DISSERTATION

LONG-TERM ANALYSIS AND APPROPRIATE METRICS OF CLIMATE CHANGE IN MONGOLIA

Submitted by

Khishigbayar Jamiyansharav

Graduate Degree Program in Ecology

In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Spring 2010

COLORADO STATE UNIVERSITY

Feb. 04, 2009

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY KHISHIGBAYAR JAMIYANSHARAV ENTITLED “LONG-TERM ANALYSIS AND APPROPRIATE METRICS OF CLIMATE CHANGE IN MONGOLIA” BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Alan Knapp

William Parton

Roger A. Pielke Sr., Co-adviser

Dennis S.Ojima, Adviser

N.LeRoy Poff, Interim director

ABSTRACT OF DISSERTATION

LONG-TERM ANALYSIS AND APPROPRIATE METRICS OF

CLIMATE CHANGE IN MONGOLIA

This study addresses three important issues related to long-term climate change study in Mongolia. Mongolia is one of the biggest land-locked countries in Asia and 75-80 percent of the land is rangeland, which is highly vulnerable to climate change. Climate will affect many sectors critical to the country's economic, social, and ecological welfare. Therefore, it is regionally and globally important to evaluate climate change in Mongolia.

Chapter 1 discusses the qualitative and descriptive study on exposure characteristics of the 17 Mongolian meteorological stations, which are part of the Global Climate Observing Network (GCON). The global average temperature anomalies are based in part on the GCON stations' meteorological data. To document the possible exposures surrounding the weather stations, the Mongolian meteorological stations were surveyed during July-August 2005. From the total 17 stations, 47 percent were determined strongly influenced by urban character landscape, 41 percent received some anthropogenic influences, and 12 percent had very little to no anthropogenic influences. Even though the Mongolian meteorological stations' exposure characteristics are better than the European and North American stations' the strict adherence in following WMO guidelines is important and urgently needed.

Chapter 2 evaluates the long-term (1961-2005) trends in seasonal and annual surface mean, maximum, minimum temperatures and precipitation. Furthermore, this study compares the long-term mean temperature trends with decadal (1998-2007) trends. This chapter also discusses the extreme climate indices on spatial and temporal scales. According to the results, the long-term linear temperature trends show a clear increasing trend whereas the decadal trends show the decreasing trend mostly in winter and spring. The analysis of extreme indices (1961-2001) indicate that most of the stations frost and icing days are decreased and summer days, tropical nights, monthly maximum value of daily minimum, maximum temperatures and growing season length are increased. Precipitation indices varied substantially and there were no unified temporal and spatial pattern. In addition to that, I am suggesting effective temperature as an appropriate metric to evaluate surface heat change because it counts not only air temperature but also surface humidity.

Chapter 3 discusses a case study of grazing intensity on surface energy budgets. To evaluate the land atmospheric interactions over the grassland area depending on the different grazing intensity I conducted the case study over the Shortgrass Steppe Long-Term Ecological Research site on Northern Great Plains of US to imply the findings in semiarid shortgrass steppe of Mongolia. The study site has much of similarities with Mongolian shortgrass steppe and has more frequent, high quality data. This study evaluates the impact of grazing on microclimate and energy budgets in a dry (163 mm) and two near-normal (262 and 260 mm) precipitation years based on continuously measured 20 minute interval data. This study helps to describe surface energy partitioning in semi-arid grasslands that has long history of grazing. The main finding of the study is grazing has a potential impact on the energy partitioning under conditions of higher water availability, but not during dry conditions.

Khishigbayar Jamiyansharav
Graduate Degree Program in Ecology
Colorado State University
Fort Collins, CO 80523
Spring 2010

ACKNOWLEDGEMENTS

I would like to acknowledge a number of people who are involved in the completion of my study and research. First, of all I am truly grateful to the Mongolian Government for the financial support to study for my degree program. In addition, I would like to give my sincere thanks to my graduate advisors, Dr. Dennis S. Ojima and Roger A. Pielke Sr., who for the past five years have been tremendously patient with me and have assisted through the tedious learning process to accomplish this research. Without their guidance and supervision, I would have never been able to complete my degree program.

Second, I would like to give my sincere gratitude to my graduate committee, Dr. William Parton, and Dr. Alan Knapp for their guidance, advice and their valuable time dedicated to review my dissertation and scientific publications. Next, I would like to give my special thanks to Jack Morgan, Daniel LeCain and David Smith (USDA-ARS) Adriana Beltrán-Przekurat, Dallas Staley (Department of Atmospheric and Oceanic Sciences and CIRES), Robin Kelly (NREL) and my former committee member David Schimel (NCAR) for their valuable guidance and time for editing the publications.

I would like to thank the support of the Shortgrass Steppe Long Term Ecological Research project by funds from the National Science Foundation award DEB 0217631 and NASA Grant NNG05GA33G (Northern Eurasian Carbon Land Use and Climate Interactions), the F/DOE/The University of Alabama in Huntsville's Utilization of Satellite Data for Climate Change Analysis project DE-FG02-04ER 63841 through the University of Alabama at Huntsville, and the Colorado Climate Center which is funded in part by the Colorado Agricultural Experiment Station. In addition, I must give special thanks to the Faculty of Graduate Degree program of Ecology and Department of Forest Rangeland Watershed and Stewardship for providing me the opportunity to study at Colorado State University and for their guidance to my scientific achievements.

My heartfelt acknowledgement goes to my husband, wonderful 2 daughters who have given me their precious love, tremendous support, helping hand to accomplish all my achievement and to my little boy who has given us all the strength, happiness and amazing laugh. They inspired me to overcome all the obstacles associated with living abroad. Tremendous thanks to my Mom, Dad and my siblings for their support and helping me get through the good and bad times during my graduate studies. Thanks to all for your love and encouragement.

Last, but not least I would like to acknowledge all my friends and staff at NREL, who have been given me their warm support and precious friendship.

DEDICATION

I would like to dedicate my dissertation to my loving 14-year old Daughter Urangua “Sisi” Mijiddorj, who passed away on bike-car accident on the way to her Poudre High School (International Baccalaureate program). My heartfelt memories are with you, my lovely girl.

In addition, I must dedicate my dissertation to Dr. Chadraa Baatar, who was the former head of Mongolian National Renewable Energy Center, where I had been working before I came here.

TABLE OF CONTENTS

INTRODUCTION

Mongolia is one of the largest land-locked countries of Asia and the capital city Ulaanbaatar is the coldest capital city in the world (Batima, 2003). Mongolia is located in central Asia sandwiched between Russia and China, covering 1.56 million square km with an average altitude of 1580 m. Rangelands in Mongolia cover 75-80 percent of the total territory (Erdentuya and Khudulmur 2005, Fernandez-Gimenez and Allen-Diaz 1999). “A significant portion of rangeland in Mongolia can be considered one of the “virgin” steppe landscapes in the world” (Zamba 2007). These areas are important to the Mongolian animal husbandry industry, a key economic resource, which directly depends on the vegetation and climate conditions. Range conditions within the last several years have degraded rapidly because of extreme weather events (drought and blizzards), an increasing livestock population and greater concentration of people, especially around urban areas during the transition period to the free market economy. Therefore, to monitor the long-term change and trends for climate features are very important to examine the climate changes in local individual sites as well as their influence on the regional climate.

Specific objectives of this study are to:

- Evaluate exposure characteristics of the Mongolian meteorological stations to check if they comply to World Meteorological Organization (WMO) standards
- Document photographically meteorological stations exposure characteristics
- Determine the long-term (1961-2004) as well as the short-term (1998-2007) trends in seasonal and annual surface temperatures across Mongolia

- Analyze the extreme climate indices for chosen stations and compare the surface trends with the upper air temperature trends
- Determine if present surface air temperature data over- or under-estimate surface heating in Mongolia
- Conduct a case study on surface energy flux partitioning over the northern semiarid shortgrass steppe of US to imply the findings in semiarid shortgrass steppe of Mongolia
- Address how variation in aboveground biomass affects surface energy budgets, soil and air temperatures

Hypotheses:

- Mongolia has big open lands and density of the population is very low comparison to other Asian, European and American countries therefore, the meteorological stations would have better exposure characteristics.
- Country side meteorological stations should have better exposure characteristics than the crowded city stations.
- There is a greater warming trend in winter than in summer months because of transpiration of vegetation and monsoonal precipitation during the summer.
- The climate indices would indicate temperature increase associated with global warming.
- Temperature increase may not indicate the surface heat increase especially during the summer when the humidity increases.
- In semi-arid grasslands, the main affect of rainfall events on the energy balance is to increase the ratio of latent to sensible heat fluxes for a brief period, seldom

exceeding five days. This effect is expected to be more pronounced with increases in leaf area, and consequently, greatest in the ungrazed pasture.

- Since green biomass declines with increasing grazing intensity, heavily grazed pastures will have higher sensible and lower latent heat fluxes compared to moderately and ungrazed pastures.

The global average temperature anomalies are based on the Global Climate Observing Network (GCON) stations' data. According to the WMO guidelines, meteorological observing stations should be chosen to minimize the effects of their surroundings such as trees, buildings, and other obstructions by at least a 100 m radius (WMO, 1996). Unfortunately, it is difficult to find historical information about the meteorological observing stations' site exposure characteristics, to insure the reliability of the data. Therefore, to contribute to documenting the GCON meteorological observing stations' exposure characteristics, fieldwork was conducted in Mongolia between July-August 2005 within this dissertation framework. Chapter 1 will document and discuss the results of the fieldwork.

Mongolian climate is characterized by distinctive cold, long winter with short mild summer. Distance from the seas and considerable elevation above sea level contributes to the very dry and continental climate. Furthermore, the climate is very harsh with large seasonal (up to 90°C) and daily (up to 30°C) temperature fluctuations, and dust storms, drought and "zud" (harsh winter conditions with heavy snowfalls) are common. The coldest month is January with –20°C average temperature. Typically, in some regions, especially in the northern part of Mongolia, the temperature drops to less than negative 40°C. The hottest month is July with 18°C average temperature. Sometimes in the Gobi Desert temperature reaches 40°C. Mongolia is the land of winds, especially sharp winds that blow in the spring. In the Gobi and steppe areas, winds often develop into devastating storms reaching velocities of 15 to 25 ms^{-1}. The mean annual precipitation is 200 to 300 mm (8-12") of which 70 percent falls within the three summer months from June to August (Hilbig, 1995). The total amount of precipitation is rather low and decreases from 400 mm per year at the Khangai, Khovsgol, and Khentii mountains to 25 mm per year or less in the Gobi Desert (Zamba, 2007, Erdenetuya and Khudulmur, 2005, and Gunin et al., 1999). The chapter 2 will address the trends and patterns in the Mongolian long-term (1961-2004) versus short-term (1998-2007) climate features and compares European Centre for Medium-Range Weather Forecasts (ECMWF), National Center for Environmental Prediction (NCEP) model data and discusses the climate extreme indices and appropriate metrics.

Chapter 3 will discuss the case study that took place at the Shortgrass Steppe Long-Term Ecological Research (SGS-LTER) site US to imply the findings in semiarid grassland of Mongolia. The study site is located at the northern limit of the semi-arid shortgrass steppe grassland on the western edge of the North American Great Plains used extensively for livestock grazing. The study site has much of similarities with Mongolian shortgrass steppe and has more frequent, high quality data. This study evaluates the impact of grazing on microclimate and energy budgets at SGS-LTER site in a dry (163 mm) and two near-normal (262 and 260 mm) precipitation years based on continuously measured 20 minute interval data to describe surface energy partitioning in semi-arid grasslands that has long history of grazing.

CHAPTER 1: EXPOSURE CHARACTERISTICS OF THE MONGOLIAN WEATHER STATIONS

Khishigbayar Jamiyansharav[11], Dr. Dennis Ojima[1] and Dr. Roger A. Pielke Sr.[2]
[1]Graduate Degree Program in Ecology,
Colorado State University, Fort Collins, CO, 80523
[2]CIRES, University of Colorado, Boulder, CO 80309

Nov 30, 2008

Submitted to the International Journal of Climatology

KEY WORDS: GCON; Mongolia; meteorological stations; exposure characteristics

---

[1] Corresponding author, Graduate Degree Program in Ecology, Colorado State University, Fort Collins, CO 80523, jkhishig@nrel.colostate.edu, Phone: 970-491-1604/Fax: 970-491-1965

ABSTRACT

The global average temperature anomalies are based in part on the Global Climate Observing Network (GCON) stations' data. To document the possible exposures surrounding the weather stations, the Mongolian GCON stations are visited during July-August 2005. Mongolia is a large continental region of Asia at the junction of the Siberian taiga forests, Dahurian steppes, and Gobi Desert. According to the World Meteorological Organizations (WMO) guidelines, meteorological observing stations should be chosen to minimize the effects of their surroundings such as trees, buildings, and other obstructions by at least a 100 m radius. However, in the documental photo survey, some of the GCON stations did not meet the WMO standards. Therefore, the reliability of the data from these stations should be assessed and used carefully in surface temperature trend assessments. Following the WMO guidelines for GCON sites should be a priority.

I. INTRODUCTION

To insure uniform publication of observations and statistics, the WMO published technical regulations supplemented by a number of guides and manuals to be followed by the Member countries of the Organization. According to this guide, meteorological stations proposed to be representative of an area in accordance with its application. For example, to define in meso and larger scales, synoptic observations typically represent an area up to 100 km around the station, and for local applications, the area might be up to 10 km (WMO, 1996). Meteorological observing stations should be chosen to minimize the effects of the surrounding area, such as trees, buildings, walls, and other obstructions, and should not be placed in steeply sloping ground or in a hollow (WMO, 1996).

Acknowledging these guidelines, the following questions are posed:

- Do the GCON meteorological observing stations meet these guidelines?
- Are their data free from microclimate exposure and reliable for a long-term climate change study?
- Do we have historical information about the changes in the station instruments and their movements, which might influence homogeneity of data from the stations?

It is difficult to find historical information due to the lack of historical documentation about the meteorological observing stations' site exposure. Therefore, to document one of the GCON region's microclimate exposure characteristics, the field work was conducted in Mongolia between July-August 2005. Similar studies took place in eastern Colorado (Davey and Pielke Sr., 2005, Hanamean et al., 2003) but no other similar work has been done for Mongolia. Within the frame of this field study, 17 stations in 17 different province centers (Fig. 1.1), including the Mongolian capital city, Ulaanbaatar, were visited, concentrating on nine GCON sites. Name, location, GPS position, and altitude of each station were recorded in a meteorological stations' basic data table (Table 1.1). These sites are located in different natural zones including steppe, and forest-steppe to desert area (Dorjgotov et al., 2004). The majority of them are located in a residential area close to buildings and household fences. Unfortunately, the minority of the visited stations met WMO site exposure guidelines.

All the meteorological instruments are surrounded by an iron net fence with 25 × 25 × 1.5 m dimensions, preventing outside influences such as animals and different human activities. On the other hand, the fence itself affects vegetation cover and causes vegetation cover differences inside and outside the fence. For example, vegetation inside the fence was taller than outside and also vegetation community types were different at the Uliastai, Bulgan, and Ondorkhaan stations (Fig. 1.2).

Most of the stations are equipped with old, Russian instruments and there were no extra supplies or reserved instruments in case of any damage. Most of the sites are equipped with an automatic weather station (made in Japan: R28 (121) and Finland: Vaisala) in 2004 and collecting parallel measurements except one in Uliastai was inoperable at the time of the visit (July 2004) due to a broken data-logger. The Mandalgovi, Altai, and Ondorkhaan stations did not have automatic stations yet. Some of the stations, founded before the 1950s were operated by Russian specialists (e.g., the Ulaangom station was operated by Russian specialists until 1966). Three of the stations were moved from their primary position (Ondorkhaan, Uliastai, and Ulaangom), and two of them were moved twice (Ulaanbaatar and Choibalsan).

II. METHODS

2.1 Study site

Mongolia is located in the central part of Asia between 41°35"-52°06" N latitude and 87°47"- 119°57" E longitude, neighboring Russia in the north and China in the south. Mongolia is the 17th largest country in the world by size of territory, which is 1.56 million square km with an average altitude of 1580 m above sea level (NSOM, 2003). Mongolia is completely land-locked and geographically characterized by an ultra-continental climate. The Mongolian territory was lifted to a relatively high altitude above the sea level. Eighty-one percent of Mongolia is situated above 1000 m and 50 percent is higher than 1500 m (Erdenetuya and Khudulmur, 2005). The most of the highlands consist of mountainous areas with gentle to steep slopes, which are mostly in the western, northern, and southwestern part of Mongolia. As a whole, the territory of Mongolia is characterized by great diversity and a particularly complex spatial structure of soil and vegetation cover.

The climate of Mongolia is dry and continental. Distance from the seas and considerable elevation above sea level contributes to the very dry and continental climate. Furthermore, the climate is very harsh with large seasonal (up to 90°C) and daily (up to 30°C) temperature fluctuations, and dust storms, drought and “zud” (harsh winter conditions with heavy snowfalls) are common. The coldest month is January with –20°C average temperature. Typically, in some regions, especially in the northern part of Mongolia, the temperature drops to less than –40°C. The hottest month is July with 18°C average temperature. Sometimes in the Gobi Desert temperature reaches 40°C.

Mongolia is the land of winds, especially sharp winds that blow in the spring. In the Gobi and steppe areas, winds often develop into devastating storms reaching velocities of 15 to 25 ms^{-1}. The Mongolian capital city, Ulaanbaatar, is the coldest capital in the world (Batima, 2003). According to the long-term data (1969-2004) from the Mongolian Institute of Meteorology and Hydrology, the average annual mean temperature is –0.9°C.

A characteristic feature for Mongolia is the combination of low relative humidity values with considerably low winter temperatures. The mean annual precipitation is 200 to 300 mm (8-12") of which 70 percent falls within the three summer months from June to August (Hilbig, 1995). The total amount of precipitation is rather low and decreases from 400 mm per year at the Khangai, Khovsgol, and Khentii mountains to 25 mm per year or less in the Gobi Desert (Zamba, 2007, Erdenetuya and Khudulmur, 2005, and Gunin et al., 1999). Mongolia is located between the southern edge of eternal glaciers and northernmost boundaries of deserts. The geographical location and severe continental climate create two different processes, aridization (desertification) and very low temperatures (cryogenesis) that strongly affect the distribution, structure, and dynamics of vegetation cover. The prevailing soils are light loams and loamy sands, mainly not salinized, with considerable amounts of rock detritus and pebbles. Due to the high vulnerability of arid and semi-arid regions, even relatively weak human impacts can seriously damage the natural ecological balance and trigger processes of progressive degradation and desertification (Gunin et al., 1999). On the other hand, long-term climate change in semiarid lands is expected to have important implications for the nomadic people’s life in Mongolia. Mongolian pastoral systems are very vulnerable to climate variability and its extreme events such as zud (very cold winter with heavy snow and snowstorms) and drought. Early growing season precipitation is the major determinant of the vegetation cover and thus sustainability of the pastoral systems in Mongolia (Chuluun and Ojima, 2002).

2.2 Research Approach

Most of the stations were surveyed in July 2005. At each site the center point was chosen as the middle point of the station's north side fence. At the center point, the latitude and longitude coordinates were measured using the Garmin Plus III unit and compared with the station data. Next, site surroundings from the center point were described using visible estimates of distances and heights of each object, within a radius of 100 m. Site exposure description worksheets similar to a B-44 form were completed according to the observation for each site. Finally, photos were taken to document each site and show the four cardinal directions of the exposure characteristics from the center point. If necessary, additional photos were taken to depict close objects more clearly and also to show a panoramic view of the station's surroundings.

Each station's mean wind speed, direction, and frequency (shown at the east and west bottom of the each stations' figure) were plotted using Wind Rose Plots for Meteorological Data Version 5.0.1 (The' et al., 2005) based on hourly data for the last 15 years (1990-2004) obtained from the National Climatic Data Center (NCDC, 2005). Each station's location (shown at the right upper corner of each stations' figure) and digital elevation maps of the country were created using ArcGIS9.0.

The sites were classified into three types as described by Hanamean et al. (2003): Pristine, Pristine–Rural and Rural-Urban. Pristine sites are considered to have little or no anthropogenic influences. Pristine–Rural sites have some anthropogenic influence though surrounded by pristine class landscape. Rural-Urban sites are heavily influenced by vegetation though widely surrounded by urban character.

III. RESULTS

3.1 GCON sites in residential areas

3.1.1 Rural-Urban sites

The Khovd station (Fig. 1.3) in the Khovd province is located in the middle of a residential area and surrounded by concrete walls (about 1.5 m high) from the south (S), west (W), and north (N) sides at about 10-30 m distances. In 1982, walls were built on the southeast side of the station by the military. The household fence was built in 1999 inside the wall on the northeastern corner at about 30 m distance. The meteorological station's office building, built in 1983, is on the east side at about 100 m distance. There are mountains on the north and south side at about 6-7 km, and on the west side at about 8-10 km.

The Moron station in the Khovsgol province is also located in the middle of a residential area in a valley of the "Delger" river and is close to buildings and fences at about 30-80 m distances (Fig. 1.4). Before the 1990s, the airport was located near the station and there were no other household fences and buildings except the meteorological office building to the east. After the airport was relocated to another location, and due to economic crisis and harsh winters, herders settled in the province center and it became more and more crowded each year. The station had been surrounded with household fences and buildings since about 1992.

The next station is the Uliastai station of Zavkhan province. The station was moved to this location in the 1980's to avoid the residential area, which had been located on the northeast side since 1936. However the station is located too close to the meteorological station office buildings on the east side (Fig. 1.5). Vegetation cover under the instruments inside the fence is different by type and height than outside (Fig. 1.2a). The province center is surrounded by mountains and the mountains in the west are about 2 km closer to the meteorological station.

The Ulaangom station in the Uvs province is located on the south side of the airport. This station is close to the buildings on the N, northeast (NE), and northwest (NW) sides at about 20-30 m and household buildings and fences on the southwest (SW) side at about 70-90 m distances (Fig. 1.6). The station was moved to the current location on 09.01.1967.

The Dalanzadgad station in Omnogovi province is located in the middle of a residential area. Household fences and buildings are close to the instruments at about 40-50 m distances on the north side. Old radar buildings are on NE, and southeast (SE) sides and the meteorological station office building is on the east (E) side at about 90 m distance (Fig. 1.7).

3.1.2 Pristine-Rural sites

The Bulgan station in Bulgan province is located in the valley of the “Achuut” River and “Bulgan” Mountain. This site is characterized as a Pristine-Rural site. The meteorological stations office building (with some deciduous trees in the front) is located on the northwest side at about 100 m. The agricultural meteorological station’s wooden fence was built in the 1970s on the north side at about 5-25 m distance (Fig. 1.8). Inside the fence there were nine saplings at about 10-50 m distances with 0.5-2 m heights. The pollution monitoring cabin (1.5 × 1.5 × 2 m) is on the west side at about 1.5 m from the fence. It was typical for most visited stations to have a pollution monitoring cabin close to (about 1-2 m distance) the station instruments' fence. The vegetation cover under the instruments, inside the fence is different by type and height from the outside (Fig. 1.2b).

The Mandalgovi station in Dundgovi province is located on the west side of the airport. The meteorological station's office building, fuel storage house, and airport buildings are close to the station's fence at about 40, 50, and 60 m on the N, NW, and NE sides respectively (Fig. 1.9). The other three sides are free from exposures.

The Arvaikheer station in Ovorkhangai province is located on the west side of an airport. Airport buildings with a concrete fence are close to the stations at about a 50-60 m distance on the southeast. A pollution monitoring cabin (1.5 × 1.5 × 2 m) is located about 1 m from the fence. A gas station is located at about a 90 m distance on the NW side. In between there is unpaved road (Fig. 1.10).

The Choibalsan station in Dornod province is located in the middle of a residential area. Fortunately, the residential area is located farther than a 100 m radius. There is unpaved road on the north at about 2-3 m. The meteorological office building is located to the south at about 70 m and an aerology building is to the southeast at about a 60 m distance (Fig. 1.11). The station has been displaced two times and came to the current location in 1974. The primary location was about 4 km further to the west (1936-1969) and the next one was about 6 km further east (1969-1974) than the current location.

3.2 Non-GCON sites

3.2.1 Rural-Urban sites

The Ulaanbaatar station of the capital city is located in the middle of a residential area in a first district. The station is moved to the current location called "Takhilt" hill in

Oct. 1978 (Fig. 1.12). The station was previously located in the Bayanzurkh district between 1960-1978 years and at the "Byant-Ukhaa" airport between 1936-1960 years. The transition to a free market economy and multi-year drought and "zud" highly influenced the large migration of population from the countryside to the city. Therefore, the capital city is become more crowded each year. Consequently, the Ulaanbaatar station is more closely surrounded by household fences and buildings. The Mobicom Corporation, a mobile phone company, built their antenna at the high hillside location on the south of the weather station in 2004.

The Baruunkharaa station in Selenge province is the next Rural-Urban site. It is surrounded by household fences and buildings within about a 50 m radius (Fig. 1.13). The unpaved road is on the north side at about a 3-5 m distance. The station's office building used to be in the second floor of the former telecommunication building on the south side which was destroyed by fire in 1994. The new meteorological office building is built at about a 30 m to the north and the telecommunication building is constructed on the former location in 1994 but changed into a one-story building.

The Altai station in Govi-Altai province is also included one of the Rural-Urban sites due to buildings on the east, southeast, and south sides. This station is located on the northwestern side of the airport. Small hills are on the north at about 150 m. Buildings are close to 30-50 m distances on the south and southeast sides (Fig. 1.14). Recently, the household fence was built to the south at about 50 m distance but it has been requested to be moved. Only the west side is relatively open.

3.2.2 Pristine-Rural sites

The Tsetserleg station in Arkhangai province is located on the southeast side of the province center. The meteorological station's office building is located at about 50 m distance on the north side (Fig. 1.15). The province center is located in between mountains. The mountains on the north are especially close to the station at about 1-2 km. Mountains to the south, west, and east are about 0.2-0.3 km, 2-3 km and 10-15 km away, respectively.

The Ondorkhaan station in Khentii province is located on the south side of the airport. The airport fence was built in 2001 about 2 m to the north from the meteorological instruments' fence. The concrete aircraft apron and runway tarmac is located at about 50 m distance on the north side (Fig. 1.16). The meteorological stations office building is situated on the northeast side at about 70 m distance. The station was moved to the current location in 1982. The airport has not received any airplanes since December 2004 and is operating as a reserve airport. The airport gas station is located about 100 m to the southeast. The vegetation cover under the instruments, inside the fence was different by type and height from the outside vegetation (Fig. 1.2c,d). Grasses inside the fence were higher (4-20 cm) than outside (1-5 cm).

The Choir station in Govi-sumber province is located on the southeast side of the city. The Choir station is a good looking site except for the west side wooden fence with buildings at about 80 m distance (Fig. 1.17). The vegetation cover under instruments was representative to the entire area.

3.2.3 Pristine sites

The Sainshand station in Dornogovi province is characterized as a Pristine site that satisfies WMO requirements. It is located on an open flat space. The type of land cover under the instruments was typical to the entire region. The meteorological office building is located on the west side at about a 100 m distance (Fig. 1.18). Household buildings and fences are about 300 m to the southeast and on the north side at about 500 m distances.

Another Pristine site is Bayankhongor station in Bayankhongor province. The station is located on the east side of the airport at about 200 m. The meteorological station office building with few deciduous trees is on the west side at about 100 m distance (Fig. 1.19). The office building was extended into a two floor building in 2004. All other sites are open within a 100 m radius. The mountains are to the east at 2-3 km distances and a residential area is on the north at about a 1 km distance.

IY. DISCUSSION

A total of 17 stations were surveyed in this study. From the GCON sites, Khovd, Moron, Uliastai, Ulaangom, and Dalanzadgad stations are characterized as Rural-Urban sites in residential areas composing 56 percent, and Bulgan, Arvaikheer, Mandalgovi, Choibalsan stations are characterized as Pristine-Rural sites composing 44 percent. Within the non-GCON sites Ulaanbaatar, Baruunkharaa, Altai stations are characterized as Rural-Urban sites, Tsetserleg, Ondorkhaan, and Choir stations are characterized as Pristine-Rural sites, and Sainshand and Bayankhongor stations are characterized as Pristine sites. From the total 17 stations, 47 percent are qualified as strongly influenced by urban character landscape, 41 percent received some anthropogenic influences, and 12 percent had very little to no anthropogenic influences.

According to this study, most of the surveyed stations were qualified as Rural-Urban sites and did not satisfy the WMO exposure guidelines. Consequently, this implies the global-averaged temperature anomalies based on the data from these stations do not completely satisfy WMO standards. Therefore, reliability of the data from these stations should be questioned and considered carefully in further studies. Strict adherence in following WMO guidelines is important and urgently needed. Proper action such as removing at least unused objects close to the instruments is recommended. Recently, there were many houses moved and other buildings and houses constructed closer to the meteorological station's fence. Therefore, it is important to restrict at least new settlements close to these stations and strengthen the regulations to ensure that data be representative to the whole region.

This study is the preliminary and qualitative study for documenting the exposure characteristics surrounding weather stations. Further studies on the quantitative influences of the close objects are highly recommended.

ACKNOWLEDGEMENTS

K. Jamiyansharav was supported by a Mongolian Governmental Fellowship, NASA Grant NNG05GA33G (Northern Eurasian Carbon Land Use and Climate Interactions), the F/DOE/The University of Alabama in Huntsville's Utilization of Satellite Data for Climate Change Analysis project DE-FG02-04ER 63841 through the University of Alabama at Huntsville, and the Colorado Climate Center which is funded in part by the Colorado Agricultural Experiment Station. R.A. Pielke Sr. was supported on this study through the University of Colorado in Boulder (CIRES/ATOC) and NASA LULC Grant NNX06AG74G_S02. Last but not least, I would like to acknowledge Dallas Staley for completing her usual outstanding editing of the paper.

LIST OF REFERENCES

Batima P. 2003. *Climate change: Pasture-livestock*. ADMON Publishing, Ulaanbaatar.120 p.

Chuluun T, Ojima DS. 2002. Sustainability of pastoral systems in Mongolia in editors Chuluun T, and Ojima DS. *Fundamental Issues Affecting Sustainability of the Mongolian Steppe*. Interpress Publishing and Printing, Ulaanbaatar. 372p.

Davey CA, Pielke Sr RA. 2005. Microclimate exposures of surface-based weather stations - implications for the assessment of long-term temperature trends. *Bulletin of the American Meteorological Society* **86:4**, 497–504.

Dorjgotov D, Orshih N, Ouynchimeg T. Eds. 2004. *Geographic Atlas of Mongolia*. Administration of Land Affairs, Geodesy and Cartography, Ulaanbaatar.

Erdenetuya M, Khudulmur S. 2005. *Land cover change and pasture estimation of Mongolia from space*. Available at: http://www.gisdevelopment.net/application/environment/conservation/envc0002.htm Accessed on 09.08.2005

Gunin PD, Vostokova EA, Dorofeyuk NI, Tarasov PE, Black CC Eds. 1999. *Vegetation Dynamics of Mongolia*. Geobotany vol.**26**. Kluwer Academic Publishing, Dordrecht. 238p.

Hanamean Jr. JR, Pielke Sr. RA, Castro CL, Ojima DS, Reed BC, Gao Z. 2003. Vegetation impacts on maximum and minimum temperatures in northeast Colorado. *Meteorological Applications* **10,** 203-215.

Hilbig W. 1995. *The Vegetation of Mongolia*. SPB Academic Publishing, Amsterdam. 258p.

[NSOM] National Statistical Office of Mongolia. 2003. *Mongolian Statistical Yearbook 2002*. Kopir Tekh Co. Ltd., Ulaanbaatar.

[NCDC] National Climatic Data Center. 2005. *NNDC climate data online*. Available at http://cdo.ncdc.noaa.gov/CDO/cdo Accessed on 05.15.2005.

The' LJ The' CL, Johnson MA, Shatalov O, Borodavka S. 2005. Lakes Environmental Software. 1998-2005. *WRPLOT View. Wind Rose Plots for Meteorological Data. Version 5.0.1*. Lakes Environmental: Ontario.

[WMO] World Meteorological Organization, 1996. *Guide to Meteorological Instruments and Methods of Observation*. Sixth edition, Secretariat of the World Meteorological Organization: Geneva.

Zamba Batjargal. 2007. *Fragile Environment, Vulnerable People and Sensitive Society.* Kaihatu-Sha co.ltd., Tokyo.

LIST OF TABLES

LIST OF FIGURES

Figure 1.7 The sensor exposure characteristics of Dalanzadgad station in Omnogovi province of Mongolia, 44373. 43 N 104 E. Altitude. 1470 m. Photos indicate that Dalanzadgad is a Rural-Urban site. Household buildings and fences are on the north side at about 40-50 m, on the east side meteorological station's building at about 85-95 m, old radar buildings on the E, SE sides at about 25, 65 m, respectively and aerology building on the SE side at about 85 m distance. (a-e) same as fig. 1.3

Figure 1.8 The sensor exposure characteristics of Bulgan station in Bulgan province of Mongolia, 44239. 48 N 103 E. Altitude. 1217 m. Photos indicate that Bulgan is a Pristine-Rural site. (a) Station sensors, (b-e) same as fig. 1.3

Figure 1.9 The sensor exposure characteristics of Mandalgovi station in Dundgovi province of Mongolia, 44259. 45 N 106 E. Altitude. 1400 m. Photos indicate that Mandalgovi is a Pristine-Rural site, close to the airport on the NE side at about 60 m and a meteorological office building on the north side at about 40 m, fuel storage building at about 50 m distances. (a-e) same as fig. 1.3

Figure 1.10 The sensor exposure characteristics of Arvaikheer station in Uvurkhangai province of Mongolia, 44288. 46 N 102 E. Altitude. 1813 m. Photos indicate that Arvaikheer is a Pristine-Rural site, close to the airport buildings on the SE side at about 50 m, and to the pollution monitoring cabin at about 1 m on the east side. (a-e) same as fig. 1.3

Figure 1.11 The sensor exposure characteristics of Choibalsan station in Dornod province of Mongolia, 44259. 48 N 114 E. Altitude. 750 m. Photos indicate that Choibalsan is Pristine-Rural site. The meteorological office building and trees at about 70-80 m on the south side and an unpaved road is about 2-3 m close on the north side. (a-e) same as fig. 1.3

Figure 1.12 The sensor exposure characteristics of Ulaanbaatar station in the capital city of Mongolia, 44292. 47 N 106 E. Altitude. 1306 m. Photos indicate that Ulaanbaatar is a Rural-Urban site, close to the household fence on the east side at about 5 m, which as built in 2005. The Mobicom antenna and office building is on the SW corner at about 5-10 m, built in 2004. The meteorological station office building is on the NW side at about 50 m distance. The station was moved two times and came to the current location in 1978. A large residential area called First District is on the south at about 200 m. (a-e) same as fig. 1.3

Figure 1.13 The sensor exposure characteristics of Baruunkharaa station in Selenge province of Mongolia, 44241. 48 N 106 E. Altitude. 821 m. Photos indicate that Baruunkharaa is a Rural-Urban site located in the middle of a residential area. It is close to buildings, trees and fences at 50 m radius. (a-e) same as fig. 1.3

Figure 1.14 The sensor exposure characteristics of Altai station in Govi-Altai province of

Mongolia, 44277. 46 N 96 E. Altitude. 2183 m. Photos indicate that Altai is a Rural-Urban site surrounded by a metal net fence on the east and north side. Buildings are close to 30-50 m distances on the S and SE sides. Small hills are on the north side at about 150 m and only the west side is relatively open. (a-e) same as fig. 1.3

Figure 1.15 The sensor exposure characteristics of the Tsetserleg station in Arkhangai province of Mongolia, 44282. 47 N 101 E. Altitude. 1693 m. Photos indicate that Tsetserleg is a Pristine-Rural site. The north side building is at about 50 m distance. (a-e) same as fig. 1.3

Figure 1.16 The sensor exposure characteristics of Ondorkhaan station in Khentii province of Mongolia, 44304. 47 N. 110 E. Altitude. 1039 m. Photos indicate that Ondorkhaan is a Pristine-Rural site because of the north side airport apron and the NE and E side buildings. (a-e) same as fig. 1.3

Figure 1.17 The sensor exposure characteristics of Choir station in Govi-Sumber province of Mongolia, 44298. 46 N 108 E. Altitude. 1286 m. Photos indicate that Choir is a Pristine-Rural site. The west side wooden fence with buildings is at 80 m distance. (a-e) same as fig. 1.3

Figure 1.18 The sensor exposure characteristics of Sainshand station in Dornogovi province of Mongolia, 44354. 44 N 110 E. Altitude. 936 m. Photos indicate that Sainshand is a Pristine site that satisfies with the WMO requirements. (a-e) same as fig. 1.3

Figure 1.19 The sensor exposure characteristics of Bayankhongor station in Bayankhongor province of Mongolia, 44287. 46 N 100 E. Altitude. 1862 m. Photos indicate that Bayankhongor is a Pristine site that satisfies WMO requirements. (a-e) same as fig. 1.3

Table 1.1 Meteorological stations basic data

Site name and classification	Network and ID	Natural zone	Province	Begin year	GPS position	Altitude, m
Khovd Rural-Urban	GCON 44218	Dry steppe	Khovd	1936	Lat: 48°01' Lon: 91°39'	1406
Moron Rural-Urban	GCON 44231	Steppe	Khovsgol	1938	Lat: 49°55' Lon: 100°15'	1288
Uliastai Rural-Urban	GCON 44272	Forest-steppe	Zavkhan	1936	Lat: 47°45' Lon: 96°51'	1767
Ulaangom Rural-Urban	GCON 44212	Desert-steppe	Uvs	1936	Lat: 49°48' Lon: 92°05'	940
Dalanzadgad Rural-Urban	GCON 44373	Semi-desert	Omnogovi	1935	Lat: 43°25' Lon: 104°25'	1450
Bulgan Pristine-Rural	GCON 44239	Forest-steppe	Bulgan	1941	Lat: 48°48' Lon: 103°33'	1210
Mandalgovi Pristine-Rural	GCON 44341	Desert-steppe	Dundgovi	1944	Lat: 45°46' Lon: 106°17'	1393
Arvaikheer Pristine-Rural	GCON 44288	Steppe	Ovorkhangai	1940	Lat: 46°16' Lon: 102°47'	1813
Choibalsan Pristine-Rural	GCON 44259	Steppe	Dornod	1936	Lat: 48°05' Lon: 114°33'	756
Ulaanbaatar Rural-Urban	44292	Forest-steppe	Capital city Ulaanbaatar	1936	Lat: 47°56' Lon: 106°54'	1306
Baruunkharaa Rural-Urban	44241	Forest-steppe	Selenge	1939	Lat: 48°55' Lon: 106°04'	807
Altai Rural-Urban	44277	Dry steppe	Govi-Altai	1953	Lat: 46°24' Lon: 96°15'	2183
Tsetserleg Pristine-Rural	44282	Forest-steppe	Arkhangai	1936	Lat: 47°27' Lon: 101°28'	1693
Ondorkhaan Pristine-Rural	44304	Steppe	Khentii	1937	Lat: 47°19' Lon: 110°38'	1033
Choir Pristine-Rural	44298	Dry steppe	Govi-Sumber	1949	Lat: 46°27' Lon: 108°13'	1286
Sainshand Pristine	44354	Semi-desert	Dornogovi	1936	Lat: 44°54' Lon: 110°07'	936
Bayankhongor Pristine	44287	Dry steppe	Bayankhongor	1962	Lat: 46°08' Lon: 100°41'	1859

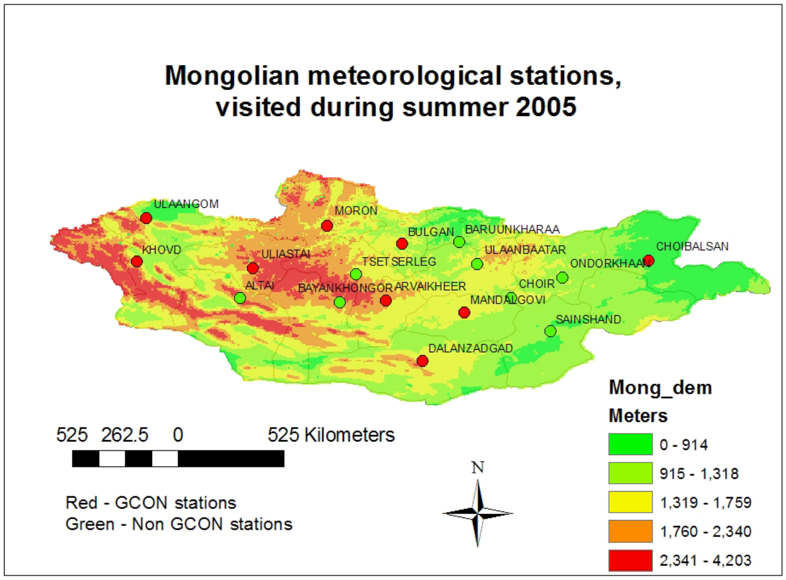


Figure 1.1 Mongolian meteorological stations surveyed between July-August 2005.

