Research paper

Diurnal and Annual Temperature Variations in Experimental Forests of the Taiwan Forestry Research Institute

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【Summary】

Temperature regimes are the main factor that determine the type of forest ecosystems and the most important factor for seed germination and vegetative growth. Diurnal and annual temperature variations for 10 meteorological stations of the Taiwan Forestry Research Institute (TFRI) were analyzed in this report. The results indicate that the highest and lowest air temperatures occurred in July and January, respectively, at all stations of TFRI. Monthly average air temperatures ranged from 6.5 to 28.6℃, and those extremes occurred in January at the Piluchi station and in July at the Taimali station, respectively. The diurnal range of temperature is relatively large owing to the shortness of the daily cycle. The largest daily temperature discrepancy was found at the Piluchi station which had a range of 22.1℃, while the smallest discrepancy was at the Hengchen station with a range of 11.8℃. Times of highest temperatures within a day occurred before noon for stations at higher elevations, while those of other stations occurred after noon and mostly around 14:00. Cloud cover was the possible reason for the earlier occurrence of the highest temperature at higher elevations because clouds are usually present before noon particularly in summer months. The lowest temperature within a day mostly occurred at about 06:00 before dawn and had no relationship with elevation or season.

Key words: temperature variation, meteorological station, diurnal temperature range.

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研究報告

林業試驗所各林區氣溫日變化及年變化

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摘 要

溫度及其變化會影響種子發芽與林木生長，亦為決定森林生態系特性的首要環境因子。本研究報告分析林業試驗所10座氣象站氣溫的年與日變化量，獲知所有氣象站最高與最低月平均氣溫均分別發生於7月及1月，月平均最高氣溫及最低氣溫分別為太麻里氣象站7月的28.6℃及畢祿溪氣象站的

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6.52℃。由於週期較短，日溫差相對地顯現較大的變異幅度，其中日溫差變化最大的測站為畢祿溪，高達22.1℃，最小則為恆春測站的11.8℃。海拔較高的測站，因受地形及雲霧等影響每日最高氣溫多發生於中午之前，而其他測站則發生於午後，並以14:00為最多。每日最低氣溫多發生於清晨06:00日出前，且發生時間地形不受地形及海拔高影響。

關鍵詞：氣溫變化、氣象站、日溫差。

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INTRODUCTION

Temperature is a measurement of the degree of hotness or coldness of a body, i.e., of the quantity of internal or heat energy that it contains. It is the most important factor for seed germination and vegetative growth. Temperature and moisture content are 2 major climatic parameters that govern vegetative growth and distribution and also the most important limiting factors for forest growth and agricultural production (Botkin and Keller 1987, Lookingbill and Urban 2003). Although the climate of Taiwan is characterized by high precipitation and high temperature, the influence of temperature is not as great as that in high-latitude regions. However, the great topographic relief combined with the latitude makes the effects of temperature on the vegetation distribution so outstanding that it produces weather of alpine, temperate, to tropical regions on this island. Therefore, temperature regimes are the main factor that determines the forest ecosystems of this island. The meteorological characteristics of forested lands of TFRI were analyzed by Lu et al. (2000). However, the climate of a particular location may depend upon extreme or infrequent conditions rather than on long-term averages. More than a simply average temperature and precipitation are required to describe climatic conditions of a region (Botkin and Keller 1987, Boostsma 1994). In discussing the influences of climate on an ecosystem, one must pay particular attention to the seasonal and diurnal variations in temperature of a region since temperature variability is an important controlling factor for most ecological processes (Stephenson 1990, Moonen et al. 2002). In this context, temperature records of meteorological stations of TFRI, which are considered adequate to represent weather conditions for nearly all forest ecosystems in Taiwan, are valuable information not only for forestry management but also for ecological studies.

TFRI has gradually upgraded its meteorological stations from manual mode to automatic mode since 1993. In the automatic mode, records are stored in digital format and the resolution is as detailed as "hourly". Those digital records are considered sufficiently precise and are useful materials for diurnal variation analysis. Temperature regimes are the basic information for wildlife behavior and ecosystem studies, however, they have seldom been investigated in Taiwan. This report makes a detailed analysis of diurnal and seasonal variations for the main forested ecosystems of Taiwan. Hopefully, this study will help further understanding of conditions of forested ecosystems in Taiwan, and this kind of information will improve future confidence in assessments of climate change impacts on ecosystems and forest hydrological conditions.

