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Distribution of Soil Temperature Regimes and Climate Change in the Mojave Desert Region

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Distribution of Soil Temperature Regimes and Climate Change in the Mojave Desert Region

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by

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ABSTRACT OF THE DISSERTATION

Distribution of Soil Temperature Regimes and Climate Change in the
Mojave Desert Region

by

YanYing Bai

Doctor of Philosophy, Graduate Program in Geological Sciences
University of California, Riverside, December 2009
Dr. Richard A. Minnich, Co-Chairperson
Dr. Thomas A. Scott, Co-Chairperson

Soil temperature plays an important role in physical, biological and microbiological processes occurring in the soil. It can be used as indicative of regional climate change. A long-term soil temperature database was collected at 75 locations in the Mojave Desert region by the Pallmann method from 1982-2000. This long-term database of soil temperature is invaluable and was used to analyze the spatiotemporal change pattern of soil temperature, and to examine the relationship between regional climate change and soil temperature over an extended period of time.

The main conclusions of this research are: 1) the accuracy and consistency of the Pallmann method was good in comparison with two other temperature measurement methods: thermistor sensor and diffusion-cell method. The Pallmann method is an ideal method for studying the spatial variation in soil temperature and long-term climate changes.

2) Elevation is the dominated factor governing the spatial variation of soil temperature in the Mojave Desert region and can be used to estimate the spatial distribution of soil temperature. In the Mojave Desert region, hyperthermic soil is the most extensive one, which accounts for around 55% of the whole region. Thermic soil accounts for 38.7%. Frigid and mesic soils only occur at high elevation mountains. 3) Seasonal soil temperatures vary greatly in the Mojave Desert region and decrease linearly with elevation. The differences of the summer and winter soil temperature are around 20 °C under the same elevation. The effect of elevation on soil temperature is more pronounced in summer season than in winter season. 4) Soil and air temperature are highly correlated in the Mojave Desert region. Both of the soil and air temperature were found to be highly correlated with elevation and their spatiotemporal variations are highly positively correlated. 5) The Mojave Desert is experiencing a warming trend. Based on continued measurements across the region, the air and soil temperatures have risen at the rates of 0.79 and 0.63°C per 10 year from 1982 to 2000. The anomalies of annual precipitation were inversely correlated with those of soil temperature. The soil temperature of the Mojave Desert would be cooler than normal under El Niño conditions. 6) The climatic variables of air temperature, precipitation and evaporation had significant correlation with soil temperature. The spatial-temporal variation of soil temperature can be predicted based on the linear regression equation with air temperature and precipitation as independent variables.

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Chapter 1

INTRODUCTION

Soil temperature regulates the biogeochemistry of terrestrial environment, especially those occurring below ground (Lin, 1980; Seyfried et al., 2001; Qi and Song, 2003). Changes in soil temperature may alter the distribution, physiology, and growth of plant species, the decomposition of soil organic carbon, and the CO_2 emissions from the soil to the atmosphere (Trumbore et al., 1996; Goulden et al., 1998; Brooks et al., 2004; Schimel et al., 2004). Changes in soil temperature are linked to changes in soil properties such as pH and ionic strength of soil solution. Both local and global climate changes could have significant consequences to the soil temperature thus the dynamics of ecosystem functions (Zhang et al., 2005).

Most climate records and climate change scenarios projected by the general circulation models are for atmospheric conditions. Soil temperature data, especially areal-wide long-term data, are seldom recorded. Soil temperature is governed by the heat transfer process between the atmosphere and the soil surface and is expected to respond to changes in the air temperature. However, the relationship is complex. The soil temperature is regulated by a number of factors that include:

(1) Geographic variables, including latitude, altitude, slope, and aspect;

(2) Meteorological conditions, such as surface global radiation, and air temperature;

(3) Site characteristics, including surface conditions and surface temperature, leaf area index, ground litter stores, landscaping, drainage, microclimate, and water table; and

(4) Thermal physical properties of the soil, such as albedo of surface, water content and texture (Moustafa et al., 1981; Kang et al., 2000).

The warming trends projected by outcomes of global change simulation models do not accurately estimate the change in soil temperature (Schmidt et al., 2001; Zhang et al., 2001; Zhang et al., 2005). The air and soil are distinctively different heat transfer media and possess distinctively different heat capacities. To understand how the terrestrial ecosystems respond to global climate changes, it is imperative that how soil temperature changes in response to ambient climate changes be delineated.

In Soil Taxonomy (Soil Survey Staff, 1999), soil temperature is factored into the soil classification system in which the soil temperature regimes are defined in terms of the mean annual soil temperature (MAST) and the difference between mean summer soil temperatures (MSST) and mean winter soil temperatures (MWST). For an accurate inventory of soil resource, the spatial distribution of soil temperature regimes is imperative. As the soil temperatures vary markedly with geographic factors including elevation, latitude, longitude, slope and aspects, it is challenging to delineate soil temperature regimes in an area with diverse topography like the Mojave Desert.

It is impractical, especially prior to the advent of remote sensing and in situ data logger, to install areal-wide monitoring network to account for geographic variations in soil temperature measurements. One often results to estimating the soil temperature (Tenge et al., 1998). However, the accuracy of the traditional method of estimating MAST by adding 1°C to the mean annual air temperature (MAAT) is questionable in mid-latitudes and is especially problematic in the snowblet areas (Isard and Schaetzl, 1995; Soil Survey Staff, 1999; Schaetzl et al., 2005; Mirsal, 2008). Computer models accounting for the thermal properties of soils may be employed to simulate soil temperature under varying boundary conditions. However, the models are complex and require many parameters that are often not readily measurable and available. Again, the linkage between MAST and metrological and geographic factors may shed light on devising an expedient method of determining soil temperature. .

In the early 1980's, Professor Lanny J. Lund of University of California, Riverside initiated measurements of soil temperature throughout the Mojave Desert for future uses in soil classification. The data collection continued at 75 sites from 1982 to 2000. In addition, information on ambient temperature, precipitation, evaporation, and vegetation distribution of the region were also included. The data set would illustrate the long-term soil temperature trends of the Mojave Desert under the influences of the regional climate change. Soil temperature measurements at rural locations are free of anthropogenic influences and are telling measures of the climate fluctuations and trends of the region integrating impacts of the ambient air temperature, precipitation, evaporation, and vegetation distribution to the terrestrial environment (Changnon, 1999).

I used this database to analyze the spatial and temporal change patterns of soil temperature, to assess the effect of geographic and meteorological factors on the spatiotemporal change pattern of soil temperature, and to examine the relationship between regional climate change and soil temperature change over an extended period of time in the Mojave Desert region. The work is divided into four sections:

- Chapter 3: Evaluation of Pallmann method for long-term measurements of soil temperature.
- Chapter 4: Examination of the effects of different geographic factors on the spatial variation of soil temperature and linking the spatial variations of soil temperature with geographic factors; characterize the spatial pattern of soil temperature regimes and its seasonal and temporal variations in the Mojave Desert region.
- Chapter 5: An analysis of the temporal change of soil and air temperature during the period of 1982-2000 and the long-term climate change in the Mojave Desert region.
- Chapter 6: Examination of the correlation between soil temperature and different meteorological factors and link the spatial variations of soil temperature with

climatic factors, extrapolate the historic soil temperature based on records from weather stations in the Mojave Desert region.

A thorough literature review is presented in Chapter 2 and a general conclusion is presented in Chapter 7.

Chapter 2

LITERATURE REVIEW

2.1 Climate Change and Its Impacts on Soil Environment

The Earth's climate has varied cyclically between cold, glacial conditions and warm, interglacial periods over the past 500,000 years. The cyclicity is driven by changes in the distribution of sunlight on the Earth's surface as the planet's orbit varies slightly through time. Over the past 100 years, the Earth's climate has warmed by approximately 0.8°C with two main periods warming, between 1910 and 1945 and from 1976 onwards (Seinfeld, 2008; Hansen et al., 2006). The rate of warming during the latter periods has been approximately double that of the first and greater than at any other time during the last 1,000 years (Walther et al., 2002).

Many factors influence climate: solar activity, oscillations in Earth's orbit, greenhouse gases, ice cover, vegetation cover, the configuration of the continents, dust thrown up by volcanoes or wind, the weathering of rocks, etc. Complex interactions between many of these factors amplify or dampen changes in temperature (Seinfeld, 2008). The current warming trend is mainly due to increasing concentration of greenhouse gases (GHGs) in the atmosphere induced by human activity (IPCC, 2001; Khandekar et al., 2005; Lindzen, 1994; Murphy and Timbal, 2008; Alley et al., 2003; Scavia et al., 2002).

A portion of the incident infrared radiation escapes from higher and colder parts of the atmosphere. As GHG levels increase, the atmosphere becomes more opaque to infrared, and leading to less outgoing radiation. The result is that the planet receives more solar energy than it loses. Many atmospheric gases have the ability to absorb infrared radiation, but only those present at significant concentrations can affect appreciably the Earth's energy balance. Water vapor and carbon dioxide (CO_2) are the major atmospheric absorber of infrared radiation.

While the current warming is nearly worldwide, change on a regional or local scale is often more subtle and variable. Generally, warming over the oceans is less than that over land; this is the expected response to a forced climate change because of the large thermal inertia of the ocean. The largest warming has taken place over remote regions, especially at high latitudes in the Northern Hemisphere (Seinfeld, 2008).

Anthropogenically driven climate change will significantly impact on the environment (Donnelly et al., 2004). In soils, these changes will mainly impact four general areas of the soil environment temperature, moisture content, ecological functions, and structure.

2.1.1 Soil Temperature

Soil temperature and air temperature are interrelated and a warming world is expected to lead to warmer soils, however, the heat conductivity of soil is mediated by the mineralogy, organic matter content, soil moisture effects, surface albedo, and vegetation. Temperature regulates the rates of most soil process, especially those that are biologically-driven. Soil temperature changes have the most noticeable impacts in the permafrost regions at high latitudes (Kane et al., 1991). Waelbroeck (1993) found that the active layer depth in soils of permafrost terrain could increase by 75% in response to a 3°C increase in air temperatures. However, such a change only had minimal effects on the total net mineralization of tundra soils (Jonasson et al., 1993).

Changes in soil temperature have been linked to changes in soil properties such as pH and ion concentrations that in turn may affect soil respiration, microbial decomposition and mineralization, and turnover of soil organic carbon (Zhang et al., 2005). Consequently, changes of soil temperature could profoundly impact the carbon balance in the terrestrial ecosystems and have significant environmental consequences locally and globally.

2.1.2 Soil Moisture Content

Global changes in precipitation patterns will alter water movement into and out of soils, altering soil moisture distributions. The soil moisture exerts a substantial influence on ranges of soil processes and may dictate how soils may be used for. In soils, the water content is controlled by processes such as infiltration, percolation, runoff and drainage.

Water mobility and distribution in the soil profile respond to inputs such as precipitation and irrigation. The warming trends projected by the global climate changes not only impact the soil water contents through enhanced plant growth, longer growing seasons and consumptive use but also alter mobility of soil as the surface tension and viscosity of water are reduced. The fluctuations of soil water fluxes in turn influence the local climate as they exacerbate the soil drying, alter circulation patterns vital to storm development, and increase air temperatures (McCorcle, 1990).

Soil temperature and soil moisture are two key characteristics controlling the biological processes of the soils that are directly influenced by the ambient climate characteristics, such as air temperature and precipitation and are further modified by vegetation cover, topography, and soil properties (Moustafa et al., 1981; Kang et al., 2000). Soil temperature and soil moisture are collectively referred to as soil-climate, as opposed to ambient climate, which may exert great influences on the complex interactions between soil, vegetation and ambient climate.

2.1.3 Soil Ecological Functions

Soil temperature and its seasonal variations will impact the regional ecosystem functions of terrestrial environment (Peters-Lidard et al., 1998). Plant growth, soil respiration, microbial decomposition, organic matter storage and mineralization, and a variety of chemical reactions and pedogenic processes of the soils would respond to the soil temperature changes (Lin, 1980; Seyfried, 2001; Brooks et al., 2004; Schimel et al., 2004). For examples, seed germination is most rapid when soil temperature is in the optimal ranges (Krishnan and Rao, 1979). The mineralization of plant nutrients, such as nitrogen, along with the consequent liberation of carbon dioxide, is also strongly temperature dependent. Soil organisms may also be affected by elevated atmospheric CO_2 concentrations (Rounsevell et al., 1996). There are ample evidences of the clearly visible ecological responses to recent the climate change. The responses of both flora and fauna span an array of ecosystems and organizational hierarchies, from the species to the community levels (Walther et al., 2002).

2.1.4 Soil Structure

Climate changes might be expected to modify soil structure through its influence on the physical processes, and through changes in soil organic matter levels (Carter and Stewart, 1996). Climate change will directly impact on the quality of soil organic matter and aggregate size primarily through temperature and precipitation mediated effects (Cole et al., 1993), and indirectly by changing land use patterns. In addition to the soil organic matter, climate change may accelerate the rate of weathering and clay surface processes (Wagenet et al., 1994). Weathering involves the physical disruption of rock structures followed by chemical changes within the constituent minerals. Weathering rates depend on temperature and the rate of water percolation, both of which will be influenced by climate change. Over time, this will result in changes to the global distribution of soil types, concurrent with changes in the use to which these soils may be put.

2.1.5 Soil Degradation

On a regional scale, climate change may enhance land degradation through salinization, acidification and especially erosion. An increase in temperature coupled with reduced rainfall will lead to predominantly upward water movement in soils, as currently seen in the more arid parts of the world, and this will result in the accumulation of salts in the upper soil layers. Such effects will be intensified if poor quality irrigation water is used on agricultural soils. Salinity and waterlogging currently lower productivity on 25% of the world's irrigated cropland, and will have significant impacts on future agricultural production under a changed climate (Brown and Young, 1990). Soil erosion rates may be increased where climate change leads to increases in the frequency and intensity of precipitation events (Botterweg, 1994), and changes in land use (Boardman et al., 1990). Soil nitrogen loss from the soil profile through volatilization of ammonia is enhanced at higher temperatures and in a drier soil. Therefore, warmer and drier climatic conditions, arising from climate change, would be expected to enhance volatilization and thus, ammonia losses (Rounsevell et al., 1996; Bradbury and Powlson, 1994). In addition, increased plant growth in a CO_2 enriched atmosphere may rapidly deplete soil nutrients and consequently the positive effects of CO_2 increase may not persist as soil fertility decreases.

2.2 Soil Temperature and Air Temperature

The change in air temperature can translates into a change of soil temperature through three heat transfer mechanisms: (1) sensible heat flux; (2) latent heat flux (cooling the surface by evaporation); and (3) infrared heat flux (cooling by emission and warming by absorption) (Seinfeld, 2008). The latent heat flux tends to be the dominant term in soil temperature calculations. In warm, wet areas, evaporative heat transfer is so effective that the surface temperature remains close to the overlying air temperature, and in-surface temperature follows that of the troposphere just above the surface. By contrast, the daytime surface of the desert soils tends to be much warmer than the overlying air, because in the absence of moisture, the relatively inefficient sensible and radiative heat transfer requires a relatively large temperature difference to generate the necessary heat flux.

Furthermore, vegetation can influence greatly the surface energy balance (Cermak et al., 1992). Experimental studies have shown that vegetation canopies can lower soil temperature during growing season significantly and reduce mean annual soil temperature (Li, 1926; Jemison, 1934; Qashu and Zinke, 1964; Armson, 1977; Munn et al., 1978; Cermak et al., 1992).

The snow cover also has significant impacts on the linkage between the soil and air temperature. Dark colored soils generally capture a much high proportion of the radiant energy than do light colored soils (albedo). Snow has high albedo and emissivity that cool the snow surface, high absorptivity that tends to warm the snow surface, low thermal conductivity so that a snow layer acts as an insulator, and high latent heat due to snowmelt that is a heat sink. The overall impact of snow cover on the ground temperature depends on the timing, duration, accumulation, and melting processes of seasonal snow cover; density, structure, and thickness of seasonal snow cover; and interactions of snow cover with micrometeorological conditions, local micro relief, vegetation, and the geographical locations (see the review by Zhang, 2005). Over different timescales either the cooling or warming impact of seasonal snow cover may dominate. In the continuous permafrost regions, impact of seasonal snow cover can result in an increase of the mean annual ground and permafrost surface temperature by several degrees, whereas in discontinuous and sporadic permafrost regions the absence of seasonal snow cover may be a key factor for permafrost development. Brown (1970) reported a difference of 3°C between annual mean air and soil temperatures for Canada's permafrost areas. The difference in annual mean air and soil temperatures was mainly due to the much higher soil temperature during the winter months because of the insulating effect of the snow cover.

In addition to the consistent difference in their annual means, soil and air temperature may also differ in their daily and annual pattern as well as long-term trend. Both soil and air temperature are dynamic in nature having a yearly cyclic appearance due to seasonal changes and having a diurnal variation of periodic nature on a daily basis.

The daily pattern of air temperature normally follows a sine curve with the minimum occurring in the early morning hours near sunrise and the maximum sometime after the peak of solar radiation has been reached. A time lag exists between air and soil temperatures due to the relatively large heat capacity of the ground. Nevertheless, typical lags between air temperature and soil temperature at a depth of 10 cm are approximately 4 h for minimum temperatures and 6 h for maximum temperatures (Lee, 1978). If snow is present, the relationship between air and soil temperatures will be different from that without snow due to insulation of the snow. The daily amplitude of soil temperature at the surface is greater than the daily amplitude of air temperature for clear days and is less for cloudy days.

The annual wave of air temperature follows a similar pattern respect to the annual wave of solar radiation, namely reaching the peak in the summer months and approaching the lowest in the winter months. Again, the peak of the temperature lags that of the radiation by sometime depending on the characteristics of the location. The annual amplitude is affected by local atmospheric cycles. ENSO is one of them. ENSO is an irregular phenomenon that alternates between its two phases, El Niño and La Niña, approximately every 2–7 years (Allan et al., 1996; Markgraf and Diaz, 2000). ENSO is a periodic reorganization of Sea Surface Temperature (SST) and atmospheric circulation in the tropical Pacific that results in vast redistributions of major rainfall-producing systems (Rasmusson and Carpenter, 1983; Allan, 2000). Generally, El Niño (La Niña) events cause a warming (cooling) in tropical Pacific and Indian Oceans that suppresses (enhances) rainfall in western (eastern) Pacific regions (Allan et al., 1996). A ‘typical’ ENSO event tends to last for 18–24 months with peaks in amplitude mostly occurring in the austral summer (December–February) (Rasmusson and Carpenter, 1983; Allan, 2000).

Many stations across the United States have long-term records of daily air temperature; few climate stations monitor soil temperature since it is often difficult and costly to measure (Zheng et al., 1993). Deriving a method to predict soil temperature from air temperature could decrease the amount of time and cost necessary for on-site monitoring of soil temperature and allow researchers to use data from other sources. In addition, linking soil temperature with daily air temperature from permanent weather station data could allow researchers to explore historic trends in soil temperature data beyond the period of actual onsite monitoring.

Soil temperature might be estimated by two different approaches based upon: (1) soil heat flow and energy balance (Campbell, 1977; Parton, 1984; Stathers et al., 1985; Nobel and Geller, 1987; Thunholm, 1990; Rosenberg et al., 1983; Marshall et al., 1996), and (2) empirical correlations with easily acquired variables (Zheng et al., 1993). Theory-based models may provide accurate estimates of soil temperature at small scales, but they are computationally demanding and parameter intensive (Qin et al., 2002). These models may not be practical for estimation of soil temperature at continental and global scales as many parameters required may vary drastically over short distances. Empirical regional regression models, such as the one developed by Zheng et al (1993), require only a few variables such as air temperature and LAI, but depend on good estimates of some key regression coefficients specific to each region. The limitation can be improved when the structure and parameterization process of model are modified in terms of heat transfer physics (Kang et al., 2000).

2.3 Methods for Soil Temperature Measurement

Temperature is a measure of the average energy of motion (kenetic energy) of the atoms or molecules that make up a substance (McGee, 1988). Temperature is one of the seven base quantities used in the SI system, from which all other measurable quantities are derived. Temperature can never be measured directly, meaning that every temperature measurement involves the use of some type of calibrated sensor/transducer to convert a measureable quantity into a temperature value. There are many different techniques depending on the temperature measurement requirements.

A wide variety of different types of instrument is used to measure low temperature. The common ones include platinum resistance thermometers, other metallic resistance thermometers, semiconductor resistance thermometers, diode thermometers, thermocouples, vapor pressure thermometers and gas thermometers (Bentley, 1998).

For measuring high temperatures, radiation thermometry is often used. All materials emit thermal radiation (radiant heat) and the amount of thermal radiation emitted increases with temperature. The measurement of the amount of thermal radiation emitted by a material can therefore be used as an indicator of its temperature. Instruments designed to measure temperature in this way are called radiation thermometers. Radiation thermometers are now usable to much lower temperatures.

In addition to these common used types of thermometry, there are unconventional thermometry based on different physical systems with an extrinsic property related to its temperature like acoustic methods, eddy-current method, coherent anti-Raman spectroscopy, gas-viscosity thermometry, noise thermometry, optical-fibre methods(Bentley, 1998).

For measuring soil temperature, thermal couples and thermistors are commonly used. A thermal couple consists of two wires of different metals or alloys with their two ends welded together. If the two end junctures are at different temperatures, a voltage difference in proportion to the temperature difference appears and this voltage is not affected by the length of the wires or temperature variation along the wires. One thermal couple wire is usually cut and the voltage is measured between its two open ends. The relation between voltage and temperature difference is very well calibrated and stays unchanged for a given type of thermal couple. Thermocouples are good for laboratory usage. For field application, there are downsides. It is cumbersome to use long thermal couple wires and to maintain a steady reference temperature. A thermistor is a solid, semiconducting oxide. It is electrical resistance decreases rapidly with increasing temperature, a characteristics that avails itself a good sensor for high precision temperature measurements. For high precision measurements, each thermistor even of the same type should be individually calibrated. Periodic calibration is needed to correct for a drifting temperature-resistance relation.

Measurements of temperatures that are averaged or integrated over long time spans are needed for a variety of purposes. Customarily, mean temperatures are obtained in a two-step process of observation and numerical or graphical summation of periodic values. Pallmann introduced a temperature technique using the fact that the rate of inversion of a solution of sucrose to invert sugar (mixture of glucose and fructose) is temperature-dependent (Pallmann et al., 1940). Trembour et al (1988) proposed a diffusion-cell method to measure the mean soil temperature. This method measured the temperature dependent diffusion rates of water and sodium chloride separated by a molecular sieve (a hollow sphere of water-permeable plastic) inside a polycarbonate test tube. Owing to the high but constant gradient of water vapor pressure between the interior and exterior of the sphere, water diffuse through the plastic wall at a rate which is a function of temperature. The change of in weight of the cell is a function of the time and integrated temperature that the cell experienced. Compared to the thermal sensor method like thermal couples and thermistors in which thousands and hundreds of points had to be recorded and then transferred to a computer to calculate average or integrated annual temperature, the Pallmann method and the diffusion cell method measured the mean temperature directly and may better reflect the real ecological processes in soil.

Soil temperature varies with the depth of the soil profile. Measurements of soil temperature are commonly obtained at a profile depth of approximately 50 cm. At shallower depths, fluctuations due to diurnal changes of air temperature are expected. Deeper in the profile, the seasonal pattern suffers a time lag and seasonality becomes less apparent until at some depth it is no longer discernible (Watson, 1980). This depth usually is much affected by latitude and the presence or absence of groundwater. The 50-cm soil temperature data taken in rural sites should be free from any urban influences and serve as a meaningful measure of the general climate fluctuations and trends.

2.4 Soil Temperature Regime

Classification systems in general are developed as a tool for communication, for aggregation of information into logical units, for interpretation, and for the extrapolation of interpretations and information among units with similar properties. Most nations develop systems of soil classification that reflect their own preferences and needs aims to group soils in a manner useful for practical (Isbell, 1992; Yaalon, 1995). Soil temperature was first used in soil survey in the United States in 1965 (Schmidlin et al., 1983). In 1975, Soil Taxonomy was published by the United States Department of Agriculture's Soil Survey Staff (USDA, 1975). It is one of the most widely used soil classification systems in the world. It integrates both soil genesis and soil morphology into a hierarchical system. No classification scheme can remain static. As new knowledge is gained, soil classifications need to be modified and improved. This USDA system for classifying soils has undergone numerous changes since that time, and the 2nd edition was published in 1999. After original publication of the 1975 comprehensive Soil Taxonomy, abridged keys have been published since 1983 about every two years (1983, 1985, 1987, 1990, 1992, 1994, 1996, 1998, 2003, and 2006) which included the approved changes as recommended by the International Soil Classification Committees (ICOMs).

In the U.S. Soil Taxonomy, the soil temperature regimes were defined by MAST, and seasonal fluctuations at 50 cm depth (see Appendix I). Soil temperature is classified as hyperthermic, thermic, mesic, and frigid, when the difference between MSST and MWST is more than 5 °C. If the difference between MSST and MWST is less than 5 °C, the pedon is considered to have an Isotemperature regime with prefix “Iso” in its name.

The limits of the temperature regimes in Soil Taxonomy were established on the basis of several major crops grown in the United States, thus allowing spring wheat to be distinguished from winter wheat (8 °C) and the lower limit to be set for crops such as cotton, pineapple, and sugarcane (15 °C) (Smith, 1986; Nimlos, 1987). The “iso” prefix was defined to differentiate tropical climate soils from their temperate counterparts, given that the seasonal temperature fluctuations in the former do not pose problems for plant growth. Now, there are two main controversies in the definition of “Iso” Soil temperature regimes (Tejedor et al., 2009). One is the difference between MSST and MWST should be 5 °C as defined in the first edition of Soil Taxonomy (Soil Survey Staff, 1975) or be 6 °C as in the second edition (Soil Survey Staff, 1999) and later keys (Soil Survey Staff, 2006). The other important controversy arising in relation to “iso” regimes centers on the months used to define them.

While the soil temperature regimes were parameters initially developed to locate areas for suitable for agricultural crops, they are also ecological indicators of plant distributions and wildlife habitats. In practice, knowledge of the soil temperature regimes is important: 1) to understand the development and formation of specific soils; 2) to consistently classify and accurately map soils; 3) to apply that knowledge to the use and management of soil-plant-water systems (Mount and Paetzold, 2002).

Scientists have made great efforts to identify the spatial distribution of soil temperature regimes (Krishnan and Rao, 1979; Watson, 1980, Mahrer, 1980; Moustafa, 1981; Schmidlin et al., 1983; Tajchman, 1986; Titus, 2002; Berndtsson, 1996; Hlavinka et al., 2007; Mazhitova, 2008). The common means of extrapolating soil temperature facts from measured sites to other locations, or to a map display of soil temperature regime is to correlate the MAST with geographic parameters. These geographic parameters then can be used to estimate soil temperature at other locations or to plot soil temperature regime distribution maps.

