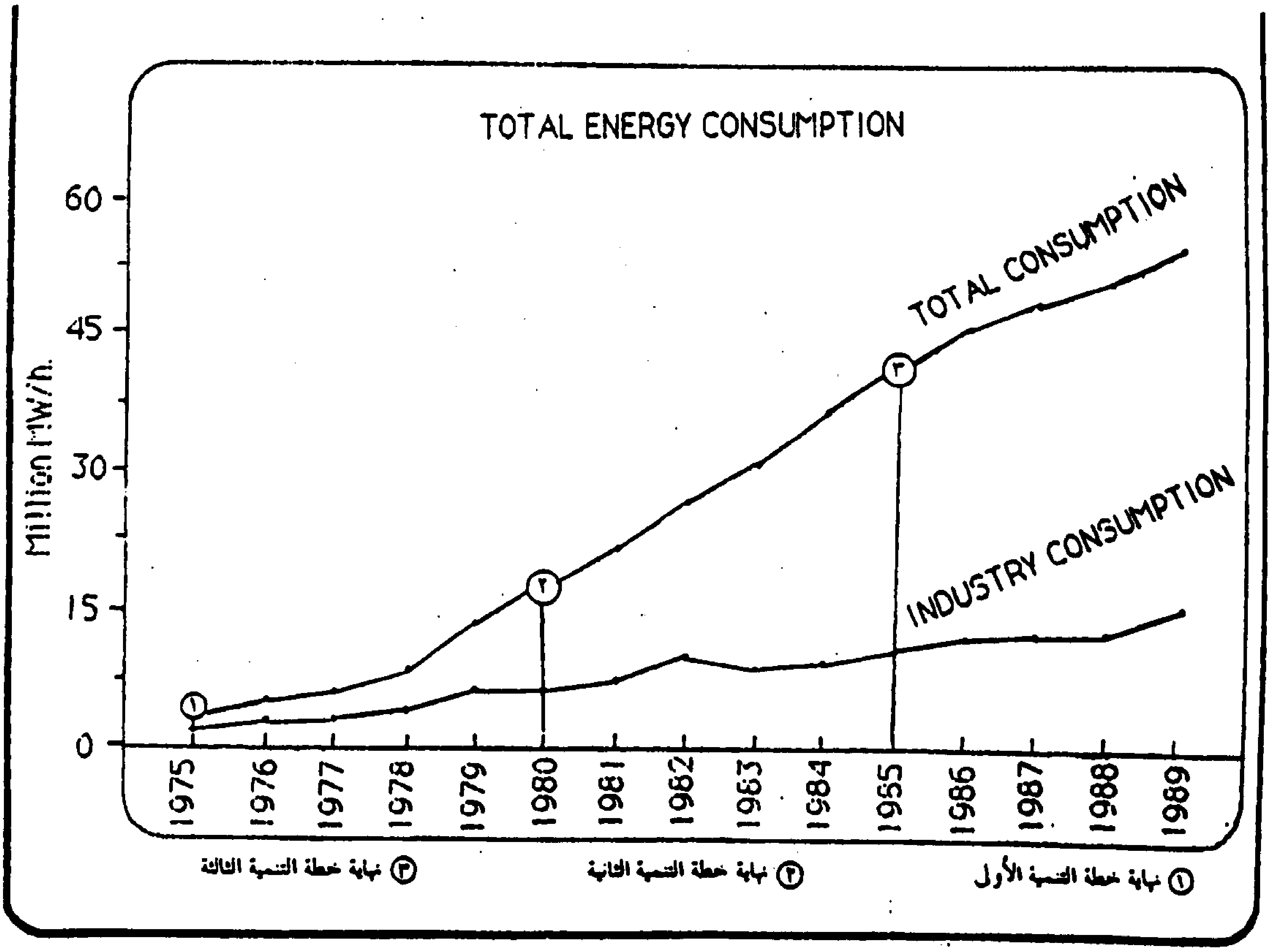


Fig. (8.5)

Total Electrical energy consumption in Saudi Arabia

Source : Ministry of Industry and Electricity, Undated.

The total fuel consumed in the electricity generation plants in Saudi Arabia reached 3.53 million metric tonnes of diesel, 5.33 million metric tonnes of crude oil, and 5.67 million cubic meters of natural gas in 1989, as shown in table (8.1). The total fuel consumption for electricity generation in the southwestern region alone in 1989 was 1.10 million metric tonnes of crude oil, which represents 12.4 per cent of the total fuel consumption for electricity generation. If solar powered generation could be widely applied in the southwestern region the most favourable for such development, then consumption of fossil fuels will be significantly reduced.

Table (8.1)
Fuel Consumption for Electricity Generators in Saudi Arabia

Type Year	Diesel (metric tonnes)	Crude oil (metric tonnes)	Natural Gas (million cubic metres)
1980	2080188	1245040	795
1981	2397224	1945197	4948
1982	3049794	2195127	5224
1983	3040252	3298827	4755
1984	3398311	3389790	4313
1985	3401872	3926926	4145
1986	3454788	4148422	4628
1987	3273478	5085517	4478
1988	3317844	5258372	4685
1989	3525907	5327374	5669

Source : Ministry of Industry and Electricity, Undated.

Amongst the several alternative technologies for solar energy conversion, photovoltaic electric systems have some unique and attractive features. Photovoltaic systems convert light falling on a flat semiconductor material to electricity directly, without intermediate stages of conversion to thermal and mechanical energy prior to conversion to electrical energy (Ahmad, 1981). Moreover, photovoltaic components and systems have a potentially longer life and enjoy lower maintenance costs, particularly in hot arid regions such as Saudi Arabia where summer temperature may reach to 49° C. Photovoltaic (PV) systems have characteristics that make them suitable for a variety of applications. Because they produce electricity during daytime, PV systems are well-suited to feeding power into the utility grid to meet daytime peak demand. In addition, storage batteries can be used to enable a system to meet the demand when the sun does not shine (IEA, 1991).

8.4 Population Density

Population density plays a significant role in determining the location of solar energy plants. At low population densities, solar energy plants should be located near population centres, thus reducing the cost of electricity transmission by grid. The 16.9 million population of Saudi Arabia is widely distributed in spatially separated communities which make the cost of extension of the electricity grid extremely high.

Due to its relatively large area (2,250,000 km^2), the population density of Saudi Arabia is low, only 3/km^2. This low value is partly attributed to the fact that more than one fourth of the country's area is uninhabited arid deserts. Even taking this into consideration, there is a great variation in the population density from one part of the country to another. The highest population density is found in Jizan area in the south western part of the country, where the density reaches an average of $23/km^{-2}$ as a result of the agricultural and fishing activities in this area. (Al-Shareef 1987). The second highest population density is at Mekkah, Baha, and Asir areas where the density ranges between $5 - 15/km^{-2}$ due to the location of the Holy Mosque in the first area and to the relatively high average of rainfall in the latter two areas. The third highest population density in the country is found at the capital Riyadh in the central part and at Medinah in the western part of the country where the average density reaches $2 - 5/km^{-2}$. Finally the lowest population density is found in the northern and eastern parts of the country which comprise the arid deserts such as Ar-Rub' Al-Khali and Al-Nafud. The density in these areas is less than $3/km^{-2}$ (Al Shareef, 1987). The pattern of the population density is shown in Figure (8.6).

The population distribution coincides with the distribution of solar radiation intensity over the country, as shown in fig. (8.7). This advantage should reduce the overall cost of solar powered generation plants for Saudi Arabia. Moreover, more than 40 per cent of the population live in rural areas particularly in the southwestern part of the country, which makes it ideal for solar powered generation plants due to the cost advantage of small scale solar energy schemes.

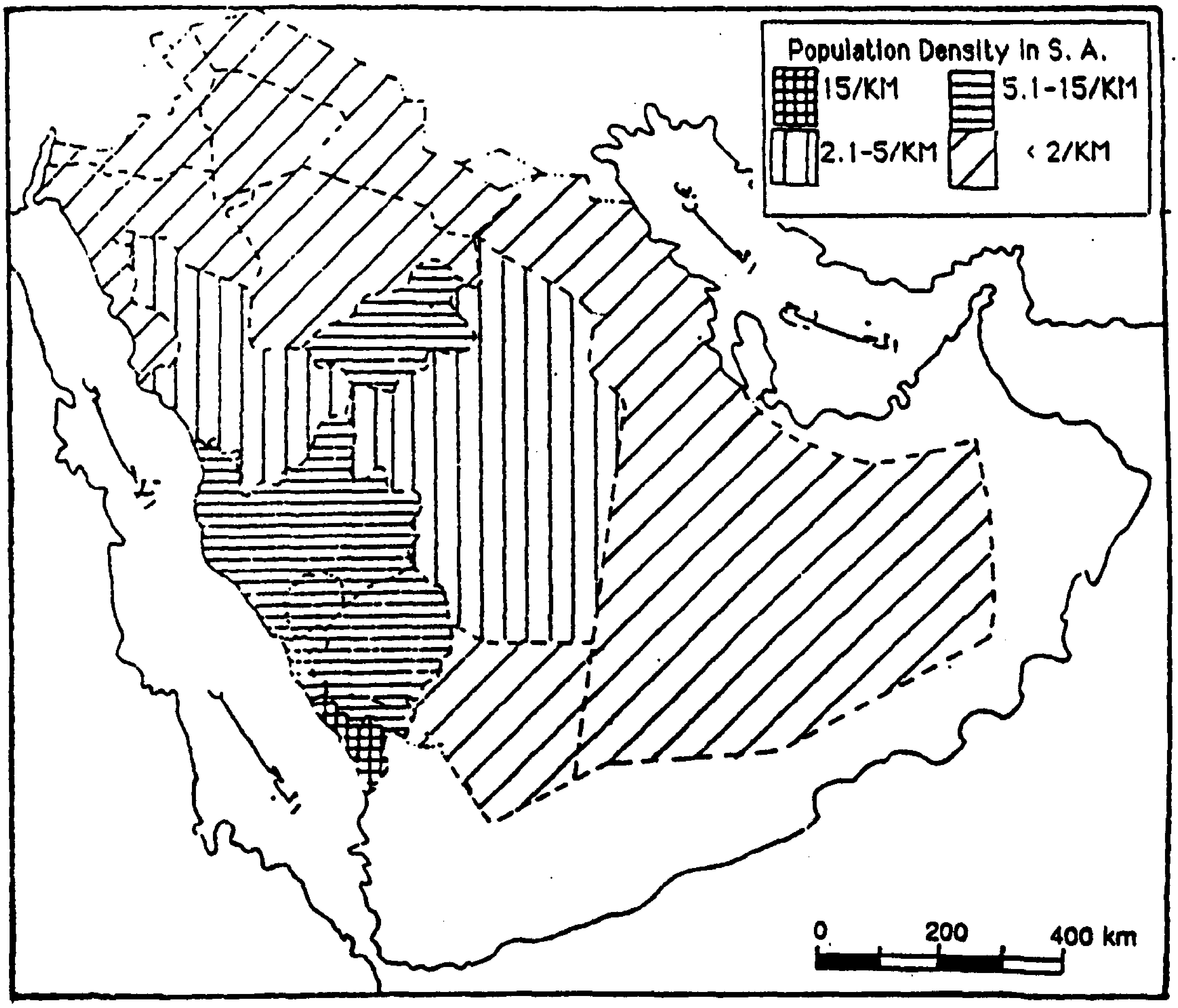
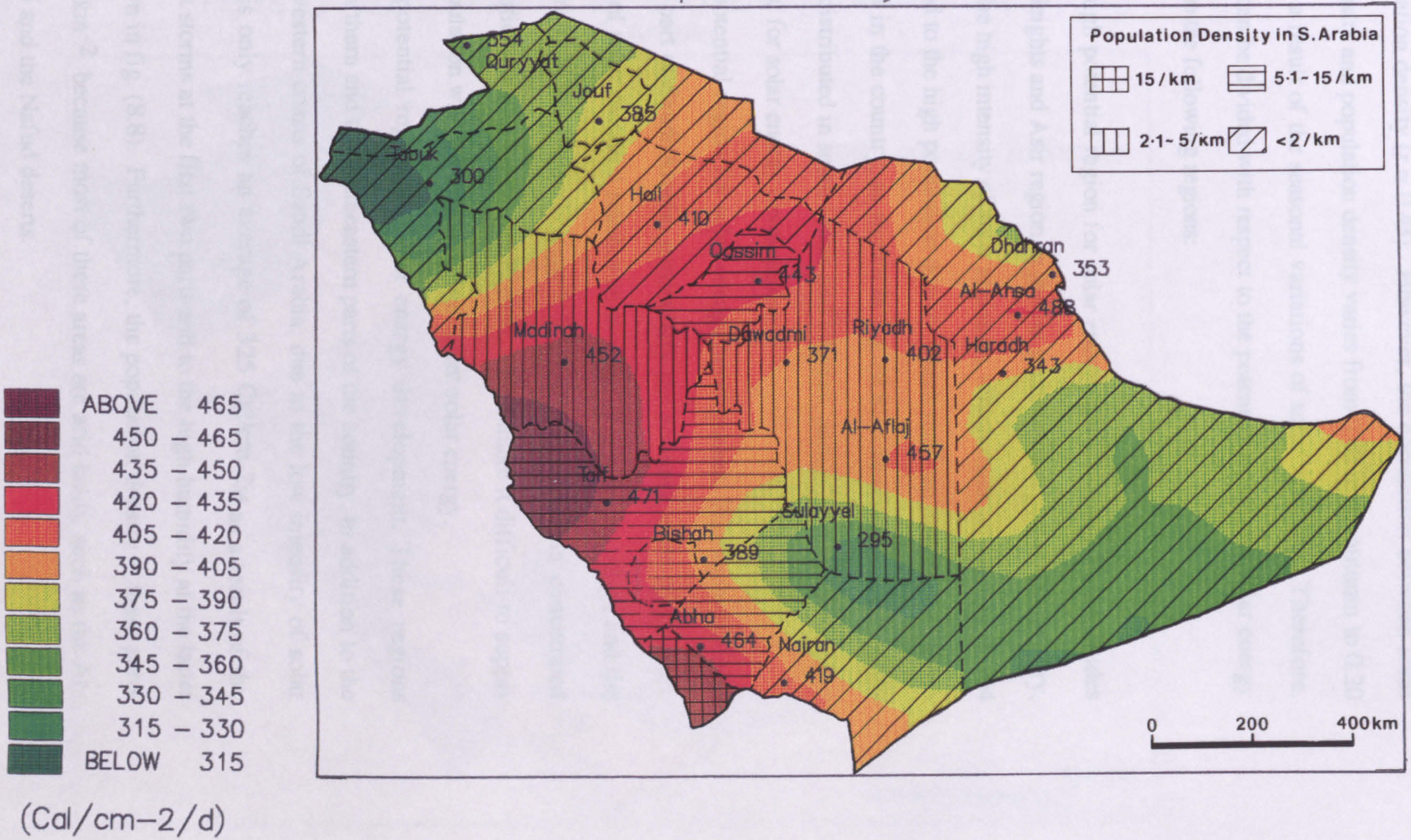


Fig. (8.6)

Population Density in Saudi Arabia.

