No.

JAPAN INTENRATIONAL COOERATION AGENCY (JICA)

NATIONAL COMMISSSION FOR WILDLIFE
CONSERVATION & DEVELOPMENT

# THE JOINT STUDY PROJECT
# ON
# THE CONSERVATION OF JUNIPER WOODLANDS
# IN
# THE KINGDOM OF SAUDI ARABIA

## FINAL REPORT

January 2007

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## FOREWORD

The juniper forest is a critical part of the biodiversity of the Kingdom and increasing emphasis is placed on its sustainable management. It was in this context that the joint project between NCWCD and JICA, as part of the bilateral cooperation between the Kingdom of Saudi Arabia and Japan, was initiated to study the ecology and conservation of the juniper woodlands particularly with a view to decipher the complex phenomena of die-back and die-off. This report presents the findings of the joint, multidisciplinary team that carried out the studies during the period 1999-2002.

The report addresses a wide range of topics including field ecology, labouratory studies of pathogenic microbes, climatic profiles and social studies. Although we still need to undertake further investigations to conclusively prove the cause of the twin syndromes of die-back and die-off, the study concludes that the two phenomena are unrelated to each other. The study also clearly rules out the possibility of die-back being a traditional pruning of the trees enhances susceptibility to die-back. The suggestion of climate change as a possible causative factor of die-back is worth further investigation. The fact that 460 plant species have been collected from the area underlines its importance as a key biodiversity site in the Kingdom. The recommendations for conservation actions provided in the report will be appropriately addressed in NCWCD's future work in the area.

The conservation and sustainable use of biodiversity is placed within the national development strategy and this is to be further taken forward with the active participation of the local communities. Restoration of critical species and the establishment of a national system of protected areas are milestones in our conservation work. However tireless efforts are needed to maintain the conservation achievements and to attain further progress. Scientific research such as the present work will be crucial in this respect.

NCWCD values our long time cooperation with JICA and compliments the researchers for this well-carried out study.

**National Commission for Wildlife Conservation and Development (NCWCD)**
**Kingdom of Saudi Arabia**

## FOREWORD

In response to a request from the Kingdom of Saudi Arabia, the Government of Japan decided to conduct a study on "The Joint Study Project on the Conservation of Juniper Woodlands in The Kingdom of Saudi Arabia" and entrusted the implementation of the study to the Japan International Cooperation Agency (JICA).

The purpose of the study is to make clear the serious die-back phenomena of Juniper woods in the Kingdom and to propose a management plan for the conservation, regeneration and sustainable utilization of Juniper woodlands.

JICA dispatched a study team consisting of Japanese researchers between April 1999 and March 2002. The Japanese researchers and Saudi Arabian researchers organized a joint study team and carried out praiseworthy studies in mountainous regions in the Kingdom. Upon returning to Japan, the team undertook further studies and prepared this final report.

We hope that this report will contribute to the improvement in conservation of Juniper woodlands and to the enhancement of friendly relationship between the two countries.

Finally, I wish to express my sincere appreciation to the concerned officials and other related people of the Kingdom of Saudi Arabia for their close cooperation extended to the study team.

**Japan International Cooperation Agency (JICA)**
**Japan**

# PREFACE

Areas where trees grow collectively are called woodlands. The total area of woodlands in Saudi Arabia is estimated to be 27,000 km2 (1.2% of the total land). Juniper woodlands are dominated trees belonging to genus Juniperus and occur in the semi-arid montane regions of the Arabian Peninsula. The Juniper woodlands in the Asir Mountains are estimated to occupy about 7,600 km2 and represent 28.1% of the total woodlands of the Kingdom.

The genus Juniperus is represented by three species, J. phoenicea, J. excelsa and J. procera, in the Arabian Peninsula. Among them two species, J. phoenicea and J. procera occur in Saudi Arabia. Juniperus excelsa is represented by subsp.polycarpos and is found only in the highest areas of the central massif of Jebel al Akhdhar and the outlying mountains of Jebel Qubal and Jebel Kawr in Oman. Juniperus phoenicea is a Mediterranean element extending the range southeast direction along the Hijaz mountains to ca. 21º N near Taif. Juniperus procera, an East African element distributed mainly in from Tanzania to Ethiopia, occurs patchily in the Asir Mountains of the southwest and west of the Arabian Peninsula.

More than 2,000 years ago, people recognized Juniperus procera, called Ar-ar, and it has been used for various purposes. In the 20th Century, the woodlands in the Asir Mountains were subjected to intense use, which led to the decline of many of them and their associated ecosystems thus the juniper woodlands now remained mainly in the high mountains and deep valleys. It is necessary to enlighten the local people and visitors that the juniper woodlands provide us not only with the actual benefits of firewood, housing materials, and fields for beekeeping, but also indirect benefits such as the protection of water resources, soil protection, air purification, and particularly wildlife habitat and resources of tourism. The value of the Juniper woodlands is considerably increasing under the 21st Century model of human life maintaining higher biodiversity and sustaining natural resources.

Since early 1990's the die-off and serious dieback of the juniper trees have become conspicuous. Die-off is defined here as withering or appearing to be a withering of the whole tree. Dieback is withering of branches gradually from the terminal portion toward the base, but the trees do not always die.

Because the causes of the die-off and dieback were unknown, many Saudi scientists were worried about the disappearance of Juniperus and the Juniper woodlands. The die-off and dieback became a trigger to make a comprehensive study on the conservation and effective management of the Juniper woodlands. In 1999 the National Commission for Wildlife Conservation and Development (NCWCD) and Japan International Cooperation Agency (JICA) established a joint study project on the conservation of the Juniper woodlands in Saudi Arabia.

The project, started in 1999, expired in 2003 and provides some scientific evidence on

Juniperus procera and the Juniper woodlands including regional studies of the Asir Mountains covering various subjects of natural and social sciences.

This report aims to provide our results of the studies for discussing the conservation and effective management of the Juniper woodlands and also discussing the matter on the die-off and dieback.

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A view of Raydah Nature Reserve, near Abha-city, Saudi Arabia.

Photo taken by Kazumori Nagao.

## CONTENTS

# Introduction

Areas where trees grow collectively are called woodlands. The total area of woodlands in Saudi Arabia is estimated to be 27,000 $km^2$ (1.2% of the total land). Juniper woodlands are dominated trees belonging to genus *Juniperus* and occur in the semi-arid montane regions of the Arabian Peninsula. The Juniper woodlands in the Asir Mountains are estimated to occupy about 7,600 $km^2$ and represent 28.1% of the total woodlands of the Kingdom.

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More than 2,000 years ago, people recognized *Juniperus procera*, called Ar-ar, and it has been used for various purposes. In the 20th century, the woodlands in the Asir Mountains were subjected to intense use, which led to the decline of many of them and their associated ecosystems So that now the juniper woodlands remain mainly in the high mountains and deep valleys. It is necessary to enlighten the local people and visitors that the juniper woodlands provide us not only with the actual benefits of firewood, housing materials, and fields for beekeeping, but also indirect benefits such as the protection of water resources, soil protection, air purification, and particularly wildlife habitat and resources of tourism. The value of the Juniper woodlands is considerably increasing under the 21st Century model of human life maintaining higher biodiversity and sustaining natural resources.

This chapter intends to explain the area surveyed, geographical features of the Asir Mountains, and also die-off and dieback of the *Juniperus* in order to provide a comprehensive understanding of the area concerned.

## The area surveyed

Field studies were made at several places in the Asir Mountains, but the detailed analyses were done at the Raydah Nature Reserve.

### The Raydah Nature Reserve.

The main experimental station was prepared in the Raydah Nature Reserve. The reserve was established in 1989 near Abha City (18°23` N – 42°22` E.). It is characterized by its undisturbed habitats and its rich avifauna. The reserve is on a steep slope extending from As-Sahab National Park to Raydah village at the bottom of a valley of which the source is located in the reserve. The highest point of the Reserve is about 2800 meters above sea level and supports a rich and diverse flora. The size of the reserve is about 9 sq. km with various types of vegetations including the Juniper woodlands.

## Geography of the Asir Mountnains

The western chain of mountains lies along the western edge of the Arabian Peninsula and comprises escarpments, deep valleys, rolling lands, rocky hills, wadis, small ponds and seasonal streams. The southwest mountains form a continuous chain of escarpments extending from Taif to the Fayfa Mountains. In the vicinity of Taif and in the Jizan region, the mountains rise to approximate 2000 m. The highest peak, Jabal Soodah, reaches about 3050m. The mountains range from 10 to 40 km wide. The boulder-strewn slopes are covered with woodlands of *Juniperus procera* which are thickest along the lip of the main precipice where they form a pure stand. The plateau is gently inclined to the east and limited westward by a great escarpment descending more than two thousand meters. It features rocky hills composed of large boulders. The wadis are generally dry except for a few weeks, during which the wadis fill with water after heavy monsoon rains.

The Asir Mountains were formed from rocks of the Pre-Cambrian and Cambrian intrusive periods. They contain metamorphosed sedimentary rocks, volcanic rock and green stone, showing lineaments, basement gneiss and late tectonic calc-alkaline granite rocks, (Brown, 1972). Geologically, Fayfa and adjoining mountains, such as Jabal Tallan and Bari Malik, consist of crystalline basement rocks and are characterized by pre-Permian granites, diorites, greenstone, marble and quartizite, imerrupted by Tertiary basalts, andesites and diabases. Gravels, sand, silt and clay are also found at the base of the mountains (Basahy, 1996).

The soil is usually thin and erosive. In certain areas, particularly at Jabal Soodah, the soil is rocky and of various depths and textures, ranging from sandy loam to sand mixed with small rocks.

Exposed rocks are generally brown or darkish brown, due to the presence of iron oxide (Abulfatih, 1984). Fayfa and adjoining mountains of the escarpment and high plateau consists of volcanic rocks. Limestone and sandstone can also be found in many places.

Although the climatic features of the Asir Mountains and other area surveyed will be mentioned in the chapter 1, seasonal change and prominence of the climate are briefly explained.

The climate is more or less temperate in the higher elevations of the Asir Mountains, such as at Jabal Soodah, having cool temperatures, increased amount of fog and relatively high humidity. Rainfall can be expected throughout the year, particularly during the spring and summer. In Abha and Jabal Soodah, the average annual rainfall is about 655 mm, and the mean annual temperature is about 16.5°C.

In and around Jabal Fayfa, Jabal Tallan and Jabal Hashr, where the juniper woodlands are in a highly degraded state, the climate is characterized by cold winters and cool summers. Most of the rain is from April to September. Summer rains usually occur as afternoon thunderstorms in the coastal zone. The eastern slopes are generally dry, with a few unpredictable showers. The climate data from the Fayfa station shows that in winter the mean temperature varies from year to year. In January 1994 the mean temperature was only 13.22°C while in January 1985 it was 21.43°C., whereas in summer it varies from 24.47°C in November 1990 to 27.95°C in July 1991. The highest average rainfall in the Fayfa-mountains was reported to be 168 mm in 1985 and the lowest was reported to be 27.84 mm in 1991.

## Dieback and die-off of *Juniperus procera*

Scientists have various opinions about the cause of the dieback and die-off of Juniperus *procera*. Some are of the view that the major damage and poor regeneration of these trees is due to infestation by the tortricid moth, *Strepsicrates cryptosema* on the female cones (Hajar et al, 1991). This view has been rejected since long-lived *Juniperus*, bearing thousands of cones can produce a sufficient number of viable seeds every year that at least a few of them escape predation (Gardner and Fisher, 1994).

Others suspect that the dieback might be a cyclical phenomenon in juniper woodlands growing under extremely critical conditions. Since trees in the Asir Mountains and elsewhere are of the same age, the dieback may have occurred at regular cycles in the past. All these views have been rejected for one reason or the other. According to a study of *Juniperus excelsa* in the northern mountains of Oman, the poor regeneration of the junipers may be due to human disturbance, grazing

pressure or climatic change (Gardner and Fisher, 1994).

The dieback in the Juniper woodland is a matter of concern to the Government of Saudi Arabia in general and to the National Commission for Wildlife Conservation and Development (NCWCD) in particular.

Fisher (1997) proposed four possible hypotheses (three of which involve climate change), for the dieback in the Raydah Reserve:

1. Overgrazing by livestock has altered the local the vegetation structure, causing woodland decline at lower altitudes through effects on the environment.

2. Global temperature rise in the twentieth century, with elevated spring temperatures in the Middle East, is causing woodland decline through temperature–included dieback in the lower juniper ecotone.

3. Dieback is caused by periodic droughts combined with long regeneration cycles, the effects of which are more marked at lower, hotter elevations.

4. The present arid phase in the climate of Arabia, which began between 4000 and 6500 years ago, is still developing, causing woodland dieback through long–term increase in aridity.

Until now the studies on this matter were quite insufficient and made it nearly impossible to refute any of the hypotehses. It is therefore very urgent to gather substantial evidences to detect the causes of the dieback and die-off to establish a conservation and effective management system of the Juniper woodlands.

Since 1994, NCWCD has undertaken preliminary research on the ailing juniper trees in the southwestern region, assisted by Japanese scientists dispatched from Japan International Cooperation Agency (JICA). Before that Yoshikawa and Yamamoto visited the Asir Mountains in 1985 and made a preliminary survey of the dieback of *Juniperus procera*. After that several Japanese scientists, under the guidance by Chiharu Miyamoto, a long-term JICA expert who worked at NCWCD, visited the Raydah Nature Reserve and the adjacent areas, and carried out preliminary surveys on the following items: 1) to assess the current status of the flora and fauna of the Raydah Nature Reserve, 2) to assess the status of the Juniper woodlands to determine the cause of the dieback and 3) to collect information to develop a management plan for the reserve.

Their preliminary studies concluded that dieback of trees was closely related to environmental stress factors, including water deficiency, low temperature, lack of nutrients, air pollutants, insect attack, overgrazing by herbivorous animals, erosion and disease. They recognised serious degraded

situations of Junpers not only the Raydah Nature Reserve but also Jabal Tallan, Bani Milik, Jabal Fayfa and so on. They discussed causes of the dieback and die-off and thought to make survey of the Juniperus and the Juniper woodlands in order to conserve and manage in helthy condition from the data related to that physiological adaptation of *Juniperus ptocera* to a drought environment, structures and population dynamics of the woodlands, water balance in junipers under fluctuating environmental conditions, species composition and vegetation of the woodlands, and also meteorological characters.

Based on the preliminary studies and in line with discussions with scientists attending a symposium held in 1999 at NCWCD, Riyadh, on the dieback of the *Juniperus*, a project of long term comprehensive researach has been developed. In order to conserve and effectively manage the Juniper woodlands NCWCD has initiated this joint study project in the cooperation with JICA.

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# 1 Climate, meteorology, and hydrology

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## Introduction

For any discussion on the distribution of the juniper woodlands, analysis of the climate becomes indispensable. Knowledge of the climate is also necessary to explain causes of dieback and die-off in these forests. Most available meteorological data, however, is related to cities and limited meteorological data is available for the juniper forests.

We, therefore, constructed a meteorological observation tower and set up three poles with meteorological data recorders using sensors to measure air temperature and humidity in the Raydah Nature Reserve where juniper woodlands are extensive, and the occurrence and density of juniper trees along with dieback and die-off vary with elevation or slope direction. To analyze the distributional patterns of the woodlands, it was necessary to obtain environmental data for small areas. The measurements obtained using the data recorders are reported in this section.

## Climate in the Asir Mountains

Fig. 1-1 shows temperature readings and rainfall amounts at various sites in the Arabian Peninsula. As in the northern part of the peninsula, rainfall increases in the winter under the influence of the Mediterranean low pressure system. Cities close to the Mediterranean Sea, such as Amman and Damascus, are within the area with a typical Mediterranean climate, where water conditions in the winter are relatively better.

Farther south of the Mediterranean Sea, as the climatic influence of the Mediterranean weakens, the climate becomes drier, with less rainfall and higher temperatures. The climate around the Rub Al Khali Desert is the most arid, while the area extending from the Asir Mountains region to the seaboard region of the Red Sea has rainfall in summer under the influence of the monsoon (Siraji, 1984). In the southern Asir Mountains, where humid air from the Red Sea rises and rapidly cools, fog is frequent and rainfall is significant.