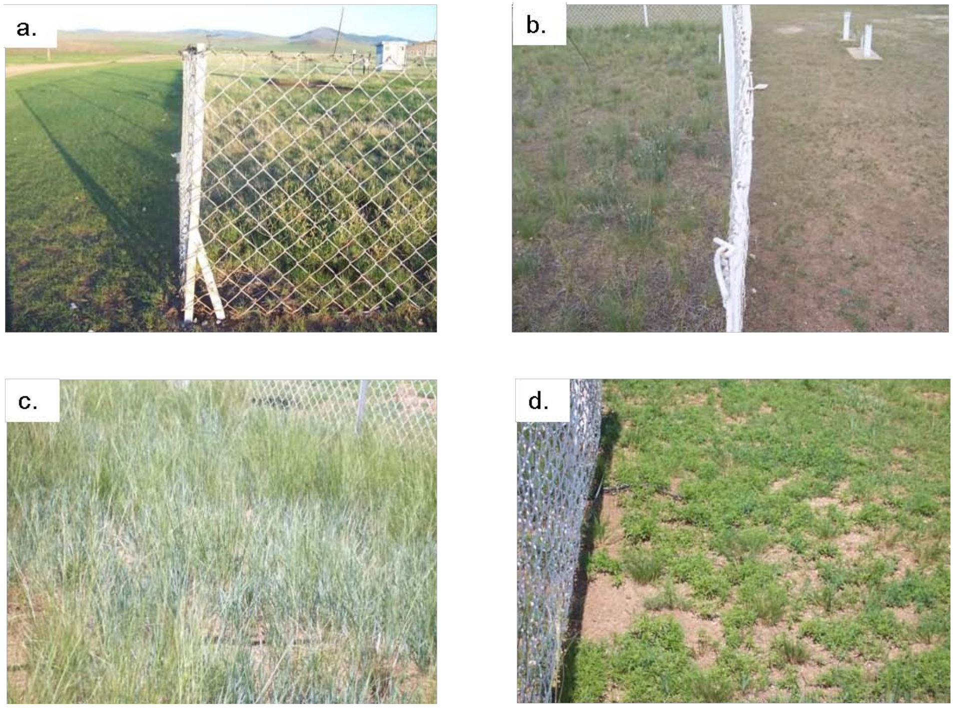


Figure 1.2 Vegetation cover was different inside and outside the fence. (a) Uliastai station, (b) Bulgan station, (c) Ondorkhaan station: inside the fence, (d) Ondorkhaan station: outside the fence

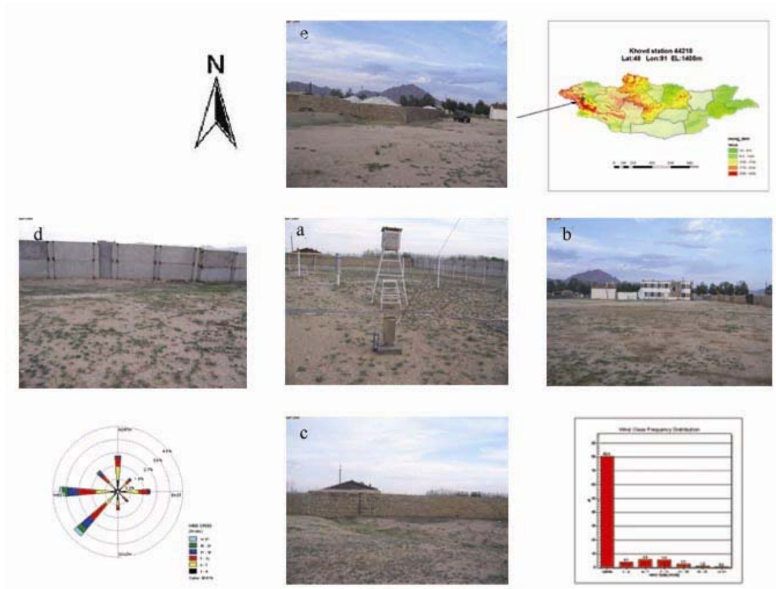


Figure 1.3 The sensor exposure characteristics of Khovd station in Khovd province of Mongolia, 44218. 48 N 91 E. Altitude. 1411 m. Khovd is a Rural-Urban site, surrounded by concrete walls on the S, W, and N side and houses to the north. A meteorological station office building is on the east side at about 100 m distance. (a) Station sensors, (b-e) Illustration of exposures viewed from the center point looking east, south, west, and north respectively. Station's mean wind speed and direction are shown on the east bottom corner, wind speed frequency is on the west bottom corner and station's location is shown at the country map on the upper right corner of the figure.

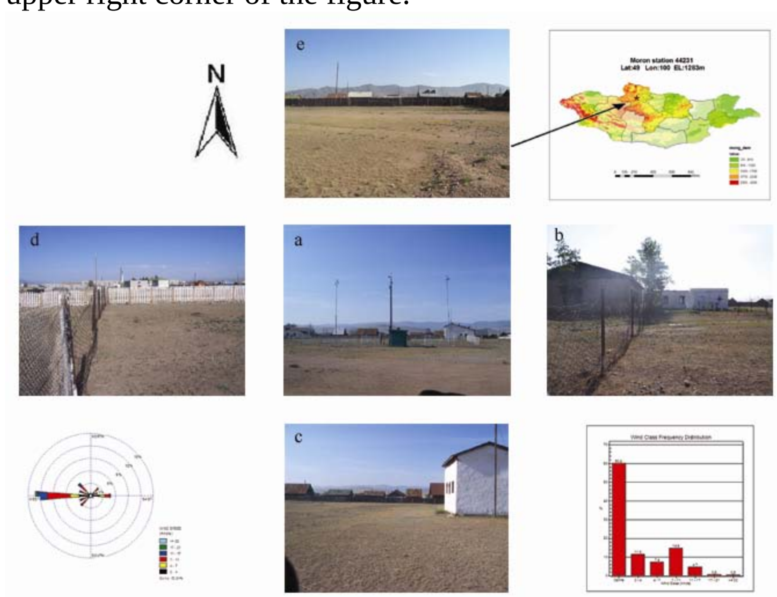


Figure 1.4 The sensor exposure characteristics of Moron station in Khovsgol province of Mongolia, 44231. 49 N 100 E. Altitude. 1290 m. Photos indicate that Moron is a Rural-Urban site. It is too close to the buildings and fences on N, E, SE, and SW sides with several trees and fences on the east side. A wooden fence was located 30 m to the west. (a-e) same as fig. 1.3

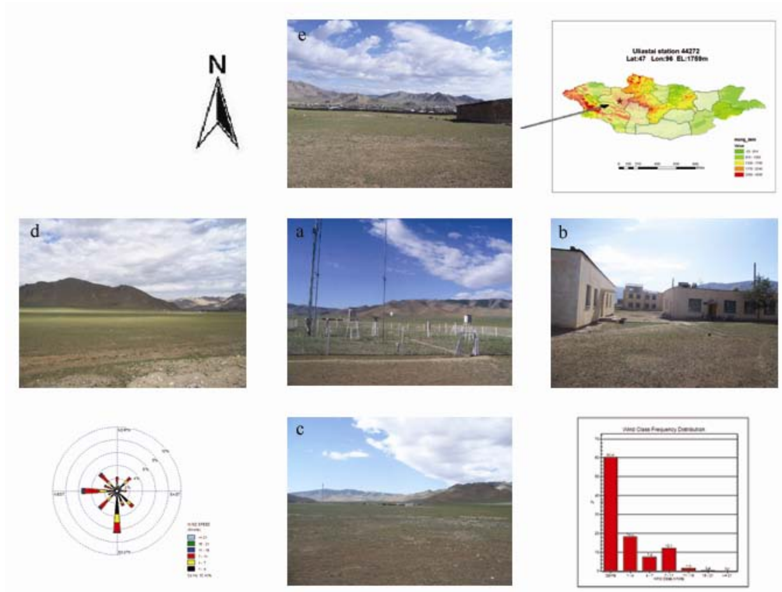


Figure 1.5 The sensor exposure characteristics of Uliastai station in Zavkhan province of Mongolia, 44272. 47 N 96 E. Altitude. 1780 m. Photos indicate that Uliastai is a Rural-Urban site located close to the meteorological station's office and other buildings in a range of 5-80 m distances on the east side. Another building is located at about 30-35 m on the north side. (a-e) same as fig.1.3

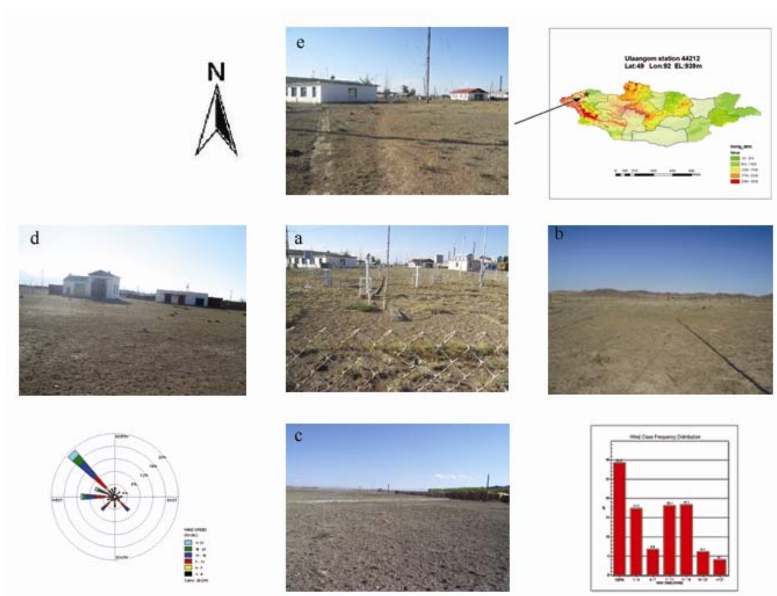


Figure 1.6 The sensor exposure characteristics of Ulaangom station in Uvs province of Mongolia, 44212. 49 N 92 E. Altitude. 941 m. Photos indicate that Ulaangom is a Rural-Urban site, which is close to the buildings on NW, N, NE sides at about 20-30 m and close to the household fences and buildings (built in around 1999) on the SW side at about 50-60 m from the instrument fence. The Ulaangom station was moved to the current location on 09.01.1967. (a-e) same as fig. 1.3

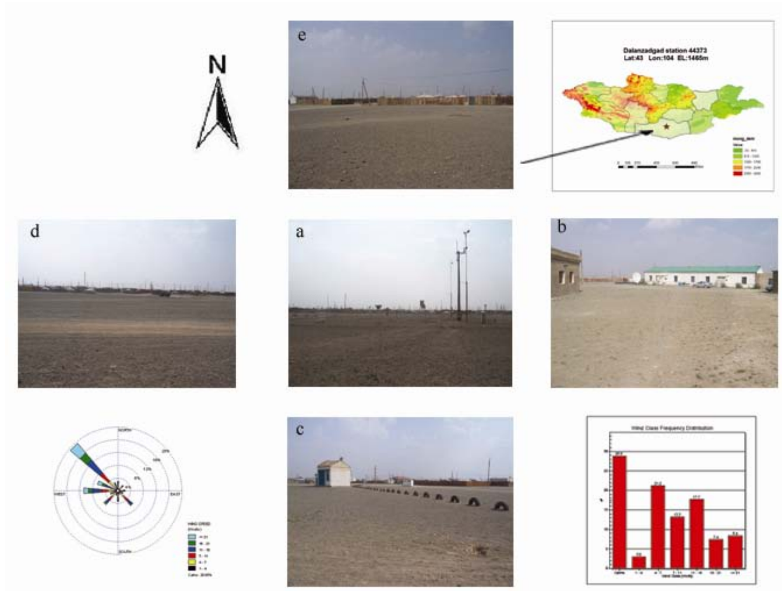


Figure 1.7 The sensor exposure characteristics of Dalanzadgad station in Omnogovi province of Mongolia, 44373. 43 N 104 E. Altitude. 1470 m. Photos indicate that Dalanzadgad is a Rural-Urban site. Household buildings and fences are on the north side at about 40-50 m, on the east side meteorological station's building at about 85-95 m, old radar buildings on the E, SE sides at about 25, 65 m, respectively and aerology building on the SE side at about 85 m distance. (a-e) same as fig. 1.3

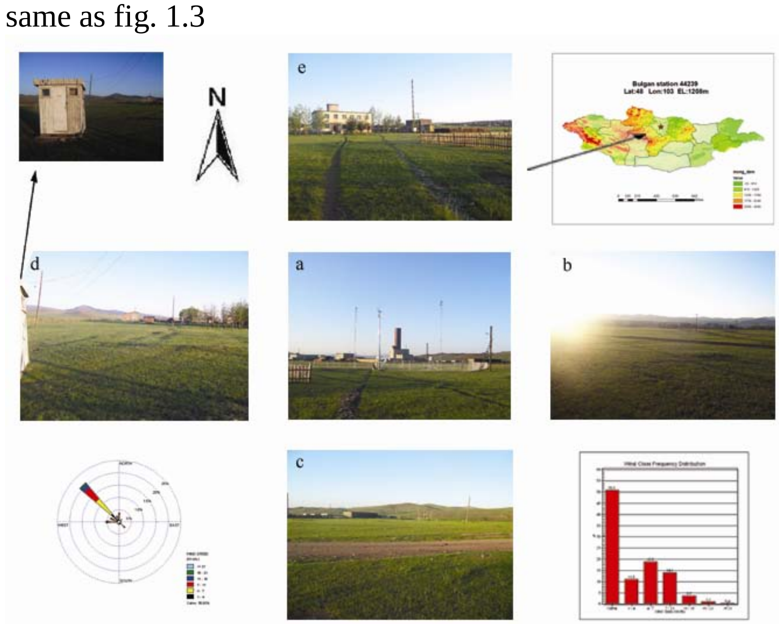


Figure 1.8 The sensor exposure characteristics of Bulgan station in Bulgan province of Mongolia, 44239. 48 N 103 E. Altitude. 1217 m. Photos indicate that Bulgan is a Pristine-Rural site. (a-e) same as fig. 1.3

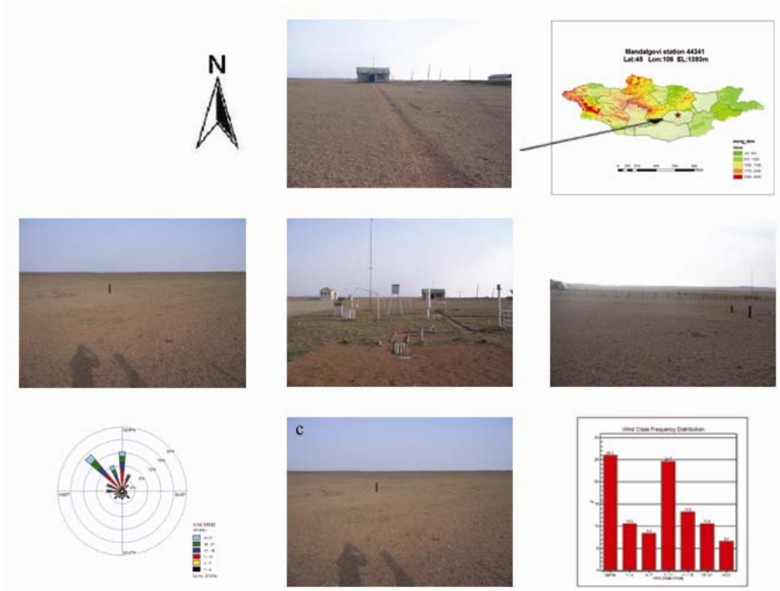


Figure 1.9 The sensor exposure characteristics of Mandalgovi station in Dundgovi province of Mongolia, 44259. 45 N 106 E. Altitude. 1400 m. Photos indicate that Mandalgovi is a Pristine-Rural site, close to the airport on the NE side at about 60 m and a meteorological office building on the north side at about 40 m, fuel storage building at about 50 m distances. (a-e) same as fig. 1.3

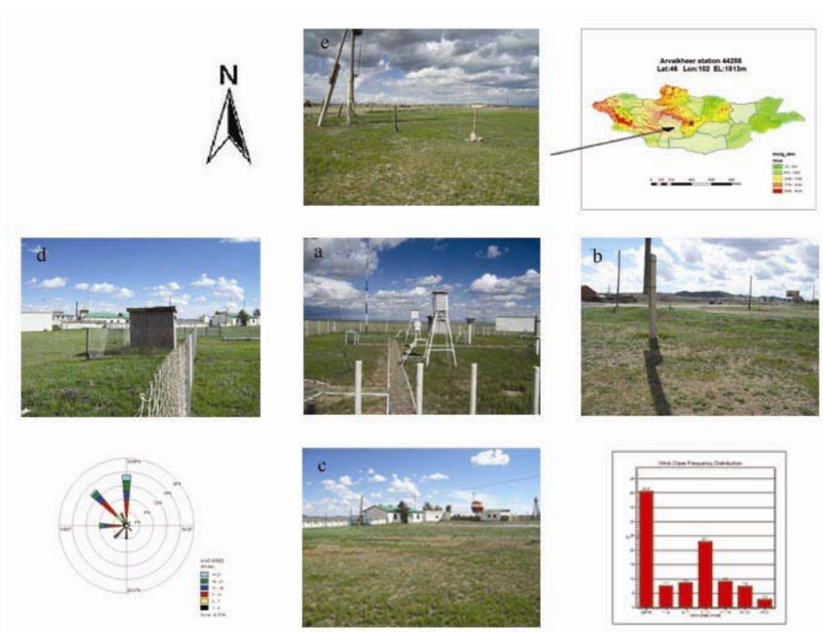


Figure 1.10 The sensor exposure characteristics of Arvaikheer station in Uvurkhangai province of Mongolia, 44288. 46 N 102 E. Altitude. 1813 m. Photos indicate that Arvaikheer is a Pristine-Rural site, close to the airport buildings on the SE side at about 50 m, and to the pollution monitoring cabin at about 1 m on the east side. (a-e) same as fig. 1.3

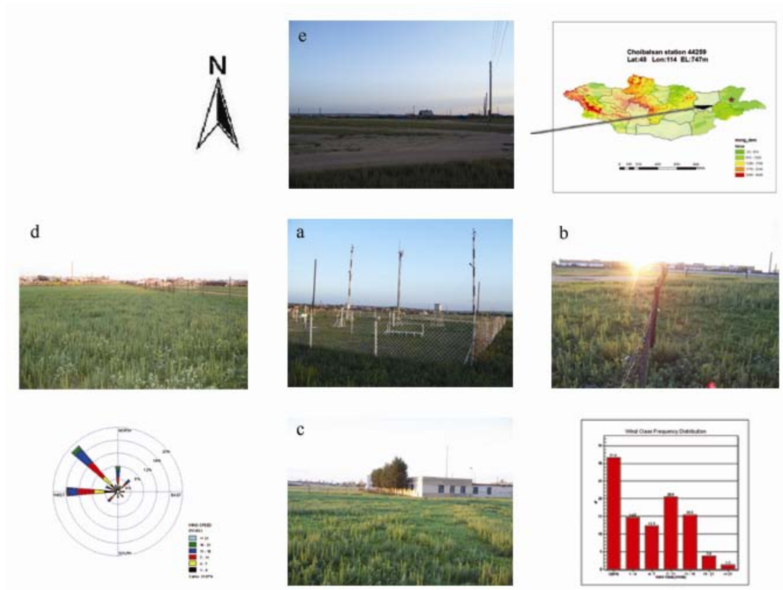


Figure 1.11 The sensor exposure characteristics of Choibalsan station in Dornod province of Mongolia, 44259. 48 N 114 E. Altitude. 750 m. Photos indicate that Choibalsan is Pristine-Rural site. The meteorological office building and trees at about 70-80 m on the south side and an unpaved road is about 2-3 m close on the north side. (a-e) same as fig. 1.3

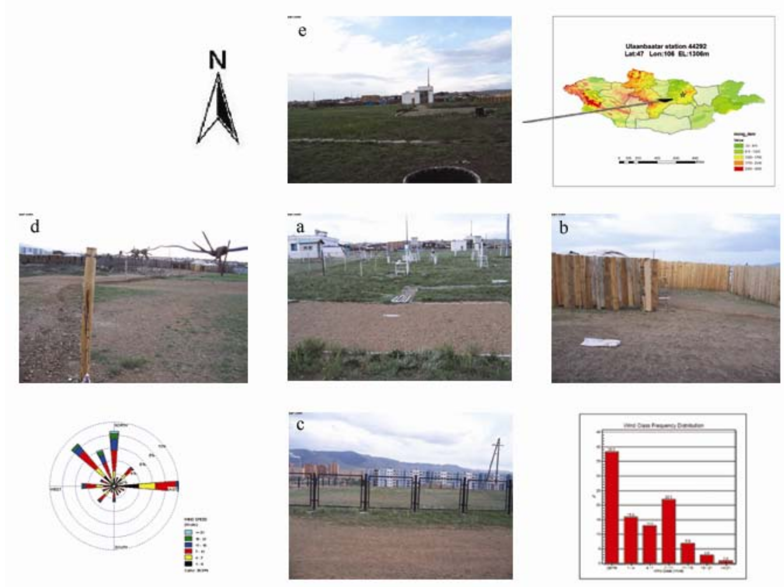


Figure 1.12 The sensor exposure characteristics of Ulaanbaatar station in the capital city of Mongolia, 44292. 47 N 106 E. Altitude. 1306 m. Photos indicate that Ulaanbaatar is a Rural-Urban site, close to the household fence on the east side at about 5 m, which was built in 2005. The Mobicom antenna and office building is on the SW corner at about 5-10 m, built in 2004. The meteorological station office building is on the NW side at about 50 m distance. The station was moved two times and came to the current location in 1978. A large residential area called First District is on the south at about 200 m. (a-e) same as fig. 1.3

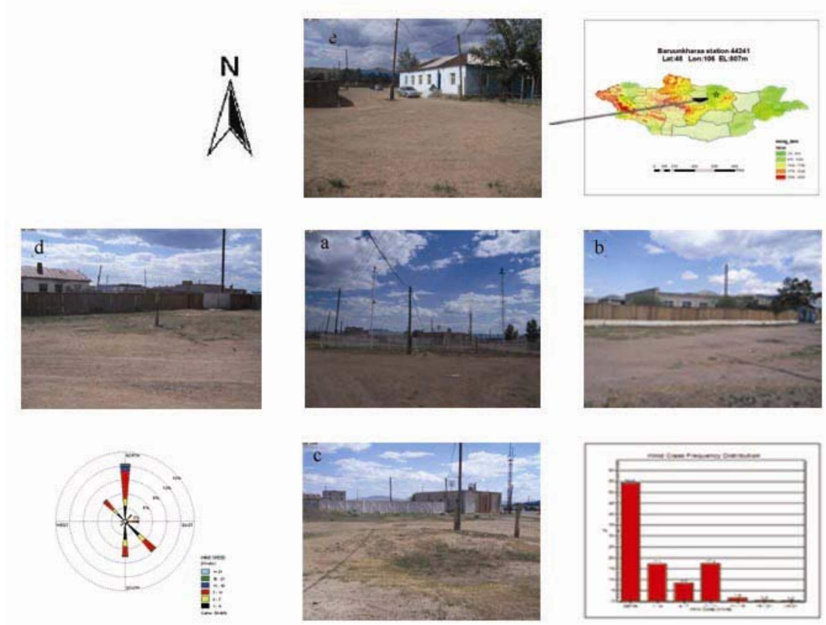


Figure 1.13 The sensor exposure characteristics of Baruunkharaa station in Selenge province of Mongolia, 44241. 48 N 106 E. Altitude. 821 m. Photos indicate that Baruunkharaa is a Rural-Urban site located in the middle of a residential area. It is close to buildings, trees and fences at 50 m radius. (a-e) same as fig. 1.3

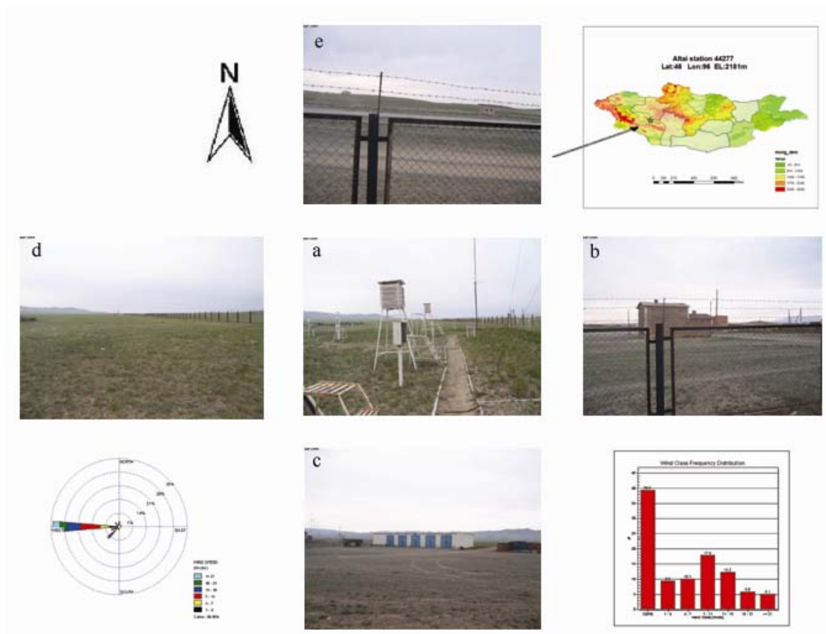


Figure 1.14 The sensor exposure characteristics of Altai station in Govi-Altai province of Mongolia, 44277. 46 N 96 E. Altitude. 2183 m. Photos indicate that Altai is a Rural-Urban site surrounded by a metal net fence on the east and north side. Buildings are close to 30-50 m distances on the S and SE sides. Small hills are on the north side at about 150 m and only the west side is relatively open. (a-e) same as fig.1.3

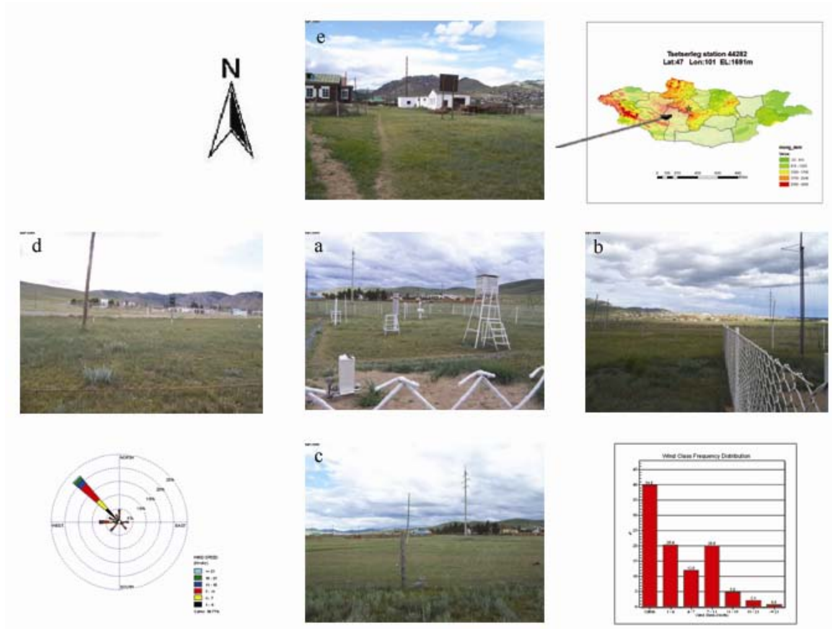


Figure 1.15 The sensor exposure characteristics of the Tsetserleg station in Arkhangai province of Mongolia, 44282. 47 N 101 E. Altitude. 1693 m. Photos indicate that Tsetserleg is a Pristine-Rural site. The north side building is at about 50 m distance. (a-e) same as fig. 1.3

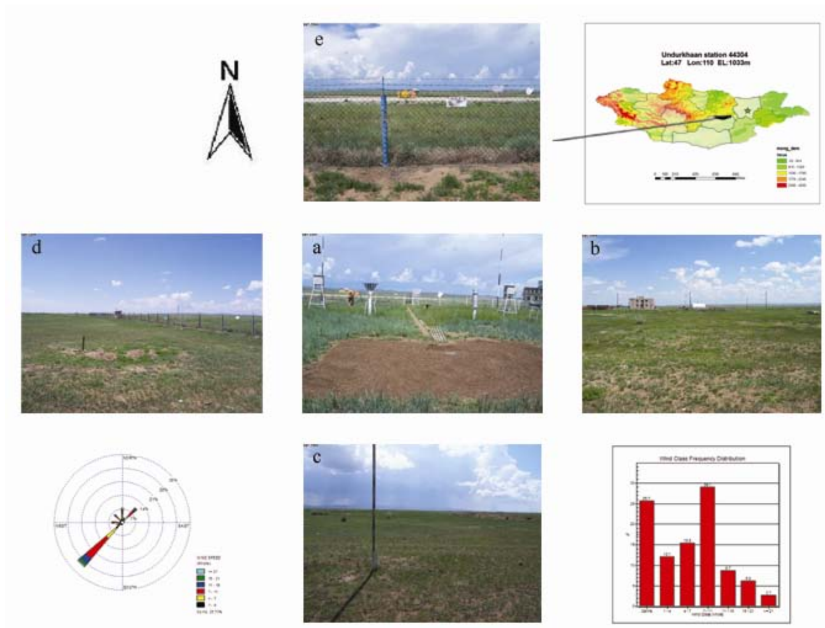


Figure 1.16 The sensor exposure characteristics of Ondorkhaan station in Khentii province of Mongolia, 44304. 47 N. 110 E. Altitude. 1039 m. Photos indicate that Ondorkhaan is a Pristine-Rural site because of the north side airport apron and the NE and E side buildings. (a-e) same as fig. 1.3

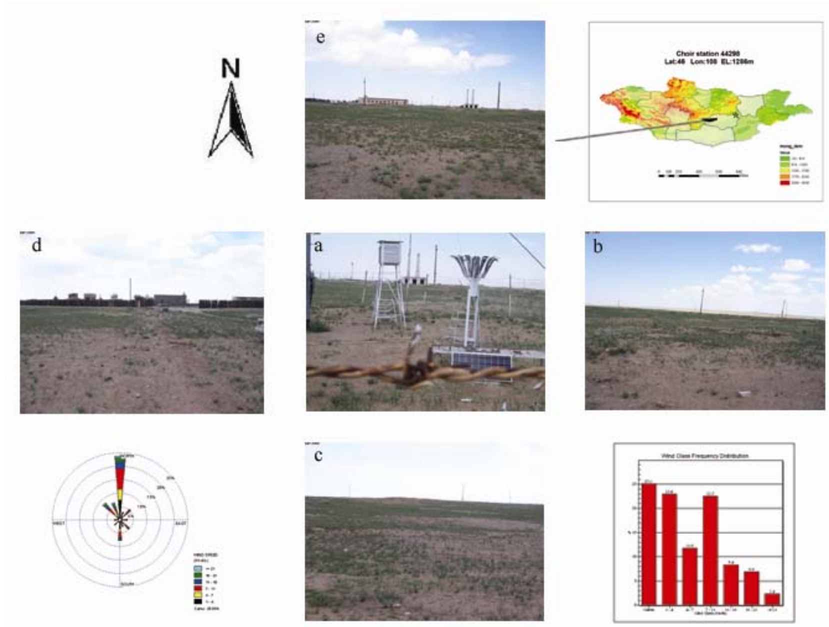


Figure 1.17 The sensor exposure characteristics of Choir station in Govi-Sumber province of Mongolia, 44298. 46 N 108 E. Altitude. 1286 m. Photos indicate that Choir is a Pristine-Rural site. The west side wooden fence with buildings is at 80 m distance. (a-e) same as fig. 1.3

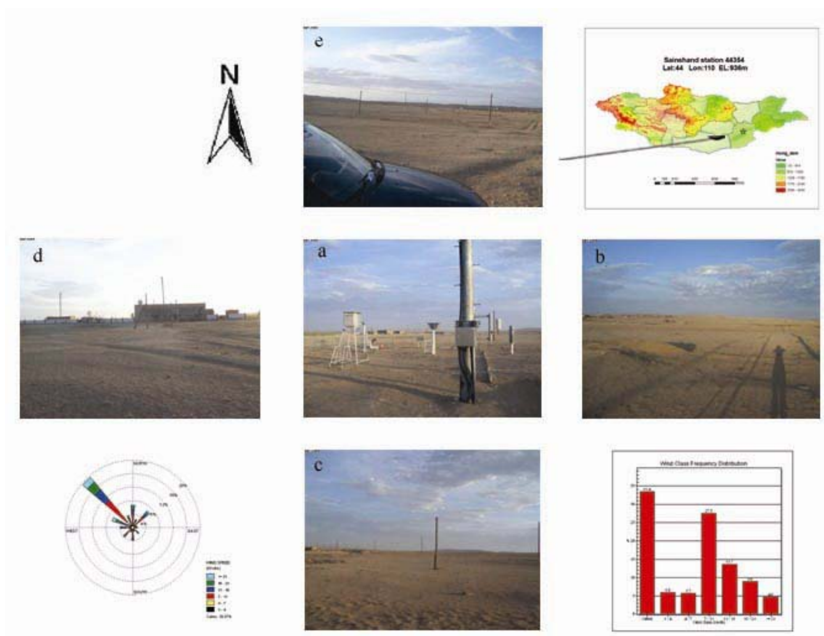


Figure 1.18 The sensor exposure characteristics of Sainshand station in Dornogovi province of Mongolia, 44354. 44 N 110 E. Altitude. 936 m. Photos indicate that Sainshand is a Pristine site that satisfies with the WMO requirements. (a-e) same as fig. 1.3

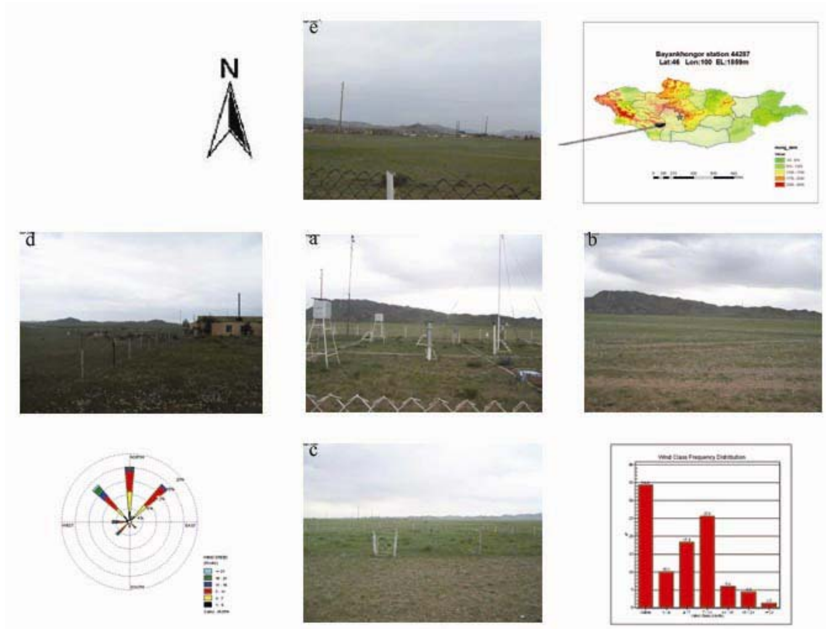


Figure 1.19 The sensor exposure characteristics of Bayankhongor station in Bayankhongor province of Mongolia, 44287. 46 N 100 E. Altitude. 1862 m. Photos indicate that Bayankhongor is a Pristine site that satisfies WMO requirements. (a-e) same as fig. 1.3

CHAPTER 2: MONGOLIAN CLIMATE TRENDS

Khishigbayar Jamiyansharav[11], Dr. Dennis Ojima[1] and Dr. Roger A. Pielke Sr.[2]

[1]Graduate Degree Program in Ecology, Colorado State University,

Fort Collins, CO, 80523

[2]CIRES, University of Colorado, Boulder, CO 80309

Oct. 10, 2009

KEY WORDS: Mongolia; climate; trends; ECMWF; NCEP; climate indices

---

[1] Corresponding author, Graduate Degree Program in Ecology, Colorado State University, Fort Collins, CO 80523, jkhishig@nrel.colostate.edu, Phone: 970-491-1604/Fax: 970-491-1965

ABSTRACT

Mongolia is one of the largest land-locked countries of Asia and the capital city Ulaanbaatar is the coldest city in the world. Rangelands in Mongolia cover 75-80 percent of the total territory. These areas are important to the Mongolian animal husbandry industry, a key economic resource, which directly depends on the vegetation and climate conditions. This study will examine the long-term climate changes and trends seasonally across Mongolia at individual sites. A comparative analysis of long-term (1961-2004) versus decadal (1998-2007) trends, as well as the surface temperature versus surface heating, effective temperature and upper air trends at these sites are studied.

The linear trend over the 1961-2004 years indicated the highest annual and seasonal temperature changes mostly occurred in the coldest north western mountain area of the country. The least changes occurred in the eastern plain. The results supported our expectations that the most temperature increase (2.3°C) occurred during the winter months. According to the calculated seventeen climate change indices most of the stations frost and icing days decreased and summer days, tropical nights, monthly maximum value of daily minimum and maximum temperatures are increased. In addition to that, growing season length is increased at all sites. Clearly, we observed temperature increasing trend at most of the stations. Precipitation indices varied substantially and there were no consistent temporal and spatial pattern. We observed similar trends in seasonal surface heat, effective temperature and 2 m air temperature for winter, spring and fall at seventeen stations but not for the summer when the air humidity is higher. The temperature increase (or decrease) did not correlate to the surface heat increase (or

decrease) during the summer. The multivariate correlation indicates that the most of the surface and ECMWF data well correlated but NCEP data were a little different.

I. INTRODUCTION

Mean surface temperature has been the primary index used to estimate climate change and global warming ([NAS] 2005). However, “warming” is more appropriately assessed in terms of heat content (Joules). The surface heat content depends on air temperature and specific humidity. Therefore, temperature by itself is an incomplete characterization of surface heat content (Pielke et al. 2004). A surface temperature increase may not correspond to a surface heat content increase because it also depends on changes in humidity (Pielke 2001). High relative humidity in hot weather makes us feel hotter than it really is by retarding evaporation or perspiration (Ahrens 2003).

The mean annual surface air temperature of Mongolia has increased by 1.66°C during the last 60 years (Batima 2003). However, we do not know if this surface air temperature increase over- or under- estimates surface heat content in Mongolia. The proposed study will examine the amount of surface heat change that has occurred during the last 10 years in Mongolia as well as surface heat change geographically and seasonally for seventeen local provinces.

Vegetation plays an important role in determining surface heat content throughout a growing season as it removes moisture from the soil that is lost through transpiration (Lu et al. 2001). During the day, transpiring vegetation converts incoming solar energy into latent heat, thus reducing maximum air temperature. At night, higher water vapor above vegetated areas increases minimum air temperatures (Hanamean et al. 2003). However, semiarid or arid rangelands may contribute little to increased water vapor over those surfaces. Climate and land cover interaction over the Asia monsoon region is particularly strong first, in terms of natural processes and second, in terms of human impacts in land cover over the Asia connected with long history of civilization (Kabat et al. 2004).

Rangelands in Mongolia cover 75-80 percent of the total territory (Erdenetuya and Khudulmur 2005; Fernandez-Gimenez and Allen-Diaz 1999). These areas are important in the economy of animal husbandry (Mongolian main economic branch), which directly depends on the vegetation and climate. Range conditions within the last several years have degraded rapidly because of extreme weather events (drought and blizzards), an increasing livestock population and greater concentration of people, especially around urban areas during the transition period to the free market economy. Therefore, monitoring the long-term change and trends for climate features are very important to examine the climate changes in local individual sites as well as their influence on the regional climate. Understanding the vulnerability of arid and semi-arid areas to climate change and human disturbances are very important for their sustainable management.

1.1 Key Questions

This chapter deals with two fundamental questions related to climate trends over Mongolia given the overall warming observations estimate over Eurasia. These questions are:

1. How do local Mongolian climate trends reflect the large scale regional climate warming trends observed over the past 40 years?

2. Do local surface heat energy estimates coincide with observed temperature trends experience at local weather stations across Mongolia?

1.2 Specific study objectives are to:

1. Determine the long-term trends in seasonal and annual surface mean, maximum, minimum temperatures and precipitation across Mongolia.

   1a. Compare the surface trends with the upper air temperature trends to see if there is a certain pattern and relationship.

   1b. Analyze the main climate indices for 17 stations (e.g., number of frost and icing days, summer days, tropical nights and growing season length)

2 Determine if warming trends related to surface temperatures differ from heat energy?

   2a. Analyze the last 10 (1998-2007) years temperature trend and compare with the long-term trends to determine if present surface air temperature data over- or under- estimate surface heating in Mongolia.

II. METHODOLOGY

2.1 Study area – Geography

Mongolia is located in the central part of Asia between 41°35"-52°06" latitude and 87°47"-119°57" longitude, neighboring Russia in the North and China in the South. Mongolia is the 17th largest country in the world by size of territory, which is 1.56 million square km (385 million acre) with an average altitude of 1580 m (5184 ft) above sea level ([NSOM] 2006). Mongolia is completely land-locked and geographically characterized by an ultra continental climate. The Mongolian territory was lifted to a relatively high altitude above the sea level. Eighty one percent of Mongolia is situated above 1000 m and 50 percent is higher than 1500 m. (Erdenetuya and Khudulmur 2005).

The most of the highlands consist of mountainous areas with gentle to steep slopes, which are in the western, northern and southwestern part of Mongolia. The highest peak is 4374 m called “Khuiten” mount in the west and lowest is 560 m in the Eastern Plain.

2.2 Climate

The climate of Mongolia is dry and continental. Distance from the seas and considerable elevation above sea level contributes to the very dry and continental climate. Furthermore, the climate is very harsh with large seasonal (up to 90°C) and daily (up to 30°C) temperature fluctuations, and dust storms, drought and “zud” (harsh winter conditions with heavy snowfalls) are common. The coldest month is January with -20°C average temperature. Typically in some regions, especially in the northern part of Mongolia, the temperature drops to less than -40°C. The hottest month is July with 18°C average temperature. But sometimes in the Gobi Desert, temperature reaches 40°C.

Mongolia is the land of winds, especially sharp winds that blow in the spring. In the Gobi and steppe areas, winds often develop into devastating storms reaching velocities of 15 to 25 ms^{-1}. The Mongolian capital city, Ulaanbaatar, is the coldest capital in the world (Batima 2003).

A characteristic feature for Mongolia is the combination of low relative humidity values with rather low winter temperatures. The mean annual precipitation is 200 to 300 mm (8-12") of which 70 percent falls within the three summer months from June to August (Hilbig 1995). The total amount of precipitation is rather low; it decreases from 400 mm per year at the Khangai, Khovsgol, and Khentii mountains to 25 mm per year or less in the Gobi Desert (Erdenetuya and Khudulmur 2005; Gunin et al. 1999).

Mongolia is located between the southern edge of eternal glaciers and northernmost boundaries of deserts. These conditions contribute to two different processes, aridization (desertification) and very low temperatures (cryogenesis) that strongly affect the distribution, structure, and dynamics of vegetation cover. The prevailing soils are light loams and loamy sands, mainly not salinized, with considerable amounts of rock detritus and pebbles. Due to high vulnerability of arid and semi-arid regions, even relatively weak human impacts can seriously damage the natural ecological balance and trigger processes of progressive degradation and desertification (Gunin et al. 1999). On the other hand, climate change in semiarid lands expected to have important implications for the nomadic people's life. Early growing season precipitation is the major determinant of the vegetation cover and thus sustainability of the pastoral systems in Mongolia (Chuluun and Ojima 2002). Mongolian pastoral systems are very vulnerable to climate variability and extreme events such as zud (very cold winter with heavy snow and snowstorms) and drought.