MATERIALS AND METHODS

Materials

TFRI has 13 meteorological stations located at its research centers as described by Lu et al. (2000), and 10 of those stations were selected as the study sites for this study (Table 1). The high-quality digital hourly mean, maximum, and minimum air temperature, as well as rainfall, and radiation records collected from the years 1998 to 2002 of meteorological stations of TFRI comprise the basic data for diurnal variation analysis of this study. In addition, the historical daily temperature records (from the beginning of observation to December 2002) were used for seasonal variation analysis and were also considered in this study. Those records were stored on sheets of paper and must be transformed into digital format before they can be analyzed.

In automatic mode, classic climatic factors are monitored by a programmable datalogger and automatically recorded in computer compatible digital format. The monitoring system consists of a CR10 datalogger produced by Campbell Scientific Incorporated for all TFRI's stations. The average, maximum, and minimum air temperatures, relative humidity, wind velocity and direction, solar radiation, and rainfall amount are recorded hourly by the automatic CR10 system. The system detects these factors every 10 min. The hourly average is the average of the 6 measurements within that hour, and the maximum and minimum records are the maximum and minimum of the 6 measurements for that hour, respectively. Hourly rainfall and radiation amounts are the sum of all 6 measurements taken within that hour.

The HYGROMER MP100A meteorology probe is the instrument used for measuring temperature and humidity. Temperature measurements range from -40 to 60℃ and those of relative humidity from 0 to 100%; and the measurement accuracies for temperature and relative humidity are ±0.3℃ (-20 to 40℃), ±0.5℃ (-40 to 55℃), and ±2.5% (0 to 100%), respectively. Sensors are kept in a shelter to avoid exposure to direct radiation.

Methods

Hourly records were rearranged from the original sequential format data files. They were arranged in a 24×31 data matrix in which rows are hourly records for the corresponding column's date for each parameter analyzed. If more than 12 of the hourly records of a day were missing, the

Table 1. Location and elevation of meteorological stations of TFRI

Name (abbreviation)	Longitude	Latitude	Elevation (m)	Start date
Fushan (FS)	121°34'E	24°46'N	570	July 1988
Piluchi (PL)	121°19'E	24°14'N	2350	June 1971
Lienhuachih (LH)	120°54'E	23°56'N	744	Jan 1961
Shehhu (SH)	120°09'E	23°40'N	4	Feb 1993
Fonkang (FK)	120°42'E	23°01'N	1510	Mar 1986
Liukuei (LK)	120°38'E	23°00'N	251	Aug 1980
Shanping (SP)	120°41'E	22°55'N	700	Aug 1980
Donna (DN)	120°43'E	22°47'N	1050	Mar 1986
Taimali (TM)	120°58'E	22°36'N	90	Aug 1980
Hengchun (HC)	120°49'E	21°57'N	230	Sept 1980

entire day's records were excluded from the analysis. The average value of records of the same row is the daily average of the corresponding date and the average value of records in the same column are the monthly average for that particular time. The times of occurrence for the daily maximum and minimum temperatures (the highest and lowest temperatures of a particular day) and their values were also selected from the original data files for the analysis of extremes of temperature. For clear and easy presentation, diurnal variations were subjectively grouped into 4 seasons. They are from March to May (spring), June to August (summer), September to November (autumn), and December to the following February (winter).

The historical daily mean (the average value of hourly records within a day for the automatic mode, or the average value of all observations within a day for the manual mode) air temperatures were used for calculating monthly averages. A similar criterion of excluding missing data was made for the monthly analysis if daily records for more than 15 days were missing within a month. If missing data occurred, the mean was the average of the remaining records.