The Asir region has a relatively narrow coastal area. The west side of the ridge forms a very steep escarpment, while the east slopes gently inland (Fig. 1-2).

In Asir region, rainfall is relatively high for the Arabian Peninsula, and changes along an altitudinal gradient from the Red Sea inland (Fig. 1-3).

In southwest Saudi Arabia, the following vegetational zones are recognized, distributed according rainfall and differences in temperature along an altitudinal gradient (Fig. 1-4 ,Abulfatih, 1992).

1) Coastal plain: 0-300 m a.s.l.

2) Foothills: 300-1,000 m a.s.l.

3) Lower escarpment: 1,000-1,600 m a.s.l.

4) Upper escarpment: 1,600-2,200 m a.s.l.

5) High mountains: 2,200-3,000 m a.s.l.

6) Rain shadow slopes: 1,700-2,200 m a.s.l.

Figs. 1-3 and 1-5 show that total annual rainfall is less than 100 mm on the coastal Red Sea plains and increases along an altitudinal gradient to about 500 mm in the mountains. It then decreases to less than 200 mm on rain shadow slopes.

Air temperature generally decreases with an increase in altitude. The average daily maximum and minimum air temperature in December on the rain shadow slopes is lower than in the high mountains, even though the elevation is higher. Relative humidity decreases from the coastal plain facing the Red Sea to the rain shadow slopes. Relative humidity is higher in winter than summer (Abulfatih, 1992).

Each vegetational zone has characteristic plant communities. In the high mountains, trees of *Juniperus procera* grow to more than 10 m in height and form forests. This region with forests is exceptional in the Arabian Peninsula.

These forests are dependent not only on rainfall, but also on fog, rising from the Red Sea. There are no data, however, on the amount of water supplied by fog in the Asir Mountains, but measurements of water from fog in the mountains of Oman were reported by Price et al. (1988), who reported rainfall totaling 1.5 mm and 1.8 mm for each of two days in August 1985; water collected from fog at 4.2 m above the ground was 34.5 liters/$m^2$ and 35.6 liters/$m^2$, and at 0.9 m it was 12.7 liters/$m^2$ and 9.41 liters/$m^2$, respectively. In addition, the amount of water is considerably more than from rainfall, suggesting that water from fog is important for the vegetation.

It is assumed, therefore, rainfall and fog are important for the growth of juniper trees at high elevations in the Asir Mountains. Juniper trees are not distributed uniformly throughout the entire high mountain zone in Asir Mountains and there is not sufficient meteorological data to allow us to

speculate on dieback and die-off in relation to climatic conditions.

## Measurement of air temperature and humidity using thermo-hygrometers

To determine climatic conditions in in the Raydah Nature Reserve, small data recorders (RT-11 thermo recorder, Tabai Espec Corp.) with sensors to measure air temperature and humidity were set up at 14 sites within the reserve as well as in two sites in the juniper woodlands of Tamniyah, about 40 km southeast of Raydah, and at one site in front of a private house near the top of Jabal Tallan, about 130 km southeast of Raydah (Map 2-1). Additional thermo recorders were set up in the juniper woodlands of Billasmar, about 60 km north of Raydah. Those thermo-hygrometers that were set up in Billasmar were destroyed, and were abandoned. In Jabal Tallan, the location was changed to a site just in front of a private house because the device was stolen. These thermo-hygrometers measure air temperature within a range of 0 to 50°C and relative humidity between 10 and 95%; when relative humidity approaches 100%, the thermo-hygrometer records it as 99%.

To guard against damage by animals, each thermo-hygrometer was put in a cage attached to the branch of a tree (Photo 2-1). The measurement intervals were 10 minutes or 15 minutes in Raydah, 15 or 20 minutes in Tamniyah, and 20 or 30 minutes in Jabal Tallan.

## Results and discussion

Table 1-1 shows the altitude and period of measurements for each site.

Measurement periods were not always regular. The most frequent interruptions occurred because the data collection intervals were beyond the memory capacity of the loggers and/or breakdown of the equipment. One day data was lost through a mistake in its management.

The data collected show that air temperature and humidity vary on a large scale throughout the day, and from day to day.

Fig. 1-6 shows the change in air temperature and relative humidity on 1 May 2000 at each recording site in the Raydah Nature Reserve. In the early morning, the relative humidity was relatively high. Air temperature increased as the sun rose and inversely the relative humidity decreased. Around noon, the air temperature decreased rather quickly and the relative humidity increased drastically to nearly 100%. At high altitude sites, humidity near 100% continued for a long duration. Humidity at the low elevation sites showed a tendency to decrease. At sites below 2,000 m a.s.l., the duration when humidity was near 100% was very limited. When humidity is

nearly 100% fog may occur, and at the sites above 2,300 m a.s.l. fog occurred continuously to some extent. Fog at sites below 2000 m a.s.l. appeared to be insignificant.

Figs. 1-7 and 1-8 show the measurement results of air temperature and relative humidity at Tamniyah and Jabal Tallan on 1 May 2000. The data from Tamniyah were similar to those from Raydah. At Jabal Tallan, the humidity before dawn was considerable, but the general pattern of air temperature and humidity was similar to that of Raydah and Tamniyah.

Fig. 1-9 shows the change in air temperature and relative humidity at each site in Raydah on 17 May 2000. In the morning, the air temperature increased as the sun rose and conversely the relative humidity tended to decrease at all sites. In the afternoon, when air temperature decreased rapidly, the relative humidity increased rapidly and approached 100%. Humid conditions continued for a long time at high elevation sites. At low elevation sites, however, air temperature decreased and humidity increased in the afternoon. The increase in air temperature was less than at high altitudes and the humidity decreased gradually. While fog occurred at high altitudes, there was little fog below 2300 m a.s.l.

Figs. 1-10 and 1-11 show the air temperature and relative humidity at Tamniyah and Jabal Tallan on 17 May 2000. The changes in humidity were similar to the pattern at Raydah, but the increase in humidity in the afternoon at Tamniyah was less than at sites at nearly the same altitude in Raydah.

When air temperature decreases rapidly and humidity increases, fog occurs in the afternoon. At high altitudes, the period of high humidity tended to be longer than at lower altitudes. Days with similar patterns were frequent in the spring, but at other seasons days with similar but weaker patterns were observed.

Fig. 1-12 shows the changes in air temperature and humidity at each site in Raydah on 1 July 2000. During the day, there was little change in humidity and relative humidity at nearly all the sites was less than 40%. In daytime, the humidity decreased slightly. Differences in humidity due to elevation were not obvious.

Figs. 1-13 and 1-14 show air temperature and relative humidity at Tamniyah and Jabal Tallan on the same day. At these sites, the changes in relative humidity were slightly greater than in Raydah, but the relative humidity was still as low as in Raydah.

Days with low humidity throughout the day tended to be more frequent in the summer.

Fig. 1-15 shows change in air temperature and relative humidity in Raydah on 12 December 2000. The pattern of change in air temperature and relative humidity shown in this figure was quite

different from the patterns described above.

Fig. 1-16 shows the change in air temperature and relative humidity at Tamniyah the same day. As in Raydah, the relative humidity was high all day and humidity decreased slightly in daytime. The extent of decrease at Tamniyah, however, was greater than at sites at nearly the same altitude as Raydah. Because data could not be obtained at Jabal Tallan for the same day, it was impossible to include that site in our comparison.

The pattern of high humidity throughout the day was observed only in the winter. Humidity was generally very high, especially at high elevations. Relative humidity was nearly 100% throughout the day. Except for data obtained at site No. 3, which appeared to be unusual due to a deterioration of the sensor, the relative humidity decreased obviously in the daytime at sites below the "Wood Pole" site of 2,160 m a.s.l. The decrease in humidity at these sites tended to be more conspicuous at lower elevations.

Figs. 1-17 to 1-21 show changes in daily maximum air temperature, daily average air temperature, and daily minimum air temperature at the sites in Raydah between July 1999 and August 2001. Table 1 shows the monthly averages of daily maximum, daily average, and daily minimum air temperatures and correlations between altitude and monthly averages for the same period at sites in the Raydah Nature Reserve. Figs. 1-22 to 1-29 show the changes in daily maximum, daily average, and daily minimum air temperature at sites in Tamniyah and Jabal Tallan.

Air temperature increased from February to June and reached a maximum between June and August. After August, the air temperature decreased and reached the minimum in December and January.

There was a high correlation between altitude and average or minimum air temperatures. The lapse rate of the average air temperature was between 4.85 and 10.69°C/100 m and tended to be high in summer and lower in winter. The lapse rate of minimum air temperature was between 4.41 and 9.79°C/100 m and there was no seasonal tendency. The correlation between altitude and maximum air temperature was sometimes low and the lapse rate of maximum air temperature varied widely.

Figs. 1-30 to 1-34 show the change in daily maximum, average, and minimum relative humidity at the sites in Raydah between July 1999 and August 2001. Table 3 shows the monthly averages of daily maximum, average, and minimum relative humidity and the correlation with altitude, and the monthly averages for the same period at the sites in Raydah Nature Reserve. Figs. 1-35 to 1-42 show the change in daily maximum, average, and minimum relative humidity at the sites in Tamniyah and Jabal Tallan.

As shown in Figs. 1-30 to 1-42, relative humidity varied more widely than air temperature and there were periods with both high and low humidity within a month. The monthly average of daily average and daily minimum relative humidity tended to be lower in the winter. Those values did not increase much in the winter of 1999-2000, but increased remarkably in the winter of 2000-2001. Thus, the monthly average of daily average and daily minimum relative humidity varied from year to year. The change in relative humidity in Tamniyah and Jabal Tallan was very similar to the change in Raydah. Relative humidity showed similar changes within the range of these sites.

The relationship between altitude and relative humidity shown in Table 3 as a correlation coefficient varied widely and the inclination of the regression line varied from negative to positive. Months with negative values of inclination for regression lines of the monthly average of daily average and daily minimum relative humidity occurred mainly in the winter. In most months, relative humidity tended to be higher at higher elevations.

Figs. 1-43 to 1-46, using meteorological data from the Meteorology & Environmental Protection Administration (MEPA), show changes in daily maximum, daily average, and daily minimum air temperatures in seven cities around the Asir Mountains between July 1999 and April 2001. Figs. 1-47 to 1-50 show changes in daily maximum, daily average, and daily minimum relative humidity.

The changes in air temperature were similar in all cities. The daily range and yearly range of changes in air temperature were both small at Jizan in the coastal region. For the other side at Bisha and Najran in the inland region, the daily range and yearly range of changes in air temperature were both large. At cities such as Abha and Kamis Mushait in mountains area, the ranges of air temperature were medium. The values for yearly change from the thermo-hygrometers shown in Figs. 1-17 to 1-29 and the MEPA data were similar and the yearly range of the change was nearly the same, but the daily range in the change was small within juniper forests, such as in the Raydah Nature Reserve.

The change in relative humidity has a general tendency to be high in the winter and low in the summer for all cities. In Jizan in the coastal region, the fluctuation in relative humidity was small and the daily maximum relative humidity was not always high. The yearly range of change was also small, but the daily average was high. In Najran and Bisha in the inland region, the relative humidity was low and the daily range of change was small. Throughout the year, the difference between the values obtained in the winter and those from the summer are obvious. In Baha, the

change in relative humidity was similar to the changes seen in other cities, but the fluctuation in humidity in the winter was larger. In Taif, the trends were similar and the fluctuation in humidity was larger than in Baha. In Abha and Khamis Mushait, the daily maximum value in relative humidity was still higher than in other cities and the range of daily change in relative humidity was large. The differences between winter and summer were, therefore, not completely clear. Figs. 1-30 to 1-42 compare the values obtained from the thermo-hygrometers with the MEPA data, although the measuring methods and the accuracy of the two recording methods differed. The daily maximum relative humidity tended to be higher as was the yearly fluctuation in respect to the daily maximum relative humidity in juniper forests such as the Raydah Nature Reserve.

Figs. 1-51 to 1-53 show the monthly average air temperature, relative humidity, and rainfall in seven cities from January 1978 to April 2001.

As shown in Fig. 1-51, the yearly range of fluctuation in air temperature was large in Najran and Bisha in the inland region and small in Jizan in the coastal region. The yearly range was slightly larger in Abha and Khamis Mushait than in Jizan. The monthly average air temperature within the period shown in Fig. 1-51 indicated a slight increase. At Najran and Bisha, the average air temperature increased between 1978 and 1990, then decreased in 1992, but increased again after 1992. Other cities showed similar tendencies, but less clearly than in Najran and Bisha.

Fig. 1-52 shows the change in annual average air temperature between 1978 and 2000 at seven cities. In all cities, a tendency toward increasing temperature was recognized. The average increase in air temperature for 22 years from 1978 to 2000 was 0.0557 degrees/year and the total increase was more than 1.2 degrees for the same period.

As shown in Fig. 1-53, while the fluctuation in humidity was small in Jizan, the annual fluctuation in humidity was large in Abha and Khamis Mushait. In Najran, Khamis Mushait, and Abha, the relative humidity decreased until around 1989, then increased until around 1996, and again decreased until around 2000. Such tendencies are remarkable in Najran. Fig. 1-54 shows the change in the annual average relative humidity between 1978 and 2000 at seven cities. Although a slight decrease in relative humidity was recognized in Baha, Abha, Khamis Mushait, and Bisha, relative humidity increased slightly in the other cities. A clear tendency was not recognized for relative humidity.

At Abha and Khamis Mushait, which have relatively large amounts of rainfall, the amount was stable over time. In the other cities, the fluctuation in rainfall was large. The yearly change in rainfall showed no clear tendency (Figs. 1-55, 1-56).

The MEPA data for the 20 years did not show a drying tendency, but did show a trend towards a slight increase in air temperature.

## Future subjects

To clarify the characteristics of the environment, especially meteorological characteristics, measurements using thermo-hygrometers were used. The results provided information on changes in air temperature and relative humidity due to differences in elevation and over time. Since the fluctuation in relative humidity was especially large, however, more data and more detailed analyses are necessary. The horizontal differences in the environment could not be obtained as the sensors could not be set up over a wide range.

Meteorological data are important as fundamental data for discussing and conserving the juniper woodlands. To clarify the effects of meteorological factors on the growth of juniper trees and the juniper woodlands ecosystem, it is necessary to study the junipers physiologically and the water supply in the juniper forests. It is also necessary to continue to collect meteorological data for a longer period of time.