Mongolia has six vegetation zones: high mountain, forest steppe, steppe, dry steppe, desert steppe, and desert. According to multi-date land cover maps (Landsat) of 1992 and 1997 the total forest area (including deciduous needle-leaf, deciduous broadleaf, coniferous forest and all mixed forest) is about 12.7 percent. Grassland areas (52.3%) include steppe, dry steppe, and cropland. Barren areas include high mountain rocks, desert shrub and sparse vegetated areas of about 34.2 percent. Water covers only 0.7 percent of the total territory of Mongolia (Erdenetuya and Khudulmur 2005).

2.3 Data collection

Daily minimum, maximum, and mean air temperatures and precipitation data for 1961 to 2004 were obtained from these 17 stations for long-term analysis. Nine of the stations are part of the Global Climate Observing Network (GCON). GCON is an organization ensuring that observations and information needed to address climate-related issues are obtained and made available to all potential users. Data from the remaining stations were obtained from the Mongolian Institute of Meteorology and Hydrology. In addition, 3-hourly temperature and relative humidity data for the last ten years (1998-2007) from the National Climatic Data Center (NCDC) ([NCDC] 2008) were extracted to determine the surface heating trend at each station. Also upper air model data for 1961-2002 years are obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) (available at: http://data.ecmwf.int/data/) and National Center for Environmental Prediction (NCEP) 40 year reanalysis data (Kalnay et al. 1996) which has now been updated from 1961-2005, and obtained from the Climate Diagnostic Center (CDC) web server at (http://www.cdc.noaa.gov/cgi-bin/Timeseries/timeseries1.pl).

2.4 Research approach

Analysis of statistically significant seasonal and annual surface air temperature, precipitation and surface heat trends for the seventeen sites were carried out. Variations in surface heat content over time were estimated using [eq 1]. The surface heat energy (H_e) or moist enthalpy accounts not only for the surface temperature but also for the contribution of water vapor to the surface heat content (Davey and Pielke Sr. 2005) and is expressed as:

$$H_e = C_pT+L_vr \quad [1]$$

where C_p is the specific heat content of the air at constant pressure (at 20°C, C_p=1.005 J g^{-1} $°K^{-1}$), T is the observed air temperature at 2 m height in °K, L_v is the latent heat of vaporization (at 20°C, L_v = 2450 J g^{-1}), r is the mixing ratio or the ratio between the mass of water vapor to the mass of dry air (g g^{-1}) and expressed as:

$$r = 0.622e/(p-e) \quad [2]$$

where p is pressure (hPa) and e is vapor pressure (hPa) and expressed as:

$$e = e_0 * exp(L_v/R_v*(1/T_o-1/T_d) \quad [3]$$

where e_0 is reference saturation vapor pressure (e_0 = 6.11hPa), R_v is gas constant for water vapor (R_v = 461.5 J/kg * ^oK), T_d is dew point temperature in °K and T_o is reference temperature in °K (T_o = 273.15^{o}K)

To express enthalpy in degrees for comparison to air temperature we use the term effective temperature (T_e), expressed as:

$$T_e = H_e/C_p = T + L_v r/C_p \qquad [4]$$

where T_e is the effective temperature that accounts for specific humidity of the air; therefore it has contributions from both sensible and latent heat (Pielke et al. 2004).

Winter season includes December, January and February of the following year, so the winter trends always started from the year 1962 instead 1961. Each season has three months of duration. Arvaikheer and Ulaanbaatar stations data started from 1969 and Bayankhongor station data started from 1962 due to data availability. All other station's data are from 1961-2004. Maximum and minimum temperature analysis based on the 1961-2003 data. The long-term climate data are analyzed for the linear trends and mapped for seasonal and annual changes for the study period using ARCGIS 9.1. Long-term temperature and precipitation trend graphs and significant changes (α = 0.05) are analyzed using Excel software (Microsoft Office 2007) for different regional sites. Heating or cooling trends for each individual site are calculated by integrating surface temperature and specific humidity data [eq 1] and then effective temperature trends are calculated by using [eq 4].

A total of 17 climate indices are calculated using a R based software package and FORTRAN program for the 17 stations during 1961-2001 year period. They are based on daily temperature values or daily precipitation amount. Some are based on fixed thresholds that are of relevance to particular applications. In these cases, thresholds are the same for all stations. Data quality control procedure and simple procedure for detecting inhomogeneities are integrated in the software packages. The details of those 17 indices described at (http://cccma.seos.uvic.ca/ETCCDMI/list_27_indices.shtml).

III. RESULTS

3.1 Mean temperature trends

We analyzed 17 stations mean temperature trends from 1961 to 2004. According to the linear trend the highest annual and seasonal temperature changes mostly occurred in the coldest north western mountain area of the country. The least changes occurred in the eastern plain. The results are supported our expectations that the most temperature increase occurred during the winter months as it is shown in the large scale regional climate warming trends (Jones and Moberg 2003) observed over the past 40 years (Fig. 2.1)

According to the linear trend, the annual mean temperatures increased significantly ($p < 0.05$) for all of the stations except at Ondorkhaan station. The temperature increase at Ondorkhaan station was 0.38^{o}C, which is not significant (p=0.39). Ulaangom, Khovd, Moron (Western mountain region) and Dalanzadgad (Gobi decert region) had more than two degrees of an increase and the rest of them had between one to two degrees increase for the study period. The magnitudes of the increases were different throughout the country and shown in Table 2.1 and Figure 2.2. The average annual mean temperature increase was 1.73^{o}C for 17 stations.

The winter mean temperatures increased significantly ($p < 0.05$) except at the Ulaanbaatar ($p = 0.87$) and Ondorkhaan ($p = 0.56$) stations. The most changes occurred at the Khovd (4.71^{o}C), Ulaangom (4.08^{o}C), Dalanzadgad (4.26^{o}C), Bayankhongor (3.17^{o}C) and Moron (3.13^{o}C) stations (Fig. 2.3 and Table 2.2). The average winter mean temperature increase was 2.32^{o}C for 17 stations.

The summer mean temperatures increased significantly ($p < 0.05$) except at the Ulaangom ($p = 0.07$) station. The most temperature increase for the summer has occurred at the Ulaanbaatar (3.15^{o}C) station. The magnitudes of the winter and summer temperature increases were different throughout the country and shown in Figure 2.4 and Table 2.2. The average summer mean temperature increase was 1.68^{o}C for 17 stations, which is close to regional average (Jones and Moberg 2003) for the last 40 years (Fig. 2.5).

The spring mean temperatures increased significantly ($p < 0.05$) except at the Uliastai ($p = 0.23$), Altai ($p = 0.43$) and Ondorkhaan ($p = 0.25$) stations. The most change is occurred at the Ulaanbaatar (3.26^{o}C) station. The rest of the stations' temperatures changed between one and three degrees (Fig. 2.6 and Table 2.3). The average summer mean temperature increase was 1.67^{o}C for 17 stations.

The fall mean temperatures increased significantly ($p < 0.05$) except at the Ulaanbaatar ($p = 0.52$), Bulgan ($p = 0.22$), Baruunkharaa ($p = 0.24$), Arvaikheer ($p = 0.17$) and Ondorkhaan ($p = 0.53$) stations. The most change is occurred at the Moron (2.41^{o}C) station (Fig. 2.7 and Table 2.3). The average fall mean temperature increase was 1.16^{o}C for 17 stations.

Overall, the annual and seasonal mean temperatures mostly have significant increasing trends. The annual mean temperatures significantly increased at sixteen stations and slightly increased at the Ondorkhaan station. Winter mean temperatures significantly increased at fifteen stations, and slightly decreased at two stations. Summer minimum temperatures significantly increased at sixteen stations, and slightly increased at the Ulaangom station. Spring mean temperatures significantly increased at fourteen stations, and slightly increased at three stations. Fall mean temperatures significantly increased at twelve stations and slightly increased at five stations (Fig. 2.8). In addition to that, the annual and seasonal mean temperatures have increasing trends with increasing elevations except in the spring. They also had increasing trends with increasing latitude. Spring and summer mean temperatures were slightly increasing and winter, fall, and annual mean temperatures were decreasing with increasing longitude.

3.2 Maximum temperature trends

We analyzed 17 stations' maximum temperature (T_{max}) trends for the 1961-2003 year period annually and seasonally. Annual and seasonal T_{max} had slightly increasing trends with increasing elevations except during the spring. Winter and fall T_{max} trends were slightly decreasing and spring, summer, and annual T_{max} trends were increasing with increasing latitude. Annual and seasonal T_{max} had decreasing trends with increasing longitude.

According to the linear trend, the annual maximum temperatures increased from 0.5°C (at the Ondorkhaan station) to 1.59°C (at the Bayankhongor station) for the last 43 years. Out of 17 stations the annual T_{max} increases were significant ($p < 0.05$) at eleven stations: Khovd, Moron, Uliastai, Ulaangom, Mandalgovi, Choibalsan, Ulaanbaatar, Baruunkharaa, Altai, Tsetserleg, and Bayankhongor. The magnitudes of the increases are shown in Figure 2.9 and Table 2.4. The average annual maximum temperature increase was 1.17°C for 17 stations.

The winter maximum temperatures increased from 0.43°C (at the Ulaanbaatar station) to 4.11°C (at the Ulaangom station) for the last 42 years. The winter T_{max} increases were significant ($p < 0.05$) for eight stations: Khovd, Uliastai, Ulaangom, Dalanzadgad, Mandalgovi, Altai, Tsetserleg, and Bayankhongor. The winter T_{max} had slightly decreasing trends at the Arvaikheer, Baruunkharaa, and Ondorkhaan stations (Table 2.5). The magnitudes of the increases are shown in Figure 2.10 and Table 2.5. The average winter maximum temperature increase was 1.61°C for 17 stations.

According to the linear trend, the summer maximum temperatures increased from 0.62°C (at Sainshand station) to 2.96°C (at Baruunkharaa station) for the last 43 years. The summer T_{max} increases were significant ($p < 0.05$) for fourteen stations: Khovd, Moron, Uliastai, Dalanzadgad, Bulgan, Mandalgovi, Arvaikheer, Ulaanbaatar, Baruunkharaa, Altai, Tsetserleg, Ondorkhaan, Choir, and Bayankhongor. The magnitudes of the increases are shown in Figure 2.11 and Table 2.5. The average summer maximum temperature increase was 1.59°C for 17 stations.

The spring maximum temperatures increased from 0.28^oC (at Altai station) to 2.44^oC (at the Ulaangom station) for the last 43 years. The spring T_{max} increases were significant ($p < 0.05$) for four stations (Moron, Ulaangom, Ulaanbaatar, Baruunkharaa). The spring T_{max} had decreasing (not significant) trends at Dalanzadgad and Sainshand stations (Table 2.6). The magnitudes of the changes are shown in Figure 2.12 and Table 2.6. The average spring maximum temperature increase was 0.93^oC for 17 stations.

The fall maximum temperatures increased from zero (at Sainshand station) to 1.19^oC (at the Bayankhongor station) for the last 43 years. The fall T_{max} increases were not significant ($p < 0.05$) for all stations and had slightly decreasing trends at Arvaikheer and Baruunkharaa stations (Table 2.6). The magnitudes of the increases are shown in Figure 2.13 and Table 2.6. The average fall maximum temperature increase was 0.35^oC for 17 stations.

Overall, the annual T_{max} significantly increased at eleven stations and slightly increased at six stations. The winter maximum temperatures significantly increased at eight stations, slightly increased at six stations, and decreased (not significantly) at three stations. Summer maximum temperatures significantly increased at fourteen stations, and slightly increased three stations. Spring maximum temperatures significantly increased at four stations, slightly increased at eleven stations and decreased (not significantly) at two stations. Fall maximum temperatures slightly increased at fifteen stations and also slightly decreased at two stations (Fig. 2.14). Mostly, the maximum temperature significantly increased in winter and summer seasons and slightly increased in spring and fall seasons. Some of the stations had decreasing trends but none were significant.

3.3 Minimum temperature trends

We analyzed 17 stations' minimum temperature (T_{min}) trends for the 1961-2003 year period annually and seasonally. Annual and seasonal T_{min} had slightly increasing trends with station's latitude increases. Winter T_{min} trends were slightly increasing with increasing elevations except spring. Annual and seasonal T_{min} had decreasing trends with increasing longitude.

According to the linear trend, the annual minimum temperatures increased significantly from 0.83^oC (at Dalanzadgad station) to 3.42^oC (at Moron station) and only at the Ondorkhaan station it is decreased (not significantly) by 0.33^oC for the last 43 years. The magnitudes of the changes are shown in Figure 2.15 and Table 2.7. The average annual minimum temperature increase was 1.87^oC for 17 stations.

The winter minimum temperatures increased from 1.08 ^oC (at Choibalsan station) to 5.36^oC (at Khovd station) for the last 42 years. The winter T_{min} had slightly decreasing trend at Ondorkhaan station (Table 2.8). The winter T_{min} increases were significant ($p < 0.05$) for eight stations: Khovd, Uliastai, Ulaangom, Dalanzadgad, Mandalgovi, Altai, Tsetserleg, and Bayankhongor. The magnitudes of the increases are shown in Figure 2.16 and Table 2.8. The average winter minimum temperature increase was 2.45^oC for 17 stations.

The summer minimum temperatures increased from 0.62^oC (at Sainshand station) to 2.96^oC (at Baruunkharaa station) for the last 43 years. The summer T_{min} increases were significant ($p < 0.05$) for fourteen stations: Khovd, Moron, Uliastai, Dalanzadgad, Bulgan, Mandalgovi, Arvaikheer, Ulaanbaatar, Baruunkharaa, Altai, Tsetserleg, Ondorkhaan, Choir, and Bayankhongor. The magnitudes of the increases are shown in

Figure 2.17 and Table 2.8. The average summer minimum temperature increase was 1.64°C for 17 stations.

The spring minimum temperatures increased from 0.08°C (at Ondorkhaan station) to 3.44°C (at Moron station) for the last 43 years. The spring T_{min} increases were significant ($p < 0.05$) for four stations: Moron, Ulaangom, Ulaanbaatar, and Baruunkharaa. The spring T_{min} had decreasing trends at the Dalanzadgad and Sainshand stations. The magnitudes of the changes are shown in Figure 2.18 and Table 2.9. The average spring minimum temperature increase was 1.75°C for 17 stations.

The fall minimum temperatures increased from zero (at Sainshand station) to 1.19°C (at Bayankhongor station) for the last 43 years. The fall T_{min} increases were not significant ($p < 0.05$) for all of the stations and had slightly decreasing trends at the Arvaikheer and Baruunkharaa stations. The magnitudes of the increases are shown in Figure 2.19 and Table 2.9. The average fall minimum temperature increase was 1.12°C for 17 stations.

Overall, the annual minimum temperatures significantly increased at sixteen stations and slightly decreased at the Ondorkhaan station. Winter minimum temperatures significantly increased at eight stations, slightly increased at eight stations and decreased (not significantly) at the Ondorkhaan station. Summer minimum temperatures significantly increased at fourteen stations, and increased (not significantly) three stations. Spring minimum temperatures significantly increased at four stations, and slightly increased at thirteen stations. Fall minimum temperatures slightly increased at sixteen stations and also slightly decreased at the Ondorkhaan station (Fig. 2.20). Mostly, the minimum temperatures significantly increased in winter and summer seasons and slightly increased in spring and fall seasons. Only the Ondorkhaan station had slightly decreasing trends in annual, winter and fall temperature.

3.4 Station annual averages and 5-year running means

Station annual averages and 5-year running means calculated for all 17 stations and combined average for the stations are shown in the Figure 2.21. All stations had increasing mean annual temperature trends. Three stations that are in the Gobi-desert region (Mandalgovi, Dalanzadgad and Sainshand) had above zero annual mean temperatures for the whole study period. Two stations (Uliastai and Ulaangom), which are in Great lake basin had below zero mean annual temperatures for the whole study period. Bulgan, Altai, Ulaanbaatar and Baruunkharaa stations, which are in the central region had most of the time below zero mean annual temperatures.

3.5 Comparison of last 10 years: 1998-2007 trends

3.5.1 Air temperature trend versus surface heat trend

We observed similar trends in seasonal surface heat energy or moist enthalpy, (H_e) and 2 m mean air temperature (T_{mean}), for winter, spring and fall at 17 stations but not for the summer when the air humidity is higher. Eight stations had decreasing H_e but increasing T_{mean} and one station (Bayankhongor) had increasing H_e but decreasing T_{mean} during the summer for the last ten years. This indicates the temperature increase (or decrease) does not really mean the H_e increase (or decrease) because it also depends on the humidity. When it is dry during the winter only Sainshand station had opposite trend: increasing T_{mean} but the decreasing H_e. During the spring, Uliastai and Baruunkharaa stations had increasing H_e but decreasing T_{mean} whereas Tsetserleg station had decreasing H_e but increasing $T_{\mathrm{mean.}}$ During the fall, Dalanzadgad and Mandalgovi stations had decreasing H_e but increasing $T_{mean.}$ Annually, Mandalgovi, Arvaikheer, Choibalsan, Tsetserleg and Ondorkhaan stations had decreasing H_e but increasing $T_{mean.}$ The rest of the stations had similar trends (Figs. 2.22 and 2.23, Tables 2.10 and 2.11).

3.5.2 Effective temperature versus air temperature

We observed similar trends in seasonal effective temperature (T_e) and 2 m mean air temperature (T_{mean}), for winter, spring and fall at 17 stations but not for the summer when the air humidity is higher. Eight stations had decreasing T_e but increasing T_{mean} and two stations (Uliastai and Bayankhongor) had increasing T_e but decreasing T_{mean} during the summer for the last ten years. This indicates the effective temperature would more correctly indicate the warming and cooling because it accounts the humidity value. When it is dry during the winter Mandalgovi, and Sainshand stations had increasing T_{mean} but the decreasing T_e and Ulaanbaatar station had decreasing T_{mean} but the increasing T_e. During the spring, Uliastai, Baruunkharaa, and Bayankhongor stations had increasing T_e but decreasing T_{mean} whereas Tsetserleg station had decreasing T_e but increasing $T_{mean.}$ During the fall, Uliastai, Dalanzadgad and Mandalgovi stations had decreasing T_e but increasing $T_{mean.}$ Annually, Mandalgovi, Arvaikheer, Choibalsan, Tsetserleg and Ondorkhaan stations had decreasing T_e but increasing $T_{mean.}$ The rest of the stations had similar trends (Figs. 2.23 and 2.24, Tables 2.11 and 2.12).

3.5.3 Decadal temperature trend versus long-term temperature trend

Most of the stations decadal (1998-2007) temperature trends indicate decreasing trend (Fig. 2.23) during the winter and spring due to very cold winter and spring of 2000, 2002 and especially 2005, which was not included in the long-term (1961-2004) trend

(Fig. 2.8). Ten, 13, 5, 2, and 2 stations had decreasing T_{mean} trends respectively for winter, spring, summer, fall and annually that are opposite from the long-term trends (Fig. 2.23 and Table 2.11). Ondorkhaan station had increasing T_{mean} decadal trend but decreasing long-term trend for fall and annual.

3.6 Climate change indices

A total of 17 climate indices were calculated using a R based software package and FORTRAN program for the 17 stations during 1961-2001 year period. They are based on daily temperature values or daily precipitation amount (Wang 2003). Some are based on fixed thresholds that are of relevance to particular applications. In these cases, thresholds are the same for all stations. Data quality control procedure and simple procedure for detecting inhomogeneities are integrated in the software packages (Peterson et al.1998).

Temperature and precipitation indices' trends are shown in the Table 2.13 and 2.14 respectively. The details of those seventeen indices are described at (http://cccma.seos.uvic.ca/ETCCDMI/list_27_indices.shtml).

1. **su25:** The trend of the number of summer days, which is when the daily maximum temperature is greater than 25^{o}C, has significantly increased at all of the stations except Sainshand (decreased), Ulaangom (not significantly increased) and Choibalsan (no trend) for the years 1961-2001.

2. **tr20:** The trend of the number of tropical nights, which is when daily minimum temperature is greater than 20^{o}C, has significantly increased at all of the stations except

Ulaangom, Arvaikheer (not significantly increased), Uliastai, Bulgan, Altai, and Tsetserleg (no trends) stations.

3. **id0:** The trend of the number of icing days, which is when the daily maximum temperature is less than 0^{o}C, has decreased (not significantly) at all of the stations except Baruunkharaa, Ondorkhaan, Choir, Sainshand and Byankhongor (not significantly increased) stations.

4. **fd0:** The trend of the number of frost days, which is when daily minimum temperature is less than 0^{o}C, has significantly decreased at all of the stations except Ulaangom, Altai and Ondorkhaan (not significantly decreased) stations.

5. **txx:** The trend of the monthly maximum value of daily maximum temperature has increased at all of the stations and eight of them were significant.

6. **txn:** the trend of the monthly minimum value of daily maximum temperature has increased (not significantly) at all of the stations except at Baruunkharaa, Ondorkhaan, Sainshand (not significantly decreased), Ulaangom and Altai (significantly increased) stations.

7. **tnx:** The trend of the monthly maximum value of daily minimum temperature has significantly increased at all of the stations except Choibalsan, Shainshand and Altai (not significantly increased) stations.

8. **tnn:** The trend of the monthly minimum value of daily minimum temperature has significantly increased at all of the stations except at Ondorkhaan, Sainshand (not significantly decreased) Uliastai, Bulgan, Mandalgovi, Ulaanbaatar, Tsetserleg, Choir, and Bayankhongor stations (not significantly increased).

9. **dtr:** the trend of the daily temperature range, which is monthly mean difference between daily maximum and minimum temperature, has significantly decreased at all of the stations except at Uliastai, Ulaangom, Choir (no trends), Altai (not significantly increased), and Ondorkhaan (significantly increased) stations.

10. **rx1day:** The trend of the monthly maximum 1-day precipitation has slightly decreased at all of the stations except at Khovd, Uliastai, Ulaangom, Arvaikheer, Ulaanbaatar, Sainshand, and Bayankhongor (not significantly increased) stations.

11. **rx5day:** The trend of the monthly maximum consecutive 5-day precipitation has slightly decreased at all of the stations except at Uliastai, Ulaangom, Dalanzadgad, Arvaikheer, Ulaanbaatar, Altai, Sainshand, and Bayankhongor (not significantly increased) stations.

12. **sdii:** The trend of the simple precipitation intensity index, which is when the precipitation is equal or greater than 1 mm, has slightly decreased at all of the stations except Khovd, Uliastai, Ulaanbaatar, Choir, Sainshand (no trends), Bulgan and Arvaikheer (not significantly increased) stations.

13. **r10mm:** The trend of the annual count of days, where precipitation is greater than 10 mm, has slightly decreased at all of the stations except at Khovd, Arvaikheer, Ulaanbaatar (not significantly increased) and Uliastai (no trend) stations.

14. **r20mm:** The trend of the annual count of days, where precipitation is greater than 20 mm, has slightly decreased at all of the stations except at Uliastai, Bulgan, Arvaikheer, Ulaanbaatar, Sainshand (not significantly increased), Ulaangom Dalanzadgad, Choibalsan and Altai (no trends) stations.

15. **cwd:** The trend of the maximum length of wet spell, which is when the maximum number of consecutive days with precipitation is equal or greater than 1 mm, has slightly increased at all of the stations except at Moron, Bulgan, Baruunkharaa, Ondorkhaan, Choir (not significantly decreased), and Dalanzadgad (no trend) stations.

16. **cdd:** The trend of the maximum length of dry spell, which is when the maximum number of consecutive days with precipitation is less than 1mm, has slightly decreased at all of the stations except at Khovd, Bulgan, Arvaikheer, Baruunkharaa, Sainshand (not significantly increased) stations.

17. **gsl:** The trend of the growing season length has increased significantly at Moron and Baruunkharaa stations and slightly increased at rest of the stations.

According to the 17 climate change indices most of the stations frost and icing days decreased and summer days, tropical nights, monthly maximum value of daily minimum and maximum temperatures are increased (Table 2.13). In addition to that, GSL increased at all sites (Table 2.14). Precipitation indices varied a lot and there were no unified temporal and spatial pattern (Table 2.14). Clearly, we observed the temperature increasing trend at most of the stations.

3.7 Precipitation

According to the linear trend for last 45 years winter precipitation has not changed much. The precipitation at Baruunkharaa station decreased by 2.46 mm (the only station that has decreasing trend) and at Moron station increased by 3.23 mm. The rest of them changed in between (Table 2.15 and Fig. 2.25). All of them slightly increased.

The spring precipitation slightly increased. The highest increase (13.8 mm) was observed at the Moron station and next at Ulaanbaatar (8.8 mm) station. Dalanzadgad station precipitation decreased by 23 mm, which is the lowest and rest of them changed in between (Fig. 2.26).

The most precipitation change occurred (mainly decreased) in the summer (mainly decreased). For example Moron station had the most decrease (-44.8 mm), and next Baruunkharaa (-28.2 mm) and Ondorkhaan (-22.9 mm) stations (Fig. 2.27).

The fall precipitation has not changed much but mainly decreased (Fig. 2.28). It changed from -6.4 (Bulgan) to 1.1 (Sainshand).

Moron has the most decrease in annual precipitation due to the summer rain decrease. Bayankhongor has the highest increase (13.7 mm) in annual change and rest of them changed in between (Fig. 2.29). The seasonal and annual precipitation changes were not significant. The linear trend diminishes the biggest monthly changes. The monthly precipitation of the stations varied a lot throughout the country and between the months. Table 2.16 shows the monthly precipitation means, standard deviations and coefficient of variations.

Overall, according to the average of 17 stations winter, spring and annual precipitation increased by 1, 3, and 1 mm whereas summer and fall season precipitation decreased by 10 and 2 mm respectively. The standard deviations and coefficient of variations were very high. Precipitation varied lot from one station to others and between the months and years.

3.8 The surface climate data in comparison to the upper air model data for selected nine (GCON) stations

There are significant increasing trends in spring surface mean temperature between 1961-2004 years. The highest temperature increase (2.52^{o}C) for last 44 years was in Moron whereas the lowest (0.85^{o}C) was in Uliastai (Table. 2.17).

ECMWF data at 700 mb level had also increasing trends except one in Dalanzadgad (-0.2^{o}C). The highest temperature increase (1.07^{o}C) for 42 years (1961-2002) was in Moron (consistent with surface) and the lowest was (0.29^{o}C) in Arvaikheer.

NCEP data at 700 mb level had decreasing (opposite than ECMWF and surface) trends except one in Choibalsan (0.3^{o}C). The highest temperature decrease (-1.07^{o}C) for last 45 years (1961-2005) was in Moron (opposite than ECMWF and surface) and the lowest (-0.29^{o}C) was in Arvaikheer (consistent with ECMWF but not with NCEP).

ECMWF data at 500 mb level had mainly increasing trends except in Khovd (-0.07^{o}C), Arvaikheer (-0.31^{o}C), Mandalgovi (-0.37^{o}C), and Dalanzadgad (-0.94^{o}C). The highest temperature increase (0.79^{o}C) was in Moron (consistent with surface) and the lowest was (0.22^{o}C) was in Choibalsan. NCEP data at 500 mb level had decreasing (opposite than ECMWF and surface) trends except one in Ulaangom (0.69^{o}C). The highest temperature decrease (-1.96^{o}C) was in Dalanzadgad and the lowest (-0.67^{o}C) was in Moron.

During the spring the surface temperature had increasing trend that is consistent with ECMWF temperature trends but opposite with NCEP trends. The NCEP data indicate that mostly cooling occurred but was not significant. The upper air model data and surface data had different trends at different stations.

There are significant increasing trends in summer surface mean temperature between 1961-2004 years. The highest temperature increase (2.13°C) was in Moron whereas the lowest (0.87°C) was in Ulaangom (Table 2.18).

ECMWF data at 700 mb level had also increasing trends except in Dalanzadgad (-0.14°C) and Choibalsan (-0.11°C). The highest temperature increase (1.1°C) was in Uliastai and the lowest was (0.41°C) was in Mandalgovi. NCEP data at 700 mb level had decreasing trends except one in Ulaangom (0.13°C). The highest temperature decrease (-2.08°C) was in Dalanzadgad and the lowest (-0.11°C) was in Choibalsan.

ECMWF data at 500 mb level had mainly increasing trends except in Dalanzadgad (-0.14°C) and Choibalsan (-0.008°C). The highest temperature increase (1.16°C) was in Ulaangom and the lowest was (0.12°C) was in Mandalgovi. NCEP data at 500 mb level had decreasing trends except one in Ulaangom (0.04°C). The highest temperature decrease (-1.54°C) was in Arvaikheer and the lowest (-0.52°C) was in Khovd.

During the summer the surface temperature had increasing trend but it was not consistent with troposphere levels. NCEP data had decreasing trends but ECMWF data had different trends for different stations. There was no significant summer trend in upper air temperature.

There are significant increasing trends in fall surface temperature between 1961-2004 years. The highest temperature increase (2.41°C) was in Moron whereas the lowest (0.74°C) was in Bulgan (Table 2.19).

ECMWF data at 700 mb level had also increasing trends. The highest temperature increase (1.46°C) was in Uliastai and the lowest was (0.62°C) was in Choibalsan. NCEP data at 700 mb level had decreasing trends except in Khovd (0.44^{o}C) and Ulaangom (0.48^{o}C). The highest temperature decrease (-1.14^{o}C) was in Mandalgovi and Bulgan (-1.14^{o}C) whereas the lowest (-0.004^{o}C) was in Choibalsan.

ECMWF data at 500 mb level had increasing trends. The highest temperature increase (1.46^{o}C) was in Moron and the lowest was (0.3^{o}C) was in Dalanzadgad. NCEP data at 500 mb level had decreasing trends except one in Ulaangom (0.86^{o}C). The highest temperature decrease (-0.73^{o}C) was in Dalanzadgad and the lowest (-0.05^{o}C) was in Choibalsan.

During the fall season surface and ECMWF temperature had increasing trends whereas NCEP data had mostly decreasing trends.

There are significant increasing trends in winter surface mean temperature between 1961-2004 years. The highest temperature increase (4.71^{o}C) was in Khovd whereas the lowest (1.06^{o}C) was in Bulgan (Table 2.19).

ECMWF data at 700 mb level had also increasing trends. The highest temperature increase (2.82^{o}C) was in Mandalgovi and the lowest was (1.48^{o}C) was in Ulaangom. NCEP data at 700 mb level had increasing trends. The highest temperature increase (2.46^{o}C) was in Choibalsan and the lowest (0.91^{o}C) was in Arvaikheer.

ECMWF data at 500 mb level had increasing trends. The highest temperature increase (2.01^{o}C) was in Bulgan and the lowest was (1.12^{o}C) was in Dalanzadgad. NCEP data at 500 mb level had increasing trends: the highest temperature increase (1.17^{o}C) was in Choibalsan and the lowest (0.32^{o}C) was in Dalanzadgad.

During the winter the highest temperature increase occurred throughout the country and it was consistent at the surface and troposphere levels.

There are significant increasing trends in annual surface mean temperature between 1961-2004 years. The highest temperature increase (2.49^{o}C) was in Moron whereas the lowest (1.24^{o}C) was in Bulgan (Table 2.20).

ECMWF data at 700 mb level had also increasing trends. The highest temperature increase (1.77^{o}C) was in Mandalgovi and the lowest was (0.9^{o}C) was in Dalanzadgad. NCEP data at 700 mb level had mainly decreasing trends. The highest temperature decrease (-0.55^{o}C) was in Dalanzadgad and the lowest (-0.1^{o}C) was in Uliastai. Increasing trends observed in remaining 4 stations. The highest increase (0.6^{o}C) was in Khovd whereas the lowest (0.05^{o}C) was in Moron.

ECMWF data at 500 mb level had increasing trends. The highest temperature increase (1.36^{o}C) was in Moron and the lowest was (0.24^{o}C) was in Dalanzadgad. NCEP data at 500 mb level had decreasing trends. The highest temperature decrease (-0.79^{o}C) was in Dalanzadgad and the lowest (-0.06^{o}C) was in Moron.

Annually, surface and ECMWF temperature had increasing trends whereas NCEP data had mostly decreasing trends.

According to the multivariate correlation, the most of the surface, ECMWF and NCEP data were very well correlated with each other (Table 2.21).

IY. CONCLUSIONS

We analyzed 17 stations' mean temperature trends from 1961 to 2004. According to the linear trend, the highest annual and seasonal temperature changes mostly occurred in the coldest north western mountain area of the country. The least changes occurred in the eastern plain. The results supported our hypotheses that the most temperature increase occurred during the winter months. We also analyzed maximum and minimum temperature trends for the years 1961-2003 annually and seasonally. The annual T_{max} significantly increased at eleven stations and slightly (not significant) increased at eight stations. Mostly, the maximum temperature significantly increased in winter and summer seasons and slightly increased during spring and fall seasons. Some of the stations had decreasing trends but none were significant. The annual minimum temperature significantly increased at sixteen stations and slightly decreased at Ondorkhaan station. Mostly, the minimum temperature significantly increased in the winter and summer, and slightly increased during the spring and fall seasons. Only the Ondorkhaan station had decreasing trends in annual, winter and fall temperatures. Overall, all of the stations had increasing mean annual temperature trends. Mandalgovi, Dalanzadgad and Sainshand stations in the Gobi-desert region had above zero annual mean temperatures for the whole study period. Uliastai and Ulaangom stations, in the Great lake basin had below zero mean annual temperatures for the whole study period. Bulgan, Altai, Ulaanbaatar and Baruunkharaa stations in the central regions had below zero mean annual temperatures for most of the time.

We compared the last ten (1998-2007) years 2 m mean air temperature, effective temperature and surface heat trends. In addition to that decadal temperature trends to the long-term trends. We observed the similar trends in seasonal surface heat, effective temperature and 2 m air temperature for winter, spring and fall at 17 stations but not for the summer when the air humidity is higher. During the summer, some of the stations (8 out of 17) had opposite temperature and surface heat trends but surface heat and effective temperature trends are very well correlated with each other. This indicates the temperature increase (or decrease) does not really mean the surface heat increase (or decrease) because it also depends on the humidity (Figs. 2.22 – 2.24). Therefore, we are suggesting effective temperature as a better metric to evaluate the surface heat change instead of air temperature.

Most of the stations' decadal temperature analysis indicate, decreasing trends during the winter and spring due to very cold winter and spring of 2000, 2002 and especially 2005, which was not included in the long-term (1961-2004) trend. Ten, 13, 5, 2, and 2 stations had decreasing T_{mean} trends respectively for winter, spring, summer, fall and annual, which are opposite from long-term trends. The Ondorkhaan station had increasing T_{mean} decadal trend but decreasing long-term trend for the fall and annual.

A total of seventeen climate change indices were calculated using R based software package and FORTRAN program for the 17 stations during 1961-2001 year period. They are based on daily temperature values or daily precipitation amount. Data quality control procedure and simple procedure for detecting inhomogeneities are integrated in the software packages. According to the 17 climate change indices most of the stations frost and icing days decreased and summer days, tropical nights, monthly maximum value of daily minimum and maximum temperatures are increased. In addition to that, GSL increased at all sites. Clearly, we observed the increasing temperature trend at most of the stations. Precipitation indices varied a lot and there were no unified temporal and spatial pattern.

The precipitation varied a lot spatially and temporally. The linear trend diminishes the biggest monthly changes and the annual and seasonal precipitation changes were not significant. The most precipitation change occurred in the summer and it mainly decreased at most of stations. For example Moron station had the most decrease (-44.8

mm), and next Baruunkharaa (-28.2 mm) and Ondorkhaan (-22.9 mm) station. According to the average of 17 stations, winter, spring and annual precipitation increased by 1, 3, and 1 mm whereas summer and fall season precipitation decreased by 10 and 2 mm respectively. The standard deviations and coefficient of variations were very high.

We compared the surface temperature data to the upper air (at 500 and 700 mb level) ECMWF and NCEP model data for the selected nine (GCON) stations. According to the multivariate correlations, the most of the surface and ECMWF data well correlated with each other but NCEP data were a little different.

ACKNOWLEDGEMENTS

I would like to express my special thanks to P. Gomboluudev, B. Batima, Adriana Beltran, Tom Riley, and Steve Knox, who helped me to obtain the meteorological data. Also, I would like to extend special gratitude to my childhood friend J. Munkhbileg, who helped me to collect the information from Mongolia.

LIST OF REFERENCES

Ahrens CD. 2003. *Meteorology Today: An Introduction to Weather, Climate, and the Environment.* Seventh edition. Pacific Grove, CA. Brooks/Cole-Thompson Learning[tm]. 544 p.

Batima P. 2003. *Climate change: Pasture-livestock.* ADMON Publishing, Ulaanbaatar. 120 p.

Chuluun T, Ojima DS. 2002. Sustainability of pastoral systems in Mongolia in editors Chuluun T, and Ojima DS. *Fundamental Issues Affecting Sustainability of the Mongolian Steppe*. Interpress Publishing and Printing, Ulaanbaatar. 372p.

Davey CA, RA. Pielke Sr. 2005. Microclimate exposures of surface-based weather stations- implications for the assessment of long-term temperature trends. *Bulletin of the American Meteorological Society* **86:4,** 497–504.

Erdenetuya M. and S. Khudulmur 2005. Land cover change and pasture estimation of Mongolia from space. Available at: http://www.gisdevelopment.net/application/environment/conservation/envc0002.htm Accessed: 5 March 2005.

Fernandez-Gimenez ME. and B. Allen-Diaz 1999. Testing a non-equilibrium model of rangeland vegetation dynamics in Mongolia. *Journal of Applied Ecology* **36**, 871-885

Gunin PD., EA. Vostokova, NI. Dorofeyuk, PE. Tarasov, and CC. Black Eds. 1999. *Vegetation Dynamics of Mongolia*. Geobotany vol.**26**. Kluwer Academic Publishing, Dordrecht. 238p.

Jones PD. and A.Moberg 2003. Hemispheric and Large-Scale Surface Air Temperature Variations: An Extensive Revision and an Update to 2001. *Journal of Climate* **16**, 206-223

Kabat P., M. Claussen, PA. Dirmeyer, J.H.C.Gash, L.B.Deguenni, M. Meybeck, R.A. Pielke Sr., C.J. Voeroesmarty, R.W.A. Hutjes, S. Luetkemeier editors. 2004. *Vegetation, Water, Humans and the Climate: A new perspective on an Interactive System*. Springer-Verlag. Berlin, Heidelberg. 566 p.

Kalnay E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W.Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, Roy Jenne, and Dennis Joseph. 1996. The NCEP/NCAR 40-Year Reanalysis Project. *Bulletin of the American Meteorological Society* **77**, 437-431.

Hanamean Jr., JR., RA Pielke Sr., CL. Castro, DS. Ojima, BC. Reed, and Z. Gao. 2003. Vegetation impacts on maximum and minimum temperatures in northeast Colorado. *Meteorological Applications* **10**, 203-215.

Hilbig W. 1995. *The Vegetation of Mongolia*. SPB Academic Publishing, Amsterdam. 258p.

Lu L., RA. Pielke Sr., GE. Liston, WJ. Parton, DS. Ojima, and M. Hartman. 2001. Implementation of a two-way interactive atmospheric and ecological model and its application to the central United States. *Journal of Climate* **14**, 900-919.

[NAS] National Academy of Sciences. 2005. *Radiative Forcing of Climate Change: Expanding the Concept and Addressing Uncertainties.* National Academies Press., Washington D.C., Available at: http://www.nap.edu/books/0309095069/html/ Accessed: 4 February 2005.

[NCDC] National Climatic Data Center. 2008. NNDC climate data online. Available at http://cdo.ncdc.noaa.gov/CDO/cdo Accessed on 09.15.2008.

[NSOM] National Statistical Office of Mongolia. 2006. *Mongolian Statistical Yearbook* 2005. Kopir Tekh Co. Ltd., Ulaanbaatar.

Peterson, TC., DR. Easterling, TR. Karl, P. Groisman, N. Nicholls, N. Plummer, S. Torok, I. Auer, R. Bohm, D. Gullett, L. Vincent, R. Heino, H. Tuomenvirta, O. Mestre, T. Szentimrey, J. Salinger, EJ. Foland, I. Hanssen-Bauer, H. Alexanderson, P. Jones, and D. Parker, 1998. Homogeneity adjustments of in situ atmospheric climate data: a review. *International Journal of Climatology,* **18**, 1493-1517.

Pielke Sr., RA., C. Davey, and J. Morgan. 2004. Assessing "global warming" with surface heat content. EOS, *American Geophysical Union,* **85**, 210-211.

Pielke Sr., RA. 2001. Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. *Reviews of Geophysics* **39,** 151-177.

Wang, XL., 2003. Comments on "Detection of undocumented changepoints: A revision of the two-phase regression model". *Journal of Climate,* **16,** 3383-3385.

LIST OF TABLES

LIST OF FIGURES

Table 2.1 Annual mean temperature change for 17 stations. Station latitude, longitude, elevation, linear regression equation, R-square and temperature change ($_{\Delta}T_{ann.}$) for the period (1961-2004) are shown.