Data records must pass through the threshold of an outlier test before they can be accepted for analysis. Outliers are data points that depart significantly from the trend of the remaining data, and the retention or deletion of these records can significantly affect the magnitude of statistics computed from the data. The equations below were used to detect high and low outliers:

$Yh = \acute{Y} + Kn*Sy$, and $Yl = \acute{Y} - Kn*Sy$;

where Yh and Yl are the high and low outlier thresholds in log units, respectively, $\acute{Y}$ is the average of the data set, Sy is the standard deviation, and Kn equals 2.577 and 2.653 for sample sizes of n = 31 and 30, respectively (US Water Resources Council 1981).

RESULTS AND DISCUSSION

Annual variations

The annual air temperature variations for those 10 stations are shown in Fig. 1, and the numerical values are tabulated in Table 2. The highest and lowest monthly average temperatures (historical extremes of monthly average) occurred during July and January, respectively, at all TFRI stations. Although Taiwan is a subtropical oceanic island and has heavy rainfall in all summer months, temperatures of TFRI's forested land showed noticeable annual variations. The period with average monthly temperatures exceeding 20℃, what we herein call summer weather, lasts about 6 to 7 mo for stations located in northern Taiwan, while for stations located in southern Taiwan, it persists for 9 to 10 mo in general. In the central and southern parts of

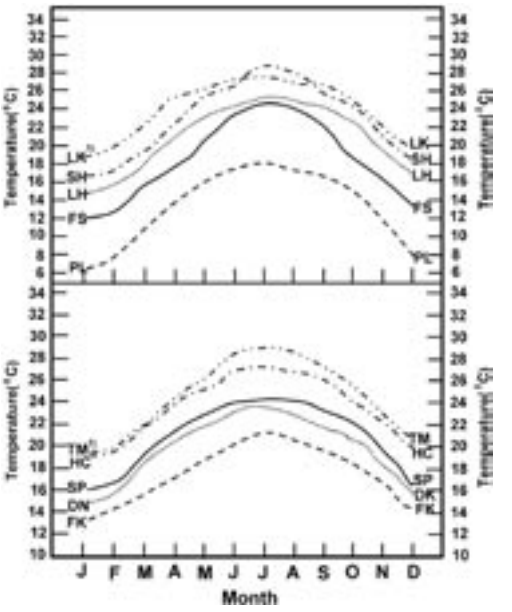

Fig. 1. Monthly average air temperatures for stations TFRI.

Table 2. Monthly average air temperatures[1] for TFRI's stations (in ℃)

Station	FS[2]	PL	LH	SS	FK	LK	SP	DN	HC	TM
Jan	12.0	6.5	14.8	16.8	13.3	18.8	16.0	14.6	19.1	19.4
Feb	12.9	7.9	15.8	17.4	14.5	19.9	16.8	15.8	19.0	19.9
Mar	15.4	11.0	18.2	19.5	15.7	22.2	19.4	18.6	21.8	21.9
Apr	17.2	14.0	21.0	22.4	17.4	25.0	21.5	20.5	24.0	24.3
May	20.6	16.0	23.1	25.3	18.7	26.3	23.1	21.9	25.3	26.2
June	23.4	17.5	24.4	26.7	20.2	27.2	23.9	23.3	26.8	28.3
July	24.6	18.1	25.3	28.6	21.1	27.6	24.4	23.7	27.2	29.0
Aug	24.2	17.4	24.8	28.0	20.7	27.1	24.2	22.9	27.0	28.6
Sept	22.1	16.7	24.3	25.9	19.7	26.8	23.2	21.8	26.2	27.2
Oct	18.6	15.0	22.6	24.3	18.3	25.2	22.0	20.9	24.2	25.5
Nov	16.4	11.9	19.6	21.1	16.6	22.1	19.8	18.4	22.4	23.0
Dec	13.4	7.9	16.6	18.4	14.5	19.9	16.8	15.7	19.8	20.2
Avg.	18.4	13.3	20.9	22.9	17.5	24.0	20.9	19.8	23.6	24.5

[1] From the beginning of observation of each station to 31 Dec. 2000.
[2] Abbreviations for stations are defined in Table 1.

Taiwan, the sun is high in the sky throughout the year and the northeast winter monsoon has little or no influence, and this accounts for the smaller depression in winter temperatures. Because the northern part of Taiwan is subject to invasions of maritime cold air masses in the winter and early spring, the depression in winter temperatures at the Fushan station is significant.