Chapter 3

EVALUATING METHODS FOR MEASURING THE MEAN SOIL TEMPERATURE

3.1 Introduction

Soil temperature is an important environmental factor that regulates the exchange of heat energy between the land surface and atmosphere (Jackson et al., 2008). It determines the rates of physical, chemical, and biological reactions in soils and has strong influences on plant growth and over the long run on soil formation (Trumbore et al., 1996; Tenge et al., 1998; Seyfried et al., 2001; Qi and Song, 2003; Brooks et al., 2004). Soil temperature is a key parameter in Soil Taxonomy (Soil Survey Staff, 1999). It is incorporated into the soil classification system through the soil temperature regimes, namely the mean annual soil temperature (MAST) and the difference between mean summer temperatures and mean winter soil temperatures.

Mean annual soil temperature, a standard index for the thermal climates of soil, is necessary for accurate soil resource inventory and for climates studies. It has been universally used as an independent variable relating the average reaction rates of physical and biological processes occurring in soil environment (Lee, 1969). Measurements of mean temperature usually require integration and sampling over a temporal scale; which introduces two potential sources of bias, sampling method and data interpolation, into estimates of climate, such as soil temperature. The common way to measure the soil temperature is to plant soil temperature sensors at a given depth in the soil and connecting them to various types of automated data acquisition system such as data loggers. Thermistors, thermocouples, thermocouple wire, and averaging thermocouples are standard soil temperature sensors that are available. This approach is costly, especially when a large numbers of sensors are needed to cover the spatial variation in soil temperature in a large region (Costello and Horst, 1991; Plauborg, 2002). Annual or seasonal estimates of mean soil temperature must balance the accuracy of frequent sampling against the logistical costs of maintaining functional sensors for long periods of time, and the storing and transferring data for analyses.

With technology development, temperature can be measured rapidly, continuously and precisely. However, the arithmetic-mean soil temperature measured by thermal sensors may not reflect the real ecological processes in soil as the biochemical reactions respond in a nonlinear manner to temperature (Friedman and Norton, 1981). According to

Vant Hoff's law, the rate of chemical reaction doubles for each 10 °C rise in temperature (Van Wambeke, 1992).

The Pallmann technique, developed in the 1940s, offers an alternative to data collection by temperature sensors in long term areal-wide climate studies, because it was dependent on rate of a temperature driven chemical reaction to integrate temperature over a long period time (Pallmann et al., 1940). A sampling unit may be planted in the ground and recovered after a set time interval, and the chemical reaction rate would reflect the mean temperature for that period of time. The technique is ideally suited for areal-wide studies that require simultaneous measurements of the temperature at multiple locations, especially measurement sites that are unattended, infrequently visited, or difficult to maintain. The Pallmann method had been employed in many soil temperature studies (Murdock, 1956; Schmitz and Volkert, 1959; Friedman and Norton, 1981; Norton and Friedman, 1981; Olmsted et al., 1981), and the cost of field sensors and laboratory analyses are minimal.

A diffusion cell method to measure the mean temperature was first proposed by Ambrose (1980) and later modified by Trembour et al (1988). This method measured the temperature dependent diffusion rates of water and sodium chloride separated by a molecular sieve (a hollow sphere of water-permeable plastic) inside a polycarbonate test tube. Owing to the high but constant gradient of water vapor pressure between the interior and exterior of the sphere, water diffuse through the plastic wall at a rate which is a function of temperature. The change of in weight of the cell is a function of the time and integrated temperature that the cell experienced.

The Pallmann method and diffusion cell method avoid many of the shortfalls of electronic sensors, but the accuracy of these non electron sensors however has not been comprehensively compared with outcomes of automated electronic sensors for extended periods of time and under highly variable conditions. In this chapter, the performances of three soil temperature measurement methods namely the Pallmann method, diffusion method, and thermistor continuous temperature sensors were evaluated based on data collecting from a long-term climate change investigation project.

3.2 Materials and Methods

3.2.1 Basic Theory of the Pallmann Method

The Pallmann method makes use of the fact that the rate of inversion of sucrose to invert sugar (mixture of glucose and fructose) in a solution is temperature-dependent given the pH does not change during the process. It is an irreversible reaction that:

$$\text{Sucrose}\,(+) \rightarrow \text{Glucose}\,(+) + \text{Fructose}\,(-) \qquad \text{[Eq. 3-1]}$$

Assuming the initial concentration of sucrose is A and an amount of x inverts to glucose and fructose after time t, the mean reaction velocity coefficient ($\bar{k}$) during the time period t can be described as:

$$\bar{k} = (1/t)\log[A/(A-x)] \qquad \text{[Eq. 3-2]}$$

The reaction velocity is proportion to the hydrogen ion concentration H^+ (i.e. pH). Change of sucrose concentration can be expressed in term of rotation angle. Under specific pH, the Eq. 3-2 becomes:

$$\bar{k} = (1/H^+t)\log[(R_0 - R_\infty)/(R_t - R_\infty)] \qquad \text{[Eq. 3-3a]}$$

or

$$\log\bar{k} = pH - \log t + \log[\log(R_0 - R_\infty) - \log(R_t - R_\infty)] \qquad \text{[Eq. 3-3b]}$$

where R_0, R_t and R_∞ refer to the rotation angles of sucrose solution in degree at time of 0, t, and infinity (when all the sucrose has inverted to invert sugar), respectively.

In the Pallmann method, it was assumed that the reaction depends on temperature according to the Van Hoff-Arrhenius law, namely, the logarithm of the velocity coefficient $\bar{k}$ varies linearly with the reciprocal of absolute temperature T.

$$\log\bar{k} = b - \frac{a}{T} \qquad \text{[Eq. 3-4]}$$

where a and b are empirical constants. Combing Eq. 3-3b and Eq.3-4, the mean temperature, T, in degrees Kelvin (^oK) over a period of time t (days) may be calculated by the following equation:

$$T = \frac{-a}{pH - b - \log t + \log[\log(R_0 - R_\infty) - \log(R_t - R_\infty)]} \qquad \text{[Eq. 3-5]}$$

Eq. 3-5 allows the calculation of the mean reaction temperature of sucrose hydrolysis if the pH, reaction time, and the three specific rotation angles are known.

In general, a difference in ambient temperature of 0.1 °C corresponds to an optical rotation difference of about 0.4 degree. If R_0 = 60 degree, R_t = 20 degree, and R_∞ = -20 degree, $\Delta T/\Delta R_t \approx 0.25$ °C deg^{-1}. Based on polarimeter accuracy of ±0.01 degree, therefore, read-out sensitivity is equivalent to ±0.0025 °C. Norton and Friedman (1981) demonstrated that the precision of the Pallmann method is less than ±0.1 °C. The precision of the Pallmann method to measure the mean temperature during the specific period is one of its principal advantages.

3.2.2 Field Application of the Pallmann Method

To apply the Pallmann method in the fields, it is usually first to prepare the Pallmann temperature sensing elements by sealing small aliquots of the sucrose solution in clear glass ampoules and then expose the sensors at measurement sites in soil, air or water bodies over the time period of interest. Upon recovery from the field, the rotation angle of the ampoule contents is analyzed and the mean temperature during the study period can be calculated based on constants obtained through batch of experiments in the laboratory that calibrate Logk vs. 1/T according to Eq. 3-4. For a given sensor set (sensors prepared from the same batch of solution), Eq. 3-5 reduces to an expression in T and R_t.

The absolute accuracy of the Pallmann method is influenced by laboratory and field measurement issues. Several approaches may be adapted to improve the accuracy of the Pallmann method: 1) preventing the hydrolysis during the period of preparation and transportation to the field by freezing the sensors; 2) adjusting the pH of the sensing solution to insure that inversion occurs rapidly enough to be measured accurately. The pH level must be chosen to coincide with the length of the measurement period and the expected mean temperature. A minimum practical pH level ranges from 1.2-1.6, which requires a minimum observation period in the middle latitudes of about 5-15 days in summer or 15-30 days in winter; 3) preventing the deterioration of the solution by bacterial growth by adding a small amount of formaldehyde to the solution.

There are other factors that may affect the accuracy of the method. If a sensor is exposed to direct solar radiation, it may, due to absorption of heat, induce a temperature rise in the solution that is not characteristic of the ambient air. The impurities in the solution may change its specific rotation, thus the relationship between optical rotation and sucrose- or invert-sugar concentrations. The effects of added substances such as HCl and formaldehyde are relatively minor. With precautions to keep $R_t > 0$ and R_0 near its maximum, resultant errors in T do not exceed ±0.05 °C. A pH change may occur during hydrolysis. Richard Lee (1969) reported that there was a -0.044 °C change for mean pH of their experiments.

In field applications, the Pallmann solution freezes at about -5 °C (Pallmann et al., 1940). If a sensing element is exposed to temperature lower than -5 °C, the solution solidifies and hydrolysis ceases. Moreover, a frozen sensor cannot respond to rising temperatures until completely thaw. It follows that the Pallmann sensors will not integrate temperatures below the freezing point, and will not respond predictably when freezing and thawing occur during a measurement period. These limitations suggest the advisability of lowering the melting point of the Pallmann solution for cold weather temperature measurement. A reagent grade sodium chloride, 150 g L^{-1} can be added to the normal solution to serve as an antifreeze. This quantity of salt depresses the freezing point of the salt-sugar solution below -20 °C.

3.2.3 Data Collection

The Pallmann solution was made according to those given by O'Brien (1971). It composed of two solutions mixed in 1:1 volume to volume. One solution contained 1,500 g of sucrose in 1,000 ml of water, and the other consisted of 404 ml of 0.2 M sodium citrate (buffer) and 596 ml of hydrochloric acid (0.2 M or other concentration). The pH of the solution was adjusted to targeted values ±0.02 units by varying the concentration of HCl. A small amount of formaldehyde was added to the solution to prevent deterioration of the solution by bacterial growth.

The Pallmann temperature sensors were made by filling 4 ml glass ampoules with the Pallmann solution, sealed, and kept frozen. At the time of use, the temperature sensors were thawed and planted at the 50 cm depth below soil surface at sites. The temperature sensors were removed from the ground one year later and placed immediately in a container with dry ice for transporting to the laboratory. The optical rotation angles of the samples were measured with a Rudolph Model 52A2 Polarimeter with a mercury lamp at 546.07 nm. The MAST at each collection site was obtained based on the standard curve derived in the laboratory.

At 21 of the 75 sites, the soil temperature was measured with two other sensing techniques: thermistor sensor and the diffusion-cell method (Ambrose, 1980). A Fenwal

Electronic UUT51J1 thermistor in water resistant coating (Campbell Scientific, Inc. (CSI), model 107) was used. The accuracy of the probe, in the worst case scenario, is ±0.4 °C as specified by the manufacturer. The sensor was placed at 50 cm depth below the soil surface and the temperature was recorded every 10 minute with CSI CR10 data logger. The recorded data were then averaged to derive the MAST. The data were collected continuously at these sites for a period of 15 years (1984-1999).

The diffusion-cell method is similar to the Pallmann method in that sensors are left in the ground with no information on the temperature changes until the cell contents are analyzed at the end the time period. We determined the MAST at 50 cm depth continuously for 8 years (1992-1999) at the sites according to the method described by Trembour et al (1988). The MASTs were calculated based on the mean weight change of the cell (R, mg day^{-1}) and laboratory obtained as:

$$MAST(^{o}C) = (\log R + 0.76)/0.027 \qquad \text{[Eq.3-6]}$$

3.3 Results and Discussion

3.3.1 Linearity of the Pallmann method

The major concern of the Pallmann method is the linearity of sensor response to temperature, namely, whether the hydrolysis reaction of sugars was dependent on the temperature according to the Van Hoff-Arrhenius law (Eq. 3-4). Batch of experiments were conducted to check the relationships between the rate of sucrose hydrolysis, Logk (according to Eq.3-2), and the temperature under Pallmann solutions of 9 different pH.

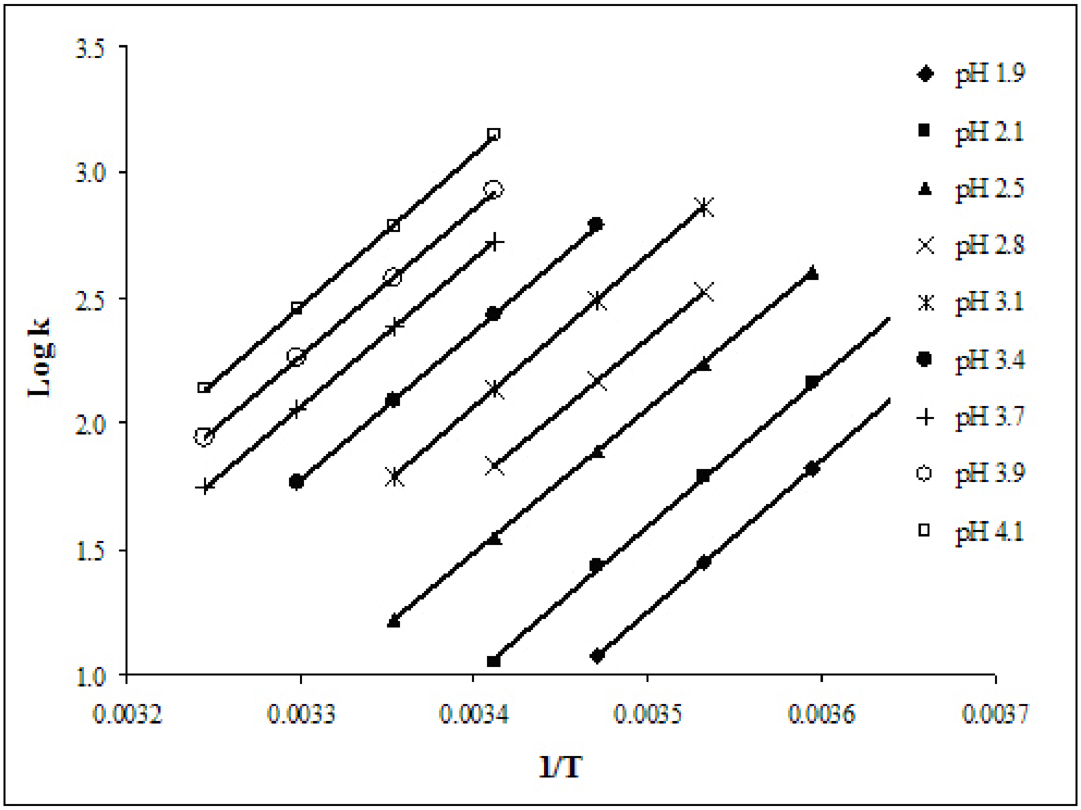

Figure 3-1. Correlation between temperature and the rate of sucrose hydrolysis (Log k) under 9 different solution pH. The data were fitted to the Van Hoff-Arrhenius equation (Eq. 3-4).

The Logk for Pallmann solutions with pH ranging from 1.9 to 4.1 changed according to the Arrhenius equation (Eq. 3-4). As illustrated in Figure 3-1, Logk decreased linearly when the temperature increased for temperature varied from 5 °C to 35 °C. Hypothetically, constant a and b do not change with the solution pH (Table 3-1). The fitted constant a varied from 5,744 to 6,030 with mean = 5,922 and standard deviation = 111. The coefficient of variation (CV) of constant a, for pH varied from 1.9 to 4.1, was 1.9%

indicating a narrow dispersion of the data. The outcomes were comparable to those reported by Pallmann (1940) and Norton and Friedman (1981) that constant a varied from 5,914 to 5,867 with mean = 5,846 and standard deviation = 66. The fitted constant b varied from 17.25 to 19.85 with mean = 18.14 and standard deviation = 0.87. The CV of constant b was 5% indicating a narrow dispersion of the data. The outcomes again were comparable to those reported by Pallmann (1940) and Norton and Friedman (1981) that mean = 20.17 and standard deviation = 0.25. In all, the linearity of the hydrolysis reaction with respect to temperature was verified. The temperature measurement based on Pallmann method would be accurate and precise and applicable to fields of large spatial scale and over long temporal period.

Table 3-1. Fitted Pallmann equation constants a and b at different solution pH.

Solution pH	**a**	**b**	**R^2**
1.9	6030	19.852	0.9999
2.1	5937	19.186	0.9996
2.5	5744	18.045	1
2.8	5762	17.826	1
3.1	6029	18.43	1
3.4	5937	17.818	1
3.7	5892	17.376	1
3.9	5915	17.251	0.9999
4.1	6054	17.51	0.9995

The data may be pooled to obtain the overall rate of sucrose hydrolysis over the pH range (Figure 3-2). The mean soil temperature (in degree, °C) may be calculated as:

$$T(^{o}C) = 5.46 - 14.975(\log k - pH) \qquad \text{[Eq.3-7a]}$$

With $$k = (1/t)\log[(R_0 - R_\infty)/(R_t - R_\infty)] \qquad \text{[Eq.3-7b]}$$

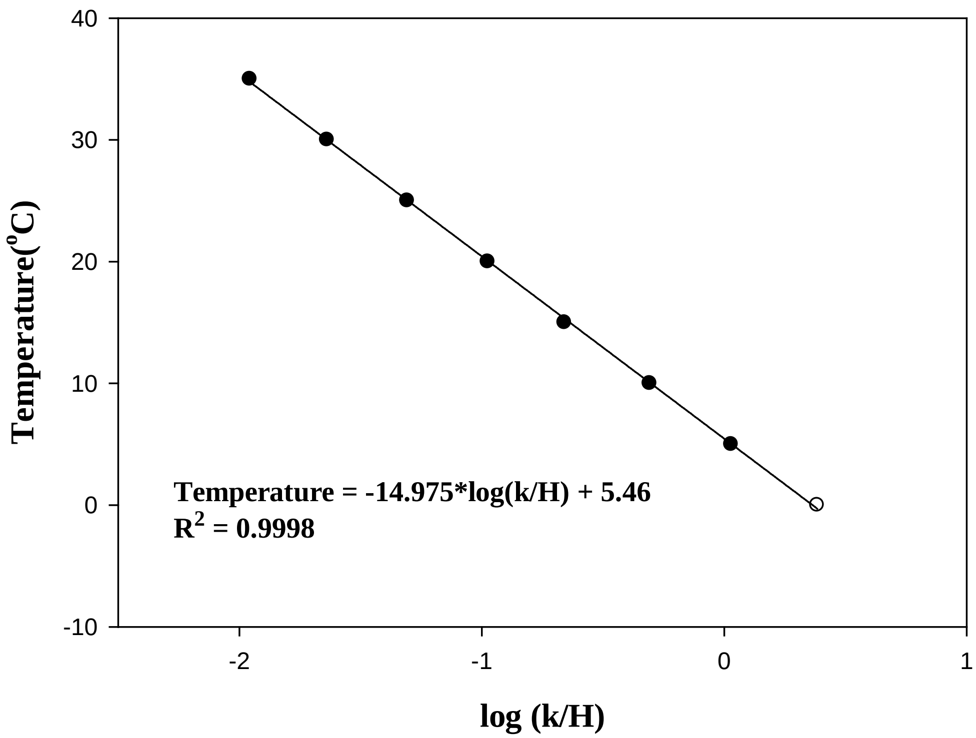

Figure 3-2. Linear correlation between temperature and Log(k/H), where k and H refer to the average reaction rate defined in Eq. 7b and the hydrogen ion concentration, respectively.

3.3.2 Accuracy of the Pallmann Method

The field sites for soil temperature measurements we compared were adequately distributed spatially across the Mojave Desert and were monitored over long periods of time. The mean annual soil temperatures measured varied from approximately 10 °C to over 25 °C (Figure 3-3). The MASTs measured by the Pallmann method and diffusion-cell method were comparable (Figure 3-3).

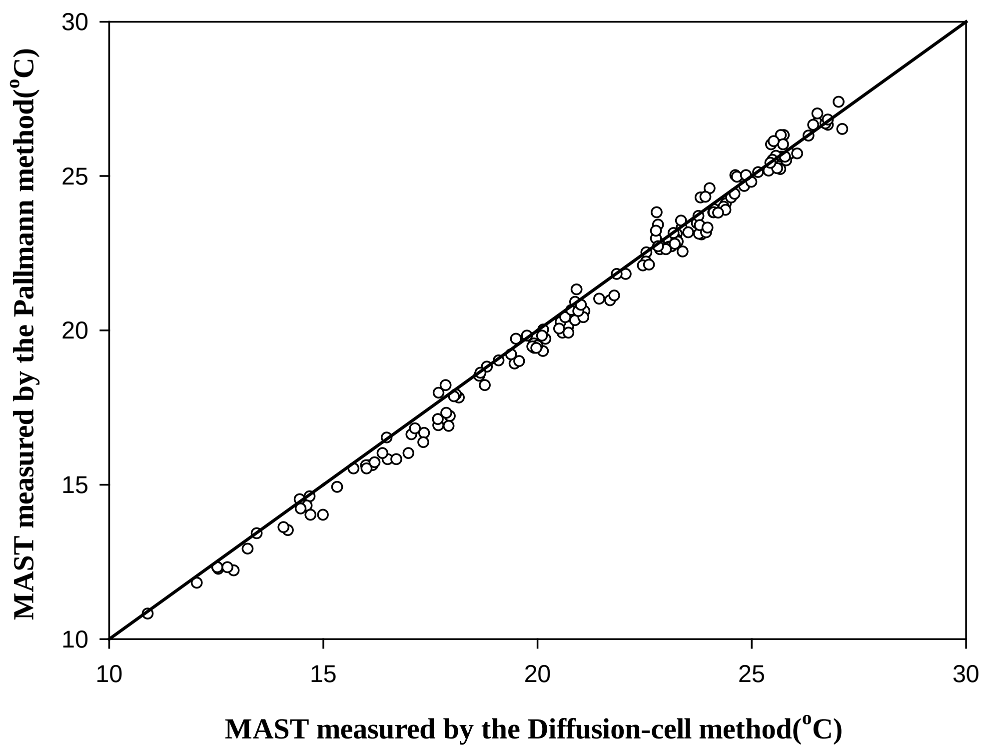

Figure 3-3. Comparison of mean annual soil temperature (MAST) measured by the Pallmann method and the diffusion-cell method at the same monitoring sites.

While the differences between the corresponding measurements by Pallmann method and diffusion-cell method varied from -1.01 °C to 1.06 °C, 70% of the MASTs measured by these two methods were apart by ±0.5 °C or less. Average over the measuring period, the MAST obtained by the Pallmann method was lower than that measured with the diffusion-cell method by 0.27 °C.

While both the Pallmann method and the diffusion cell method measure the mean temperature directly, they are based on quite different principle. The former is based on chemical reaction rate, while the later is based on the diffusion rates of water. It is not unexpected that there is a systemic difference for measurement of the mean soil temperature.

The MASTs measured by the Pallmann method were generally higher than those measured by the thermistor sensor method (Figure 3-4). Over 80% of the MASTs measured by the Pallmann method were higher than those measured by the thermistor sensor. While differences of the MASTs measured by the Pallmann method and the corresponding MASTs measured by thermistor sensor varied from -1.72 °C to 2.70 °C, 70% of them differed by ±1.0 °C or less. The MASTs obtained by the Pallmann method were on average higher than those measured with the thermistor sensor by 0.64 °C.

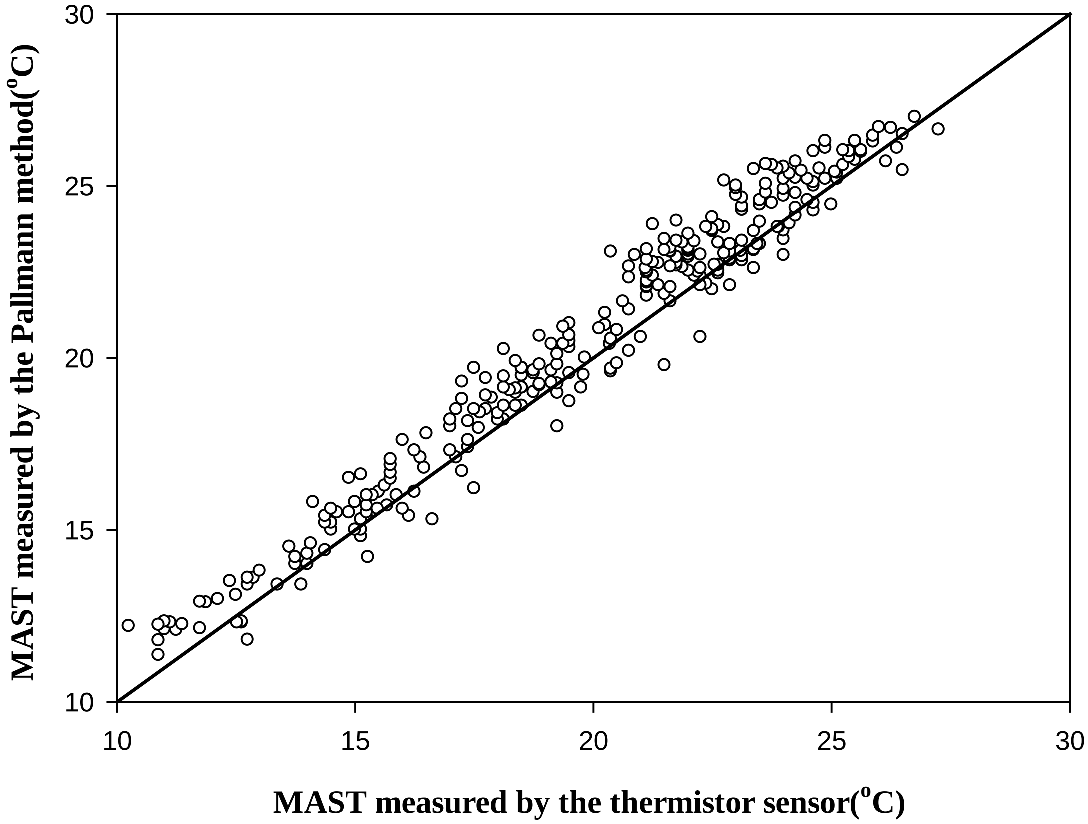

Figure 3-4. Comparison of mean annual soil temperature (MAST) measured by the Pallmann method and thermistor sensor at the same monitoring sites.