Station name & ID	Lat.	Long.	Elevation	Regression equation	R^2	$_{\Delta}T_{ann.}$
Khovd, 44218	48°01’	91°39’	1406	y = 0.0554x-1.25	0.36	2.44
Moron, 44231	49°55’	100°15’	1288	y = 0.0565x-1.27	0.46	2.49
Uliastai, 44272	47°45’	96°51’	1767	y = 0.0361x-0.81	0.28	1.59
Ulaangom, 44212	49°48’	92°05’	940	y = 0.053x-1.19	0.37	2.33
Dalanzadgad, 44373	43°25’	104°25’	1470	y = 0.0467x-1.05	0.45	2.05
Bulgan, 44239	48°48’	103°33’	1210	y = 0.0282x-0.64	0.24	1.24
Mandalgovi, 44341	45°46’	106°17’	1393	y = 0.0402x-0.90	0.38	1.77
Arvaikheer, 44288	46°16’	102°47’	1813	y = 0.0555x-1.47	0.47	2.00
Choibalsan, 44259	48°05’	114°33’	756	y = 0.0401x-0.90	0.32	1.76
Ulaanbaatar, 44292	47°56’	106°54’	1306	y = 0.0434x-1.15	0.38	1.91
Baruunkharaa, 44241	48°55’	106°04’	807	y = 0.0424x-0.95	0.46	1.87
Altai, 44277	46°24’	96°15’	2183	y = 0.0348x-0.78	0.26	1.53
Tsetserleg, 44282	47°27’	101°28’	1693	y = 0.0364x-0.82	0.32	1.60
Ondorkhaan, 44304	47°19’	110°38’	1033	y = 0.0086x-0.19	0.02	0.38
Choir, 44298	46°27’	108°13’	1286	y = 0.0366x-0.82	0.31	1.61
Sainshand, 44354	44°54’	110°07’	936	y = 0.0268x-0.60	0.21	1.18
Bayankhongor, 44287	46°08’	100°41’	1859	y = 0.0401x-0.94	0.31	1.76

Table 2.2 Winter and summer mean temperature changes for 17 stations. The linear regression equation, R-square and temperature change ($_{\Delta}T_{win.}$ and $_{\Delta}T_{summ.}$) for the study period shown for winter and summer respectively.

Station name & ID	Regression equation	R^2	$_{\Delta}T_{win.}$	Regression equation	R^2	$_{\Delta}T_{summ.}$
Khovd 44218	y = 0.1095x-2.41	0.17	4.71	y = 0.0334x-0.75	0.19	1.47
Moron 44231	y = 0.0727x-1.60	0.13	3.13	y = 0.0483x-1.09	0.29	2.13
Uliastai 44272	y = 0.0695x-1.53	0.20	2.99	y = 0.0328x-0.74	0.13	1.44
Ulaangom 44212	y = 0.0948x-2.09	0.30	4.08	y = 0.0198x-0.45	0.07	0.87
Dalanzadgad 44373	y = 0.0991x-2.18	0.31	4.26	y = 0.0379x-0.85	0.22	1.67
Bulgan 44239	y = 0.0247x-0.94	0.09	1.06	y = 0.0293x-0.66	0.12	1.29
Mandalgovi 44341	y = 0.059x-1.30	0.16	2.54	y = 0.0425x-0.96	0.26	1.87
Arvaikheer 44288	y = 0.0642x-1.67	0.20	2.25	y = 0.0569x-1.51	0.24	2.05
Choibalsan 44259	y = 0.0509x-1.12	0.10	2.19	y = 0.0354x-0.80	0.18	1.56
Ulaanbaatar 44292	y = -0.004x+0.11	0.00	-0.18	y = 0.0717x-1.90	0.31	3.15
Baruunkharaa 44241	y = 0.0483x-1.06	0.12	2.08	y = 0.0568x-1.28	0.28	2.44
Altai 44277	y = 0.0673x-1.48	0.19	2.89	y = 0.032x-0.72	0.13	1.41
Tsetserleg 44282	y = 0.0517x-1.14	0.14	2.22	y = 0.0402x-0.90	0.22	1.77
Ondorkhaan 44304	y =-0.018x+0.40	0.01	-0.78	y = 0.0296x-0.67	0.14	1.30
Choir 44298	y = 0.0464x-1.02	0.08	2.00	y = 0.0354x-0.80	0.19	1.52
Sainshand 44354	y = 0.0387x-0.85	0.06	1.66	y = 0.0217x-0.49	0.09	0.95
Bayankhongor44287	y = 0.0737x-1.70	0.19	3.17	y = 0.0392x-0.92	0.20	1.69

Table 2.3 Spring and fall mean temperature changes for 17 stations. The linear regression equation, R-square and temperature change ($_{\Delta}T_{spr.}$ and $_{\Delta}T_{fall}$) for the study period are shown for spring and fall respectively.

Station name & ID	Regression equation	R^2	$_{\Delta}T_{spr.}$	Regression equation	R^2	$_{\Delta}T_{fall}$
Khovd 44218	y = 0.0421x-0.95	0.13	1.85	y = 0.0304x-0.68	0.09	1.34
Moron 44231	y = 0.0572x-1.29	0.25	2.52	y = 0.0548x-1.23	0.24	2.41
Uliastai 44272	y = 0.0193x-0.43	0.03	0.85	y = 0.0232x-0.52	0.05	1.02
Ulaangom 44212	y = 0.0559x-1.26	0.21	2.46	y = 0.0426x-0.96	0.13	1.87
Dalanzadgad 44373	y = 0.0272x-0.61	0.09	1.20	y = 0.0294x-0.66	0.13	1.29
Bulgan 44239	y = 0.0299x-0.67	0.09	1.32	y = 0.0169x-0.38	0.04	0.74
Mandalgovi 44341	y = 0.0375x-0.84	0.14	1.65	y = 0.0273x-0.61	0.08	1.20
Arvaikheer 44288	y = 0.0579x-1.53	0.20	2.08	y = 0.0256x-0.68	0.05	0.92
Choibalsan 44259	y = 0.051x-1.15	0.18	2.24	y = 0.0248x-0.56	0.07	1.09
Ulaanbaatar 44292	y = 0.074x-1.36	0.28	3.26	y = 0.014x-0.37	0.01	0.62
Baruunkharaa 44241	y = 0.0456x-1.03	0.16	1.20	y = 0.0194x-0.44	0.03	0.85
Altai 44277	y = 0.013x-0.29	0.01	0.57	y = 0.0281x-0.63	0.08	1.24
Tsetserleg 44282	y = 0.0339x-0.76	0.11	1.49	y = 0.0257x-0.58	0.08	1.13
Ondorkhaan 44304	y = 0.0205x-0.46	0.03	0.88	y = 0.0096x-0.22	0.01	0.42
Choir 44298	y = 0.0403x-0.91	0.13	1.77	y = 0.0301x-0.68	0.08	1.32
Sainshand 44354	y = 0.0318x-0.72	0.12	1.40	y = 0.0233x-0.52	0.07	1.03
Bayankhongor44287	y = 0.0307x-0.72	0.08	1.35	y = 0.0293x-0.69	0.09	1.29

Table 2.4 Annual maximum temperature changes for 17 stations. Station latitude, longitude, elevation, linear regression equation, R-square and temperature change ($_{\Delta}T_{ann.}$) for the study period (1961-2003) are shown.

Station name & ID	Lat.	Long.	Elevation	Regression equation	R^2	$_{\Delta}T_{ann.}$
Khovd, 44218	48°01'	91°39'	1406	y = 0.0271x - 0.5956	0.09	1.19
Moron, 44231	49°55'	100°15'	1288	y = 0.034x - 0.749	0.20	1.50
Uliastai, 44272	47°45'	96°51'	1767	y = 0.034x - 0.7479	0.19	1.50
Ulaangom, 44212	49°48'	92°05'	940	y = 0.0333x - 0.7325	0.11	1.47
Dalanzadgad, 44373	43°25'	104°25'	1470	y = 0.0188x - 0.4145	0.08	0.83
Bulgan, 44239	48°48'	103°33'	1210	y = 0.0182x - 0.4013	0.08	0.80
Mandalgovi, 44341	45°46'	106°17'	1393	y = 0.0291x - 0.6277	0.20	1.28
Arvaikheer, 44288	46°16'	102°47'	1813	y = 0.0224x - 0.4027	0.02	0.78
Choibalsan, 44259	48°05'	114°33'	756	y = 0.0276x - 0.6079	0.11	1.21
Ulaanbaatar, 44292	47°56'	106°54'	1306	y = 0.0446x - 0.8021	0.31	1.56
Baruunkharaa, 44241	48°55'	106°04'	807	y = 0.0251x - 0.5533	0.11	1.10
Altai, 44277	46°24'	96°15'	2183	y = 0.0324x - 0.712	0.20	1.43
Tsetserleg, 44282	47°27'	101°28'	1693	y = 0.0324x - 0.7121	0.18	1.43
Ondorkhaan, 44304	47°19'	110°38'	1033	y = 0.0113x - 0.2493	0.02	0.50
Choir, 44298	46°27'	108°13'	1286	y = 0.0249x - 0.5414	0.12	1.10
Sainshand, 44354	44°54'	110°07'	936	y = 0.0134x - 0.2957	0.03	0.59
Bayankhongor, 44287	46°08'	100°41'	1859	y = 0.0379x - 0.8714	0.28	1.59

Table 2.5 Winter and summer maximum temperature changes for 17 stations. The linear regression equation, R-square and temperature change ($_{\Delta}T_{win.}$ and $_{\Delta}T_{summ.}$) for the study period are shown for winter and summer respectively.

Station name & ID	Regression equation	R^2	$_{\Delta}T_{win.}$	Regression equation	R^2	$_{\Delta}T_{summ.}$
Khovd 44218	Y = 0.063x - 1.35	0.06	2.70	Y = 0.03x - 0.66	0.13	1.32
Moron 44231	Y = 0.035x - 0.75	0.03	1.50	Y = 0.045x - 0.98	0.15	1.96
Uliastai 44272	Y = 0.064x - 1.13	0.15	2.73	Y = 0.038x - 0.83	0.12	1.65
Ulaangom 44212	Y = 0.096x - 2.05	0.25	4.11	Y = 0.023x - 0.50	0.07	1.00
Dalanzadgad 44373	Y = 0.071x - 1.5	0.14	3.06	Y = 0.027x - 0.60	0.11	1.21
Bulgan 44239	Y = 0.028x - 0.59	0.03	1.19	Y = 0.031x - 0.69	0.08	1.38
Mandalgovi 44341	Y = 0.065x - 1.37	0.13	2.79	Y = 0.038x - 0.82	0.15	1.68
Arvaikheer 44288	Y = -0.015x-0.26	0.00	-0.50	Y = 0.045x-0.81	0.06	1.57
Choibalsan 44259	Y = 0.025x - 0.54	0.02	1.08	Y = 0.015x - 0.34	0.03	0.67
Ulaanbaatar 44292	Y = 0.013x - 0.22	0.01	0.43	Y = 0.062x - 1.11	0.18	2.16
Baruunkharaa 44241	Y =-0.009x +0.19	0.00	-0.39	Y = 0.067x - 1.48	0.27	2.96
Altai 44277	Y = 0.058x - 1.24	0.17	2.49	Y = 0.043x - 0.9	0.13	1.88
Tsetserleg 44282	Y = 0.050x - 1.08	0.09	2.16	Y = 0.049x - 1.07	0.18	2.15
Ondorkhaan 44304	Y =-0.018x +0.38	0.00	-0.75	Y = 0.037x - 0.80	0.14	1.61
Choir 44298	Y = 0.028x - 0.59	0.02	1.18	Y = 0.036x - 0.77	0.13	1.56
Sainshand 44354	Y = 0.016x - 0.35	0.01	0.70	Y = 0.014x - 0.31	0.03	0.62
Bayankhongor44287	Y = 0.072x - 1.62	0.17	2.96	Y = 0.039x - 0.89	0.18	1.62

Table 2.6 Spring and fall max temperature changes for 17 stations. The linear regression equation, R-square and temperature change ($_{\Delta}T_{spr.}$ and $_{\Delta}T_{fall}$) for the study period are shown for spring and fall respectively.

Station name & ID	Regression equation	R^2	$_{\Delta}T_{spr.}$	Regression equation	R^2	$_{\Delta}T_{fall}$
Khovd 44218	y = 0.026x - 0.56	0.05	1.13	y = 0.012x - 0.26	0.01	0.83
Moron 44231	y = 0.035x - 0.77	0.09	1.54	y = 0.016x - 0.36	0.02	0.70
Uliastai 44272	y = 0.010x - 0.23	0.01	0.45	y = 0.017x - 0.38	0.02	0.76
Ulaangom 44212	y = 0.056x - 1.24	0.20	2.44	y = 0.020x - 0.43	0.03	0.86
Dalanzadgad 44373	y = -0.001x+0.03	0.00	-0.06	y = 0.0007x – 0.01	0.00	0.03
Bulgan 44239	y = 0.024x - 0.54	0.05	1.07	y = 0.0005x – 0.01	0.00	0.02
Mandalgovi 44341	y = 0.025x - 0.53	0.06	1.08	y = 0.015x - 0.31	0.02	0.64
Arvaikheer 44288	y = 0.018x-0.32	0.01	0.62	y = -0.016x+0.29	0.06	-0.56
Choibalsan 44259	y = 0.026x - 0.57	0.04	1.13	y = 0.003x - 0.06	0.00	0.11
Ulaanbaatar 44292	y = 0.063x - 1.13	0.17	2.21	y = 0.015x - 0.27	0.01	0.53
Baruunkharaa 44241	y = 0.040x - 0.88	0.11	1.76	y = -0.023x + 0.51	0.03	-1.01
Altai 44277	y = 0.006x - 0.14	0.00	0.28	y = 0.018x - 0.40	0.03	0.81
Tsetserleg 44282	y = 0.018x - 0.39	0.02	0.78	y = 0.013x - 0.28	0.01	0.56
Ondorkhaan 44304	y = 0.021x - 0.47	0.03	0.94	y = 0.005x - 0.11	0.00	0.22
Choir 44298	y = 0.022x - 0.49	0.03	0.99	y = 0.006x - 0.12	0.00	0.25
Sainshand 44354	y = -0.036x+0.17	0.02	-1.59	y = 0.001x - 0.02	0.00	0.00
Bayankhongor44287	y = 0.025x - 0.59	0.05	1.07	y = 0.028x - 0.65	0.08	1.19

Table 2.7 Annual minimum temperature changes for 17 stations. Station latitude, longitude, elevation, linear regression equation, R-square and temperature change ($_{\Delta}T_{ann.}$) for the study period (1961-2003) are shown.

Station name & ID	Lat.	Long.	Elevation	Regression equation	R^2	$_{\Delta}T_{ann.}$
Khovd, 44218	48°01'	91°39'	1406	y = 0.0704x - 1.548	0.44	3.13
Moron, 44231	49°55'	100°15'	1288	y = 0.0778x - 1.712	0.59	3.42
Uliastai, 44272	47°45'	96°51'	1767	y = 0.032x - 0.7037	0.21	1.41
Ulaangom, 44212	49°48'	92°05'	940	y = 0.0453x - 0.996	0.19	1.99
Dalanzadgad, 44373	43°25'	104°25'	1470	y = 0.0577x - 1.2684	0.57	2.54
Bulgan, 44239	48°48'	103°33'	1210	y = 0.0249x - 0.5469	0.15	1.10
Mandalgovi, 44341	45°46'	106°17'	1393	y = 0.0433x - 0.9328	0.42	1.91
Arvaikheer, 44288	46°16'	102°47'	1813	y = 0.0651x-1.1724	0.25	2.28
Choibalsan, 44259	48°05'	114°33'	756	y = 0.0276x - 0.6079	0.11	1.21
Ulaanbaatar, 44292	47°56'	106°54'	1306	y = 0.0604x - 1.0865	0.48	2.11
Baruunkharaa, 44241	48°55'	106°04'	807	y = 0.0685x - 1.5071	0.52	3.01
Altai, 44277	46°24'	96°15'	2183	y = 0.0265x - 0.5828	0.16	1.17
Tsetserleg, 44282	47°27'	101°28'	1693	y = 0.0374x - 0.8226	0.35	1.65
Ondorkhaan, 44304	47°19'	110°38'	1033	y = -0.0074x + 0.1635	0.01	-0.33
Choir, 44298	46°27'	108°13'	1286	y = 0.0323x - 0.7009	0.25	1.42
Sainshand, 44354	44°54'	110°07'	936	y = 0.0381x - 0.8376	0.38	1.68
Bayankhongor, 44287	46°08'	100°41'	1859	y = 0.0499x - 1.1479	0.41	2.10

Table 2.8 Winter and summer minimum temperature changes for 17 stations. The linear regression equation, R-square and temperature change ($_{\Delta}T_{win.}$ and $_{\Delta}T_{summ.}$) for the study period are shown for winter and summer respectively.

Station name & ID	Regression equation	R^2	$_{\Delta}T_{win.}$	Regression equation	R^2	$_{\Delta}T_{summ.}$
Khovd 44218	y = 0.125x - 2.68	0.20	5.36	y = 0.052x - 1.15	0.36	2.29
Moron 44231	y = 0.084x - 1.81	0.18	3.62	y = 0.066x - 1.44	0.50	2.89
Uliastai 44272	y = 0.068x - 2.51	0.18	2.93	y = 0.026x - 0.58	0.17	1.15
Ulaangom 44212	y = 0.070x - 1.51	0.14	3.03	y = 0.023x - 0.50	0.11	1.01
Dalanzadgad 44373	y = 0.109x - 2.34	0.38	4.68	y = 0.051x - 1.12	0.39	2.24
Bulgan 44239	y = 0.031x - 0.67	0.05	1.33	y = 0.028x - 0.62	0.17	1.24
Mandalgovi 44341	y = 0.073x - 1.53	0.23	3.12	y = 0.046x - 0.99	0.37	2.02
Arvaikheer 44288	y = 0.080x - 1.41	0.27	2.73	y = 0.059x - 1.06	0.16	2.06
Choibalsan 44259	y = 0.025x - 0.54	0.02	1.08	y = 0.015x - 0.34	0.03	0.67
Ulaanbaatar 44292	y = 0.034x - 0.60	0.06	1.16	y = 0.062x - 1.12	0.36	2.18
Baruunkharaa 44241	y = 0.085x - 1.83	0.28	3.66	y = 0.060x - 1.31	0.38	2.63
Altai 44277	y = 0.050x - 1.07	0.10	2.15	y = 0.027x - 0.60	0.15	1.20
Tsetserleg 44282	y = 0.055x - 1.18	0.17	2.37	y = 0.035x - 0.78	0.34	1.55
Ondorkhaan 44304	y =-0.036x+ 0.78	0.04	-1.56	y = 0.018x - 0.40	0.06	0.79
Choir 44298	y = 0.031x - 0.66	0.05	1.32	y = 0.024x - 0.51	0.13	1.03
Sainshand 44354	y = 0.042x - 0.90	0.07	1.79	y = 0.024x - 0.54	0.19	1.07
Bayankhongor44287	y = 0.069x - 1.52	0.16	2.89	y = 0.044x - 1.01	0.30	1.84

Table 2.9 Spring and fall minimum temperature changes for 17 stations. The linear regression equation, R-square and temperature change ($_{\Delta}T_{spr.}$ and $_{\Delta}T_{fall}$) for the study period are shown for spring and fall respectively.

Station name & ID	Regression equation	R^2	$_{\Delta}T_{spr.}$	Regression equation	R^2	$_{\Delta}T_{fall}$
Khovd 44218	y = 0.051x - 1.12	0.21	2.24	y = 0.039x - 0.85	0.12	1.70
Moron 44231	y = 0.078x - 1.78	0.38	3.44	y = 0.080x - 1.75	0.37	3.50
Uliastai 44272	y = 0.011x - 0.23	0.01	0.47	y = 0.015x - 0.33	0.02	0.67
Ulaangom 44212	y = 0.049x - 1.10	0.14	2.16	y = 0.039x - 0.85	0.08	1.71
Dalanzadgad 44373	y = 0.037x - 0.82	0.18	1.64	y = 0.041x - 0.89	0.23	1.78
Bulgan 44239	y = 0.028x - 0.61	0.07	1.21	y = 0.009x - 0.20	0.01	0.40
Mandalgovi 44341	y = 0.048x - 1.03	0.23	2.11	y = 0.030x - 0.64	0.10	1.32
Arvaikheer 44288	y = 0.070x - 1.26	0.17	2.46	y = 0.026x - 0.47	0.03	0.91
Choibalsan 44259	y = 0.026x - 0.57	0.04	1.13	y = 0.003x - 0.06	0.00	0.11
Ulaanbaatar 44292	y = 0.093x - 1.67	0.41	3.25	y = 0.025x - 0.45	0.04	0.88
Baruunkharaa 44241	y = 0.071x - 1.56	0.31	3.12	y = 0.037x - 0.82	0.12	1.64
Altai 44277	y = 0.004x - 0.09	0.00	0.08	y = 0.017x - 0.37	0.03	0.73
Tsetserleg 44282	y = 0.018x - 0.39	0.02	0.78	y = 0.025x - 0.56	0.10	1.11
Ondorkhaan 44304	y = 0.002x - 0.04	0.00	0.08	y =-0.017x + 0.38	0.03	-0.76
Choir 44298	y = 0.038x - 0.83	0.12	1.69	y = 0.016x - 0.35	0.03	0.70
Sainshand 44354	y = 0.049x - 1.02	0.26	2.16	y = 0.026x - 0.58	0.09	1.16
Bayankhongor44287	y = 0.041x - 0.95	0.15	1.73	y = 0.034x - 0.79	0.10	1.43

Table 2.10 Seventeen stations' seasonal and annual surface heat (kJ kg^{-1}) change for the last 10 years (1998-2007).

Station name & ID	$_{\Delta}H_e$win.	$_{\Delta}H_e$spr.	$_{\Delta}H_e$sum.	$_{\Delta}H_e$fall	$_{\Delta}H_e$ann.
Khovd, 44218	-4.99	-4.04	-6.81	-1.41	-4.29
Moron, 44231	-1.85	0.04	1.82	2.37	0.64
Uliastai, 44272	-1.46	0.26	-0.57	0.31	-0.15
Ulaangom, 44212	-2.02	-1.66	-3.54	0.30	-1.72
Dalanzadgad, 44373	-2.27	-3.49	-7.47	-0.37	-4.22
Bulgan, 44239	-3.05	-2.17	-0.66	0.50	-1.14
Mandalgovi, 44341	0.70	-3.94	-6.02	-1.37	-2.77
Arvaikheer, 44288	0.43	0.45	-2.46	0.25	-0.21
Choibalsan, 44259	-2.52	-2.35	-2.19	1.35	-1.20
Ulaanbaatar, 44292	-0.75	-2.49	2.12	1.77	0.73
Baruunkharaa, 44241	0.52	0.40	3.16	3.66	2.26
Altai, 44277	-0.75	0.65	-1.84	-1.49	-0.85
Tsetserleg, 44282	-0.85	-1.15	-1.74	0.22	-0.75
Ondorkhaan, 44304	-0.47	-2.55	-2.71	1.03	-0.79
Choir, 44298	1.64	-2.11	-0.17	2.32	0.74
Sainshand, 44354	-2.31	-0.64	4.09	3.92	0.95
Bayankhongor, 44287	0.39	1.34	2.33	1.03	1.19

Table 2.11 Seventeen stations' seasonal and annual mean temperature (^oC) change for the last 10 years (1998-2007).

Station name & ID	$\Delta T_{win.}$	$\Delta T_{spr.}$	$\Delta T_{sum.}$	ΔT_{fall}	$\Delta T_{ann.}$
Khovd, 44218	-4.14	-0.31	-0.61	-0.15	-1.27
Moron, 44231	-1.81	0.05	0.14	1.47	0.00
Uliastai, 44272	-1.43	-0.17	-0.45	0.18	-0.38
Ulaangom, 44212	-1.99	-0.98	-0.36	0.75	-0.62
Dalanzadgad, 44373	-1.49	-0.24	0.29	0.25	-0.26
Bulgan, 44239	-2.32	-0.85	0.41	0.68	-0.36
Mandalgovi, 44341	0.04	-0.91	1.35	1.63	0.72
Arvaikheer, 44288	0.38	0.31	0.48	1.21	0.73
Choibalsan, 44259	-2.20	-1.93	2.30	2.89	0.46
Ulaanbaatar, 44292	-0.93	-1.61	2.55	1.98	0.71
Baruunkharaa, 44241	0.28	-1.61	0.31	2.01	0.54
Altai, 44277	-0.98	0.06	-0.28	-0.41	-0.35
Tsetserleg, 44282	-0.42	0.52	0.35	1.18	0.52
Ondorkhaan, 44304	-0.16	-1.72	1.96	3.25	1.17
Choir, 44298	1.61	-1.50	1.73	2.67	1.41
Sainshand, 44354	1.37	-0.95	1.88	2.68	1.51
Bayankhongor, 44287	0.34	-0.08	-0.05	0.49	0.11

Table 2.12 Seventeen stations' seasonal and annual effective temperature (T_e) change in degrees Celsius for the last 10 years (1998-2007).

Station name & ID	ΔT_ewin.	ΔT_espr.	ΔT_esum.	ΔT_efall	ΔT_eann.
Khovd, 44218	-4.96	-4.02	-0.68	-1.40	-4.27
Moron, 44231	-1.84	0.04	1.81	2.36	0.63
Uliastai, 44272	-1.45	0.25	0.56	-0.31	-0.15
Ulaangom, 44212	-2.01	-1.65	-3.53	0.30	-1.71
Dalanzadgad, 44373	-2.26	-3.47	-7.43	-3.71	-4.20
Bulgan, 44239	-3.03	-2.16	-0.65	0.50	-1.14
Mandalgovi, 44341	-0.70	-3.92	-5.99	-1.36	-2.76
Arvaikheer, 44288	0.43	0.45	-2.45	0.25	-0.21
Choibalsan, 44259	-2.51	-2.34	-2.18	1.35	-1.19
Ulaanbaatar, 44292	0.75	-2.48	2.11	1.77	0.72
Baruunkharaa, 44241	0.52	0.40	3.14	3.64	2.25
Altai, 44277	-0.74	0.65	-1.83	-1.48	-0.85
Tsetserleg, 44282	-0.84	-1.15	-1.73	0.22	-0.75
Ondorkhaan, 44304	-0.46	-2.53	-2.70	1.02	-0.78
Choir, 44298	1.63	-2.10	-0.17	2.31	0.73
Sainshand, 44354	-2.30	-0.63	4.07	3.90	0.94
Bayankhongor, 44287	0.39	1.33	2.31	1.02	1.18

Table 2.13 Temperature indices' trend slopes, standard deviations and p-values.

Stid & Name	Indices	su25	id0	tr20	fd0	txx	txn	tnx	tnn	Dtr
44218 Khovd	Slope	0.44	-0.07	0.05	-0.36	0.05	0.08	0.09	0.15	-0.04
	Stdev	0.17	0.14	0.01	0.08	0.03	0.04	0.02	0.05	0.01
	P-value	0.01	0.61	0.00	0.00	0.13	0.08	0.00	0.00	0.00
44231 Moron	Slope	0.50	-0.04	0.01	-0.63	0.07	0.08	0.07	0.13	-0.04
	Stdev	0.18	0.13	0.00	0.09	0.03	0.05	0.02	0.04	0.01
	P-value	0.01	0.73	0.01	0.00	0.02	0.13	0.00	0.00	0.00
44272 Uliastai	Slope	0.50	-0.09	0.00	-0.16	0.08	0.06	0.07	0.04	0.00
	Stdev	0.15	0.15	0.00	0.08	0.03	0.03	0.02	0.03	0.01
	P-value	0.00	0.56	0.17	0.05	0.01	0.08	0.00	0.22	0.55
44212 Ulaangom	Slope	0.14	-0.19	0.01	-0.12	0.01	0.12	0.04	0.08	0.00
	Stdev	0.18	0.11	0.01	0.08	0.03	0.04	0.02	0.03	0.01
	P-value	0.47	0.10	0.17	0.15	0.76	0.00	0.02	0.03	0.95
44373 Dalanzadgad	Slope	0.28	-0.25	0.23	-0.36	0.03	0.08	0.05	0.10	-0.04
	Stdev	0.12	0.14	0.06	0.08	0.02	0.05	0.02	0.03	0.00
	P-value	0.02	0.08	0.00	0.00	0.13	0.07	0.02	0.00	0.00
44239 Bulgan	Slope	0.33	-0.10	0.00	-0.23	0.06	0.01	0.05	0.03	-0.01
	Stdev	0.16	0.14	0.00	0.09	0.03	0.04	0.02	0.04	0.01
	P-value	0.04	0.48	0.17	0.01	0.02	0.81	0.02	0.48	0.43
44341 Mandalgovi	Slope	0.53	-0.10	0.06	-0.26	0.06	0.03	0.07	0.07	-0.01
	Stdev	0.15	0.14	0.02	0.09	0.02	0.03	0.02	0.03	0.01
	P-value	0.00	0.46	0.01	0.01	0.02	0.45	0.00	0.06	0.05
44288 Arvaikheer	Slope	0.39	-0.11	0.02	-0.52	0.07	0.05	0.11	0.11	-0.04
	Stdev	0.17	0.26	0.01	0.20	0.03	0.06	0.03	0.04	0.01
	P-value	0.02	0.67	0.10	0.02	0.02	0.38	0.00	0.02	0.00
44259 Choibalsan	Slope	0.00	-0.04	0.05	-0.32	0.01	0.04	0.02	0.07	-0.03
	Stdev	0.14	0.14	0.03	0.08	0.03	0.04	0.02	0.03	0.01
	P-value	0.98	0.79	0.05	0.00	0.82	0.33	0.30	0.03	0.00
44292 Ulaanbaatar	Slope	0.53	-0.25	0.04	-0.60	0.08	0.01	0.09	0.02	-0.02
	Stdev	0.20	0.18	0.02	0.08	0.03	0.05	0.03	0.05	0.01
	P-value	0.01	0.16	0.01	0.00	0.02	0.78	0.01	0.68	0.03
44241 Baruunkharaa	Slope	0.55	0.10	0.05	-0.48	0.09	-0.02	0.10	0.11	-0.04
	Stdev	0.15	0.13	0.01	0.06	0.03	0.04	0.03	0.03	0.01
	P-value	0.00	0.46	0.00	0.00	0.00	0.58	0.00	0.00	0.00
44277 Altai	Slope	0.18	-0.07	0.00	-0.13	0.04	0.08	0.04	0.08	0.01
	Stdev	0.06	0.13	0.00	0.07	0.02	0.04	0.02	0.03	0.01
	P-value	0.01	0.59	NA	0.09	0.08	0.04	0.07	0.03	0.27
44282 Tsetserleg	Slope	0.40	-0.09	0.00	-0.39	0.05	0.08	0.03	0.07	-0.01
	Stdev	0.12	0.16	0.00	0.07	0.03	0.04	0.01	0.04	0.01
	P-value	0.00	0.58	NA	0.00	0.08	0.05	0.02	0.08	0.30
44304 Ondorkhaan	Slope	0.39	0.03	0.02	-0.01	0.02	-0.05	0.06	-0.05	0.02
	Stdev	0.14	0.14	0.01	0.09	0.03	0.05	0.02	0.04	0.01
	P-value	0.01	0.83	0.01	0.89	0.48	0.36	0.00	0.24	0.01
44298 Choir	Slope	0.47	0.02	0.06	-0.31	0.06	0.03	0.04	0.03	0.00
	Stdev	0.13	0.14	0.02	0.09	0.02	0.04	0.02	0.04	0.01
	P-value	0.00	0.91	0.00	0.00	0.01	0.55	0.04	0.47	0.74
44354 Sainshand	Slope	-0.08	0.03	0.19	-0.33	0.02	-0.07	0.04	-0.01	-0.03
	Stdev	0.12	0.13	0.06	0.08	0.02	0.03	0.02	0.03	0.01
	P-value	0.52	0.84	0.00	0.00	0.37	0.05	0.08	0.79	0.00
44287 Bayankhongor	Slope	0.40	0.06	0.01	-0.37	0.04	0.04	0.08	0.07	-0.04
	Stdev	0.16	0.18	0.00	0.09	0.03	0.04	0.02	0.04	0.01
	P-value	0.02	0.73	0.04	0.00	0.10	0.30	0.00	0.08	0.00

Table 2.14 Precipitation indices' trend slopes, standard deviations and p-values.

Stid & Name	Indices	rx1day	rx5day	sdii	r10mm	r20mm	Cdd	cwd	gsl
44218 Khovd	Slope	0.03	-0.08	0.00	0.01	-0.01	0.88	0.01	0.20
	Stdev	0.10	0.22	0.02	0.02	0.01	0.70	0.01	0.15
	P-value	0.75	0.70	0.81	0.83	0.38	0.22	0.43	0.18
44231 Moron	Slope	-0.17	-0.35	-0.02	-0.02	-0.01	-0.08	-0.02	0.51
	Stdev	0.16	0.23	0.01	0.04	0.02	0.58	0.02	0.15
	P-value	0.29	0.13	0.06	0.56	0.58	0.89	0.37	0.00
44272 Uliastai	Slope	0.02	0.26	0.00	0.00	0.01	-0.23	0.02	0.05
	Stdev	0.09	0.17	0.01	0.04	0.01	0.32	0.02	0.16
	P-value	0.81	0.13	0.92	0.98	0.38	0.48	0.29	0.74
44212 Ulaangom	Slope	0.12	0.04	-0.02	-0.02	0.00	-0.30	0.03	0.23
	Stdev	0.17	0.22	0.02	0.03	0.01	0.46	0.01	0.12
	P-value	0.50	0.87	0.32	0.60	0.88	0.51	0.07	0.07
44373 Dalanzadgad	Slope	-0.01	0.03	-0.01	-0.04	0.00	-0.41	0.00	0.19
	Stdev	0.14	0.21	0.02	0.03	0.01	0.58	0.02	0.15
	P-value	0.96	0.88	0.46	0.13	0.95	0.48	0.91	0.21
44239 Bulgan	Slope	-0.01	-0.30	0.01	-0.02	0.02	0.13	-0.01	0.07
	Stdev	0.23	0.25	0.01	0.04	0.02	0.40	0.02	0.15
	P-value	0.97	0.23	0.47	0.72	0.37	0.74	0.56	0.67
44341 Mandalgovi	Slope	-0.24	-0.37	-0.04	-0.03	-0.01	-0.94	0.01	0.19
	Stdev	0.18	0.25	0.03	0.02	0.02	0.67	0.01	0.16
	P-value	0.19	0.15	0.14	0.13	0.46	0.17	0.64	0.24
44288 Arvaikheer	Slope	0.26	0.76	0.01	0.04	0.02	0.01	0.05	0.33
	Stdev	0.23	0.31	0.03	0.05	0.02	0.77	0.02	0.33
	P-value	0.26	0.02	0.60	0.37	0.39	0.99	0.03	0.32
44259 Choibalsan	Slope	-0.02	-0.32	-0.01	-0.04	0.00	-0.04	0.02	0.11
	Stdev	0.23	0.30	0.02	0.04	0.02	0.42	0.02	0.17
	P-value	0.92	0.29	0.46	0.26	0.90	0.92	0.22	0.51
44292 Ulaanbaatar	Slope	0.37	0.36	0.00	0.04	0.04	-0.32	0.02	0.40
	Stdev	0.19	0.33	0.02	0.06	0.03	0.51	0.03	0.19
	P-value	0.05	0.29	0.80	0.52	0.20	0.53	0.56	0.04
44241 Baruunkharaa	Slope	-0.61	-0.81	-0.03	-0.08	-0.04	0.70	-0.02	0.41
	Stdev	0.40	0.41	0.02	0.05	0.02	0.30	0.02	0.16
	P-value	0.14	0.06	0.11	0.10	0.05	0.03	0.33	0.02
44277 Altai	Slope	-0.02	0.26	-0.01	-0.03	0.00	-0.06	0.02	0.14
	Stdev	0.13	0.19	0.01	0.03	0.01	0.39	0.02	0.19
	P-value	0.87	0.19	0.46	0.43	0.93	0.88	0.24	0.44
44282 Tsetserleg	Slope	-0.07	-0.05	-0.01	-0.04	-0.03	-0.29	0.03	0.30
	Stdev	0.16	0.24	0.01	0.03	0.02	0.32	0.02	0.20
	P-value	0.65	0.84	0.21	0.23	0.17	0.36	0.19	0.15
44304 Ondorkhaan	Slope	-0.11	-0.24	-0.01	-0.05	-0.01	-0.05	-0.01	0.10
	Stdev	0.18	0.24	0.02	0.04	0.02	0.51	0.02	0.15
	P-value	0.55	0.34	0.72	0.15	0.67	0.93	0.63	0.51
44298 Choir	Slope	-0.12	-0.36	0.00	-0.04	-0.02	-0.12	-0.02	0.38
	Stdev	0.16	0.19	0.02	0.03	0.02	0.57	0.01	0.17
	P-value	0.48	0.07	0.93	0.17	0.40	0.84	0.16	0.03
44354 Sainshand	Slope	0.10	0.13	0.00	-0.01	0.01	0.10	0.02	0.46
	Stdev	0.26	0.27	0.02	0.03	0.01	0.70	0.01	0.16
	P-value	0.71	0.63	0.95	0.66	0.66	0.89	0.11	0.01
44287 Bayankhongor	Slope	0.04	0.03	-0.05	-0.03	-0.02	-3.69	0.04	0.16
	Stdev	0.16	0.28	0.02	0.05	0.02	1.84	0.02	0.16
	P-value	0.80	0.92	0.02	0.55	0.49	0.05	0.09	0.33

Table 2.15 Precipitation change for the last 45 years.

Winter	$\Delta T_{win.}$	$\Delta T_{spr.}$	$\Delta T_{summ.}$	ΔT_{fall}	$\Delta T_{ann.}$
Khovd 44218	0.22	5.36	0.30	-0.35	6.12
Moron 44231	3.23	13.82	-44.71	-3.44	-27.78
Uliastai 44272	1.41	5.05	-5.72	-1.94	5.76
Ulaangom 44212	2.88	1.56	5.16	-1.18	6.73
Dalanzadgad 44373	0.97	-3.00	-5.25	-2.19	-2.27
Bulgan 44239	0.14	0.34	-10.13	-6.35	4.72
Mandalgovi 44341	0.30	2.20	-5.03	-3.07	-2.47
Arvaikheer 44288	0.33	2.97	0.00	-3.32	0.39
Choibalsan 44259	0.00	3.24	-17.43	-1.62	1.47
Ulaanbaatar 44292	2.15	10.02	-6.76	-1.52	0.96
Baruunkharaa 44241	-2.46	-2.27	-28.23	-4.63	-2.13
Altai 44277	0.99	-1.63	3.18	-0.40	0.54
Tsetserleg 44282	1.05	4.37	-17.94	-3.61	6.62
Ondorkhaan 44304	0.80	4.86	-22.94	-3.24	2.27
Choir 44298	1.03	-0.18	-5.72	-0.49	-1.28
Sainshand 44354	0.81	-0.81	-0.88	1.05	-0.26
Bayankhongor 44287	2.43	8.78	2.61	0.89	13.71
Mean	0.96	3.22	-9.38	-2.08	0.77

Table 2.16 Monthly precipitation means, standard deviations and coefficient of variations.

Stid & Name	Precip.	1	2	3	4	5	6	7	8	9	10	11	12	Ann
44218 Khovd	Mean	1.2	1.0	2.5	6.0	11.3	25.3	39.0	26.2	9.7	4.0	1.8	1.7	129.9
	Stdev	1.7	1.5	3.0	5.8	10.6	21.3	24.1	20.0	8.6	6.5	2.8	1.7	41.7
	CV	1.4	1.4	1.2	1.0	0.9	0.8	0.6	0.8	0.9	1.6	1.5	0.9	0.3
44231 Moron	Mean	1.6	1.1	1.1	6.5	17.3	44.1	73.2	61.1	19.1	5.3	2.2	2.4	234.6
	Stdev	1.7	1.5	1.5	7.0	13.2	31.4	31.2	33.8	16.1	5.5	2.1	2.7	64.5
	CV	1.1	1.4	1.3	1.1	0.8	0.7	0.4	0.6	0.8	1.0	0.9	1.1	0.3
44272 Uliastai	Mean	2.3	1.8	4.9	8.9	15.4	35.1	63.6	48.9	24.4	9.3	5.1	3.5	223.5
	Stdev	2.1	1.5	4.7	6.8	10.6	19.8	36.0	23.4	21.0	7.6	3.2	3.1	69.8
	CV	0.9	0.8	1.0	0.8	0.7	0.6	0.6	0.5	0.9	0.8	0.6	0.9	0.3
44212 Ulaangom	Mean	2.1	1.9	3.6	3.8	6.5	25.3	40.8	26.9	12.8	4.2	8.0	5.1	141.0
	Stdev	1.8	1.4	3.3	4.1	6.2	23.3	32.0	17.0	12.3	4.9	4.4	3.9	55.2
	CV	0.9	0.7	0.9	1.1	1.0	0.9	0.8	0.6	1.0	1.2	0.5	0.8	0.4
44373 Dalanzadgad	Mean	1.5	1.5	3.4	4.9	11.6	19.7	33.7	31.7	11.2	4.5	2.4	1.6	124.6
	Stdev	0.4	1.1	2.4	5.9	10.0	16.8	21.1	18.7	9.3	6.3	1.4	1.8	44.7
	CV	0.3	0.7	0.7	1.2	0.9	0.9	0.6	0.6	0.8	1.4	0.6	1.2	0.4
44239 Bulgan	Mean	1.7	1.8	3.7	10.3	23.1	57.3	111.2	78.7	31.2	10.4	3.9	2.1	335.2
	Stdev	1.8	1.9	3.1	7.7	25.4	27.4	45.2	36.6	20.2	8.7	3.1	1.7	76.8
	CV	1.0	1.0	0.8	0.7	1.1	0.5	0.4	0.5	0.6	0.8	0.8	0.8	0.2
44341 Mandalgovi	Mean	0.6	1.3	2.0	3.9	11.7	23.8	41.7	47.2	13.5	4.7	2.3	1.4	153.9
	Stdev	0.9	1.7	2.0	4.9	11.0	18.2	22.4	35.2	15.7	6.3	2.5	1.5	53.9
	CV	1.5	1.3	1.0	1.3	0.9	0.8	0.5	0.7	1.2	1.3	1.1	1.1	0.3
44288 Arvaikheer	Mean	0.8	1.4	2.9	4.3	15.9	35.5	77.4	62.0	20.0	6.3	2.4	1.2	229.9
	Stdev	1.0	2.0	3.2	4.3	12.9	22.8	42.8	30.2	12.8	8.4	2.7	1.3	58.1
	CV	1.2	1.4	1.1	1.0	0.8	0.6	0.6	0.5	0.6	1.3	1.1	1.1	0.3
44259 Choibalsan	Mean	1.9	2.0	3.5	6.4	15.3	36.2	74.4	57.2	28.2	7.7	3.2	2.9	238.8
	Stdev	1.9	2.5	3.4	6.9	13.9	24.2	44.0	39.2	19.5	7.3	3.4	2.7	79.8
	CV	1.0	1.3	1.0	1.1	0.9	0.7	0.6	0.7	0.7	1.0	1.1	0.9	0.3
44292 Ulaanbaatar	Mean	2.0	2.0	3.2	8.6	13.9	49.3	65.4	76.2	32.2	8.3	4.8	3.3	269.1
	Stdev	1.7	2.1	3.0	16.3	14.0	28.4	29.7	38.3	20.8	5.6	5.0	2.6	66.4
	CV	0.9	1.1	0.9	1.9	1.0	0.6	0.5	0.5	0.6	0.7	1.1	0.8	0.2
44241 Baruunkharaa	Mean	3.6	2.8	3.8	9.0	24.4	50.3	75.8	71.2	35.8	11.4	6.8	4.7	299.6
	Stdev	3.5	3.3	5.9	7.3	40.5	28.2	35.8	35.1	20.6	10.3	6.6	3.5	89.9
	CV	1.0	1.2	1.6	0.8	1.7	0.6	0.5	0.5	0.6	0.9	1.0	0.7	0.3
44277 Altai	Mean	1.2	2.0	5.7	10.4	13.5	29.0	49.5	41.3	15.9	7.8	3.3	2.0	181.5
	Stdev	1.4	2.4	5.0	6.6	11.4	16.5	30.9	25.6	13.7	6.4	2.5	1.8	52.4
	CV	1.2	1.2	0.9	0.6	0.8	0.6	0.6	0.6	0.9	0.8	0.8	0.9	0.3
44282 Tsetserleg	Mean	2.3	3.0	7.0	15.9	32.7	64.2	88.7	81.5	25.7	12.7	6.1	2.9	342.7
	Stdev	2.0	3.1	4.3	9.3	20.2	28.2	34.4	50.5	13.3	9.9	3.5	2.3	72.4
	CV	0.9	1.0	0.6	0.6	0.6	0.4	0.4	0.6	0.5	0.8	0.6	0.8	0.2
44304 Ondorkhaan	Mean	1.6	2.5	2.8	7.5	15.1	44.7	72.0	65.4	23.9	7.6	3.3	2.7	247.6
	Stdev	1.8	2.4	2.8	7.8	10.3	29.0	38.0	41.8	15.0	7.2	3.1	2.4	60.1
	CV	1.1	1.0	1.0	1.0	0.7	0.6	0.5	0.6	0.6	0.9	0.9	0.9	0.2
44298 Choir	Mean	0.9	1.6	1.6	4.1	10.6	30.5	64.3	48.8	18.8	5.0	3.7	2.0	191.7
	Stdev	1.2	1.9	1.8	4.3	8.7	27.3	52.2	34.9	16.0	5.7	5.4	1.9	64.2
	CV	1.3	1.2	1.2	1.1	0.8	0.9	0.8	0.7	0.9	1.2	1.5	0.9	0.3
44354 Sainshand	Mean	0.7	1.1	1.6	3.1	7.9	16.4	32.8	31.3	10.6	3.9	2.4	1.6	112.8
	Stdev	1.2	1.9	2.2	5.7	8.8	15.0	24.2	22.7	10.6	4.4	3.0	2.1	45.6
	CV	1.7	1.6	1.3	1.8	1.1	0.9	0.7	0.7	1.0	1.1	1.3	1.3	0.4
44287 Bayankhongor	Mean	2.0	2.9	4.4	7.9	15.5	30.7	53.4	44.7	17.3	6.9	2.1	2.3	187.8
	Stdev	2.1	3.4	4.8	9.2	17.6	24.2	35.0	34.5	13.4	8.5	2.8	2.6	79.0
	CV	1.1	1.1	1.1	1.2	1.1	0.8	0.7	0.8	0.8	1.2	1.3	1.1	0.4

Table 2.17 Comparison of spring temperature trends: surface and troposphere levels at 700mb and 500mb.

