***Taiwania*, 51**(4): 317-329, 2006

Climatic Characteristics of the Subtropical Mountainous Cloud Forest at the Yuanyang Lake Long-Term Ecological Research Site, Taiwan

I-Ling Lai(1), Shih-Chieh Chang(2), Po-Hsiung Lin(3), Chang-Hung Chou(4) and Jiunn-Tzong Wu(1,5,6)

(Manuscript received 25 May, 2006; accepted 20 September, 2006)

ABSTRACT: To better understand the climatic characteristics in a subtropical mountainous cloud forest at the Yuanyang Lake long-term ecological research site, weather data collected from January 1994 to December 2004 were analyzed in the present study. The obvious seasonal changes in climatic factors were observed at this site. The annual mean air temperature was 12.7°C. The lowest temperature was recorded in February (monthly mean 5.9°C), and the highest one was taken in July (monthly mean 18.1°C). Winter featured light rain with a prolonged occurrence of fog, resulting in a large reduction of radiation. In summer, fog occurred once in the early morning and the other time from afternoon to evening. The latter one was associated with the wind direction changes and usually accompanied with short moderate to heavy convective rain. Consequently the photosynthetic photon flux density (PPFD) was high in the morning but reduced drastically in the afternoon. Typhoons occurred in the summer had contributed to 37% of the annual rainfall, usually resulting in torrential rain events and sharp increases in the water level of this lake. As a matter of fact, perhumid environment of this site was attributed to abundant rainfall (mean annual precipitation 3396 mm) and high frequency (up to 40%) of foggy time. Such conditions would reduce the intensity of solar radiation and PPFD. The average annual solar radiation at the site was 2475 MJ m^{-2}, and annual PPFD was 5713 mol m^{-2}. The average degree of reduction of PPFD under foggy condition was up to 88%. Such climatic characteristics are suggested to constrain the growth of plants and play an important role in competition among plant species in this cloud forest. It is considered that the distinct seasonal fluctuation in environmental factors, perhumid and dim light conditions are the most distinguished characteristics of this subtropical mountainous cloud forest ecosystem.

KEY WORDS: Forest climate, Fog, Solar radiation, Precipitation, Photosynthetic photon flux density (PPFD).

INTRODUCTION

Mountainous cloud forests (MCFs) occur in mountainous altitudinal band frequently enveloped by wind-derived orographic clouds (Bruijnzeel and Proctor, 1995; Still et al., 1999). They obtain more moisture from deposited fog water in addition to bulk precipitation (Weathers, 1999; Foster, 2001; Chang et al., 2002). Though the regular fog or cloud immersion of the MCFs is important to water conservation, the large reduction in solar radiation also reduces bioproductivity (Bruijnzeel and Veneklaas, 1998). Because of the unique climate, the MCFs in tropics were characterized by reduced tree stature and woody timbers, increased stem density of trees and a high proportion of epiphytes (Hamilton et al., 1995). Since the altitudinal band of cloud formation on mountains is limited, MCFs occur in fragmented strips and might be likened to island archipelagoes. This isolation and uniqueness of climatic characteristics promote speciation, high endemism, and a great sensitivity of MCFs to climatic change (Stadtmüller, 1987; Pounds et al., 1999; Still, 1999; Foster, 2001).

MCFs in subtropical regions have been less studied than those in other climate zones. However, the climatic factors in subtropical regions are known to display greater variation among seasons than those observed in tropic regions. Mesoscale climatic research in subtropical Taiwan has revealed that climate characteristics are shaped by the East Asian

---

1. Institute of Ecology and Evolutionary Biology, National Taiwan University, 1, Sec. 4, Roosevelt Rd., Taipei 106, Taiwan.
2. Institute of Natural Resources, National Dong-Hwa University, 1, Sec. 2, Da Hsueh Rd., Shou-Feng, Hualien 974, Taiwan.
3. Department of Atmospheric Sciences, National Taiwan University, 1, Sec. 4, Roosevelt Rd., Taipei 106, Taiwan.
4. Research Center for Biodiversity, China Medical University, 91, Hseuh-Shih Rd., Taichung 404, Taiwan.
5. Research Center for Biodiversity, Academia Sinica, 128, Sec. 2, Academia Rd., Taipei 115, Taiwan.
6. Corresponding author. Tel: 886-2-27899590 ext. 420; Fax: 886-2-27827954; Email: jtwu@gate.sinica.edu.tw

monsoons, namely the southwest summer monsoon and the northeast winter monsoon, and by the alternation of land and sea breezes (Chi, 1969; Lau and Li, 1984; Chen et al., 1999; Pu, 2005). This causes the uneven distribution of precipitation and wind speed, and consequently the forests located leeward and windward differ significantly in their vegetation composition (Sun et al., 1998), physiology (Kuo and Lee, 2003), and soil nutrient conditions (Chen et al., 1997). Typhoons are another climatic factor characterizing the subtropics. They produce heavy episodic rainfall and strong winds and cause severe damage to agriculture and industry (Wu and Kuo, 1999). Typhoons have been observed to cause uprooting, defoliation, and nutrient losses by increasing the amounts of litter in the lowland subtropical rain forests (Mabry et al., 1998; Lin et al., 2003). In the past, only few studies have focused on climatic factors and their effects on the subtropical MCFs in Taiwan. Rees et al. (2006) reported the potential nutrient loss by typhoon-induced defoliation. Klemm et al. (2006) performed a micro- meteorological experiment to estimate the energy fluxes in an MCF stand and found the diurnal flux of air mass affected the energy balance significantly. Fog deposition rates to MCFs were reported to be significant, especially in the context of nutrient inputs (Chang et al., 2002, 2006). However, a long-term monitoring of climatic characters is still lacking in the MCFs in Taiwan.

Yuanyang Lake (YYL) established in 1992 is one of the long-term ecological research (LTER) sites in Taiwan. The site is located at a mid-altitude in northeastern Taiwan and is a typical subtropical mountainous cloud forest. Weather data at the YYL site has been recorded since 1994, and the recording of fog began in 2000. These data are valuable, for YYL is the one of the few weather stations located at a mountainous cloud forest site in Taiwan and the only one recording fog occurrences. In this paper, eleven years of climate data from the YYL site are analyzed and the seasonal and diurnal patterns of important climatic factors are presented.

MATERIALS AND METHODS

Site description

The YYL-LTER site (121°24’E, 24°35’N) has an area of 374 ha situated in Chi-lan Mountain, at an elevation of 1650 to 2420 m above sea level (a.s.l.) in northeastern Taiwan. It is located at a middle altitude on the east slope of the Hsueh-shan Mountain Range. The vegetation contains forest, swamp, and aquatic communities in the surrounding watershed and lakeshore. The forest canopy is dominated by the relic Taiwan yellow false cypress (*Chamaecyparis obtusa* var. *formosana*) with some *Tsuga chinesis* at the mountain ridge, and the understory by *Rhododendron formosanum* and *Illicium phillippinense*. The swamp community is dominated by *Miscanthus transmorrisonensis* and some hydrophytes such as *Sparganium fallux*, *Schoenoplectus mucronatus*, and *Potamogeton octandrus* (Chou et al., 2000). Yuanyang Lake, at the central part of the LTER site, is east-west oriented and spoon-shaped, having an area of 3.7 ha with maximum length of 650 m, maximum width of 150 m, and maximum depth of ca. 4.5 m near the western part (Hwang et al., 1996). The forest is characterized by large amounts of epiphytic bryophytes, representing a unique physiognomy of the ecosystem. The bryophytes play an important role in fog water deposition (Chang et al., 2002). The site has been little disturbed by human activities for a long time. It was declared a nature reserve in 1986 to preserve the integrity of the mountain lake, the *Chamaecyparis* forests, and the rare aquatic species.