In Pallmann method, the reaction of converting sucrose to glucose and fructose exhibits hysteretic characteristics with respect to the soil temperature. An increase in temperature accelerates the cumulative reaction faster than that a decrease in temperature of equal magnitude will decelerate it. Therefore, if the sucrose solution experiences a fluctuating temperature, the reaction will be the same as if the sucrose was exposed to a constant temperature that is higher than the arithmetic-mean temperature. Therefore, it is reasonable that the temperatures measured by the Pallmann method are slightly higher than the arithmetic mean of the probe data (Norton and Friedman, 1981). The MAST estimated by the Pallmann method is consistent and reliable and the outcomes may better reflect the real ecological processes in soil.

The paired MASTs measured by the Diffusion cell method and the thermistor sensor are illustrated in Figure 3-5. Most of the MASTs measured by the diffusion cell method were higher than those measured by the thermistor sensor. The differences of the MASTs measured by the diffusion cell method and the corresponding MASTs measured by thermistor sensor varied from -1.14 °C to 3.47 °C. The MASTs obtained by the diffusion cell method were on average higher than those measured with the thermistor sensor by 1.09 °C.

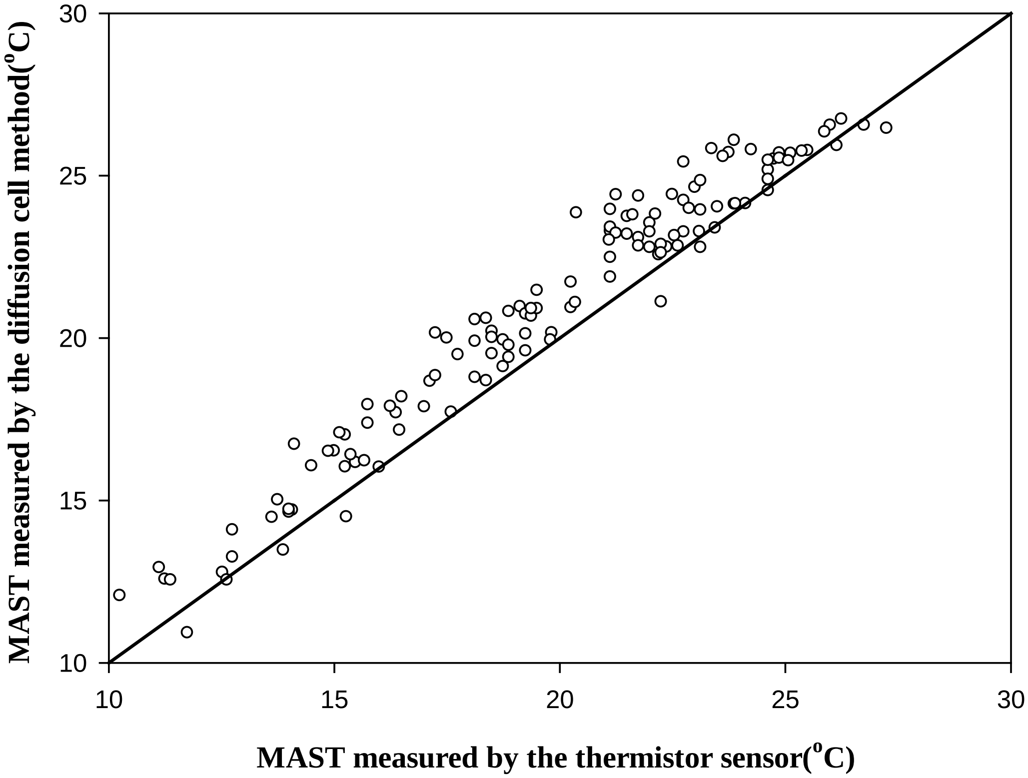

Figure 3-5. Comparison of mean annual soil temperature (MAST) measured by the diffusion-cell method and thermistor sensor at the same monitoring sites.

Statistical analysis showed that the three paired samples were highly correlated (Table 3-2). The standard deviations of the three paired group data were almost identical. The linear correlation coefficients paired data were 1.033, 0.993, and 0.953 for diffusion-cell vs. Pallmann, thermistor sensor vs. Pallmann, and diffusion cell vs. thermistor sensor, respectively. The 95% confidence intervals of the difference for these three paired data were quite narrow (Table 3-3). The results indicated that these three methods were interchangeable and comparable.

Table 3-2. Descriptive statistics of the paired comparison of diffusion cell vs Pallmann method, thermistor sensor vs. Pallmann method, and thermistor sensor vs. diffusion cell method.

Pair	Observations	Mean	Standard deviation	Standard Error	Correlations
Diffusion cell vs Pallmann	157	20.99	3.98	0.318	0.996
		20.72	4.18	0.329	
Thermistor sensor vs. Pallmann	301	19.85	4.01	0.231	0.982
		20.49	4.06	0.234	
Thermistor sensor vs. Diffusion Cell	129	19.76	4.05	0.357	0.976
		20.85	4.03	0.355	

Table 3-3. Differences of paired soil temperature measured by diffusion cell vs Pallmann method, thermistor sensor vs. Pallmann method, and thermistor sensor vs. diffusion cell method.

Pair	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference	t-value
Diffusion cell vs Pallmann	0.27	0.37	0.030	0.21-0.33	9.09
Pallmann vs Thermistor sensor	0.64	0.77	0.044	0.55-0.72	14.33
Diffusion cell vs Thermistor sensor	1.09	0.88	0.078	0.94-1.24	14.03

3.4 Conclusions

There are wide selections of devices that may measure the temperature with high resolution, fast response, and remote access. The accuracy and consistency of the mean annual soil temperature measured over a wide spatial scale and over a long temporal period by three methods namely the thermistor sensor, Pallmann sucrose hydrolysis, and sodium chloride diffusion cell were comparable and the methods could be used interchangeably without introducing significant measurement error.

For measuring the mean temperature, a direct method of observation and integration has become feasible and incorporates several distinct advantages. In climate change and ecological investigations, the spatial and temporal coverage are more significant than the speed of the measurement, the Pallmann sucrose hydrolysis and sodium chloride diffusion cell methods offer economical, reliable, and convenient approaches of collecting mean annual soil temperatures instead of building an electronic sensing network.

Chapter 4

SOIL TEMPERATURE REGIMES IN THE MOJAVE DESERT

4.1 Introduction

Soil temperature and its seasonal variations are important parameters in surface-energy transfer processes and ecosystem functions of the terrestrial environment (Peters-Lidard et al., 1998). Soil temperature affects plant growth, soil respiration, microbial decomposition, organic matter storage and mineralization, and a variety of chemical reactions and pedogenic processes in the soils (Seyfried et al., 2001; Brooks et al., 2004). Changes in soil temperature can have profound impacts on soil functions and carbon balances in ecosystems (Trumbore et al., 1996; Goulden et al., 1998; Schimel et al., 2004; Zhang et al., 2005). Consequently, change in soil temperature could have significant environmental consequences locally and globally.

In Soil Taxonomy (Soil Survey Staff, 1999), knowledge of the soil temperature regimes is fundamental to understand the development and formation of specific soils and to classify and map soils in a consistent manner. It is used in locating areas suitable for agricultural crops, managing the soil-plant-water systems in agricultural systems, and as ecological indicators of plant distributions and wildlife habitats (Mount and Paetzold, 2002; Tejedor et al., 2009). According to the U.S. Soil Taxonomy, the mean annual soil temperature (MAST), and its seasonal fluctuations at 50 cm depth, group soil temperature regimes into 6 categories from the warmest to the coldest: hyperthermic, thermic, mesic, frigid, cryic, and pergelic. In each temperature regime category, the difference between mean summer (MSST) and mean winter soil temperatures (MWST) is greater than 6 °C, except in cryic and pergelic soils, or soils where an organic layer or water table is present. If the difference between MSST and MWST is less than 6 °C, the pedon is considered to have a stable or an iso-temperature regime and the prefix "iso" is included in its naming (for details, please check the Appendix I).

The spatial distribution of soil temperature regimes is essential for accurately inventory the soil resource. Watson (1980) categorized the soil temperature regimes in southeastern Australia using criteria adopted by the U.S. Soil Taxonomy. Schmidlin et al (1983) used a regression equation of MAST vs. elevation and latitude to construct a soil temperature regime map of Nevada. Embrechts and Tavernier (1986) identified the soil temperature regimes in Cameroon as defined in Soil Taxonomy. Mazhitova (2008) classified the soil temperature regimes in the discontinuous permafrost zone in East

European Russian Arctic according to Russian classification systems. In the past three decades, the temperature regime has become a critical component of ecosystem and species-habitat modeling (Mahrer, 1980; Tajchman and Minton, 1986; Berndtsson et al., 1996; Titus et al., 2002; Hlavinka, 2007).

Soil temperatures may vary markedly with elevation. It is challenging to delineate the boundaries of soil temperature regimes in regions where the topography is diverse and the elevation varies widely such as the Mojave Desert. From 1982 through 2000, soil temperatures at the 50 cm depth had been collected at 75 locations throughout the Mojave region representing various elevations and slope aspects. Using this database, I interpolate the spatial pattern of soil temperature regimes in the Mojave Desert region. The soils in much of this region are unmapped. The outcomes of this work would aid a number of soil surveys that are in progress.

4.2 Materials and Methods

4.2.1 Description of Study Area

The Mojave desert region occupies a significant portion of southeastern California and smaller parts of central California, southern Nevada, southwestern Utah and northwestern Arizona, in the United States. Variations in elevation and soil composition and different orientations to the wind and sun, along with desert springs, moist seeps, and two major riparian corridors, provide isolated microclimates and ecosystems throughout the region. The harsh yet diverse environment of the Mojave Desert has facilitated the evolution of numerous endemic and specially adapted species of plants and wildlife on islands of unique habitat, supporting 130 different plant alliances. The Mojave Desert is home to extraordinary plants. The common habitats of the region are creosote bush scrub, desert saltbush, Joshua tree scrub, desert wash, alkali scrub, and juniper-pinyon woodlands (Bunn et al., 2007).

The Mojave Desert experiences winter temperatures below -7 °C on valley floors, and below -18 °C at higher elevations. In summer, temperatures on valley floors can exceed 49 °C and 54 °C at the lowest elevations (US National Weather Service: http://www.nws.noaa.gov/). The Mojave Desert receives small amounts of precipitation each year, generally <150 mm of rain with most areas receiving <100 mm. Most of the precipitation occurs in the winter. The region's weather is significantly affected by Pacific storms in the winter and spring seasons. The elevation which ranges from -86 m to 3,633 m is the other major factor affecting the region's weather.

To characterize the soil temperature regimes across the Mojave Desert region, 75 monitoring sites were established (Figure 4-1). These sites were chosen based on geographic parameters and convenience for access. The geographic information for each site, including elevation, latitude, and longitude, was recorded at the time of selection of the monitoring sites. The sites were between longitude 118.00^{o} to 113.97^{o} W and latitude 33.67^{o} to 37.50^{o} N with elevation below sea level to 2,363 m and slope from flat to 20.6^{o}. Detail information about the monitoring sites is given in Appendix II.

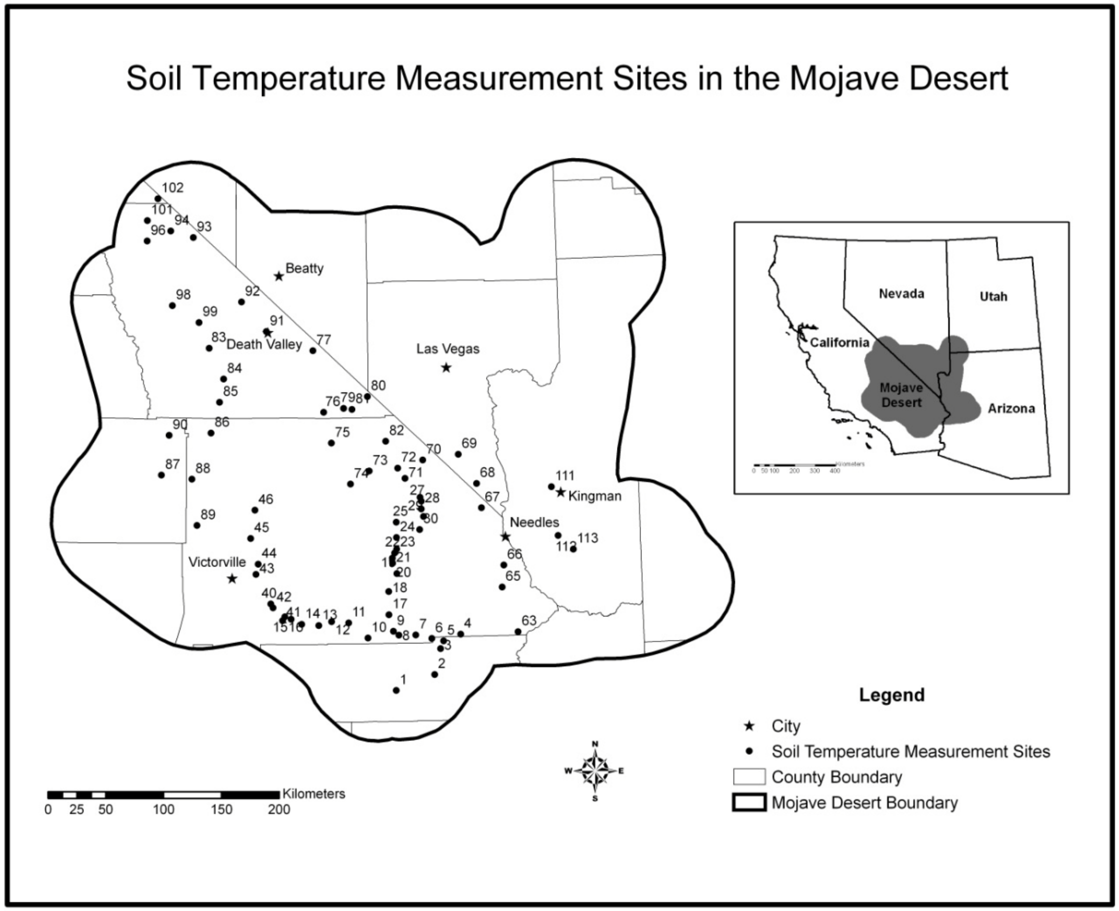

Figure 4-1. Locations of the soil temperature monitoring sites in the Mojave Desert region.

4.2.2 Data Collection

Through efforts initiated over two decades ago, a long-term database of soil temperature has been collected at these selected locations across the Mojave Desert region from 1982 to 2000. The Pallmann method of soil temperature measurement was used to measure the MAST at these locations (see chapter 3). At 25 of the 75 monitoring sites, soil temperature data were collected quarterly. Detail information and statistical descriptions of MAST collect at each monitoring sites are given in Appendix III.

30*30m DEM data were downloaded from Mojave Desert Ecosystem Program (http://www.mojavedata.gov/). 19 DEM maps were downloaded in this project. Those DEM maps are based on the Elevation data from USGS 250k quadrangle. Extents include: Bakersfield, Caliente, Cedar City, Death Valley, Fresno, Goldfield, Grand Canyon, Kingman, Las Vegas, Los Angeles, Mariposa, Needles, Phoenix, Prescott, Salton Sea, San Bernardino, Santa Ana, Trona, and Williams. The DEM map of Mojave Desert region is derived by mosicing those 19 individual maps together, and then cropping with the polygon Shapefile of Mojave Desert boundary (Figure 4-2).

The slope and aspect information for each study site were derived by masking the slope map and aspect map with the point shapefile of study sites. Slope and aspect information extracted from DEM raster data are listed in Appendix IV

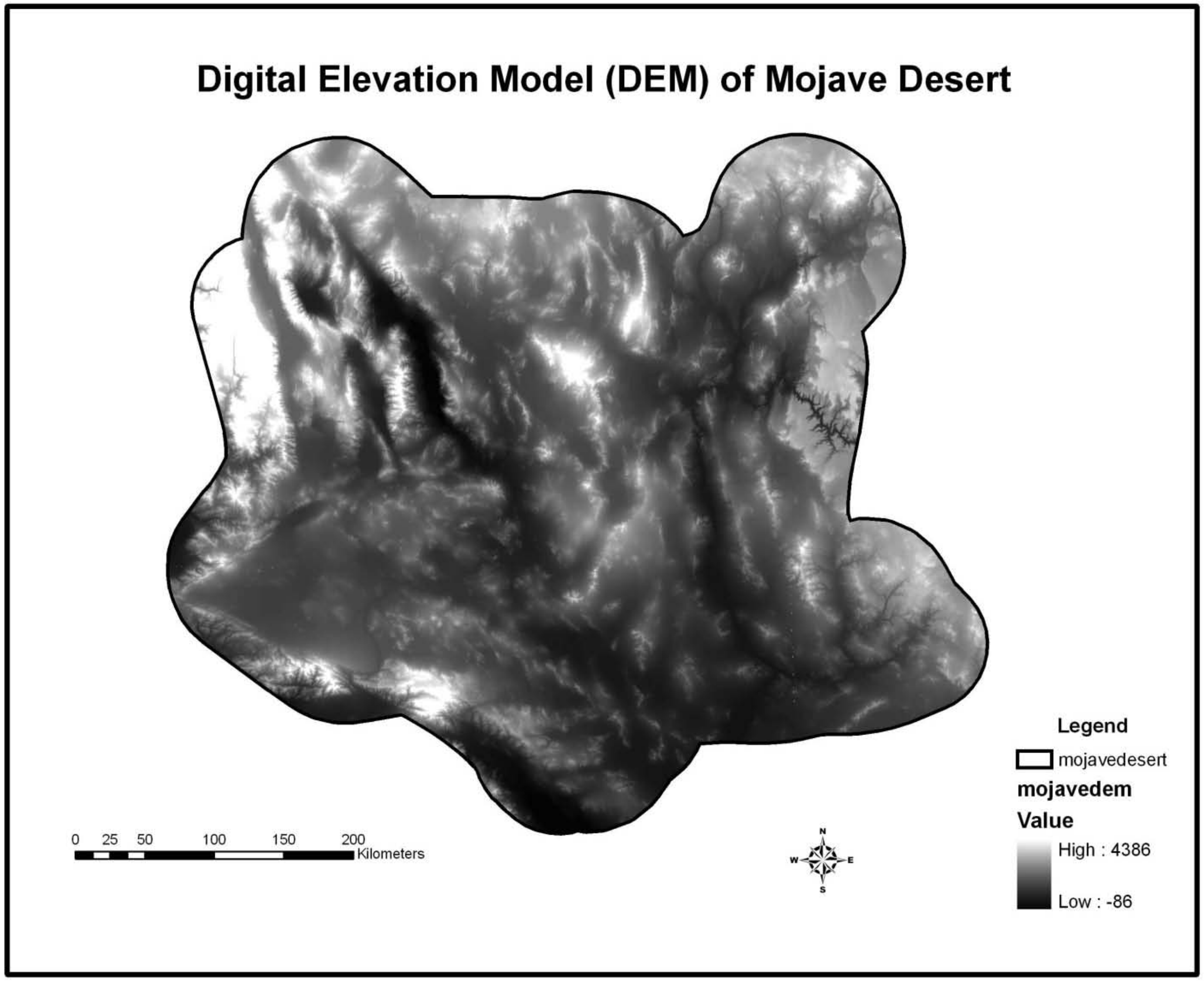

Figure 4-2. Digital Elevation Model (DEM) map of the Mojave Desert region.

4.2.3 Mapping the Soil Temperature Regimes

The soil temperature regime map for the Mojave Desert region was constructed with support of GIS software (ArcGIS 9.3). Multiple linear regression analysis was conducted to link the spatial variation of MAST with geographic factors including elevation, latitude, longitude, slope and aspect. The spatial distribution of MAST was obtained based on the regression model using the map calculator function in ArcGIS. The data were then translated into soil temperature regime classification systems according the catalog defined in Table 4-1.

Table 4-1. Criteria for soil temperature regimes in Soil Taxonomy (soil survey staff, 1999).

Temperature	MAST (50 cm)	MSST - MWST
Frigid	< 8 °C	> 6 °C
Mesic	8 -15 °C	> 6 °C
Thermic	15-22 °C	> 6 °C
Hyperthermic	>22 °C	> 6 °C

4.3 Results and Discussion

4.3.1 Correlations of MAST with Geographic Parameters

Geographic parameters such as elevation, latitude, longitude, slope, and aspect may affect soil temperature but the strength of these relationships is dependent on their interaction across regions of the study area. Figure 4-3 illustrates the linear correlations between MAST in the Mojave Desert and each geographic parameter. Table 4-2 summarizes the linear regression results.

Mean annual soil temperature is closely correlated with elevation (R^2 = 0.852). As the elevation increased from below sea level to nearly 2.5 km, the MAST in the Mojave Desert decreased linearly at a rate of 7.50 °C per 1,000 m. It appears that the estimated lapse rate of soil temperature with respect to elevation is higher than that of the atmosphere as the recognized international standard rate is 6.49 °C per 1,000 m. Since the solar radiation heats the atmosphere from the bottom and not from the top, temperature often decreases with elevation.

Table 4-2. Linear regression results with MAST as the dependent variable and elevation, latitude, longitude, or slope as the independent variable, respectively.

Independent variable	Estimated slope coefficient	Standard error	t-Value	p-Value	R^2
Elevation	-0.00750	0.00036	-20.50	<0.0001	0.8520
Latitude	-0.371	0.533	-0.70	0.4882	0.0066
Longitude	1.274	0.4658	2.74	0.0078	0.093
Slope	-0.615	0.1622	-3.79	0.0003	0.1647

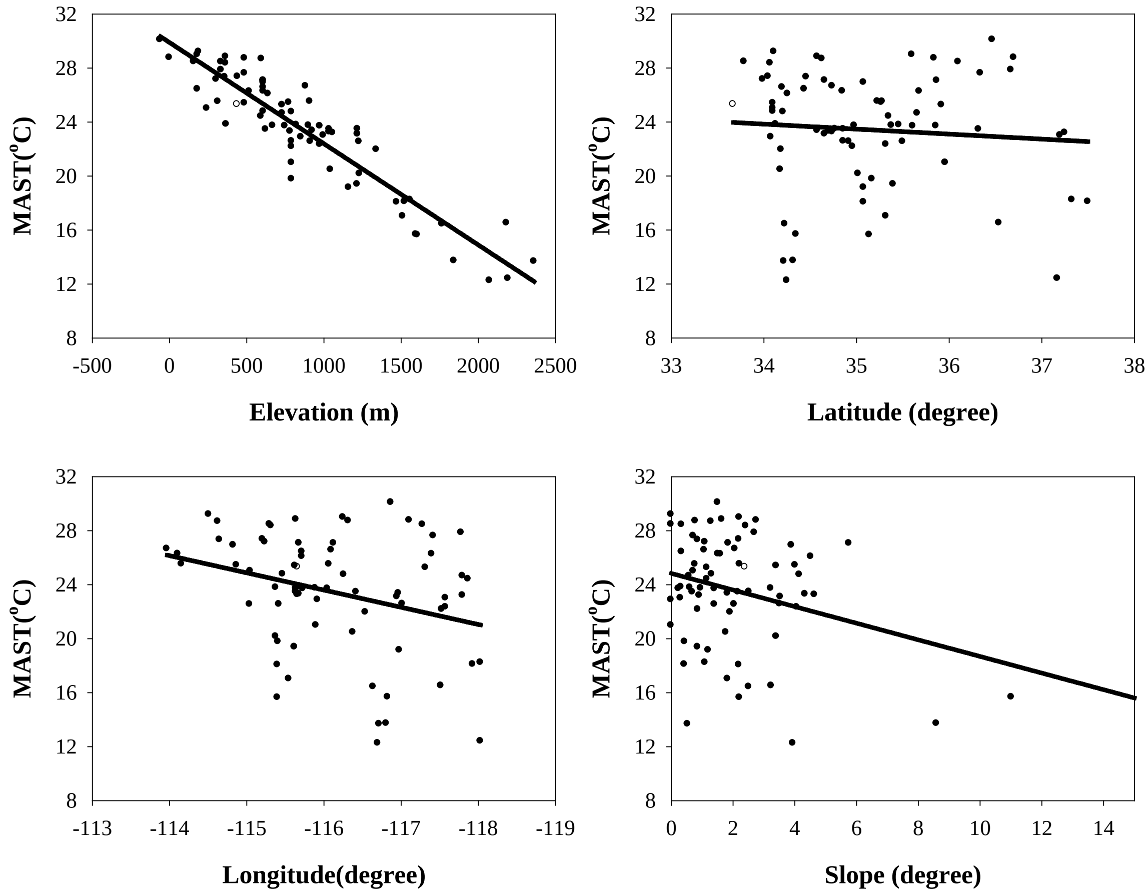

Figure 4-3. Correlation of MAST with elevation, latitude, longitude or slope in the Mojave Desert region.

Latitude is the primary factor causing unequal heating of the Earth's atmosphere. The further away from the equator, the less and weaker sunlight strikes. Therefore, the atmospheric temperature generally decreases with latitude given all other conditions are same. The MAST in the Mojave Desert is not significantly correlated to the latitude (at $p > 0.05$), suggesting soil temperature does not vary significant from south to north across this region. The Mojave Desert region has a wide range in elevation and diverse topography. The spatial variation of MAST in the region is dominated by the elevation (see Figure 4-2). Judging from the dispersion of the data, the impact of latitude on soil temperature in this case might have been masked by factors such as the elevation.

There is a significant linear correlation between MAST and the longitude at $p < 0.05$. However, only 9.3% of the variability in the MAST of Mojave Desert may be accounted for by the variability in the longitude (R^2=0.093). The results indicate that the MAST slightly increases from the east toward the west across the Mojave Desert region, attributable to temperature modulation by the Pacific Ocean.

The MAST in Mojave Desert is also significantly correlated to the slope at $p<0.05$. Approximately 16.5% of the variability in the soil temperature may be accounted for by the variability in the slope (R^2=0.1647). The slopes of most monitoring sites were less than 5 per cent. Again, the dispersion of the data (Figure 4-3) indicated that other factors might have influenced the outcomes.

When the data was sorted according to the aspects of the slope, the MAST of both north-facing and south-facing sites decreases linearly with elevation (Figure 4-4). The soil temperature of north-facing sites is lower than that of the south-facing sites when elevation is less than 2,000 m and the differences between the north-facing sites and south-facing sites widened as the elevation decreased. When the elevation is above 2000 m, the difference is approaching 0. The north-facing slope generally receives less incoming sunlight per unit area than the south-facing slope.

The results of linear regression analysis showed that among the five geographic parameters, elevation is the dominant factor governing the spatial variation of soil temperature across the Mojave Desert region. In addition, longitude, slope, and aspect also account for the spatial variability of soil temperature. However, their contribution is much smaller. Multivariate linear regression analysis was conducted to decide whether it was necessary to take other factors into account together with elevation to estimate soil temperature.