It can be seen that elevation rather than latitude is the dominant factor affecting annual temperature variation in TFRI's forested land. Air temperature varies with elevation and decreases with height, on average, at a rate of 6.5℃/km (the lapse rate) in the troposphere (Miller and Thompson, 1975). Fonkang, Liukuei, Shanping, and Donna are located at about the same latitude but have different elevations. The average monthly temperatures of those stations significantly differ and have the same rank from low to high as their elevations, although the decrease rates show some deviations from the general rule. Influence of topography and atmospheric circulation are the possible reasons for the deviation.

Effects of forests on temperatures

In general, forest absorbs 60 to 90% of the total solar energy received. The amount absorbed by any forest stand depends on its density and the development of its foliage. The incident energy is primarily consumed by evaporation and transpiration on forested land, provided requisite moisture is available during the growing season (Reifsnyder and Lull 1965). It has been proven that the under-canopy temperature can be reduced owing to the consumption of energy during the daytime, and it is higher than that outside of the canopy owing to the blockage of outgoing long-wave radiation by the canopy during the nighttime (Aston 1985, McCaughey 1985). A complex interaction between solar radiation and the atmosphere system governs air temperatures. Therefore, to what degree forests can lower the surrounding temperatures is still controversial and difficult to identify. Table 3 tabulates the average monthly air temperature for stations in cities that are somewhat close to TFRI forests. Although not all monthly average temperatures for stations in cities are higher

Table 3. Monthly average air temperatures[1)] for stations in cities nearby TFRI's forested land (in ℃, Central Weather Bureau 2001)

Location	Ilan	Taichung	Chiayi	Kaohsiung	Taitung	Hengchun
Jan	16.0	16.2	16.1	18.8	19.2	20.6
Feb	16.4	16.8	16.8	19.7	19.6	21.1
Mar	18.7	19.4	19.4	22.3	21.7	23.1
Apr	21.6	23.0	22.9	25.2	24.0	25.2
May	24.2	25.7	25.5	27.2	26.0	26.9
June	26.7	27.5	27.6	28.4	27.7	27.9
July	28.4	28.5	28.4	28.9	28.7	28.3
Aug	28.0	28.0	27.8	28.3	28.4	27.9
Sept	26.2	27.2	26.7	27.9	27.3	27.4
Oct	23.4	24.9	24.3	26.4	25.6	26.3
Nov	20.2	21.4	20.9	23.4	23.0	24.0
Dec	17.3	17.8	17.4	20.2	20.4	21.6
Avg.	22.3	23.0	22.8	24.7	24.3	25.0

[1)] From Jan 1971 to Dec 2000.

than those of the corresponding TFRI station, the yearly average temperatures are all higher. There are many factors such as atmosphere circulation, maritime influences, the urban heat-island effect, and wind velocity other than land use and solar energy received that can affect air temperatures. The effects of land use on temperature are insignificant in comparison with those of others factors.

Temperatures under the canopy of natural hardwood forest and a betel nut plantation in the Lienhuachih area were monitored from 2000 to 2001 (Lu et al. 2002). Table 4 tabulates the monthly average temperatures below the canopy of a natural hardwood forest and the corresponding temperatures at the Lienhuachih station. The effect of elevation on temperature can be ignored since the elevation of the hardwood plot is only 16 m higher than Lienhuachih. Although the difference between temperatures inside and outside the canopy had no statistic significance (*t*-value of 0.332, inside the critical region), still all average monthly temperatures under the canopy were lower than those outside of the canopy except in the coldest month (January). This indicates that the forest can reduce the range of temperatures difference and lower the air temperature inside and above it.