Source : Al-Shareef, 1987.

Fig (8.7) The Relationship between Solar Radiation Intensity and Population Density in Saudi Arabia



There is a significant relationship between the intensity of solar radiation and the population density (r = 0.43). However, the correlation between solar radiation intensity and population density varies from 0.62 in the autumn to 0.20 in summer as a result of the seasonal variations of solar radiation. Therefore, Saudi Arabia can be divided with respect to the potential regions for solar energy development to the following regions:

1: Very high potential region for solar energy development. This includes the Western Heights and Asir region in the far southwestern part of the country, as a result of the high intensity of solar radiation, which reach an average of 464 Cal/cm-2/d and to the high population density,which reach an average of 15/km-2 , the highest in the country, as shown in fig. (8.8). Moreover, most of the population is distributed in small towns and villages, particularly in Asir region, which are ideal for solar energy development.

2: High potential region for solar energy development. This includes most of the central part of Saudi Arabia, particularly the northren areas of this part. The intensity of solar radiation reaches an average of 403 Cal/cm^{-2}/d , and the population density in this region is 3/km^{-2}. Thus, the population is concetrated in the major cities, such as the capital Riyadh, which make it difficult to supply such large population with their needs of sufficient solar energy.

3: Low potential region for solar energy development. These regions include the northern and the southeastern parts of the country, in addition to the eastern and western coasts of Saudi Arabia, due to the low intensity of solar radiation. This only reaches an average of 325 Cal/cm-2/d as a result of the persistent dust storms at the first two parts and to the high humidity at the latter parts, as shown in fig. (8.8). Furthermore, the population density in these parts is less than 2/km^{-2} because most of these areas are arid lands, such as the Ar-Rub' Al-Khali and the Nafud deserts.

Seasonal variations of incoming solar [illegible] changing the potential regions for solar energy [illegible] population density is relatively stable. For example, [illegible] noticable decrease in the intensity of solar radiation [illegible] southwestern part, as seen in fig. (8.9). This decrease [illegible] decreases the production of solar energy plants , and thus, affects [illegible] this region to be a major location for solar energy plants. Likewise, [illegible] there is an increase in the intensity of incoming solar radi[illegible] northern parts of the country as a result of an increase in [illegible] and insolation index at this time of the year. This increase in [illegible] regions make them very potential for solar energy deve[illegible] particularly around Qassim area where the intensity o[illegible] 540 Cal/cm⁻²/d, as shown in fig. (8.10) .

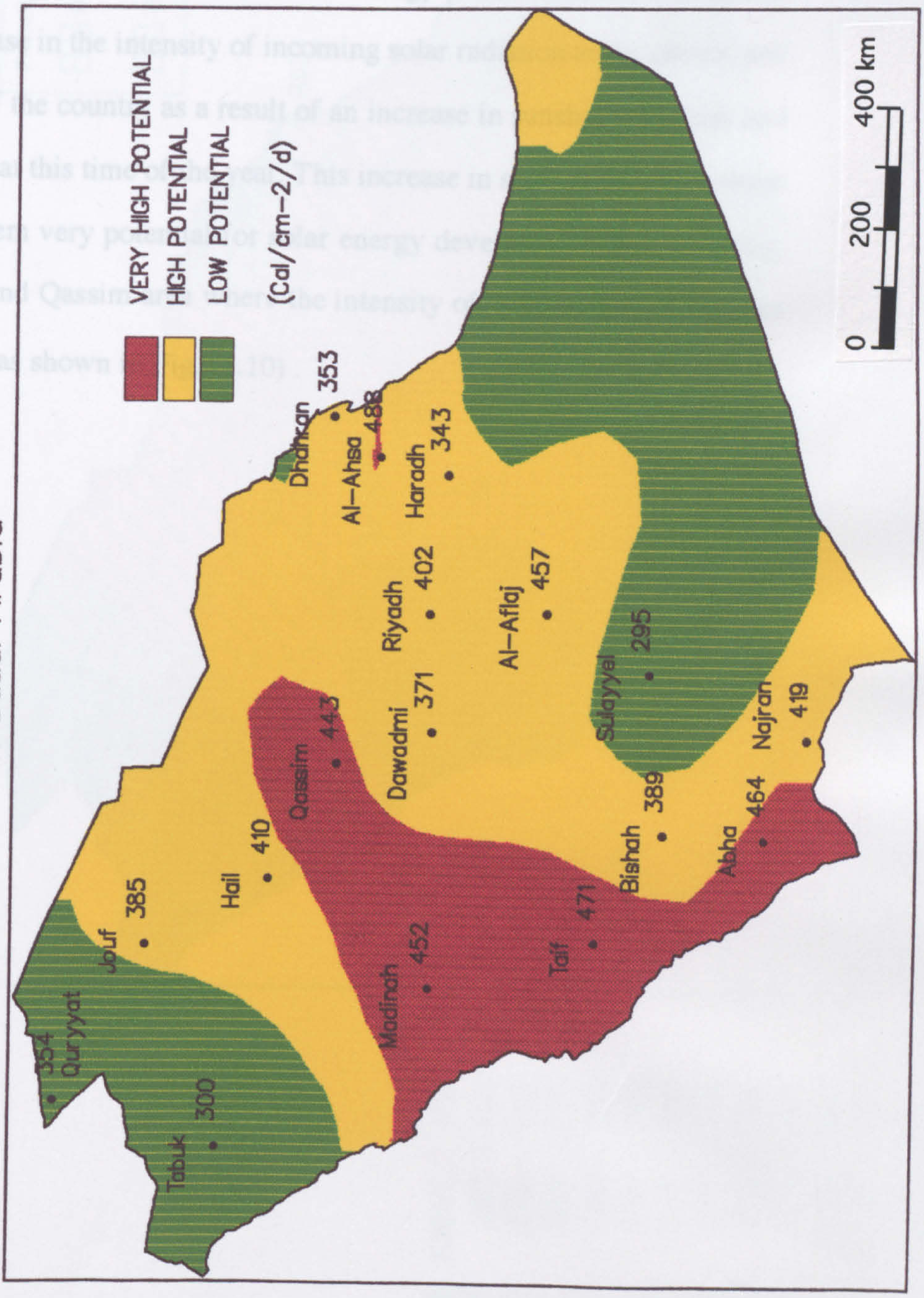


Fig (8.8) Potential Regions for Solar Energy Development in Saudi Arabia

Seasonal variations of incoming solar radiation play a significant role in changing the potential regions for solar energy development, though the population density is relatively stable. For example, in winter, there is a noticable decrease in the intensity of solar radiaiton, particularly at the southwestern part, as seen in fig. (8.9). This decrease in solar radiation decreases the production of solar energy plants , and thus, affects the potential of this region to be a major location for solar energy plants. Likewise, in spring there is an increase in the intensity of incoming solar radiation at the central and northern parts of the country as a result of an increase in sunshine duration and insolation index at this time of the year. This increase in solar radiation in these regions make them very potential for solar energy development during spring, particularly around Qassim area where the intensity of solar radiation reaches 540 Cal/cm^{-2}/d, as shown in Fig. (8.10) .

Fig (8.9) The Relationship between Solar Radiation Intensity and Population Density in Saudi Arabia (Winter)

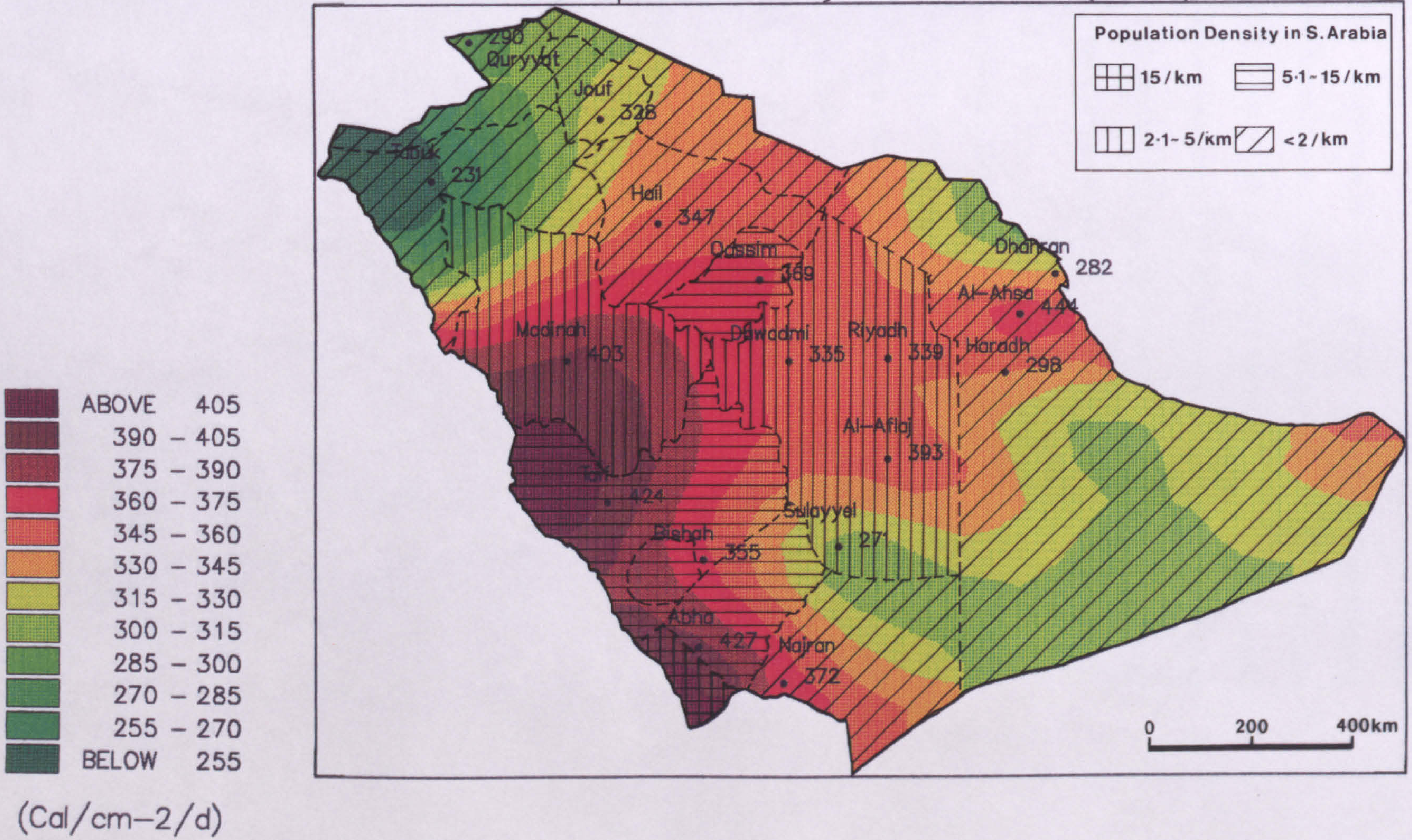
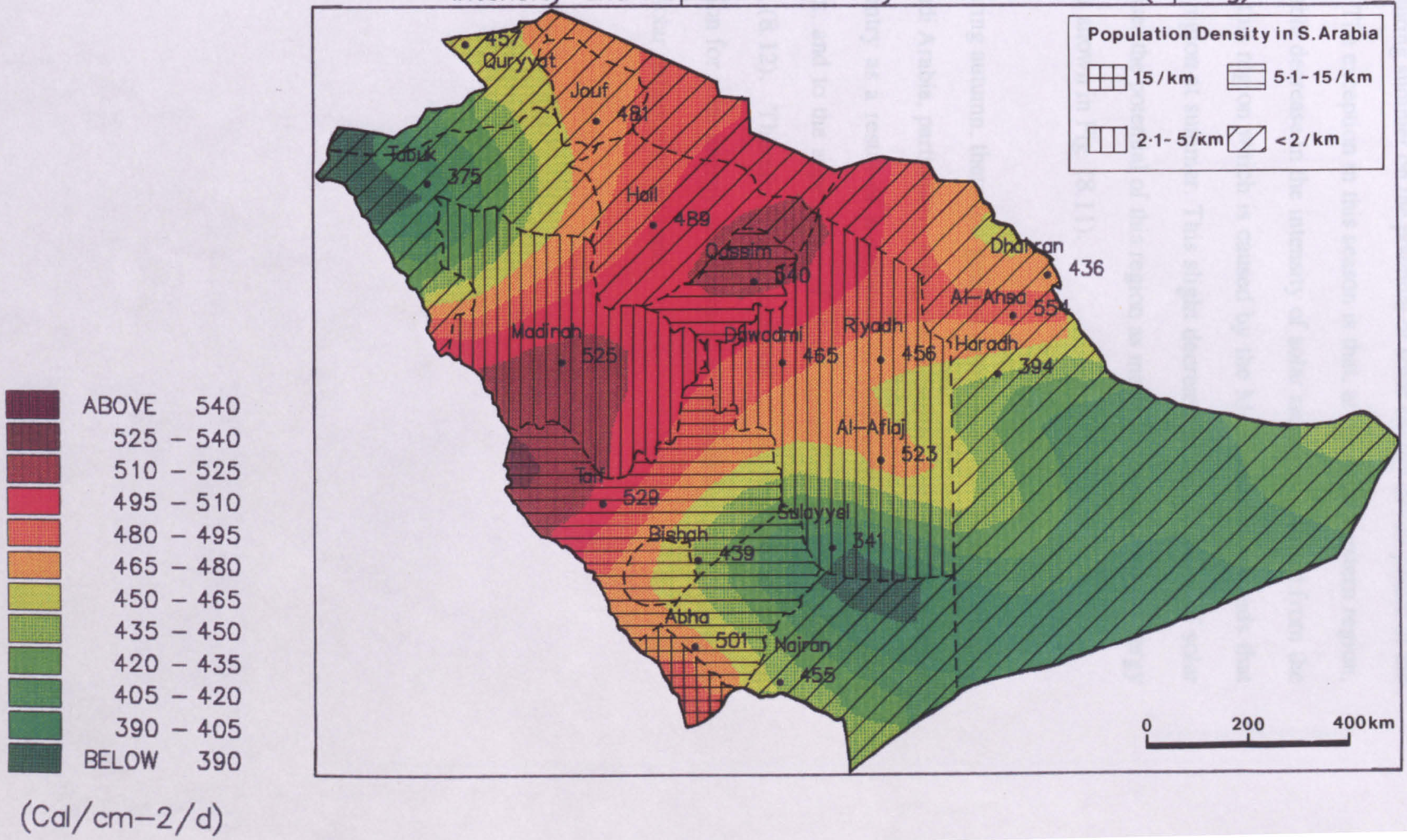