Data collection

Three weather stations were built to monitor the climatic parameters (Fig. 1). The first one (S1) was located at the eastern pass of the watershed. It was built in an open field on the side of the forest logging road near the entrance to YYL in 1993 and had successfully collected the weather data since January 1994. The second one (S2) was built near the lakeshore for monitoring the change of water level after typhoon “Herb” caused high water level of the Yuanyang Lake in October of 1996. The third one (S3) was built at the swamp area inside the YYL site in July 2000 to record instantaneous change of light intensity and as the cross reference to the data from S1 station. Parameters including air temperature, relative humidity, solar radiation (wavelength: 0.28-2.80 μm, unit in W m^{-2}), photosynthetic photon flux density (PPFD, wavelength: 0.40-0.70 μm, unit in μmol m^{-2} s^{-1}), precipitation, wind direction, wind speed, and water level were recorded automatically. The sensors of the stations are listed in Table 1. The measured data were computed and saved in the datalogger (Model CR-10, with SM 192 module, Campbell Sci. Inc., USA) of each weather station.

During typhoon periods, about 17% of the data got lost due to destruction of the monitoring system. In this case, the missing precipitation data were substituted by adopting those from the nearest

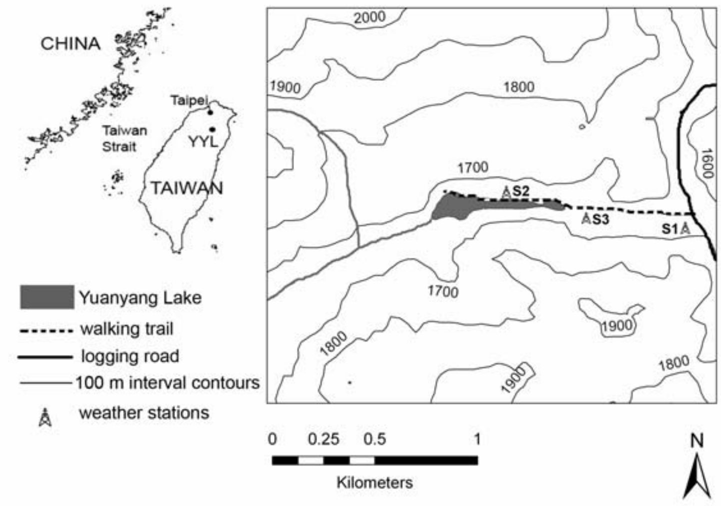


Fig. 1. Map of Yuanyang Lake (YYL) long-term ecological research site in Taiwan, showing the localities of the three weather stations (S1-S3) installed.

Table 1. The monitoring parameters and sensors used at the three weather stations of this study.

Monitoring parameters	Sensor	Station	Sensor model	Producer
Solar radiation	Precision spectral pyranometer	S1	Model PSP	Eppley Laboratory, USA
Photosynthetical photon flux density (PPFD)	Quantum sensor	S1 S3	LI-190A	LI-COR Co., USA
Temperature/relative humidity	Hygro-thermometer	S1 S3	HMP 35A	Vaisala, Finland
Precipitation	Rain gauge	S1 S3		Takeda Co., Japan
Lake water levels	Submersible pressure transmitter	S2	PS 9800	Instrumentation Northwest, Inc., USA
Wind speed/wind direction	Wind speed and direction meter	S3	Young 05103	Campbell Sci. Inc., USA
Visibility	MIRA visibility sensor	S3	Model 3544	Aanderaa instruments, Norway

weather station of Taiwan Central Weather Bureau (CWB) at Taiping Mt. (121°32'E, 24°30'N, altitude: 1930 m a.s.l.). This weather station located in the same climate zone as YYL site (Su, 1984), and its recorded daily precipitation was correlated closely with the latter (regression slope = 0.98, r^2 = 0.55 from data of 3021 days).

Terminology

For data analysis, clear days were defined as those with bell-shaped diurnal light intensity pattern, the highest light intensity higher than 1200 μmol m^{-2} s^{-1}, and the visibility higher than 2800 m at daytime. Rainy days were defined as those with daily precipitation higher than 0.5 mm. Rainfall intensity was ranked light, moderate, heavy, and torrential, when the daily precipitation was less than 10 mm or hourly precipitation not over 0.5 mm, 10-50 mm, 50-200 mm, and over 200 mm, respectively, followed the classification of Taiwan CWB. Although "fog" and "cloud" were usually used as synonyms when the large-scale landscape or vegetation was described in numerous literatures, in this study "foggy" was defined for those with a visibility below 1000 m (Chen and Chi, 1988). Fog intensities were classified as light, medium, and heavy when visibility was less than 100 m, 100-500 m, and 500-1000 m, respectively. A foggy day was defined as the day with fog persisted for at least 15 min (Gordon et al., 1994).

Estimation of reduction in potential global solar radiation and PPFD

To evaluate the transmission effect of fog on solar radiation and PPFD, the solar radiative transfer model (CLIRAD-SW) developed at the NASA Goddard Climate and Radiation Branch (Chou and Suarez, 1999) was used to compute the surface potential solar radiation and potential photosynthetically active radiation (PAR, wavelength: 0.4-0.7 μm, unit in W m^{-2}) on cloudless days. The model takes into account the absorption due to water vapor, ozone, O_2, CO_2 and aerosols and has been verified to be applicable to the Taiwan area (Lin et al., 2002; Lai and Lin, 2005; Lin, 2005). The atmosphere status parameters, content of water vapor, aerosols, and molecules (Rayleigh scattering) needed in the model, was derived from the average rawinsonde records from the Banchiao rawinsonde station (121°26'06"E, 24°59' 58"N, 9.7 m a.s.l) between 2002 and 2004. Due to the lack of ozone, O_2, or CO_2 profiles in Taiwan, the parameters were taken from the global estimation (Chou, 1990; Chou and Lee, 1996). The altitudinal effects were taken into account by eliminating the sounding profile lower than 1650 m. The degrees of reduction (in percentage) of solar radiation and PPFD were calculated using the reduced measured values of either parameter with respect to the potential one. The potential PPFD were calculated by multiplying the potential PAR with 4.57, the general conversion coefficient of PAR to PPFD in sunny daylight condition (McCree, 1981; Thimijan and Heins, 1983).