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Table 1-1. Sites and periods of measurement by thermo-hygrometers

| No. | Area | Name | Altitude (m) | 1999 | | | | | | 2000 | | | | | | | | | | | | 2001 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug |
| 1 | Raydah | Fog 1 | 2800 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | Raydah | Tower | 2760 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3 | Raydah | Fog 2 | 2570 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 4 | Raydah | Plot 2 | 2560 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5 | Raydah | Plot 3 | 2550 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 6 | Raydah | No. 2 | 2550 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7 | Raydah | Fog 3 | 2450 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 8 | Raydah | Plot 4 | 2420 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 9 | Raydah | Plot 5 | 2395 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 10 | Raydah | No. 3 | 2295 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 11 | Raydah | Wood Pole | 2160 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 12 | Raydah | Plot 7 | 2050 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 13 | Raydah | No. 5 | 1890 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 14 | Raydah | 5m Pole | 1830 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 15 | Tamniyah | TN1 | 2505 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 16 | Tamniyah | TN2 | 2520 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 17 | Jabel Tallan | Tallan | 2100 | | | | | | | | | | | | | | | | | | | | | | | | | | |

Table 1-2. Monthly averages of daily maximum, daily average, and daily minimum air temperature and the correlation between the altitudes of sites and monthly averages of air temperature in the Raydah Nature Reserve

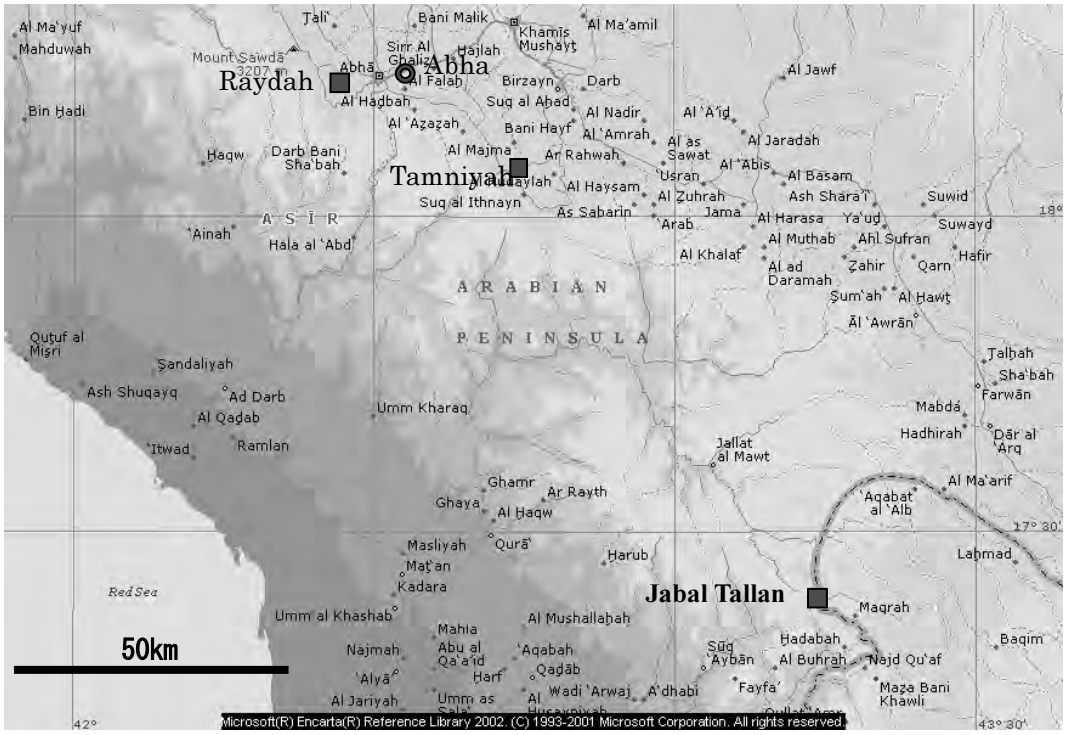
| Month | No. of Days | Temperature (℃) | | | Average Temperature | | | Maximum Temperature | | | Minimum Temperature | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Average | Maximum | Minimum | r2 | a | b | r2 | a | b | r2 | a | b |
| Jul-99 | 6 | 21.5 | 31.5 | 14.2 | 0.945 | −0.00778 | 39.0 | 0.956 | −0.01115 | 56.5 | 0.980 | −0.00666 | 29.2 |
| Aug-99 | 6 | 21.2 | 31.7 | 13.2 | 0.895 | −0.00718 | 37.3 | 0.714 | −0.00805 | 49.8 | 0.923 | −0.00609 | 26.8 |
| Sep-99 | 6 | 20.6 | 30.0 | 13.9 | 0.930 | −0.00768 | 37.9 | 0.785 | −0.01010 | 52.7 | 0.872 | −0.00592 | 27.2 |
| Oct-99 | 6 | 18.3 | 28.5 | 12.8 | 0.969 | −0.00746 | 35.1 | 0.721 | −0.00789 | 46.2 | 0.810 | −0.00476 | 23.5 |
| Nov-99 | 5 | 16.6 | 26.3 | 10.2 | 0.927 | −0.00634 | 30.2 | 0.269 | −0.00524 | 37.5 | 0.915 | −0.00754 | 26.4 |
| Dec-99 | 6 | 13.0 | 24.8 | 6.4 | 0.910 | −0.00673 | 28.1 | 0.523 | −0.01243 | 52.7 | 0.636 | −0.00554 | 18.8 |
| Jan-00 | 10 | 13.2 | 22.5 | 7.5 | 0.886 | −0.00618 | 27.3 | 0.718 | −0.00976 | 44.9 | 0.845 | −0.00540 | 19.8 |
| Feb-00 | 11 | 13.9 | 23.0 | 7.9 | 0.741 | −0.00485 | 25.2 | 0.528 | −0.00677 | 38.7 | 0.712 | −0.00507 | 19.7 |
| Mar-00 | 9 | 15.9 | 25.6 | 9.6 | 0.791 | −0.00642 | 30.9 | 0.582 | −0.00931 | 47.3 | 0.649 | −0.00441 | 19.9 |
| Apr-00 | 14 | 19.4 | 29.2 | 11.1 | 0.942 | −0.00787 | 38.1 | 0.589 | −0.01242 | 58.7 | 0.872 | −0.00559 | 24.3 |
| May-00 | 14 | 20.3 | 32.4 | 10.9 | 0.945 | −0.00862 | 40.8 | 0.591 | −0.00783 | 51.0 | 0.965 | −0.00831 | 30.6 |
| Jun-00 | 14 | 21.7 | 33.2 | 13.8 | 0.936 | −0.00859 | 42.1 | 0.582 | −0.00796 | 52.1 | 0.918 | −0.00768 | 32.0 |
| Jul-00 | 14 | 22.1 | 32.7 | 14.5 | 0.889 | −0.00694 | 38.6 | 0.421 | −0.00622 | 47.5 | 0.756 | −0.00579 | 28.2 |
| Aug-00 | 1 | 23.1 | 31.5 | 15.7 | | | | | | | | | |
| Sep-00 | 13 | 19.8 | 31.3 | 14.3 | 0.954 | −0.00778 | 38.0 | 0.502 | −0.00761 | 49.1 | 0.605 | −0.00583 | 27.9 |
| Oct-00 | 12 | 16.9 | 28.2 | 9.5 | 0.938 | −0.00790 | 35.6 | 0.403 | −0.00674 | 44.1 | 0.736 | −0.00964 | 32.4 |
| Nov-00 | 12 | 13.5 | 22.4 | 8.5 | 0.908 | −0.00740 | 31.0 | 0.486 | −0.00869 | 42.9 | 0.890 | −0.00659 | 24.1 |
| Dec-00 | 9 | 13.0 | 25.5 | 6.0 | 0.771 | −0.00540 | 25.5 | 0.018 | −0.00261 | 31.5 | 0.774 | −0.00865 | 26.0 |
| Jan-01 | 11 | 11.3 | 23.2 | 4.2 | 0.812 | −0.00593 | 25.0 | 0.071 | −0.00394 | 32.3 | 0.785 | −0.00841 | 23.6 |
| Feb-01 | 10 | 13.8 | 25.5 | 6.1 | 0.886 | −0.00613 | 27.9 | 0.683 | −0.01011 | 48.5 | 0.687 | −0.00586 | 19.5 |
| Mar-01 | 10 | 16.1 | 26.8 | 10.3 | 0.964 | −0.00806 | 34.6 | 0.634 | −0.00947 | 48.5 | 0.922 | −0.00851 | 29.8 |
| Apr-01 | 10 | 18.6 | 29.7 | 8.6 | 0.933 | −0.00883 | 38.8 | 0.699 | −0.00982 | 52.2 | 0.948 | −0.00979 | 31.0 |
| May-01 | 10 | 20.7 | 31.0 | 10.3 | 0.935 | −0.00982 | 43.2 | 0.756 | −0.01084 | 55.8 | 0.786 | −0.00969 | 32.6 |
| Jun-01 | 10 | 22.5 | 32.3 | 14.5 | 0.947 | −0.00952 | 44.4 | 0.835 | −0.01022 | 55.7 | 0.871 | −0.00843 | 33.8 |
| Jul-01 | 11 | 22.0 | 31.6 | 13.5 | 0.936 | −0.01069 | 46.7 | 0.741 | −0.01291 | 61.5 | 0.539 | −0.00826 | 32.7 |
| Aug-01 | 10 | 19.4 | 29.5 | 13.2 | 0.869 | −0.00679 | 35.3 | 0.322 | −0.00943 | 51.6 | 0.847 | −0.00583 | 26.9 |

r : correlation coefficient
Y = aX + b
Y : temperature
X : altitude

Table 1-3. Monthly averages of daily maximum, daily average, and daily minimum relative humidity and the correlation between the altitudes of sites and monthly averages of relative humidity in the Raydah Nature Reserve

| Month | No. of Days | Himidity(%) | | | Average Humiidty | | | Maximum Humidigy | | | Minimum humidity | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Average | Maximum | Minimum | r2 | a | b | r2 | a | b | r2 | a | b |
| Jul-99 | 6 | 53.0 | 99.0 | 14.5 | 0.482 | 0.00785 | 35.4 | 1.000 | 0.00000 | 99.0 | 0.934 | 0.00598 | 1.1 |
| Aug-99 | 6 | 54.1 | 99.0 | 13.2 | 0.111 | 0.00469 | 43.5 | 1.000 | 0.00000 | 99.0 | 0.636 | 0.00376 | 4.7 |
| Sep-99 | 6 | 49.0 | 99.0 | 13.0 | 0.566 | 0.01100 | 24.3 | 1.000 | 0.00000 | 99.0 | 0.692 | 0.00408 | 3.8 |
| Oct-99 | 6 | 48.7 | 99.0 | 13.2 | 0.916 | −0.01338 | 18.6 | 1.000 | 0.00000 | 99.0 | 0.485 | 0.00408 | 4.0 |
| Nov-99 | 5 | 56.0 | 99.0 | 12.8 | 0.651 | 0.00468 | 46.0 | 1.000 | 0.00000 | 99.0 | 0.017 | 0.00073 | 11.2 |
| Dec-99 | 6 | 60.5 | 99.0 | 20.0 | 0.004 | −0.00072 | 62.2 | 1.000 | 0.00000 | 99.0 | 0.009 | −0.00086 | 21.9 |
| Jan-00 | 10 | 57.5 | 99.0 | 16.5 | 0.148 | −0.00437 | 67.5 | 1.000 | 0.00000 | 99.0 | 0.720 | 0.00710 | 0.2 |
| Feb-00 | 11 | 56.1 | 96.0 | 22.5 | 0.654 | −0.02811 | 121.1 | 0.002 | −0.00069 | 97.6 | 0.386 | −0.01317 | 53.0 |
| Mar-00 | 9 | 55.0 | 98.3 | 18.7 | 0.004 | 0.00011 | 54.7 | 0.061 | −0.00149 | 101.8 | 0.202 | 0.00708 | 2.1 |
| Apr-00 | 14 | 47.5 | 98.5 | 18.4 | 0.511 | 0.01344 | 15.6 | 0.220 | 0.00294 | 91.5 | 0.276 | 0.00720 | 1.3 |
| May-00 | 14 | 47.0 | 99.0 | 11.7 | 0.623 | 0.01538 | 10.5 | 1.000 | 0.00000 | 99.0 | 0.569 | 0.00304 | 4.5 |
| Jun-00 | 14 | 40.1 | 98.5 | 10.5 | 0.394 | 0.00958 | 17.4 | 0.006 | 0.00050 | 97.3 | 0.463 | 0.00306 | 3.2 |
| Jul-00 | 14 | 41.3 | 98.6 | 12.4 | 0.012 | 0.00139 | 38.0 | 0.006 | 0.00035 | 97.8 | 0.007 | 0.00052 | 11.2 |
| Aug-00 | 1 | 53.5 | 99.0 | 13.0 | | | | | | | | | |
| Sep-00 | 13 | 42.2 | 96.6 | 11.2 | 0.664 | 0.01233 | 13.3 | 0.290 | 0.00597 | 82.6 | 0.268 | 0.00180 | 6.9 |
| Oct-00 | 12 | 54.7 | 99.0 | 13.3 | 0.682 | 0.01767 | 12.9 | 1.000 | 0.00000 | 99.0 | 0.224 | 0.00289 | 6.5 |
| Nov-00 | 12 | 79.2 | 99.0 | 30.3 | 0.571 | 0.02098 | 31.0 | 1.000 | 0.00000 | 99.0 | 0.242 | 0.00903 | 8.9 |
| Dec-00 | 9 | 67.3 | 99.0 | 20.3 | 0.039 | 0.00683 | 51.5 | 1.000 | 0.00000 | 99.0 | 0.055 | −0.00299 | 27.2 |
| Jan-01 | 11 | 65.1 | 98.8 | 19.9 | 0.003 | −0.00235 | 70.5 | 0.000 | 0.00001 | 98.8 | 0.038 | −0.00493 | 31.3 |
| Feb-01 | 10 | 55.2 | 90.9 | 16.7 | 0.150 | −0.01782 | 96.0 | 0.016 | −0.00874 | 110.9 | 0.231 | 0.00494 | 5.4 |
| Mar-01 | 10 | 54.9 | 90.6 | 16.0 | 0.008 | −0.00439 | 65.0 | 0.023 | −0.01042 | 114.5 | 0.200 | 0.00536 | 3.7 |
| Apr-01 | 10 | 45.9 | 96.5 | 12.8 | 0.000 | 0.00058 | 44.6 | 0.296 | −0.01292 | 126.1 | 0.154 | 0.00218 | 7.8 |
| May-01 | 10 | 38.5 | 96.6 | 11.9 | 0.027 | 0.00606 | 24.6 | 0.219 | −0.00791 | 114.7 | 0.646 | 0.00290 | 5.2 |
| Jun-01 | 10 | 27.2 | 91.6 | 10.9 | 0.076 | 0.00590 | 13.7 | 0.182 | −0.02055 | 138.7 | 0.709 | 0.00275 | 4.6 |
| Jul-01 | 11 | 35.7 | 96.1 | 12.5 | 0.178 | 0.01493 | 1.2 | 0.088 | −0.00610 | 110.2 | 0.252 | 0.00515 | 0.9 |
| Aug-01 | 10 | 57.1 | 92.7 | 15.0 | 0.108 | −0.01784 | 98.8 | 0.099 | −0.01155 | 119.7 | 0.118 | 0.00312 | 7.7 |

r : correlation coefficient
Y = aX + b
Y : humidity
X : altitude




Map 2-1. Location map of Raydah, Tamuniyah and Jabal Tallan

Photo 2-1. Thermo-hygrometer in a protective cage

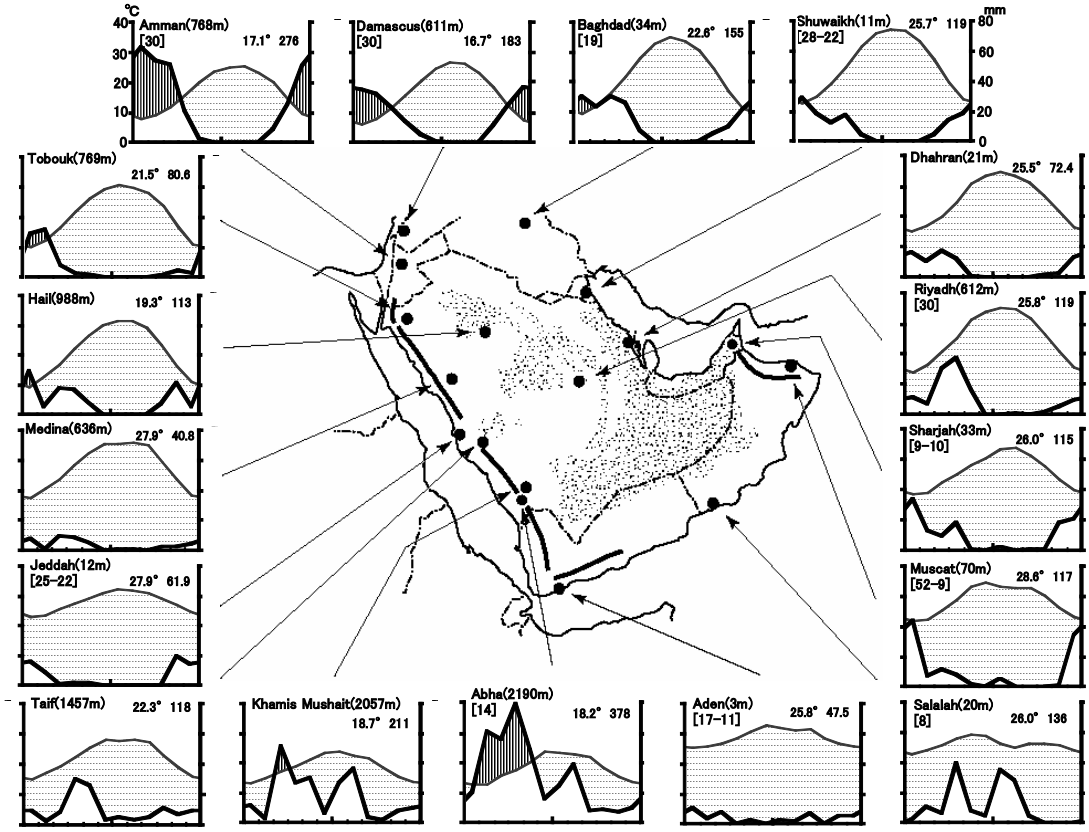



Fig. 1-1. Temperature and rainfall in the Arabian Peninsula

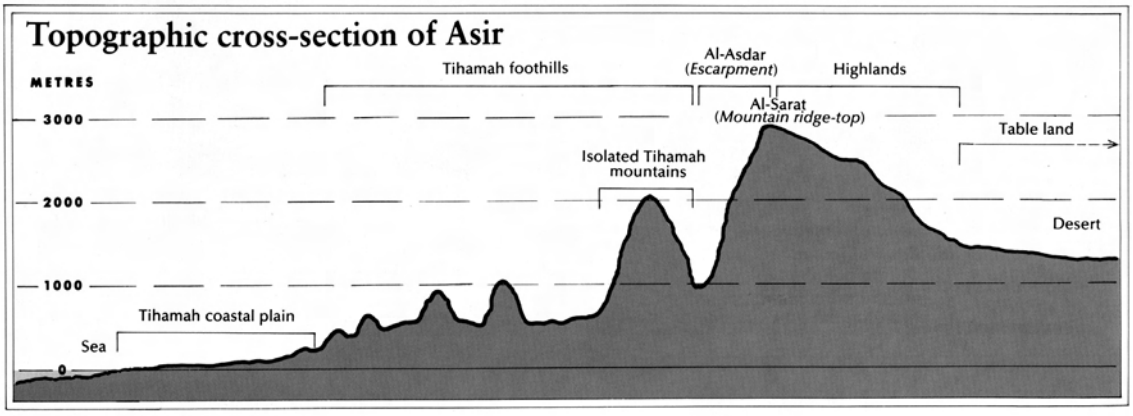



Fig. 1-2. Topographic cross-section of Asir (Mauger, 1993)