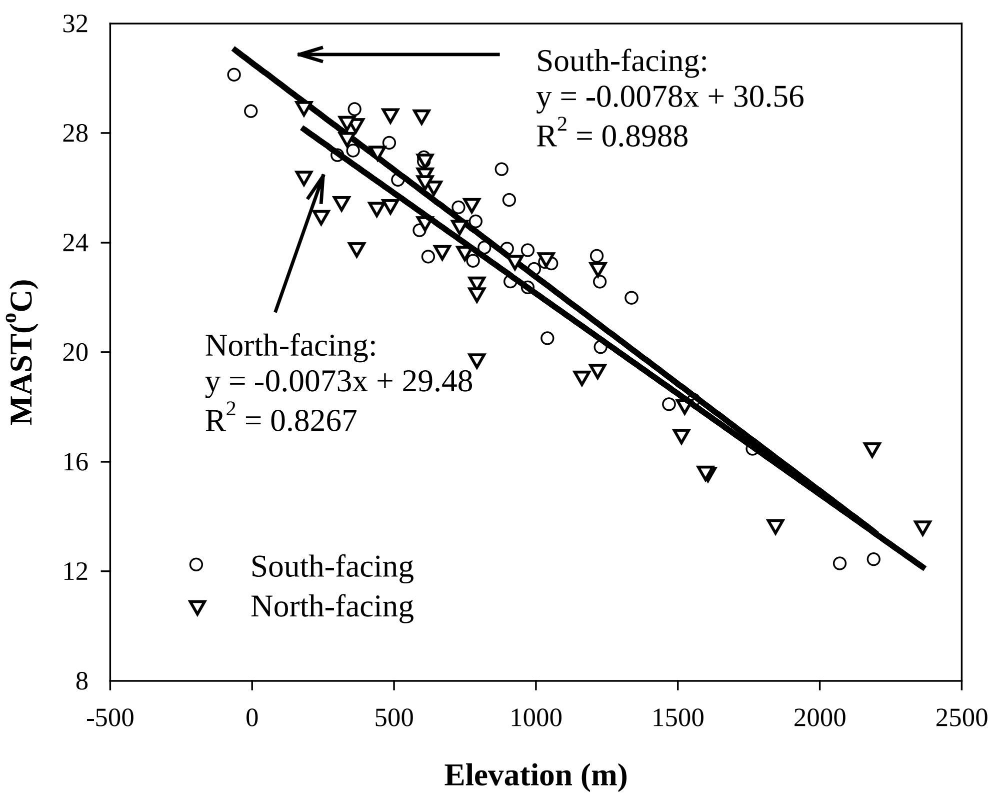

Figure 4-4. Effect of aspect facing on the soil temperature in the Mojave Desert region.

4.3.2 Multivariate Regression Analysis

A multiple linear regression analysis was conducted to link the spatial variation of soil temperature with the geographic factors. The multiple linear regression analysis was achieved through SAS software. In the multiple linear regression analysis, aspect was divided into two categories, aspect-south and aspect-north. The database was split into model-building set and validation set.

Table 4-3. Multivariate regression results with MAST as the dependent variable and five geographic factors as independent variables based on the model-building dataset.

Variable	Estimated slope coefficient	Standard error	t-Value	p-Value
Elevation	-0.0077	0.000743	-10.36	<.0001
Latitude	-0.483	0.797	-0.61	0.5491
Longitude	-0.410	0.629	-0.65	0.5187
Slope	-0.065	0.152	-0.43	0.6712
Aspect_N	-0.089	1.413	-0.06	0.9500
Aspect_S	1.085	1.460	0.74	0.4632

The full model analysis showed that only elevation had significant correlation with soil temperature (Table 4-3). No clear pattern was observed in the plot of residuals against predicted values. The best lambda given by the Box-Cox Transformations analysis was

1.000. In addition, there is no clear departure from normality based on the normal Q-Q plot. All these facts pointed out that the quality of the data was good and no remedial measures (such as data transformation and removal of outliers) were needed.

Table 4-4. Model selection results based on different criterions

Standard	Variable predictor(s) selected in the best three models
F-test based stepwise selection	1) Elevation(R^2=0.8506, p<0.0001) 2) Elevation and Aspect-S (R^2=0.8632, P=0.0855) 3)Stopped
Akaike's Information Criterion (AIC)	1) Elevation and Aspect-S (AIC= 41.31); 2)Elevation Aspect-N (AIC=41.48); 3) Elevation (AIC =42.57)
Schwartz's Bayesian Information Criterion(BIC)	1)Elevation (BIC =45.79) ; 2) Elevation and Aspect-S (BIC=46.14); 3)Elevation and Aspect-N (BIC=46.32)
Mallows's Cp	1)Elevation and Aspect-S (Cp=0.0969); 2) Elevation and Aspect-N(Cp= 0.2449); 3) Elevation (Cp=0.9658)
Adjust R-square*	1) Elevation and Aspect-S (Adjust R^2 =0.8551); 2) Elevation and Aspect-N (Adjust R^2 0.8545), 3) Elevation, Aspect-S and Latitude (Adjust R^2 0.8534)

*note: the adjust R-square of the model using elevation as the only variable predictor is 0.8463 and rank 20.

Five commonly used criterions including F-test based Stepwise selection, Akaike's Information Criterion (AIC), Schwartz's Bayesian Information Criterion(BIC), Mallows's Cp, and adjust R^2 criterion were employed to find the best model. The model selection results based on these criterions are summarized in Table 4-4. The results showed that elevation was the dominant factor and aspect was subordinate to it. Inclusion of aspect into the model did not significantly improve the model's capability. Therefore, only elevation was selected as the variable predictor. The best model based on the model-building dataset is given as:

$$MAST = -0.00744*Elevation + 29.425 \qquad [Eq.4-1]$$

The model was used to predict the validation dataset. The mean squared prediction error (MSPR = 2.859) does not differ greatly from the mean square error (MSE = 2.998) of the model building dataset, indicating that the regression equation derived from the model building dataset is a reasonable and valid indicator of the predictive ability of the fitted regression model. The model obtained based on the validation dataset is very similar to that based on model-building dataset, especially for the slope coefficients which are almost identical, which is given as:

$$MAST = -0.00738*Elevation + 30.186 \qquad [Eq.4-2]$$

Since both the model-building dataset and validation dataset work well, the whole dataset was use to get the final model:

$$MAST = -0.00751*Elevation + 29.89 \qquad [Eq.4-3]$$

4.3.3 Soil Temperature Regimes in the Mojave Desert region

Based on the developed regression model (Eq.4-3), the spatial distribution of soil temperature regime in the Mojave Desert region was predicted (Figure 4-5). Four soil temperature regimes were identified: frigid, mesic, thermic, and hyperthermic. It changes from a cold desert in the northern section to a hot desert in the southern section.

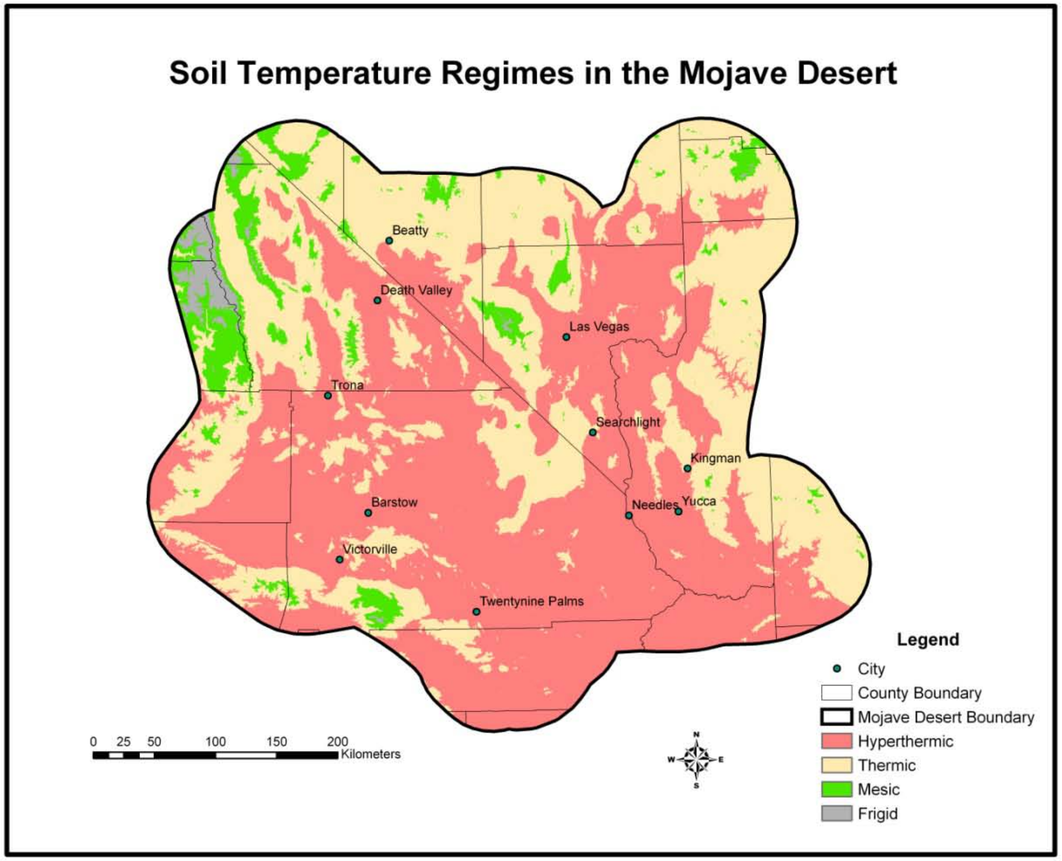

Figure 4-5. Spatial distribution of soil temperature regimes in the Mojave Desert.

Table 4-5 summarizes the elevational boundaries between different soil temperature regimes and the proportion of each regime. Around 94% of the region has hyperthermic (MAST > 22 °C) or thermic soil (MAST between 15 °C and 22 °C), which are generally located in valleys or on foothills of mountains. The mesic soil (MAST between 8 C and 15 °C) accounts for 5.2% of the area, while the frigid soil (MAST < 8 °C) accounts for less than 1.2% of the study area. The mesic and frigid soils mainly occur in high mountain ranges such as the San Bernardino Mountains (CA) and the Spring Mountains (NV).

Table 4-5. Elevation boundary and percentage of each identified soil temperature regime in the Mojave Desert region.

Soil Temperature Regime	Elevation Boundary (m)	Percentage (%)
Frigid	>2918	1.20
Mesic	1985-2918	5.20
Thermic	1051-1983	38.66
Hyperthermic	<1052	54.94

4.3.4 Seasonal Soil Temperature Regime

At the 25 of the 75 monitoring sites where soil temperature data were collected quarterly, it was found that the mean seasonal soil temperatures were also closely correlated with elevation (Figure 4-6). The regression equation for each season is given in Table 4-6. The seasonal soil temperatures varied greatly in the Mojave Desert region. The differences between the summer and winter periods are more than 20 °C, as shown by the difference in intercepts of the linear regression equations. The lapse rates for spring, summer and fall are similar and higher than that for the winter. The results indicate that the effect of elevation on soil temperature is more pronounced in summer than in winter.

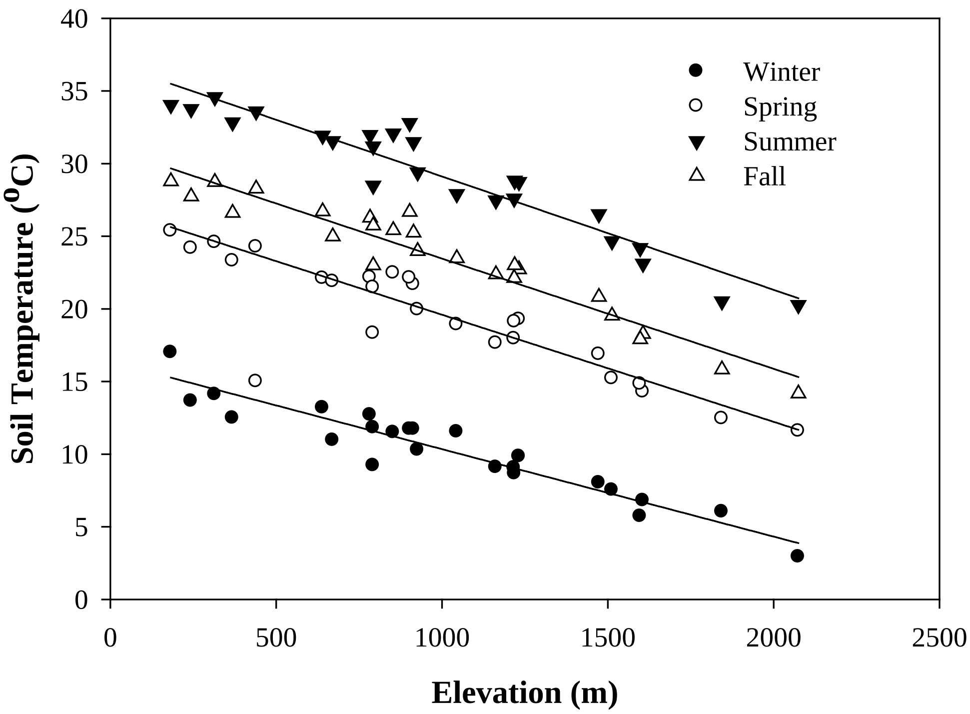

Figure 4-6. Variation of seasonal soil temperature with elevation in the Mojave Desert region.

As was done for MAST, the spatial distribution of seasonal soil temperature in the Mojave Desert region was constructed based on the regression equation given in Table 4-6 with help of ArcGIS (Figure 4-7). For comparison purpose, the seasonal soil temperatures were divided into the same categories as those that define for soil temperature regimes.

The percentages of each category for the winter, spring, summer, and fall season are summarized in Table 4-7.

Table 4-6. Linear regression equation for estimating seasonal soil temperature with elevation (Elv, m).

Season	Regression equation*	R^2
Winter	y = -0.0060*Elv + 16.38	0.8946
Spring	y= -0.0074*Elv + 26.98	0.9261
Summer	y = -0.0078*Elv + 36.92	0.9048
Fall	y = -0.0076*Elv + 31.06	0.9232

Table 4-7. Percentage of each soil temperature regime under the winter, spring, summer and fall season.

Soil Temperature Category	Percentage of each soil temperature category (%)			
	Winter	Spring	Summer	Fall
<8 °C	26.42	2.18	0.10	0.97
8-15 °C	68.92	14.09	1.32	3.89
15-22 °C	4.66	58.23	6.11	32.00
>22 °C	0.00	25.49	92.48	63.13

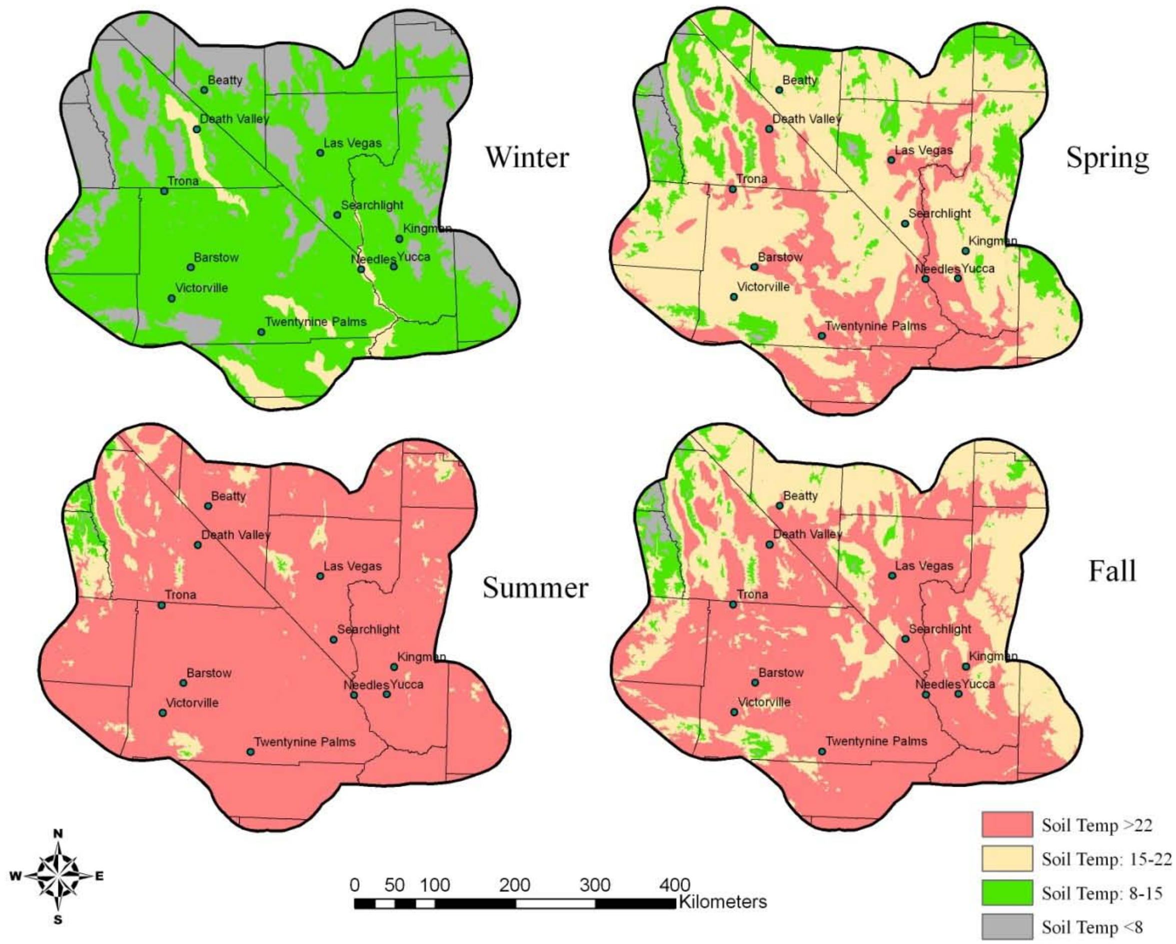

Figure 4-7. Seasonal soil temperature regimes in the Mojave Desert region

More than 95% of the area has soil temperatures <15 °C in winter, while more than 98% of the area has soil temperatures > 15° C in summer. No area has soil temperatures > 22 °C in winter. In contrast, 93% of the region has soil temperatures > 22° C in summer. The area that has soil temperatures < 8 °C almost disappears in the summer, but in the winter, it accounts for more than one quarter of the region.

The spatial distributions of soil temperature in the spring and fall are intermediate between those of the winter and summer. During the spring, soil temperatures increase. The area with soil temperatures <15 °C decreases from 95 % in the winter to 16 % and 25 % of the region has soil temperatures >22 °C. During the fall season, soil temperatures decrease. The area with soil temperatures > 22 °C decreases from 92% in the summer to 63 %. Meanwhile, the area with soil temperatures <15 °C increases from 1% in the summer to 5% in the fall.

4.3.5 Temporal Variation of Soil Temperature Regimes in the Mojave Desert Region

Along with the regional climate changes, the soil temperature may change with time during the study period. Therefore, the resulting spatial distribution of soil temperature regimes may not be the same based on the data used. Tracking the temporal changes of soil temperature regimes may provide insight into the regional climate changes. In the previous section, the spatial distribution of soil temperature regime in the Mojave Desert region was constructed based on the linear regression equation driving from the whole dataset collected from 1982-2000. In this section, the spatial distribution of soil temperature regime was constructed based on individual year data and a 5-year group data to investigate the spatiotemporal changes of soil temperature.

The linear regression equations for predication the MAST from elevation based on individual year data are summarized in Table 4-8. The correlations between MAST and elevation are good for all years with R^2 varying from 0.79 for year of 1985 to 0.97 for year of 1982. It was found that the slope of the regression, namely, the lapse rate decrease linearly with time while the intercept of the regression increase with time (see Figure 4-8), suggesting that there was a warming trend in the Mojave Desert region during the study period.

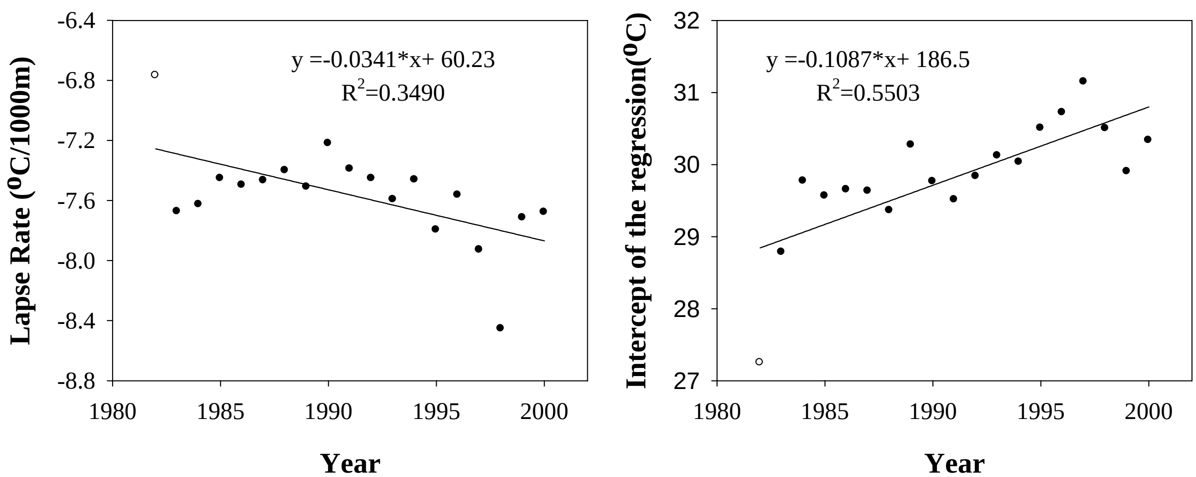

Figure 4-8. Temporal variation of the lapse rate and intercept of the regression equation.

Table 4-8. Linear regression equations for prediction of MAST from elevation based on different year of data.

Year	Equation	a	b	R^2
1982	y = -0.006769 x + 27.246345	-0.006769	27.246345	0.973142
1983	y = -0.007675 x + 28.780739	-0.007675	28.780739	0.820162
1984	y = -0.007628 x + 29.767849	-0.007628	29.767849	0.828122
1985	y = -0.007454 x + 29.561181	-0.007454	29.561181	0.790298
1986	y = -0.007499 x + 29.647828	-0.007499	29.647828	0.824928
1987	y = -0.007468 x + 29.628301	-0.007468	29.628301	0.820675
1988	y = -0.007402 x + 29.359406	-0.007402	29.359406	0.810039
1989	y = -0.007512 x + 30.267611	-0.007512	30.267611	0.828161
1990	y = -0.007221 x + 29.761861	-0.007221	29.761861	0.814941
1991	y = -0.007391 x + 29.508641	-0.007391	29.508641	0.835534
1992	y = -0.007454 x + 29.832744	-0.007454	29.832744	0.853242
1993	y = -0.007595 x + 30.116895	-0.007595	30.116895	0.828215
1994	y = -0.007464 x + 30.030855	-0.007464	30.030855	0.845161
1995	y = -0.007797 x + 30.500143	-0.007797	30.500143	0.826051
1996	y = -0.007565 x + 30.718164	-0.007565	30.718164	0.850191
1997	y = -0.007930 x + 31.143744	-0.007930	31.143744	0.832680
1998	y = -0.008456 x + 30.495277	-0.008456	30.495277	0.821036
1999	y = -0.007716 x + 29.899694	-0.007716	29.899694	0.864088
2000	y = -0.007680 x + 30.332968	-0.007680	30.332968	0.852482
Overall	y = -0.007500x + 29.889000	-0.007500	29.889000	0.852000

Based on the regression equations listed in the Table 4-8, the spatial distribution map of soil temperature regimes was made in ArcGIS for each year. The percentage of each soil temperature regime in each year is summarized in Table 4-9. The resulting spatial distribution of soil temperature regimes based on data collected at different year is quite different. The percentage of hyperthermic in the Mojave Desert region varied from 33.32% at year of 1982 to 60.84% at year of 1997. The temporal variation of hyperthermic soil was found to be highly correlated to regional averaged MAST (Figure 4-9). The coldest year of 1982 had the lowest percentage of hyperthermic soil while the hottest year 1997 has the highest percentage of hyperthermic soil

Table 4-9. Percentage of each soil temperature regime based on data collected at different year.

Year	Hyperthermic	Thermic	Mesic	Frigid
1982	33.32%	56.62%	8.70%	1.35%
1983	42.36%	47.27%	8.66%	1.71%
1984	52.40%	40.43%	5.84%	1.33%
1985	52.16%	41.07%	5.53%	1.24%
1986	52.46%	40.77%	5.52%	1.25%
1987	52.59%	40.71%	5.47%	1.24%
1988	51.00%	41.87%	5.87%	1.25%
1989	58.20%	36.07%	4.64%	1.10%
1990	56.18%	38.20%	4.62%	1.00%
1991	52.21%	41.15%	5.42%	1.21%
1992	54.89%	38.77%	5.17%	1.16%
1993	55.84%	37.83%	5.12%	1.21%
1994	56.24%	37.81%	4.83%	1.12%
1995	57.13%	36.51%	5.10%	1.25%
1996	60.78%	34.05%	4.16%	1.02%
1997	60.84%	33.45%	4.51%	1.20%
1998	51.57%	39.19%	7.36%	1.88%
1999	52.71%	40.04%	5.88%	1.36%
2000	56.83%	36.92%	5.04%	1.22%
Overall	54.94%	38.66%	5.20%	1.20%

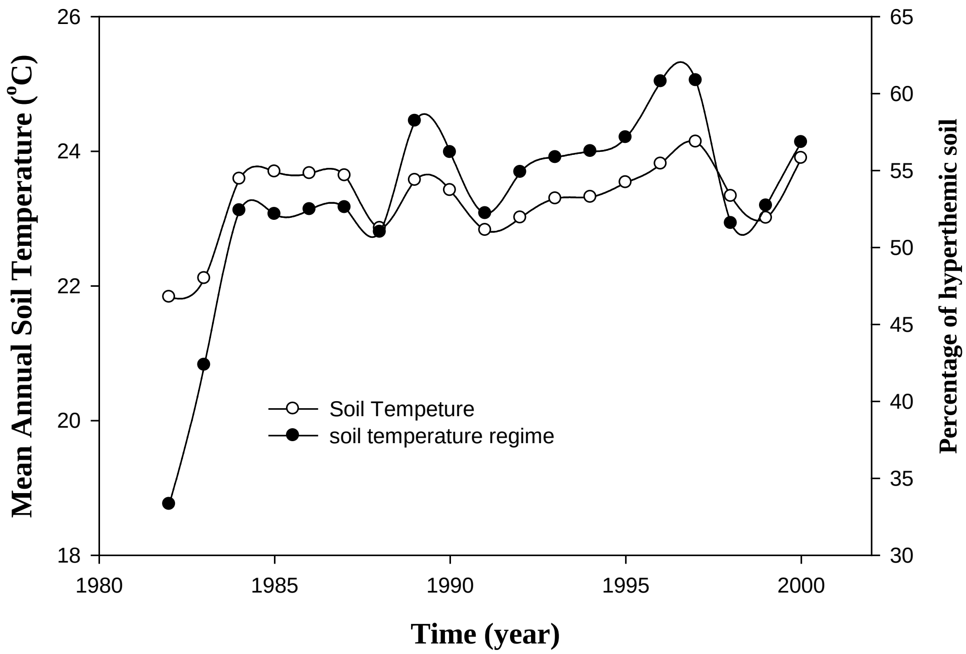

Figure 4-9. Temporal change of mean annual soil temperature and percentage of hyperthermic soil in the Mojave Desert region.