Data management

Data were downloaded on site once or twice a month and were integrated into the database with Microsoft Visual Foxpro software (Version 6.0, Microsoft Co. Seattle, USA). The available replicates of the same parameters in S1 and S3, such as PPFD, precipitation, temperature and relative humidity were compared by each data points. When the difference between the replicates was smaller than 5%, the data from S1 were taken for further summary of general climatic condition. Otherwise, the average of replicates was taken when the difference between replicates was larger than 5% and it is impossible to exclude any of them by comparing with other parameters. For further comparison of the climatic factors along elevation gradients in Taiwan, the daily weather data from 1994 to 2004 were taken from another three weather stations, the urban CWB weather station on I-Lan Plain (121º44'52"E, 24º45'56"N, 7.4 m a.s.l.), the Fushan LTER forest site, (121º35'05"E, 24º45'59"N, 455 m a.s.l.), and the CWB weather station at Yushan (120º57'06"E, 23º29'25"N, 3845 m a.s.l.). The data acquired from Fushan climatic data annual reports (http://metacat.ndhu.edu.tw/) and the annual data reports of the CWB of Taiwan were used for this purpose.

For further statistic analyses, such as analyses of variance (ANOVA), linear regression, and correlation, software STATISTICA (Version 6.0, StatSoft, Inc., Tulsa, OK, USA) was used.

RESULTS

Climatic pattern at the YYL site

The average annual temperature was 12.7°C over the period from 1994 to 2004, with the highest annual temperature of 13.2°C in both 1998 and 2000 and the lowest one of 11.9°C in 1997 (Fig. 2A). The highest recorded temperature was 29.1°C in July of 2003 while the lowest one was -5.3°C in December of 1999. The relative humidity was usually higher than 90%. The annual precipitation varied between 2109 mm (in 1995) and 4727 mm (in 2001), with an average of 3396 mm (Fig. 2B). The variation in precipitation was attributed to the occurrence of typhoons. On average, there were 239 rainy days per year (Fig. 2C). Heavy and torrential rainy days were 12±4 days per year. Compared with the rainy day records at the weather stations at I-Lan (205 days), Fushan (228 days), and Yushan (149 days), the YYL site apparently had more rainy days.

Over the last eleven years, 61 typhoons have passed through Taiwan (Shieh et al., 1998; Hsiao, 2005). Typhoons contributed up to 40% of yearly precipitation at the YYL site, usually occurring between July and October (Fig. 3A). The highest daily precipitation, 868.5 mm, was recorded in 1996 when Typhoon "Herb" passed this site. The highest total precipitation event (1083 mm) was Typhoon "Nari" in 2001. The measured wind speed at the YYL site was lower than that at the lowland weather stations. For instance, during Typhoon "Billis" in August 2000, the maximum wind speed measured at the YYL site was 18 m s^{-1}, while at low elevation I-Lan, it was 30 m s^{-1}.

There was significant seasonality in temperature, precipitation, fog duration, and amounts of radiation at the YYL site. The warmest month was July with a mean temperature of 18.1°C, and the coldest was January with a mean of 5.9°C. In a year, there had been 8-15 days with air temperatures below 0°C, but rarely with snowfall. With over 15 rainy days and precipitation over 100 mm every month, there was practically no dry season at the YYL site. However, there was seasonal variation in the amount of precipitation, with higher values from August to October, and lower ones in March and April (Fig. 3A). The amount of precipitation was not correlated with the number of rainy days. Fig. 3B shows that higher precipitation resulted from both the heavy rain and torrential rain that occurred during typhoon season, particularly from August to October. In fact, 57% of the heavy rain events were associated with typhoons or typhoon-induced air flows. Torrential rain took place in summer, and all of it was associated with typhoon events.

Over half of rainy days were contributed by light rain. Fig. 4C shows that both the daily rainy hours and the fraction of light rain changed in a similar pattern over a year, with lower values in summer and higher ones in winter. In summer, the rainy time was short with moderate to heavy rain. In winter, on the contrary, the light rain prevailed and lasted for longer time.

The amount of precipitation strongly affects the water level of YYL. Over the study period, the monthly average water level of YYL presented a similar fluctuation pattern with that of precipitation,

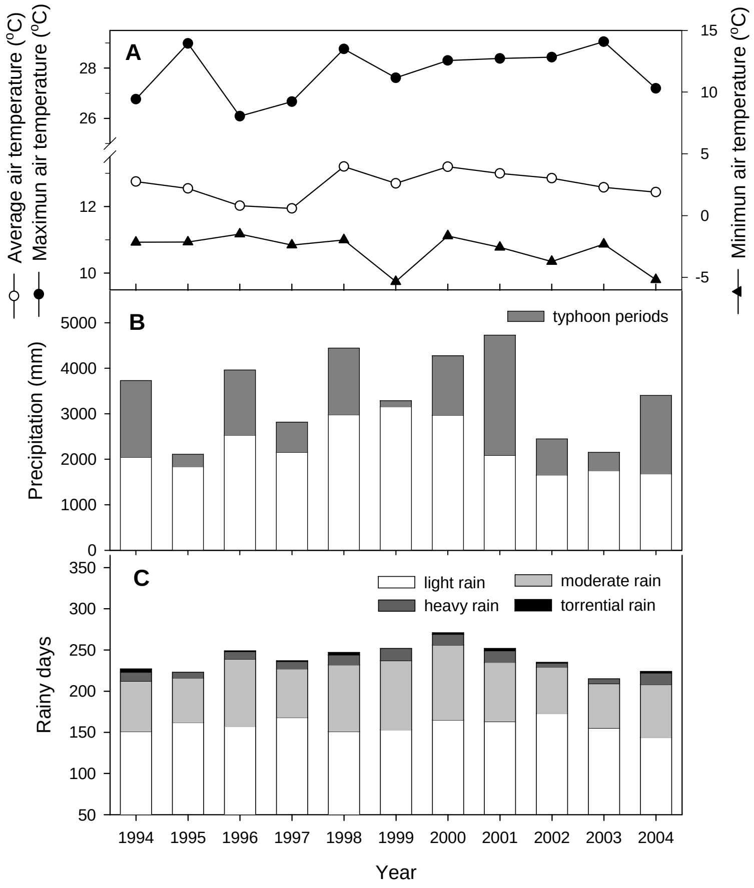


Fig. 2. Annual fluctuations in air temperature and precipitation from 1994 to 2004 at the YYL site. A: average, maximum and minimum recorded air temperature. B: precipitation, those recorded during typhoon events were showed by grey columns. C: the number of rainy days of four different ranks of precipitation.

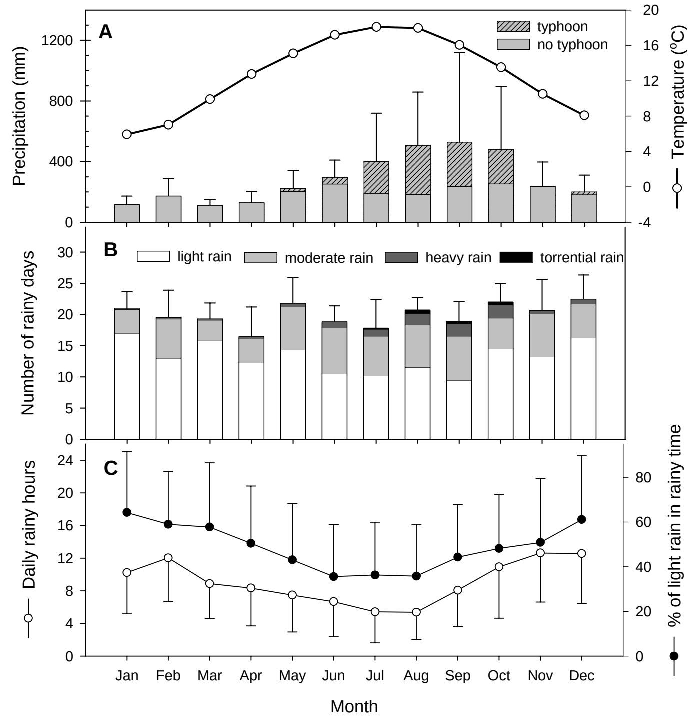


Fig. 3. Seasonal variations in air temperature and precipitation at the YYL site. A: Monthly accumulated precipitation and the mean temperature. Stripped columns indicates the precipitation associated with typhoon. B: The numbers of different ranks of rainy days in each month. C: Mean daily rainy hours and percentage of light rainy time in each month. The error bar presented standard error.