Diurnal temperature variations

Diurnal air temperature variations of the studied sites are shown in Fig. 2. The horizontal lines in each figure are the daily average temperature for different seasons,

Table 4. Monthly average temperatures under the canopy of a natural hardwood forest and corresponding temperatures at the Lienhuachih station (in ℃)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hardwood	13.7	14.8	17.2	19.7	21.2	22.4	23.2	22.4	22.2	22.1	19.3	16.8
Lienhuachih	12.8	15.2	17.8	20.2	21.9	23.3	23.9	23.3	22.8	22.7	19.8	16.9
△t	0.9	-0.4	-0.6	-0.5	-0.7	-0.9	-0.7	-0.9	-0.6	-0.6	-0.5	-0.1

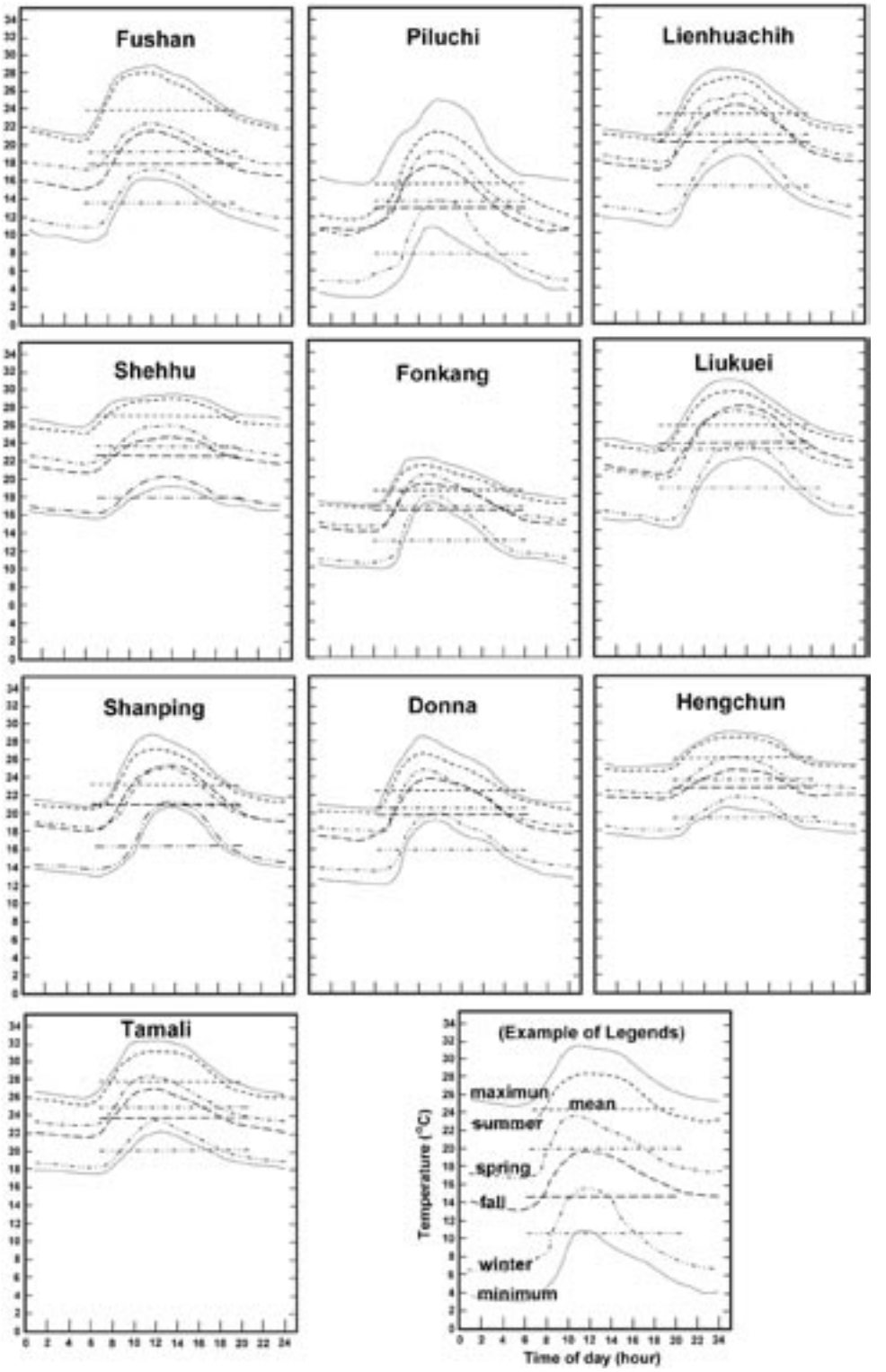

Fig. 2. Diurnal temperature variations at TFRI's stations.