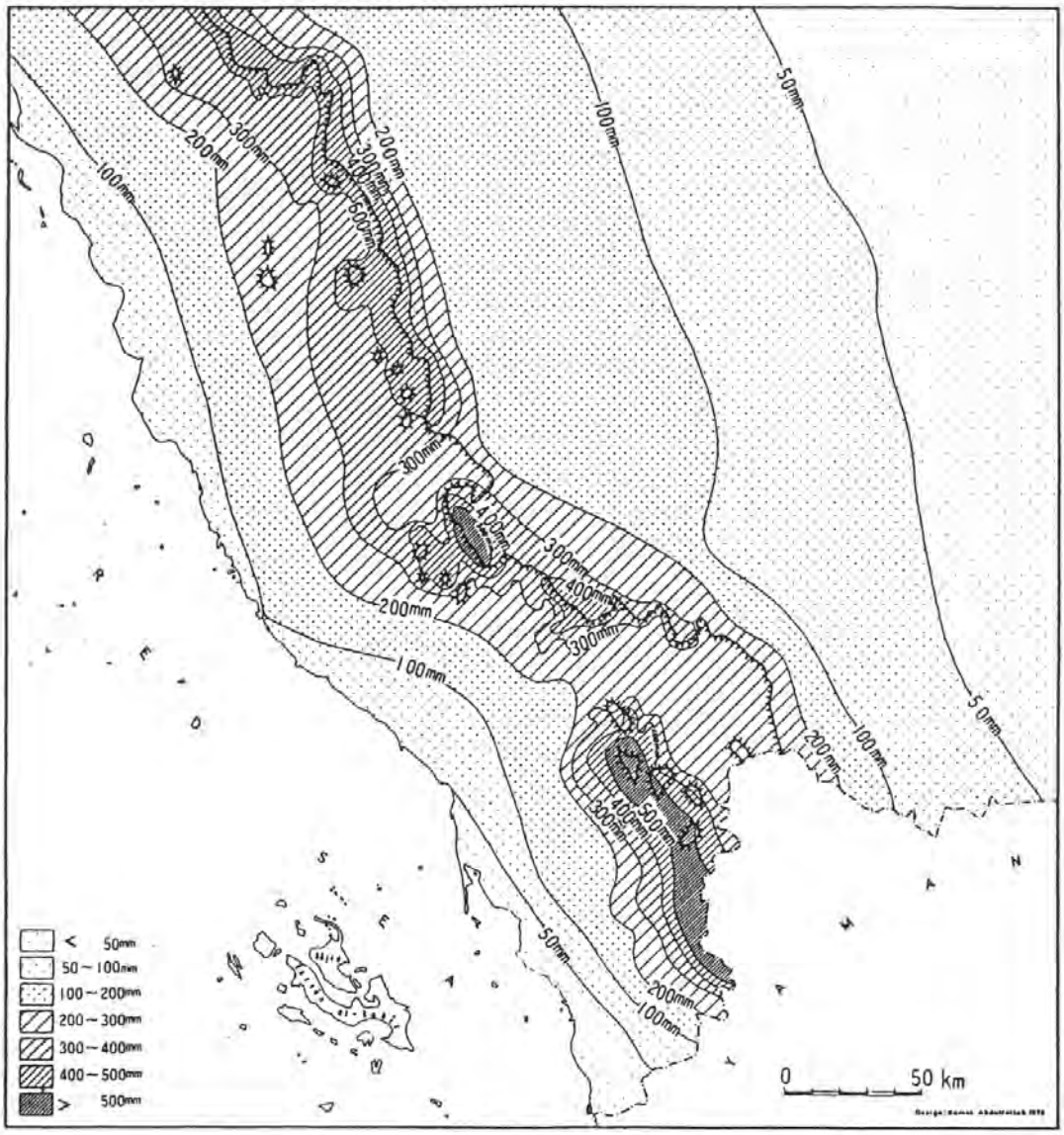



Fig. 1-3. Annual average rainfall in the Asir Region (Abdulfattah, 1981)

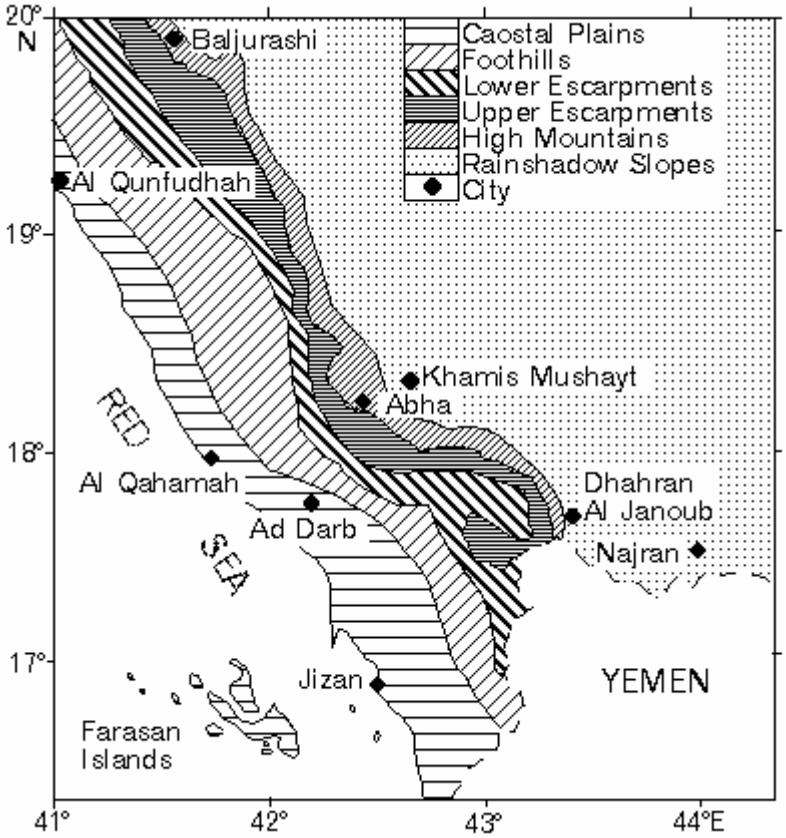



Fig. 1-4. Vegetational zones in the Asir Region (Abulfatih, 1992)

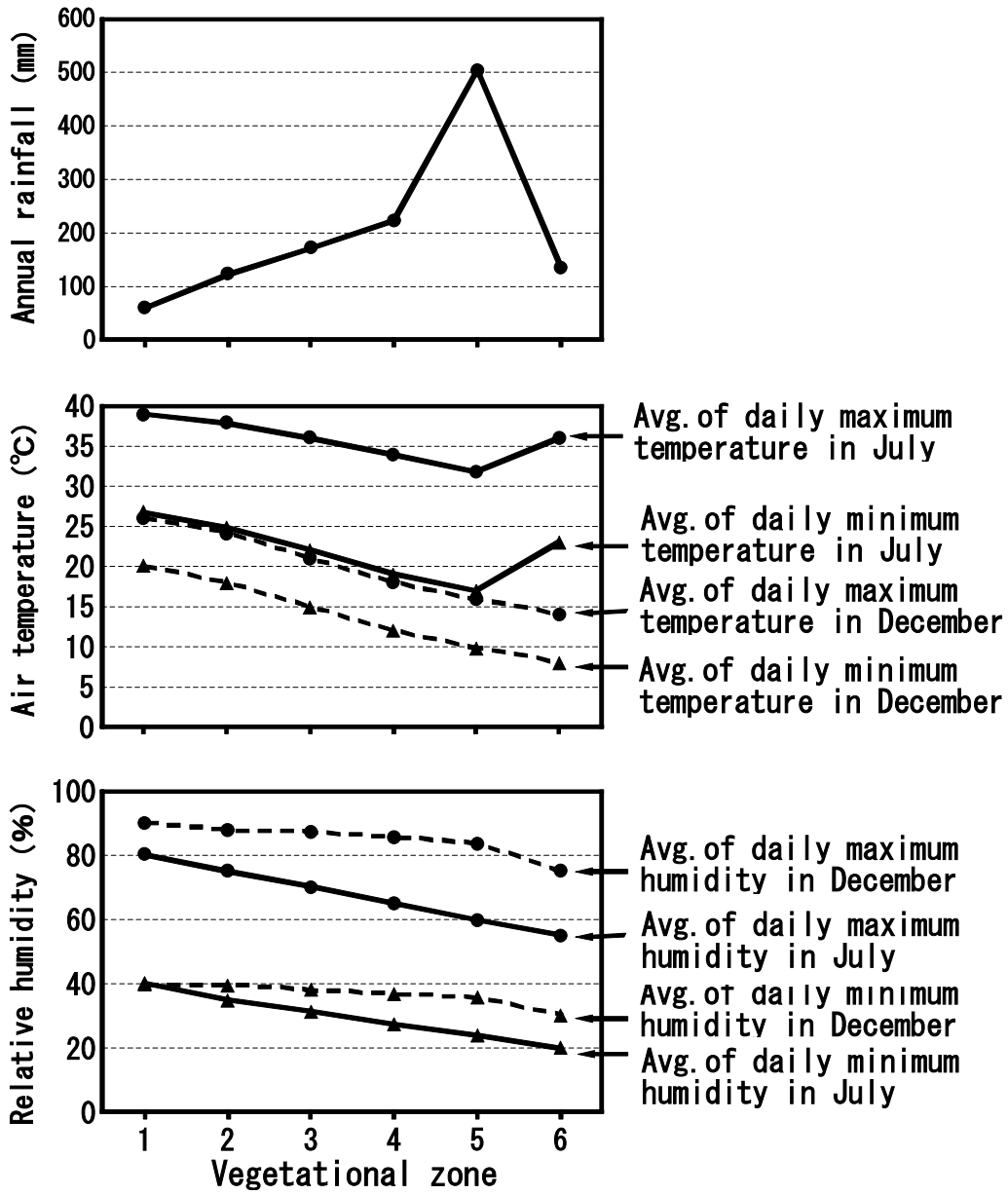



Fig. 1-5. Annual rainfall, air temperature, and relative humidity in each vegetational zone (Abulfatih, 1992)

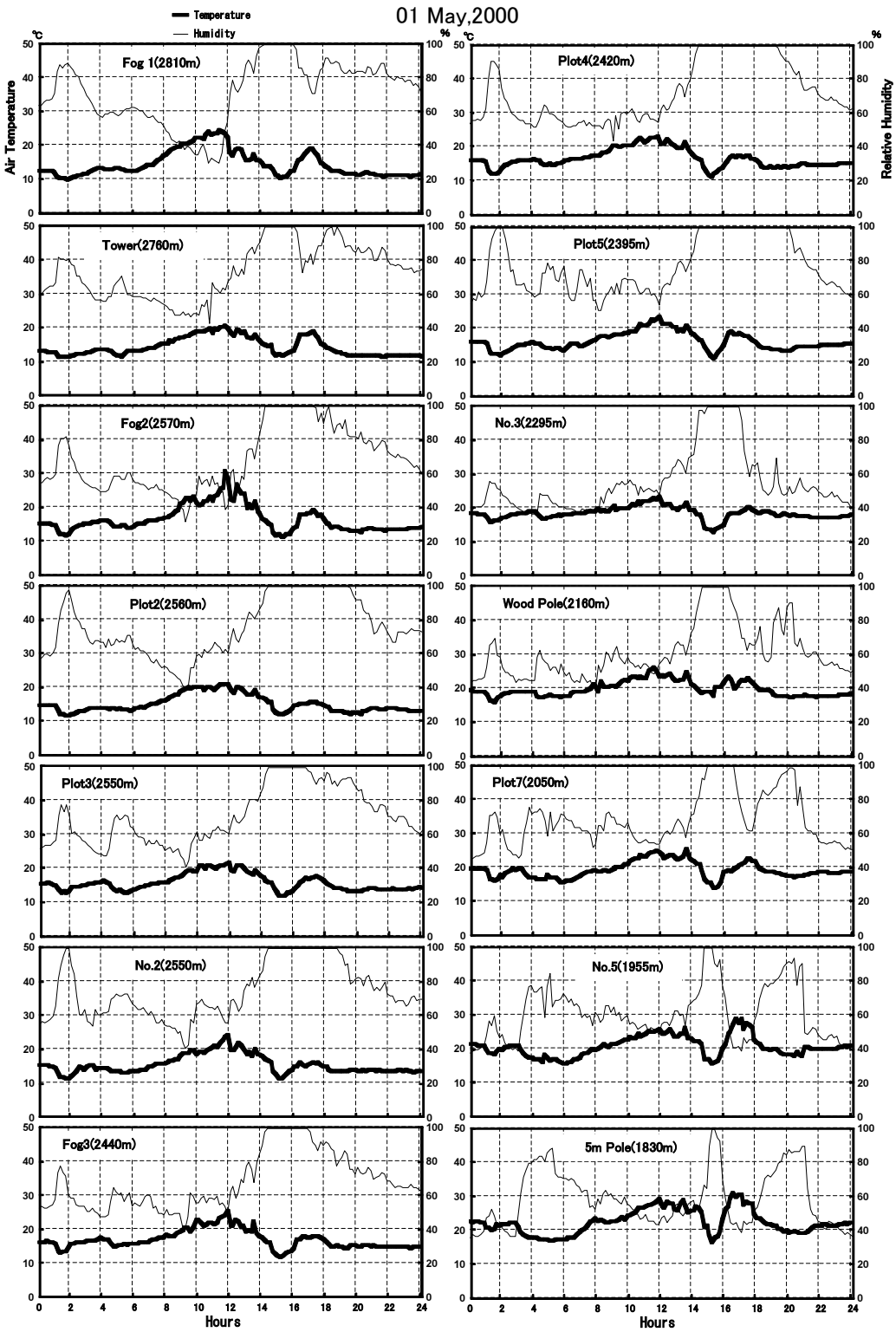



Fig. 1-6. Air temperature and relative humidity on 01 May 2000 at each measurement site in the Raydah Nature Reserve