The temporal variations of thermic soil are opposite to those of hyperthermic soil (Figure 4-10). The coldest year of 1982 had the highest percentage of thermic soil of 56.62% while the hottest year 1997 has the lowest percentage of thermic soil of 33.45%. The majority of the Mojave Desert region has either the hyperthermic soil or thermic soil. These two types together account for 89.63% of the region in 1983 to 94.83% in 1996. The percentage of mesic soil varies from 8.7% in 1982 to 4.16% in 1996. The percentage of frigid soil varies from 1.00% in 1990 to 1.88% in 1998. Together, the mesic and frigid soil account for from 5.18% in the warmest year of 1997 to over 10% in the coldest year of 1982 and 1983.

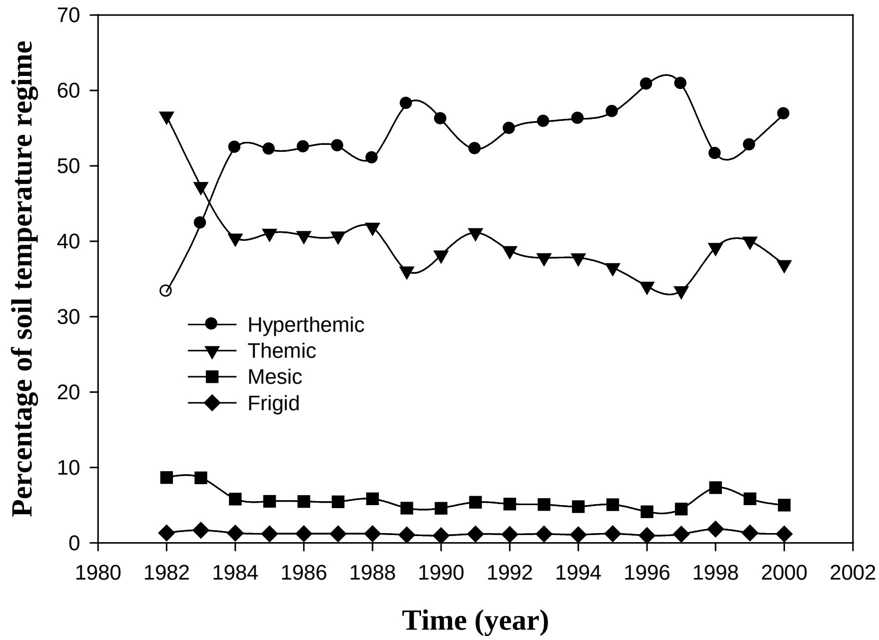

Figure 4-10. Temporal variation of percentage of four different soil temperature regimes identified in the Mojave Desert region.

Overall, the results indicated that the resulting spatial distribution of soil temperature regime depends on the data used. Tracking the temporal changes of soil temperature regimes provides additional information on the regional climate changes. In practice, the long-term soil temperature data are not always available. Given that, the spatial distribution of soil temperature regime was further studied by dividing the data into four groups, namely, 1982-1985, 1986-1990, 1990-1995, and 1996-2000. Table 4-10 summarizes the percentage of each regime for these four periods. The percentage of hyperthermic soil increases slightly from 50.37% in the period 1982-1985 to 56.83% in the period of 1996-2000 while the percentage of thermic soil decreases slightly from

42.17% to 36.77%. Both the hyperthermic and thermic soils account for 92.54% of the region during the period of 1982-1985, which is much lower than those of the other three periods. On the contrary, the mesic and frigid soil together accounts for 7.46% of the region, which is much higher than those of the other three periods. These facts indicated that the period of 1982-1985 was relatively colder than other three periods.

Table 4-10. Percentage of each soil temperature regime based on data collected at different year.

Year	Hyperthermic	Thermic	Mesic	Frigid
1982-1985	50.37%	42.17%	6.12%	1.34%
1986-1990	55.15%	38.66%	5.07%	1.13%
1991-1995	55.95%	37.88%	5.03%	1.14%
1996-2000	56.83%	36.77%	5.14%	1.26%

4.4 Conclusion

Results of regression analysis showed that elevation is the dominant factor controlling soil temperature and it can be used to delineate the spatial distribution of soil temperatures in the Mojave Desert region. The resulting map delineates the boundaries between frigid, mesic, thermic, and hyperthemic soil. Hyperthemic soils are most extensive in the region (around 55%) with an elevation boundary of <1051 m. Thermic soils account for 39% of the region with an elevation range between 1,051 and 1,983 m. Frigid and mesic soils are not extensive and only occur in high elevation mountains.

Seasonal soil temperatures that play important role in plant distribution are found to vary greatly. The seasonal soil temperatures also decrease linearly with elevation. Under the same elevation, the differences of the summer and winder soil temperature are around 20 °C. The effect of elevation on soil temperature is more pronounced in summer season than in winter season. The resulting spatial distribution of soil temperature regimes based on data collected at different year is quite different. Tracking the temporal changes of soil temperature regimes provides insight into the regional climate changes.

Chapter 5

CLIMATE CHANGE IMPLICATIONS OF SOIL TEMPERATURE IN THE MOJAVE DESERT

5.1 Introduction

In the past century, the Earth's atmospheric temperature has risen by approximately 0.8 °C with two main warming periods, between 1910 and 1945 and from 1976 onwards (Hansen et al., 2006; Seinfeld, 2008). The rate of warming based on the mean ambient temperature during the latter period approximately doubled that of the first period and exceeded any other time periods in the last 1,000 years (Walther et al., 2002). The current warming is mostly in northern hemisphere. Change on a regional or local scale is often more subtle and variable.

Most climate records and climate change scenarios projected by the general circulation models are for the atmospheric conditions. Soil temperature data, especially long- term area-wide records, are rare (Zheng et al., 1993). The soil temperature responds to and fluctuates with air temperature as both are governed by the heat energy balance at the interface of atmosphere and lithosphere. The inter relationship however is complex and the change in soil temperature cannot be estimated by the projected regional warming trends (Williams and Smith, 1989). Soil temperature is directly influenced by the ambient climate characteristics such as air temperature and precipitation and is further modified by vegetative cover, topography, and soil properties (Moustafa et al., 1981; Kang et al., 2000).

Soil temperature and its seasonal variations are important parameters impacting regional ecosystem functions of the terrestrial environment (Peters-Lidard et al., 1998). Plant growth, soil respiration, microbial decomposition, organic matter storage and mineralization, and a variety of chemical reactions and pedogenic processes in the soils are all affected by the soil temperature (Lin, 1980; Seyfried, 2001; Brooks et al., 2004; Schimel et al., 2004). Understanding how soil temperature responds to atmospheric climate change is imperative to understand the impacts and feedbacks of climate change processes to terrestrial ecosystems (Donnelly et al., 2004). Hu and Feng (2003) showed that the soil temperature of the contiguous U.S. has been rising at 0.31 °C per 10 year. Through analysis of historical soil temperature data, Zhang et al (2001) extrapolated that in some regions of the world the soil temperature could have raised by roughly a 2°C since the early 1900s.

The impacts of climate change on the vegetative cover of terrestrial ecosystems are unclear (Zhang et al., 2001; Cannell and Hooper, 1990; Woodward, 1992; Holten et al., 1993; Dirnbock et al., 2003). As soil temperature controls the rate of ecological processes in the soil, especially those that are biologically-mediated, soil temperature may provide the mechanistic link between the phenomenon of climate change and the distribution of plant species. The successful establishment and survival of many plant species are greatly influenced by soil temperature extremes (Loik et al., 2000). Soil temperature may be used as an indicator to assess the pattern and impact of climate change which are telling measures of the climate fluctuations and trends of the region integrating impacts of the ambient air temperature, precipitation, evaporation, and vegetation distribution to the terrestrial environment (Changnon, 1999).

The soil temperatures in southeastern California portion of the Mojave Desert were measured for extended periods of time at the 50 cm soil depth at 75 monitoring sites for 18 years, from 1982-2000. This dataset characterizes the temporal fluctuations in soil temperature, a common and integrative parameter for areas of this desert experiencing climate changes in the past two decades. Effects of El Niño – Southern Oscillation (ENSO) on the climate of the Mojave Desert were examined and the correlation between air and soil temperature was evaluated.

This study will provide crucial bearing on how the climate changes at the local level may be evaluated.

5.2 Materials and Methods

5.2.1 Description of Study Area

The Mojave Desert region, covering 152,000 km^2 of southeastern California, southern Nevada, southwest Utah, and northwestern Arizona, has a complex geology and diverse topography. The elevation in this vast region ranges from below sea level at Badwater in Death Valley (-86 m) to Charleston Peak at 3,633 m northwest of Las Vegas. Accordingly, the ambient temperatures also vary widely across the region with extremes ranging from -9 °C to 57 °C. In the Mojave Desert, summers are long and hot. While there are short periods of freezing temperatures during winter at high elevations, winter mean air temperatures seldom drops below 0 °C at the low elevations. The Mojave Desert receives small amounts of precipitation each year, generally <150 mm of rain with many areas receiving <100 mm. Most of the precipitation occurs in the winter.

For more information about the region, please see section 4.2.1

5.2.2 Data Collection

A soil temperature measurement project was initiated in the early 1980’s to study the soil temperature changes in Mojave Desert region. 75 monitoring sites were established through the region. Soil temperature data were continuously collected annually or seasonally at these sites for 19 years (1982-2000). The soil temperature (mean annual soil temperature or mean season soil temperature) at 50 cm depth was measured based on the Pallmann method (see chapter 3).

The ambient temperature and precipitation records were collected from 67 weather stations in the Mojave Desert region (Western Regional Climate Center, www.wrcc.dri.edu). The data were temporally integrated and recorded daily. When there is more than 5 days data missing in a month, the data for that month will not be used for calculation. When there is s data missing for one or more month, the annual data for that year will not be used. For precipitation analysis, the data were organized based on the hydrologic year, namely starts in July and continues to the following June.

Figure 5-1 illustrates the spatial distribution of the soil temperature monitoring sites and weather stations using for data collection.

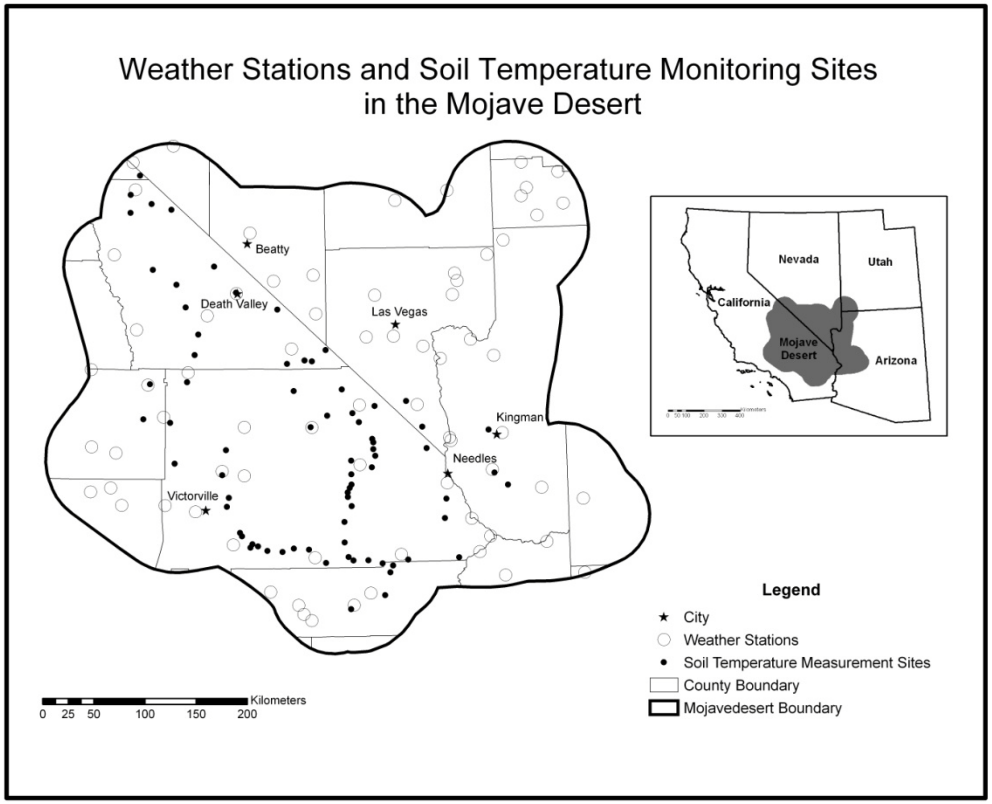

Figure 5-1. Spatial distribution of the soil temperature monitoring sites and weather stations using for data collection in the Mojave Desert region.

5.2.3 Data Analysis

Standardized anomalies of air and soil temperature were calculated by subtracting the mean from each observation, then dividing by the standard deviation. In this way, the distance between a data value and its mean can be measured in standard units and the unusual values can be easy to discern. Anomalies in temperature data were smoothed by the 7-point binomial filter method with different weighting coefficients (1, 7, 21, 35, 21, 7, 1). By doing this, extreme values were damped out to examine the overall change in data over the 18 year period.

5.3 Results and Discussion

5.3.1 Climate Changes in the Mojave Desert during the Last Two Decades

The temporal changes of soil temperature generally coincided with those of air temperature. Starting from a relatively cold period (1982-1983), the air temperature peaked in 1996 and the soil temperature peaked in 1997. Globally, the air temperature peaked in 1998.

Spatially, the mean annual soil temperature could vary from approximately 10 °C to over 30 °C and the mean annual air temperature varied from 8 °C to 25 °C. At a given location, the temporal changes of the mean annual soil temperature were not always apparent. When the data of the entire region was pooled, the soil temperature was on average 4.24 °C higher than the air temperature (Figure 5-2). The differences varied from

3.44 °C to 5.30 °C. The change in air temperature near the surface may translate into a change of soil temperature through three mechanisms: sensible heat flux; latent heat flux, and infrared heat flux. In an arid desert environment, the latent heat flux is relatively inefficient and the ground surface energy balance is mainly governed through the sensible and infrared heat flux. The sensible and radiative heat transfer requires a relatively large temperature difference. As a result, the soil temperature in the desert tends to be much warmer than the ambient air temperature.

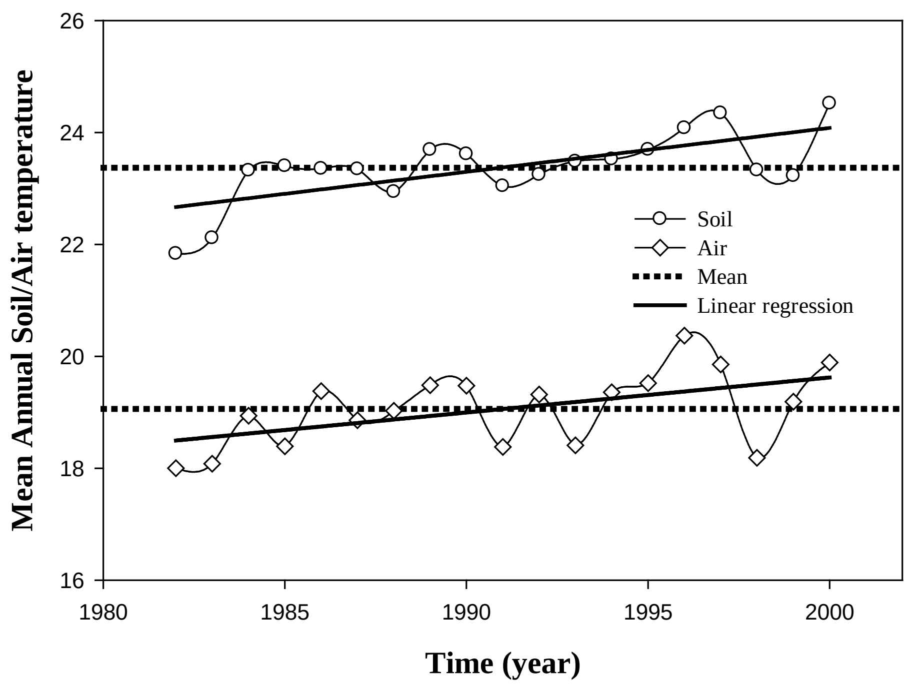

Figure 5-2. Temporal changes of mean annual soil and air temperature during the period of 1982-2000 in the Mojave Desert region, dash line shows the mean temperature of this period.

The linear regressions of both the soil and air temperature showed that there was a warming trend over the monitoring period ($p < 0.05$). The soil temperature at the 50-cm depth increased at an average rate of 0.79 °C per 10 year in the Mojave Desert region from 1982 to 2000. This was two times faster than the rate of warming reported by Hu and Feng (2003). The rate of warming of air temperature is slower than that of the soil temperature at an average rate of 0.63 °C per 10 year.

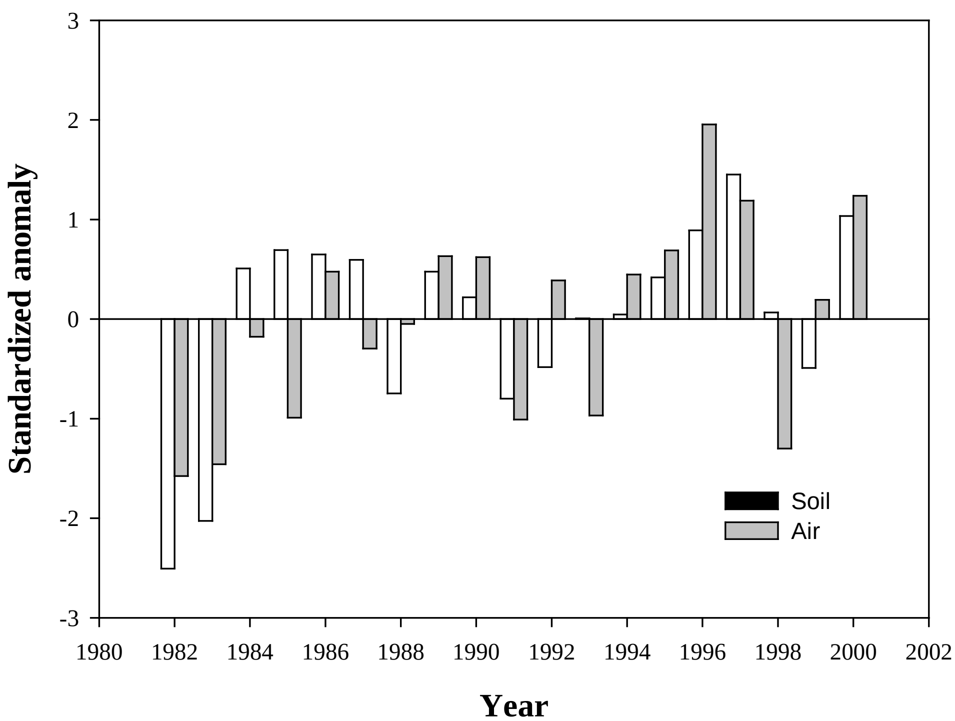

Figure 5-3. Temporal changes of soil and air temperature anomaly during the period of 1982-2000 in the Mojave Desert region. The standardized anomaly was calculated by subtracting the mean from each observation, then dividing by the standard deviation.

When the soil and air temperatures were compared in terms of the anomaly, the mean annual soil and air temperatures showed the same warming or cooling trend in two third of the cases (Figure 5-3). For the remainders, the anomaly of soil and air temperatures was opposite and in most cases coincided with the ENSO events to be discussed later. The two highest positive air and soil temperature anomalies were found in 1996 and 1997, indicating these two years were much warmer than other years. Contrarily, the year of 1982 and 1983 were much colder than other years and had the highest negative soil and air anomalies.

When the annual temperature anomaly was broken down to quarterly temperature anomaly, the warming and cooling temperature cycles were distinctive (Figure 5-4). The quarterly temperature anomalies deviated from 0 to > ±3. There were 3 to 6 consecutive quarters of warming and cooling periods throughout that were marked by the fluctuations of 7 point binomial smothering lines. Similar to the annual data, a warming trend was observed from the quarterly temperature data. The cooling periods occurred mostly before 1990 and the warming periods took place mostly after 1990.

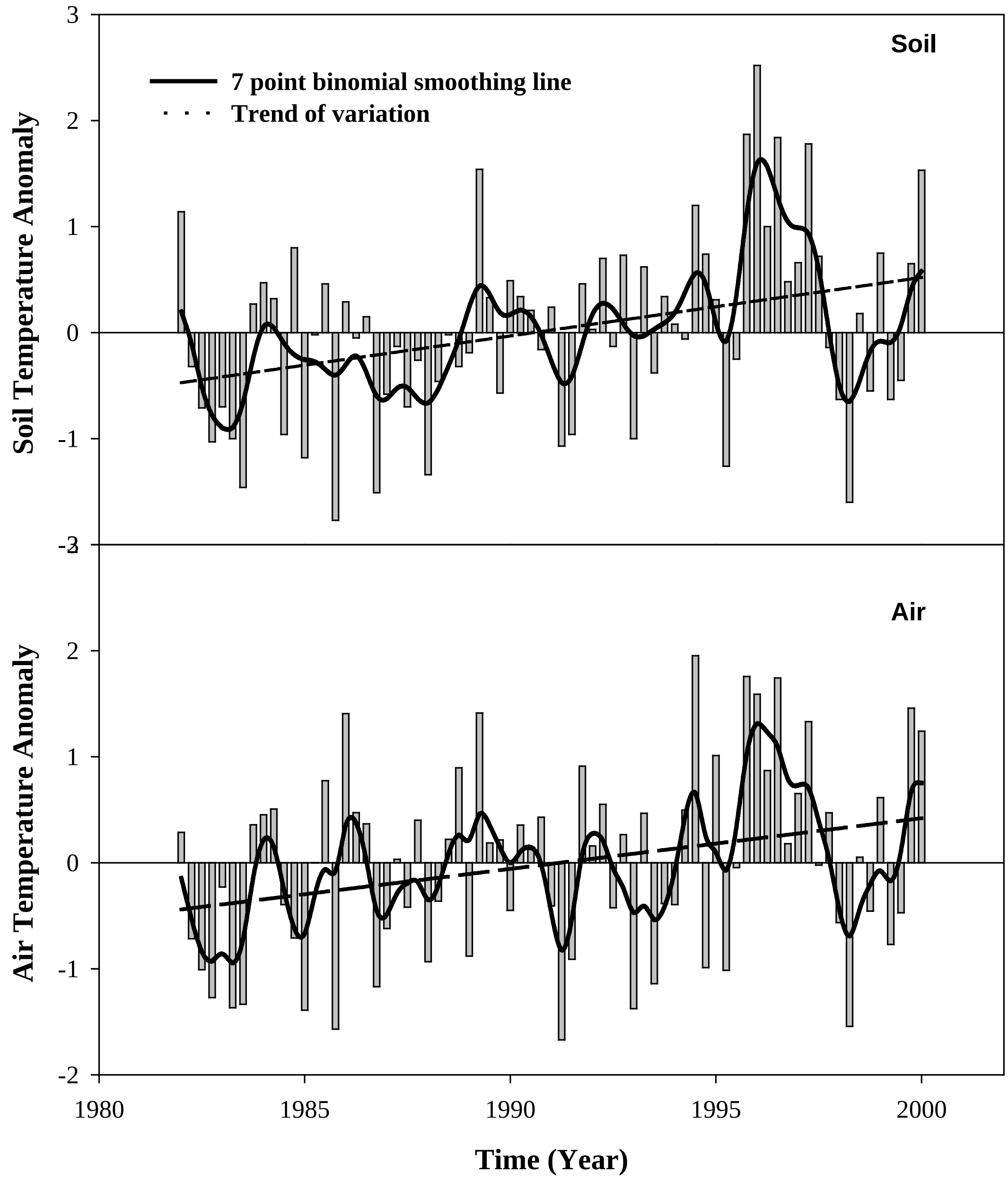

Figure 5-4. Trend of soil and air temperature variation during the period of 1982-2000 in the Mojave Desert region. The solid and dash line show the 7 point binomial smoothing and trend of variation, respectively.

Soil temperature may not change temporally in the same trend for all sites with different geographic characteristics. Based on the results from previous chapter, the spatial variation of soil temperature in the Mojave Desert region was dominated by the elevation. Figure 5-5 illustrates the temporal changes of soil temperature at monitoring sites of different elevation ranges of <500 m, 500-1000 m, 1000-1500 m, and >1500 m. The variations of soil temperature at different elevation ranges follow a similar pattern. The soil temperature at monitoring sites of all these four ranges of elevation follows a warming trend (Table 5-1). The estimated warming trend is 1.126, 0.806, 0.665 and 0.815 °C per 10 year, respectively, for the elevation range of <500 m, 500-1000 m, 1000-1500 m, and >1500 m. The soil temperature at the elevation <500 m warms faster than those at the higher elevation. The precipitation and soil moisture content at lower elevations is lower than those at higher elevations (see chapter 6 for details). This may be attributed to the relative faster warming trend at low elevations.