and the highest and lowest seasonal average temperatures (absolute hourly extremes) are tabulated in Tables 5 and 6, respectively. The highest temperatures occurred from 11:00 to 14:00 at all stations of TFRI. In general, the time of highest temperature for stations at higher elevation, such as Piluchi, Fonkang, and Donna, occurred before noon in all seasons, and that of other stations occurred in the afternoon, mostly at around 14:00. The lowest temperature within a day occurred at about 06:00 before dawn for most stations and had no relationship with elevation or season.

Solar radiation is the primary source of energy for heating the air and ground surface, although most of the energy is reradiated as long-wave radiation. Therefore, the amount of solar radiation received can significantly affect air temperatures near the ground. The amount of radiation received depends on the slope and aspect. In the northern hemisphere, a south-facing slope faces the sun more directly than does a north-facing slope and receives more radiation than does a north-facing slope. Most of TFRI's stations are located in relatively flat open areas, and the effects of aspect are not significant. However

Table 5. Peak values of diurnal temperature variations and the time of occurrence in different seasons at TFRI's meteorological stations (temperature in ℃)

Location	Spring		Summer		Fall		Winter	
	Occur.	Temp.	Occur.	Temp.	Occur.	Temp.	Occur.	Temp.
Fushan	12:00	20.5	12:00	27.2	12:00	21.2	12:00	16.5
Piluchi	11:00	17.9	12:00	21.5	12:00	19.3	12:00	14.0
Lienhuachih	13:00	24.6	13:00	27.6	14:00	25.8	14:00	20.6
Shehhu	14:00	17.6	14:00	23.0	14:00	19.1	14:00	16.5
Fonkang	11:00	19.4	11:00	21.3	11:00	20.3	11:00	18.0
Liukuei	14:00	27.9	14:00	29.4	14:00	27.3	14:00	23.6
Shanping	14:00	25.6	14:00	26.9	13:00	25.4	14:00	21.6
Donna	11:00	23.8	10:00	26.7	11:00	24.9	11:00	20.0
Taimali	12:00	27.2	12:00	31.4	12:00	28.5	12:00	23.6
Hengchun	13:00	24.7	13:00	28.4	13:00	26.0	13:00	21.6

Table 6. Lowest values of diurnal temperature variation, and the time of occurrence in different seasons at TFRI's meteorological stations (temperature in ℃)

Location	Spring		Summer		Fall		Winter	
	Occur.	Temp.	Occur.	Temp.	Occur.	Temp.	Occur.	Temp.
Fushan	06:00	15.2	06:00	20.8	06:00	17.0	06:00	11.1
Piluchi	04:00	10.6	04:00	11.8	04:00	10.2	04:00	4.8
Lienhuachih	06:00	17.3	06:00	20.5	06:00	18.1	07:00	12.2
Shehhu	06:00	16.3	06:00	19.9	06:00	15.3	07:00	13.2
Fonkang	06:00	14.0	06:00	16.6	06:00	14.5	05:00	10.6
Liukuei	06:00	20.2	06:00	22.8	06:00	19.9	06:00	15.2
Shanping	06:00	18.3	06:00	20.7	06:00	18.6	07:00	14.0
Donna	05:00	17.1	05:00	20.0	06:00	18.0	05:00	13.6
Taimali	06:00	21.8	06:00	25.4	06:00	23.1	06:00	18.4
Hengchun	06:00	21.4	05:00	24.6	06:00	22.1	06:00	18.0

except for the Shehhu, Liukuei, Hungchen, and Taimali stations, other TFRI stations are located in mountainous areas. The effects of slope and topography are significant for solar radiation as well as air temperature for those stations located in the mountains especially for stations located in valleys i.e., Piluchi and Shanping. The later temperature rise and the maximum temperature occurring before noon are mainly caused by those effects.