	Spring	Regression	R^2	ΔT/per.	Sur.	E700	N700	E500	N500
Khovd 44218	Surface	y =0.0421x-0.9478	0.13	1.8524	1.00	0.58	0.35	0.64	0.48
	ECMWF.700mb	y =0.099x-0.2125	0.01	4.158	0.64	1.00	0.89	0.95	0.84
	NCEP.700mb	y=-0.0085x+0.20	0.01	-0.3825	0.48	0.89	1.00	0.81	0.90
	ECMWF.500mb	y=-0.0016x+0.04	0.00	-0.0672	0.58	0.95	0.81	1.00	0.87
	NCEP.500mb	y=-0.0304x+0.70	0.11	-1.368	0.35	0.84	0.90	0.87	1.00
Ulaangom 44212	Surface	y=0.0559x-1.259	0.21	2.4596	1.00	0.61	0.55	0.57	0.45
	ECMWF.700mb	y=0.0225x-0.484	0.04	0.945	0.57	1.00	0.91	0.96	0.86
	NCEP.700mb	y=-0.0022x+0.05	0.00	-0.099	0.45	0.91	1.00	0.89	0.94
	ECMWF.500mb	y=0.0112x-0.241	0.01	0.4704	0.61	0.96	0.89	1.00	0.92
	NCEP.500mb	y=0.0153x-0.352	0.03	0.6885	0.55	0.86	0.94	0.92	1.00
Uliastai 44272	Surface	y=0.0193x-0.434	0.03	0.8492	1.00	0.76	0.62	0.73	0.58
	ECMWF.700mb	y=0.0173x-0.372	0.02	0.7266	0.76	1.00	0.67	0.96	0.70
	NCEP.700mb	y=-0.0238x+0.55	0.05	-1.071	0.62	0.67	1.00	0.68	0.89
	ECMWF.500mb	y=0.0063x-0.134	0.00	0.2646	0.73	0.96	0.68	1.00	0.79
	NCEP.500mb	y=-0.0372x+0.86	0.15	-1.674	0.58	0.70	0.89	0.79	1.00
Moron 44231	Surface	y=0.572x-1.2872	0.25	2.5168	1.00	0.84	0.72	0.79	0.66
	ECMWF.700mb	y=0.0254x-0.547	0.05	1.0668	0.84	1.00	0.81	0.95	0.81
	NCEP.700mb	y=-0.0082x+0.19	0.01	-0.369	0.72	0.81	1.00	0.76	0.90
	ECMWF.500mb	y=0.0187x-0.402	0.03	0.7854	0.79	0.95	0.76	1.00	0.86
	NCEP.500mb	y=-0.0149x+0.34	0.03	-0.6705	0.66	0.81	0.90	0.86	1.00
Bulgan 44239	Surface	y=0.0299x-0.674	0.09	1.3156	1.00	0.64	0.71	0.60	0.60
	ECMWF.700mb	y=0.017x-0.3661	0.03	0.714	0.64	1.00	0.68	0.93	0.72
	NCEP.700mb	y=-0.0137x+0.32	0.02	-0.6165	0.71	0.68	1.00	0.67	0.86
	ECMWF.500mb	y=0.0068x-0.15	0.00	0.2856	0.60	0.93	0.67	1.00	0.84
	NCEP.500mb	y=-0.0227x+0.53	0.06	-1.0215	0.60	0.72	0.86	0.84	1.00
Arvaikheer 44288	Surface	y=0.0579x-1.535	0.20	2.0844	1.00	0.83	0.65	0.73	0.58
	ECMWF.700mb	y=0.0084x-0.181	0.01	0.2856	0.83	1.00	0.57	0.90	0.62
	NCEP.700mb	y=-0.0313x+0.72	0.10	-1.1581	0.65	0.57	1.00	0.65	0.89
	ECMWF.500mb	y=-0.009x+0.194	0.01	-0.306	0.73	0.90	0.65	1.00	0.83
	NCEP.500mb	y=-0.0415x+0.95	0.18	-1.5355	0.58	0.62	0.89	0.83	1.00
Dalanzadgad 44373	Surface	y=0.0272x-0.612	0.09	1.1968	1.00	0.79	0.58	0.61	0.44
	ECMWF.700mb	y=-0.0047x+0.10	0.00	-0.1974	0.79	1.00	0.80	0.91	0.75
	NCEP.700mb	y=-0.0377x+0.87	0.17	-1.6965	0.58	0.80	1.00	0.84	0.91
	ECMWF.500mb	y=-0.0224x+0.48	0.05	-0.9408	0.61	0.91	0.84	1.00	0.92
	NCEP.500mb	y=-0.0436x+1.00	0.21	-1.962	0.44	0.75	0.91	0.92	1.00
Mandalgovi 44341	Surface	y=0.0375x-0.844	0.14	1.65	1.00	0.73	0.62	0.59	0.42
	ECMWF.700mb	y=0.0087x-0.187	0.01	0.3654	0.73	1.00	0.67	0.89	0.64
	NCEP.700mb	y=-0.0271x+0.62	0.08	-1.2195	0.62	0.67	1.00	0.75	0.86
	ECMWF.500mb	y=-0.0088x+0.19	0.01	-0.3696	0.59	0.89	0.75	1.00	0.87
	NCEP.500mb	y=-0.0373x+0.86	0.14	-1.6785	0.42	0.64	0.86	0.87	1.00
Choibalsan 44259	Surface	y=0.051x-1.1486	0.18	2.244	1.00	0.79	0.77	0.68	0.61
	ECMWF.700mb	y=0.0192x-0.412	0.03	0.8064	0.79	1.00	0.96	0.93	0.84
	NCEP.700mb	y=0.0066x-0.152	0.00	0.297	0.77	0.96	1.00	0.93	0.92
	ECMWF.500mb	y=0.0053x-0.113	0.00	0.2226	0.68	0.93	0.93	1.00	0.95
	NCEP.500mb	y=-0.0072x+0.17	0.01	-0.324	0.61	0.84	0.92	0.95	1.00

Table 2.18 Comparison of summer temperature trends: surface and troposphere levels at 700mb and 500mb.

	Summer	Regression	R^2	ΔT/per.	Sur.	E700	N700	E500	N500
Khovd	Surface	y=0.0334x-0.752	0.19	1.4696	1.00	0.74	0.56	0.67	0.37
	ECMWF.700mb	y=0.0113x-0.243	0.02	0.4746	0.74	1.00	0.83	0.72	0.64
	NCEP.700mb	y=-0.0055x+0.13	0.01	-0.2475	0.56	0.83	1.00	0.62	0.81
	ECMWF.500mb	y=0.0232x-0.498	0.17	0.9744	0.67	0.72	0.62	1.00	0.73
	NCEP.500mb	y=-0.0116x+0.27	0.05	-0.522	0.37	0.64	0.81	0.73	1.00
Ulaangom	Surface	y=0.0198x-0.446	0.07	0.8712	1.00	0.89	0.81	0.66	0.59
	ECMWF.700mb	y=0.0188x-0.404	0.07	0.7896	0.89	1.00	0.86	0.79	0.70
	NCEP.700mb	y=0.0028x-0.064	0.00	0.126	0.81	0.86	1.00	0.69	0.83
	ECMWF.500mb	y=0.0277x-0.595	0.22	1.1634	0.66	0.79	0.69	1.00	0.80
	NCEP.500mb	y=0.0008x-0.019	0.00	0.036	0.59	0.70	0.83	0.80	1.00
Uliastai	Surface	y=0.0328x-0.738	0.13	1.4432	1.00	0.69	0.51	0.48	0.26
	ECMWF.700mb	y=0.0263x-0.565	0.08	1.1046	0.69	1.00	0.59	0.64	0.36
	NCEP.700mb	y=-0.0192x+0.44	0.05	-0.864	0.51	0.59	1.00	0.30	0.83
	ECMWF.500mb	y=0.02x-0.4296	0.16	0.84	0.48	0.64	0.30	1.00	0.42
	NCEP.500mb	y=-0.027x+0.621	0.16	-1.215	0.26	0.36	0.83	0.42	1.00
Moron	Surface	y=0.483x-1.0862	0.29	2.1252	1.00	0.73	0.58	0.52	0.35
	ECMWF.700mb	y=0.0176x-0.377	0.06	0.7392	0.73	1.00	0.66	0.77	0.45
	NCEP.700mb	y=-0.0144x+0.33	0.03	-0.648	0.58	0.66	1.00	0.40	0.82
	ECMWF.500mb	y=0.0201x-0.432	0.14	0.8442	0.52	0.77	0.40	1.00	0.52
	NCEP.500mb	y=-0.016x+0.368	0.07	-0.72	0.35	0.45	0.82	0.52	1.00
Bulgan	Surface	y=0.0293x-0.660	0.12	1.2892	1.00	0.59	0.53	0.52	0.38
	ECMWF.700mb	y=0.0243x-0.522	0.09	1.0206	0.59	1.00	0.44	0.78	0.27
	NCEP.700mb	y=-0.0265x+0.61	0.10	-1.1925	0.53	0.44	1.00	0.42	0.84
	ECMWF.500mb	y=0.0106x-0.227	0.05	0.4452	0.52	0.78	0.42	1.00	0.49
	NCEP.500mb	y=-0.0235x+0.54	0.14	-1.0575	0.38	0.27	0.84	0.49	1.00
Arvaikheer	Surface	y=0.0569x-1.509	0.24	2.0484	1.00	0.63	0.54	0.64	0.47
	ECMWF.700mb	y=0.0212x-0.455	0.07	0.7208	0.63	1.00	0.40	0.74	0.33
	NCEP.700mb	y=-0.0373x+0.86	0.16	-1.3801	0.54	0.40	1.00	0.56	0.88
	ECMWF.500mb	y=0.0048x-0.103	0.01	0.1632	0.64	0.74	0.56	1.00	0.70
	NCEP.500mb	y=-0.0358x+0.82	0.24	-1.5355	0.47	0.33	0.88	0.70	1.00
Dalanzadga	Surface	y=0.0379x-0.852	0.22	1.6676	1.00	0.49	0.22	0.42	0.16
	ECMWF.700mb	y=-0.0034x+0.07	0.00	-0.1428	0.49	1.00	0.60	0.55	0.50
	NCEP.700mb	y=-0.0463x+1.06	0.34	-2.0835	0.22	0.60	1.00	0.62	0.88
	ECMWF.500mb	y=-0.0034x+0.07	0.00	-0.1428	0.42	0.55	0.62	1.00	0.82
	NCEP.500mb	y=-0.0333x+0.77	0.22	-1.4985	0.16	0.50	0.88	0.82	1.00
Mandalgovi	Surface	y=0.0425x-0.957	0.26	1.87	1.00	0.52	0.18	0.55	0.12
	ECMWF.700mb	y=0.0097x-0.208	0.02	0.4074	0.52	1.00	0.29	0.62	0.21
	NCEP.700mb	y=-0.0458x+1.05	0.21	-2.061	0.18	0.29	1.00	0.57	0.90
	ECMWF.500mb	y=0.0029x-0.062	0.00	0.1218	0.55	0.62	0.57	1.00	0.69
	NCEP.500mb	y=-0.0287x+0.66	0.19	-1.2915	0.12	0.21	0.90	0.69	1.00
Choibalsan	Surface	y=0.0354x-0.797	0.18	1.5576	1.00	0.54	0.33	0.55	0.28
	ECMWF.700mb	y=-0.0027x+0.06	0.00	-0.1134	0.54	1.00	0.79	0.82	0.69
	NCEP.700mb	y=-0.013x+0.299	0.03	-0.585	0.33	0.79	1.00	0.79	0.87
	ECMWF.500mb	y=-0.0002x+0.01	0.00	-0.0084	0.55	0.82	0.79	1.00	0.90
	NCEP.500mb	y=-0.0119x+0.27	0.04	-0.5355	0.28	0.69	0.87	0.90	1.00

Table 2.19 Comparison of fall temperature trends: surface and troposphere levels at 700mb and 500mb.

	Fall	Regression	R^2	ΔT/per.	Sur.	E700	N700	E500	N500
Khovd	Surface	y=0.0304x-0.684	0.09	1.3376	1.00	0.59	0.51	0.57	0.48
	ECMWF.700mb	y=0.0324x-0.68	0.09	1.148	0.59	1.00	0.91	0.95	0.86
	NCEP.700mb	y=0.01x-0.2259	0.01	-0.0836	0.51	0.91	1.00	0.84	0.92
	ECMWF.500mb	y=0.028x-0.5878	0.10	1.3284	0.57	0.95	0.84	1.00	0.89
	NCEP.500mb	y=-0.0019x+0.04	0.00	0.44	0.48	0.86	0.92	0.89	1.00
Ulaangom	Surface	y=0.0426x-0.960	0.13	1.8744	1.00	0.85	0.80	0.85	0.80
	ECMWF.700mb	y=0.0314x-0.66	0.08	1.3776	0.85	1.00	0.94	0.96	0.91
	NCEP.700mb	y=0.0108x-0.244	0.01	0.858	0.80	0.94	1.00	0.89	0.95
	ECMWF.500mb	y=0.0336x-0.705	0.12	1.2874	0.85	0.96	0.89	1.00	0.92
	NCEP.500mb	y=0.0195x-0.448	0.04	0.4752	0.80	0.91	0.95	0.92	1.00
Uliastai	Surface	y=0.0232x-0.523	0.05	1.0208	1.00	0.60	0.51	0.59	0.51
	ECMWF.700mb	y=0.0356x-0.748	0.11	1.4022	0.60	1.00	0.68	0.96	0.73
	NCEP.700mb	y=-0.0122x+0.27	0.02	-0.5368	0.51	0.68	1.00	0.65	0.90
	ECMWF.500mb	y=0.0342x-0.717	0.13	1.4596	0.59	0.96	0.65	1.00	0.76
	NCEP.500mb	y=-0.0122x+0.27	0.02	-0.5368	0.51	0.73	0.90	0.76	1.00
Moron	Surface	y=0.0548x-1.233	0.24	2.4112	1.00	0.60	0.45	0.66	0.60
	ECMWF.700mb	y=0.0284x-0.596	0.06	1.4596	0.60	1.00	0.76	0.97	0.83
	NCEP.700mb	y=-0.0188x+0.42	0.04	-0.264	0.45	0.76	1.00	0.69	0.93
	ECMWF.500mb	y=0.0356x-0.747	0.12	1.1644	0.66	0.97	0.69	1.00	0.83
	NCEP.500mb	y=-0.006x+0.135	0.01	-0.8272	0.60	0.83	0.93	0.83	1.00
Bulgan	Surface	y=0.0169x-0.381	0.04	0.7436	1.00	0.47	0.42	0.49	0.50
	ECMWF.700mb	y=0.0316x-0.663	0.09	1.3079	0.47	1.00	0.62	0.95	0.76
	NCEP.700mb	y=-0.026x+0.585	0.07	-0.4796	0.42	0.62	1.00	0.56	0.92
	ECMWF.500mb	y=0.0319x-0.670	0.11	1.2956	0.49	0.95	0.56	1.00	0.77
	NCEP.500mb	y=-0.0109x+0.25	0.02	-1.144	0.50	0.76	0.92	0.77	1.00
Arvaikheer	Surface	y=0.0256x-0.678	0.05	0.9216	1.00	0.50	0.49	0.44	0.45
	ECMWF.700mb	y=0.029x-0.6082	0.09	0.693	0.50	1.00	0.58	0.93	0.72
	NCEP.700mb	y=-0.0297x+0.67	0.10	-0.6192	0.49	0.58	1.00	0.56	0.90
	ECMWF.500mb	y=0.021x-0.4418	0.06	0.957	0.44	0.93	0.56	1.00	0.79
	NCEP.500mb	y=-0.0172x+0.39	0.05	-1.0692	0.45	0.72	0.90	0.79	1.00
Dalanzadga	Surface	y=0.0294x-0.661	0.13	1.2936	1.00	0.62	0.43	0.47	0.35
	ECMWF.700mb	y=0.0171x-0.359	0.04	0.3034	0.62	1.00	0.79	0.91	0.78
	NCEP.700mb	y=-0.0166x+0.37	0.04	-0.7348	0.43	0.79	1.00	0.79	0.90
	ECMWF.500mb	y=0.0074x-0.156	0.01	0.7011	0.47	0.91	0.79	1.00	0.91
	NCEP.500mb	y=-0.0167x+0.38	0.05	-0.7304	0.35	0.78	0.90	0.91	1.00
Mandalgovi	Surface	y=0.0273x-0.614	0.08	1.2012	1.00	0.48	0.39	0.41	0.35
	ECMWF.700mb	y=0.0268x-0.562	0.07	0.7831	0.48	1.00	0.59	0.91	0.69
	NCEP.700mb	y=-0.0268x+0.60	0.10	-0.6468	0.39	0.59	1.00	0.60	0.88
	ECMWF.500mb	y=0.0191x-0.401	0.05	1.066	0.41	0.91	0.60	1.00	0.82
	NCEP.500mb	y=-0.0147x+0.33	0.04	-1.144	0.35	0.69	0.88	0.82	1.00
Choibalsan	Surface	y=0.0248x-0.558	0.07	1.0912	1.00	0.60	0.57	0.57	0.54
	ECMWF.700mb	y=0.015x-0.3159	0.03	0.6478	0.60	1.00	0.96	0.92	0.89
	NCEP.700mb	y=-0.0001x+0.01	0.00	-0.0528	0.57	0.96	1.00	0.91	0.94
	ECMWF.500mb	y=0.0158x-0.331	0.05	0.615	0.57	0.92	0.91	1.00	0.95
	NCEP.500mb	y=-0.0012x+0.03	0.00	-0.0044	0.54	0.89	0.94	0.95	1.00

Table 2.20 Comparison of winter temperature trends: surface and troposphere levels at 700mb and 500mb.

	Winter	Regression	R^2	ΔT/per.	Sur.	E700	N700	E500	N500
Khovd	Surface	y=0.1095x-2.409	0.17	4.7085	1.00	0.36	0.28	0.41	0.36
	ECMWF.700mb	y=0.0438x-0.920	0.09	1.7958	0.36	1.00	0.95	0.97	0.95
	NCEP.700mb	y=0.0391x-0.879	0.08	1.7204	0.28	0.95	1.00	0.92	0.94
	ECMWF.500mb	y=0.0347x-0.729	0.09	1.4227	0.41	0.97	0.92	1.00	0.96
	NCEP.500mb	y=0.0085x-0.191	0.01	0.374	0.36	0.95	0.94	0.96	1.00
Ulaangom	Surface	y=0.0948x-2.087	0.30	4.0764	1.00	0.50	0.40	0.50	0.43
	ECMWF.700mb	y=0.0361x-0.758	0.05	1.4801	0.50	1.00	0.97	0.98	0.97
	NCEP.700mb	y=0.025x-0.5632	0.03	1.1	0.40	0.97	1.00	0.95	0.97
	ECMWF.500mb	y=0.0294x-0.618	0.05	1.2054	0.50	0.98	0.95	1.00	0.98
	NCEP.500mb	y=0.0083x-0.188	0.01	0.3652	0.43	0.97	0.97	0.98	1.00
Uliastai	Surface	y=0.0695x-1.528	0.20	2.9885	1.00	0.73	0.67	0.71	0.72
	ECMWF.700mb	y=0.051x-1.0706	0.13	2.091	0.73	1.00	0.90	0.98	0.94
	NCEP.700mb	y=0.0293x-0.659	0.05	1.2892	0.67	0.90	1.00	0.83	0.93
	ECMWF.500mb	y=0.0431x-0.904	0.13	1.7671	0.71	0.98	0.83	1.00	0.91
	NCEP.500mb	y=0.0097x-0.218	0.01	0.4268	0.72	0.94	0.93	0.91	1.00
Moron	Surface	y=0.0727x-1.599	0.13	3.1261	1.00	0.44	0.33	0.50	0.40
	ECMWF.700mb	y=0.0515x-1.081	0.11	2.1115	0.44	1.00	0.93	0.97	0.96
	NCEP.700mb	y=0.0285x-0.640	0.04	1.254	0.33	0.93	1.00	0.85	0.96
	ECMWF.500mb	y=0.0428x-0.899	0.10	1.7548	0.50	0.97	0.85	1.00	0.93
	NCEP.500mb	y=0.0184x-0.414	0.02	0.8096	0.40	0.96	0.96	0.93	1.00
Bulgan	Surface	y=0.0247x-0.94	0.09	1.0621	1.00	0.65	0.59	0.61	0.60
	ECMWF.700mb	y=0.0627x-1.316	0.18	2.5707	0.65	1.00	0.87	0.98	0.93
	NCEP.700mb	y=0.0304x-0.638	0.05	1.3376	0.59	0.87	1.00	0.78	0.94
	ECMWF.500mb	y=0.0491x-1.031	0.16	2.0131	0.61	0.98	0.78	1.00	0.90
	NCEP.500mb	y=0.0179x-0.402	0.03	0.7876	0.60	0.93	0.94	0.90	1.00
Arvaikheer	Surface	y=0.0642x-1.670	0.20	2.247	1.00	0.84	0.72	0.77	0.72
	ECMWF.700mb	y=0.0635x-1.333	0.22	2.0955	0.84	1.00	0.76	0.97	0.87
	NCEP.700mb	y=0.0252x-0.567	0.04	0.9072	0.72	0.76	1.00	0.72	0.94
	ECMWF.500mb	y=0.0414x-0.870	0.16	1.3662	0.77	0.97	0.72	1.00	0.87
	NCEP.500mb	y=0.0105x-0.236	0.01	0.3675	0.72	0.87	0.94	0.87	1.00
Dalanzadga	Surface	y=0.0991x-2.181	0.31	4.2613	1.00	0.77	0.65	0.68	0.61
	ECMWF.700mb	y=0.0581x-1.220	0.21	2.3821	0.77	1.00	0.83	0.94	0.87
	NCEP.700mb	y=0.0286x-0.644	0.08	1.2584	0.65	0.83	1.00	0.74	0.90
	ECMWF.500mb	y=0.0273x-0.574	0.09	1.1193	0.68	0.94	0.74	1.00	0.90
	NCEP.500mb	y=0.0073x-0.164	0.01	0.3212	0.61	0.87	0.90	0.90	1.00
Mandalgov	Surface	y=0.059x-1.2989	0.16	2.537	1.00	0.70	0.63	0.65	0.64
	ECMWF.700mb	y=0.0687x-1.443	0.23	2.8167	0.70	1.00	0.78	0.97	0.88
	NCEP.700mb	y=0.0292x-0.656	0.06	1.2848	0.63	0.78	1.00	0.72	0.91
	ECMWF.500mb	y=0.042x-0.8811	0.15	1.722	0.65	0.97	0.72	1.00	0.89
	NCEP.500mb	y=0.0135x-0.304	0.02	0.594	0.64	0.88	0.91	0.89	1.00
Choibalsan	Surface	y=0.0509x-1.120	0.10	2.1887	1.00	0.57	0.58	0.50	0.54
	ECMWF.700mb	y=0.0625x-1.312	0.20	2.5625	0.57	1.00	0.97	0.96	0.93
	NCEP.700mb	y=0.0558x-1.255	0.17	2.4552	0.58	0.97	1.00	0.92	0.96
	ECMWF.500mb	y=0.037x-0.777	0.11	1.517	0.50	0.96	0.92	1.00	0.95
	NCEP.500mb	y=0.0266x-0.598	0.06	1.1704	0.54	0.93	0.96	0.95	1.00

Table 2.21 Comparison of annual temperature trends: surface and troposphere levels at 700mb and 500mb.

	Annual	Regression	R^2	ΔT/per.	Sur.	E700	N700	E500	N500
Khovd	Surface	y=0.0554x-1.247	0.36	2.4376	1.00	0.42	0.38	0.51	0.27
	ECMWF.700mb	y=0.0291x-0.625	0.15	1.2222	0.42	1.00	0.81	0.92	0.67
	NCEP.700mb	y=0.0133x-0.305	0.05	0.5985	0.38	0.81	1.00	0.77	0.83
	ECMWF.500mb	y=0.0234x-0.504	0.16	0.9828	0.51	0.92	0.77	1.00	0.76
	NCEP.500mb	y=-0.0053x+0.12	0.01	-0.2385	0.27	0.67	0.83	0.76	1.00
Ulaangom	Surface	y=0.053x-1.1931	0.37	2.332	1.00	0.66	0.55	0.72	0.55
	ECMWF.700mb	y=0.032x-0.6881	0.17	1.344	0.66	1.00	0.85	0.95	0.78
	NCEP.700mb	y=0.0131x-0.301	0.04	0.5895	0.55	0.85	1.00	0.83	0.92
	ECMWF.500mb	y=0.0282x-0.606	0.20	1.1844	0.72	0.95	0.83	1.00	0.84
	NCEP.500mb	y=0.0026x-0.061	0.00	-0.117	0.55	0.78	0.92	0.84	1.00
Uliastai	Surface	y=0.0361x-0.812	0.28	1.5884	1.00	0.50	0.40	0.53	0.35
	ECMWF.700mb	y=0.0383x-0.824	0.21	1.6086	0.50	1.00	0.45	0.91	0.42
	NCEP.700mb	y=-0.0022x+0.05	0.00	-0.099	0.40	0.45	1.00	0.41	0.83
	ECMWF.500mb	y=0.0284x-0.610	0.20	1.1928	0.53	0.91	0.41	1.00	0.53
	NCEP.500mb	y=-0.0131x+0.30	0.06	-0.5895	0.35	0.42	0.83	0.53	1.00
Moron	Surface	y=0.0565x-1.271	0.46	2.486	1.00	0.52	0.27	0.56	0.33
	ECMWF.700mb	y=0.0364x-0.783	0.20	1.5288	0.52	1.00	0.56	0.94	0.60
	NCEP.700mb	y=0.0011x-0.03	0.00	0.0495	0.27	0.56	1.00	0.48	0.88
	ECMWF.500mb	y=0.0324x-0.698	0.21	1.3608	0.56	0.94	0.48	1.00	0.65
	NCEP.500mb	y=-0.0013x+0.03	0.00	-0.0585	0.33	0.60	0.88	0.65	1.00
Bulgan	Surface	y=0.0282x-0.635	0.24	1.2408	1.00	0.45	0.50	0.47	0.54
	ECMWF.700mb	y=0.0391x-0.840	0.23	1.6422	0.45	1.00	0.35	0.93	0.45
	NCEP.700mb	y=-0.0041x+0.09	0.00	-0.1845	0.50	0.35	1.00	0.32	0.83
	ECMWF.500mb	y=0.0276x-0.594	0.18	1.1592	0.47	0.93	0.32	1.00	0.58
	NCEP.500mb	y=-0.0062x+0.14	0.01	-0.279	0.54	0.45	0.83	0.58	1.00
Arvaikheer	Surface	y=0.0555x-1.471	0.47	1.998	1.00	0.64	0.38	0.62	0.41
	ECMWF.700mb	y=0.0354x-0.761	0.21	1.2036	0.64	1.00	0.19	0.91	0.32
	NCEP.700mb	y=-0.0127x+0.30	0.04	-0.4699	0.38	0.19	1.00	0.28	0.87
	ECMWF.500mb	y=0.0176x-0.378	0.10	0.5984	0.62	0.91	0.28	1.00	0.54
	NCEP.500mb	y=-0.0173x+0.40	0.10	-0.6401	0.41	0.32	0.87	0.54	1.00
Dalanzadga	Surface	y=0.0467x-1.050	0.45	2.0548	1.00	0.53	0.16	0.37	0.05
	ECMWF.700mb	y=0.0214x-0.461	0.11	0.8988	0.53	1.00	0.46	0.89	0.45
	NCEP.700mb	y=-0.0123x+0.28	0.05	-0.5535	0.16	0.46	1.00	0.63	0.90
	ECMWF.500mb	y=0.0058x-0.125	0.13	0.2436	0.37	0.89	0.63	1.00	0.72
	NCEP.500mb	y=-0.0175x+0.40	0.12	-0.7875	0.05	0.45	0.90	0.72	1.00
Mandalgovi	Surface	y=0.0402x-0.904	0.38	1.7688	1.00	0.53	0.28	0.47	0.21
	ECMWF.700mb	y=0.0331x-0.712	0.20	1.3902	0.53	1.00	0.21	0.89	0.31
	NCEP.700mb	y=-0.0121x+0.28	0.04	-0.5445	0.28	0.21	1.00	0.38	0.86
	ECMWF.500mb	y=0.0171x-0.368	0.09	0.7182	0.47	0.89	0.38	1.00	0.60
	NCEP.500mb	y=-0.0129x+0.30	0.06	-0.5805	0.21	0.31	0.86	0.60	1.00
Choibalsan 44259	Surface	y=0.0401x-0.902	0.32	1.7644	1.00	0.61	0.70	0.50	0.54
	ECMWF.700mb	y=0.029x-0.6225	0.17	1.218	0.61	1.00	0.83	0.93	0.72
	NCEP.700mb	y=0.0176x-0.405	0.08	0.792	0.70	0.83	1.00	0.84	0.93
	ECMWF.500mb	y=0.0194x-0.417	0.09	0.8148	0.50	0.93	0.84	1.00	0.84
	NCEP.500mb	y=0.0059x-0.137	0.01	-0.2655	0.54	0.72	0.93	0.84	1.00
	NCEP.500mb	y=0.0059x-0.137	0.01	-0.2655	0.54	0.72	0.93	0.84	1.00

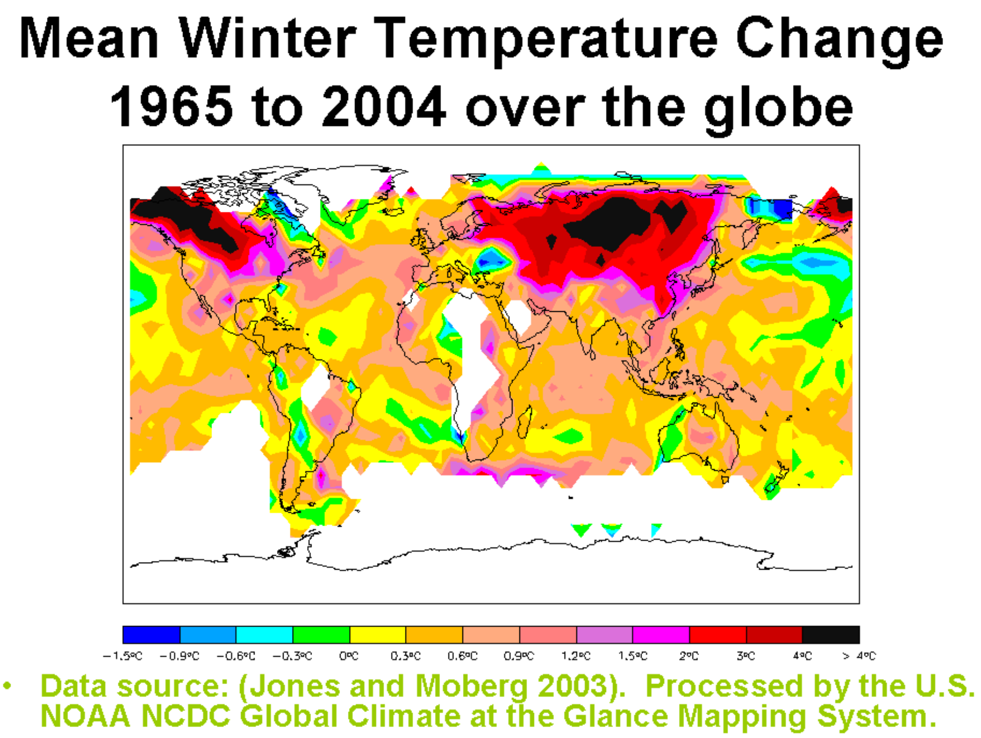


Figure 2.1 Mean winter temperature change 1965-2004 over the globe. Data source: (Jones and Moberg 2003).

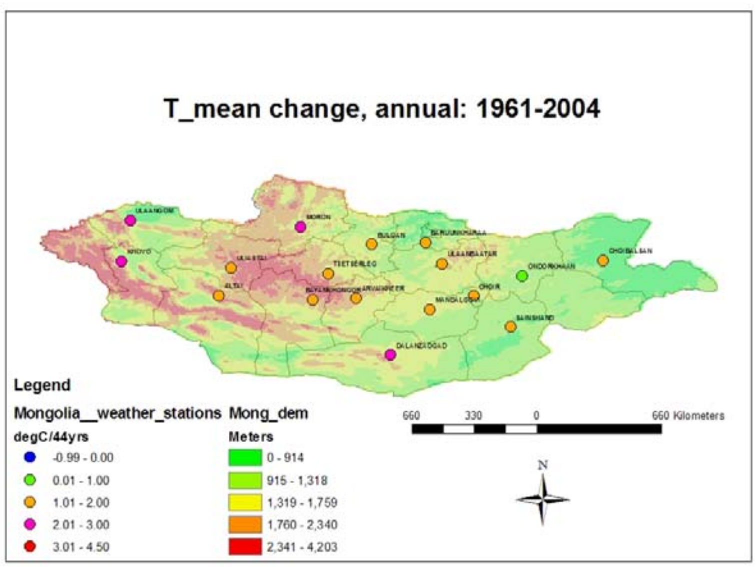


Figure 2.2 Mean annual temperature change between 1961-2004 years.

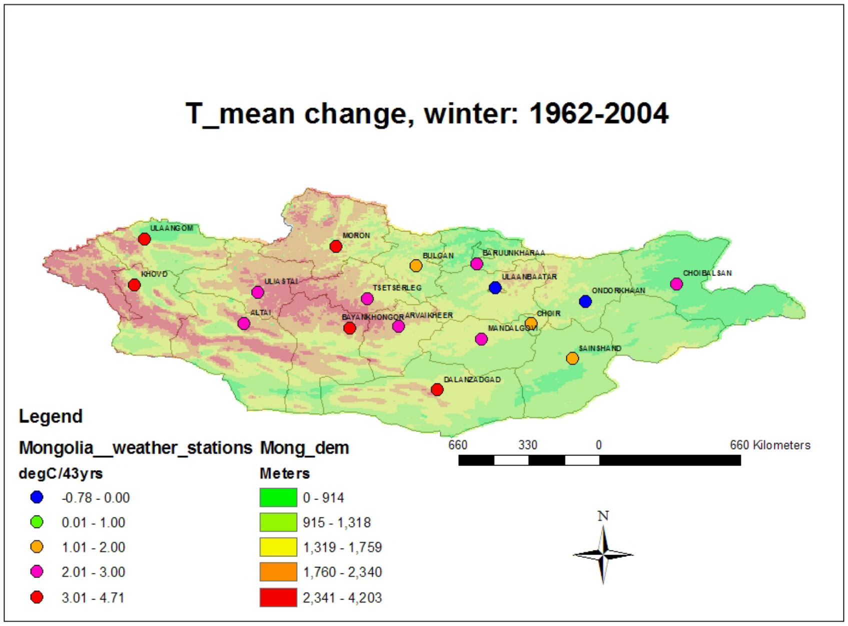


Figure 2.3 Mean winter temperature change between 1962-2004 years.

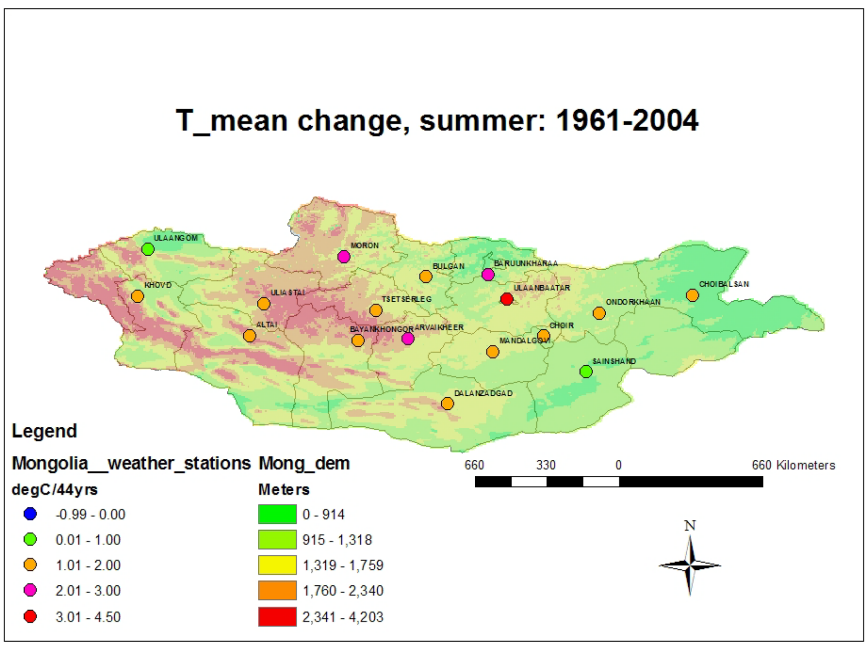


Figure 2.4 Mean summer temperature change between 1961-2004 years.

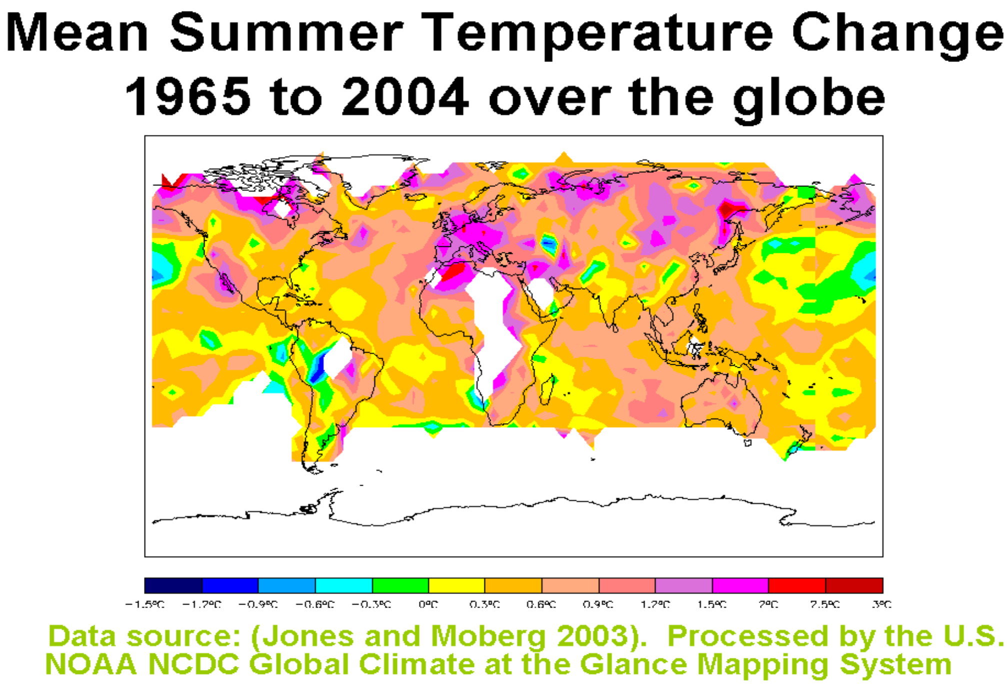


Figure 2.5 Mean summer temperature change 1965-2004 over the globe. Data source: (Jones and Moberg 2003).