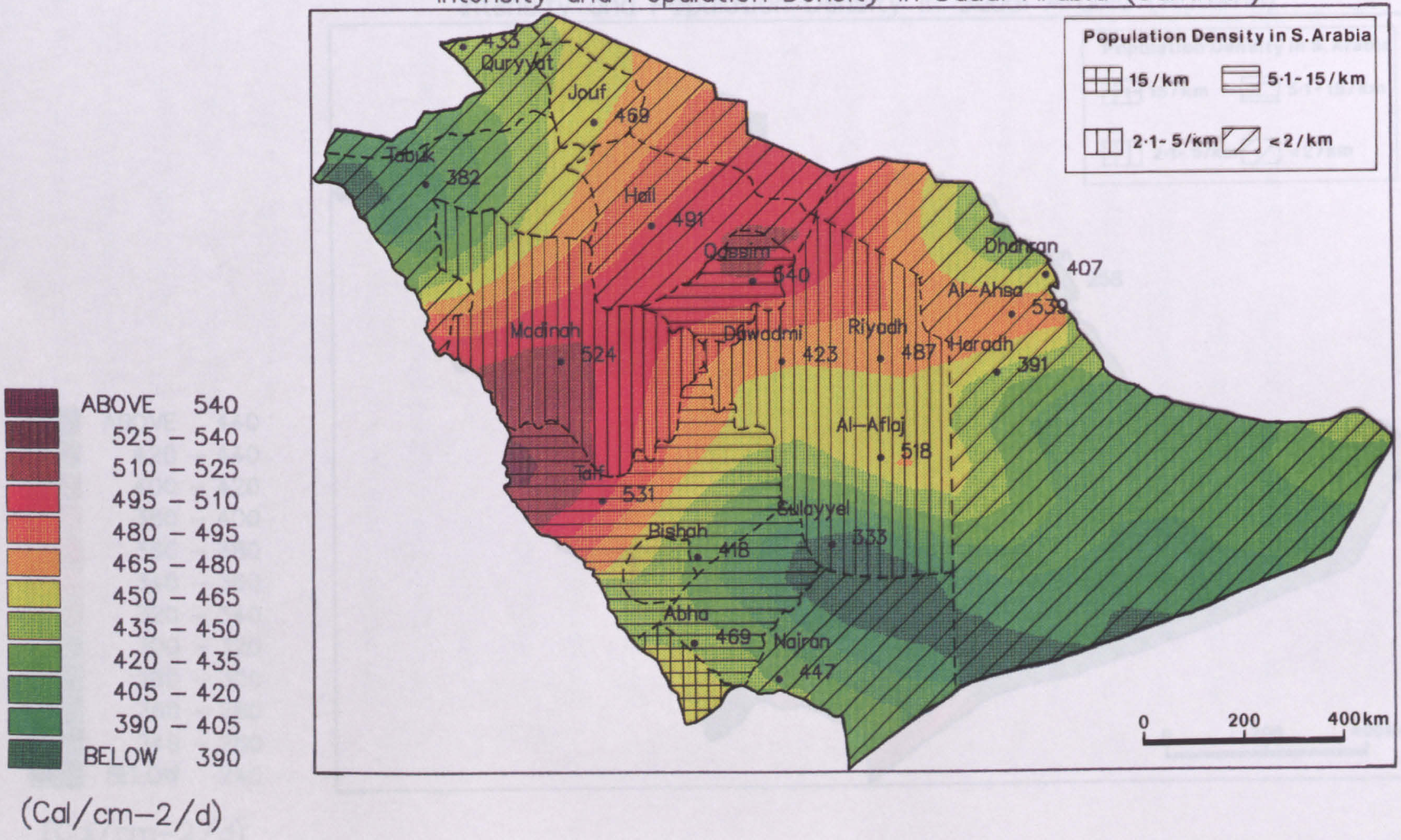
Fig (8.10) The Relationship between Solar Radiation Intensity and Population Density in Saudi Arabia (Spring)



The same thing may be said about the effect of the seasonal variation of solar radiation during summer on the potential of solar energy development at the central region. The exception in this season is that, at the southwestern region, there is a noticable decrease in the intensity of solar radiation resulted from the cloud cover at this region which is caused by the Monsoonal wet winds that blow over this region at summer. This slight decrease in the intensity of solar radiation decreases the potential of this region as major location for solar energy development, as shown in Fig. (8.11).

Finally, during autumn, there is a general decrease in the intensity of solar radiation in Saudi Arabia, particularly along the Westren Heights at the westren part of the country as a result of a decrease in both sunshine duration and insolation index, and to the appearance of cloud cover over these heights, as shown in Fig. (8.12). Therefore, the potential of the western part as an important location for solar energy development is affected by the decreased in the intensity of solar radiation at this time.

Fig (8.11) The Relationship between Solar Radiation Intensity and Population Density in Saudi Arabia (Summer)



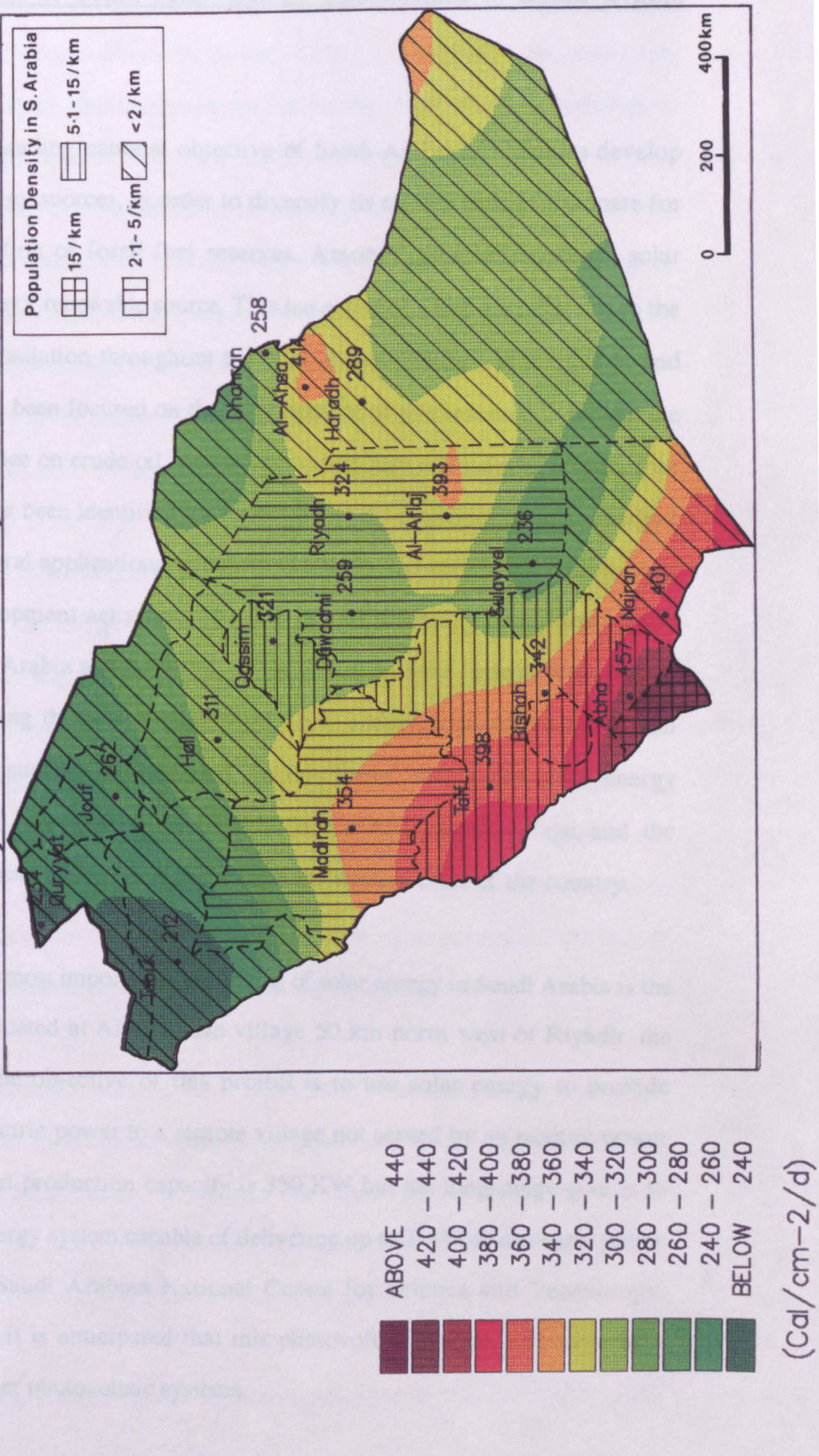


Fig (8.12) The Relationship between Solar Radiation Intensity and Population Density in Saudi Arabia (Autumn)

8.5 Evaluation of Some Solar Energy Applications in Saudi Arabia

A long-standing national objective of Saudi Arabia has been to develop alternative energy suorces, in order to diversify its energy base and prepare for eventual depletion of fossil fuel reserves. Amongst these alternatives, solar energy is the major renewable source. This has received much attention due to the high levels of radiation throughout the year in the country. Many sudies and researches have been focused on the development of this resource to reduce the heavy dependence on crude oil. According to Ministry of Planning (1985), four broad areas have been identified for research and development of solar energy : rural / agricultural applications, urban applications, industrial applications, and resource development activities. These activities are being conducted jointly between Saudi Arabia and both the United States and the Federal Republic of Germany. During the past decade, many solar energy applications have been conducted and successfuly operated. In this thesis, two major solar energy applications will be evaluated, the Solar Village at Al-Uyaynah village, and the solar powered-desalination plant at Yanbu in the western coast of the country.

One of the most important applications of solar energy in Saudi Arabia is the Solar Village located at Al-Uyaynah village 50 km north west of Riyadh, the capital city. The objective of this project is to use solar energy to provide photovaltaic electric power to a remote village not served by an electric power grid. The current production capacity is 350 KW but the long-range goal is to install a solar energy system capable of delivering up to 1MW of electrical power to the village (Saudi Arabian National Centre for Science and Technology, undated). Also it is anticipated that this photovoltaic system will serve as a prototype for other photovoltaic systems.