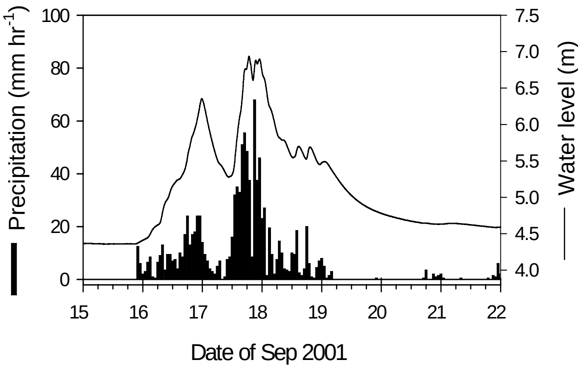


Fig. 4. Dynamic changes in precipitation and water level in Yuangyang Lake recorded over the period between 15th and 21th September of 2001, showing the influence of the invasion of Typhoon "Nari" from15th to 19th September.

with lower water level in April and higher in September. Occasionally, high fluctuation in water level had occurred when the heavy or torrential rain events took place, especially during typhoon periods. Because the outlet of lake water was small, the water level could be elevated drastically within few hours (Fig. 4). The highest water level, as high as 7.00 m, had been recorded in August of 2004 when Typhoon "Aere" passed this site. The lowest water level (i.e. 4.12 m) was recorded in May of 2002, when a severe drought occurred in Taiwan.

Fog duration

The observations from July 2000 to January 2002 showed that the foggy days have been as many as 342 days per year (ca. 94% days per year). From the 5-minute-based visibility record, the total duration time of fog was ca. 40% time of year (Fig. 5A). Light fogs occurred evenly in every month, but both the medium and heavy fogs tapered off from June to September. In summer, fog usually occurred twice a day, with the first peak before sunrise and the second one from afternoon until evening. In other seasons, such diurnal pattern of fog was not obvious. In winter, the northeastern monsoon was pronounced, and the daily fog was longer-lasting and more evenly distributed than in other seasons (Fig. 6A).

The seasonal pattern of fog occurrence was found to be related to wind direction. The winds at the YYL site were mainly easterly or westerly. In summer, eastward winds prevailed during the daytime while westward winds prevailed at night. In winter, the winds were weaker and the calms period became longer. Westward winds became quite less at nighttime than it in summer (Fig. 7).

Reduction in solar radiation and PPFD

The solar radiation and PPFD at the YYL site were reduced by the prevailing occurrence of cloud and fog. The average annual solar radiation at the YYL site was 2475 MJ m^{-2}, and annual PPFD was 5713 mol m^{-2}, equivalent to total degrees of reduction of 76.6% and 71.0%, respectively, based on the estimations from CLIRAD-SW model. The intensity of radiation at the YYL site was lower than those recorded at other weather stations throughout the year (Fig. 5B), such as I-Lan (3378 MJ m^{-2}), Fushan (3728 MJ m^{-2}), and Yushan (4369 MJ m^{-2}). Apparently, the YYL site displayed a dimmer climate condition than other weather stations.

Solar radiation and PPFD displayed a seasonal rhythm, with lower values in December and higher in July (Table 2). From October and December, solar radiation and PPFD were more remarkably reduced than in other seasons. The diurnal course of the degrees of reduction of PPFD was both lowest around 8:00 to 9:00 in winter and summer. Although in the morning the degree of reduction was ca. 20% lower in summer than in winter, it increased to a similar value in both seasons after 14:00 when the site was immersed in fog (Fig. 6B).

On cloudless days, the PPFD measured at noon ranged between 1200 and 2000 μmol m^{-2} s^{-1}, depending on the seasons (Fig. 8A). The measured PPFD values showed a close correlation with the theoretical potential PPFD estimated by the CLIRAD-SW model ($r^2 = 0.94$, slop e = 0.794). On such cloudless days, the difference of diurnal temperature was higher than 10 °C, the relative humidity reduced to around 70% and the average degree of reduction of PPFD were approximately 20%, besides slightly higher at the time near dawn and dusk (Fig. 9). In fact, the cloudless days were rare in summer, because fog associated with the convective rain usually occurred in summer afternoon. As a result, a remarkable reduction in solar radiation and PPFD was observed (Fig. 8C). Foggy days characterized with a small difference in diurnal temperature, low PPFD, and high relative humidity (up to 100%) commonly occurred in winter. In such a season, long-lasting light rain was also associated with fog occurrence (Fig. 8B). Fog occurrence would strongly reduce the PPFD values. As a whole, the average degree of reduction of PPFD under fogless conditions at the site was 63%, and up to 88% when fog was present. However, the average reduction of PPFD under heavy foggy conditions was only slightly higher (ca. 5%) than under light foggy ones. The degree of reduction of PPFD might be various during a day. Under light

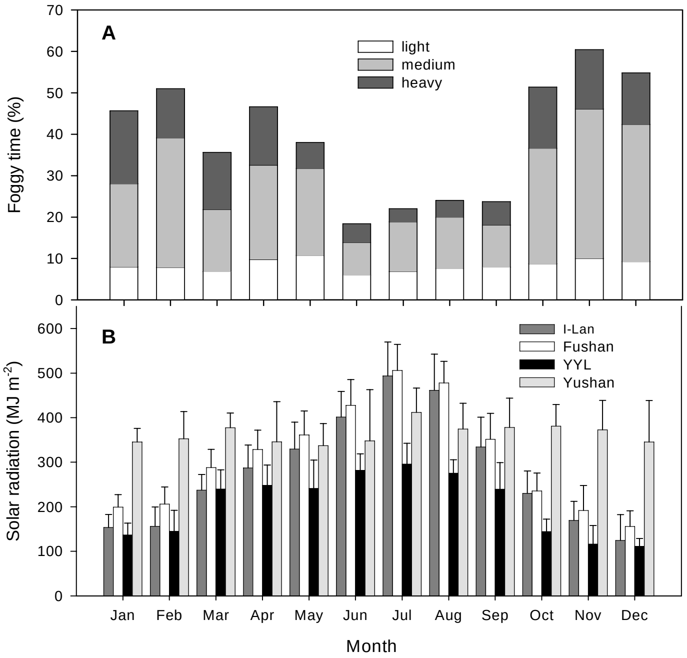


Fig. 5. Seasonal variations in foggy time and radiation at the YYL site. A: percentages of different degrees of fog. B: Average monthly solar radiation at the YYL site, compared with the stations at I-Lan, Fushan, and Yushan over 1994-2004. The error bar presented standard error.