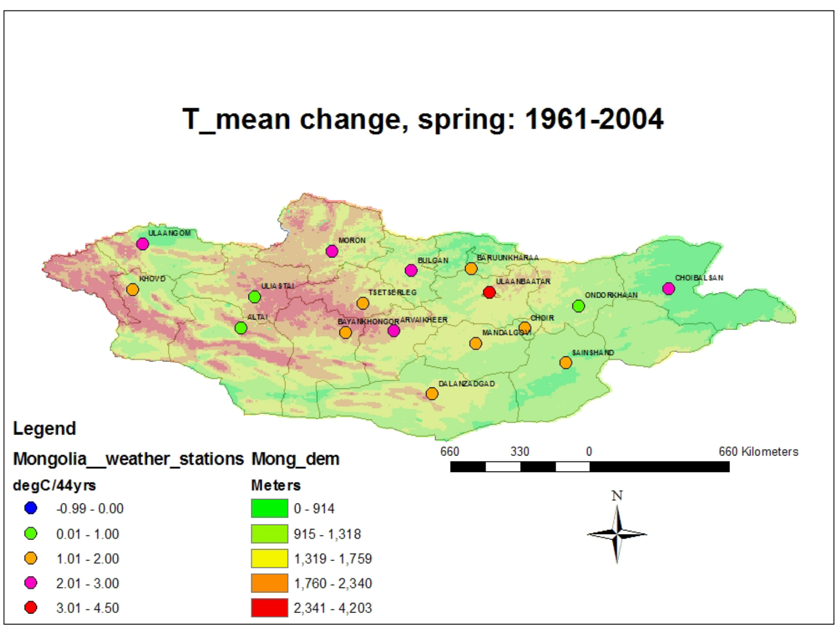


Figure 2.6 Mean spring temperature change between 1961-2004 years.

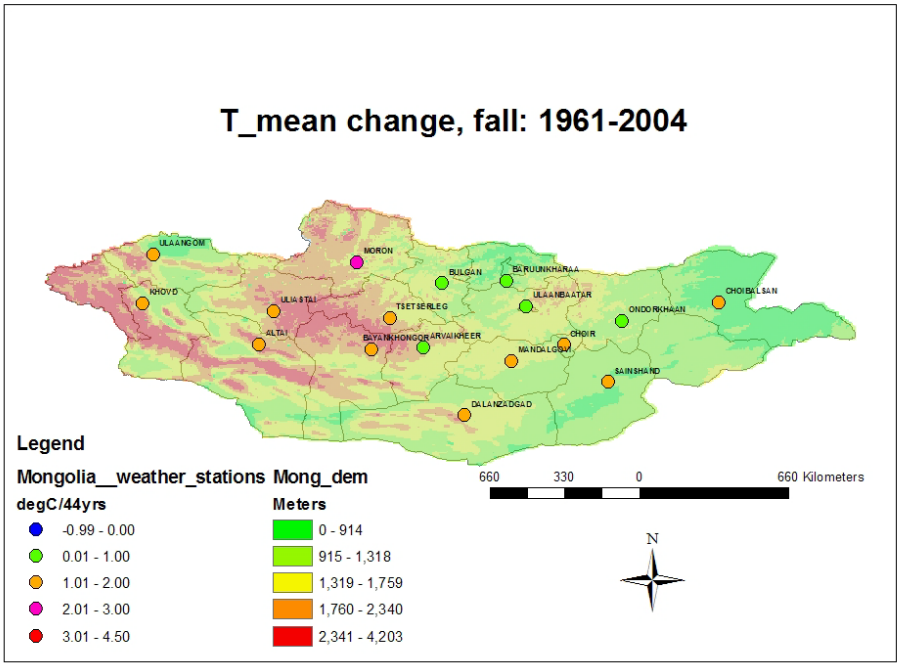


Figure 2.7 Mean fall temperature change between 1961-2004 years.

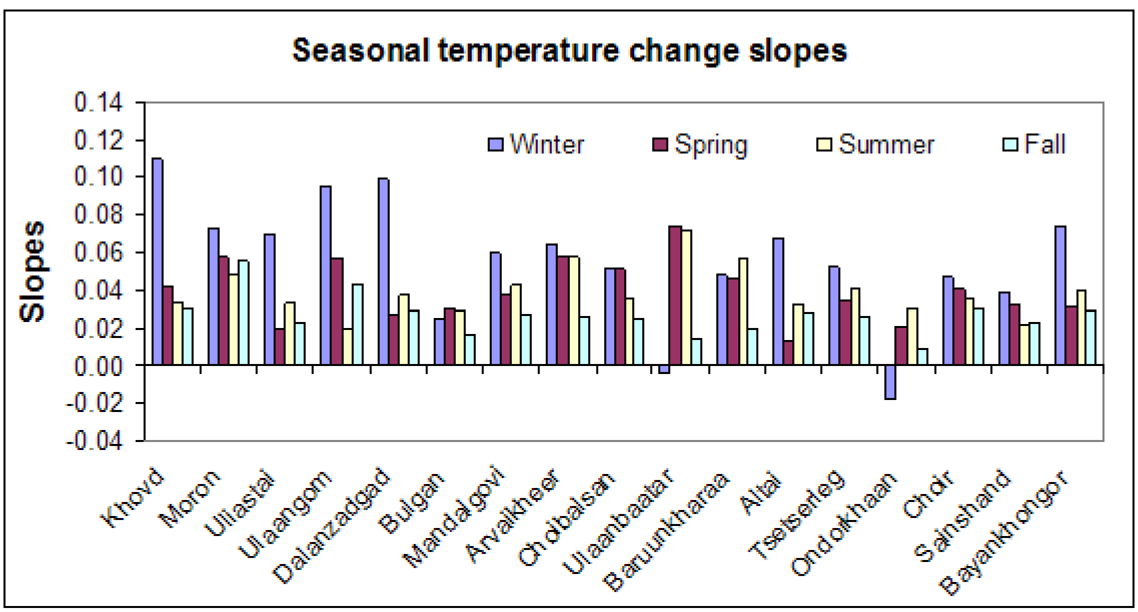


Figure 2.8 Seasonal surface mean temperature change slopes for 1961-2004.

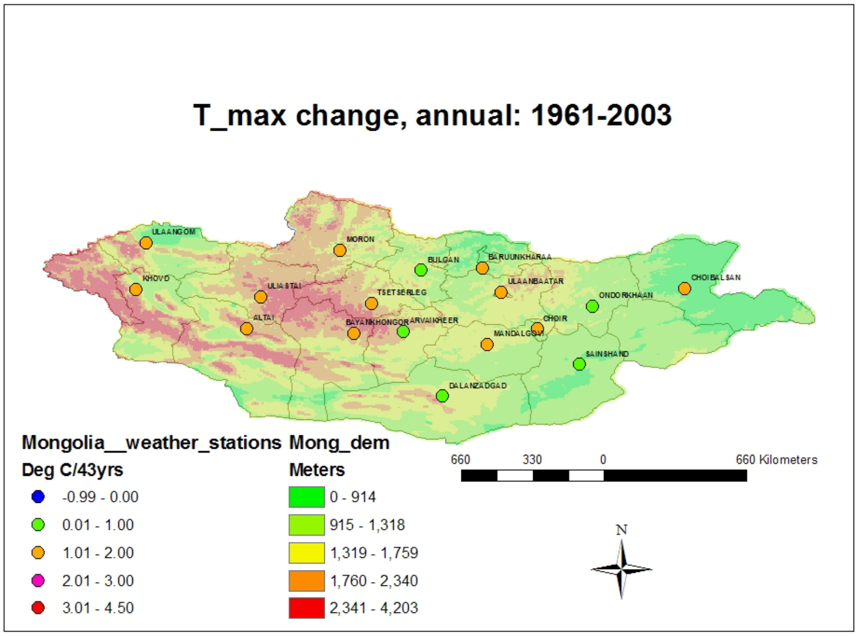


Figure 2.9 maximum annual temperature change between 1961-2003 years.

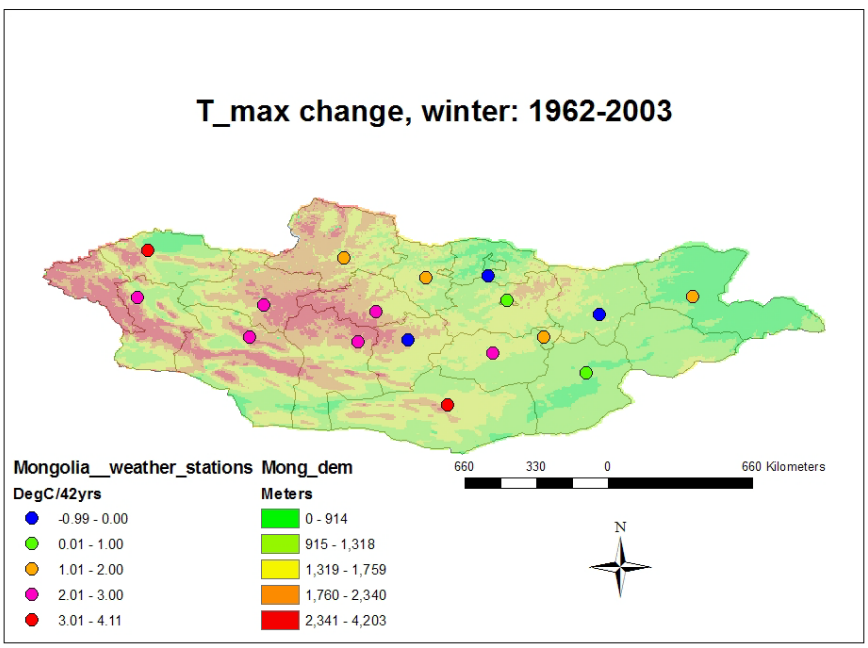


Figure 2.10 Maximum winter temperature change between 1962-2003 years.

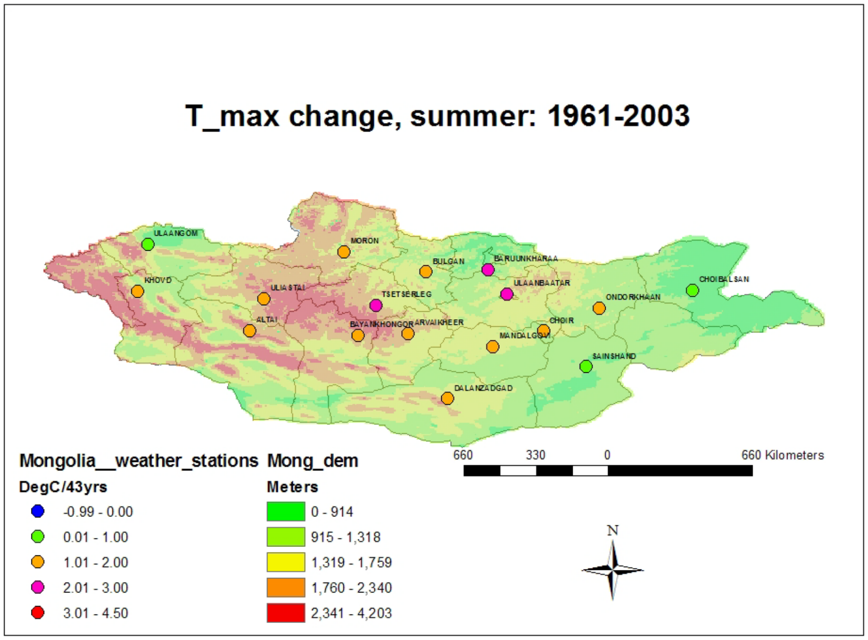


Figure 2.11 maximum summer temperature change between 1961-2003 years.

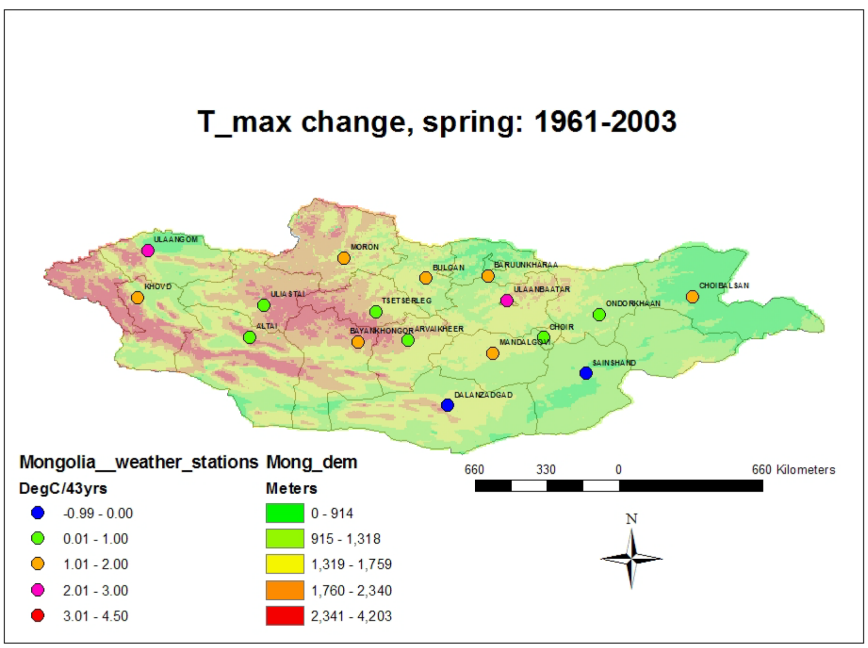


Figure 2.12 Maximum spring temperature change between 1961-2003 years.

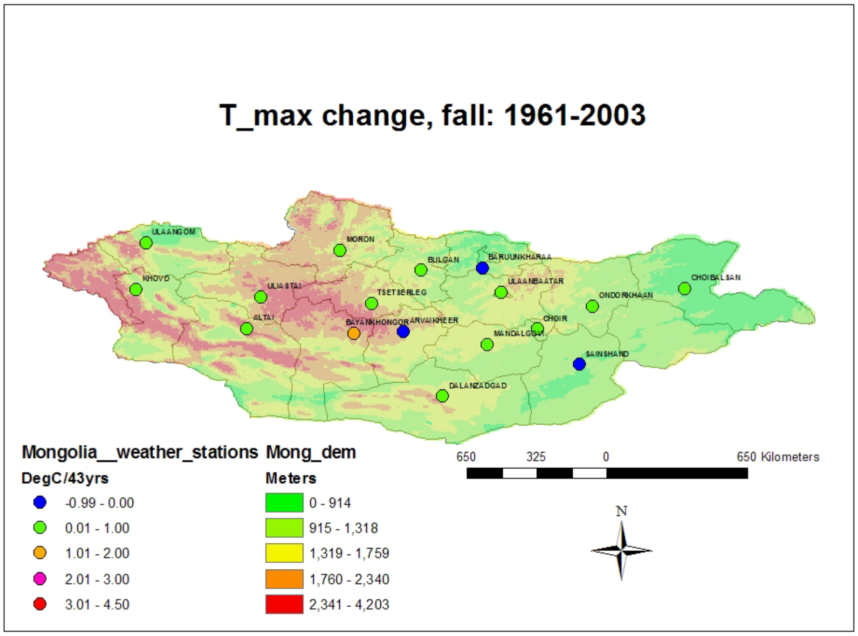


Figure 2.13 Maximum fall temperature change between 1961-2003 years.

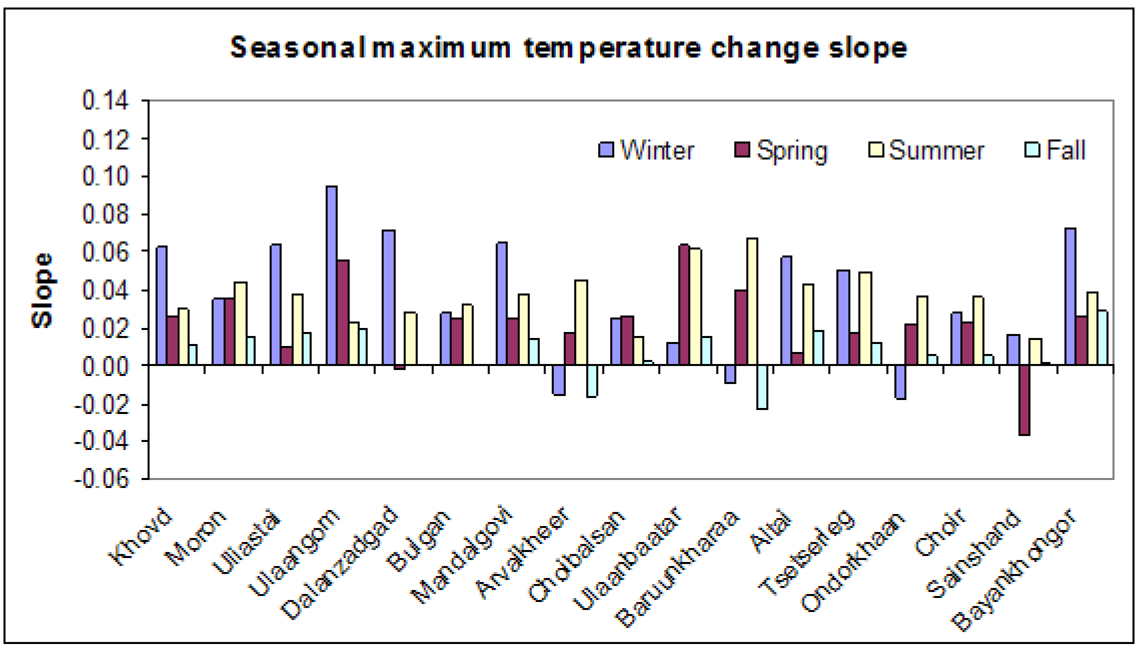


Figure 2.14 Seasonal maximum temperature change slopes for 1961-2003.

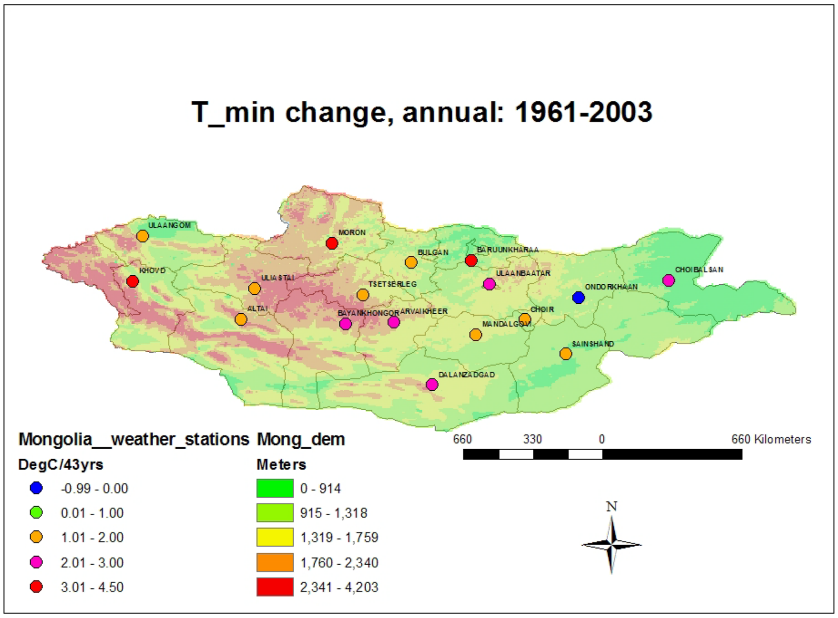


Figure 2.15 Minimum annual temperature change between 1961-2003 years.

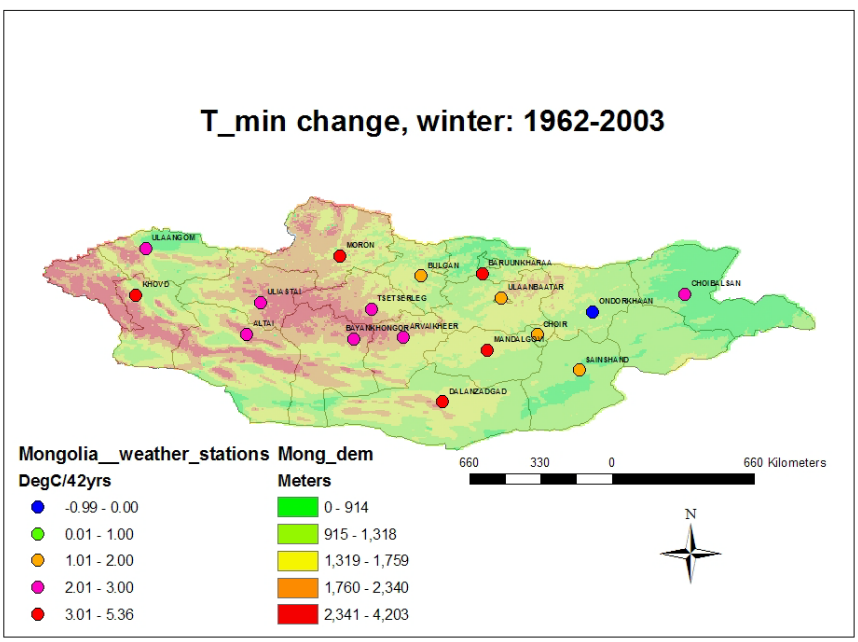


Figure 2.16 Minimum winter temperature change between 1962-2003 years.

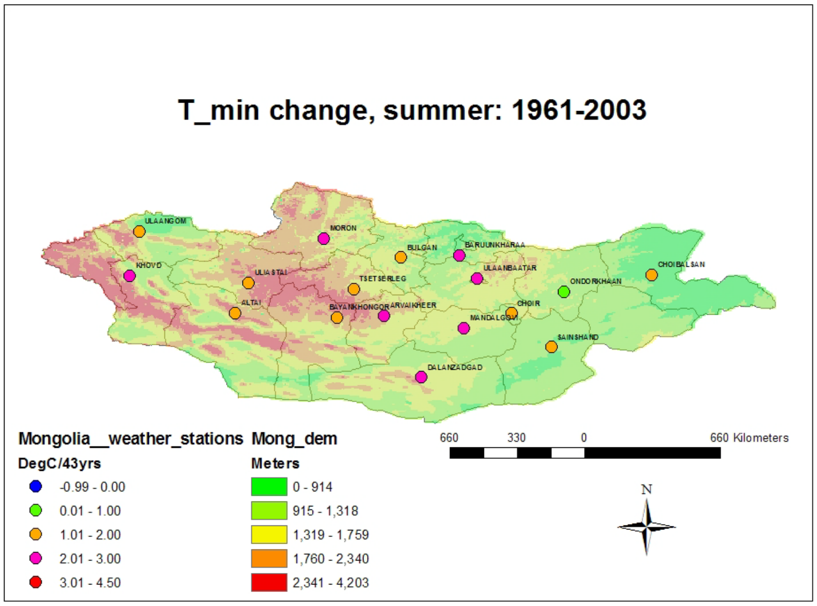


Figure 2.17 Minimum summer temperature change between 1961-2003 years.

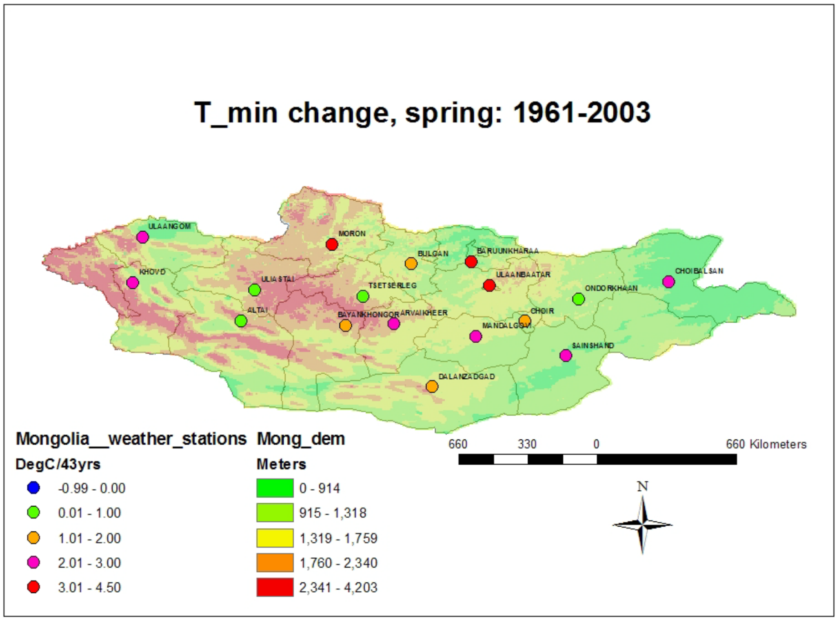


Figure 2.18 Minimum spring temperature change between 1961-2003 years.

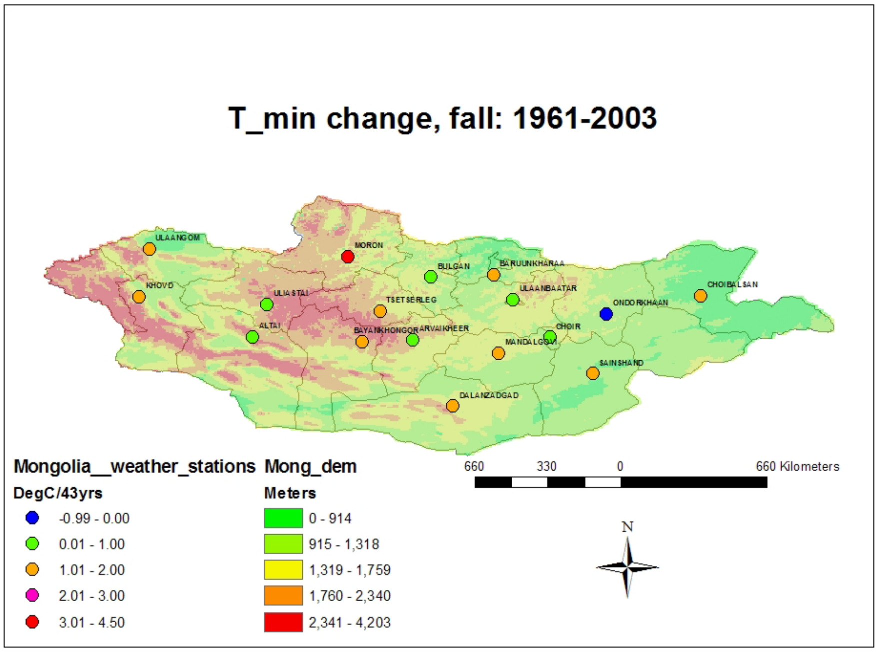


Figure 2.19 Minimum fall temperature change between 1961-2003 years.

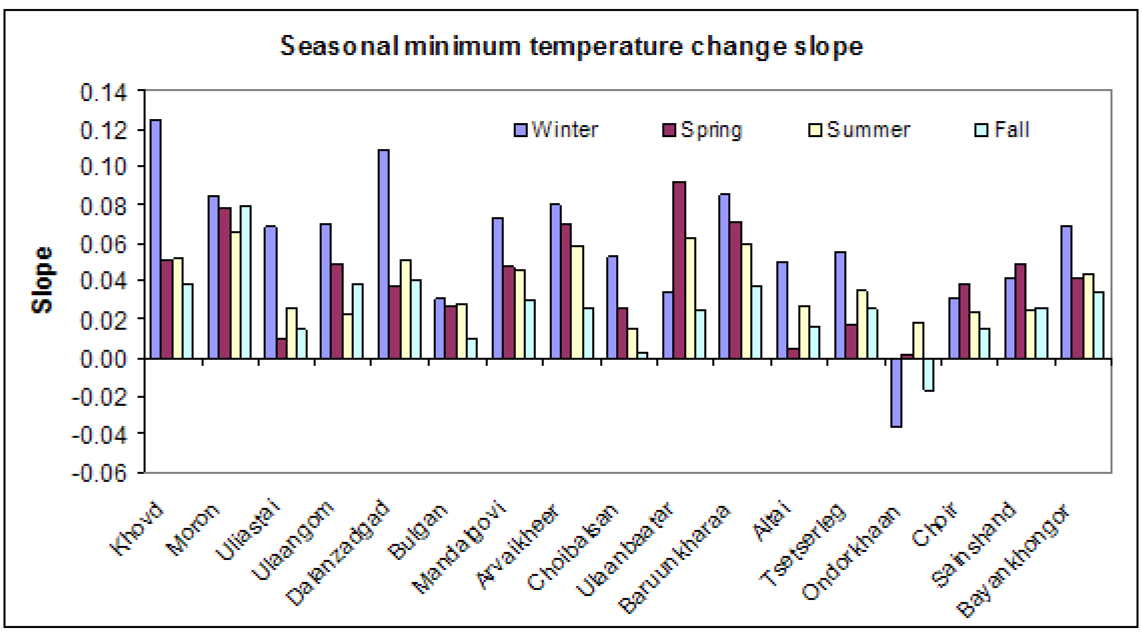


Figure 2.20 Seasonal minimum temperature change slopes for 1961-2003.

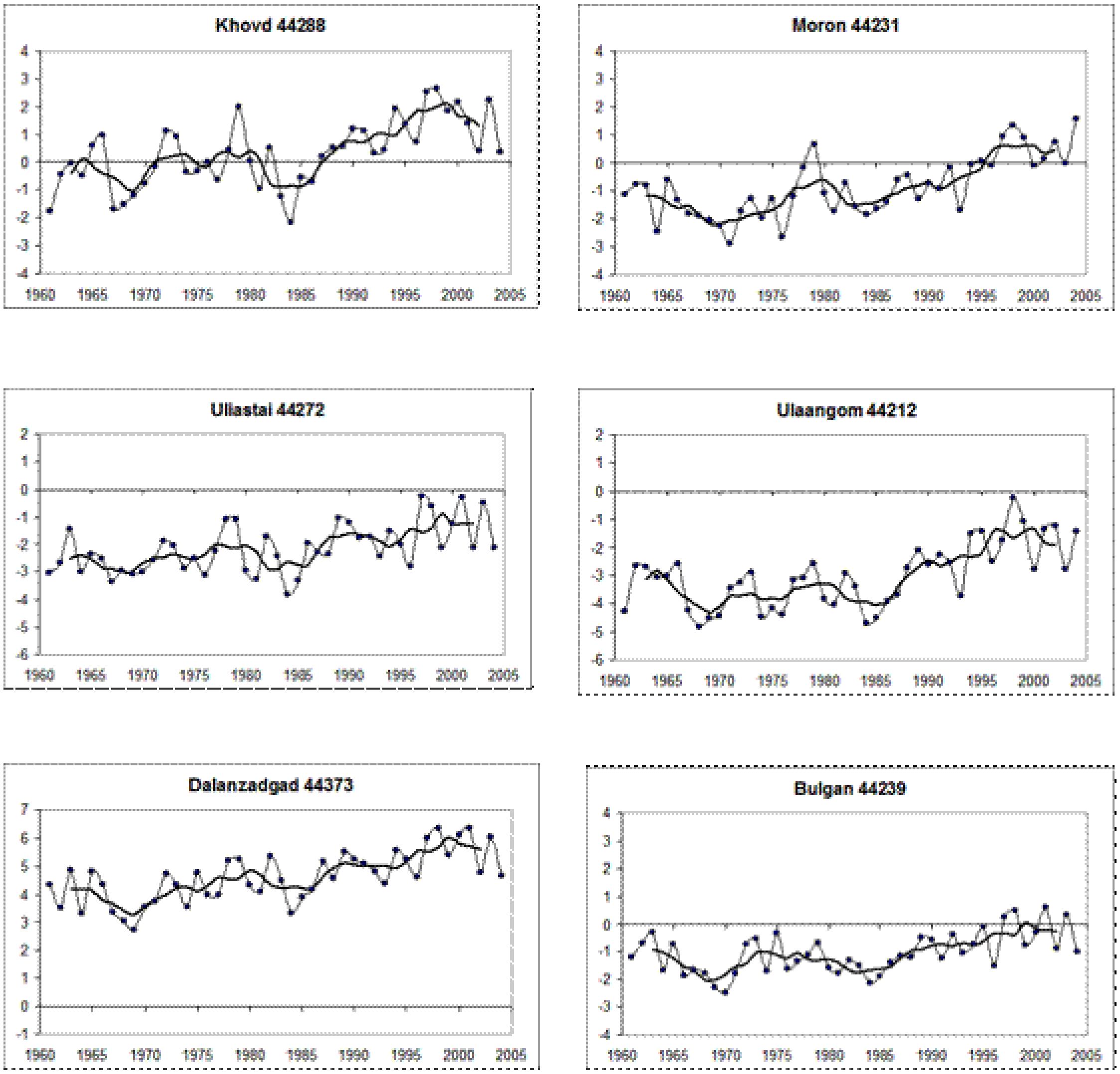


Figure 2.21 Mean annual temperatures and 5-year running mean.
Dotted lines are mean annual temperature in Celsius degrees
Bold lines are 5-year running mean

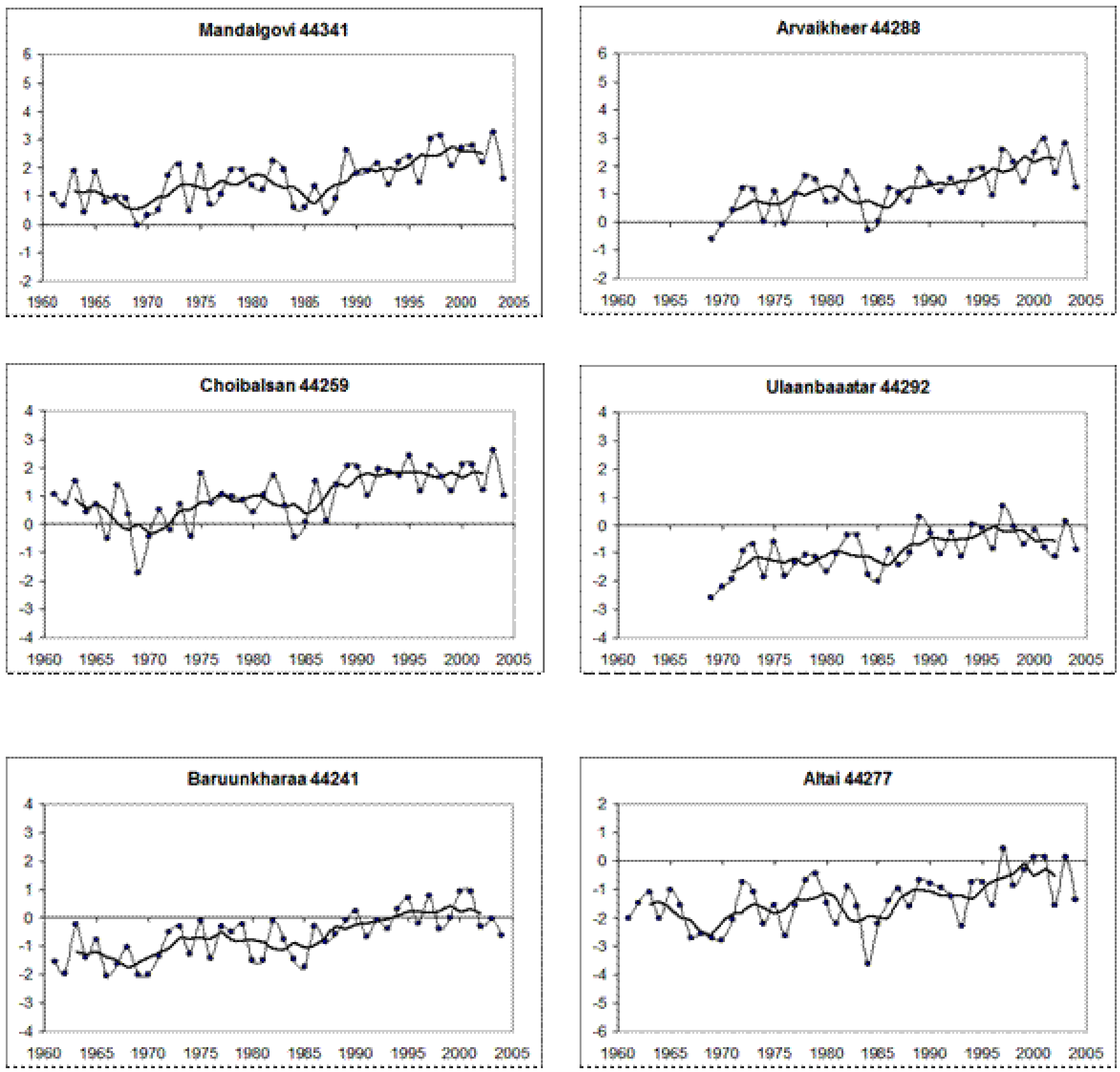


Figure 2.21 Continued. Mean annual temperatures and 5-year running mean.
Dotted lines are mean annual temperature in Celsius degrees
Bold lines are 5-year running mean

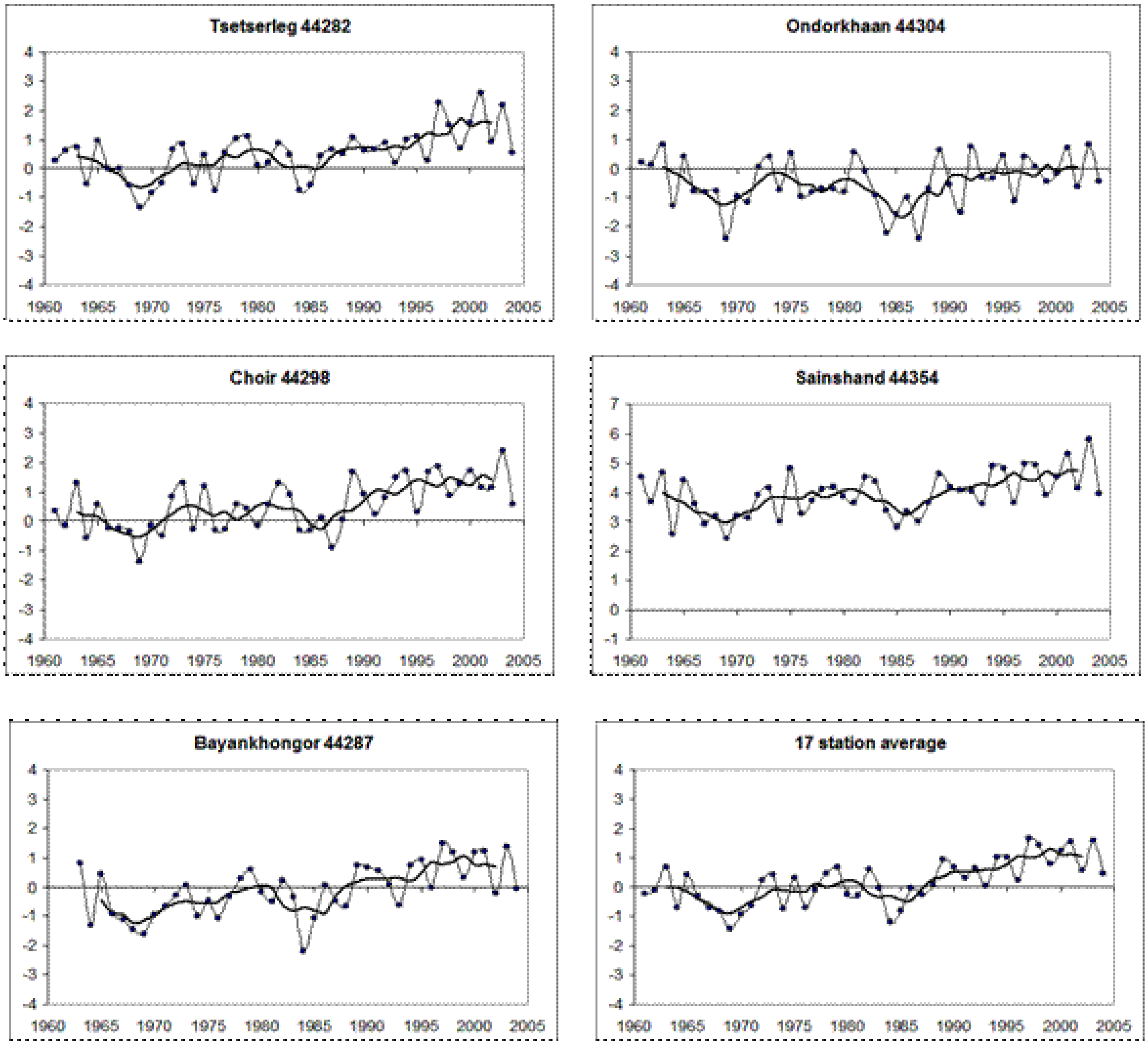


Figure 2.21 Continued. Mean annual temperatures and 5-year running mean.
Dotted lines are mean annual temperature in Celsius degrees
Bold lines are 5-year running mean

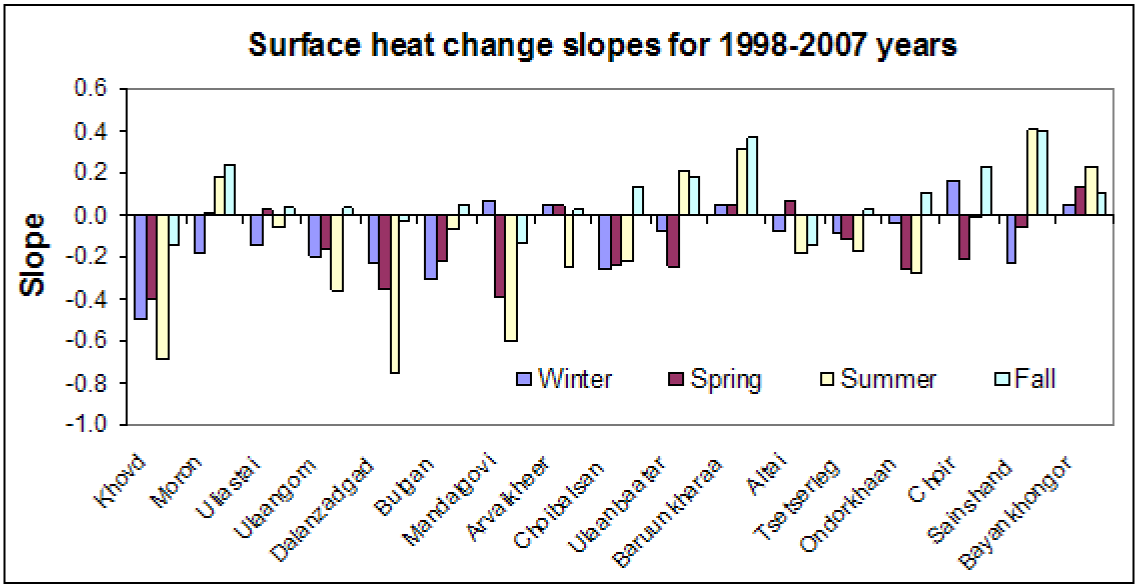


Figure 2.22 Surface heat change for last 10 years; linear trend slopes at 17 stations.