Table 5-1. Variations of mean annual soil temperature under different sites

Elevation range (m)	Estimated slope coefficient	Standard error	p-value
<500	0.1126	0.0247	0.0003
500-1000	0.0806	0.0163	0.0001
1000-1500	0.0665	0.0204	0.0046
>1500	0.0815	0.0312	0.0182

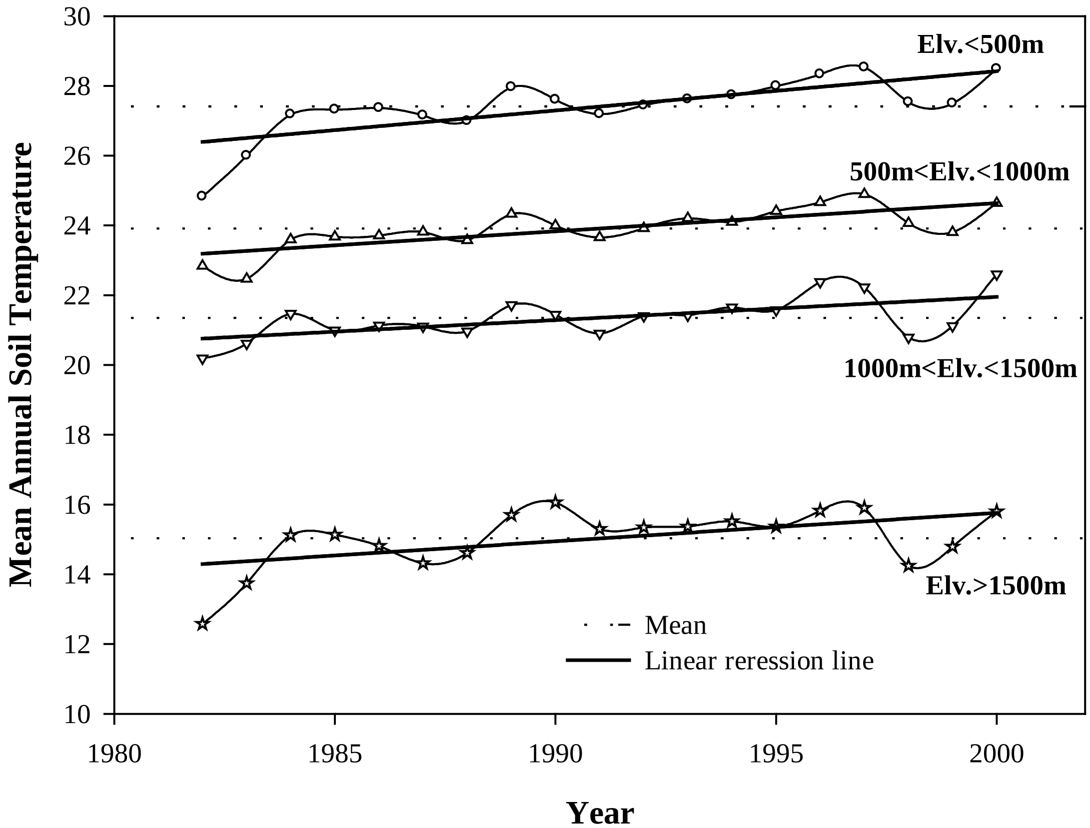

Figure 5-5. Temporal changes of soil temperature at different elevation range during the period of 1982-2000 in the Mojave Desert region.

5.3.2 Effect of El Niño–Southern Oscillation on the Climate of the Mojave Desert

The El Niño–Southern Oscillation (ENSO) is a periodic reorganization of sea surface temperature (SST) and atmospheric circulation in the tropical Pacific that results in vast redistributions of major rainfall-producing systems (Rasmusson and Carpenter, 1983; Allan, 2000). It significantly disturbs atmospheric cycles and has a variety of climatic impacts worldwide. ENSO is an irregular phenomenon that alternates between its two phases, *El Niño* and *La Niña* (Allan et al., 1996; Markgraf and Diaz, 2000; Quinn et al., 1987; Webb and Betancourt, 1992) in which *El Niño* refers to the period when water in the tropical Pacific is warmer than normal and *La Niña* refers to the period when the water in the tropical Pacific is colder than normal.

The effects of ENSO events on climate are site-specific. In the southwestern U.S., *El Niño*-like patterns was characterized by prolonged periods of weak trade winds, weak upwelling along the eastern Pacific margin, and increased precipitation. Cayan et al (1999) showed that *El Niño* episodes enhanced winter precipitation in southern California and Arizona by increasing the frequency of heavy rainfall events and the amount of precipitation during those events. *La Niña* is essentially the opposite of *El Niño* yet their impacts are generally not as pronounced as *El Niño* in the United States.

The mean annual precipitation over monitoring period was 162 mm, varying from less than 75 mm to over 300 mm (Figure 5-6). Coincide with the warming trend, there is overall a very slightly decrease in the mean annual precipitation over this period of time in the Mojave Desert. However, the decrease was not significantly related to time ($p>0.05$). There were several dry-wet year cycles in the 19-year period. The wet-dry cycles variation corresponded to the ENSO events. During the 1982-1983, 1991-1992 and 1997–1998 hydrologic years, the southwestern United States experienced pronounced *El Niño* events (Bowers, 2005). Correspondingly, three extreme wet peaks were noted. The annual precipitation in these three hydrologic years was significantly greater than the average precipitation during 1982-2000. A drought period experienced from 1988 to 1991 in the region started with *La Niña* events in two consecutive hydrological years, 1988-1989 and 1989-1990. With the strong El Niño events, the precipitation anomalies were strongly positive. However, the weak to moderate El Niño events did not necessary result in a significantly wet hydrological year in the Mojave Desert. More often than not, the annual precipitation is above the normal during an *El Niño*.

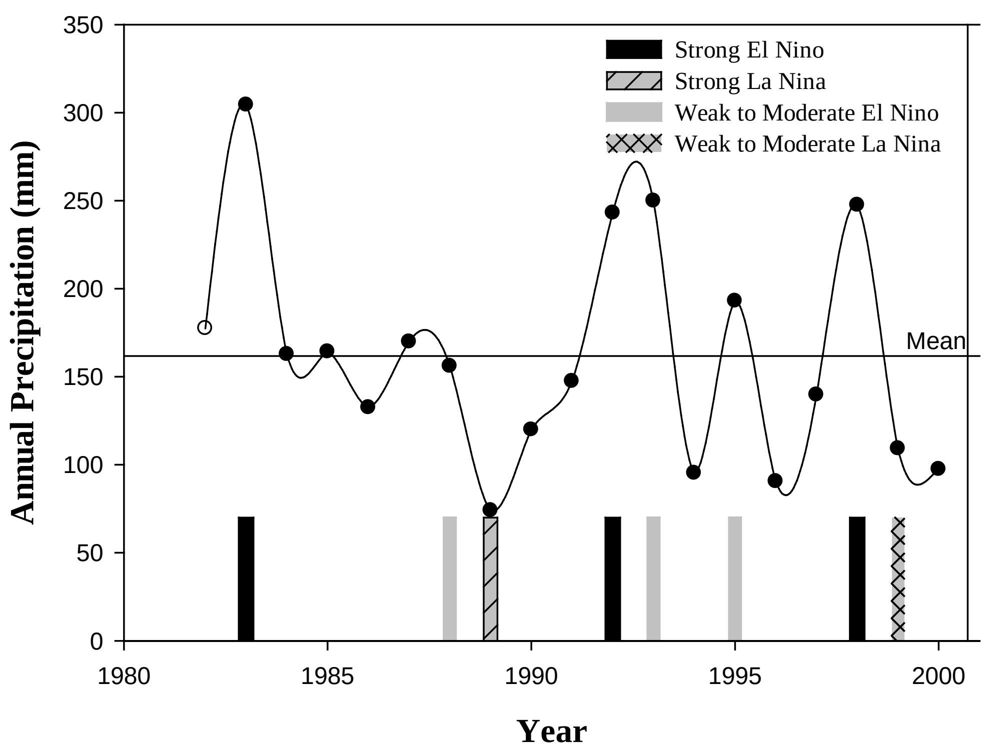

Figure 5-6. Temporal changes of precipitation during the period of 1982-2000 in the Mojave Desert region in corresponding to ENSO events.

During 1982 through 2000, there were 6 *El Niño* events and 2 *La Niña*. While the events affected the precipitation patterns, they did not overall affect the long-term precipitation. The mean annual precipitation of this period was slightly deviated from the normal. However, the ENSO may affect the regional temperature as the temperature and precipitation are often significantly correlated (Madden and Williams, 1978; Dai et al., 1999; Trenberth and Shea, 2005; Adler et al., 2008). Portmann et al (2009) showed that there is a statistically significant inverse relationship between trends in daily temperature and average daily precipitation across regions, especially in the southern United States (30 to 40°N). This inverse relationship is primarily due to reductions of solar heating by cloud covers and increases in the release of latent heat by increased surface wetness due to precipitation. In addition, for producing precipitation, cold atmospheric temperatures of storms are required. Therefore, the anomalies of soil temperature and precipitation are correlated (Figure 5-7).

In the Mojave Desert region, the anomalies of annual precipitation were inversely correlated with those of soil temperature at significant level of $p < 0.05$ and $R^2 = 0.2648$ (Figure 5-7). Therefore, the soil temperature of the Mojave Desert would be cooler than normal under El Niño conditions. As a result, strongly negative temperature anomalies were observed during the three strong El Niño events in the 1982-1983, 1991-1992 and 1997–1998 hydrologic years (Figures 5-3 and 5-4).

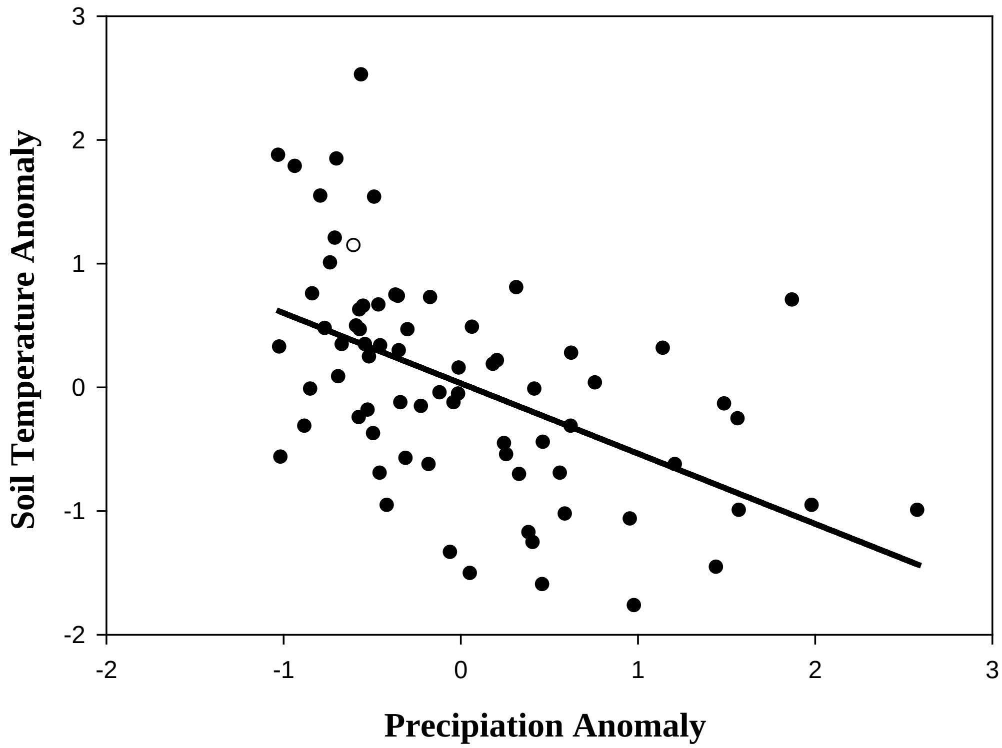

Figure 5-7. Correlation between the variation of soil temperature and precipitation. The data were standardized based on anomaly.

5.3.3 Soil Temperature as an Indicator of Climate Change

The surface energy balance is affected among many factors most significantly by the vegetation and snow covers (Cermak et al., 1992). In the Mojave Desert, the vegetation covers are low across the region and snow cover exists only in limited areas of high elevations and mountains. As a result, the soil temperature strongly responded to changes of the air temperature in the Mojave Desert region (Figure 5-8). While the temporal variations of soil temperature based on the 7-point binomial filter method lagged slightly behind the corresponding air temperature, the patterns of fluctuation were in agreement (Figure 5-8). The anomalies of the air and soil temperature were positively correlated at significant level of $p < 0.05$ and $R^2 = 0.65$ (Figure 5-9).

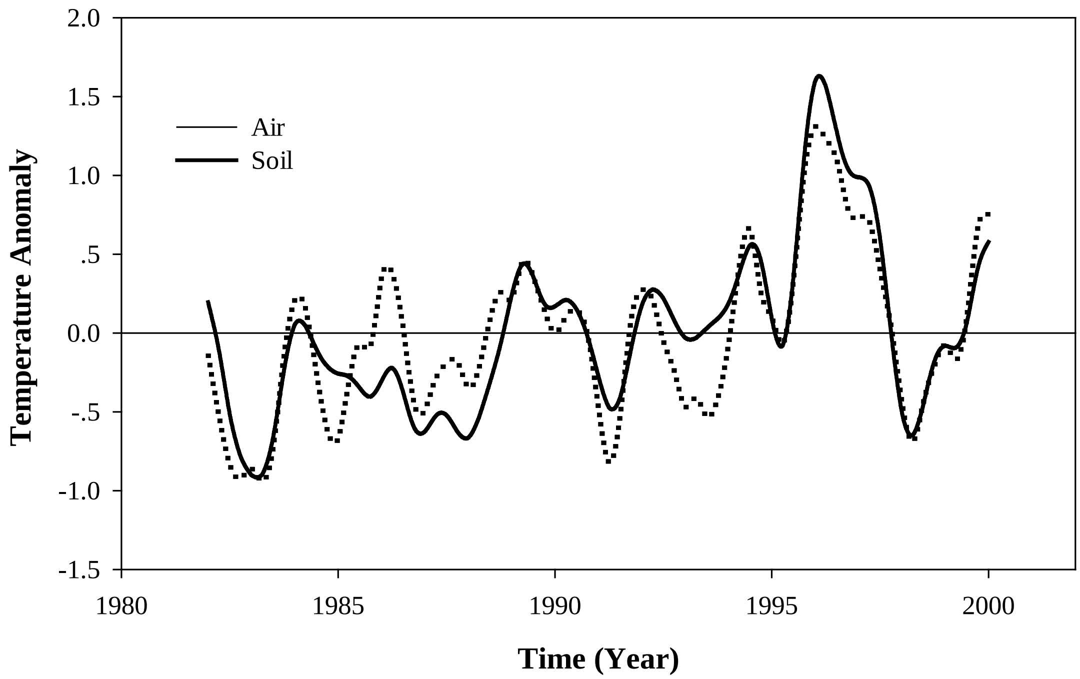

Figure 5-8. Comparison of the 7 point binomial smoothing line for seasonal air and soil temperature.

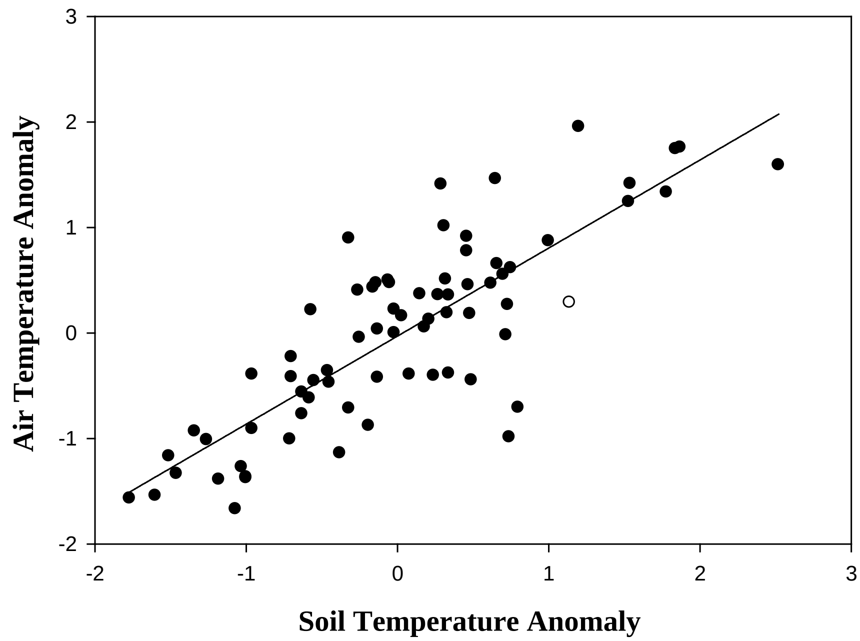

Figure 5-9. Correlation between the variation of soil and air temperature. The data were standardized based on anomaly.

Both the mean annual air temperature and mean annual soil temperature of the Mojave Desert decreased linearly with elevation at an approximate rate of 7.5 °C per 1,000 m in elevation change, indicating that soil and air temperature are highly correlated in the Mojave Desert region and their spatial variation are dominated by the same environmental factors (Figure 5-10).

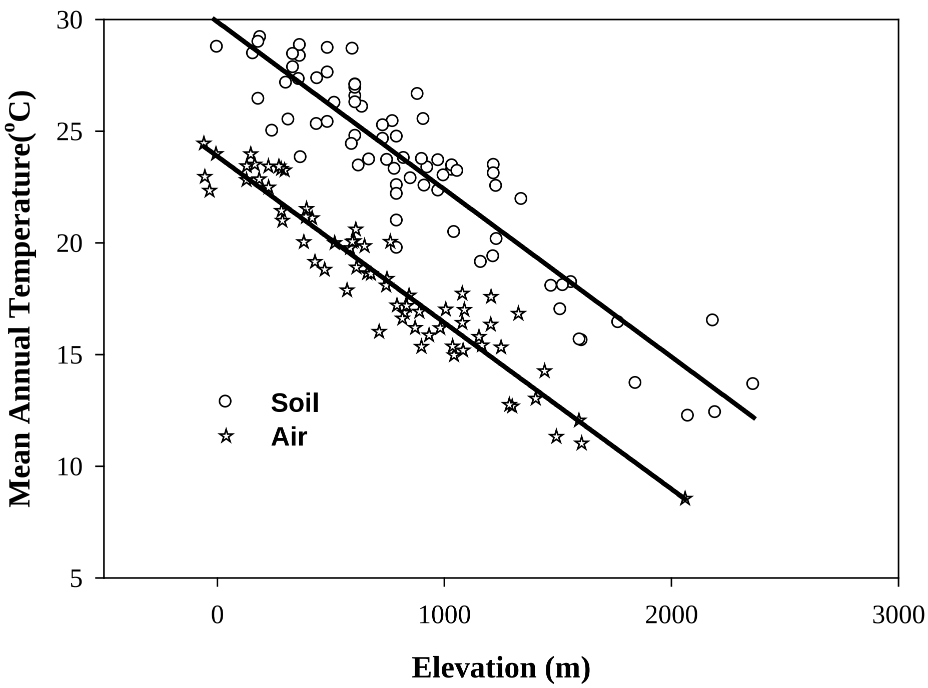

Figure 5-10. Effect of elevation on the spatial change of soil and air temperature.

The climate in Mojave Desert region has been changing. Figure 5-11 illustrates the temporal changes of averaged air temperate anomalies based on data collected from weather stations in the Mojave Desert region. The seasonal anomalies temperature data were smoothed based on the 7-point binomial filter method. There has been a warming trend in the past century in the region ($p<0.0001$). Given that soil temperature and air temperature are closely correlation, the soil temperature of the Mojave Desert region would have increased as well. As atmospheric processes are reflected in soil temperatures, tracking soil temperature can be a valuable variable in monitoring climate change. Soil temperature at a depth of 50 cm is less affected by human activities and small variations of atmospheric cycles. Soil temperature controls the rate of most soil process, especially those that are biologically-mediated. Therefore, soil temperature may provide the mechanistic link between the phenomenon of climate change and the distribution of plant species.

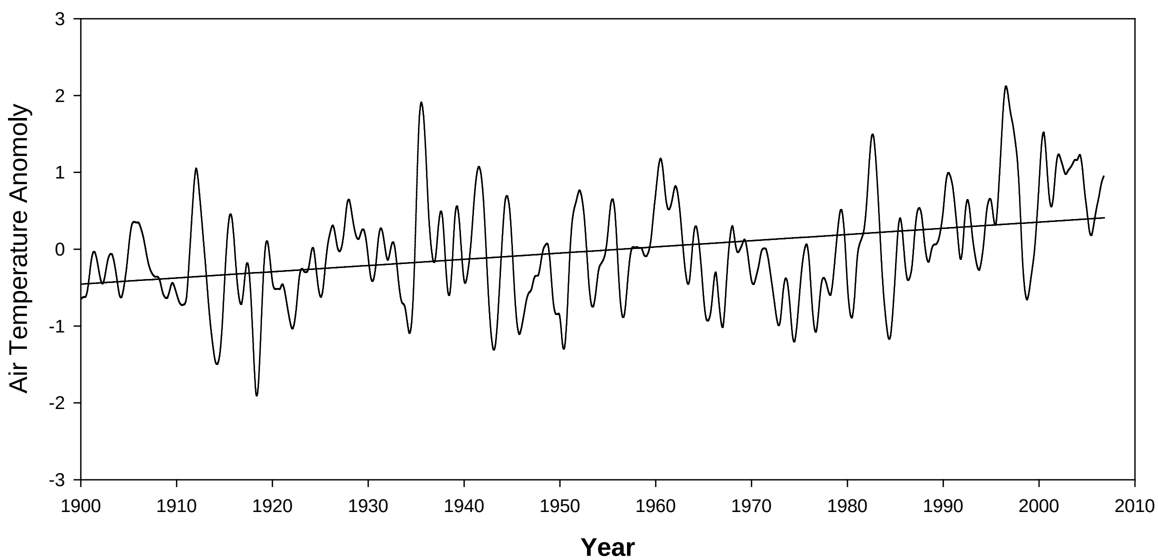

Figure 5-11. Average deviation of air temperature in Mojave Desert region during last century

5.4 Conclusions

This long-term database of soil temperature suggests the following relationships:

(1) The Mojave Desert is experiencing a warming trend. Based on continued measurements across the region, both air and soil temperatures have risen at the rates of 0.79 and 0.63 °C per 10 year from 1982 to 2000.

(2) In Mojave Desert, the air and soil temperatures are correlated and increase inversely with elevation. On the average, the soil temperature is 4.24 °C warmer than the air temperature. Their spatiotemporal variations are highly positively correlated.

(3) The anomalies of annual precipitation were inversely correlated with those of soil temperature. The soil temperature of the Mojave Desert would be cooler than normal under El Niño conditions.

Based on the temperature records, the air temperature of the Mojave Desert has been slowly risen. Given that soil temperature and air temperature are closely correlation, the soil temperature of the Mojave Desert region would have increased as well. As the soil temperature rises, the spatial distribution of vegetation would gradually change with the regional climatic conditions.

Chapter 6

PREDICTING THE TEMPORAL VARIAITON OF SOIL TEMPERATURE IN THE MOJAVE DESERT REGION

6.1 Introduction

Soil temperature provides a link between climate and sub-surface process, and has become a primary predictor of ecological processes. Nevertheless, it is logistically difficult to obtain soil temperature measurements, and many scientists have endeavored to find a best way to predict soil temperatures using measurements that are easier to obtain (Cermak et al., 1992; Kang et al., 2000; Brown et al., 2000; Zhu and Liang, 2005; Chudinova et al., 2006; Gao et al., 2007). One impediment to predicting soil temperatures is that the spatial variance of this measurement is poorly understood, confounded by temporal variance introduced by seasonal and daily weather patterns.

It has been a common practice in the U.S.A. to infer soil temperature from the air temperatures since air temperature is easier to measure and is measured at many more locations than soil temperature (Watson, 1980; Manrique, 1988; Gonzalez-Rouco et al., 2003; Zhu and Liang, 2005; Chudinova et al., 2006; Gao et al., 2007). Air temperature correlates well with soil temperature because both are determined by the energy balance at the ground surface. Toy et al (1978) used monthly mean air temperature to predict monthly soil temperature at continental scales. Hasfurther and Burman (1974) used daily air temperature as a driving variable to predict daily soil temperature by a mathematical model. Bocock et al (1977) reviewed linear regression, multiple regression or harmonic analysis methods of estimating soil temperature from air temperature and other climatic variables. Zheng et al (1993) estimated the daily soil temperature using daily air temperature and precipitation data at continental scales. Mahrer (1980) developed a numerical model for the prediction of bare and mulched soil temperatures using standard meteorological data and the physical characteristics of the soil. Projecting long-term trends in soil temperature may help to further elucidate several ecosystem processes and also may provide more information on how a changing global climate will impact forest ecosystems (Brown et al., 2000). Kang et al (2000) developed a hybrid soil temperature model to predict daily spatial patterns of soil temperature in a forested landscape by incorporating the effects of topography, canopy and ground litter. One may also use leaf area index (LAI) gained remote sensing data with climate data to predict soil temperatures at continental scale.

Since vegetation can influence greatly the surface energy balance, it is better to adjust predicted bare-soil temperatures for different LAIs (Cermak et al., 1992).

In summary, soil temperature might be estimated by two different approaches based upon: (1) soil heat flow and energy balance (Parton, 1984; Stathers et al., 1985; Nobel and Geller, 1987; Thunholm, 1990; Rosenberg et al., 1983; Marshall et al., 1996), and (2) empirical correlations with easily acquired variables (Zheng et al., 1993). Theory-based models may provide accurate estimates of soil temperature at small scales, but they are computationally demanding and parameter intensive (Qin et al., 2002). These models may not be practical for estimation of soil temperature at continental and global scales as many parameters required may vary drastically over short distances. Empirical regional regression models, such as the one developed by Zheng et al (1993), require only a few variables such as air temperature and LAI, but depend on good estimates of some key regression coefficients specific to each region. This limitation can be minimized if the structure and parameterization process of model are modified in terms of heat transfer physics (Kang et al., 2000).

Deriving a method to predict soil temperature from air temperature and other climatic factors could decrease the amount of time and cost necessary for on-site monitoring of soil temperature and allow researchers to use data from other sources. Under some conditions, detailed soil temperature data from all parts of the region were not available, thus it is useful to establish relationship between soil and air temperatures or other variables, taking the region as a whole.

In this chapter, I built up an empirical model to predict the spatial-temporal variation of soil temperature from other climatic factors, and extrapolate the long-term variation of soil temperature in the Mojave Desert region based on this model and climatic records from weather stations in the region.

6.2 Material and Methods

6.2.1 Data Collection

The soil temperature data used in this research were from a long-term soil temperature measurement project initiated in the early 1980's. In the project, soil temperature data were continuously collected annually or seasonally at 75 monitoring sites through the Mojave Desert region from 1982-2000. The soil temperature at 50 cm depth was measured based on the Pallmann method (see Chapter 3).

At each monitoring site, soil moisture content at 50 cm was measured quarterly by gravimetric method. The method involves weighing a wet sample, removing the water via drying in an oven (105 °C) for 48 hr, and reweighing the sample to determine the amount of water removed. Water content then is obtained by dividing the difference between wet and dry masses by the mass of the dry sample (g/g). When multiplied by 100, this becomes the percentage of water in the sample on a dry-mass basis. The mean annual soil moisture content is calculated as the average of the four quarterly data.