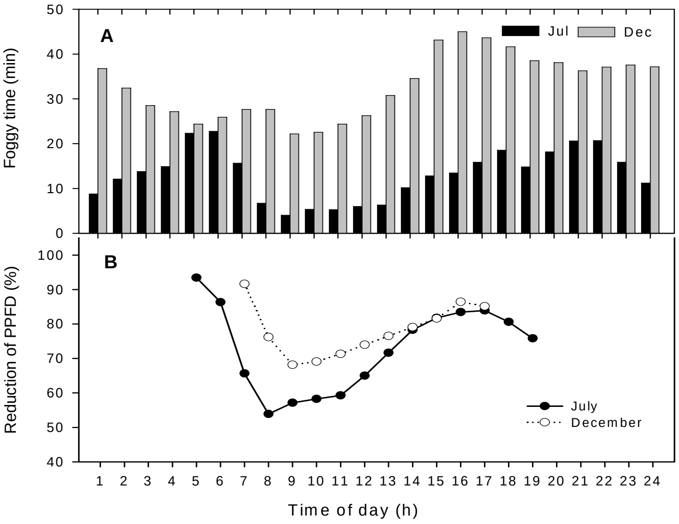
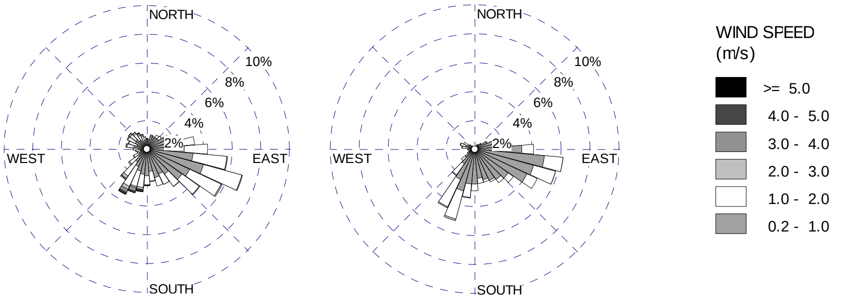


Fig. 6. Comparison of the diel changes in foggy time and degree of reduction of PPFD in July and December. A: mean foggy time, the data was derived from the accumulated fog occurrence based on the 5-minute data interval from July and December in 2000 and 2001. B: hourly average degree of reduction of PPFD.

Table 2. The monthly solar radiation, PPFD and their degrees of reduction at the YYL site. The values were obtained from the average of daily recording data from January 1994 to December 2004. The values of solar radiation and PPFD were mean ± SD.

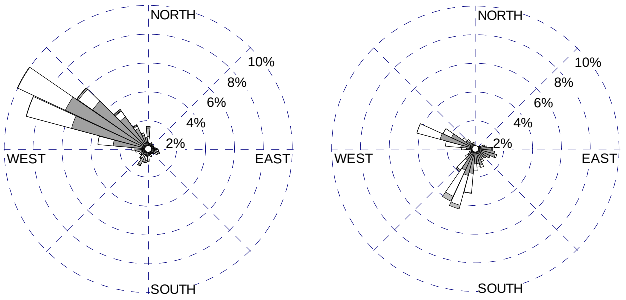
Month	Solar radiation ($MJ\ m^{-2}\ d^{-1}$)	R_{rad} (%)	PPFD ($mol\ m^{-2}\ d^{-1}$)	R_{PPFD} (%)
Jan	4.6±1.2	76.8	12.1±2.5	68.2
Feb	5.3±1.3	77.8	13.0±2.6	71.6
Mar	7.6±1.9	73.1	18.5±4.3	66.3
Apr	8.3±1.5	74.2	19.7±3.6	68.6
May	7.7±1.5	77.6	18.0±3.1	73.2
Jun	8.9±2.1	74.7	21.1±4.1	69.4
Jul	9.5±2.2	72.6	21.1±4.6	69.0
Aug	8.6±1.9	73.8	19.9±4.3	69.2
Sep	7.7±1.8	74.0	17.6±3.7	69.7
Oct	4.8±1.6	81.1	11.6±2.9	76.4
Nov	3.9±1.5	81.0	10.1±2.9	74.9
Dec	3.3±1.1	82.6	8.8±2.5	75.6
Average	6.7±2.7	76.6	16.0±5.5	71.0

R_{rad}: degrees of reduction of solar radiation; R_{PPFD}: degrees of reduction of PPFD.



A: daytime of July

C: daytime of December



B: nighttime of July

D: nighttime of December

Fig. 7. Comparison of the distribution of wind speeds and wind directions in July with those in December at the YYL site. The data was based on the average wind speed/direction records of 5-miniute data interval from July and December in 2000 and 2001. A: daytime of July. B: nighttime of July. C: daytime of December. D: nighttime of December.

foggy condition, less reduction was measured at time between 7:00 and 9:00 am. Under medium and heavy foggy conditions, the reduction of PPFD was about the same throughout the daytime (Fig. 9).

DISCUSSION

Seasonality of climate

Under strong influence of East Asia monsoon, the climate at the YYL site displayed an obvious seasonality. In summer, on the leeward slope of Central Mountain Range where the YYL site is located, the southwest monsoon enhances the local convection (Lin and Chen, 2002). The moderate to heavy convective rain occurred in the afternoon at the YYL site implied the coincidence with the monsoon and local terrain interaction. From October to February, the winter monsoon cold surges affected the weather condition in Taiwan prominently and the rainfall gradually transforms to light, stable precipitation (Chen and Chen, 2003). The lasting light rain, fog occurrence, and the large reduction of radiation at the YYL site were considered as the phenomena of the northeast monsoon.

The MCF at the YYL site differs from those in tropics in the absence of tropical plant species, such as plants of Moraceae and Euphorbiaceae. Instead, some temperate broadleaf species e.g. *Illicium philippinense* and *Rhododendron formosanum* were found at the YYL site (Liao et al., 2003). At the YYL site, winter temperature was usually below 10ºC while there was no obvious seasonal change in temperature at MCFs in tropics (Kitayama, 1995). Such a cold temperature stress might explain the lacking of tropical plant species at the YYL site.

Perhumid climatic characteristics and fog occurrence pattern

The cloud/fog occurrence in tropical montane cloud forest was mainly due to the trade wind inversion, congestion and ascent of air masses in mountain areas or the transitions between coastal fogs and orographic clouds (Stadtmüller, 1987). The humid monsoon in East Asia and the island location seem to result in more fog occurrence and foggy days at the YYL site, especially in winter when the YYL site is on the windward slope facing the monsoon blowing from the Pacific Ocean. Such perhumid climatic conditions favor the growth of some humid plants such as bryophytes and ferns.