According to Saudi Arabian National Center for Science and Technology (undated), the location of the Solar Village was chosen as an example to rural and agricultural applications of solar technology with the objective of enhancing the quality of rural life by employing systems that utilize renewable energy resources for domestic, agricultural, and local industrial applications. However, the location of this frist experiment in the central region is not appropriate for two reasons: First, the intensity of solar radiation is not very high in the central region compared with the southwestern region of Saudi Arabia. Second, the energy porduction cost of solar energy at the current location is expected to be high and not competitive with the conventional energy resources due to its approximity to urban areas which could be easily connected to the national electricity network. Therefore, the location of the Solar Village should have been chosen in the southwestern part of the country where the intensity of solar radiation is high and the remoteness of the villages in this part makes convetional supplies of electricity both diffecult and expensive to provide. However, the location of the Solar Village 'within Al-Uyaynah district' is ideal due to its location on top of a flat hill close to the village of Al-Uyaynah, as seen in plates (8.3) and (8.4). This will reduce the amount of solar radiation attenuated by dust storms, water vapour and other atmospheric particles as a result of the clear atmosphere at higher altitudes. Moreover, this location increases the duration of sunshine because of the lack of shading particles such as buildings, trees and higher mountains.

From the economic point of view, the location of this scheme is optimal due to its proximity to Al-Uyaynah village which reduces the cost of the electricity transmission and maintenance. In addition, the labour force, though very small, is drawn from the nearby village with the exception of some high skilled technicians who have to travel from Riyadh, approximately 50km away.

Although the current electricity production (350 kw) is not sufficient to supply the villagers of Al-Uyaynah with all their electricity needs due to the increase in population since 1982, this project provides the village with a large proportion of their electricity. The rest is supplied by diesel powered generation. However, the Solar Village is an experimental project and is not intended to provide this village with all its electricity needs, but as the cost of solar system decreases, it is planned to increase electricity production up to 1MW. Moreover, as the solar system becomes economically competitive with other energy sources, the results of this project are likely to be widely applied throughout the country.

Plate (8.3)

The ideal location of the Solar Village at a top of a mountain near Al-Uyaynah villaga.

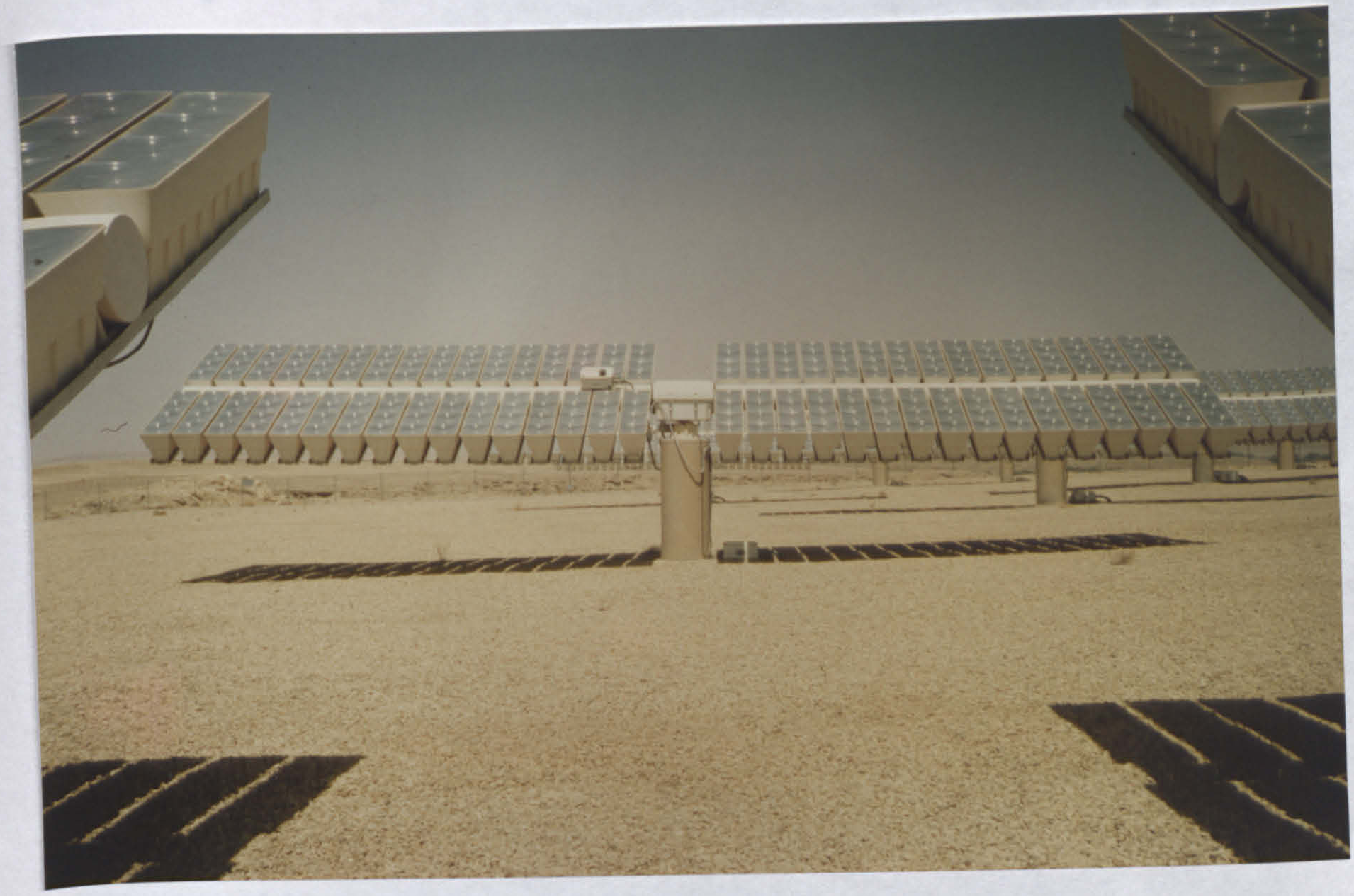


Plate (8.4)

Part of the solar panels at the Solar Village northwest of the capital Riyadh.

A second major solar energy application in Saudi Arabia is the solar-powered desalination plant in Yanbu on the western coast of the country. This pilot plant is designed to produce 200 cubic metres (52,834 gallons) of potable water daily. Moreover, this plant is based on the design of a larger, commercial-sized unit capable of processing sea water to produce 6,000 cubic metres (1.6 million gallons) of potable water daily (SOLERAS, undated). As shown in Figure (8.13), this pilot plant is located at the seashore of the Red Sea, therefore, the effect of humidity is expected to be high, particularly during summer. Thus large amounts of solar radiation are attenuated by water vapour especially at the beginning and end of the day when solar radiation is incident at an oblique angle and passes through a thicker and more absorbent atmosphere. As seen in Chapter Seven, water vapour may decrease the intensity of solar radiation by as much as 40 percent at the coastal areas. A comparison between station 12 (Dhahran) and station 10 (Al-Ahsa) for all months clearly reveals this effect.

Moreover, in coastal areas, solar radiation is further attenuated by the formation of dew drops. This occurs particularly in the early morning and the drop's cover the solar cells with a blanket of water, and hence, reduce the efficiency of the solar energy production. The thickness of dew drops is higher at middle latitudes, where Saudi Arabia is located, than higher latitudes. According to Ahrens (1988), the annual average of dew at middle latitudes yields a blanket of water between 12 and 50mm (0.5 and 2in.) thick. Ideally solar-powered desalination plants should be located at least 10 km from the coast to reduce the effect of humidity in decreasing solar radiation through absorption process. This effect is shown in Figure (8.14) where the intensity of specific humidity at Yanbu, a seaport at the Red Sea, is compared with the intensity of specific humidity at Riyadh, in the central region.

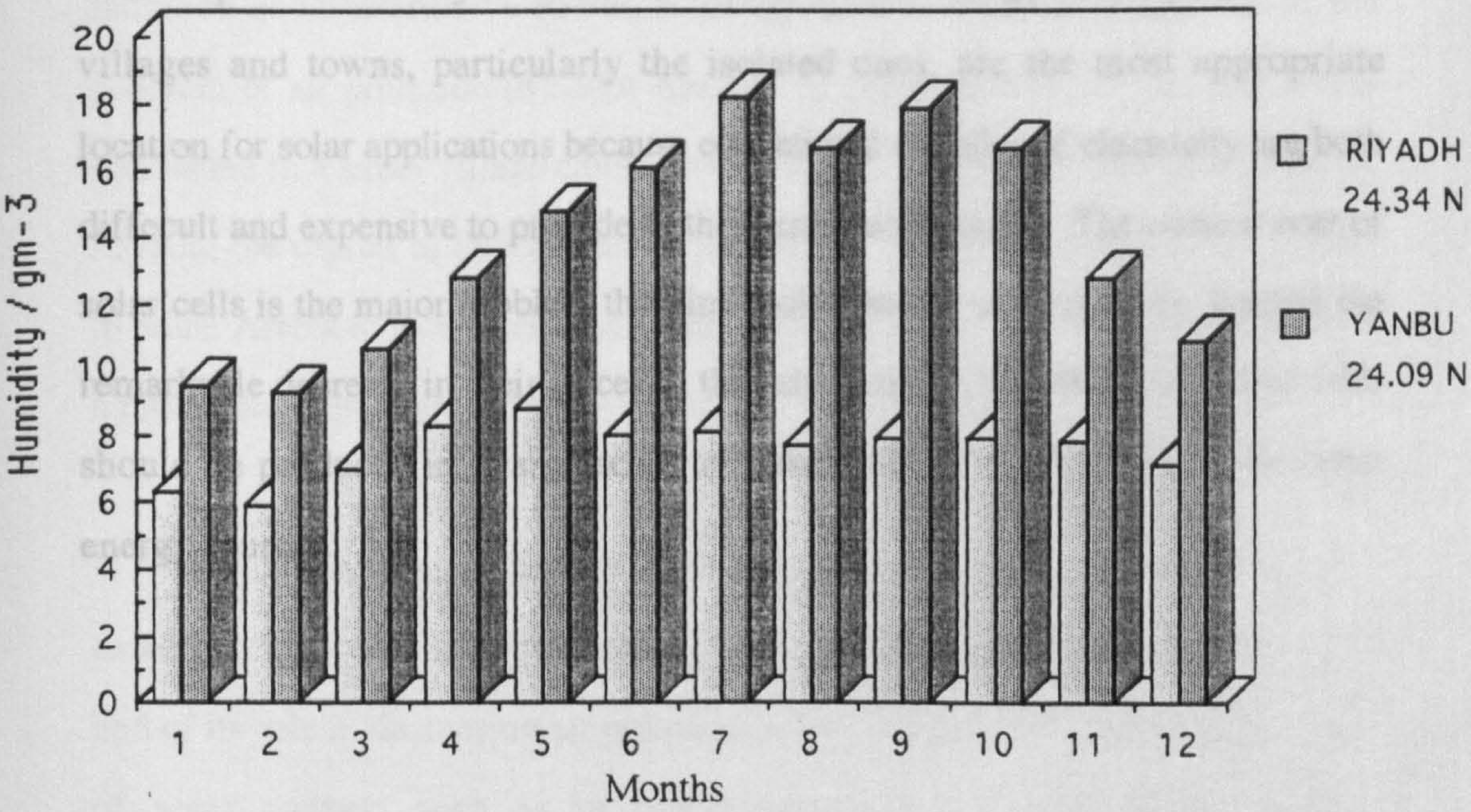
Fig. (8.13)

Location of the Solar Desalination Pilot Plant at Yanbu, on the Western Coast of Saudi Arabia.

Source : SOLERAS, Undated.

Fig (8.14)

The Intensity of Specific Humidity at Certain Cities in Saudi Arabia



Data Source: Ministry of Agriculture and Water (1980-1989).

As conclusion, there are many factors that play a significant role in determining the appropriate location for solar energy plants in Saudi Arabia. Amongst these factors, solar radiation intensity is the most important one. In addition, the site should be located at, relatively, high altitude to decrease the density of atmospheric molecules which attinuate solar radiation. Furthermore, the areas that have persistent cloud cover, high humidity, and dust storms should be avoided.

Population density is a crucial element in solar energy development. Small villages and towns, particularly the isolated ones, are the most appropriate location for solar applications because convetional supplies of electricity are both diffecult and expensive to provide to these isolated villages. The current cost of solar cells is the major problem that limit solar energy development, despite the remarkable decrease in their prices in the last decades. Therefore, the solar cells should be produced in a large scale to make them competitive with the other energy sources.

CHAPTER NINE

HUMAN PERSPECTIVE ON THE POTENTIAL OF SOLAR RADIATION IN SAUDI ARABIA

The people of Saudi Arabia are a very crucial component in the development of solar energy because they are the ultimate users of solar energy. It is very important to find out the opinions and perspectives of people about solar radiation as an alternative source of power, and as a means of addressing the problem of air pollution in Saudi Arabia. A questionnaire for this thesis was conducted in a small village called "Al-Uyaynah", located 50 km north west of Riyadh, the capital of Saudi Arabia. In 1982, Al-Uyaynah was the first village in Saudi Arabia to receive electricity generated by solar plant located at the top of a mountain to the north-east of Al-Uyaynah Village, as seen in Fig. (9.1).

The enhancement of solar energy development depends, to a considerable extent, on people's perception of its potential as a renewable source of energy, and of its role in decreasing air pollution level. This applies to the various uses of solar energy, such as in power stations, industrial plants and in transportation. These are the main sources of air pollution in Saudi Arabia. Therefore, the questionnaire attempted to measure the awareness of the people of Al-Uyaynah Village about the potential of solar energy, in the light of their experience as the first people to receive solar powered generation.