Since the daily cycle is short, the diurnal range of temperature is relatively large. The largest hourly temperature range (the difference between the historical maximum and minimum hourly records) was found at the Piluchi station which has a range of 22.1℃. The smallest range was at the Hengchen station with a value of 11.8℃ (Table 7). On account of the shortness of the cycle, the horizontal exchanges of heat are relatively unimportant, except along coasts where an alternating system of land and sea breezes develops. This viewpoint can be confirmed from the Hengchun and Shehhu stations which have small diurnal temperature ranges and are close to the coast. Since the daily variation at the same elevation is large in low latitudes and small in high latitudes, the diurnal range generally decreases from the equator toward the poles.

Table 7. Extreme values of diurnal temperature variations and their ranges for TFRI's meteorological stations (in ℃)

Location	Highest	Lowest	Range
Fushan	27.8	10.0	17.8
Piluchi	25.2	3.1	22.1
Lienhuachih	28.5	11.0	17.5
Shehhu	30.0	16.0	14.0
Fonkang	22.2	9.9	12.3
Liukuei	30.8	14.3	16.5
Shanping	29.0	13.3	15.7
Donna	28.5	12.0	16.5
Taimali	32.5	17.7	17.5
Hengchun	28.9	17.1	11.8

The diurnal range is also much influenced by the cloud cover and wind speed. Clouds reduce the incoming radiation during the day and augment downward radiation from the sky at night. For stations in cloud-forest areas like the Donna and Fonkang stations, where cloud cover usually occurs before noon particularly in summer months, the highest temperature occurs 1 or 2 h earier than that at other stations. Because clouds cover the entire sky during typhoon periods, the range of diurnal temperatures is relatively smaller during these periods. Furthermore, heat exchange affects a deep layer of air on windy days, and the range of temperatures at the surface is smaller than on calm days.

The amount of moisture in the air also exerts a noticeable influence. With lesser vapor, a larger amount of outgoing radiation can escape to space. Other conditions being the same, the night minimum temperature will be lower when the air column contains little moisture. Since the climate of Taiwan can be characterized by high humidity and temperatures, the moisture content in the air is usually abundant. However, Taiwan has obvious wet and dry seasons particularly in its central and southern parts (Lu et al. 2000). The nighttime temperature in the winter drops quickly for stations in the southern part of Taiwan, particular for stations located at low elevations, such as Liukuei, Shehhu and Hengchen. In addition, the composition of the soil is also important. The conductive capacity of the soil increases with wetness, so that the diurnal range will be smaller over wet than over dry land.

Traditionally, daily climatic records are observed and recorded manually at 09:00, and these observations are used to represent the average values for that day. Whether such

observations can really represent an entire day's weather characteristics has often been questioned and criticized. Choosing a time which is best for observation also has been controversial. It can be found from Fig. 2 that intersections of the horizontal average lines and the curved variation lines are situated differently in each season. Intersections are located on the X-coordinate of 06:00 to 09:00 and 18:00 to 20:00 in 2 groups. This indicates that the best time for observations varies from season to season. Generally, the observed temperature value that can represent the entire day's average for 1-observation stations should be taken at 07:00 in the summer, 08:00 in the spring and fall, and 09:00 in the winter for most of TFRI's stations.

CONCLUSIONS

The temperature of TFRI's forested lands is mostly influenced by elevation and topographic conditions rather than latitude. The highest and lowest monthly average temperatures occurred in July and January, respectively, at all TFRI's station with ranges from 6.5 to 28.6℃. Diurnal ranges of temperature were relatively large and greatly differed among stations. The largest and smallest daily temperature discrepancies were 22.1℃ at the Piluchi station and 11.8℃ at Hengchen, respectively. Diurnal temperature variations are significantly affected by topography and elevation because these 2 factors strongly determine the amount of solar radiation that is received. Times of highest temperature within a day occurred from 11:00 to 14:00 with a general rule of the higher the elevation, the earlier was the occurrence of the highest temperature. The lowest temperature within a day mostly occurred at about 06:00 before dawn and had no relationship with elevation or season. Further studies of the effects of rainfall on temperature, and temperature lag, and the relationships among climatic parameters are needed to improve our understanding of climate conditions and build confidence in future assessments of climate change impacts to ecosystems.

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