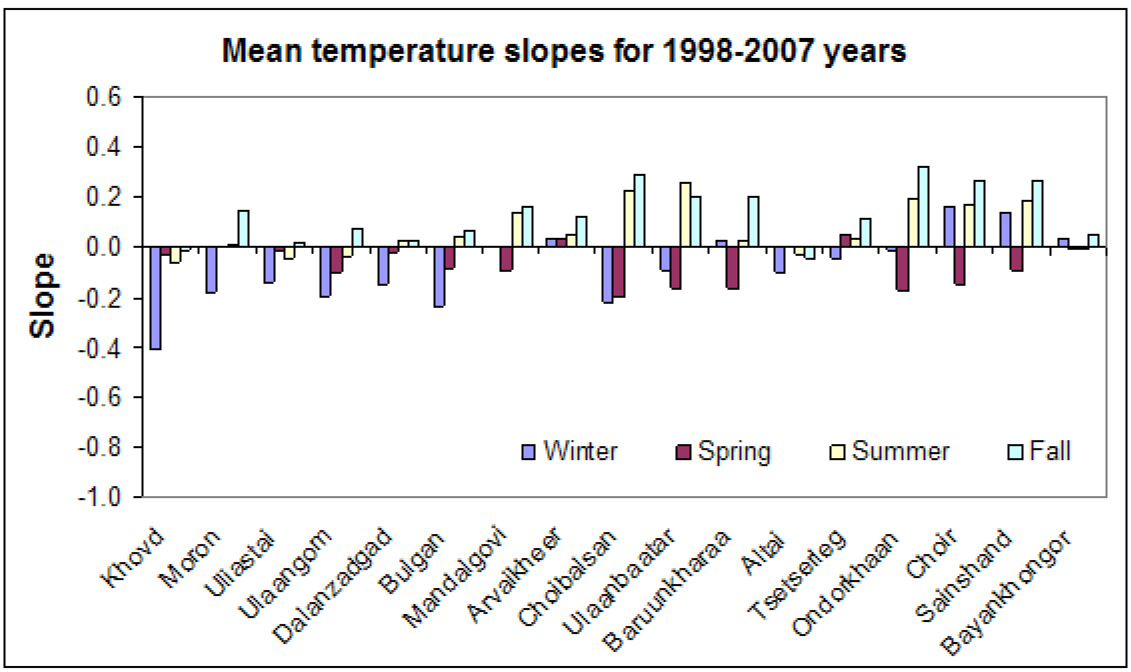


Figure 2.23 Mean temperature change for last 10 years; linear trend slopes at 17 stations.

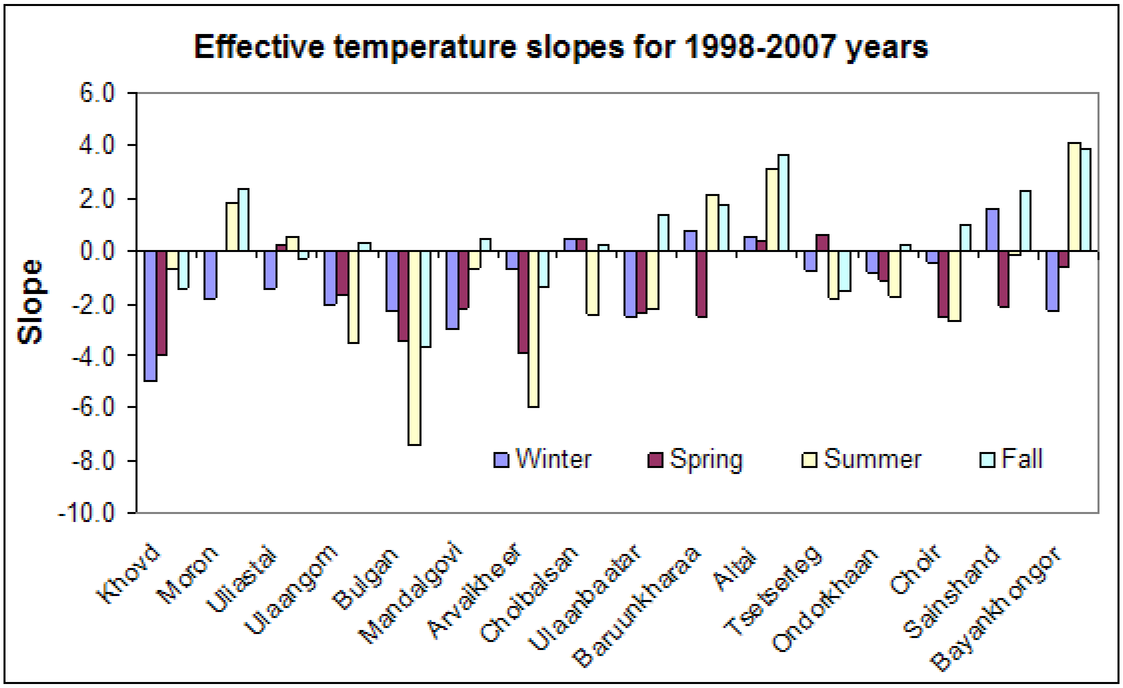


Figure 2.24 Effective temperature change for last 10 years; linear trend slopes at 17 stations.

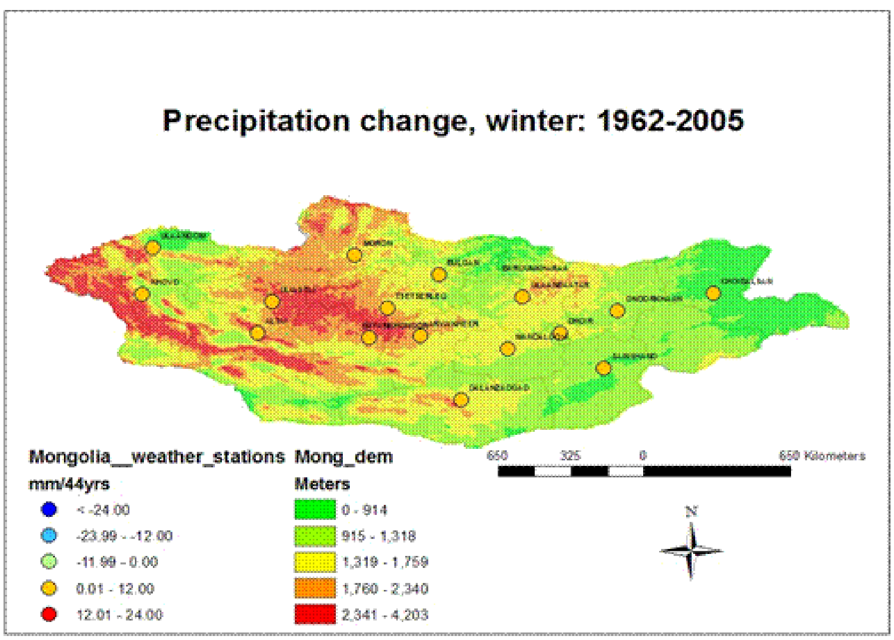


Figure 2.25 The winter precipitation change: 1962-2005.

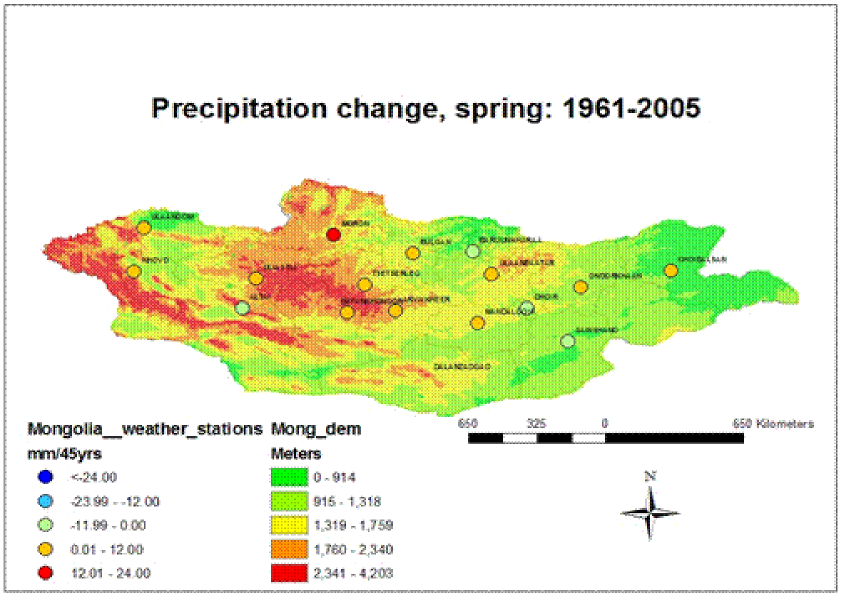


Figure 2.26 The spring precipitation change: 1961-2005.

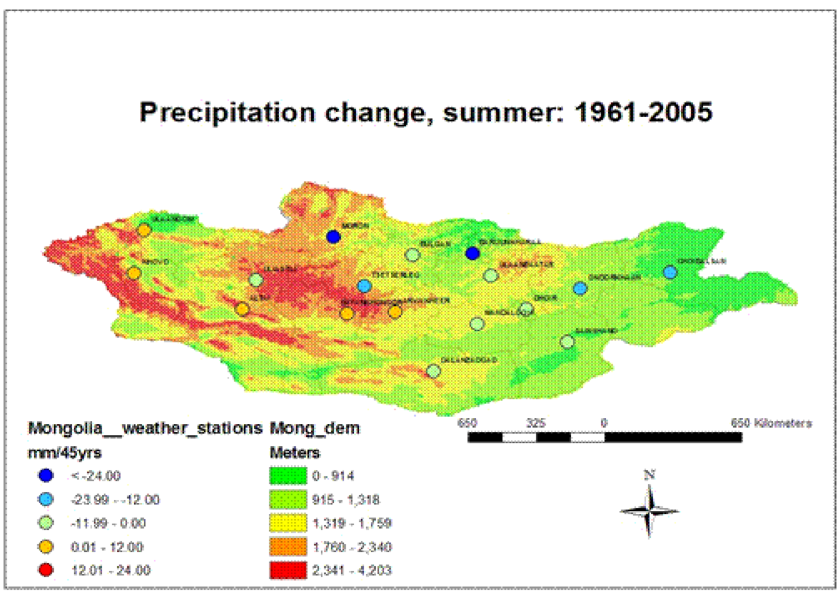


Figure 2.27 The summer precipitation change: 1961-2005.

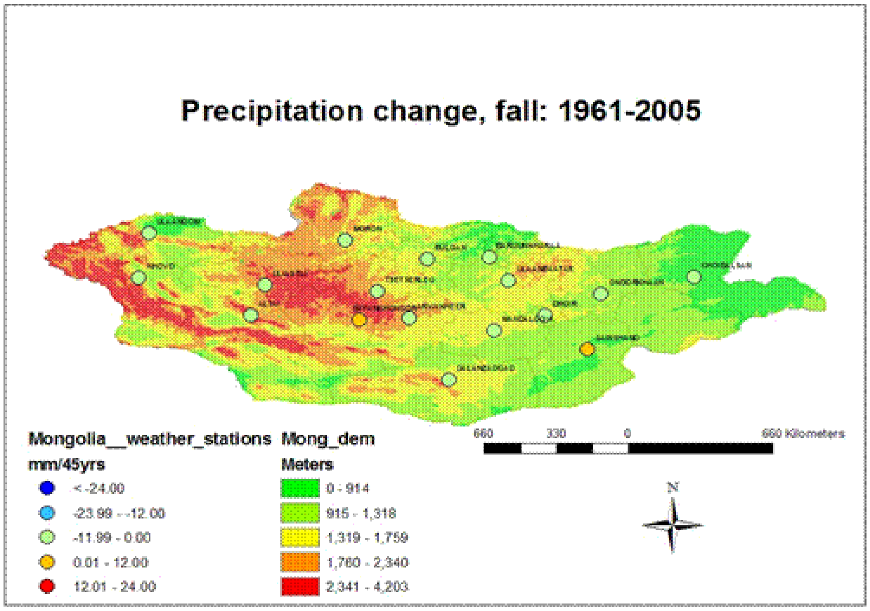


Figure 2.28 The fall precipitation change: 1961-2005.

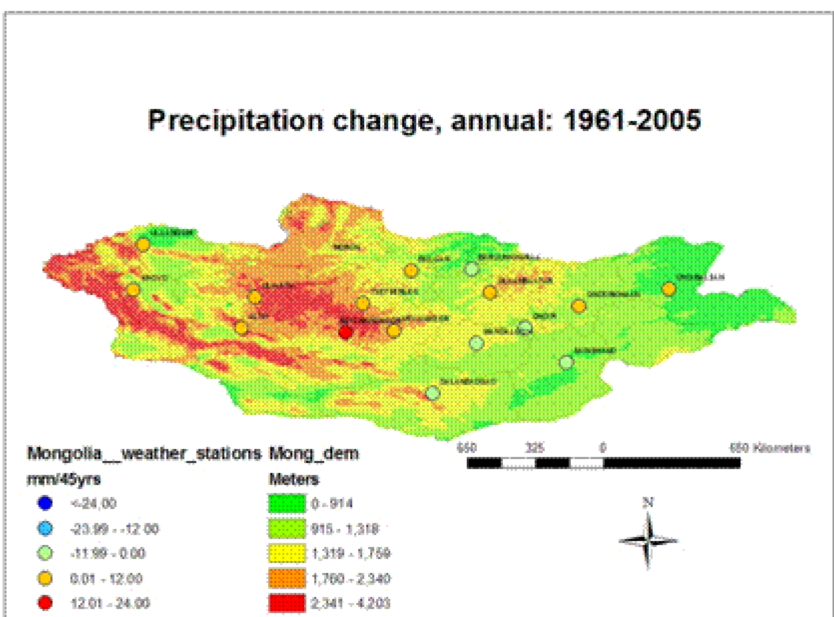


Figure 2.29 The annual precipitation change: 1961-2005.

CHAPTER 3: SEASONAL AND INTERANNUAL VARIABILITY IN SURFACE ENERGY PARTITIONING AND VEGETATION COVER WITH GRAZING AT SHORTGRASS STEPPE

Khishigbayar Jamiyansharav[1] Dennis Ojima[1] Roger A. Pielke[2] Sr.,

William Parton[1], Jack Morgan[3], Adriana Beltrán-Przekurat[2],

Daniel LeCain[3] and David Smith[3]

[1]Graduate Degree Program in Ecology, NREL, CSU, Fort Collins, CO

[2]Department of Atmospheric and Oceanic Sciences and CIRES, CU-Boulder, CO,

[3]USDA-ARS Fort Collins, CO, 80523

KEY WORDS: Shortgrass steppe; energy fluxes; grazing; vegetation

Oct 30, 2009

Submitted to the Agricultural and Forest Meteorology Journal

[1] Corresponding author, Graduate Degree Program in Ecology, Colorado State University, Fort Collins, CO 80523, jkhishig@nrel.colostate.edu, Phone: 970-491-1604/Fax: 970-491-1965

ABSTRACT

We evaluated shortgrass steppe energy budgets based on the Bowen Ratio Energy Balance method for three different grazing intensity treatments at the Central Plains Experimental Range Long-Term Ecological Research (CPER-LTER) site. We tested the correlations between aboveground biomass and surface energy fluxes for three different precipitation years based on continuously measured 20 minute interval data. Grazing has a potential impact on energy partitioning under conditions of higher water availability, but not during dry conditions. Our study confirms that precipitation, not grazing treatment, explains the majority of variation in aboveground biomass at the CPER-LTER site. In addition, we are suggesting effective temperature, not air temperature, as a superior metric to evaluate surface heat change. Effective temperature takes into account humidity as well as air temperature.

I. INTRODUCTION

Grazing practices can have a major impact on vegetation production, composition, and structure depending on grazing intensity and type of plant community (Milchunas and Lauenroth 1993). Annual forage removal in shortgrass steppe (SGS) can range from 40% in moderately grazed to 75% in heavily grazed sites (Morgan et al. 2004).Vegetation plays an important role in determining surface heat content throughout the growing season as it removes moisture from the soil that is lost through transpiration (Lu et al. 2001). During the day, transpiring vegetation converts incoming solar energy into latent heat, thus reducing maximum air temperature. At night, more water vapor above vegetated areas increases minimum air temperatures (Hanamean et al. 2003). Consequently, land-surface processes are increasingly featured in climate system modeling and represented in numerical models of weather and climate (Kabat et al. 2004).

Modeling the partitioning of available energy between sensible and latent heat fluxes on land surface and accurate simulation of the diurnal, seasonal, and longer-term variations in these fluxes is an essential exercise for understanding how environmental changes may impact land-atmosphere energy exchange. Latent heat contributes water vapor to the atmosphere and tends to increase cloudiness and precipitation while increases in sensible heat tend to increase air temperature in the planetary boundary layer. Water cycling and energy flux partitioning can contribute substantially to the uncertainties of terrestrial ecosystem response to climate change. Climate change and land-use change, in turn, have strong potential to alter ecosystem functioning through their combined effects on both sensible and latent heat fluxes (Ferretti et al. 2003, Chapin et al. 2002).

At the Earth's surface, evapotranspiration (ET) is the connecting link between water and energy budgets. ET is the combination of two processes that lose water to the atmosphere by evaporation from lakes, reservoirs, wetlands, soil and snow cover, and transpiration from plants. Cell walls inside the leaf are covered with a thin film of water which readily evaporates when the stomata open to assimilate carbon for plant photosynthesis. During this trade-off, the ratio water lost to carbon dioxide (CO_2) absorbed can reach 400 (Chapin et al. 2002).

Daily and hourly water loss from a 4-year experiment at the SGS Long Term Ecological Research (LTER) site was found to be approximately equal to the potential ET rate immediately after large rain events, with a rapid decline up to four days following the event (Parton et al. 1981). Water loss was generally equal to water input while actual water loss was substantially lower than potential ET. Lapitan and Parton (1996) found that daily ET rates closely follow seasonal patterns of rainfall and high rates of ET coincide with the presence of green biomass, high solar radiation, and high soil moisture.

In semi-arid areas, energy and water fluxes are strongly influenced by rainfall and grazing. In the SGS, early season rainfall (Milchunas et al. 1994, Ojima et al. 1993a,b, Lauenroth and Sala 1992) and soil moisture (Knapp et al. 2007) are the main determinants of above ground biomass production. Semi-arid rainfall patterns are characterized by small events, 80% of which are 0.5 cm or less during any month of the year (Lapitan and Parton 1996, Sala and Lauenroth 1982), with high inter-annual variations. Low vegetation cover and low albedo are typical features of the SGS. The

SGS has evolved under grazing by large native herbivores and grazing by livestock is the current primary land-use of native rangeland (Milchunas et al. 1988). Herbivores have the potential to affect ET by removing aboveground biomass thus altering microclimate. The recommended grazing practices in SGS allows a stocking rate which removes approximately half of the current season plant production (Milchunas et al. 1989, Klipple and Costello 1960), although considerable variation in stocking rates exists among ranching enterprises and public lands which permit livestock grazing.

This study evaluates the impact of grazing on microclimate and energy budgets at the SGS-LTER site in a dry (163 mm) and two near-normal (262 and 260 mm) precipitation years. We address how variation in aboveground biomass affects energy budgets and soil and air temperatures and analyze surface heat energy or moist enthalpy (H_e), which accounts not only for surface temperature but for the contribution of water vapor to surface heat content (Pielke et al. 2005) and is a better metric for measuring changes in heat content than surface temperature alone.

Our main hypotheses were:

- In semi-arid grasslands, the main affect of rainfall events on the energy balance is to increase the ratio of latent to sensible heat fluxes for a brief period, seldom exceeding five days. This effect is expected to be more pronounced with increasing in leaf area, and consequently, greatest in ungrazed pastures (UG).
- Since maximum green biomass declines with increasing grazing intensity, heavily grazed (HG) sites will have higher sensible and lower latent heat fluxes compared to moderately grazed (MG) and UG sites.

II. METHODS

2.1. Study site and micrometeorological measurements

This experiment was conducted at the CPER (40^o 50' N, 104^o 43' W), which is a LTER site operated by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS). The CPER is located at the northern limit of the semi-arid SGS grassland on the western edge of the North American Great Plains and is used extensively for livestock grazing (Lauenroth and Milchunas 1991). Total vegetative basal cover at the site is typically 25-35% (Milchunas et al., 1989), comprised of a mixture of C_3 (e.g., *Stipa comata* [Trin and Rupr.] and *Pascopyrum smithii* [Rybd.] and C_4 (e.g., *Bouteloua gracilis* [H.B.K.] Lag.) grasses, cacti, forbs, and a sub-frutescent shrub (*Artemesia frigida* [Willd.]). *Bouteloua gracilis* accounts for 90% of the aboveground biomass of grasses and 30% of total aboveground biomass (Sala and Lauenroth 1982).

Long-term (52 yr) mean annual precipitation averages 321 $\pm$ 98 mm (Lauenroth and Sala 1992), with the majority occurring during May, June and July. Mean air temperatures are 15.6^{o}C in summer and 0.6^{o}C in winter (Singh et al. 1998).

Grazing treatments were established in 2001 in two adjacent pastures of native SGS vegetation and sampled over three years, 2001-2003. These pastures had previously been grazed by cattle for over 50 years at a moderate intensity (stocked generally from May – October at 0.16 heifers per hectare, which removes approximately 40% annual forage production). One 62-ha pasture remained as a MG pasture. The other 97-ha pasture was divided and converted into a HG pasture (34 ha stocked at a rate of 0.3 heifers per ha, resulting in an average 65% removal of annual forage), and a UG control (63 ha fenced exclosure). Bowen Ratio Energy Balance (BREB) systems (Model 023/CO_2 Bowen ratio system, Campbell Scientific Inc., Logan, UT, USA) were installed near the center of each pasture, resulting in a fetch exceeding 100 meters in all cases. MG and HG pastures were stocked with heifers from May 16 to Nov. 1 in 2001 (normal year with 262 mm precipitation, which is close to long term average), May 16 to Aug. 9 in 2002 (very dry year-163 mm precipitation) and from May 21 to Oct. 16 in 2003 (normal year-260 mm precipitation). The BREB towers were erected in spring 2000 and operated through the growing season to ensure a uniform baseline before the grazing treatments began.

We followed the methods of Dugas (1993) and Dugas et al. (1999) to calculate evapotranspirational fluxes of water (i.e. latent heat fluxes) from the BREB systems. Temperature and humidity gradients were measured every two seconds from arms mounted on micrometeorological masts positioned at 1 and 2 m height above the canopy to determine the Bowen ratio. The Bowen ratio was, in turn, used with measurements of net radiation (Model Q7 net radiometer, REBS, Seattle, WA, USA), average soil heat flux from two heat flux plates (Model HFT, REBS), and soil temperature to determine sensible heat flux. Turbulent diffusivity was assumed equal for heat and water vapor, and was calculated using 20 minute averages of sensible heat flux and air temperatures measured from the two tower arms. When meteorological conditions were not suitable for the BREB method of calculating turbulent diffusivity (approximately 10% of the time occurring primarily at night), we calculated diffusivity according to the method of Dugas et al. (1999) using wind speed, atmospheric stability, and canopy height.

Precipitation was monitored continuously with a tipping bucket rain gauge (model TE-525 mm, Texas Electronics, Dallas, Texas). Depending on the precipitation amount and frequency, water loss is nearly equal to potential ET rate immediately after a rain event and up to four days following the rain event with a rapid decrease thereafter (Parton et al. 1981). Therefore, we defined wet periods as one to four days after each individual rain event, depending on the precipitation intensity and frequency under conditions when net radiation (R_n) exceeded 300 Wm^{-2}. We defined dry periods as having little or no precipitation when the BR was greater than three.

The pastures are not in close proximity with major topographic variation so we assumed R_n and precipitation would not be substantially different among the three pastures. Soil water content on a volume basis was measured by water content reflectometers (model CS615, Campbell Scientific Inc., Logan, UT, USA) at 0-15 cm below the soil surface.

2.2 Aboveground plant biomass and leaf area

Fifteen 30 m × 30 m plots were established on a grid surrounding each of the three BREB towers. During the growing season (April-October) and corresponding with Landsat flyovers (every 32 days), nine of these grids were chosen for Leaf Area Index (LAI) and aboveground biomass measurements. One-meter-square quadrants were randomly located within each of nine grids and LAI was determined by the laser point frame method (Przeszlowska et al. 2006) using 100 points per quadrant. After LAI determination, vegetation in the quadrants was clipped to the crown, oven-dried at $60^{o}C$, and weighed to determine above-ground biomass. Both LAI and biomass samples were classified as green or brown. Necromass, as defined in this study includes standing dead brown biomass but not litter. Leaf Area Index was not measured in 2003; therefore, it was estimated from a linear regression of the prior years' collected biomass versus LAI data using the following equation:

$$LAI = Biomass \times 0.0044 + 0.044 \quad (R^2 = 0.79).$$

2.3 Research approach

If the effects of photosynthesis and lateral advection can be neglected for simplification, the energy budget of the SGS-LTER is represented as:

$$R_n = L_e + H + G_o \quad [1]$$

where R_n is the flux of net incoming radiation, L_e is the flux of latent heat into the atmosphere, H is the flux of sensible heat into the atmosphere and G_o is the flux of heat conducted into the soil, all expressed in W m^{-2}. The ratio of H and L_e is called the Bowen ratio (BR) and expressed in Eq. [2] (Brutsaert 1982):

$$BR = H/L_e \quad [2]$$

The Bowen ratio ranges from less than 0.1 for tropical oceans to greater than 10 for deserts, indicating that turbulent energy transfer depends on the nature of an ecosystem and the climate (Chapin et al. 2002).

Surface heat energy (H_e), or moist enthalpy, accounts not only for the surface temperature but also for the contribution of water vapor to surface heat content (Pielke et al. 2005) and is expressed as:

$$H_e = C_p T + L_v r \quad [3]$$

where C_p is the specific heat content of the air at constant pressure (at 20°C, C_p=1.005J g^{-1} $°K^{-1}$), T is the observed air temperature at 2 m height in °K, L_v is the latent heat of vaporization (at 20°C, L_v = 2450 J g^{-1}), r is the mixing ratio or mass of water vapor to the mass of dry air (g g^{-1}).

To express enthalpy in degrees for comparison to air temperature we use the term effective temperature (T_e), expressed as:

$$T_e = H_e/C_p = T + L_v r/C_p \qquad [4]$$

where T_e is the effective temperature that accounts for specific humidity of the air; therefore it has contributions from both sensible and latent heat (Pielke et al. 2004, 2005).

2.4 Data quality check and processing

We focused on daytime (7 am to 7 pm Mountain Standard Time) energy fluxes to avoid the prevalence of large errors in nighttime measurements due to small values in the available energy (i.e. R_n-G_o). The Bowen Ratio method closes the energy balance. Therefore, in order to detect possible errors, we summed sensible, latent, and soil heat fluxes and checked the total against net radiation data (formula 1). Differences greater than 50 Wm^{-2} were considered errors and were removed from the data. We removed 2 to 5% of the total data from each grazing treatment.

We averaged the energy fluxes and summed precipitation on a daily basis for the growing season for each of three different grazing treatments: HG, MG, and UG. Differences among treatments were determined using one-way ANOVA statistical test (SPSS, Inc. SPSS. 2004).

III. RESULTS

3.1. Green biomass and necromass

Differences in grazing intensity did not significantly impact green biomass amount harvested during the 2001-2003 growing seasons (Table 3.1). Observations did, however, tend to follow the expected pattern of higher green biomass in the UG pasture and lower green biomass in the HG pasture (Table 3.1, Fig. 3.1). Peak green biomass occurred in June, and was greatest in the MG pasture (Fig. 3.1). The UG pasture, as would be expected, showed a consistent pattern of higher necromass at the end of the season than the grazed pastures with the exception of the 2002, due to substantially lower-than-normal precipitation (Fig. 3.2).

As is common in semiarid grasslands (Knapp et al. 2007, Milchunas et al. 1994, Ojima et al. 1993a,b, Sala and Lauenroth 1982), there was substantial inter-annual variability in the amount of green biomass (Table 3.1). Consequently, maximum standing green biomass was only 24 g m^{-2} in the dry year 2002, compared to 103 and 145 g m^{-2} measured in the more normal precipitation years 2001 and 2003. Maximum necromass greatly exceeded maximum green biomass (100 g m^{-2} vs. 24 g m^{-2}) in the very low precipitation year 2002 (Figs. 3.1 and 3.2). Precipitation events led to predictable increases in volumetric soil water (data from MG shown in Fig. 3.3).

3.2 Near-surface energy fluxes

Mean H values were higher than L_e in all years and grazing treatments, expressing the impacts of ground cover, biomass and LAI in semiarid grasslands (Tables 3.1 and 3.2). As would be expected, there was a relative increase in H and G_o with respect to R_n in a dry year (Table 3.2), indicating that the energy tended to be used primarily to heat the air and soil first, and what remained was available for evaporation and transpiration. The general seasonal trends of H and L_e are shown in Figure 3.4 for the MG pasture in 2001. Soil heat flux showed no trend and was relatively low throughout the study period, averaging 52 Wm^{-2}. About 45% of incoming R_n went to H, 38 % to L_e and 18% to G_o during the normal years versus 61% of R_n to H, 19% to L_e and 20% to G_o during the dry year (Table 3.2).

With the exception of 2003, grazing treatments did not result in detectable differences in H, L_e and R_n. In 2003, R_n was greater in the HG treatment compared to the

UG ($p<0.001$) and MG ($p<0.048$) treatments (Fig. 3.5). These treatment differences in R_n became more evident later in the season (Fig. 3.5) as necromass increased (Fig. 3.2). Furthermore, *H* was greater in the UG treatment than the HG treatment ($p<0.025$), while L_e was lower in the UG treatment compared to the MG ($p<0.001$) and HG ($p<0.001$) treatments (Table 3.2), all of which did not follow expected patterns.

Overall seasonal totals of energy fluxes followed the expected relationships with precipitation and soil moisture: L_e was higher at the beginning of the season when the rainfall amount was relatively high, and decreased as the soil dried out in late summer (Fig. 3.4).

3.3 The impact of green biomass on energy variables for wet and dry periods

3.3.1. Wet periods

Wet periods were selected for this analysis as one to four days after the rain events when R_n exceeded 300 Wm^{-2}. In 2001, 2002, and 2003 there were 30, 13, and 26 days, respectively, which qualified as wet periods.

We observed a clear pattern of higher L_e with higher green biomass (Fig. 3.6). Moreover, during these wet periods, latent heat fluxes (evaporation and transpiration) for the HG treatment were generally higher than for the UG and MG treatments and this difference increased as green biomass increased. Observations of *H*, were highly variable and did not correlate with grazing intensity or green biomass. There were no significant differences observed for G_o (not shown).

To evaluate near-surface energy flow, we looked at the gradient in air temperature between 1 m and 2 m. During wet periods, the air temperature decreased as green biomass increased but there were no apparent differences due to grazing treatment (Fig.3.7).

3.3.2 Dry periods

We defined dry periods as periods with little or no precipitation when the BR was greater than three. In 2001, 2002, and 2003 there were 23, 80, and 18 days classified as dry periods. No clear relationship was observed between energy fluxes (Fig. 3.8) or air temperature gradients (not shown) and amount of green biomass during those dry periods. Values of L_e were always lower than H in dry periods with green biomass higher than 20 g m^{-2} (Fig. 3.8).

3.4 Surface energy and temperature

On a seasonal basis, grazing treatment did not impact inter-annual differences in mean, maximum, or minimum air temperatures for the study period. Therefore, air temperatures were averaged for all treatments (Table 3.3).

Under low wintertime humidity, there was no significant difference between T and T_e (Fig. 3.9). When the humidity was higher during the growing season, differences between T and T_e increased (Fig. 3.9). During the dry year (2002) T_e was lower than the years (2001 and 2003) with relatively normal precipitation levels (Table 3.3). No grazing treatment differences were found for T_e.

IY. DISCUSSION

Short-term changes in grazing intensity had little impact on this semiarid grassland which is characterized by relatively low production and standing biomass. Our results confirm the findings of Milchunas et al. (1994), Ojima et al. (1993a,b), Lauenroth and Sala (1992) that variability of forage production may be explained primarily by precipitation and soil moisture (Knapp et al. 2007), and the magnitude of that variability in forage production was more sensitive to annual fluctuations in precipitation than to short-term differences in grazing intensity. The lack of early-season rainfall in 2002 led to extremely low biomass production despite late-season precipitation events.

The general lack of major differences in near-surface fluxes between grazing treatments (Table 3.2) may be due to higher soil temperatures at the grazed sites possibly causing greater emissions of near-surface longwave radiation, as suggested by Bremer et al. (2001). On the other hand grazing treatment resulted in more uniform horizontal distribution of aboveground biomass (Milchunas et al. 1989). Grazing did not significantly influence crown biomass but there was a tendency for the relative contribution of crown material to total plant biomass to increase with grazing in SGS (Sims et al. 1978). In 2003, however, R_n was consistently and statistically significantly higher at the HG site than at the UG and MG sites throughout the growing season (Fig. 3.5). Contrary to our expectation, we found the lowest H and the highest L_e in the HG treatment. This relationship was somewhat amplified later in the growing season, possibly due to necromass accumulation, more uniform crown cover and a resultant decrease in albedo. Therefore, we suggest that further measurements of albedo are necessary to better understand the amount of absorbed incoming radiation.

We did not find any significant grazing treatment effects on air temperature. Most of the time, however, the grazed pastures had higher soil mean and maximum temperature than the UG pasture, as was suggested by Parton (1984) and Milchunas et al. (1989).

Overall, seasonal patterns of energy fluxes; higher L_e and lower H during the first half of the growing season and higher H and lower L_e at the second half of the season, and spikes in fluxes with each precipitation event (Fig. 3.4) were as expected. We clearly observed that green biomass increased with increasing latent heat flux and decreasing sensible heat flux during the wet periods (Fig. 3.6) but not during the dry periods (Fig. 3.8). It is likely that years with higher production would better illustrate these relationships (Milchunas and Lauenroth 1993). Inter-annual variability in energy partitioning between dry and normal years was observed (Table 3.2).

We did not find major grazing treatment effects on surface heat energy and effective temperature. This is due to a lack of clear response of the energy budget to grazing treatments, and no responses of humidity with sufficient magnitude between grazing treatments (Fig. 3.9). As is typical of many ecosystem responses in this strongly water-limited grassland system, inter-annual and seasonal variations in humidity have greater influence on the ecosystem than the comparatively subtle effects of grazing.

V. CONCLUSIONS

We evaluated the energy budget of three grazing treatments during two years with near-normal precipitation and a one year with very low precipitation at the SGS-LTER site, a semi-arid grassland, using the BREB method. We studied the relationship between aboveground biomass and surface heat, energy fluxes, and temperature based on continuously measured 20 minute interval data.

We found clear seasonal and inter-annual variability that followed expectations for most response variables. The UG pasture tended to have more green biomass than the grazed pastures although no statistically significant. The necromass followed the same pattern later in the growing season during years with near-normal precipitation. We did not find major differences among grazing treatments in aboveground biomass or energy fluxes. This follows findings by LeCain et al. (2000, 2002), showing mostly minor impacts of grazing treatments on seasonal and short-term CO_2 exchange. We found the same to be true for ET rate and energy fluxes in this study. Although we did not find major green biomass differences between grazing treatments at the SGS-LTER site, differences in total annual precipitation resulted in significant differences in green biomass (Table 3.1). The seasonal distribution of precipitation was a major determinant of plant growth in SGS-LTER site. At global scale, aboveground biomass is more sensitive to ecosystem-environmental variables than grazing and grazing at the SGS-LTER site has unusually small impacts relative to grasslands elsewhere in the world (Milchunas and Lauenroth 1993).

We clearly observed a pattern of higher latent heat flux with higher biomass during wet periods (Fig. 3.6). This suggests a potential impact of grazing on energy budgets if grazing treatments had led to a measurable difference on green biomass.

There were no major difference in green and total biomass among the three levels of grazing, making it difficult to detect treatment effects. Given that “the energy balance will not close perfectly at every timescale all the time even in the very best dataset from an ideal experimental site” (Kabat et al. 2004), measurements of biomass performed with greater frequency may have yielded measurable responses to grazing. This is something to consider in future studies of this semiarid system, one that is characterized by seasonally- and annually-important responses to short-term events of relatively small magnitude.

Further measurements of albedo are necessary to investigate the amount of absorbed incoming radiation for different grazing treatments. In addition, it would be useful to have separate estimates of water loss via evaporation and transpiration to be able to distinguish water loss from the soil surface versus the vegetation. We recommend further testing of the assumption that grazing treatments should have an impact on the surface energy budget when green biomass is significantly impacted. Metrics of leaf area index, vegetation greenness and albedo using remote sensing technology would help in the study of surface energy budgets because of more continuous data availability.

ACKNOWLEDGEMENTS

The first author sincerely thanks all of the co-authors who contributed and supported this energy budget study at the SGS-LTER site. Special thanks to Lara Prihodko and Robin Kelly for data processing and Robin Kelly, Dallas Staley and Daniel Milchunas for helpful editing on the manuscript. This work was supported in part by the Shortgrass Steppe Long Term Ecological Research project by funds from the National Science Foundation award DEB 0217631.

LIST OF REFERENCES

Bremer D.J., L.M. Auen, J.M. Ham, and C.E. Owensby 2001. Evapotranspiration in a prairie ecosystem: Effects of grazing by cattle. *Agron.J*. **93**, 338-348.

Brutsaert, W., 1982: Evaporation into the Atmosphere. Reidel Publishing Company, Dordrecht, Holland, 299 p.

Chapin, S.F., P.A. Matson, and H.A. Mooney, 2002: *Principles of Terrestrial Ecosystem Ecology.* Springer, New York, 436 p.

Dugas, W.A. 1993. Micrometeorological and chamber measurements of CO_2 flux from bare soil. *Agric. For. Meteorol.*, **67,** 115-128

Dugas, W.A., M.L. Heuer, and H.S. Mayeux. 1999. Carbon dioxide fluxes over bermudagrass, native prairie, and sorghum. *Agric. For. Meteorol*., **93,** 121-139.

Ferretti D.F., E. Pendall, J.A. Morgan, J.A. Nelson, D. LeCain and A.R. Mosier. 2003. Partitioning evapotranspiration fluxes from a Colorado grassland using stable isotopes: Seasonal variations and ecosystem implications of elevated atmospheric CO_2. *Plant and Soil,* **254,** 291–303.

Hanamean Jr., J.R., R.A Pielke Sr., C.L. Castro, D.S. Ojima, B.C. Reed, and Z. Gao. 2003: Vegetation impacts on maximum and minimum temperatures in northeast Colorado. *Meteorol. Appl*., **10,** 203-215.

Kabat, P., M. Claussen, P.A. Dirmeyer, J.H.C. Gash, L.B. Deguenni, M. Meybeck, R.A. Pielke Sr., C.J. Voeroesmarty, R.W.A. Hutjes, and S. Luetkemeier editors. 2004: *Vegetation, Water, Humans and the Climate: A New Perspective on an Interactive System*. Springer-Verlag, Berlin, Heidelberg, 566 p.

Klipple, G.E., and D.F. Costello. 1960. Vegetation and cattle response to different intensities of grazing on shortgrass ranges on the central Great Plains. USDA Technical Bulletin 1216, USDA, Washington, D.C., USA.

Knapp. A.K., J.M. Briggs, D.L. Childers, O.E. Sala. 2007. Estimating Aboveground Net Primary Production in Grassland- and Herbaceous-Dominated Ecosystems. in editors Fahey T.J., and A.K. Knapp. Principles and Standards for Measuring Primary Production. Oxford University Press. US. 268 p.

Lapitan, R.L., and W.J. Parton. 1996. Seasonal variabilities in the distribution of the microclimatic factors and evapotranspiration in a shortgrass steppe. *Agric. Forest Meteorol*., **79**, 113-130.

Lauenroth, W.K. and D.G. Milchunas. 1991: Short-grass steppe. Pages 183-226 *in* R.T. Coupland (editor) Ecosystems of the World 8A: Natural Grasslands. Elsevier, Amsterdam.

Lauenroth, W.K. and O.E. Sala. 1992. Long-Term Forage Production of North American Shortgrass Steppe. *Ecological Applications*, **2:4**, 397-403

LeCain, D.R., J.A. Morgan, G.E. Schuman, J.D. Reeder and R.H. Hart. 2000. Carbon exchange rates in grazed and ungrazed pastures of Wyoming. *J. Range Manage*., **53**, 199-206

LeCain, D.R., J.A. Morgan, G.E. Schuman, J.D. Reeder and R.H. Hart. 2002. Carbon exchange and species composition of grazed pastures and exclosures in the shortgrass steppe of Colorado. *Agriculture, Ecosystems & Environment*, **93:1-3**, 421-435

Lu, L., R.A. Pielke Sr., G.E. Liston, W.J. Parton, D. Ojima, and M. Hartman. 2001. Implementation of a two-way interactive atmospheric and ecological model and its application to the central United States. *J. Climate*, **14**, 900-919.