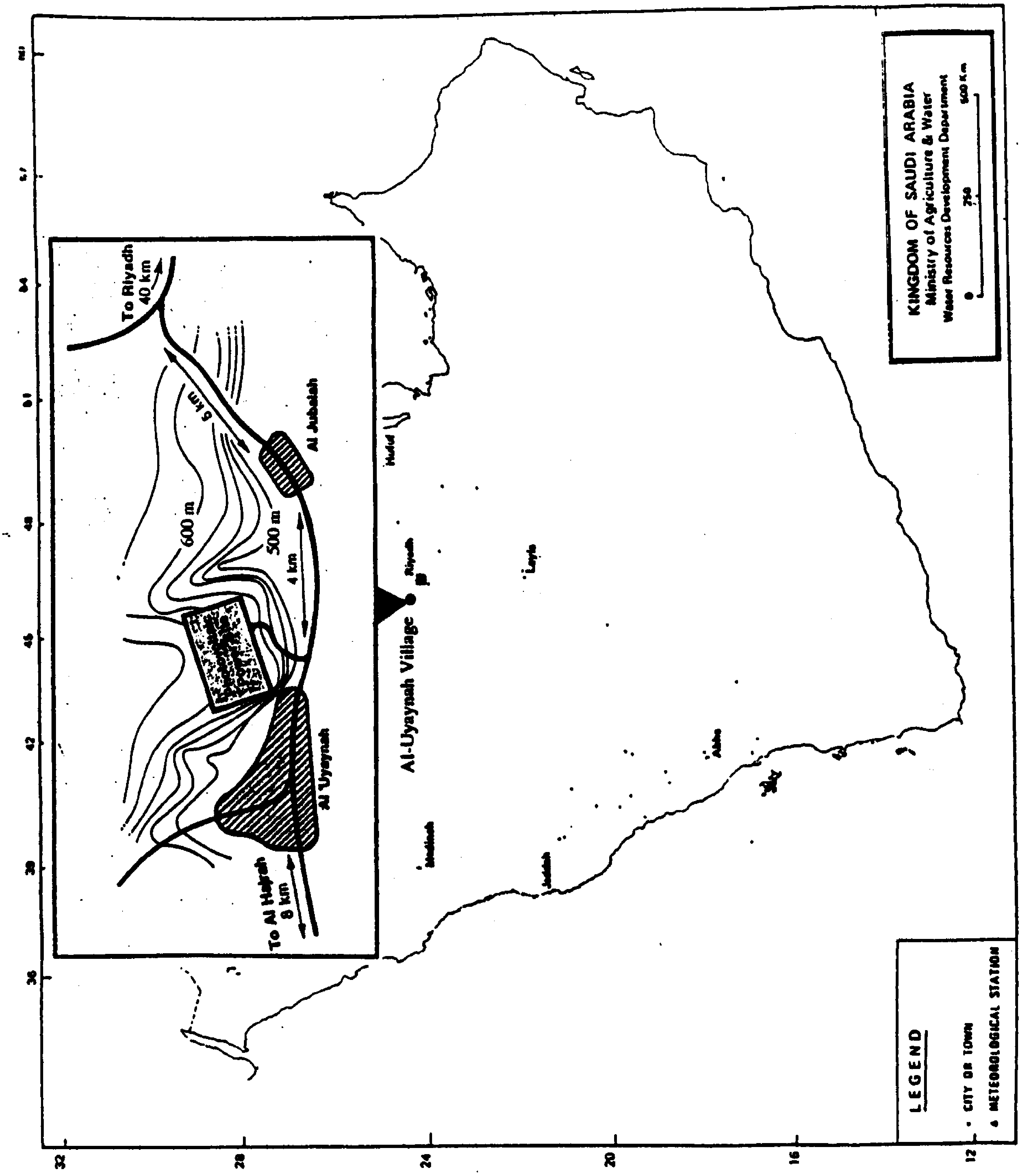


Fig. (9.1)

The location of the Solar Village at Al-Uyaynah Village northwest of Riyadh, the capital of Saudi Arabia.

Sources : Ministry of Agriculture and Water, 1984.

The Saudi Arabian National Centre for Science and Technology, Solar Village, undated.

Plate (9.1)

Al-Uyaynah village, the study area, where the questionnaire was conducted during summer, 1990.

9.1 Survey Method

The following elements of survey research as the basic sources of data regarding the development of solar energy were adopted :

1. Cross-sectional Survey,
2. Informal interviews with government officials,
3. Site visits and observations,
4. Written documents.

This multiple information-gathering methods was aimed to discover the views of both the users of solar energy and the government officials (the providers) about the development of solar energy as a major source of power in Saudi Arabia.

The cross-sectional survey is the key component of this investigation. It consists of a structured interview with the heads of the households of Al-Uyaynah Village. Questionnaire forms were delivered to the households and collected the following day in order to give sufficient time to answer the questions. The sample was made objective by a systematic procedure to represent the total population

In general, the questionnaire was organised to collect data regarding :

1. Basic information which might influence reaction to solar energy of the respondents, such as their age, occupation, education level and their original towns.
2. Satisfaction of people towards the development of solar energy, their preferences regarding the alternative sources of energy, and the role of

solar energy among these alternatives.

3. Perceptual information including the respondents' attitude and motivation with respect to the air pollution problem and their views about solving this problem.

9.1.1 Sampling Method

The next step in the survey process after selecting the study area and identifying the target population was to determine a suitable sample size for making reliable and confident generalized conclusions about the population it represented.

An obvious phenomenon in sample surveys is that a very large a sample involves a very high level of time and resources, while a very small a sample diminishes the reliability of the results. The decision to specify the sample size cannot always be made satisfactorily without setting acceptable limits of error which are tolerable in sample estimates, and specifying the magnitude of the inference margin which can be permitted. Thus, a combination of systematic and random samples were used in this survey in order to obtain a representative sample. A sample was drawn from the total number of the population of Al-Uyaynah Village in which the following formula was utilized for calculation of the sample size :

$$n = \frac{NZ^2 pq}{d(N-1)+Z^2 pq} \tag{9.1}$$

where :

$N =$ population size (4000),

$p =$ population responding one way = 0.5,

$q = 1-p$,

$d =$ half the desired interval, and

$Z =$ confidence coefficient (95%)

(Daniel & Terrell, 1979)

By applying the above formula and 5% probability of error, a total of 90 heads of households were employed to represent the population living in Al-Uyaynah Village. However, the sample size was increased to 100, a little more than the required number that was determined by the sample size formula. This was to cover the increase in the total population of the study area since the last census in 1982.

Next, a pilot study of 5% of the sample size was collected to evaluate respondents' understanding of the questionnaire and willingness to provide the answers. A review of the pilot study revealed that no significant changes were required to the final questionnaire.

9.1.2 Statistical Analysis

After the completion of the collecting information from the sample, data were coded, built into computer files and tabulated using the SPSSx system. Presentation and analysis of the data involved the following :

1. One-way tabulation to study the frequency and percentage distribution of responses, and to compare different groups' responses. As a descriptive statistic, this process was very helpful in presenting most

data in a simplified way.

2. Chi-square and cross-tabulation techniques were mainly used to discover and test the relationship among variables. The use of chi-square, a non-parametric technique, was necessary because most of the questionnaire data were in this form. It was used in this research to determine whether association between two or more variables was statistically significant.

9.2 Respondents' Socio-economic Status

The first section of the questionnaire investigated the socio-economic status of the respondents, including their age, their level of education, their occupation, and whether they are originally from Al-Uyaynah Village or not. These data were used to investigate the role of socio-economic factors in attitudes to solar energy development and the problem of air pollution in Saudi Arabia.

9.2.1 Respondents' Age

Nearly half of the respondents are under 20 years old (54 per cent). Those who are between 20 and 29 years old represent exactly 20 per cent, while those who are between 30 and 39 years old represent 16 per cent of the total population. 7 per cent of the respondents are between 40 and 49 years old, and only 3 per cent are over 50 years old, as seen in Table (9.1).

Due the relatively small sample size, the respondents were divided into two groups according to their age: First, those who are under 20 years old which are less educated and less informed. Second, those who are over 20 years old who are more educated and better informed. The differences between these two groups are expected to have substantial effects on their attitudes towards solar energy development in Saudi Arabia.

The high number of the respondents who are under the age of 20 years is attributed to two factors : First, many of the households are farmers who do not read and write, or have very simple education, and therefore cannot answer the questions properly. Instead, they let their older son answer the questions of the survey because he is more educated than them, and able to answer the questions. So, the answers represent the views of the older son of the household. Second, many people, especially the youth from this village, decided since early 1970s to migrate to the nearby cities, such as Riyadh, in order to improve their education and employment prospects and increase their income.

Solar energy is in its early stages of development and will take at least 10 to 20 years to be economically and technically competitive with the other alternative sources of energy. Therefore, it is important to know the attitudes of this younger group of population who will be involved in the development of solar energy and, to some extent, will have influence in the decision making process.

Age	Frequency	Percentage	Accumulated Percentage
10-19	54	54.0	54.0
20-29	20	20.0	74.0
30-39	16	16.0	90.0
40-49	7	7.0	97.0
50-59	3	3.0	100.0
Total	100	100.0	100.0

Table (9.1)
Respondents' Age.

9.2.2 Respondents' Education Level

The education level of the respondents is related very much to their age, particularly for respondents under 30 years old. Table (9.2) indicates that 32 per cent of the respondents hold intermediate degrees while 35 per cent have high school diplomas. Respondents who were able to complete University education represented 20 per cent of the total, and those who pursued their higher education to Master or Ph.D level represent 13 per cent. Therefore, almost two-thirds of the total respondents (67 per cent) have less than university level education and one-third of the respondents (33 per cent) have first or higher degrees. This relatively high education level indicates that the attitude of these respondents towards the development of solar energy and the air pollution problem would be expected to be positive. Moreover, many of the respondents holding higher degrees work in the Solar Village that supplies Al-Uyaynah with its electricity, and therefore, are more aware about the potential of solar energy and its economic and technical prospects.

Education Level	Frequency	Percentage	Accumulated Percentage
Intermed.	32	32.0	32.0
High School	35	35.0	67.0
University	20	20.0	87.0
Higher Degree	13	13.0	100.0
Total	100	100.0	100.0

Table (9.2)
Respondents' Education Level

9.2.3 Respondents' Town of Origin

With respect to the town of origin of the respondents, 45 per cent of them are from Al-Uyaynah Village while 55 per cent of them are newcomers to this village. The high percentage of respondents who are not originally from this village can be attributed to the fact that Al-Uyaynah Village is the largest village in this district, and contains many schools and government departments. Therefore, many people from the surrounding villages moved here either to attend the schools or to seek a better job. Conformtion of this trend can be seen in the fact that few of the respondents came from as far as Riyadh, the capital city of Saudi Arabia, which is located 50 km south-east of Al-Uyaynah Village.

9.3 Respondents' Attitude Towards Solar Energy Development with Respect to their Age.

The age of the respondents is a very important factor in determining their perception toward solar energy development in Saudi Arabia. Most of the old people of Al-Uyaynah village are either illiterate or have a simple education. On the other hand, younger people are more educated, and therefore able to specify thier attitude towards solar energy development.

The first question that the respondents were asked was about their satisfaction with solar powered generation. 84 per cent are satisfied, while 16 per cent of them are dissatisfied. The age of the respondents has a clear influence on their satisfaction. For example, 57.1 per cent of the respondents who are satisfied are under 20 years old, while 62.5 per cent of the respondents who are dissatisfied are over 20 years old. Thus, as the age of the respondents gets older, their satisfaction decreases, as shown on Table (9.3). This is may be attributed to the fact that as the age of the younger respondents increases, their awareness of the advantages of solar energy increases, especially the more educated respondents. This may also be influenced by the different demands and use patterns between the two age groups.

Satisfaction of Solar Electricity

Age		Satisfied	Dissatisfied	Total	Chi-Square
Less than 20 Years	(a)	48	6	54	1.37
	(b)	88.9	11.1		
	(c)	57.1	37.5		
More than 20 Years	(a)	36	10	46	
	(b)	78.3	21.7		
	(c)	42.9	62.5		
Total		84.0	16.0	100	

Table (9.3)

Views on Satisfaction with Solar Electricity
with respect to the Respondents'Age

a : absolute value.
b : % rows total.
c : % column total.
(this is applied to all tables in chapters 9, 10 & 11)

Although air pollution problem is not very apparent in Al-Uyaynah Village, respondents were asked whether the atmosphere was better or worse in this village after the commencement of operation of the Solar Village in 1982. 48 per cent of the respondents said that the atmosphere is better, while 52 per cent of them said that the atmosphere is worse. 56.3 per cent of the respondents who said that the atmosphere is better are more than 20 years old, while 63.5 per cent of those who said that the atmosphere is worse are under 20 years old , as seen in table (9.4). The Chi ^{2} indicates that there is no significant relationship at 0.05 level between the age of the respondents and theire awareness of the atmosphere. The large percentage of respondents who said that the earth's atmosphere is worse is attributed to the fact that the effect of the solar village on the environment improvement is small due to the high percentage of pollution emissions from various sources such as vehicles, factories and farms' water turbines which have not been changed by the advent of solar power.

	Atmospheric Condition			
Age	Better	Worse	Total	Chi-Square
				3.15
Less than 20 Years	21 38.9 43.8	33 61.1 63.5	54	
More than 20 Years	27 58.7 56.3	19 41.3 36.5	46	
Total	48.0	52.0	100	

Table (9.4)

Views on Atmospheric Condition with respect to the Respondents' Age

In order to know more about the respondents' views on air pollution problem in Saudi Arabia, respondents were asked to specify the main sources of air pollution. 74.7 per cent of the respondents said that vehicles, industrial factories, and power stations are the main sources of air pollution, while 25.3 per cent of them attribue air pollution to a single factor, such as vehicles, power plants, and, factories. 85 per cent of the respondents who are over 20 years old attributed air pollution to more than one factor compared with 66.7 per cent who are under 20 years old, as seen in table (9.5). Therefore, as the age of the respondents increases, their awareness of air pollution problem becomes more clear, as is reflected in answers about the sources of the problem of air pollution.