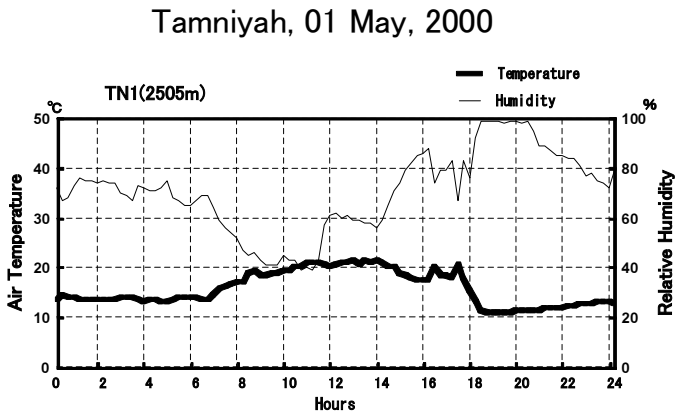



Fig. 1-7. Air temperature and relative humidity on 01 May 2000 in Tamniyah

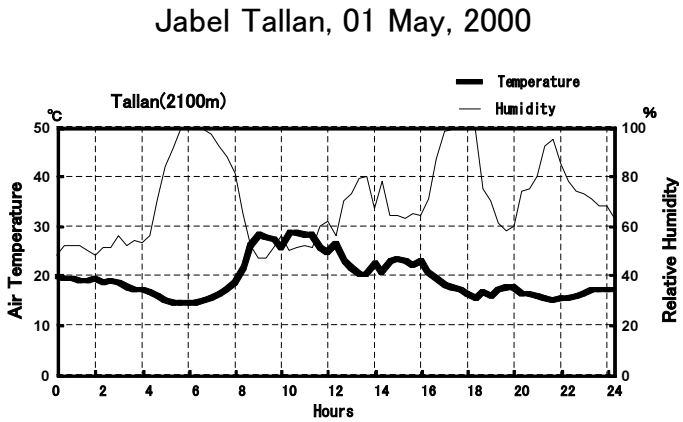



Fig. 1-8. Air temperature and relative humidity on 01 May 2000 in Jabal Tallan

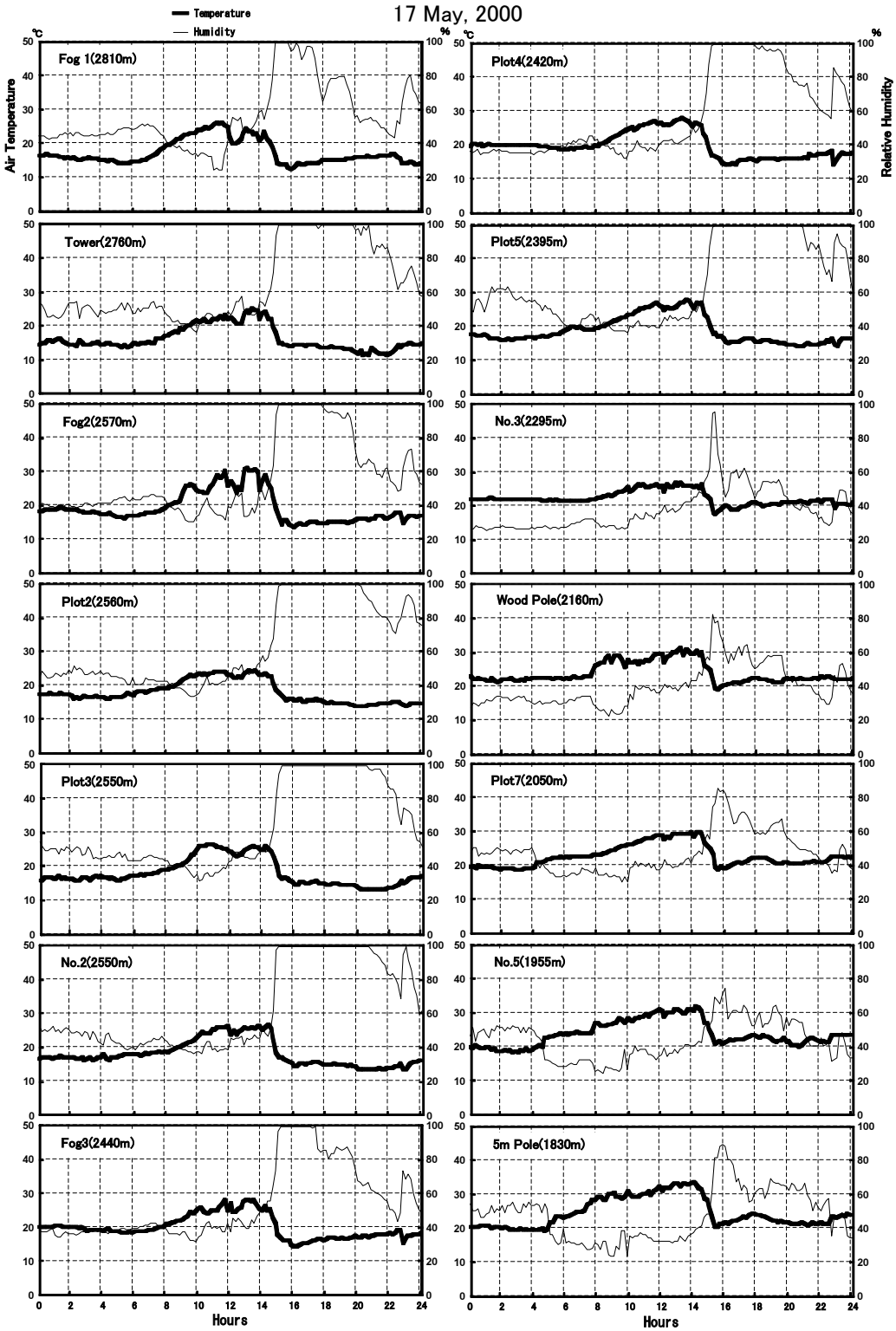



Fig. 1-9 Air temperature and relative humidity on 17 May 2000 in the Raydah Nature Reserve

Tamniyah, 17 May, 2000

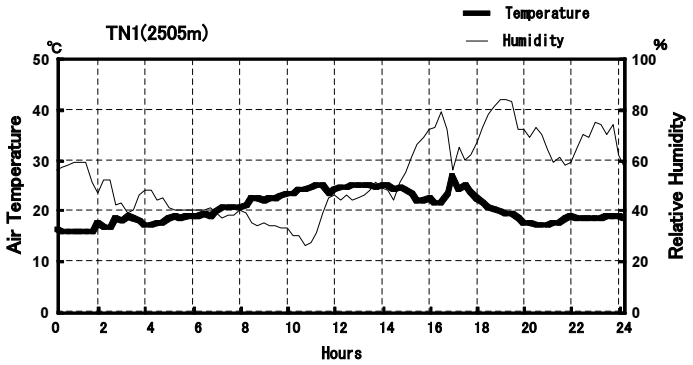



Fig. 1-10. Air temperature and relative humidity on 17 May 2000 in Tamniyah

Jabal Tallan, 17 May, 2000

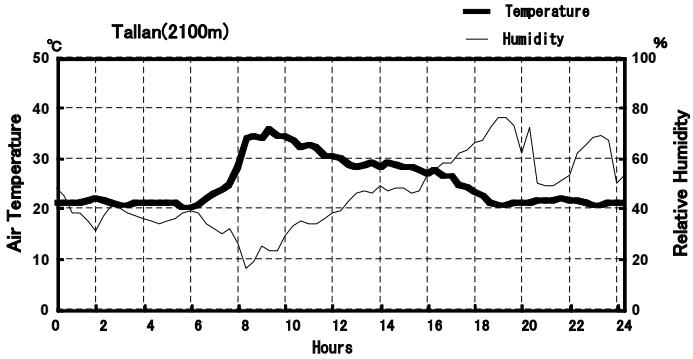



Fig. 1-11. Air temperature and relative humidity on 17 May 2000 in Jabal Tallan

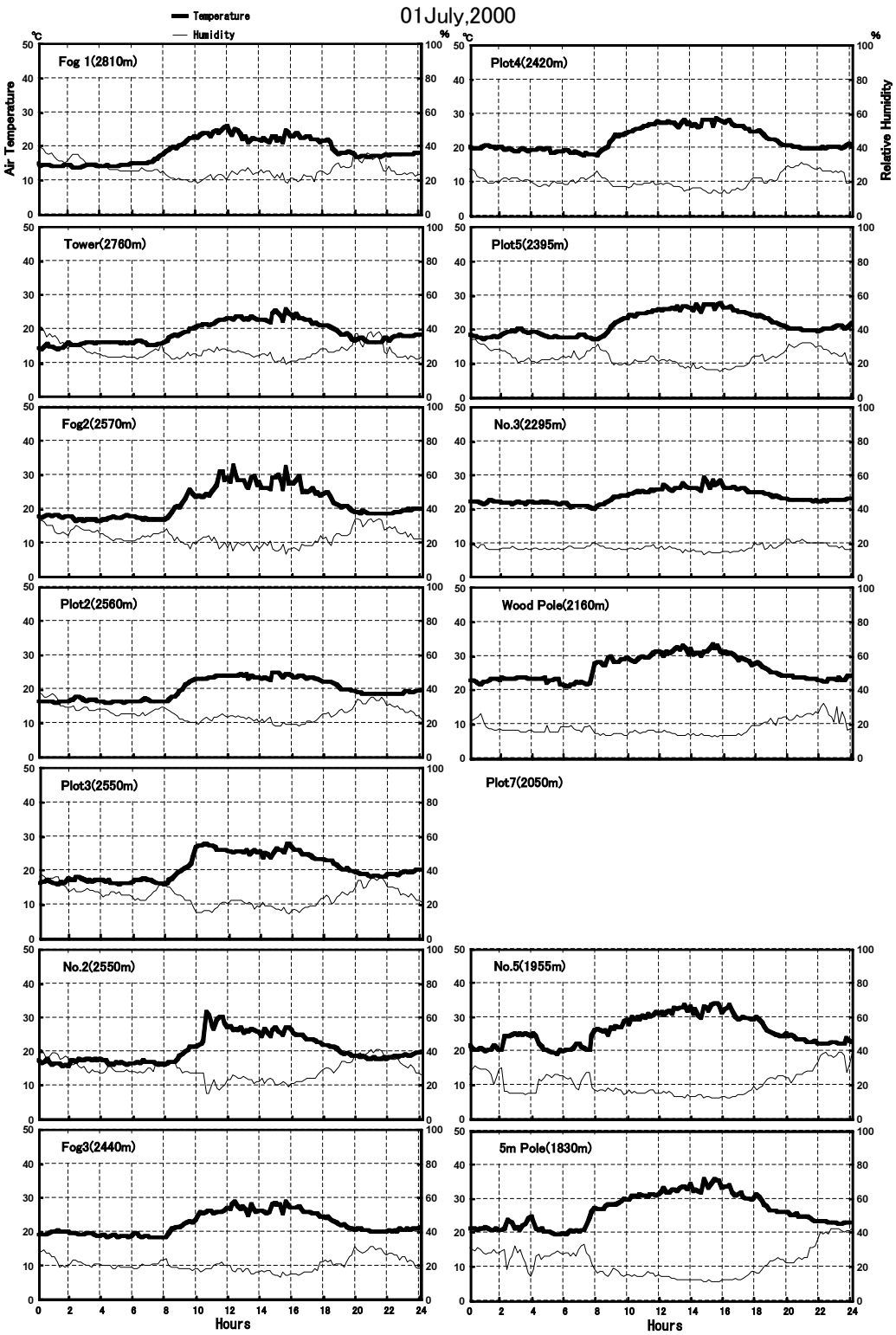



Fig. 1-12. Air temperature and relative humidity on 01 July 2000 in the Raydah Nature Reserve

Tamniyah, 01 July, 2000

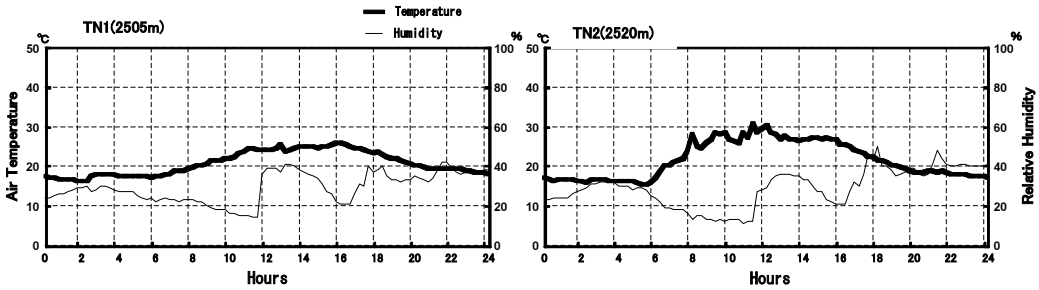



Fig. 1-13. Air temperature and relative humidity on 01 July 2000 in Tamniyah

Jabal Tallan, 01 July, 2000

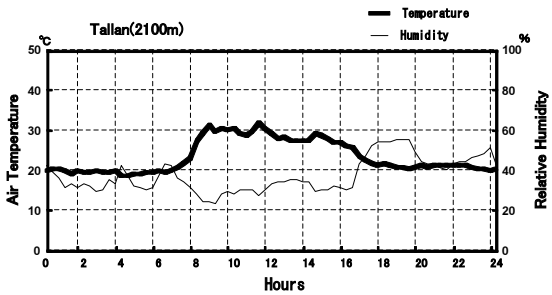



Fig. 1-14. Air temperature and relative humidity on 01 July 2000 in Jabal Tallan

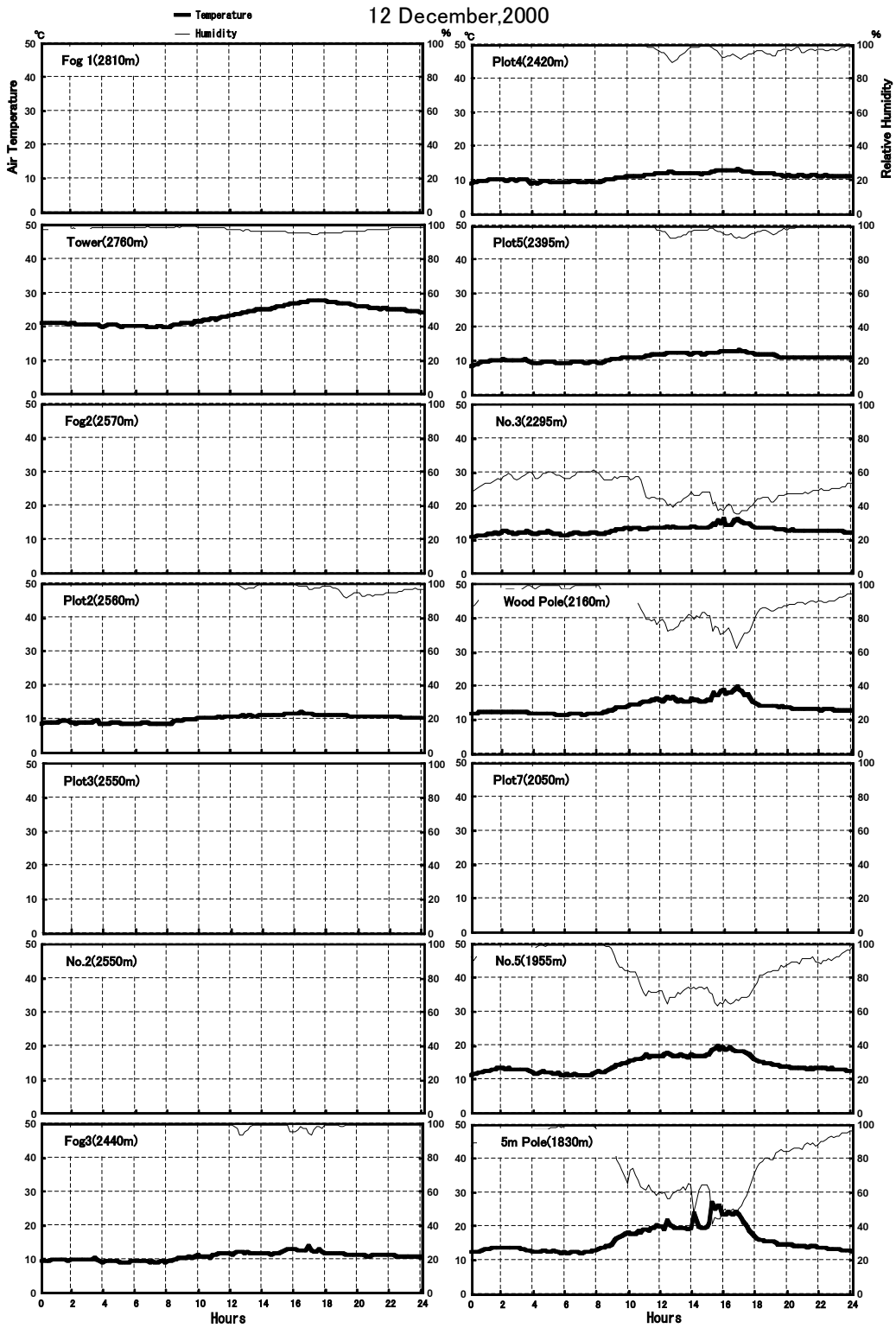



Fig. 1-15. Air temperature and relative humidity on 12 December 2000 in the Raydah Nature Reserve