The fog occurring in the early morning in summer at the site (Fig. 6A) was not surveyed at another weather station only 2.5 km away from the YYL site (Yeh, 2004). The embedded lake watershed terrain might enhance the humidity and fog formation in summer morning. Consequently the site was more humid than the nearby areas. The formation of fog in the summer afternoon and early evening might be mainly attributable to the local advection of the warm and moist eastward wind from Lan-yan valley in the daytime. Fog usually dissipates when the cool and drier mountain wind dominates at night (cf. Fig. 8C). The same patterns were reported in Klemm et al. (2006). The shift of wind direction to west at the nighttime (Fig. 7) could be the reason why the foggy time decreased after 21:00 in summer. Because the YYL site is located in a saddle area (Fig. 1), the wind direction could be more limited to west-east direction. The prevailing eastward wind in winter could be mainly resulted from northeastern monsoon in winter and the cause of lasting fog and light rain.

Reduction of solar light

In this study, the solar radiation transfer model (CLIRAD-SW) has been applied to study the reduction in solar radiation and PPFD due to cloud and fog occurrences. The application of the model can eliminate the variation of radiation transfer rate due to atmospheric composition varied in different seasons. Especially the atmospheric boundary layer was not uniform throughout the year in Taiwan (Kuan and Lin, 2005). The content of water vapors was the most important variable influencing the estimation of the potential radiation under cloudless days (Lin, 2005). For lack of mountainous radiosonde data in Taiwan, this variable was derived from the average records above 1650 m from the station in the Taipei Basin. The 20% estimate bias of potential PPFD to measured PPFD under cloudless days could be mainly caused by the underestimate of the content of water vapors at the YYL site. The relative humidity from the measurement was usually close to 100% indicating that the surface atmosphere at the YYL site should contain more water vapors than that estimated by model. Since the dry deposition was less and the wet deposition contained few components at the YYL site (Chang et al., 2002), the influence of aerosols and molecules could be less. According to the hemispheric photograph taken above the quantum sensor at S3 weather station (Fig. 10), the direct solar light was mostly shaded when the solar altitude under 15°. Nevertheless, because the correlation between the measured PPFD values and the potential PPFD values was quite high, the model was still well applicable for the purpose.

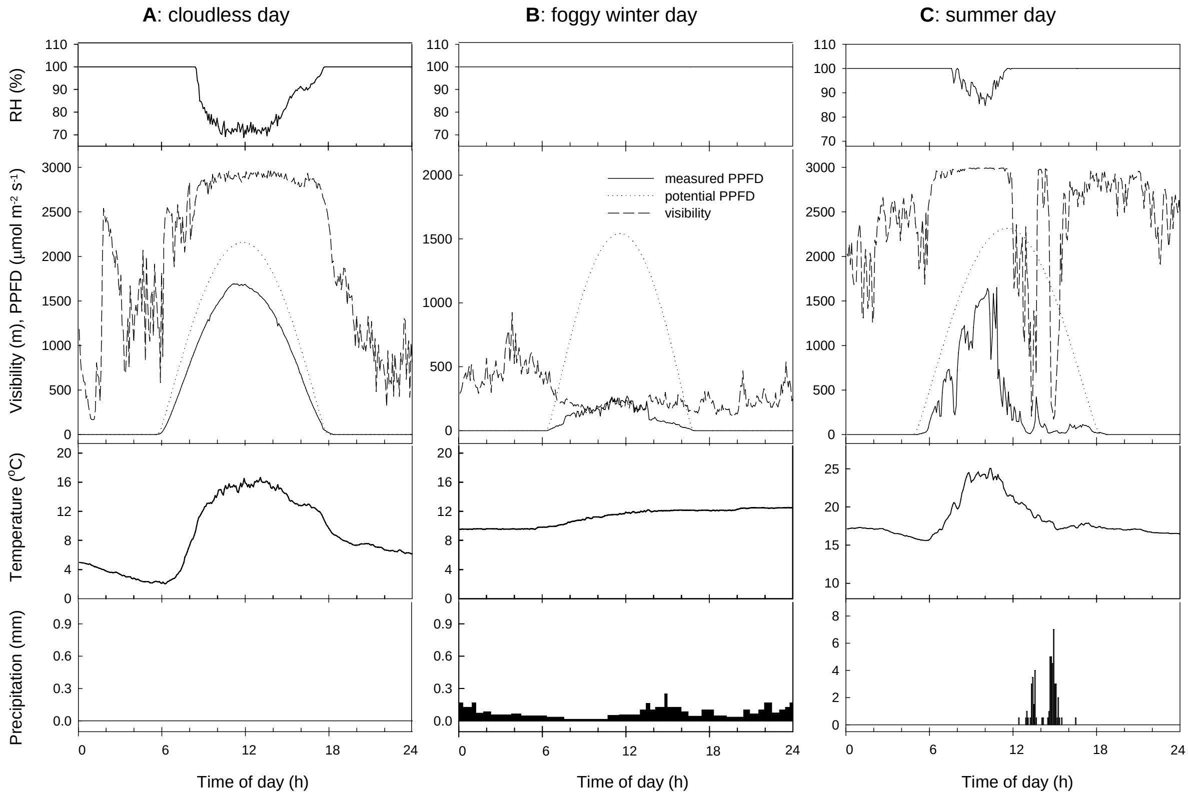


Fig. 8. Comparison of the diurnal changes in relative humidity, visibility, PPFD, air temperature, and precipitation between clear sunny day on 30 March, 2001 (A), foggy winter day on 7 Dec, 2001 (B), and summer day on 16 July, 2001 (C).

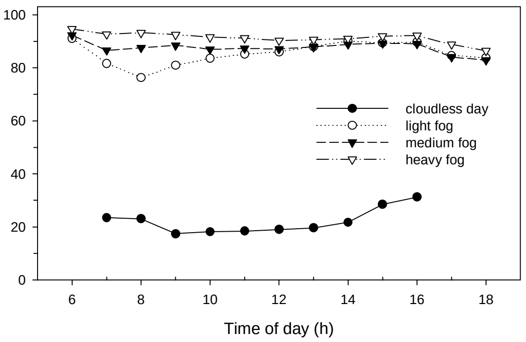


Fig. 9. The diurnal hourly degrees of reduction of PPFD under different weather conditions. The data were derived from the 5-minute records from July 2000 to February 2002. The reduction of PPFD on cloudless days was derived from 5 days. The degrees of reduction of PPFD on light fog, medium fog and heavy fog conditions were computed from the average of the 5-minute data of all data from the visibility of 1000-500 m, 500-100 m, and lower than 100 m, respectively.

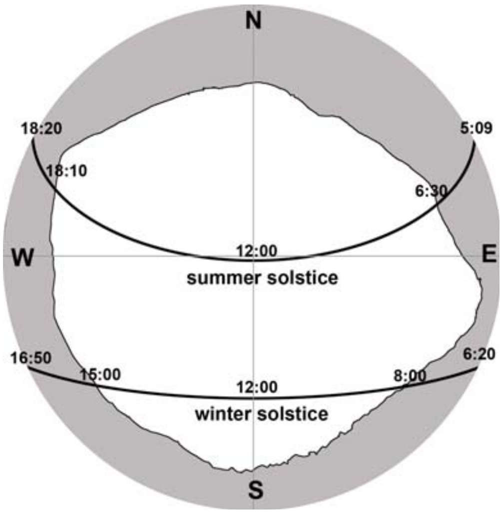


Fig. 10. Hemispheric photograph of the YYL site taken above the quantum sensor at S3 weather station during a completely cloudy day. The grey region indicated the shading by the surrounding vegetation and mountains. The two sun trajectories on summer and winter solstices were shown with the times of sunrise, transient of shade and non-shade, midday and sunset on them.