	Air Pollution Sources			
Age	One Factor	More Than One Factor	Total	Chi-Square
Less than 20 Years	17 33.3 73.9	34 66.7 50.0	51	3.08
More than 20 Years	6 15.0 26.1	34 85.0 50.0	40	
Total	25.3	74.7	91	

Table (9.5)

Views on Air Pollution Sources with respect to the Respondents'Age

Respondents were asked what was the best method of decreasing air pollution levels in Saudi Arabia. 81.3 per cent of the respondents suggested that a reduction of the amount of air pollution emissions from vehicles, industrial factories, and power stations was the best solution to air pollution problem in Saudi Arabia, while only 18.7 per cent said that public transportation was the best solution, as seen in table (9.6). The low percentage of respondents who suggested public transport may because it is not popular especially amongst Saudi citizens due to the relatively high level of wealth which allows general ownership of private cars, in addition to the tradition of Saudi citizens which dislike use of public transport by women for their own safety and privacy. Moreover, many areas are not well served with public transport because of low population density. According to Abdul Ghani and El-Shabani (1989), use of public buses is less than 5 per cent, even though the buses have separated enclosures for women, with about one third of the total seats.

Air Pollution Reduction

Age	Public Transportation	Decreasing Pollution Emmissions	Total	Chi-Square
				0.31
Less than 20 Years	8 15.7 47.1	43 84.3 58.1	51	
More than 20 Years	9 22.5 52.9	31 77.5 41.9	40	
Total	18.7	81.3	91	

Table (9.6)

Views on Air Pollution Reduction with respect to the Respondents' Age

The respondents were asked whether they preferred solar powered generation to diesel powered generation. 79 per cent of the respondents said that they prefered solar powered generation, while only 21 per cent of them prefered diesel powered generation. 57 per cent of those who prefered solar powered generation were under 20 years of age, while 43 per cent of them are over 20 years old, as seen in table (9.7). Thus, the majority of the respondents would prefer solar-powered generation as the main source of the power, particularly the younger respondents. This indicates a high level of awareness of the potential of solar energy in this small village and its role in reducing the air pollution level in the atmosphere, though the Chi ^{2} indicates that there is no significant relationship between the age of the respondents and their preference for the type of electricity.

	Electricity Preference			
Age	Solar Powered Generation	Diesel Powered Generation	Total	Chi-Square
Less than 20 Years	45 83.3 57.0	9 16.7 42.9	54	0.82
More than 20 Years	34 73.9 43.0	12 26.1 57.1	46	
Total	79.0	21.0	100	

Table (9.7)

Views on Electricity Preference with respect to the Respondents' Age

In order to know more about the attitudes of people to solar electricity costs, respondents were asked whether they thought that solar-powered generation would be more expensive to produce than diesel-powered generation. 64 per cent of the respondents think that it is not more expensive than diesel-generated electricity, while 36 per cent of them think that it is more expensive. 64.1 per cent of those who said that solar-powered generation is not more expensive than diesel-powered generation are under 20 years of age, while 35.9 of them are over 20 years old, as seen in Table (9.8). This reveals that older respondents are more aware of the real cost of solar electricity than the other age group due to their relatively high level of education. The low level of awareness amongst younger respondents is attributed to the fact that solar-powered generation is sold at the same rate as diesel-powered generation to encourage people to use this type of electricity. The Chi ^{2} indicates that there is a high significant relationship between the age of the respondents and their attitudes to solar electricity costs. However, solar powered generation is in its early stages of development and this might explain the lack of awareness of real current cost of solar energy particularly amongst younger respondents. In fact, solar-powered generation is five to ten times more expensive than diesel-powered generation.

Solar Electricity Cost

Age	Yes	No	Total	Chi-Square
				6.17 *
Less than 20 Years	13 24.1 36.1	41 75.9 64.1	54	
More than 20 Years	23 50.0 63.9	23 50.0 53.9	46	
Total	36.0	64.0	100	

* Represents Significance at the 0.05 level.

Table (9.8)

Views on Solar Electricity Cost with respect to the Respondents' Age

The awareness of respondents about the potential for solar energy in Saudi Arabia is very high. Table (9.9) indicates that 70 per cent of the respondents are aware of the potential of solar energy, while only 30 per cent of them said that there is no potential for solar energy in Saudi Arabia. They said that the high cost of solar energy and the availability of crude oil reduced the potential of solar energy in Saudi Arabia. 80 per cent of the respondents who said that there is no potential for solar energy are under 20 years old. Those young respondents are not aware of the high potential of solar power as a main energy alternative. This probably attributed to the fact that they have become a custom to the use of conventional energy resources and not aware of the problems of air poulltion generated from these sources. The Chi ^{2} indicates that there is a high significant relationship between the age of the respondents and their awareness of the potential for solar energy.

	Solar Energy Potential			
Age	Yes	No	Total	Chi-Square
Less than 20 Years	30 55.6 42.9	24 44.4 80.0	54	10.22 *
More than 20 Years	40 87.0 57.1	6 13.0 20.0	46	
Total	70.0	30.0	100	

* Represents Significance at the 0.05 level.

Table (9.9)

Views on Solar Energy Potential with respect to the Respondents' Age

In an attempt to discover the main barriers to the exploitation of solar energy in Saudi Arabia, respondents were asked to specify the factors that have a large influence in limiting solar energy exploitation. 53 per cent of the respondents mentioned a single factor as the main barrier, such as cloud cover, dust storms, or the high cost. 47 per cent said that all the factors mentioned above are important barriers. 60.4 per cent of those who mentioned only one single factor as the main barrier are under 20 years old, while 53.2 per cent of the respondents, who said that cloud cover, dust storms, and the high cost are main barriers, are over 20 years old, as seen in Table (9.10). Thus, almost half of the respondents are not well aware of the main barriers of solar energy exploitation. Also, respondents over 20 years old are more aware of the main barriers, though the Chi ^{2} test indicates that there is no significant relationship between the age of the respondents and their awareness of the main barriers to solar energy exploitation.

	Solar Energy Barriers			
Age	One Factor	More Than One Factor	Total	Chi-Square
Less than 20 Years	32 59.3 60.4	22 40.7 46.8	54	1.34
More than 20 Years	21 45.7 39.6	25 54.3 53.2	46	
Total	53.0	47.0	100	

Table (9.10)

Views on Barriers to Solar Energy with respect to the Respondents' Age

Finally, respondents were asked about the main alternative energy resources that they think should be used in Saudi Arabia over the next 20 years. 76 per cent of the respondents said that solar energy should be the main alternative to crude oil, while 24 per cent of them choose nuclear power or natural gas as the main alternative sources of energy in Saudi Arabia, as seen in Table (9.11). Thus, more than three fourth of the respondents indicated that solar energy is the main alternative source of power in Saudi Arabia.

	Main Energy Alternatives			
Age	Other Alternative	Solar Energy	Total	Chi-Square
Less than 20 Years	16 29.6 66.7	38 70.4 50.0	54	1.42
More than 20 Years	8 17.4 33.3	38 82.6 50.0	46	
Total	24.0	76.0	100	

Table (9.11)

Views on Main Energy Alternatives with respect to the Respondents' Age

In conclusion, there is a strong relationship between the respondents' age and their attitudes towards solar energy potential. Younger respondents tend to be more interested in solar energy development than older respondents. This may be attributed to the location of the Solar Village near their village, attracting a great deal of attention of the villagers about the potential of solar energy. Moreover, younger respondents are less aware of the pollution problem and the difficulties associated with solar energy development, particularly its higher cost compared with the other sources of energy. Furthermore, older respondents are more aware of the potential of solar energy and its relative role in reducing air pollution, though they are more conservative with respect to solar energy development due to its higher cost. This is particularly so amongst more educated respondents. These results emphasize the importance of the awareness of respondents which is reflected in their attitudes. Therefore, the public should be well informed (through media) about the potential of the solar energy and the problem of air pollution. Meanwhile, solar energy research and development should be continued, to reduce costs to a level competitive with the other sources of energy.

CHAPTER TEN

ATTITUDES TOWARDS SOLAR ENERGY DEVELOPMENT : THE ROLE OF EDUCATION

The education level of the respondents is the main factor that influences the prospects and attitudes of respondents. As the level of education of the respondents increases, their employment and economic prospects become wider and their attitudes become more informed. Over the last 20 years, as a consequence of increasing national wealth, education has improved dramatically in Saudi Arabia, so younger people tend to be better educated. Therefore, an educated person should be able to balance the disadvantages of solar energy supply with its positive contribution to the saving of fossil fuels, to reduction in air pollution and to its long term sustainability.

The highest educational institution in Al-Uyaynah Village is high school. This serves not only this village but also the surrounding villages. However, respondents differ with respect to their educational level. 35 per cent of them have high school diplomas, 32 per cent of them hold intermediate qualifications, 20 per cent of them hold university degrees and 13 per cent of them have higher degrees. Therefore two-thirds of the respondents hold diplomas below university level, while one-third hold university first or higher degrees. This variation of education levels among the respondents is reflected in their attitudes towards solar energy development.

The first question that respondents were asked was about their feeling towards solar energy development in Al-Uyaynah Village, particularly solar powered generation. Table (10.1) shows that 84 per cent of the respondents are satisfied, while 16 of them are dissatisfied. Therefore, the majority of the respondents are satisfied with the solar energy development.

	Satisfaction with Solar Electricity			
Education Level	Satisfied	not Satisfied	Total	Chi-Square
Less Educated	58 86.6 69.0	9 13.4 56.3	67	0.05
More Educated	26 78.8 31.0	7 21.2 43.8	33	
Total	84.0	16.0	100	

Table (10.1)

Views on Satisfaction with Solar Electricity with respect to the Respondents' Education Level

With respect to atmospheric conditions at Al-Uyaynah Village, respondents were asked whether they are better or worse, as a result of the operation of the Solar Village. 48 per cent of the respondents said that the atmospheric quality is better, while 52 per cent of them said that it is worse. 58.3 per cent of those who said that the atmospheric quality is better are less educated, while 41.7 of them are more educated. moreover, 75 per cent of those who said that the atmosphere is worse are less educated, as seen in table (10.2). This indicates that higher educated respondents are more conservative in their attitudes. Therefore, the education level has an influence, though not significant, on the respondents' opinions with respect to the atmospheric condition. However, unless it is actually measured, it is often hard to notice any change in the condition of the atmosphere, particularly in a small village like Al-Uyaynah. Moreover, the solar-powered electricity that supplies Al-Uyaynah Village with its consumption needs represents only a small element in reducing all pollution sources. The majority of pollution comes from internal combustion engines currently in use. The solar project only eliminated the pollution generated from the diesel-powered electricity that used to supply this village, and there remain many pollution sources in this village, such as vehicles, factories and more significantly, the diesel- powered engines used for water pumping in the surrounding farms.

	Atmospheric Condition			
Education Level	Better	Worse	Total	Chi-Square
				2.43
Less Educated	28 41.8 58.3	39 58.2 75.0	67	
More Educated	20 60.6 41.7	13 39.4 25.0	33	
Total	48.0	52.0	100	

Table (10.2)

Views on Atmospheric Condition with respect to the Respondents' Education Level

Respondents were asked about the main causes of air pollution, not only in Al-Uyaynah Village, but also in Saudi Arabia in general. 74.7 per cent of the respondents believe that vehicles, industrial factories and power stations are the main causes of air pollution in Saudi Arabia, while 25.3 per cent of them attribued air pollution to a single factor, such as vehicles, industrial factories or power stations. Moreover, 88.9 per cent of the respondents who are more educated attributed air pollution to more than one factor compared with 68.8 of those who are less educated, as seen in Table (10.3). Therefore, as the respondents' education level increases, their awareness of air pollution sources increases.

	Air Pollution Sources			
Education Level	One Factor	More than One Factor	Total	Chi-Square
				3.08
Less Educated	20 31.3 87.0	44 68.8 64.7	64	
More Educated	3 11.1 13.0	24 88.9 35.3	27	
Total	25.3	74.7	100	

Table (10.3)

Views on Sources of Air Pollution with respect to the Respondents' Education Level

With respect to the preference of respondents about the type of electricity, 79 per cent of respondents prefer solar-powered generation, while 21 per cent of them prefer diesel-powered generation. 69.6 per cent of those who prefer solar-powered generation are less educated (intermediate and high school diplomas), while 30.4 per cent of them are more educated (university and higher degrees), as seen in table (10.4). Also this table shows that 72.7 per cent of the more educated respondents prefer solar-powered generation, compared with 82.1 of those who are less educated. This indicates that the majority of the respondents prefer solar-powered generation, though the Chi ^{2} indicates that there is no significant relationship at 0.05 level between the education level of the respondents and their preference for the type of electricity. The stated reason behind their preference, is because solar energy is widely availabe in Saudi Arabia, in addition to its relatively simple technology compared with the other alternative energy sources such as nuclear energy, and most important it is air pollution free.