Tamniyah, 12 December, 2000

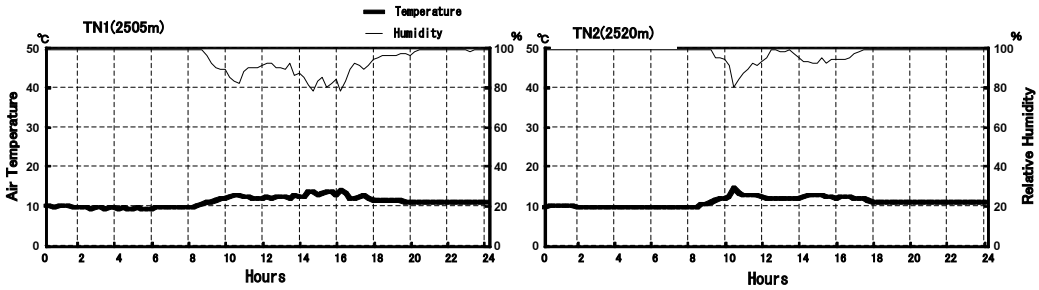



Fig. 1-16. Air temperature and relative humidity on 12 December 2000 in Tamniyah

Raydah, July to December 1999

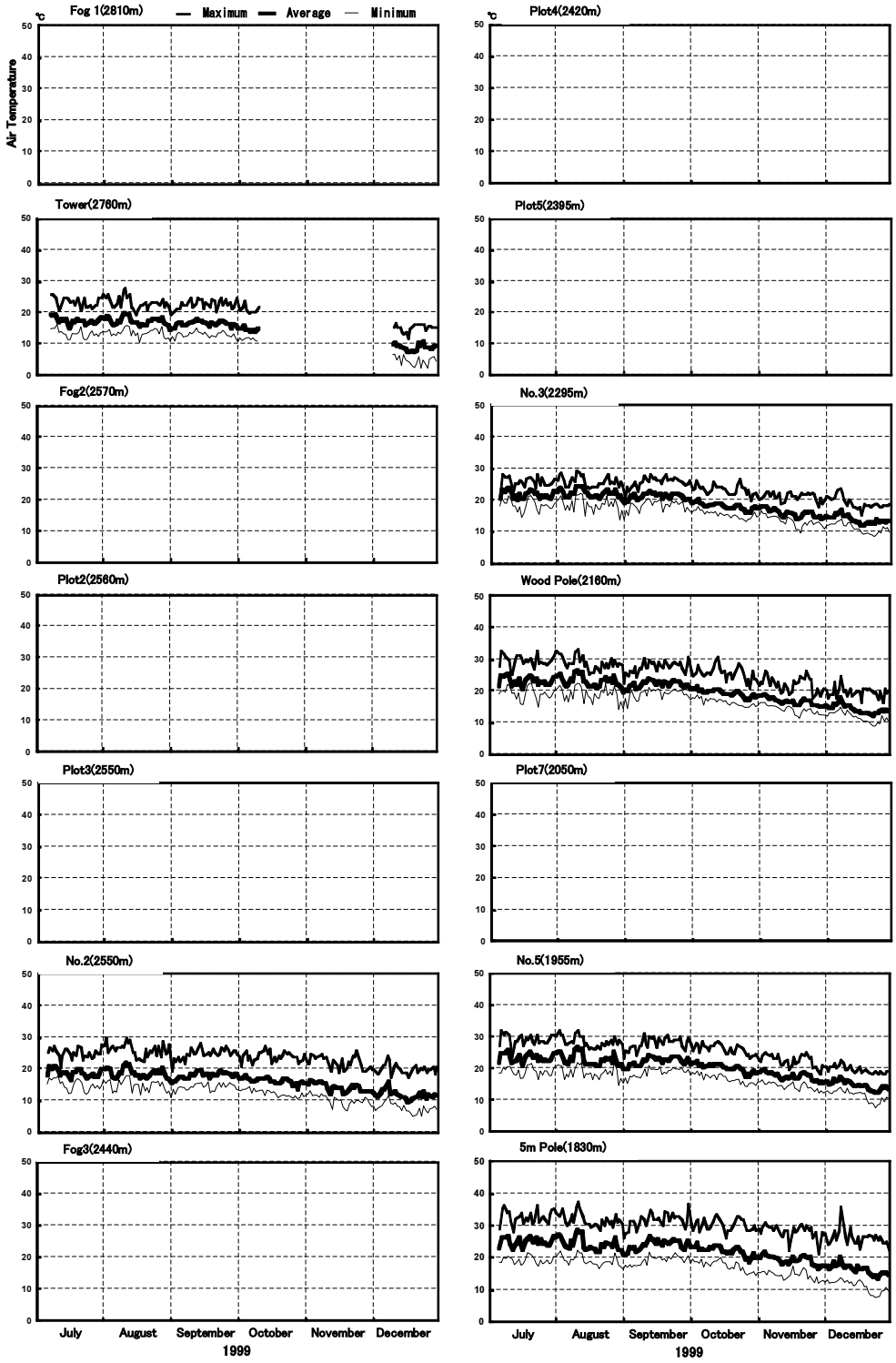



Fig. 1-17. Daily maximum, daily average, and daily minimum air temperature in Raydah from July to December 1999

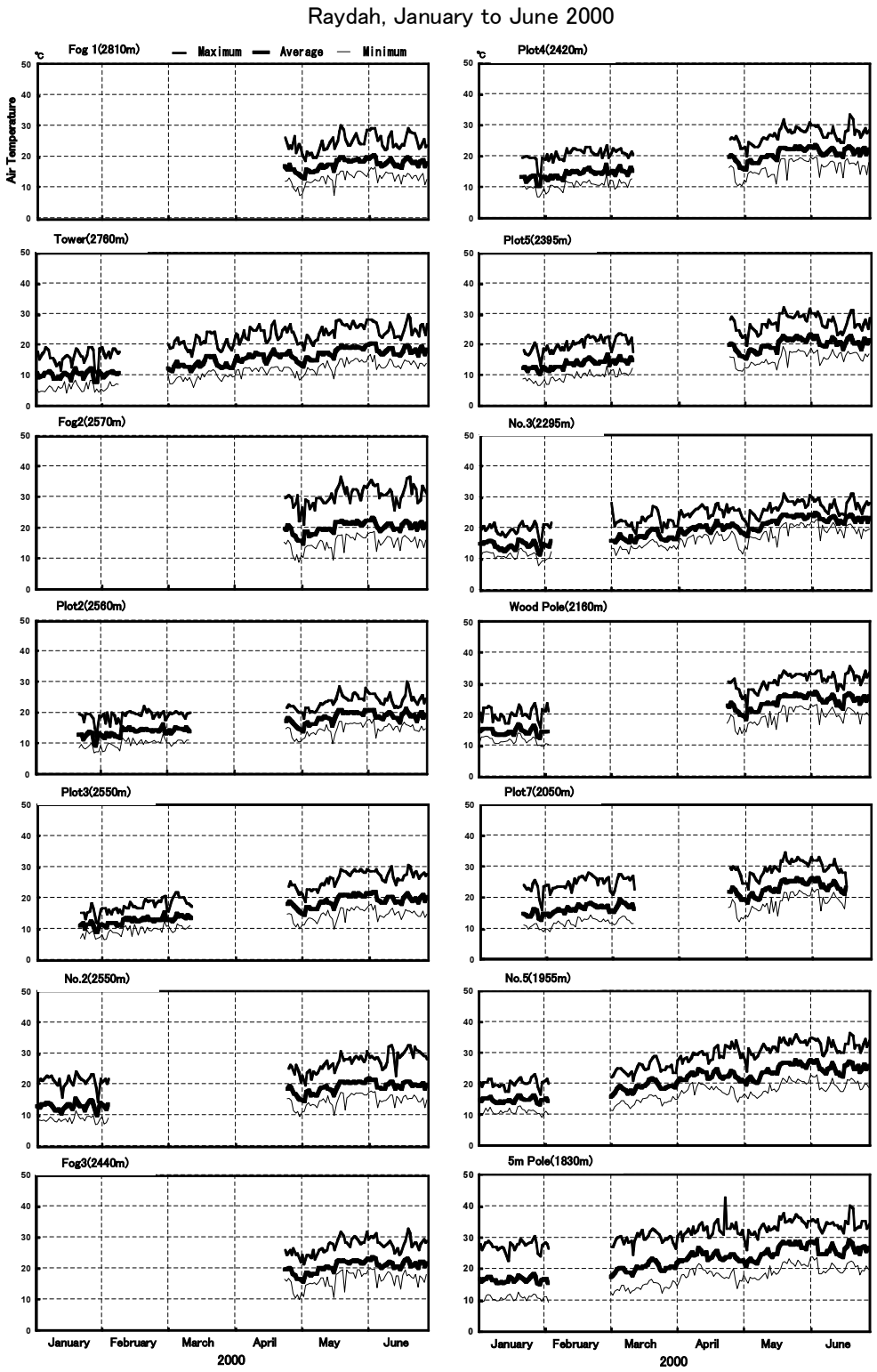



Fig. 1-18. Daily maximum, daily average, and daily minimum air temperature in Raydah from January to June 2000

Raydah, July to December 2000

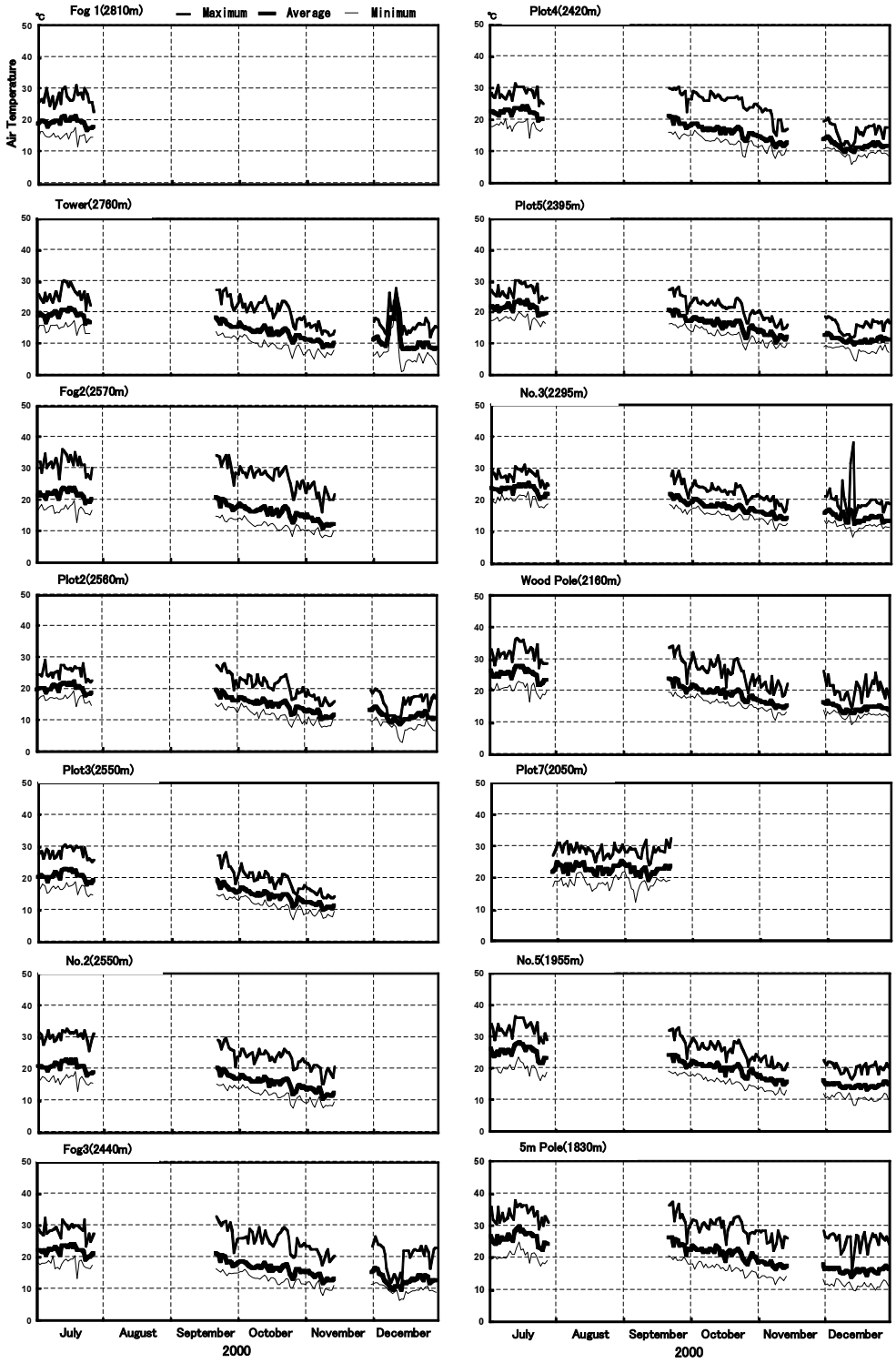



Fig. 1-19. Daily maximum, daily average, and daily minimum air temperature in Raydah from July to December 2000