PPFD is important for carbon assimilation of plants and is also an important limiting factor for the survival, growth, and competition of plant species in forest ecosystems. Our previous study showed that *C. formosensis* and *C. obtusa* var. *formosana* exhibited different acclimation ability to light intensity (Lai et al., 2005). The former was less shade-tolerant than the latter and the seedlings of *C. formosensis* could not tolerate shade environment. Thus, the frequency of fog or cloud occurrences is considered one of the important selecting factors for these two plants. It is possibly the reason why there is no *C. formosensis* plant in the YYL site.

ACKNOWLEDGEMENTS

We greatly appreciate Dr. Yuan-Hsun Hwang, former researcher in the Institute of Botany, Academia Sinica, for the establishment and maintenance of the weather stations during 1992-1996. We also thank Mr. Jin-Ching Chen and for his assistance in transportation and solving technical problems, Mr. Yun-Sen Wang for two years' data collection, and Mr. Ho-Jiunn Lin for the analysis of radiation model. The authors extend appreciation to the site management by the Forest Conservation Department of the Veterans Affairs Commission, Executive Yuan, R.O.C. (VAC).

LITERATURE CITED

Bruijnzeel, L. A. and J. Proctor. 1995. Hydrology and biogeochemistry of tropical montane cloud forests: what do we really know? In: Hamilton, L. S. et al. (eds.), Tropical Montane Cloud Forests. Springer-Verlag, New York, USA. pp. 38-78.

Bruijnzeel, L. A. and E. J. Veneklaas. 1998. Climatic conditions and tropical montane forest productivity: the fog has not lifted yet. Ecology **79**: 3-9.

Chang, S.-C., I.-L. Lai and J.-T. Wu. 2002. Estimation of fog deposition on epiphytic bryophytes in a subtropical montane forest ecosystem in northeastern Taiwan. Atmos. Res. **64**: 159-167.

Chang, S.-C., C.-F. Yeh, M.-J. Wu, Y.-J. Hsia and J.-T. Wu. 2006. Quantifying fog water deposition by in situ exposure experiments in a mountainous coniferous forest in Taiwan. For. Ecol. Manag. **224**: 11-18.

Chen, C.-S. and Y.-L. Chen. 2003. The rainfall characteristics of Taiwan. Mon. Wea. Rev. **131**: 1323-1341.

Chen, M.-C. and C.-H. Chi. 1988. A preliminary study of fog occurrences in Taiwan. Meteor. Bull. **34**: 308-318.

Chen, T.-C., M.-C. Yen, J.-C. Hsieh and R.W. Arritt. 1999. Diurnal and seasonal variations of the rainfall measured by the automatic rainfall and meteorological telemetry system in Taiwan. Bull. Amer. Meteor. Soc. **80**: 2299-2312.

Chen, Z.-S., C.-F. Hsieh, F.-Y. Jiang, T.-H. Hsieh and I.-F. Sun. 1997. Relations of soil properties to topography and vegetation in a subtropical rain forest in southern Taiwan. Plant Ecol. **132**: 229-241.

Chi, C.-H. 1969. The orographic climate of Taiwan. Bank of Taiwan Quarterly **20**: 155-207.

Chou, C.-H., T.-Y. Chen, C.-C. Liao and C.-I. Peng. 2000. Long-term ecological research in the Yuanyang Lake forest ecosystem I. Vegetation composition and analysis. Bot. Bull. Acad. Sin. **41**: 61-72.

Chou, M.-D. 1990. Parameterizations for the absorption of solar radiation by O_2 and CO_2 with application to climate studies. J. Clim. **3**: 209-217.

Chou, M.-D. and K.-T. Lee. 1996. Parameterizations for the absorption of solar radiation by water vapor and ozone. J. Atmos. Sci. **53**: 1203-1208.

Chou, M.-D. and M. J. Suarez. 1999. A shortwave radiation parameterization for atmospheric studies. Technical Report Series on Global Modeling and Data Assimilation, 15, NASA/TM-1999-104606. Hanover, USA. pp. 1-42.

Foster, P. 2001. The potential negative impacts of global climate change on tropical montane cloud forests. Earth-Sci. Rev. **55**: 73-106.

Gordon, C. A., R. Herrera and T. C. Hutchinson. 1994. Studies of fog events at two cloud forests near Caracas, Veneuzuela. II. Chemistry of fog. Atmos. Environ. **28**: 323-337.

Hamilton, L. S., J. O. Juvik and F. N. Scatena. 1995. The Puerto Rico tropical cloud forest symposium: Introduction and workshop synthesis. In: Hamilton, L. S. et al. (eds.), Tropical Montane Cloud Forests. Springer-Verlag, New York, USA. pp. 1-23.

Hsiao, C.-K. 2005. The analysis of selected weather stations and the autocorrelation of the climatic change from 1897 to 2004 in Taiwan. In: Proceedlings of Conference on Weather Analysis and Forcasting 2005. Central Weather Bureau, Taipei, Taiwan. pp. 433-438. (in Chinese)

Hwang, Y.-H., C.-W. Fang and M.-H. Yin. 1996. Primary production and chemical composition of emergent aquatic macrophytes, *Schoenoplectus mucronatus* ssp. *robustus* and *Sparganium fallax*, in Lake Yuan-yang, Taiwan. Bot. Bull. Acad. Sin. **37**: 265-273.

Kitayama, K. 1995. Biophysical conditions of the montane cloud forests of Mount Kinabalu, Sabah, Malaysia. In: Hamilton, L. S. et al. (eds.), Tropical Montane Cloud Forests. Springer-Verlag, New York, USA. pp. 183-197.

Klemm, O., S.-C. Chang and Y.-J. Hsia. 2006. Energy fluxes at a subtropical mountain cloud forest. For. Ecol. Manag. **224**: 5-10.

Kuan, D.-W. and P.-H. Lin. 2005. The analysis of characteristics of radiosonde soundings in Taiwan. In: Proceedlings of Conference on Weather Analysis and Forcasting 2005. Central Weather Bureau, Taipei, Taiwan. pp. 19-24. (in Chinese)

Kuo, Y.-L. and Y.-P. Lee. 2003. Comparing dehydration tolerance and leaf mass per area between tree species inhabiting windward and leeward sites of Nanjenshan Forest in southern Taiwan. Taiwan J. For. Sci. **18**: 283-292. (in Chinese with English summary)

Lai, I.-L., H. Scharr, A. Chavarria-Krauser, R. Kusters, J.-T. Wu, C.-H. Chou, U. Schurr and A. Walter. 2005. Leaf growth dynamics of two congener gymnosperm tree species reflect the heterogeneity of light intensities given in their natural ecological niche. Plant, Cell Environ. **28**: 1496-1505.

Lai, Y.-J. and P.-H. Lin. 2005. Estimating spatial distribution of solar irradiance in earth surface. In: Proceedlings of Conference on Weather Analysis and Forcasting 2005. Central Weather Bureau, Taipei, Taiwan. pp. 57-62. (in Chinese)

Lau, K.-M. and M.-T. Li. 1984. The monsoon of East Asia and its global associations—a survey. Bull. Amer. Meteor. Soc. **65**: 114-125.