Education Level	Electricity Preference Solar Powered Generation	 Diesel Powered Generation	Total	Chi-Square
Less Educated	55 82.1 69.6	12 17.9 57.1	67	0.67
More Educated	24 72.7 30.4	9 27.3 42.9	33	
Total	79.0	21.0	100	

Table (10.4)

Views on Electricity generator Preference with respect to the Respondents' Education Level

The majority of the respondents do not seem to be aware of the real cost of solar powered generation. Table (10.5) indicates that 64 per cent of the respondents believe that solar-powered generation is not more expensive than diesel-powered generation, while 36 per cent of them think that solar powered generation is more expensive than diesel powered generation. The reason why the majority of respondents are not aware of the actual cost of solar powered generation is because it is sold to the customers as the same as the standard price of diesel powered generation to encourage people to use this type of electricity. According to the Ministry of Industry and Electricity (Undated), both types of electricity are sold to the people at 10 Halalah per KW/h. (0.29 Pence). Moreover, table (10.5) indicates that 79.7 per cent of less educated respondents think that solar powered generation is not more expensive than diesel-powered generation to produce, compared with only 20.3 of those who are more educated. Thus, as the education level of the respondents increases, they become more aware of the real cost of solar powered generation. The Chi ^{2} indicates that there is a significant relationship at 0.05 level between the respondents' education level and their awareness of the actual cost of solar powered generation.

Solar Electricity Cost

Education Level	Yes	No	Total	Chi-Square
				11.40 *
Less Educated	16 23.9 44.4	51 76.1 79.7	67	
More Educated	20 60.6 55.6	13 39.4 20.3	33	
Total	36.0	64.0	100	

* Represents Significance at the 0.05 level.

Table (10.5)

Views on Solar Electricity Cost with respect to the Respondents' Education Level

Since the actual cost of solar-powered generation is high compared with other alternative energy sources, respondents were asked whether they would be willing to pay more for solar powered generation to improve the environment and to reduce air pollution level. The answers are almost identical, 51 per cent of the respondents are not willing to pay more for solar electricity, while 49 per cent of them are prepared to pay more. Moreover, 88.2 per cent of the less educated respondents are not willing to pay more for solar electricity, compared with only 11.8 per cent of more educated respondents, as seen in table (10.6). Therefore, as the respondents' education decreases, their willingness to pay more also decreases. This is most probably due to the awareness of air pollution problem among higher educated respondents, in addition to their ability to pay more due to their higher income compared with less educated respondents.

	Willingness to Pay More for Solar Electricity			
Education Level	Yes	No	Total	Chi-Square
Less Educated	22 32.8 44.9	45 67.2 88.2	67	2.42
More Educated	27 81.8 55.1	6 18.2 11.8	33	
Total	49.0	51.0	100	

Table (10.6)

Views on Willingness to Pay More for Solar Electricity with respect to the Respondents' Education Level

Despite the huge quantity of incoming solar radiation received at the earth's surface in Saudi Arabia, only 64 per cent of the respondents think that it is sufficient to generate useful energy. The rest, 36 per cent, do not think that it is sufficient. This is despite the fact that the Solar Village, which is located near Al-Uyaynah Village, the study area, already produces 350 KW of electricity and it is proposed in the long term to install a solar energy system capable of delivering up to 1 MW of electrical power (Saudi Arabian National Center for Science and Technology, undated).

Table (10.7) shows that 84.8 per cent of respondents who are more educated think that solar radiation received at the earth's surface is sufficient to generate useful energy, compared with only 53.7 per cent of those who are less educated. Thus, as the respondents' education level increases, they become more aware of solar radiation sufficiency and its efficiency to produce useful energy. The Chi ^{2} indicates that there is a significant relationship at 0.05 level between respondents' education level and their awareness of solar radiation sufficiency.

	Solar Radiation Sufficiency			
Education Level	Yes	No	Total	Chi-Square
Less Educated	36 53.7 56.3	31 46.3 86.1	67	7.99 *
More Educated	28 84.8 43.8	5 15.2 13.9	33	
Total	64.0	36.0	100	

* Represents Significance at the 0.05 level.

Table (10.7)

Views on Solar Radiation Sufficiency with respect to the Respondents' Education Level

Despite the fact that solar energy is in its early stages of development, there is already a widesprea use of solar-powered products, such as watches, calculators, solar heaters, etc., not only in Saudi Arabia but also world wide. Respondents were asked whether they have any solar-powered equipment. 64 per cent of them said that they use some solar-powered equipment, either in their home or office, while 36 of them do not have any solar-powered equipment. Table (10.8) indicates that 86.1 per cent of the less educated respondents do not have any solar-power equipment compared with only 13.9 per cent of more educated respondents. This indicates that there is a widespread use of solar-powered equipment amongst the more educated respondents, which reflects their awareness of the potential of solar energy as a main source of power, in addition to the high attractiveness of solar energy as a power source which is free and widespread. The Chi ^{2} indicates that there is a significant relationship at 0.05 level between the respondents' education level and the widespread use of solar-powered equipment.

	Solar Energy Equipments			
Education Level	Yes	No	Total	Chi-Square
Less Educated	36 53.7 56.3	31 46.3 86.1	67	7.99 *
More Educated	28 84.8 43.8	5 15.2 13.9	33	
Total	64.0	36.0	100	

* Represents Significance at the 0.05 level.

Table (10.8)

Views on Solar Energy Equipment with respect to the Respondents' Education Level

In conclusion, education level has a significant impact on the attitudes of the respondents towards solar energy development, as shown by the Chi ^{2} tests. More educated respondents are well aware about the potential of solar energy and its current economic and technical stage. However, more educated respondents are presently less satisfied with solar energy development due to its higher cost compared with the other convetional energy sources. Thus the main value of solar energy as a resource is seen by the educated group to be in the future rather than the present.

CHAPTER ELEVEN

ATTITUDES TOWARDS SOLAR ENERGY DEVELOPMENT : THE ROLE OF THE PLACE OF ORIGIN

The reason behind the investigation of the effect of the place of origin on the attitudes of respondents is because, it is hypothesised that the original residents of Al-Uyaynah Village are more interested in solar energy development than those who are incomers to this village as a result of the location of the Solar Village near their village. Moreover, some of the incomers whom their jobs are based on the Solar Village have a real interest in making solar energy be a success, but the rest of the incomers may not be as enthusiastic as the original residents.

In the light of the Solar Village experience, respondents were asked whether they think that there is an alternative energy source that may act as a substitute for crude oil in Saudi Arabia. 60 per cent of the respondents believed that there is an alternative, while 40 per cent did not think that there is an alternative. Table (11.1) shows that 60 per cent of the respondents who think there is an alternative source of energy are not originally from Al-Uyaynah Village, while 40 per cent of them are originally resident in this village. This result indicates that the respondents who are not from Al-Uyaynah Village are affected by the experience of the Solar Village and therefore more interested in an alternative energy source than the original residents of Al-Uyaynah Village. Though the Chi ^{2} indicates that there is no statistically significant relationship between the respondents' place of origin and their attitude towards alternative energy sources, the respondents who are not from Al-Uyaynah Village are more aware of the potential of alternative energy resources. This is may be attributed to fact that most of the respondents who are not from this village are more educated, since many of them came here to seek a better job. In addition, many younger villagers emigrated to the the major cities, particularly the capital Riyadh, to continue their higher education and to seek better opportunities. According to Al-Ankary and El-Bushra (1989), the high rural-urban migration is attributed to the limited job opportunities and inadequate social services in rural areas, compared with major urban centres which have come to develop a strong economic and infrastricture base. It was estimated that in 1972, 85 per cent of the household heads in Riyadh were immigrants and 70 per cent of the annual growth of the city was due to migration (Grill, 1984).

	Crude Oil Alternatives			
Originally Resident	Yes	No	Total	Chi-Square
Yes	24 53.3 40.0	21 46.7 52.5	45	1.05
No	36 65.5 60.0	19 34.5 47.5	55	
Total	60.0	40.0	100	

Table (11.1)

Views on Alternatives to Crude Oil with respect to the Respondents' Place of Origin

When respondents were asked about the main causes of air pollution in Saudi Arabia, 74.7 per cent of the respondents said that industrial factories, power stations, and vehicles were the main causes, while 25.3 per cent of them attributed air pollution to a single factor, such as industrial factories, power stations, or vehicles, as seen in Table (11.2). 86 per cent of the respondents who are not from Al-Uyaynah Village attributed air pollution to more than one factor, compared with 61 per cent of the respondents from this village. Thus, the respondents who are not originally from this village are more aware of the main causes of air pollution than those who are from this village. The Chi ^{2} test indicates that there is a significant relationship at 0.05 level between the residences of respondents and their attitude towards air pollution causes.

Air pollution Causes

Originally Resident	One Factor	More than One Factor	Total	Chi-Square
Yes	16 39.0 69.6	25 61.0 36.8	41	6.20 *
No	7 14.0 30.4	43 86.0 63.2	50	
Total	25.3	74.7	91	

* Represents Significance at the 0.05 level.

Table (11.2)

Views on Air pollution Causes with respect to the Respondents' Place of Origin

To see whether the place of origin has an influence on the respondents' preference of the type of electricity, the respondents were asked whether they prefered solar-powered generation to diesel-powered generation. 79 per cent of the respondents said that they prefered solar-powered generation, while only 21 per cent of them prefered diesel-powered generation. 81.8 per cent of the respondents who are not from Al-Uyaynah Village perfered solar-powered generation, compared with 75.6 per cent of the respondents from this village, as seen in Table (11.3). This indicates a high level of awareness of the potential of solar energy in this small village and its role in reducing the air pollution level in the atmosphere, and a lack of concern for potential or perceived problems in solar energy utilisation, though the Chi ^{2} indicates that there is no significant relationship between the place of origin and their preference of the type of electricity.

Originally Resident	Electricity Preference Solar Powered Generation	Diesel Powered Generation	Total	Chi-Square
Yes	34 75.6 43.0	11 24.4 52.4	45	0.27
No	45 81.8 57.0	10 18.2 47.6	55	
Total	79.0	21.0	100	

Table (11.3)

Views on Electricity Preference with respect to the Respondents' Place of Origin

Respondents were asked if they think that there is a potential for exploiting solar radiation in Saudi Arabia. 70 per cent of the respondents agreed that there is a potential, while 30 per cent of the respondents do not think that there is a potential for solar energy development in Saudi Arabia. Table (11.4) indicates that 61.4 per cent of the respondents who thought that there was a potential for exploiting solar energy are not originally from Al-Uyaynah Village, while 38.6

per cent of them were from this village. Thus, the respondents who are not originally from Al-Uyaynah Village are more aware about the high potential of solar energy in Saudi Arabia than the respondents who are originally from Al-Uyaynah Village.

Solar Energy Potential

Originally Resident	Yes	No	Total	Chi-Square
Yes	27 60.0 38.6	18 40.0 60.0	45	3.08
No	43 78.2 61.4	12 21.8 40.0	55	
Total	70.0	30.0	100	

Table (11.4)

Views on Solar Energy Potential with respect to the Respondents' Place of Origin

The last question that respondents were asked was about the main energy resource that should be used in Saudi Arabia over the next 20 years. 76 per cent of the respondents believed that solar energy should be the main alternative source of energy in the country, while 24 per cent of them chose other alternatives, such as natural gas and nuclear energy. As shown in table (11.5), 80 per cent of the respondents who believed that solar energy should be the main alternative, are not originally from Al-Uyaynah Village compared with 71.1 per cent who are from this village. Though the Chi ^{2} test indicates that there is no statistically significant relationship at 0.05 level between the residence of respondents and their attitude towards main energy alternatives, these results indicate that the respondents who are not originally from this village are more aware of the potential of solar energy as the main alternative source of energy in Saudi Arabia than those who were originally from this village.

	Main Energy Alternatives			
Originally Resident	Other Alternative	Solar Energy	Total	Chi-Square
				0.64
Yes	13 28.9 54.2	32 71.1 42.1	45	
No	11 20.0 45.8	44 80.0 57.9	55	
Total	24.0	76.0	100	

Table (11.5)

Views on Main Energy Alternatives with respect to the Respondents' Place of Origin

In conclusion, place of orign has an effect, though less significant, on the respondents' attitudes towards solar energy development. Respondents who are not from Al-Uyaynah village seem to be more aware of the potential of solar energy than the respondents from this village. This may be attributed to the fact that most of the respondents who are not form this village are more educated, particularly those working at the Solar Village.

CHAPTER TWELVE

CONCLUSION

Crude oil reserves, the main source of energy, are limited and expected to be depleted within the next five to six decades. By the turn of this century, crude oil reserves of some of the major industrialized countries, such as the United Sates and the United Kingdom, are expected to be depleted, as discussed in Chapter Two. This will impose pressures on the major oil producers, such as Saudi Arabia, Iran, and Iraq, to increase their production to meet the expected increase of world oil demand which will decrease the life-span of their oil reserves. As crude oil reserves deplete, crude oil prices may rise to more than $ 30 per barrel, during the first decade of the 21st. century, as a result of the expected high demand for crude oil in that time, particularly from the industrialized countries.

The current cheap prices of oil and natural gas for domestic consumption in Saudi Arabia will increase the reliance on these conventional resources and make any conservation measure ineffective. A reasonable pricing for domestic consumption and a development of an education programme in which Saudi citizens are tought the need to conserve the use of oil reserves and to protect the environment are the key factors for a real conservation.

Furthermore, the continuous increase of energy consumption, not only of crude oil, but also of all conventional energy resources has led to a major problem of air pollution. The increasing level of air pollution resulted in serious consequences now and in the future, such as general instability of climate system evidence of which may be seen in the increase in air temperature, floods, gust winds, and heavy snowfalls in some parts of the world.