Air temperature, precipitation and evaporation records from 18 weather stations which are close to the soil temperature monitoring sites with similar elevation were collect from Western Regional Climate Center (www.wrcc.dri.edu).

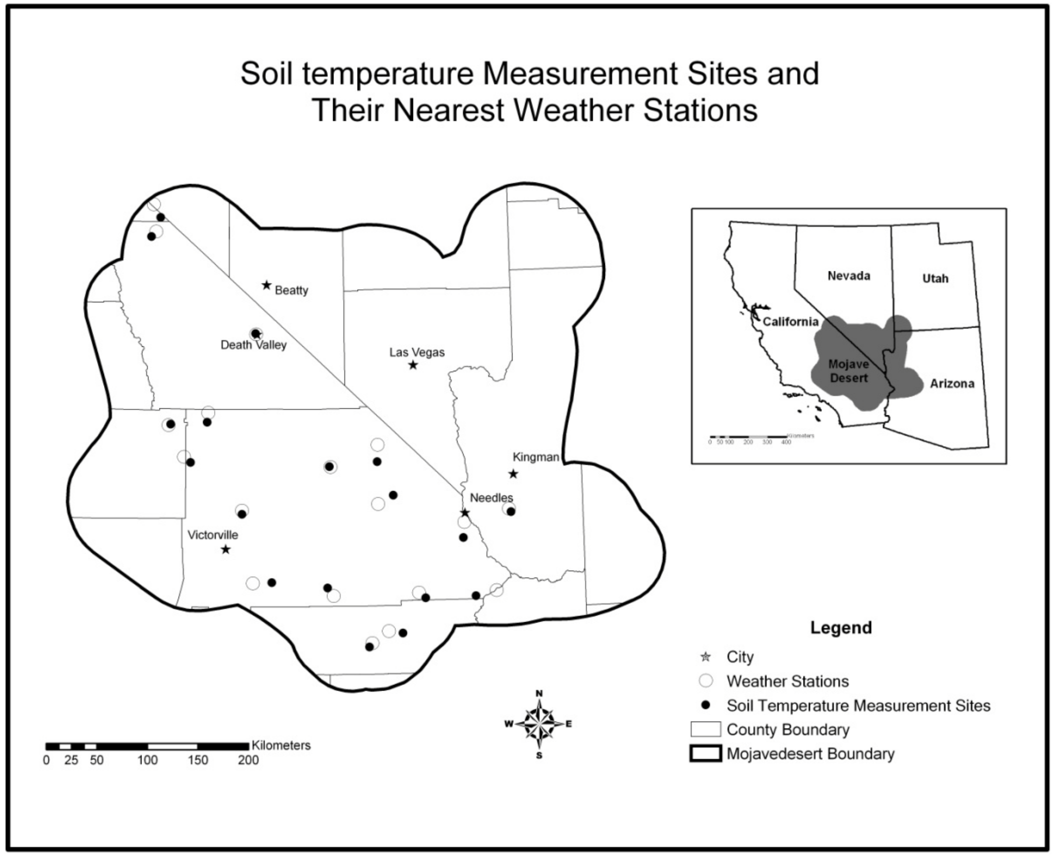

Figure 6-1. Paired soil temperature monitoring sites and weather stations used for data collection in the Mojave Desert region.

Figure 6-1 shows the spatial distribution of those weather stations and corresponding soil temperature monitoring sites in the Mojave Desert region. The data were recorded on daily based and were temporally integrated. When there is more than 5 days data missing in a month, the data for that month will not be used for calculation. When there is data missing for one or more month, the annual data for that year will not be used. Totally, 190 paired data were collected.

Long-term air temperature and precipitation records were collected from 67 weather stations through the Mojave Desert region. These data were used to extrapolate the historic variations of soil temperature in the region.

6.2.2 Data Analysis

A multiple linear regression analysis was conducted to link the spatial variation of soil temperature with other climatic factors including air temperature (MAAT), precipitation (P) and evaporation (ET_0). The multiple linear regression analysis was achieved through SAS software (version 9.0).

6.3 Results and Discussion

6.3.1 Correlations between Soil Temperature and other Climate Factors

Paired data from the soil temperature monitoring sites and their closest weather stations were used to study the correlations between soil temperature and other climate factors. Figure 6-2 illustrates the correlation between the MAST and MAAT of these paired sites. The mean annual soil temperature varied from approximately 10 °C to over 30 °C and the mean annual air temperature varied from 8 °C to 25 °C. There is a significant linear correlation between MAST and MAAT with R^2=0.8981. The linear coefficient is 0.993 and very close to 1, indicating the high correlation between air and soil temperature. As indicated by the intercept, the MAST is on average about 5.0 °C higher than the MAAT.

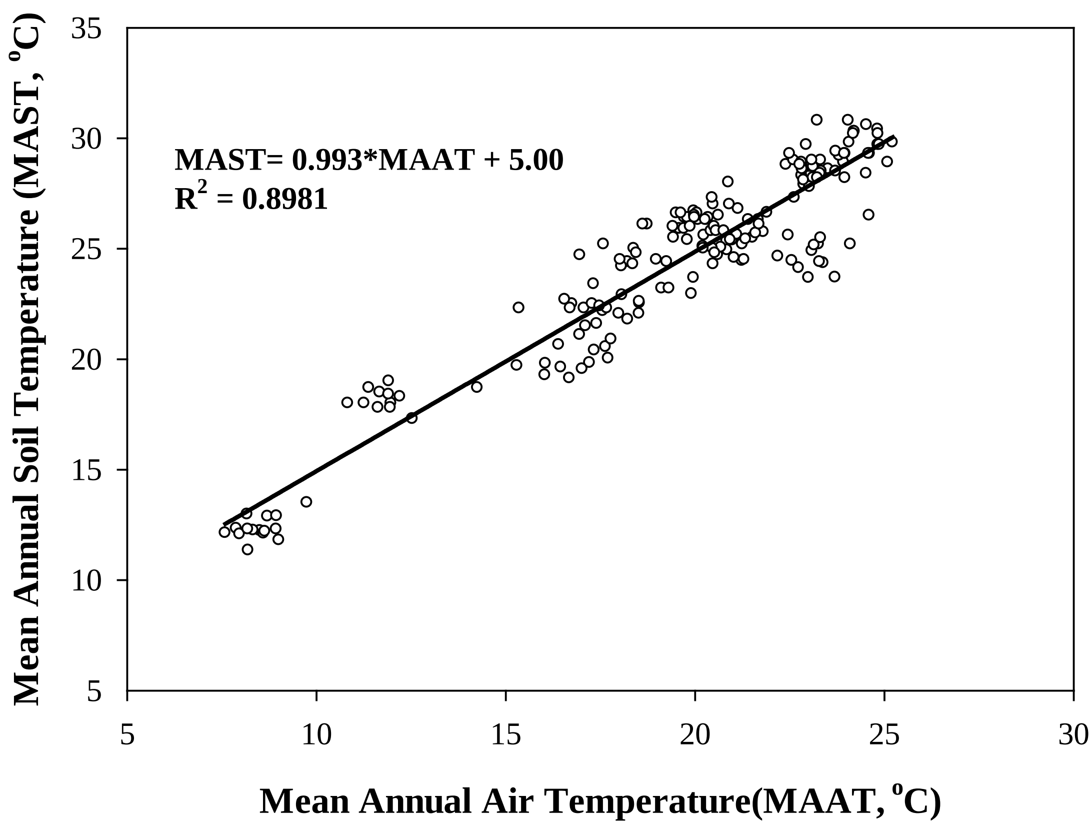

Figure 6-2. Correlation between mean annual air and soil temperature.

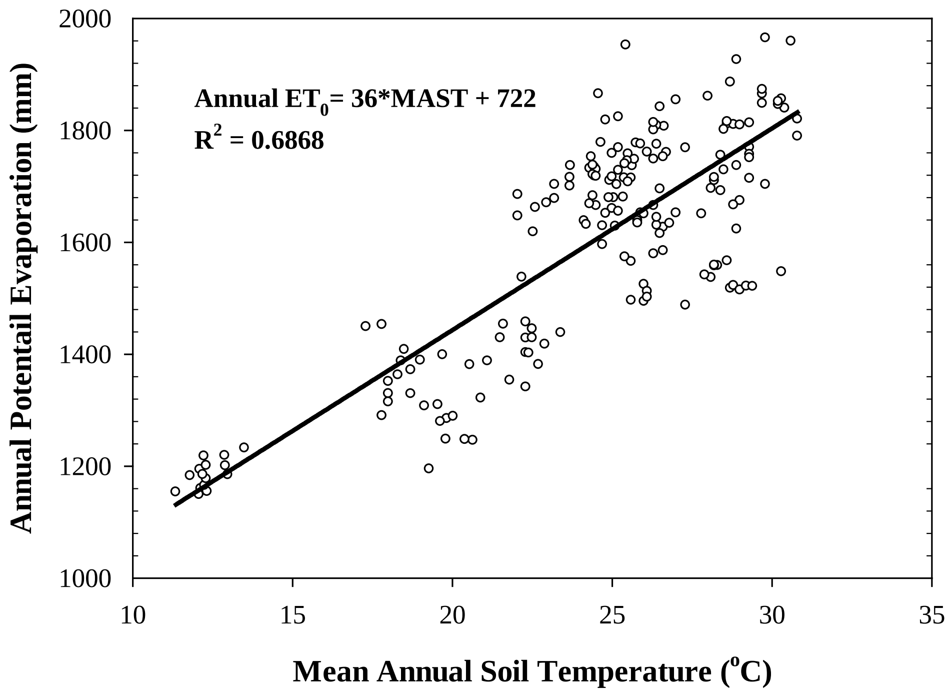

Figure 6-3. Correlation between mean annual soil temperature and evaporation.

A good correlation between soil temperature and evaporation was observed in the Mojave Desert region (Figure 6-3). The annual potential evaporation increase linearly with the mean annual soil temperature (R^2=0.6766). Due to the high air temperature and relative low air humidity, the annual potential evaporation in the Mojave Desert region is high ranging from around 1000 mm to above 3000 mm. Vast amounts of energy are needed for water evaporation. Therefore, high evaporation is generally associated with high air/soil temperature.

The amount of precipitation was found to be negatively correlated with the soil temperature with R^2=0.4518 (Figure 6-4).

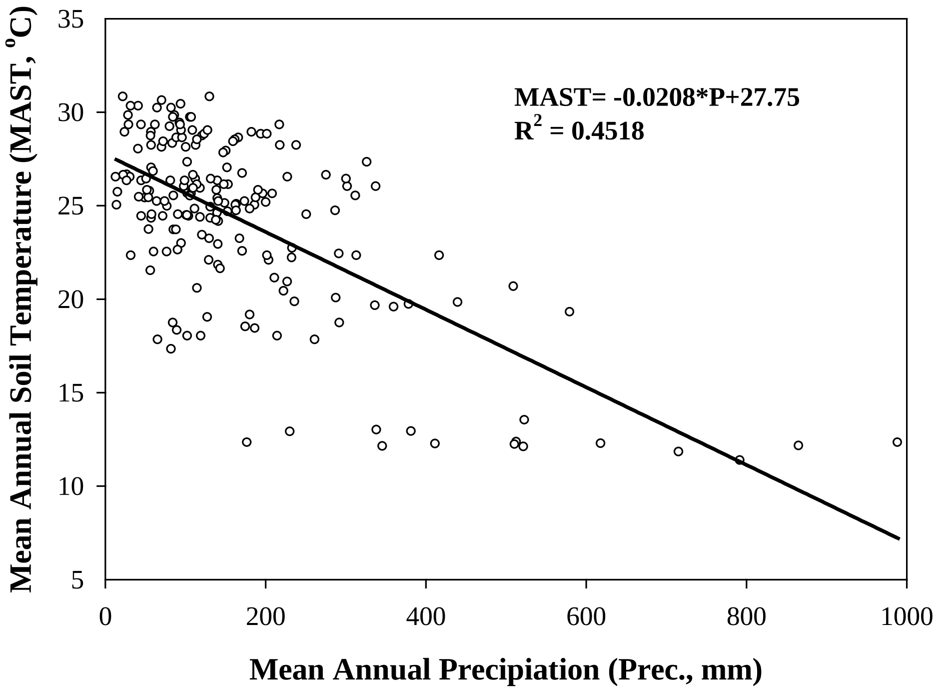

Figure 6-4. Correlation between mean annual soil temperature and precipitation.

In most of the Mojave Desert region, the annual precipitation is less than 200 mm. In some high elevation area, the annual precipitation can reach to above 400 mm. Precipitation increases soil moisture content which in turn can have significantly impacts on the exchange of heat energy between the land surface and the atmosphere. The heat capacity of water is about 5 times that of the mineral soil particles. Thus, wet soils generally warm more slowly than dry soils. Besides increasing the soil thermal capacity, soil moisture also increase the soil heat conductivity and change the soil albedo. The soil moisture content is mainly dependent on the input through precipitation and the outputs through evaporation and plant transpiration. Therefore, it is expected that the regional variations of soil temperature are affected by the amount of precipitation and evaporation.

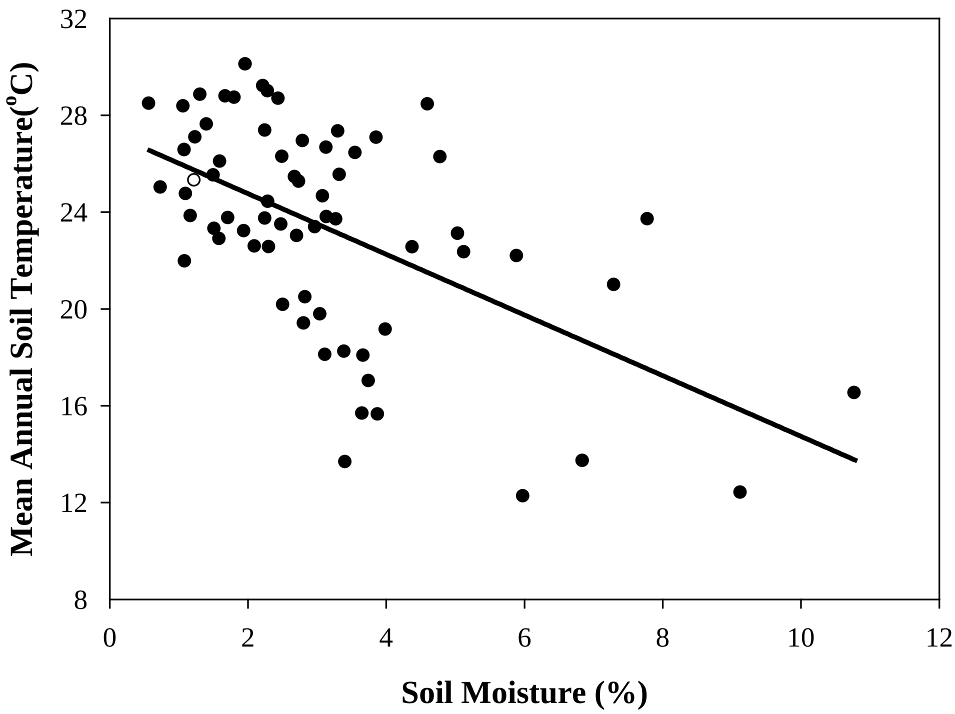

Figure 6-5. Correlation between mean annual soil temperature and soil moisture

Figure 6-5 illustrates the correlation between soil moisture on soil temperature in the Mojave Desert region. The data was based on average value for each monitoring sites. Given the high evaporation and relative low precipitation, desert soils in an arid rain-fed environment have low and limited water contents. The annual mean soil moisture at most of the monitoring sites is less than 5%. The soil temperature decreases as the soil moisture increase. The negative linear relationship is significant on a statistical basis (R^2=0.3107).

6.3.2 Correlations between Soil Temperature and Soil Aridity

The degree of dryness of the climate at a given location can be quantitatively defined through an aridity index (AI). A number of aridity indices have been proposed. The index of aridity proposed by UNEP is commonly adopted, which is given as:

$$AI = \frac{P}{PET} \qquad \text{[Eq. 6-1]}$$

where PET is the potential evapotranspiration and P is the average annual precipitation (UNEP, 1992). According the AI values, the soil was sorted into: hyperaird (AI<0.05), arid (0.05 < AI < 0.20), Semi-arid (0.20 < AI < 0.50) and dry subhumid (0.50 < AI < 0.65).

The correlation between soil temperature and aridity in the Mojave Desert region is illustrated in Figure 6-6. In most of the Mojave Desert region, the annual potential evaporation is quite high ranging from around 1000 mm to above 3000 mm while the annual precipitation is relatively low ranging from below 100 mm to around 400 mm. Consequentially, the soils are dry most of the time. Most of the region belongs to either arid or hyper arid area. The aridity index decreases exponentially as the soil temperature increases (R^2=0.5727).

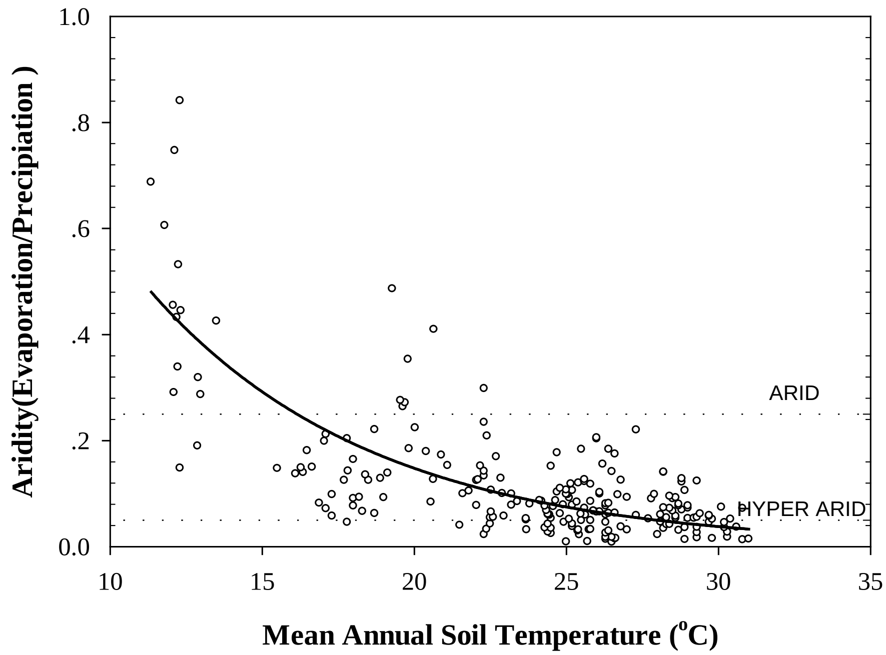

Figure 6-6. Correlation between soil temperature and aridity index (ratio of annual precipitation to potential evaporation) in the Mojave Desert region.

6.3.3 Predicting the spatial-temporal variation of soil temperature

A multiple linear regression analysis was conducted to link the spatial variation of soil temperature with the climatic factors. The database was evenly split into model-building dataset and validation dataset. The full model analysis of model building dataset showed that all the three climatic factors, air temperature, precipitation and evaporation, had significant correlation with soil temperature at p level of 0.05. However, the Variance Inflation Factors (VIF) of air temperature and evaporation are great and multicollinearity is present among these two variables. Given that air temperature is better correlated with soil temperature than evaporation, evaporation is eliminated from the multivariate linear analysis. No clear pattern was observed in the plot of residuals against predicted values. The best lambda given by the Box-Cox Transformations analysis was 1.000. In addition, there is no clear departure from normality based on the normal Q-Q plot.

The model selection results based on different criteria are summarized in Table 6-1. In the F-test based stepwise selection, air temperature was first chosen as the variable predictor, and then precipitation was included. While the R^2 and adjusted R^2 are not significantly improved with addition of precipitation, the Mallows Cp value is significantly smaller and equals to the perfect value 3. Mallows Cp is a gauge of the size of the bias introduced into the estimate of the dependent variable when independent variables are omitted from the regression equation, as computed from the number of parameters plus a measure of the difference between the predicted and true population means of the dependent variable. The results indicates that while the variation of soil temperature in the Mojave Desert region is dominated by the variation of air temperature, the impacts of precipitation cannot be omitted. The results of AIC and BIC criterion which tell how well the selected model fit the data also showed that the model's capability was improved with inclusion of precipitation into the model. The best model based on the model-building dataset is given as:

$$MAST=7.05+0.916*MAAT-0.0031*P \qquad [Eq.6\text{-}2]$$

Table 6-1. Model selection results based on different criterions.

Standard	Variable predictor(s) selected in the best three models
F-test based stepwise selection	1) Air temperature (R^2=0.8866, Cp=6.86) 2) Precipitation (R^2=0.8933, Cp=3)
Akaike's Information Criterion (AIC)	1)air temperature and precipitation(AIC =85.03); 2) air temperature (AIC =88.89) 3) precipitation (AIC =236.04)
Schwartz's Bayesian Information Criterion(BIC)	1)air temperature and precipitation(BIC =92.69); 2) air temperature (BIC =94.00) 3) precipitation (BIC =241.15)
Mallows's Cp	1)air temperature and precipitation(Cp =3); 2) air temperature (Cp =6.86), 3) precipitation (Cp =369.57)
Adjust R-square	1)air temperature and precipitation(Adjust R^2 =0.8933); 2) air temperature (Adjust R^2=0.8866), 3) precipitation (Adjust R^2=0.4661)

The model derived based on the validation dataset is very similar to that based on the model-building dataset (Table 6-2). The mean squared prediction error (MSPR=1.969) from the model build-set does not differ greatly from the mean square error of the model building dataset (MSE=2.372). The results suggest that the regression equation derived from the model- building dataset is a reasonable and valid indicator of the predictive ability of the fitted regression model.

The whole dataset was used for the model build-up and the final best model was given as:

$$MAST=6.84+0.925*MAAT-0.0031*P \qquad [Eq.6\text{-}3]$$

Table 6-2. Comparison of the regression results based on model-building dataset and validation dataset.

	Variable	Parameter estimated	Standard error	t-Value	P-Value
Model-Building dataset	Intercept	7.049	1.093	6.45	<0.0001
	Air temperature	0.9157	0.0477	19.20	<0.0001
	Precipitation	-0.0031	0.00128	-2.42	0.0175
Validation dataset	Intercept	6.68171	0.98117	6.81	<0.0001
	Air temperature	0.93278	0.04164	22.40	<0.0001
	Precipitation	-0.00311	0.00136	-2.29	0.0246

6.3.4 The long-term variation of soil temperature in the Mojave Desert region

The long-term variation of air temperature and precipitation across the Mojave Desert region were tracked based on records from weather stations. Figure 6-7 illustrates the temporal changes of air temperature during the period 1904-2008. There has been a warming trend in the Mojave Desert region, rising at a rate of 0.206 °C per 10 year. Accumulatively, air temperature of the Mojave Desert region has risen by approximately 2 °C during the last century. It is higher than the global warming reported by Hansen et al (2006) and Seinfeld (2008) that the Earth's atmospheric temperature has risen by approximately 0.8 °C during the last century. The climate change pattern is in agreement with the global trend reported by Hansen et al (2006) that two mains warming periods, between 1910 and 1945 and from 1976 onwards, are observed.

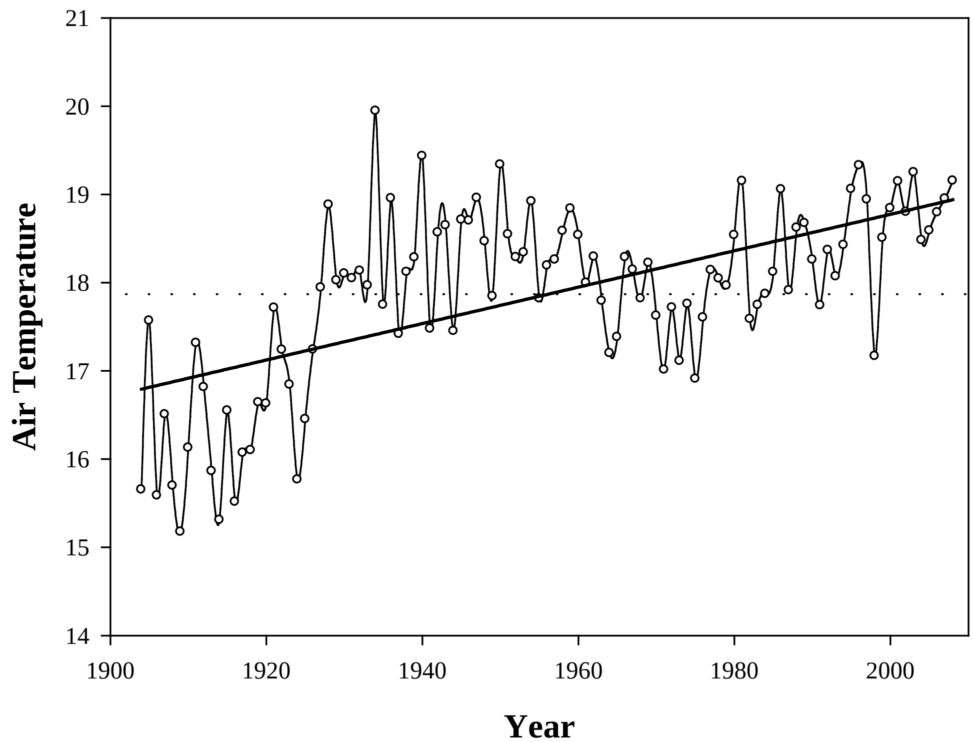

Figure 6-7. Time series of air temperature in Mojave Desert region during the period of 1904-2005

The temporal changes of precipitation in the Mojave Desert during the period 1904-2008 are illustrated in Figure 6-8. Droughts and dry conditions are distinguished from the wet episodes. During the study period, there were two dry multidecadal precipitation regimes, a mid-century dry spell from 1942–1977, and late 1980s drought. Overall, the amount of precipitation slightly decreased with time in response to the warming trend, but variation with time is insignificant ($p>0.05$).