Liao, C.-C., C.-H. Chou and J.-T. Wu. 2003. Population structure and substrates of Taiwan yellow false cypress (*Chamaecyparis obtuse* var. *formosana*) in Yuanyang Lake Nature Reserve and nearby Szumakuszu, Taiwan. Taiwania **48**: 6-21.

Lin, C.-Y. and C.-S. Chen. 2002. A study of orographic effects on mountain-generated precipitation systems under weak synoptic forcing. Meteor. Atmos. Phys. **81**: 1-25.

Lin, P.-H., M.-D. Chou, Q. Ji and S.-C. Tsay. 2002. Clear-sky surface radiation during South China Sea Monsoon Experiment. Terres. Atmos. Ocean. Sci. **13:** 185-196.

Lin, K.-C., S.-P. Hamburg, S.-L. Tang, Y.-J. Hsia and T.-C. Lin. 2003. Typhoon effects on litterfall in a subtropical forest. Can. J. For. Res. **33**: 2184-2192.

Lin, H.-J. 2005. Aerosol radiative forcing at Taiwan in spring. Ms. Thesis, Institute of Atmospheric Sciences, National Taiwan University. Taipei, Taiwan. 64pp. (in Chinese with English abstract)

Mabry, C. M., S. P. Hamburg, T.-C. Lin, F.-W. Horng, H.-B. King and Y.-J. Hsia. 1998. Typhoon disturbance and stand-level damage patterns at a subtropical forest in Taiwan. Biotropica **30**: 228-250.

McCree, K. J. 1981. Photosynthetically active radiation. In: Lange, O. L. et al. (eds.), Encyclopedia of Plant Physiology, N. S., 12A.

Spring-Verlag, Berlin, Germany. pp. 41-55.

Pounds, J. A., M. P. L. Fogden and J. H. Campbell. 1999. Biological response to climate change on a tropical mountain. Nature **398**: 611-615.

Pu, C.-P. 2005. The preliminary analysis of the seasonal variation of upper wind in North Taiwan. Aviation Weather **4**: 1-19.

Rees, R., S.-C. Chang, C.-P. Wang and E. Matzner. 2006. Release of nutrients and dissolved organic carbon during decomposition of *Chamaecyparis obtusa* var. formosana leaves in a mountain forest in Taiwan. J. Plant Nutr. Soil Sci. (in press)

Shieh, S.-L., S.-T. Wang, M.-D. Cheng and T.-C. Yeh. 1998. Tropical cyclone tracks over Taiwan from 1897 to 1996 and their applications. CWB report 86-1 M-01. Atmospheric R & D Center, Central Weather Bureau. Taipei, Taiwan. 497pp.

Stadtmüller, T. 1987. Cloud forests in the humid tropics. A bibliographic review. The United Nations University, Tokyo, Japan. 82pp.

Still, C. J., P. N. Foster and S. H. Schneider. 1999. Simulating the effects of climate change on tropical montane cloud forests. Nature **398**: 608-610.

Su, H.-J. 1984. Studies on the climate and vegetation types of the natural forests in Taiwan (II) Altitudinal vegetation zones in relation to temperature gradient. Quar. J. Chin. For. **17**: 57-73.

Sun, I.-F., C.-F. Hsieh and S. P. Hubbell. 1998. The structure and species composition of a subtropical monsoon forest in southern Taiwan on a steep wind-stress gradient. In: Francisco, D. and J. A. Comiskey (eds.), Forest Diversity Research, Monitoring and Modeling: Conceptual background and Old World Case Studies. Parthenon Publishing Co. New York, USA. pp. 565-635.

Thimijan, R. W. and R. D. Heins. 1983. Photometric, radiometric, and quantum light units of measure - a review of procedures for interconversion. HortSci. **18**: 818-822.

Weathers, K. C. 1999. The importance of cloud and fog in the maintenance of ecosystems. Trends Ecol. Evol. **14**: 214-215.

Wu, C.-C. and Y.-H. Kuo. 1999. Typhoons affecting Taiwan: current understanding and future challenges. Bull. Amer. Meteor. Soc. **80**: 67-80.

Yeh, C.-F. 2004. Estimation of biomass and fog deposition of a yellow cypress forest. Ms. Thesis. Institute of Nature Resource, National Dong Hwa University. Hualien, Taiwan. 84pp. (in Chinese with English abstract)

臺灣鴛鴦湖長期生態研究區亞熱帶雲霧林之氣候特徵

賴宜鈴(1)、張世杰(2)、林博雄(3)、周昌弘(4)、吳俊宗(1,5,6)

(收稿日期：2006 年 5 月 25 日；接受日期：2006 年 9 月 20 日)

摘　　要

本研究藉由分析 1994 年一月至 2004 年十二月在臺灣鴛鴦湖(YYL)長期生態研究區收集的氣象資料以瞭解本地亞熱帶雲霧林之氣候特徵。結果顯示此地的氣候具有明顯的季節性，並且深受東亞季風的影響；年均溫 12.7°C，二月最冷月均溫為 5.9°C，七月最暖月均溫為 18.1°C。冬季長時間籠罩在細雨與雲霧下，夏季則呈現明顯的日夜週期變化。夏季清晨和下午至晚上常有霧發生，後者與日夜交替的風向改變有關，有時並伴隨對流雨的發生。夏季時頻繁的颱風帶來平均 36.9%的年雨量，常伴隨豪大雨的降臨，導致鴛鴦湖水位急遽的升高。總體而言，此地富含雨水與雲霧，年雨量 3396 mm，一年中約有 40%的時間籠罩在雲霧之中，平均一年有 239 天下雨和 342 天起霧，造成此地非常濕潤的氣候特徵，影響太陽輻射量和光合作用可用光光子通量 (PPFD) 大幅的下降；平均年太陽輻射量為 2475 MJ m^{-2}，PPFD 為 5713 mol m^{-2}，在雲霧出現時 PPFD 的衰減率高達 88%。這樣的氣候特徵可能限制了雲霧林內植物的生長，同時對植物的競爭扮演了重要的角色。根據本文結果，本地亞熱帶雲霧林最大的氣候特徵為具有明顯的季節性差異、非常潮濕以及低光量。

關鍵詞：森林氣候、雲霧、太陽輻射、雨量、光合作用可用光光子通量(PPFD)。

---

1. 國立臺灣大學生態學與演化生物學研究所，106 台北市羅斯福路 4 段 1 號，臺灣。
2. 國立東華大學自然資源管理研究所，974 花蓮縣壽豐鄉志學村大學路 2 段 1 號，臺灣。
3. 國立臺灣大學大氣科學系，106 台北市羅斯福路 4 段 1 號，臺灣。
4. 中國醫藥大學生物多樣性中心，404 台中市學士路 91 號，臺灣。
5. 中央研究院生物多樣性中心，115 台北市研究院路 2 段 128 號，臺灣。
6. 通信作者。Tel: 886-2-27899590 ext. 420; Fax: 886-2-27827954; Email: jtwu@gate.sinica.edu.tw