Due to the gradual depletion of fossil fuels, and the increasing level of air pollution, the search for alternative energy resources is being intensified. Amongst these resources, solar energy is the main alternative due to the high amount of solar radiation that reaches the earth's surface, and its widespread availability, particularly in the middle latitudes. In addition, its renewable and clean use make it the most favourable energy in the world for future utilisation.

The investigation of incoming solar radiation in Saudi Arabia indicates that there is a high potential for exploitation of this vital resource as a main alternative energy, particularly in the southwestern part of the country, where the intensity of solar radiation reaches its maximum. Moreover, more than 40 per cent of the population is distributed in small villages mainly in the south-west. This is an ideal situation for solar energy development. At the northern and southern parts of the country, the intensity of solar radiation reaches its minimum due to the persistent dust storms at these two parts, and therefore, these areas have less potential for solar energy applications. Likewise, coastal areas, particularly the eastern coast, has a very high atmospheric water vapour content, which decreases the intensity of solar radiation, especially during summer when humidity reaches its maximum. This high humidity should be considered when choosing the appropriate sites for solar energy plants.

The major problem of solar energy development lies in its higher production cost, particularly the cost of the solar cells which make it currently not competitive with fossil fuels. Therefore, solar cells should be produced at a large-scale to reduce manufacturing cost and their effeciency should be improved to reduce the number of the solar cells used in individual solar energy plants.

In addition to physical factors, human factors play an important role in solar energy development. Public perspectives and attitudes are crucial components of solar energy development, because the public are the users of this renewable source. In a questionnaire conducted at Al-Uyaynah village, northwest of the capital Riyadh, the majority of people are in favour of solar energy development , though more educated people think that the cost of solar energy is high and still far beyond competition with other fossil fuels. Moreover, the questionnaire revealed that the less educated respondents are less aware of air pollution problems and the major sources of these problems. Therefore, the public should be better informed about the benefits of solar energy, particularly its role in improving the quality of the environment. When a large proportion of the industrial and power plants sectors are using solar energy, these will be a significant reduction in pollution gases entering the atmosphere.

Finally, the location of solar energy plants is an important decision for energy-policy makers. When choosing the appropriate site, the major factors to be considered are the intensity of solar radiation and the socio-economic factors, particularly population density. A critical evaluation of some of the solar energy plants in Saudi Arabia revealed that some of these factors do not appear to have been considered. The location of the solar-powered water desalination plant at Yanbu on the western coast is a clear example of an inappropriate location due to the high humidity in this coastal area.

12.1 Critique of the Research Programme

There are many issues revealed in this thesis which could be the subject of further studies and investigation. These include :

1. Generally there are gaps in meteorological data at many stations, especially during summer, when some employees take their annual vacation. This applies particularly to data recorded by the Ministry of Agriculture and Water. Therefore many weather stations have to be excluded from studies and investigations due to the missing data. This was the case in this thesis when the number of stations had to be reduced to only 16, the total having complete and accurate data. There is a great need to increase the quality and quantity of meteoroligical data collection in the Kingdom.

2. The effect of cloud cover on the variation of incoming solar radiation would be clearer if there was a distinction between the various types of clouds. The effect of thick clouds, such as cumulus, is much greater than thin clouds, such as cirrus. Thick clouds attenuate large proportions of solar radiation. Such a distinction will result in a more accurate measurement of the effect of clouds on the variation of solar radiation, especially in the mountain areas such as the southwestern part of Saudi Arabia, where cloud formation is higher than the other parts of the country.

3. The effect of water vapour on the variation of solar radiation is significant, particularly in coastal areas where atmospheric water vapour content is very high. In Saudi Arabia, water vapour is expressed by relative humidity, defined as the ratio of the amount of water vapour actually in the air compared to the maximum amount of water vapour the air can hold at that particular temperature (Ahrens, 1988). Thus, water vapour content changes

with respect to temperature; as temperature increases, relative humidity decreases. Therefore, relative humidity is not a precise measure of the water vapour in the earth's atmosphere. Specific humidity should be used in water vapour measurement to obtain the actual water vapour content because it measures the mass of water vapour to the total mass of air. It is the actual mass of water vapour which affects radiation received.

4. The production cost of electricity, whether diesel-powered generation or solar-powered generation, is not published, hence no accurate economic analysis of electricity production costs can be made. Production costs should be published in order to make comparative analysis between solar-powered generation and diesel-powered generation possible. This action will assit in both evaluating and planning solar energy development.

5. The questionnaire conducted at Al-Uyaynah Village indicates that many respondents (45%), prefer crude oil as the main source of energy. This relatively large percentage may be attributed to the fact that crude oil is a known method of energy production. New sources of energy imply change in mode of operation, costs for new equipment etc. These will always be resisted by society in favour of the status quo. Moreover, this preference reflects the fact that, although they are aware of air pollution problems resulting from crude oil consumption, respondents are not well informed about the hazardous effects of continuing consumption of fossil fuels. Such hazards include increase in temperature, ozone layer damage, and acid rain with resultant damage to the vegetation cover and wild life. Therefore, the public should be much better informed about these serious consequences and the opportunities for solar energy development, through media channels such as television, radio, and newspapers. Such information should carry

the endorsement of both government and the scientific community to give it more authority.

12.2 Recommendations

To reduce air pollution level and to expand the pace of solar energy development, the following recommendations are proposed :

1 - Pollution emissions from vehicles, factories and power stations should be reduced by improving engine efficiency, reducing engine size and by emission controls such as catalytic converters. This latter will not decrease CO_2 emissions.

2 - Fuel consumption by vehicles' engines should be decreased by introduction of a speed limit of 100 KM/h including motorways.

3 - Gases that damage the ozone layer, such as CFCs, should be banned from use in Saudi Arabia.

4 - Public transportation should be expanded particularly in the main cities and people should be encouraged to use it instead of their private cars.

5 - Meteorological information including data on solar radiation should be recorded daily throughout the year. Special emphasis should be given to the summer, due to the missing data found at many weather stations at this time. The network of recording stations should be extended. Remote, automatic recording stations make this process easier.

6 - Water vapour should be measured precisely, because relative humidity, the current method of measurement of water vapour, is not wholly quantitative. Specific humidity is the best measurement of water vapour in the earth's atmosphere, for use in solar energy research work.

7 - Solar cells should be produced at a large scale to reduce their current high cost, and the efficiency of these cells should be increased. Increased technological research and development in these aras is needed.

8 - Since solar-powered generation is already competitive with the other energy resources in remote villages such as those in southwestern parts of Saudi Arabia, solar-powered generation should be used at these remote villages.

9 - The public should be better informed about the serious consequences of air pollution, and the benefits of solar energy equipment with the aim of reducing the present heavy reliance on fossil fuels consumption.

10- Air pollution gases play an important role in the variation of incoming solar radiation at the earth's surface through absorption and scattering processes. Therefore, the level of such gases, including carbon dioxide and CFCs, should be measured daily throughout the year at a significant number of recording stations in order to determine their role on this variation.

12.3 Further Studies

To continue this research theme further, more investigation about the effects of air pollution on the environment, particularly its effect on respiratory systems of human beings in the major cities should be undertaken. Such studies could be based on data to be collected from hospitals, factories and power stations workers.

In addition, dust is a major factor that decreases the intensity of solar radiation at the earth's atmosphere through scattering, and reduces the efficiency of solar cells as a result of the accumulation of dust on their surfaces. Therefore, further research on effect of dust storms on the efficiency of solar cells should be carried out, to assess the consequences of these phenomena, and to find the best way to tackle this problem.

Atmospheric water vapour content is very high at coastal areas especially during summer. This reduces the intensity of solar radiation through absorption processes. The precise effects of water vapour in attenuating solar radiation, and in damaging solar panels and cells needs to be investigated further.

The cost of solar-powered generation is higher than diesel-powered generation in general, except at remote villages in the mountain areas in the south-western parts of Saudi Arabia, where the cost of solar powered generation is competitive with diesel powered generation. A comparative study of these two types of generation in remote villages would be very useful.

The occurrence of cloud cover is higher in the southwestern part of Saudi Arabia than other areas, particularly during summer. This reduces the intensity of solar radiation through reflection, absorption, and scattering processes. Therefore, an investigation of the precise effect of cloud cover on the variation of solar radiation at selected towns and villages in the southwestern part will clearly reveal this effect. This should include investigation of frequency patterns of cloud types.

Finally, a comparative study between Al-Uyaynah village, the first village to receive solar-powered generation in Saudi Arabia, and another village not yet utilising solar energy is needed to see if there are significant differences between the perspectives and attitudes of people to solar energy development.

APPENDIX ONE

THE INTERVIEW QUESTIONNAIRE

Interview no : ....
Date : ....

This questionnaire is intended to find out opinions of people about the potential of solar energy and the problem of air pollution in Saudi Arabia. This questionnaire is, in fact, a part form a ph.D thesis at Glasgow University in Scotland, U. K. entitled " Physical and Economic Factors and their Effects on Development of Solar Energy in Saudi Arabia " which focus on the factors influencing solar energy development. Your participation in answering the following questions will help to accelerate the pace of solar energy development in Saudi Arabia and will be highly appreciated.

1 **Respondents' age :**

10-19 ☐
20-29 ☐
30-39 ☐
40-49 ☐
50-59 ☐
60 or over ☐

2 **Respondets' occupation :**

Student ☐
Government ☐

Employee [ ]

Private sector employee [ ]

Self employer [ ]

Retired [ ]

Others (specify)............................

3 What is your education level ?

Intermediate school [ ]

High school [ ]

University [ ]

Higher degree [ ]

4 (a) Are you originally resident in this village ?

Yes [ ]

No [ ]

(b) If no, why did you move to this village ? ....

....

....

....

5 How satisfied are you with the supply of solar-generated electricity ?

Very satisfied [ ]

Quite satisfied [ ]

No feeling either way [ ]

Dissatisfied [ ]

6 **For how long do you think crude oil will last in Saudi Arabia ?**

10 years [ ]

50 years [ ]

100 years [ ]

More than 100 years [ ]

7 (a) **Do you think that there is an alternative energy resource that might be a substitute for crude oil in Saudi Arabia ?**

Yes [ ]

No [ ]

Don't know [ ]

(b) **Please explain ?** ....

....

....

8 (a) **Would you prefer crude oil to continue as the main source of energy in Saudi Arabia ?**

Yes [ ]

No [ ]

Don't know [ ]

(b) What are the reasons behind this answer ?

....

....

....

....

9 (a) In your local environment, have you noticed any change in the intensity of air pollution since the operation of solar village in 1983?

Yes [ ]
No [ ]
Don't know [ ]

(b) If yes, please specify ? ....

....

....

....

10 After the operation of the solar village, do you think that the earth's atmospher in this village is :

Better [ ]
Worse [ ]
About the same [ ]
Don't know [ ]

11 (a) Do you think that there is a general air pollution problem in Saudi Arabia ?

Yes [ ]
No [ ]
Don't know [ ]

(b) If the answer is on, please go to question no. 14.

(c) If you think that there is an air pollution problem in Saudi Arabia, what do you think the main causes of this problem ?

Auto vehicles [ ]
Industrial factories [ ]
Power stations [ ]
All of the above [ ]
Others (specify) ....

12 What do you think the best solution to decrease the level of air pollution in Saudi Arabia ?

By the use of public transportation [ ]
By decreasing the fuel consumption in the vehicles' engins [ ]
By reducing the amount of air pollution emmitions from the idustrial factories, auto vehicles, and power stations [ ]
Others (specify) ....

13 (a) Do you prefer solar-powered generation or deisel-powered generation for your home ?

Solar-powered generation [ ]
Deisel-powered generation [ ]
Don't know [ ]

(b) Specify the reasons of yourchoice ? ....

....

....

....

14 (a) Do you think that solar-generated electricity is more expensive than deisel-generated electricity ?

Yes [ ]
No [ ]
Don't know [ ]

(b) If yes, please specify ? ....

....

....

15 (a) Would you be prepared to pay more for electricity to improve enviromental quality if was generated

from solar sources ?

yes [ ]

No [ ]

(b) If yes, how much more are you willing to pay ?

5% [ ]

10% [ ]

15% [ ]

More than 15% [ ]

16 (a) Do you think that there is potential to exploit solar energy in Saudi Arabia ?

Yes [ ]

No [ ]

Don't know [ ]

(b) Please specify ?

....

....

....

....

17 (a) Do you think that incoming solar radiation received at the earth's surface in Saudi Arabia is sufficient to

generate useful energy ?

Yes [ ]

No [ ]

Don't know [ ]

(b) Please specify ?

....

....

....

....

18 Which do you think the important barriers that limit the ultimate exploitation of solar energy in Saudi Arabia ?

Clouds [ ]

Dust storms [ ]

High cost [ ]

All of the above [ ]

Others (specify) ....

19 (a) Do you use solar-powered equipments either in your house or your office (such as electric apparatus, solar heaters, calculators, watches, e.t.c.)?

Yes [ ]

No [ ]

(b) If yes, what are they ? ....

....

....

20 (a) What do you think should be the main energy resuorces for national use in Saudi Arabia over the next 20 years ?

Crude oil [ ]
Natural gas [ ]
Nuclear power [ ]
Solar energy [ ]
Wind energy [ ]
Others (specify)......................................

(b) Explain your reasons for this choice please ? ....

....

....

THANK YOU

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