Milchunas, D.G., O.E. Sala, and W.K. Lauenroth, 1988: A generalized model of the effects of grazing by large herbivores on grassland community structure. *The American Naturalist*, **132:**1, 87-106.

Milchunas, D.G., W.K. Lauenroth, and P.L. Chapman et al. 1989. Plant communities in relation to grazing, topography, and precipitation in a semiarid grassland. *Vegetation*, **80,** 11-23.

Milchunas, D.G. and W.K. Lauenroth, 1993: Quantitative effects of grazing on vegetation and soils over a global range of environments. *Ecological Monographs*. **63:4**, 327-366.

Milchunas, D.G., J.R. Forwood, and W.K. Lauenroth, 1994: Productivity of long-term grazing treatments in response to seasonal precipitation. *J. Range Manage*. **47**, 133-139.

Morgan, J.A., D.R. Lecain, S.J. Reeder, G.E. Schuman, J.D. Derner, W.K. Lauenroth, W.J. Parton, I.C. Burke. 2004. Drought and grazing impacts on CO_2 fluxes in the Colorado shortgrass steppe. Ecological Society of America Proceedings.

Ojima, D.S., W.J. Parton, D.S. Schimel, and J.M.O. Scurlock, 1993a. Modeling the effects of climatic and CO_2 changes on grassland storage of soil C. *Water, Air and Soil Pollution*, **70,** 643-657.

Ojima, D.S., B.O.M. Dirks, E.P. Glenn, C.E. Owensby, and J.M.O. Scurlock. 1993b: Assessment of C budget for grasslands and drylands of the world. *Water, Air and Soil Pollution*, **70**, 95-109.

Parton, W.J., W.K. Lauenroth, and F.M. Smith, 1981: Water loss from a shortgrass steppe. *Agric. Forest Meteorol.*, **24**, 97-109.

Parton, W.J., 1984: Predicting soil temperature in a shortgrass steppe. *Soil Sci.*, **138:2**, 93-101.

Pielke Sr., R.A., C. Davey, and J. Morgan, 2004. Assessing "global warming" with surface heat content. *EOS*, **85**, 210-211.

Pielke Sr., R.A., K. Wolter, O. Bliss, N. Doesken, and B. McNoldy, 2005. The July 2005 Denver heat wave: How unusual was it? *Natl. Wea. Dig.*, **31**, 24-35.

Przeszlowska, A., M. Trlica and M. Weltz. 2006. Near-ground remote sensing of green area index on the Shortgrass Prairie. *Rangeland Ecol. Management*, **59**, 422-430.

Sala, O.E. and W.K. Lauenroth. 1982. Small rainfall events: An ecological role in semiarid regions. *Oecologia*, **53**, 301-304.

Sims, P.L., J.S. Singh and W.K. Lauenroth. 1978. The structure and function of ten western North American grasslands. *Journal of Ecology*, **66**, 251-285.

Singh, J.S., D.G. Milchunas, and W.K. Lauenroth, 1998. Soil water dynamics and vegetation patterns in a semiarid grassland. *Plant Ecology*, **134**, 77-89.

SPSS, Inc SPSS. 2004: SPSS 13.0 Base Users Guide. Pearson. 712p.

LIST OF TABLES

LIST OF FIGURES

Table 3.1. Mean and maximum green biomass and leaf area index (LAI) in different grazing treatments.
UG – ungrazed; MG – moderately grazed; HG – heavily grazed

	Grazing treatments	2001	2002	2003
Green biomass (gm^{-2})	UG	47.5	11.0	55.1
	MG	43.8	7.3	45.6
	HG	36.2	9.2	40.3
	Mean	42.5	9.2	47.0
	Maximum	102.6	23.6	145.3
Leaf Area Index (m^2m^{-2})	UG	0.253	0.093	0.287
	MG	0.237	0.076	0.245
	HG	0.203	0.085	0.221
	Mean	0.231	0.084	0.251
	Maximum	0.495	0.148	0.683

Note: LAI data for 2001 and 2002 are from the measurements but for 2003 is converted from the biomass data using the following equation:
LAI=Biomass × 0.0044+0.044 (R^2 = 0.79).

Table 3.2. Mean net radiation (R_n), soil (G_o), sensible (H), and latent (L_e) heat fluxes for the growing season of 2001-2003 years for each grazing treatment.
UG – ungrazed; MG – moderately grazed; HG – heavily grazed

Energy fluxes	Grazing treatments	2001	2002	2003
R_n, Wm^{-2}	UG	285	273	278
	MG	283	285	289
	HG	292	276	305
	Mean	287	278	291
G_o, Wm^{-2}	UG	49	52	48
	MG	59	63	42
	HG	54	55	48
	Mean	54(19%R_n)	57(20%R_n)	46(16%R_n)
H, Wm^{-2}	UG	125	174	146
	MG	117	169	137
	HG	124	165	132
	Mean	122(43%R_n)	169(61%R_n)	138(47%R_n)
L_e, Wm^{-2}	UG	110	48	85
	MG	106	53	110
	HG	114	56	126
	Mean	110(38%R_n)	52(19%R_n)	107(37%R_n)

Table 3.3. Mean (T_{air}) and effective (T_e) temperatures and moist enthalpy (H_e) for the growing season of 2001-2003 years averaged for all grazing treatments.

Variables		2001	2002	2003
	Mean	16	16	16
T_{air}, ^oC	Maximum	36	38	38
	Minimum	-12	-14	-16
	Mean	28	27	27
T_e, ^oC	Maximum	61	56	59
	Minimum	-9	-11	-13
H_e, J kg^{-1}	Mean	317	313	315

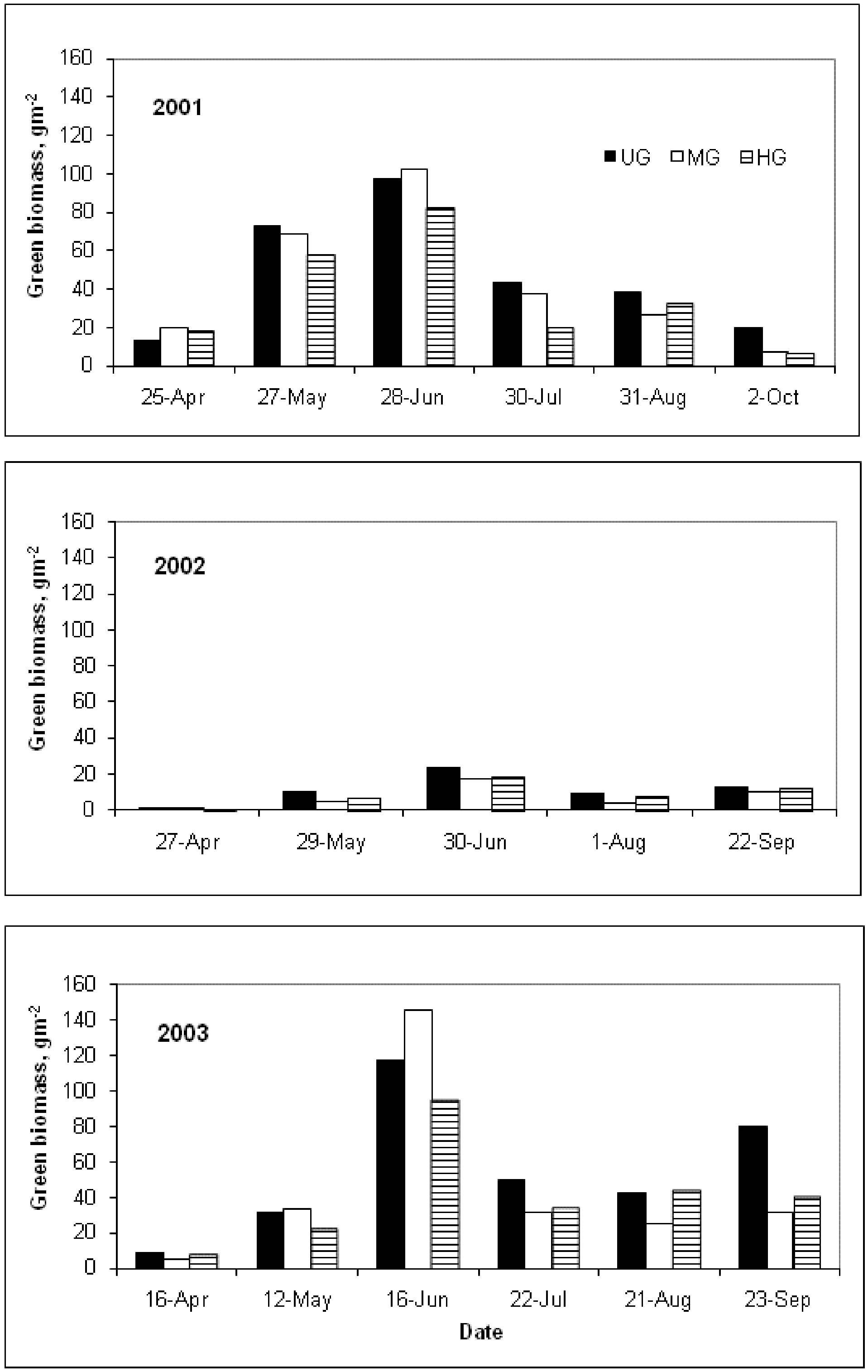


Figure 3.1. Seasonal variation of green biomass for each grazing treatments in 2001-2003. UG –ungrazed, MG –moderately grazed, HG –heavily grazed ■ UG; □ MG; ═ HG

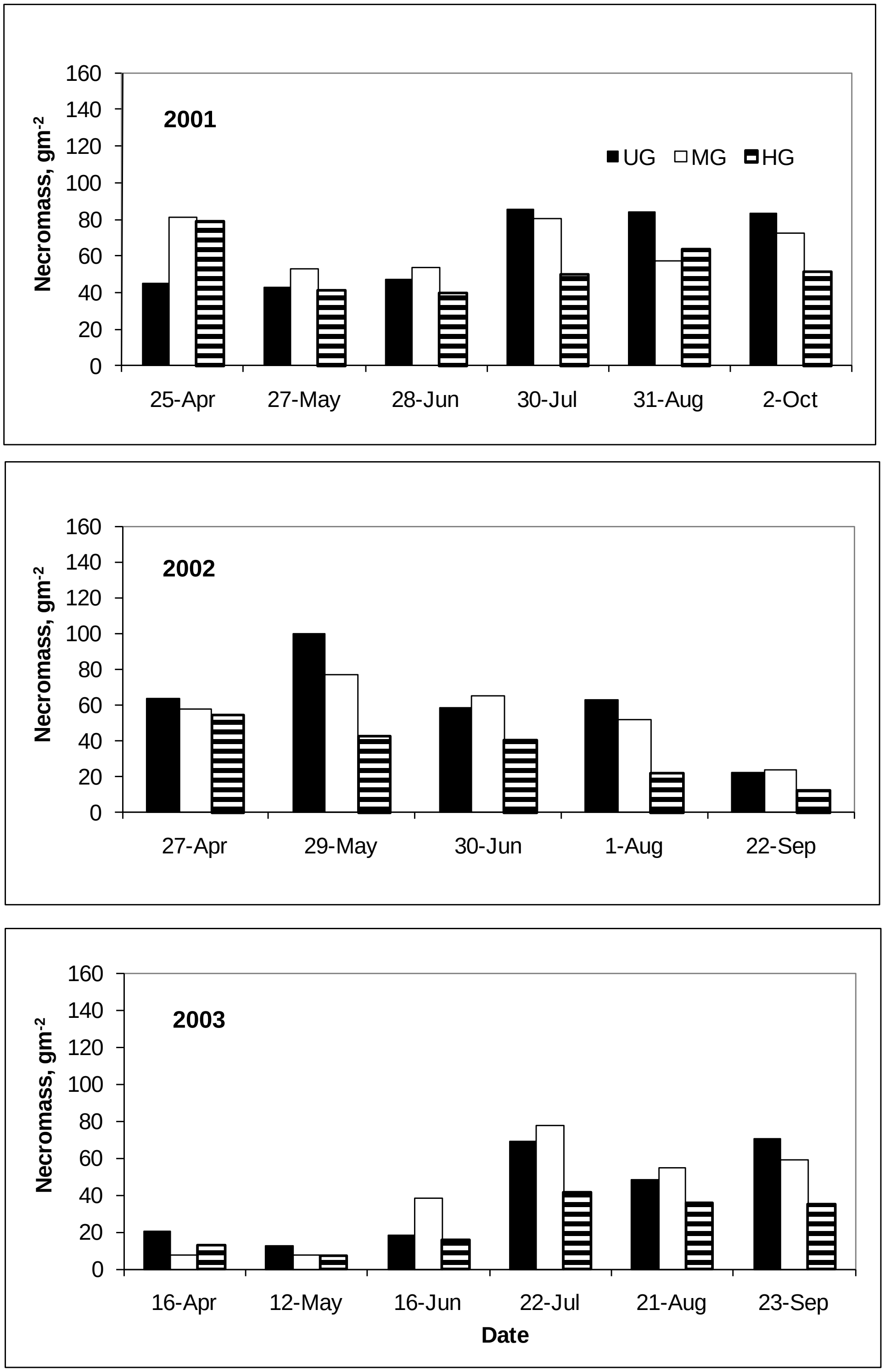


Figure 3.2. Seasonal variations of necromass for each grazing treatments in 2001-2003.
UG – ungrazed; MG – moderately grazed; HG – heavily grazed ■ UG; □ MG; ═ HG

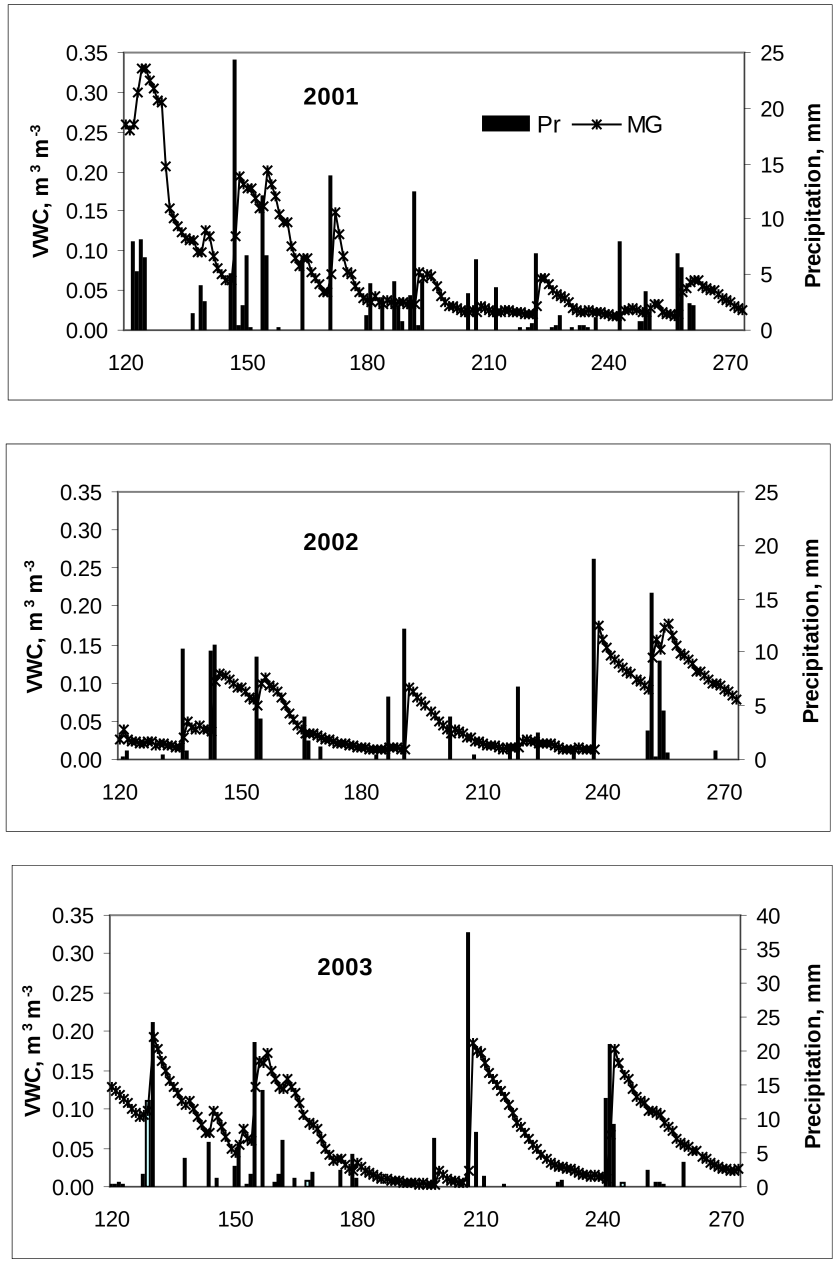


Figure 3.3. Volumetric soil water content (*VWC*) and Precipitation (*Pr*) in the moderately grazed (MG) site for 2001-2003. ▬ *Pr*; line with -x- indicate VWC.

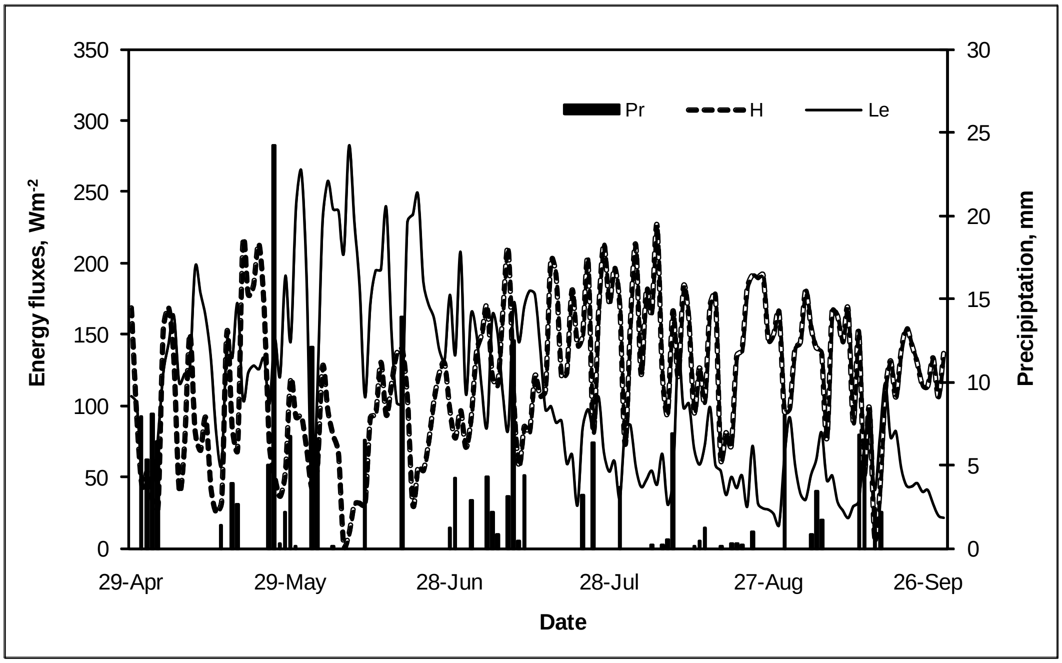


Figure 3.4. Latent (L_e) and sensible (*H*) heat energy fluxes and precipitation (*Pr*) for moderately grazed site in 2001. ▬ Pr; ---- H; —— L_e.

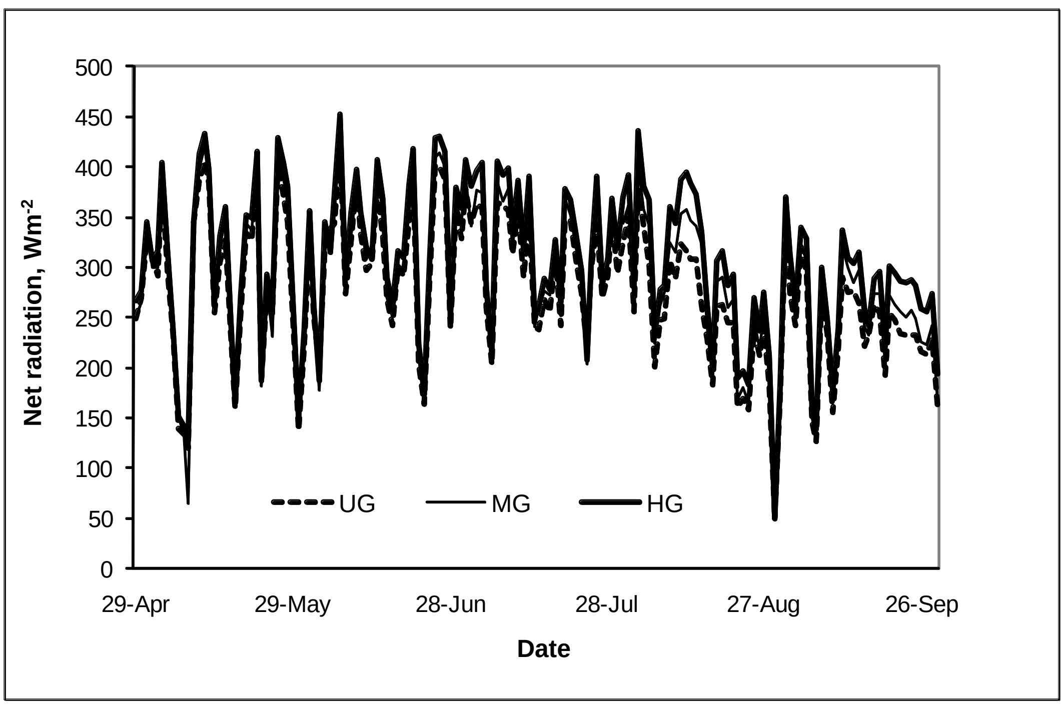


Figure 3.5. Net radiation for all grazing treatments in 2003. UG – ungrazed; MG – moderately grazed; HG – heavily grazed; _ _ _ UG; ____ MG; ____ HG.

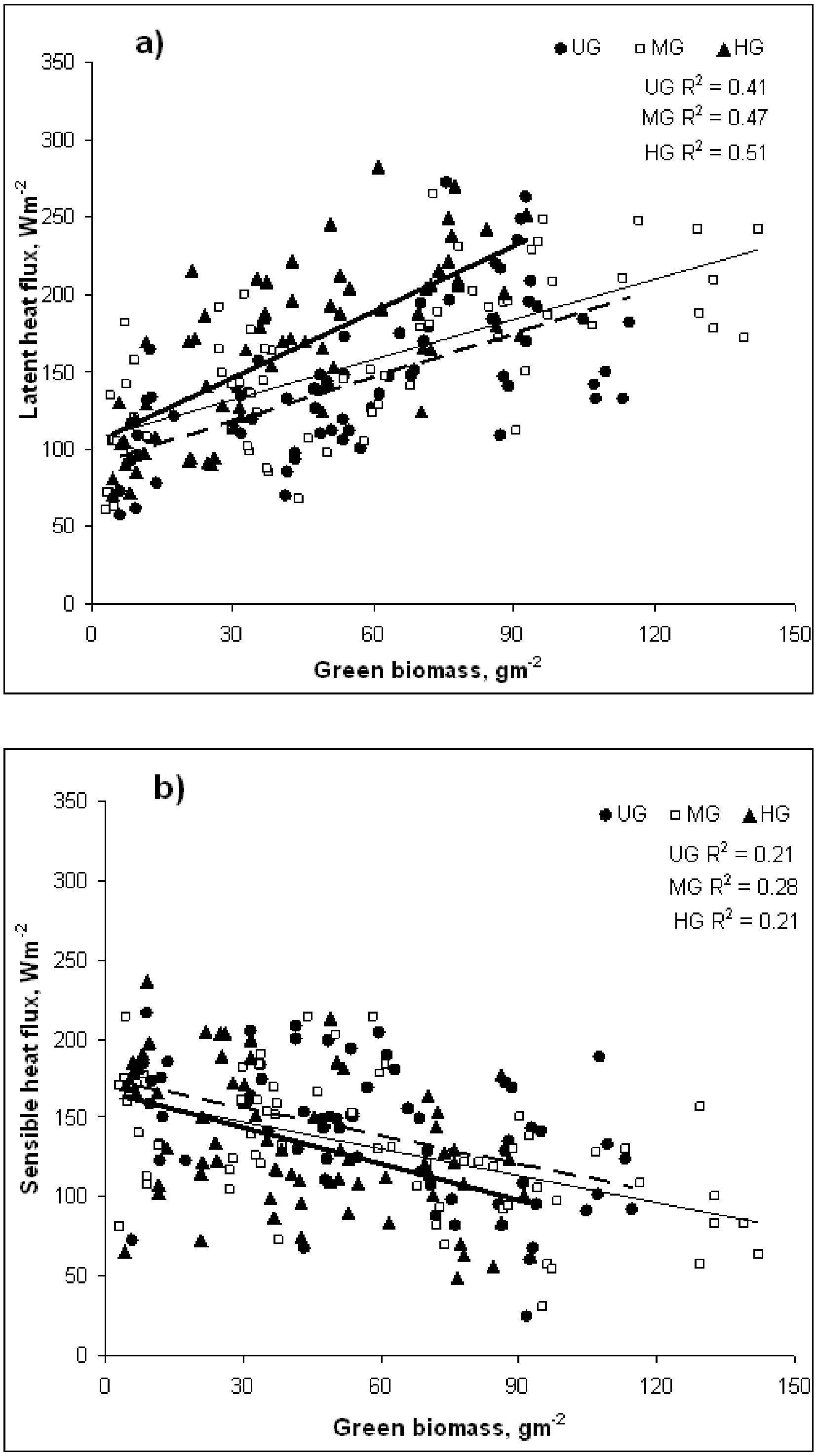


Figure 3.6. Latent (a) and sensible (b) heat fluxes versus green biomass for wet days (for all years). UG – ungrazed; MG – moderately grazed; HG – heavily grazed ● UG; _ _ _ UG linear trend; □ MG; ____ MG linear trend; ▲ HG; ____ HG linear trend.

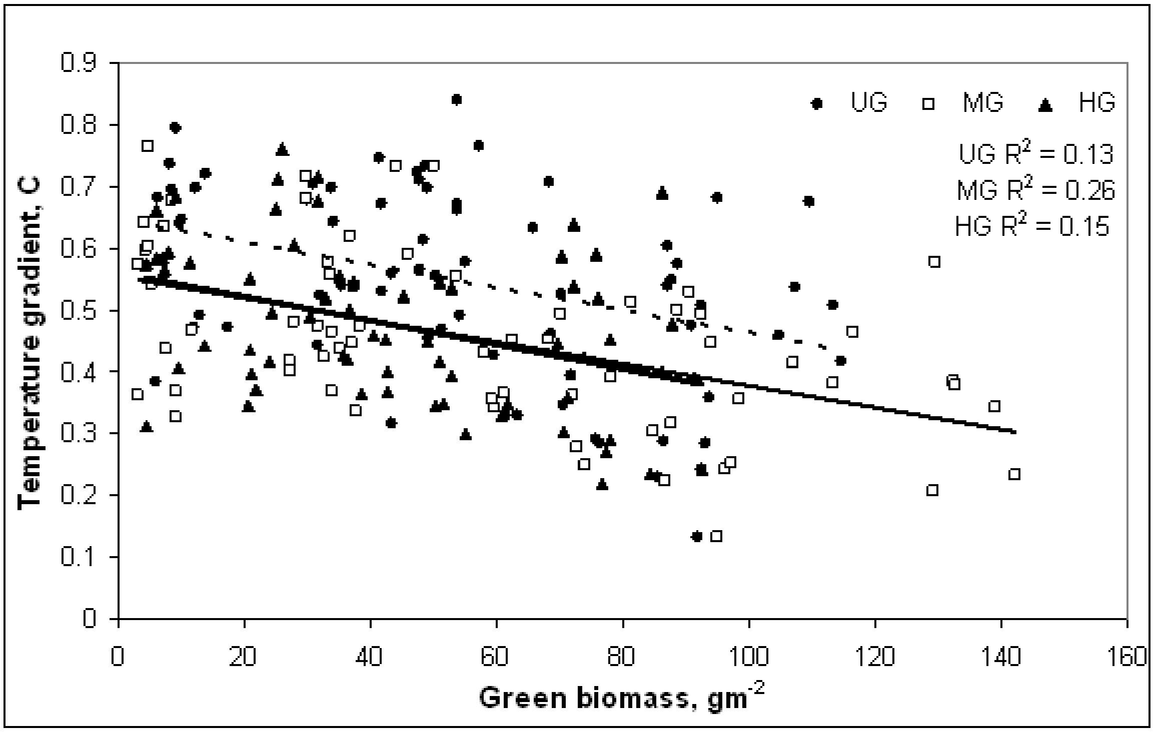
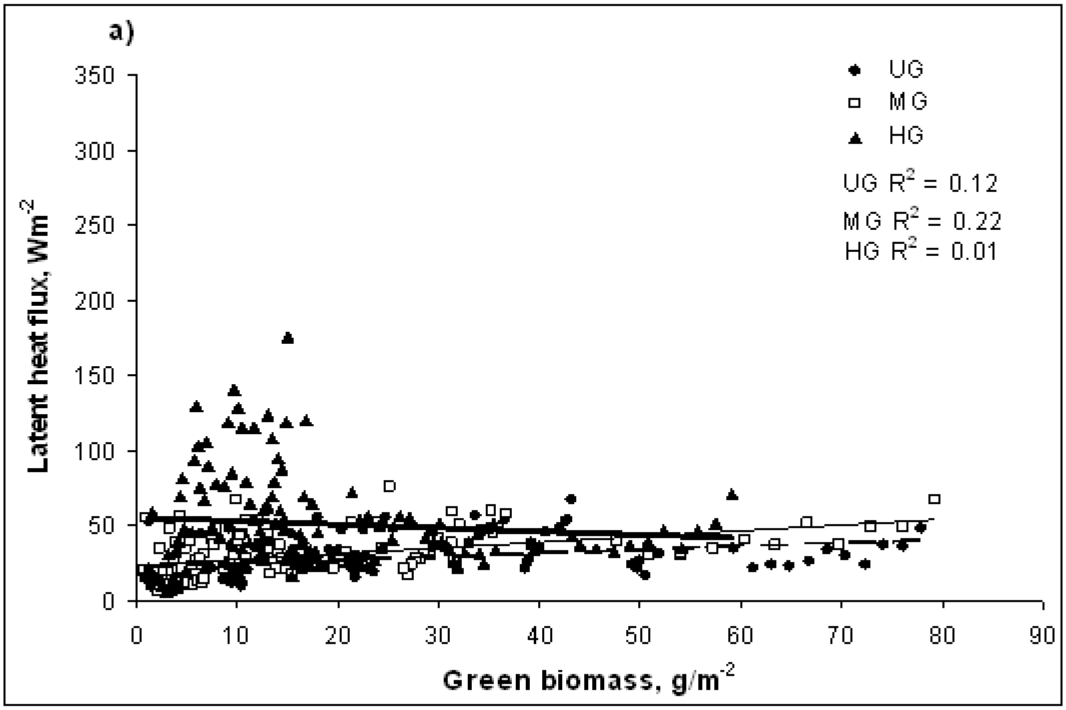


Figure 3.7. Air temperature gradient versus green biomass for wet days and all grazing treatments. UG – ungrazed, MG – moderately grazed, HG – heavily grazed
● UG; _ _ UG linear trend; □ MG; ____ MG linear trend; ▲ HG; ____ HG linear trend.



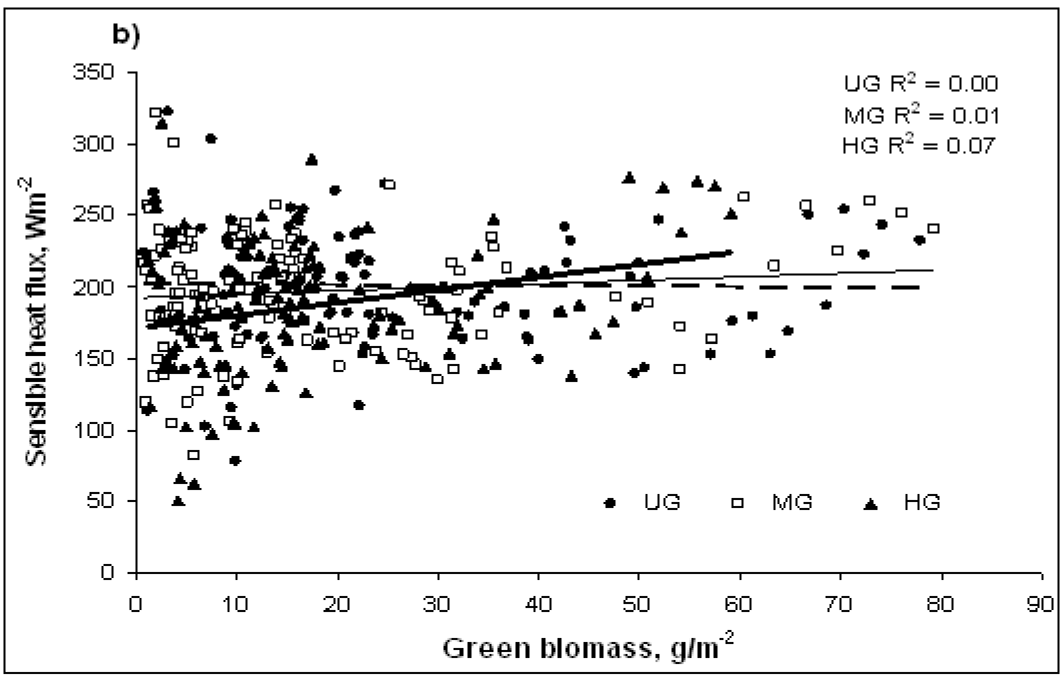


Figure 3.8. Latent (a) and sensible (b) heat fluxes versus green biomass for dry days (for all years). UG – ungrazed; MG – moderately grazed; HG – heavily grazed
● UG; _ _ UG linear trend; □ MG; ____ MG linear trend; ▲ HG; **____** HG linear trend.

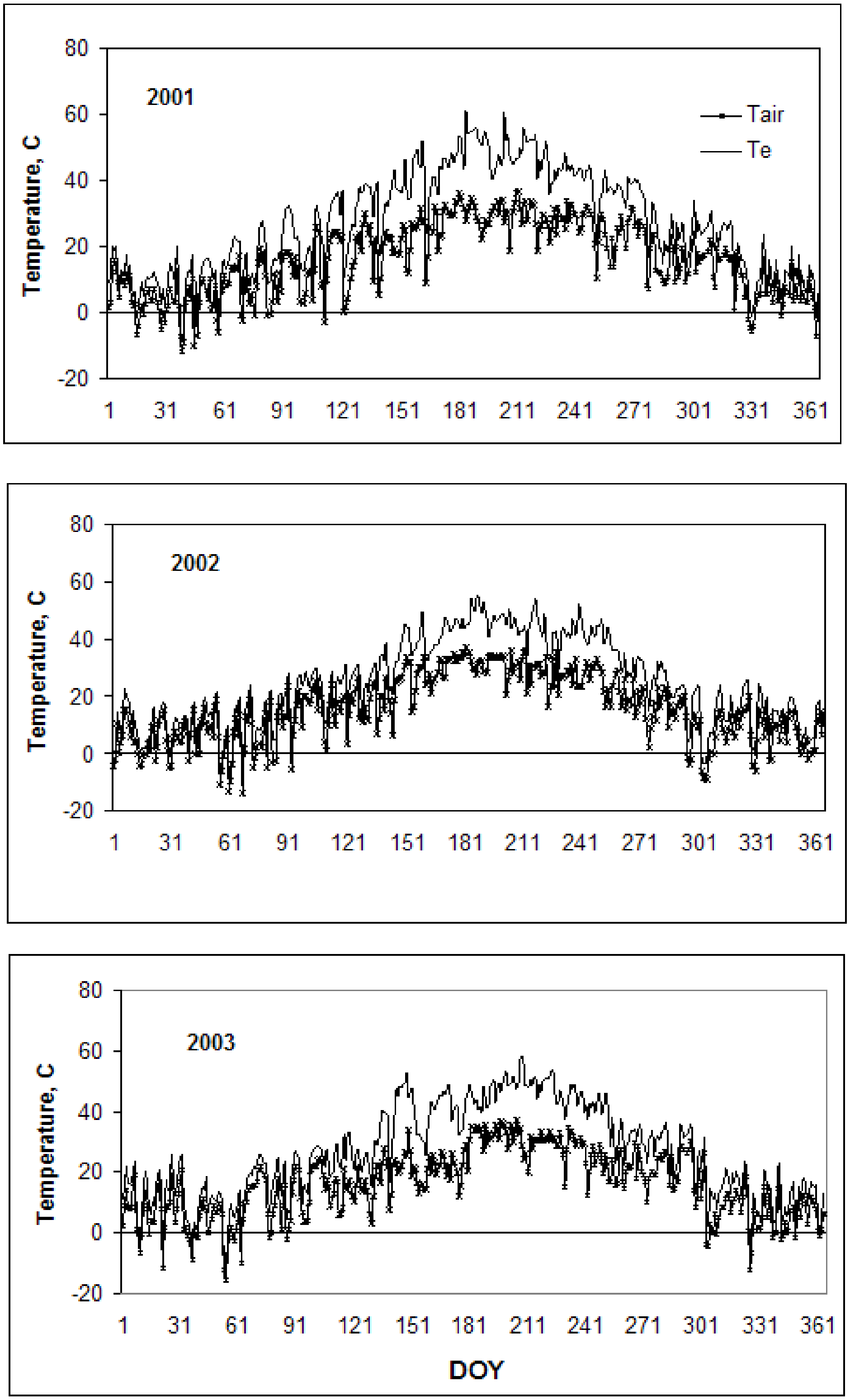


Figure 3.9. Air (line with x) and effective (line) temperatures (°C) averaged for all grazing treatments at 14:00 Mountain Standard Time: 2001-2003 years. DOY - Day of year

DISSERTATION CONCLUSIONS

This study evaluated the long-term climate change in Mongolia, one of the biggest continental regions of Asia, based on 17 meteorological stations' meteorological data. From the exposure characteristics survey of total 17 stations, 47 percent are qualified as strongly influenced by urban character landscape, 41 percent received some anthropogenic influences, and 12 percent had very little to no anthropogenic influences. Consequently, this implies the global-averaged temperature anomalies based on the data from these stations do not completely satisfy WMO standards. Therefore, strict adherence in following WMO guidelines is important and urgently needed. Proper action such as removing at least unused objects close to the instruments are recommended.

In addition to that, the study included the comparisons of surface and upper air trends at above-mentioned 17 stations and suggested effective temperature as an appropriate metric to measure the warming instead of air temperature. The main climate change indices were calculated at 17 stations based on the surface stations' daily data and long-term (1961-2004) versus decadal (1998-2007) temperature trends for annual and seasonal trends have been evaluated within this dissertation for further use of global and regional climate study. According to the linear trend analysis from 1961 to 2004, the highest annual and seasonal temperature changes mostly occurred in the coldest north western mountain area of the country. The least changes occurred in the eastern plain. The results supported our hypotheses that the most temperature increase occurred during the winter months. The annual T_{max} significantly increased at eleven stations and slightly (not significant) increased at six stations. The annual minimum temperature significantly increased at sixteen stations and slightly decreased at Ondorkhaan station. Mostly, the maximum and minimum temperatures significantly increased in winter and summer seasons and slightly increased during spring and fall seasons. Some of the stations had decreasing trends but none were significant. In addition, Mongolian grasslands degraded rapidly in recent years due to severe droughts and decertification that increases the sensible heat energy partitioning in the surface energy budgets as we studied in the case study at the SGS. This contributes to increases in the air temperature throughout the country.

We observed the similar trends in seasonal surface heat, effective temperature and 2 m air temperature for winter, spring and fall at 17 stations but not for the summer when the air humidity is higher. During the summer, some of the stations (8 out of 17) had opposite temperature and surface trends. This indicates the temperature increase (or decrease) does not really mean the surface heat increase (or decrease) because it also depends on the humidity. Therefore, we are suggesting effective temperature as an appropriate metric to measure warming instead of air temperature. The most of the stations decadal temperature analysis indicate decreasing trends during the winter and spring due to very cold winter and spring of 2000, 2002 and especially 2005, which was not included in the long-term (1961-2004) trend. Ten, 13, 5, 2, and 2 stations had decreasing T_{mean} trends respectively for winter, spring, summer, fall and annual, which are opposite from long-term trends.

According to the 17 climate change indices, most of the stations frost and icing days decreased and summer days, tropical nights, monthly maximum value of daily minimum and maximum temperatures are increased. In addition to that, GSL increased at all sites. Clearly, we observed temperature increasing trends at most of the stations. Precipitation indices varied a lot and there were no unified temporal and spatial pattern. The linear trend diminishes the biggest monthly changes and the annual and seasonal precipitation changes were not significant. The most precipitation change occurred in the summer (mainly decreased). The standard deviations and coefficient of variations were very high. Our comparisons of surface temperature data to the upper air (at 500 and 700 mb level) ECMWF and NCEP model data for the selected nine (GCON) stations show that the best correlations between surface and ECMWF data.

We studied the relationship between aboveground biomass and surface heat, energy fluxes at the SGS-LTER site as a case study, to describe semiarid grassland surface energy budgets. We found clear seasonal and interannual variability that followed expectations for most response variables. For example; the ungrazed pasture tended to have more (not significant) green biomass than the grazed pastures and the necromass followed the same pattern later in the growing season during years with near-normal precipitation. We did not find big differences among grazing treatments in aboveground biomass or energy fluxes but we clearly observed a pattern of higher latent heat flux with higher biomass during wet periods. This suggests a potential impact of grazing on energy budgets if grazing treatments had led to a measurable difference on green biomass. There were no major difference in green and total biomass among the three levels of grazing, making it difficult to detect treatment effects. Based on our findings, we suggest that further measurements of albedo are necessary to investigate the amount of absorbed incoming radiation. In addition, it would be useful to have separate estimates of water loss via evaporation and transpiration to be able to distinguish water loss from the soil surface versus the vegetation. Further testing of the assumption that “grazing treatments should have an impact on the surface energy budget when green biomass is significantly impacted among treatments” is recommended. Estimations of leaf area index, vegetation greenness and albedo using remote sensing technology would help in the study of surface energy budgets because of more continuous data availability.