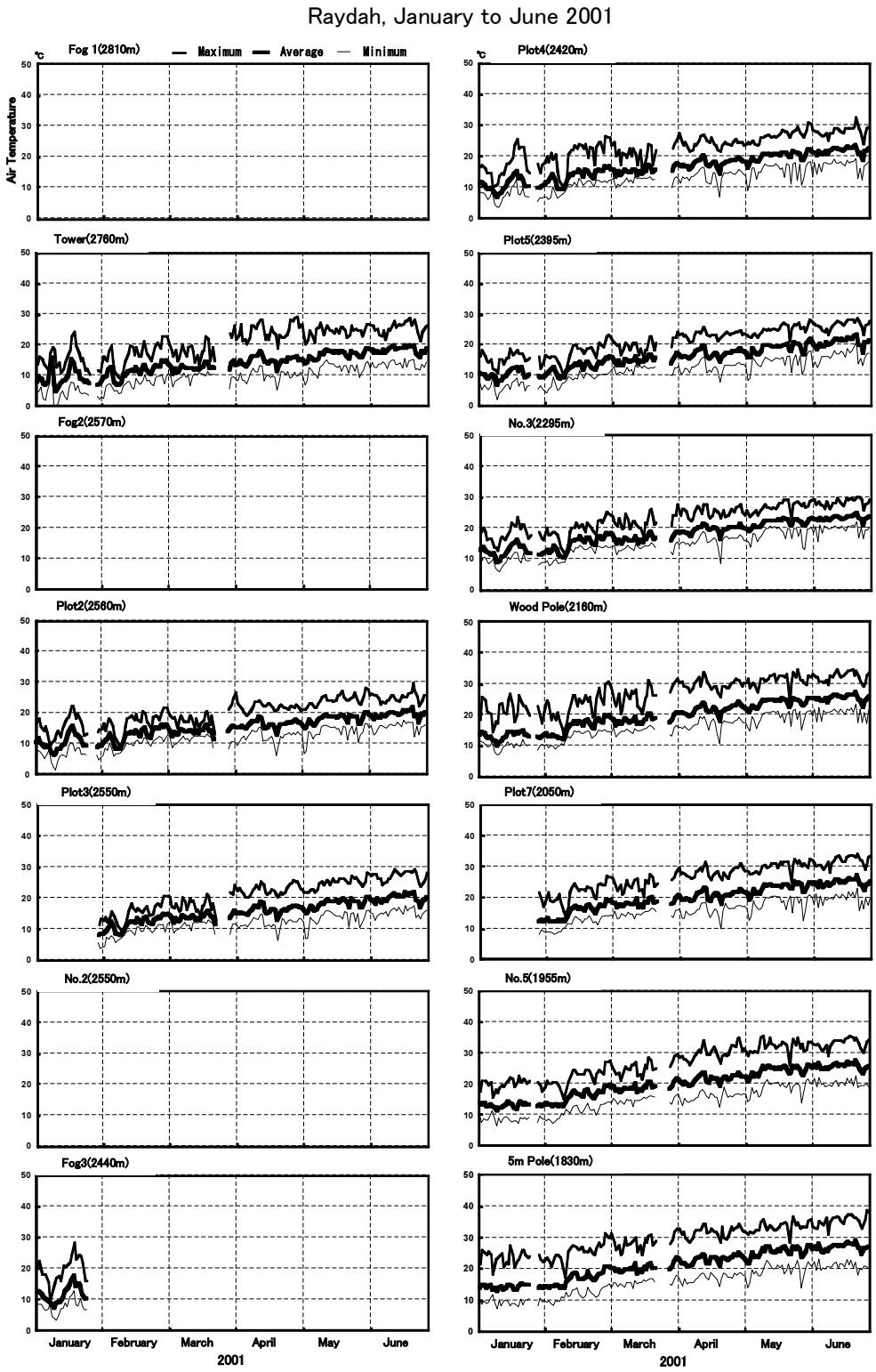



Fig. 1-20. Daily maximum, daily average, and daily minimum air temperature in Raydah from January to June 2001

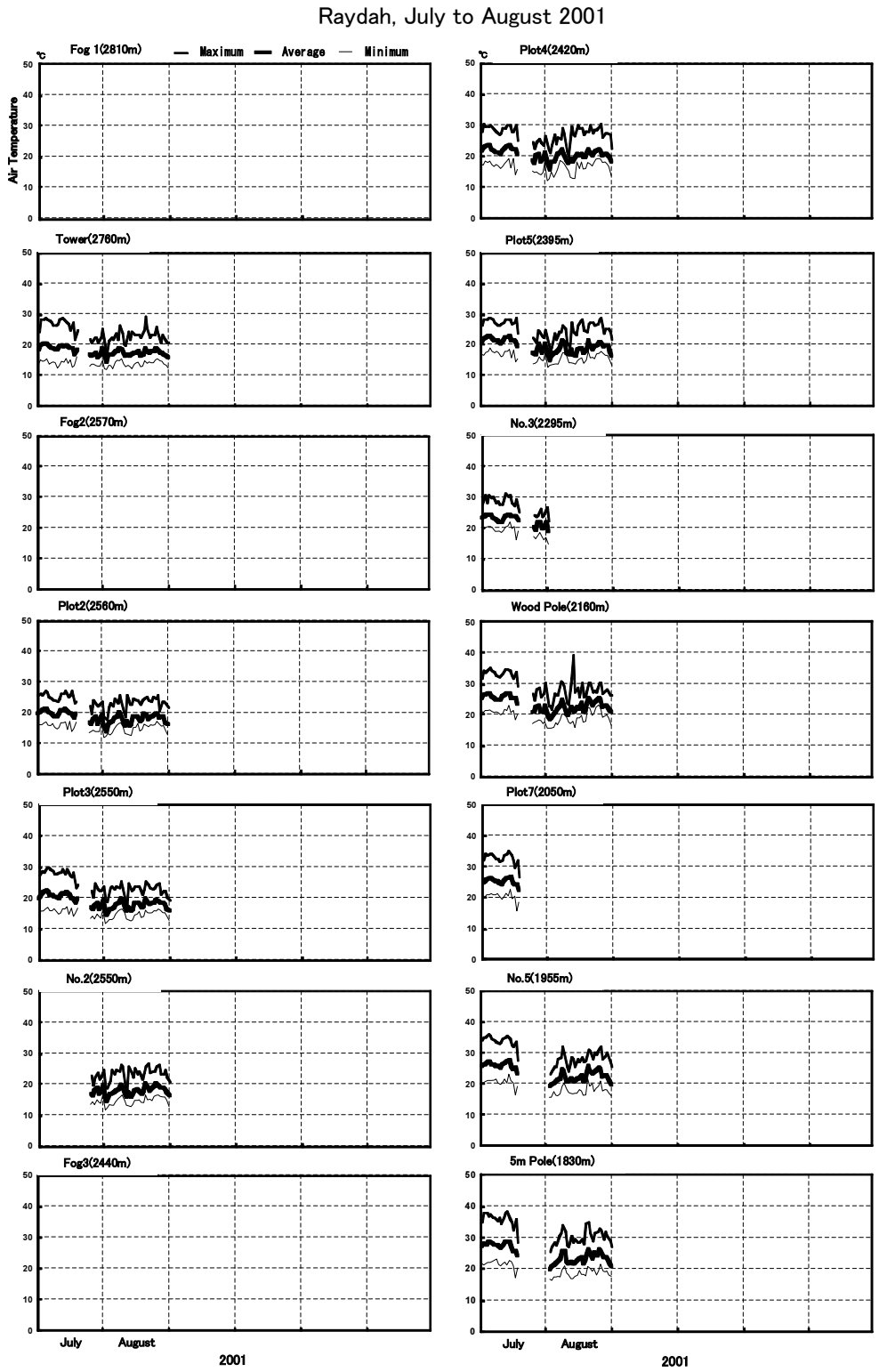



Fig. 1-21. Daily maximum, daily average, and daily minimum air temperature in Raydah from July to August 2001

Tamuniyah, January to June 2000

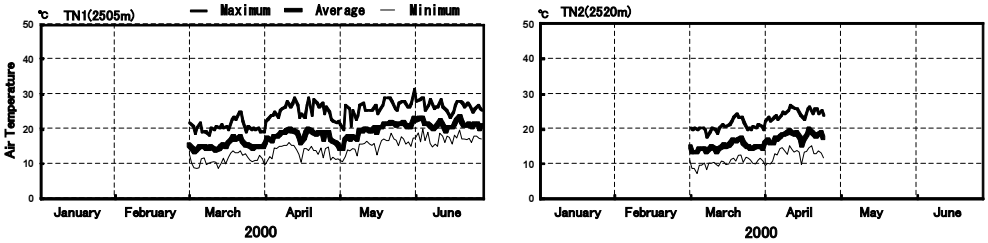



Fig. 1-22. Daily maximum, daily average, and daily minimum air temperature in Tamniyah from January to June 2000

Jabal Tallan, January to June 2000

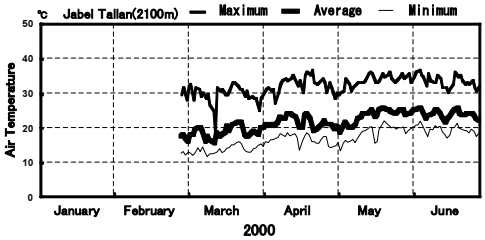



Fig. 1-23. Daily maximum, daily average, and daily minimum air temperature in Jabal Tallan from January to June 2000

Tamuniyah, July to December 2000

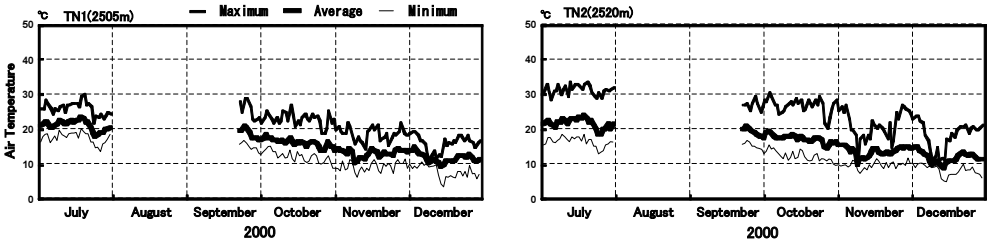



Fig. 1-24. Daily maximum, daily average, and daily minimum air temperature in Tamniyah from July to December 2000

Jabal Tallan, July to December 2000

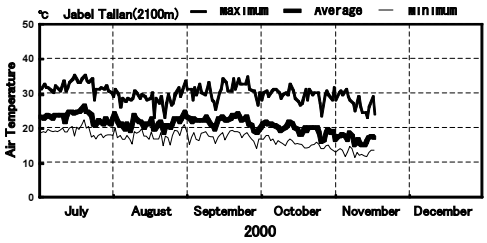



Fig. 1-25. Daily maximum, daily average, and daily minimum air temperature in Jabal Tallan from July to December 2000

Tamuniyah, January to June 2001

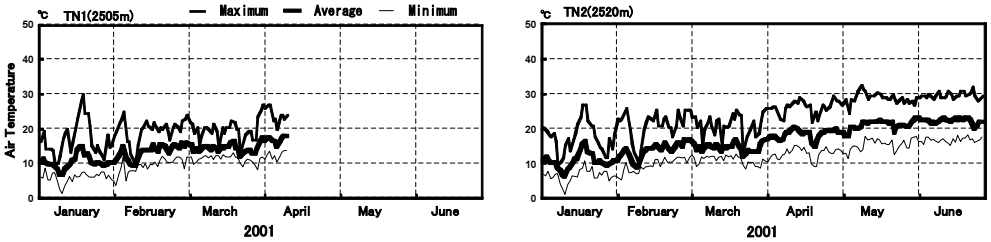



Fig. 1-26. Daily maximum, daily average, and daily minimum air temperature in Tamniyah from January to June 2001

Jabal Tallan, January to June 2001

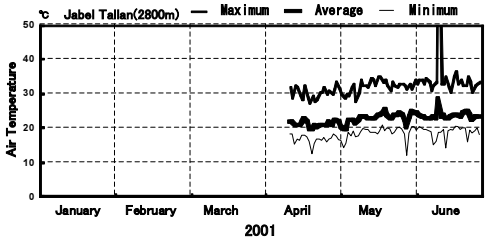



Fig. 1-27. Daily maximum, daily average, and daily minimum air temperature in Jabal Tallan from January to June 2001

Tamuniyah, July to August 2001

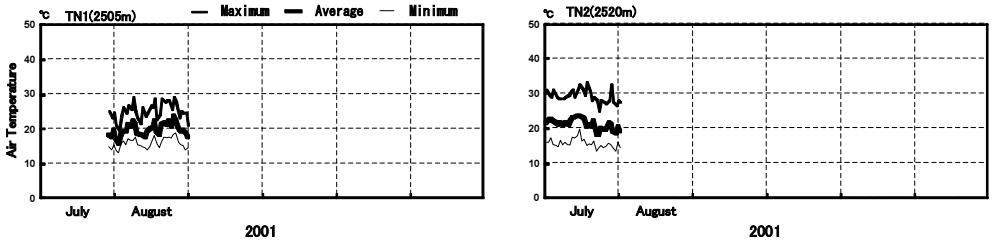



Fig. 1-28. Daily maximum, daily average, and daily minimum air temperature in Tamniyah from July to August 2001

Jabal Tallan, July to August 2001

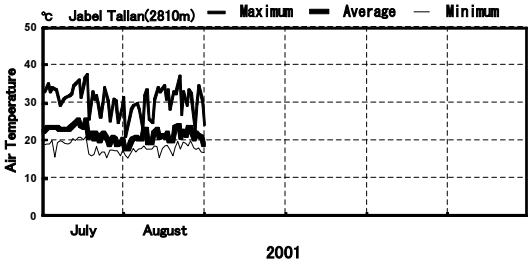



Fig. 1-29. Daily maximum, daily average, and daily minimum air temperature in Jabal Tallan from July to August 2001

Raydah, July to December 1999

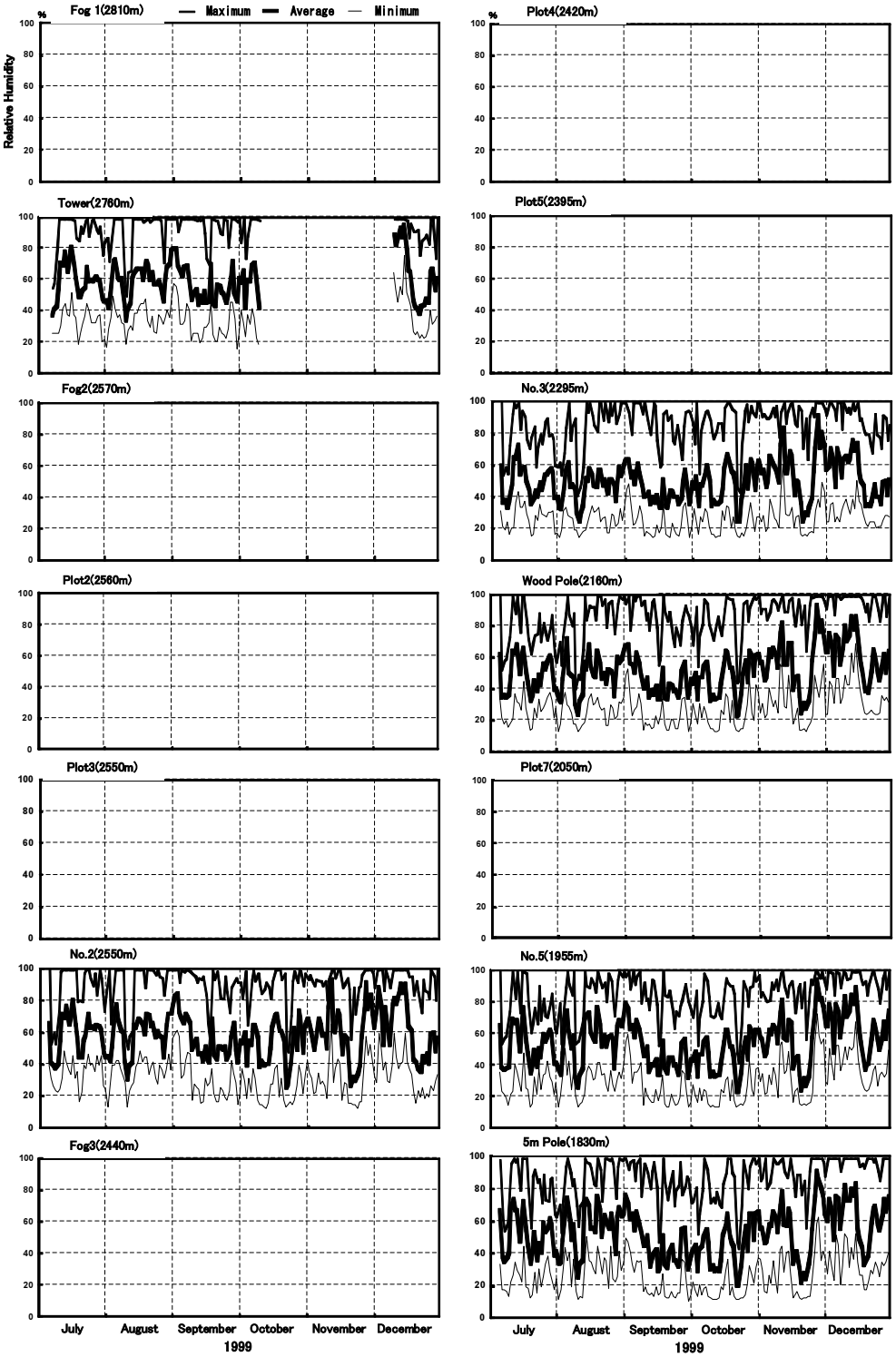



Fig. 1-30. Daily maximum, daily average, and daily minimum relative humidity in Raydah from July to December 1999