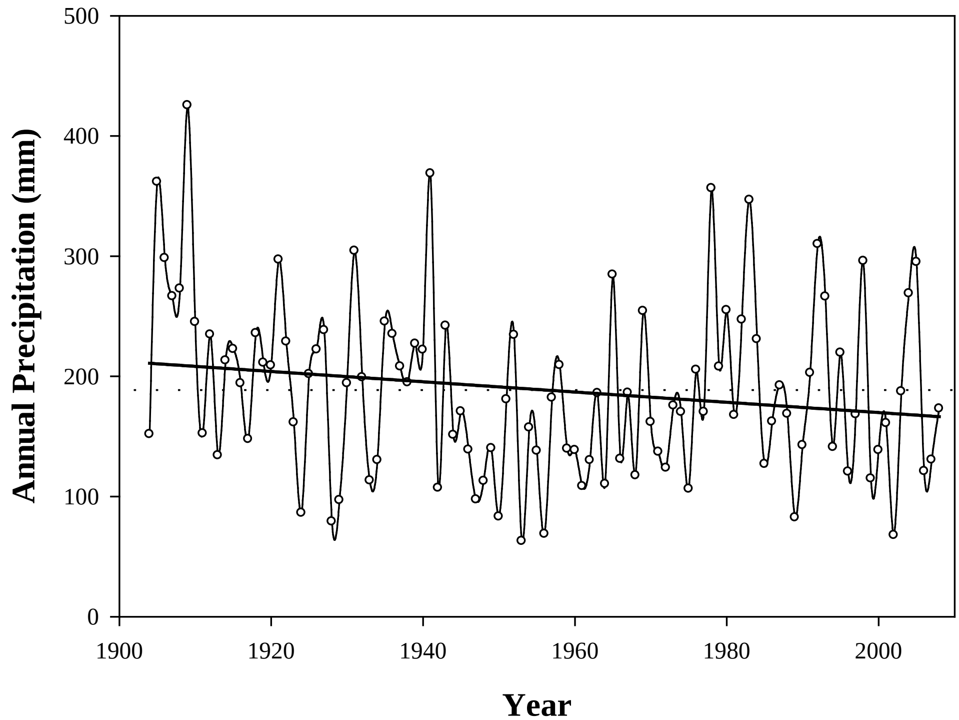

Figure 6-8. Time series f annual precipitation in Mojave Desert region during the period of 1904-2005

The long-term variation of soil temperature can be extrapolated based on the developed model (Eq.6-3) from the air temperature and precipitation data. Figure 6-9 illustrates the temporal changes of soil temperature in the Mojave Desert during the period 1904-2008. As the temporal variation of precipitation is insignificant during the last century, the soil temperature in the region follows a similar trend to that of air temperature at a warming rate of 0.204 °C per 10 year. Accumulatively, the soil temperature across the region is increased about 2 °C in the last century. The results indicate that the soil temperature at 50cm depth response to the region climate change in a similar pattern as that of air temperature. Since the variation of soil temperature integrates both the variation of air temperature and precipitation, it may be use an indicator to monitoring the region climate change.

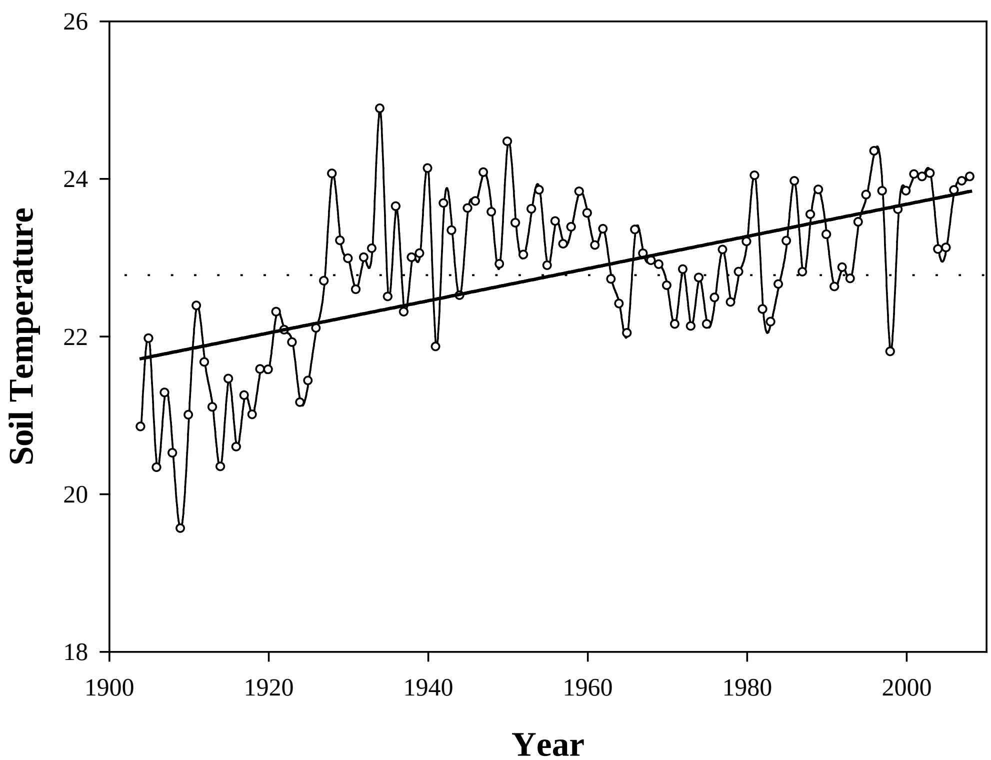

Figure 6-9. Time series of soil temperature in Mojave Desert region during the period of 1904-2005

6.4 Conclusions

Soil temperature varies in response to the air temperature and is greatly affected by the soil moisture content which is mainly dependent on the precipitation and evaporation.

There was a negative linear relationship between soil temperature and precipitation while a positive linear correlation between soil temperature and evaporation. As a result, the soil aridity defining by the ratio of potential annual evapotranspiration and the average annual precipitation increase exponentially as the soil temperature increase. The temporal variation of soil temperature can be predicted from the air temperature and precipitation as: MAST=6.84+0.925*MAAT-0.0031*P

The long-term climatic records from weather stations show that there has been a warming trend in the past century in the region. Both the air temperature and soil temperature has risen by approximately 2 °C during the last century. In response to the climate change, the amount of precipitation varied from year to year. But, the amount of precipitation did not varied significantly during the last century. The variation of soil temperature integrates both the variation of air temperature and precipitation and can be an important vague to monitoring the region climate change.

Chapter 7

GENERAL CONCLUSIONS

In the early 1980's, Dr. Lanny Lund at University of California, Riverside initiated a soil temperature measurement project through the Mojave Desert region. Soil climate data were continuously collected at 75 sites for 19 years (1982-2000). The dataset provides an opportunity to examine both the trend and fluctuations of soil temperature in this specific ecological zone, to understand the linkage between the subsurface soil temperature and environmental factors. A general conclusion of this research is given in the following.

Measurements of temperatures that are averaged or integrated over long time spans are needed for a variety of purposes such as soil resource inventory and climate studies. Mean temperatures usually are obtained in a two-step process of observation and numerical integration of periodic values. Pallmann introduced a technique using a temperature driven chemical reaction to integrate temperature over a period time. The accuracy and consistency of the Pallmann method was quite good in comparison with two other temperature measurement methods: thermistor sensor and diffusion-cell method. On average, the mean annual soil temperatures measured by the Pallmann method were 0.27 °C lower than those measured by the diffusion cell method and were 0.64 °C higher than those measured by the thermistor sensor method. While statistical analysis showed that there was significant difference between the means of these three methods, the Pallmann method may better reflect the real ecological processes in soil in comparison with the arithmetic mean temperature measured by the thermal sensors. It is an ideal method for studying the spatial variation in soil temperature and long-term climate changes.

Soil temperature is an important property that controls or has a strong influence on plant growth and soil formation. It is recognized as an important soil property in Soil Taxonomy. It is necessary to identify the spatial distribution of soil temperature regimes for accurate soil resource inventory. In the Mojave Desert region, elevation was the dominant factor governing the spatial variation of soil temperature. Around 85% of the variability in the soil temperature can be explained by the variability in the elevation. The effect of other geographic parameters on soil temperature was quite limited.

A soil temperature regime map was constructed with support of GIS software based on the linear relationship between the mean annual soil temperature (MAST) and elevation given as:

$$\text{MAST (°C)} = -7.50 * \text{Elevation (km)} + 29.89.$$

The resulting map delineated the boundaries between frigid, mesic, thermic, and hyperthemic soils. Hyperthemic soils are most extensive in the region (around 55%) with an elevation boundary of <1051 m. Thermic soils account for 39% of the region with an elevation range between 1,051 and 1,983 m. Frigid and mesic soils are not extensive and only occur in high elevation mountains.

Seasonal soil temperatures that play important role in plant distribution are found to vary greatly. The seasonal soil temperatures also decrease linearly with increased elevation. At the same elevation, the differences between summer and winter soil temperatures are around 20 °C. The effect of elevation on soil temperature is more pronounced in summer season than in winter season. During the winter season, over 95% of the area has soil temperature less than 15 °C while more than 98% of the area has soil temperature greater than 15 °C in the summer season. No area has soil temperature over 22 °C in the winter season. In contrast, 92.5% of the region has soil temperature over 22 °C in the summer season. The area that has soil temperature < 8 °C almost disappeared in the summer while it accounts for more than one quarter of the region in the winter season.

The resulting spatial distribution of soil temperature regimes is different depending on which year(s) the soil temperature data are used since the regional climate changes with time. Tracking the temporal changes of soil temperature regimes can provide insight into the regional climate changes. It was found the correlation between MAST and elevation is good for all years. The slope of the regression decreases linearly with time while the intercept of the regression increases with time, suggesting that there was a warming trend in the Mojave Desert region during the study period. The temporal variation of hyperthermic regime was found to be highly correlated to regional averaged MAST.

Soil and air temperature are highly correlated in the Mojave Desert region: a) both of the soil and air temperature were found to be highly correlated with elevation. The mean annual air temperature and mean annual soil temperature decreased linearly with elevation at an approximate rate of 7.50 °C/km. On the average, the soil temperature is 4.24 °C warmer than the air temperature. Their spatiotemporal variations are highly positively correlated; b) The spatiotemporal variations of soil temperature are highly positively correlated to those of air temperature; c) while the temporal variations of soil temperature based on the 7-point binomial filter method lagged slightly behind the corresponding air temperature, the patterns of fluctuation were in agreement. As atmospheric processes are reflected in soil temperatures, tracking soil temperature can be a valuable variable in monitoring climate change.

Based on continued measurements across the region, both air and soil temperatures have risen at the rates of 0.79 and 0.63 °C per 10 year from 1982 to 2000. The climate change in the region was found to affect by the El Niño–Southern Oscillation. The soil temperature of the Mojave Desert would be cooler than normal under El Niño conditions.

The exchange of heat energy between the land surface and the atmosphere is greatly affected by the soil moisture content which is mainly dependent on the precipitation and evaporation. There was a negative linear relationship between soil temperature and precipitation while a positive linear correlation between soil temperature and evaporation. As a result, the soil aridity defining by the ratio of potential annual evapotranspiration and the average annual precipitation increase exponentially as the soil temperature increase. Most of the Mojave Desert region belongs to either arid area or hyper arid area.

The spatial-temporal variation of soil temperature can be predicted from the air temperature and precipitation as: MAST=6.84+0.925*MAAT-0.0031*Prec. The long-term climatic records from weather stations show that there has been a warming trend in the past century in the region. Both the air temperature and soil temperature has risen by approximately 2 °C during the last century. In response to the climate change, the amount of precipitation varied from year to year. But, the amount of precipitation did not varied significantly during the last century. The variation of soil temperature integrates both the variation of air temperature and precipitation and can be an important vague to monitoring the region climate change.

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Appendix I: Classes of Soil Temperature Regimes (Soil Survey Staff, 1999)

Following is a description of the soil temperature regimes used in defining classes at various categoric levels in this taxonomy.

Cryic (Gr. kryos, coldness; meaning very cold soils).—Soils in this temperature regime have a mean annual temperature lower than 8 °C but do not have permafrost.

1. In mineral soils the mean summer soil temperature (June, July, and August in the Northern Hemisphere and December, January, and February in the Southern Hemisphere) either at a depth of 50 cm from the soil surface or at a densic, lithic, or paralithic contact, whichever is shallower, is as follows:

a. If the soil is not saturated with water during some part of the summer and

(1) If there is no O horizon: lower than 15 °C; or

(2) If there is an O horizon: lower than 8 °C; or

b. If the soil is saturated with water during some part of the summer and

(1) If there is no O horizon: lower than 13 °C; or

(2) If there is an O horizon or a histic epipedon: lower than 6 °C.

2. In organic soils the mean annual soil temperature is lower than 6 °C.

Cryic soils that have an aquic moisture regime commonly are churned by frost.

Isofrigid soils could also have a cryic temperature regime. A few with organic materials in the upper part are exceptions.

The concepts of the soil temperature regimes described below are used in defining classes of soils in the low categories.

Frigid.—A soil with a frigid temperature regime is warmer in summer than a soil with a cryic regime, but its mean annual temperature is lower than 8 °C and the difference between mean summer (June, July, and August) and mean winter (December, January, and February) soil temperatures is more than 6 °C either at a depth of 50 cm from the soil surface or at a densic, lithic, or paralithic contact, whichever is shallower.

Mesic.—The mean annual soil temperature is 8 °C or higher but lower than 15 °C, and the difference between mean summer and mean winter soil temperatures is more than 6 °C either at a depth of 50 cm from the soil surface or at a densic, lithic, or paralithic contact, whichever is shallower.

Thermic.—The mean annual soil temperature is 15 °C or higher but lower than 22 °C, and the difference between mean summer and mean winter soil temperatures is more than 6 °C either at a depth of 50 cm from the soil surface or at a densic, lithic, or paralithic contact, whichever is shallower.

Hyperthermic.—The mean annual soil temperature is 22 °C or higher, and the difference between mean summer and mean winter soil temperatures is more than 6 °C either at a depth of 50 cm from the soil surface or at a densic, lithic, or paralithic contact, whichever is shallower.

If the name of a soil temperature regime has the prefix iso, the mean summer and mean winter soil temperatures differ by less than 6 °C at a depth of 50 cm or at a densic, lithic, or paralithic contact, whichever is shallower.

Isofrigid.—The mean annual soil temperature is lower than 8 °C.

Isomesic.—The mean annual soil temperature is 8 °C or higher but lower than 15 °C.

Isothermic.—The mean annual soil temperature is 15 °C or higher but lower than 22 °C.

Isohyperthermic.—The mean annual soil temperature is 22 °C or higher.

Appendix II: Study sites information

Site #	Location	Longitude (^{o})	Latitude (^{o})	Elevation (m)
1	Hayfield Exit	-115.66	33.67	440
2	Chuckwalla Valley	-115.30	33.79	159
3	Palen Valley	-115.24	33.99	305
4	Ward Valley	-115.05	34.10	244
5	Granite Pass	-115.21	34.05	442
6	Cadiz Valley	-115.32	34.07	366
7	Cadiz Valley #2	-115.47	34.10	610
8	Dale Lake Hi 62	-115.63	34.10	488
9	Dale Lake	-115.68	34.13	369
10	Utah Trail Road	-115.92	34.08	853
11	Twenty-nine Palms	-116.10	34.20	610
12	Coyote Valley	-116.26	34.21	793
13	Yucca Mesa	-116.38	34.18	1045
14	Rim Rock	-116.54	34.19	1341
15	Vaughn Spring Flat	-116.64	34.23	1768
16	Rose Mine Flat	-116.70	34.25	2075
17	Sheep Hole Pass	-115.72	34.26	640
18	Bristol Lake	-115.72	34.44	183
19	S.Kelbaker Rd#1	-115.64	34.58	366
20	S.Kelbaker Rd#2	-115.68	34.66	610
21	S.Kelbaker Rd#3	-115.68	34.70	783
22	S.Kelbaker Rd#4	-115.66	34.74	1036
23	Granite Cove	-115.64	34.77	1219
24	N.Kelbaker Rd	-115.64	34.86	1036
25	South Kelso	-115.64	34.98	671
26	Cedar Canyon Rd	-115.41	35.17	793
27	Round Valley	-115.40	35.14	1606
28	Gold Valley	-115.40	35.08	1473
29	Hole in the Wall	-115.38	35.02	1232
30	Black Canyon Rd	-115.42	34.92	914
40	Monarch Flat	-116.83	34.35	1598
41	Broom Flat	-116.72	34.22	2363
42	Cactus Spring	-116.81	34.32	1844
43	N.Lucerne Valley	-116.97	34.58	927
44	Stoddard Valley	-116.95	34.66	1219
45	S.Barstow Road	-117.02	34.86	793
46	Coolgardia Mesa	-116.98	35.08	1163

To be continued……

Site #	Location	Longitude (^{o})	Latitude (^{o})	Elevation (m)
63	South Vidal	-114.51	34.11	191
65	Chemehuevi Vy.	-114.65	34.46	361
66	Lobecks Pass	-114.63	34.63	597
67	Piute Valley Cal	-114.83	35.08	610
68	Piute Valley Nev	-114.87	35.27	774
69	W.Searchlight	-115.04	35.50	1230
70	West Nipton	-115.38	35.46	823
71	Cima Dome	-115.55	35.32	1513
72	Shadow Valley	-115.62	35.40	1218
73	Halloran Springs	-115.89	35.38	903
74	Baker	-116.07	35.28	315
75	Val Jean Valley	-116.25	35.60	183
76	McLain Park	-116.32	35.84	488
77	Amargosa Desert	-116.42	36.32	625
79	Chicago Valley	-116.13	35.87	610
80	Pahrump Valley	-115.90	35.96	793
81	California Vy	-116.05	35.86	750
82	Shadow Valley	-115.73	35.61	975
83	Panamint Springs	-117.42	36.34	488
84	Panamint Valley	-117.28	36.10	335
85	Searles Valley	-117.32	35.92	732
86	Salt Wells Cyn	-117.40	35.68	518
87	Saltdale	-117.87	35.35	594
88	Atolia	-117.58	35.32	975
89	Kramer Junction	-117.53	34.96	793
90	Inyokern	-117.80	35.66	732
91	Death Valley	-116.87	36.47	-59
92	Death Valley	-117.11	36.70	0
93	N.Death Valley	-117.58	37.20	998
94	Eureka Valley	-117.80	37.25	1059
96	Cowhorn Valley	-118.03	37.17	2195
98	Saline Valley	-117.78	36.67	335
99	Hunter Mtn.	-117.52	36.54	2185
101	Deep Springs Vy	-118.03	37.33	1561
102	Dyer	-117.93	37.50	1524
111	W.Kingman Ariz.	-114.16	35.23	910
112	E.Yucca Ariz.	-114.11	34.85	610
113	Alamo Rd Ariz.	-113.97	34.74	884

Appendix III: **Statistical descriptions of MAST collected at each monitoring site**

Site #	Average	Minimum	Maximum	Stdev	Data Collection Year
1	25.3	24.3	26.6	0.6165	1982-1999
2	28.5	25.6	30.3	0.9994	1982-1998
3	27.1	25.0	28.1	1.2381	1982-1986
4	25.0	23.7	27.9	1.0745	1982-1999
5	27.3	24.2	28.8	1.0125	1982-1987, 1990-1999
6	28.3	25.4	29.7	1.1231	1982-1999
7	24.8	23.2	25.5	0.9209	1982-1986
8	25.4	23.3	26.2	1.2337	1982-1986
9	23.8	22.9	25.2	0.6601	1982-1999
10	22.9	21.9	24.3	0.5984	1983-1999
11	26.5	23.2	28.0	1.0983	1982-1998
12	24.7	22.0	26.1	0.9765	1982-1999
13	20.5	19.4	22.2	0.7132	1982-1999
14	21.9	19.3	23.3	0.9027	1982-1998
15	16.4	14.4	17.2	1.1883	1982-1986
16	12.2	10.8	13.5	0.6104	1982-1999
17	26.1	23.0	27.8	1.5301	1983-2000
18	26.4	25.5	28.6	0.7270	1982-1999
19	28.8	25.4	30.3	1.0085	1982-1999
20	27.1	23.8	28.3	1.0006	1982-1993, 1995-1998
21	23.3	22.4	24.8	0.6675	1982-1999
22	23.2	21.0	24.1	1.3012	1982-1986
23	23.5	20.0	24.4	1.0085	1982-1997
24	23.4	20.4	24.6	1.7401	1982-1986
25	23.7	22.0	26.1	1.3184	1982-1989, 1991-1999
26	19.7	19.0	21.1	0.5522	1983-1999
27	15.6	14.6	17.2	0.6688	1983-1999
28	18.0	16.8	19.4	0.6270	1983-1999
29	20.1	19.1	21.8	0.6703	1983-1999
30	22.5	21.4	24.4	0.7300	1983-1999
40	15.7	14.3	16.9	0.5978	1984-1999
41	13.6	11.2	15.2	0.9651	1982, 1984-1999
42	13.7	12.3	14.9	0.6777	1983-1999
43	23.3	20.5	24.8	1.4808	1983-1999
44	23.1	19.6	24.9	1.9430	1983-1999
45	22.6	21.6	23.7	0.5047	1983-1999

To be continued……

46	19.1	18.2	20.6	0.5864	1983-1998
63	29.2	28.2	30.8	0.7405	1984-1991, 1993-2000
65	27.3	26.5	28.6	0.5460	1984-2000
66	28.7	27.8	29.8	0.5421	1984-2000
67	26.9	26.0	28.2	0.5555	1984-2000
68	25.4	23.4	26.7	0.9096	1984-1987,1989-1990,1992-2000
69	22.5	21.5	23.6	0.5788	1984-1993, 1995-2000
70	23.8	23.2	24.9	0.4716	1984-2000
71	17.0	15.5	18.9	0.9180	1984-1998
72	19.4	18.2	20.8	0.8269	1984-1999
73	23.7	22.5	26.6	1.2351	1984-1999
74	25.5	24.6	26.8	0.5638	1986-1999
75	29.0	28.4	30.1	0.4623	1984-2000
76	28.7	27.9	30.1	0.5774	1984-1999
77	23.4	23.0	24.0	0.2548	1984-2000
79	27.0	26.4	28.2	0.3939	1984-2000
80	21.0	20.0	21.9	0.5314	1984-2000
81	23.7	23.0	24.8	0.4535	1984-1999
82	23.7	22.9	24.7	0.4727	1984-2000
83	27.6	27.1	28.6	0.4139	1984-1999
84	28.4	27.3	29.4	0.4867	1984-2000
85	25.2	24.4	26.2	0.3968	1984-2000
86	26.2	25.6	27.1	0.3938	1984-2000
87	24.4	24.0	25.0	0.3950	1985-1990
88	22.3	21.1	23.4	0.5655	1985-1999
89	22.2	21.6	23.2	0.3906	1984-2000
90	24.6	24.1	25.8	0.4514	1987-2000
91	30.1	28.9	31.0	0.5972	1985-2000
92	28.8	27.9	29.5	0.4033	1985-2000
93	23.0	22.3	24.5	0.5682	1987-2000
94	23.2	22.6	24.2	0.4400	1987-2000
96	12.4	10.7	13.5	0.7026	1986-1989, 1991-2000
98	27.8	27.5	28.3	0.4163	1985-1987
99	16.5	16.0	17.4	0.4472	1985-1996, 1999
101	18.2	17.2	19.1	0.4890	1988-2000
102	18.1	17.3	19.0	0.4920	1989-2000
111	25.5	24.7	26.7	0.5900	1987-1989, 1991-1994, 1996-2000
112	26.3	25.4	27.0	0.4536	1985-1995, 1998-2000
113	26.6	25.9	27.6	0.5225	1985-2000

Appendix IV: **Slope and aspect information for each monitoring site.**

(N: north facing; S: south facing; F: flat)

Site #	LOCATION	Slope	Aspect	Aspect Facing*
1	Hayfield Exit	2.4	37	N
2	Chuckwalla Valley	0.0	-1	F
3	Palen Valley	1.1	236	S
4	Ward Valley	0.7	18	N
5	Granite Pass	2.2	304	N
6	Cadiz Valley	2.4	66	N
7	Cadiz Valley #2	1.3	80	N
8	Dale Lake Hi 62	3.4	333	N
9	Dale Lale	0.3	315	N
10	Utah Trail Road	0.0	-1	F
11	Twenty-nine Palms	1.1	82	N
12	Coyote Valley	4.2	114	S
13	Yucca Mesa	1.8	121	S
14	Rim Rock	1.9	97	S
15	Vaughn Spring Flat	2.5	92	S
16	Rose Mine Flat	3.9	236	S
17	Sheep Hole Pass	4.5	20	N
18	Bristol Lake	0.3	63	N
19	S.Kelbaker Rd#1	1.6	146	S
20	S.Kelbaker Rd#2	1.9	189	S
21	S.Kelbaker Rd#3	4.3	183	S
22	S.Kelbaker Rd#4	4.6	177	S
23	Granite Cove	2.5	185	S
24	N.Kelbaker Rd	2.2	342	N
25	South Kelso	3.2	315	N
26	Cedar Canyon Rd	0.4	31	N
27	Round Valley	2.2	74	N
28	Gold Valley	2.2	124	S
29	Hole in the Wall	3.4	153	S
30	Black Canyon Rd	2.0	207	S
40	Monarch Flat	11.0	335	N
41	Broom Flat	0.5	45	N
42	Cactus Spring	8.6	334	N
43	N.Lucerne Valley	1.8	73	N
44	Stoddard Valley	3.5	335	N
45	S.Barstow Road	3.5	85	N

To be continued……

46	Coolgardia Mesa	1.2	342	N
63	South Vidal	0.0	-1	F
65	Chemehuevi Valley	0.9	225	S
66	Lobecks Pass	1.3	320	N
67	Piute Valley Cal	3.9	249	S
68	Piute Valley Nev	4.0	335	N
69	W.Searchlight	1.4	103	S
70	West Nipton	0.6	90	S
71	Cima Dome	1.8	315	N
72	Shadow Valley	0.9	315	N
73	Halloran Springs	1.0	252	S
74	Baker	0.8	281	N
75	Val Jean Valley	2.2	2	N
76	McLain Park	0.8	331	N
77	Amargosa Desert	0.7	186	S
79	Chicago Valley	5.8	301	N
80	Pahrump Valley	0.0	-1	F
81	California Vy	0.2	72	N
82	Shadow Valley	1.4	257	S
83	Panamint Springs	0.7	162	S
84	Panamint Valley	0.3	27	N
85	Searles Valley	1.2	247	S
86	Salt Wells Cyn	1.6	115	S
87	Saltdale	1.2	247	S
88	Atolia	4.1	172	S
89	Kramer Junction	0.9	52	N
90	Inyokern	0.6	23	N
91	Death Valley	1.5	229	S
92	Death Valley	2.8	246	S
93	N.Death Valley	0.3	90	S
94	Eureka Valley	0.9	180	S
96	Cowhorn Valley	20.6	128	S
98	Saline Valley	2.7	68	N
99	Hunter Mtn.	3.2	309	N
101	Deep Springs Vy	1.1	146	S
102	Dyer	0.4	45	N
111	W.Kingman Ariz.	2.2	239	S
112	E.Yucca Ariz.	1.5	270	N
113	Alamo Rd Ariz.	2.1	220	S