Raydah, January to June 2001

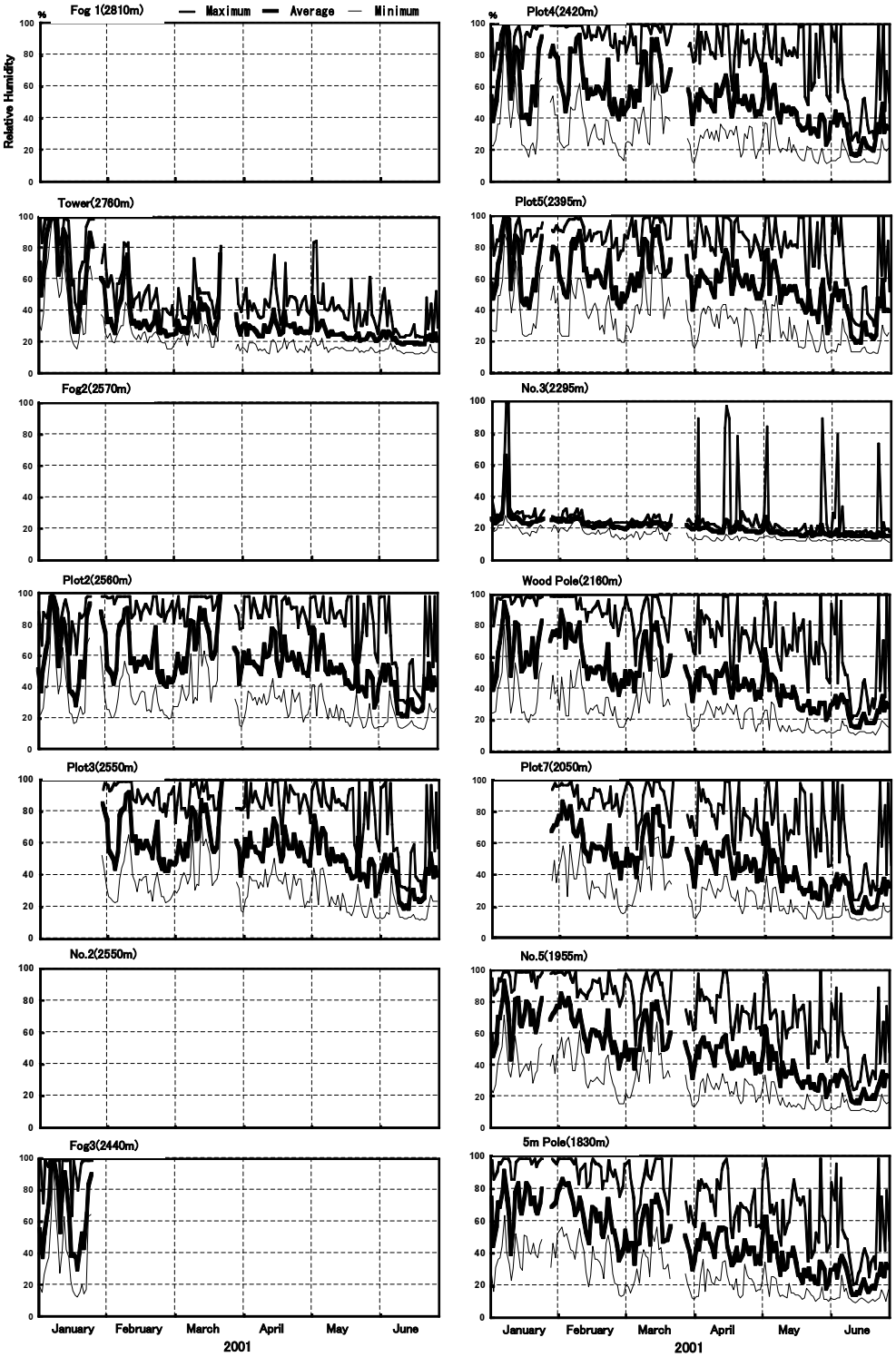



Fig. 1-31. Daily maximum, daily average, and daily minimum relative humidity in Raydah from January to June 2000

Raydah, July to December 2000

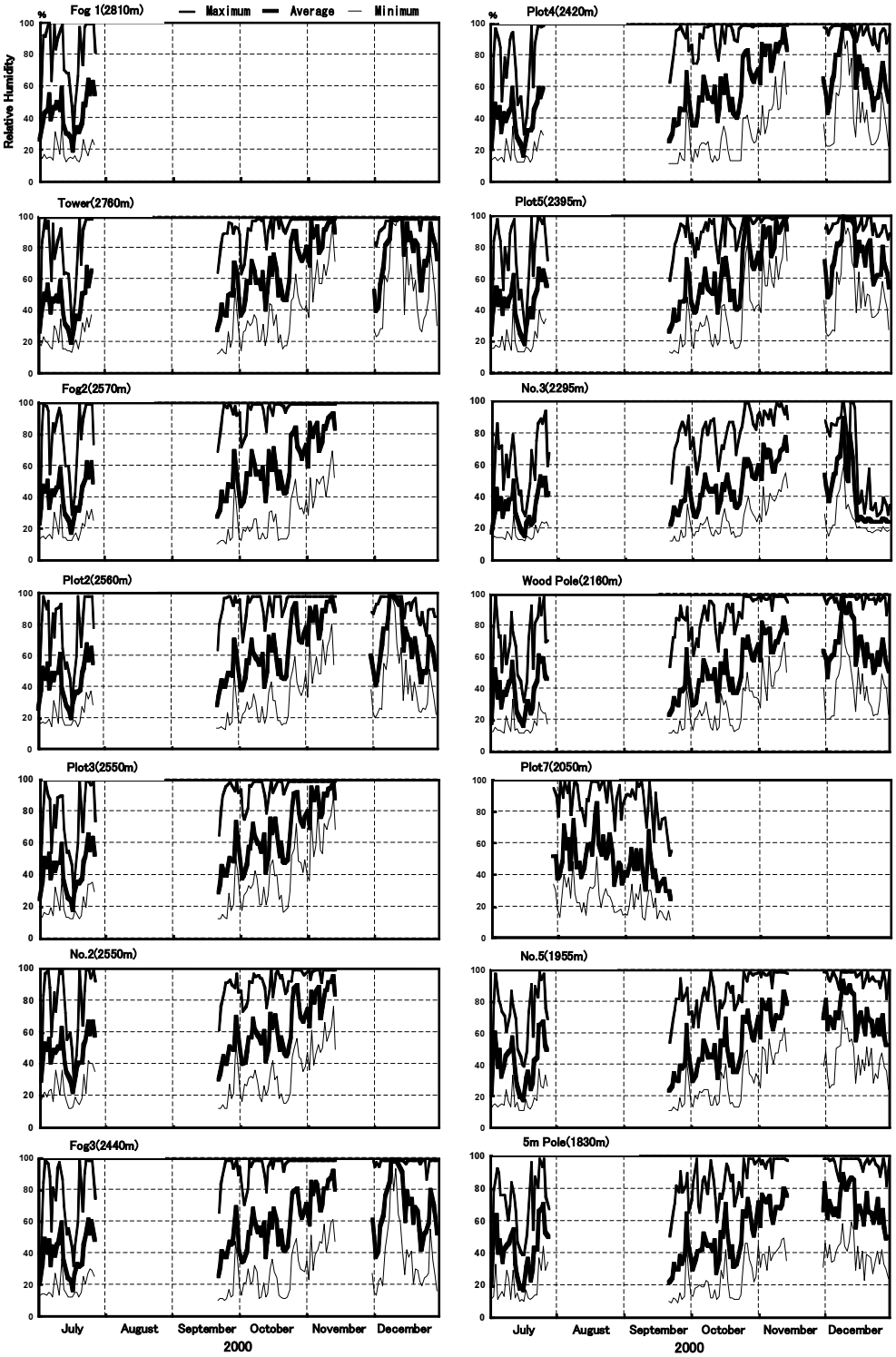



Fig. 1-32. Daily maximum, daily average, and daily minimum relative humidity in Raydah from July to December 2000

Raydah, January to June 2001

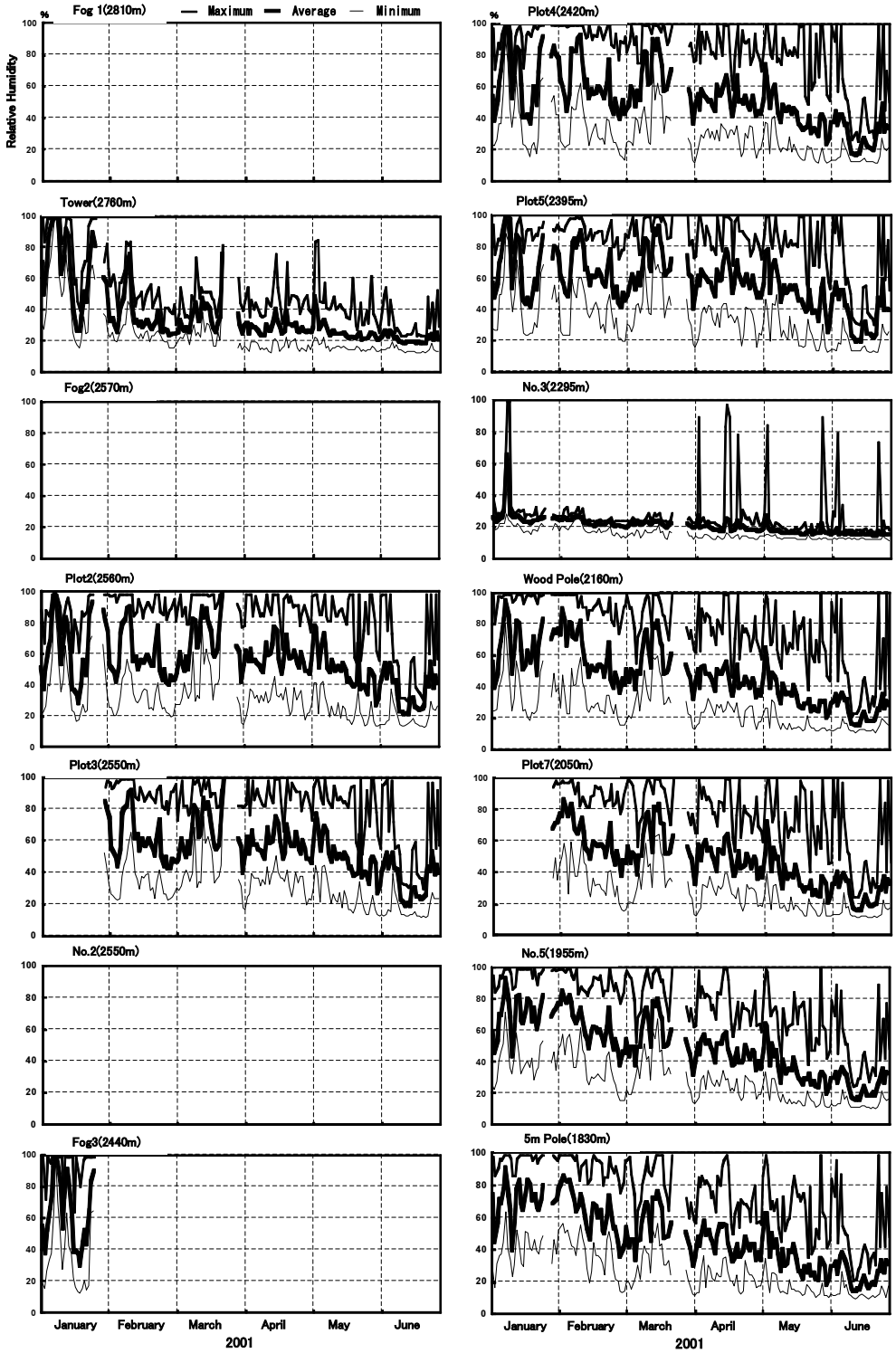



Fig. 1-33. Daily maximum, daily average, and daily minimum relative humidity in Raydah from January to June 2001

Raydah, July to August 2001

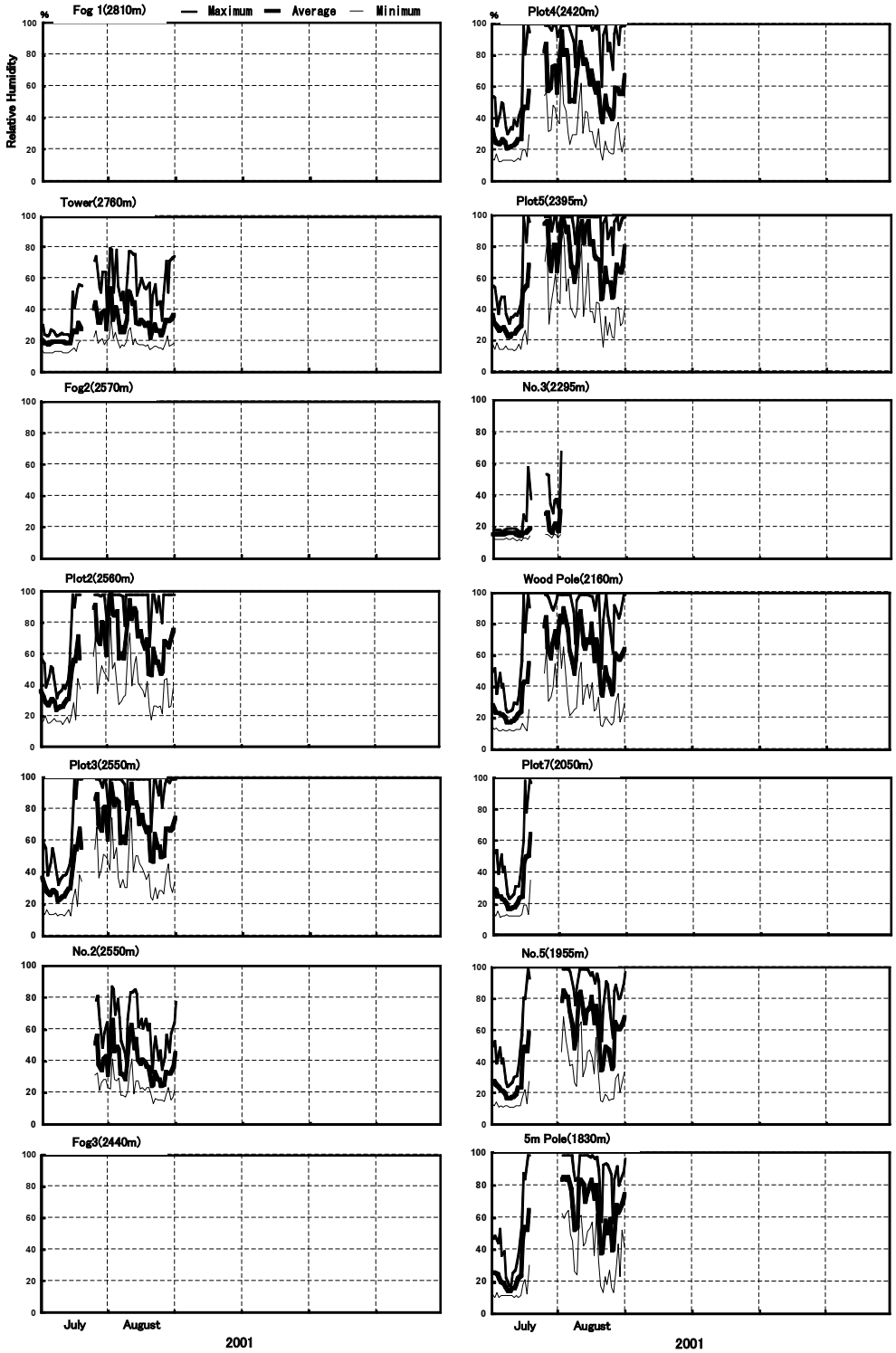



Fig. 1-34. Daily maximum, daily average, and daily minimum relative humidity in Raydah from July to August 2001