Fog drip and fog chemistry in the tropical seasonal rain forest of

Xishuangbanna, South-West China

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Abstract: Fog drip and related microclimatic factors were measured between January 1999 and December 2002 at a tropical seasonal rain forest in Xishuangbanna, South-West China. In addition, fogwater, fog drip and rainwater chemistry were examined between November 2001 and October 2002. During the study period, the annual average fog drip was 89.4 ± 13.5 mm (mean $\pm$ 1SD). Fog drip contributes an estimated 5% of the annual rainfall, with 86% of the fog drip occurring in the dry season (November-April). The mean pH of fogwater, fog drip and rainwater were 6.78, 7.30, and 6.13, respectively. The ion with the highest concentration for fog- and rainwater was HCO_3^-, followed by Ca^{2+}, Mg^{2+} and NH_4^+. Concentrations of NO_3^-, HCO_3^-, NH_4^+, Ca^{2+}, and K^+ in fogwater samples collected at the middle to end dry season were significantly greater when compared to those collected early in the dry season. It was found that the ionic concentrations in fog drip were higher than those in fogwater, except for NH_4^+ and H^+, which was attributed to the washout of the soil- and ash-oriented ions deposited on the leaves and the alkaline ionic emissions by the leaves.

1. INTRODUCTION

The Xishuangbanna forest reserve ($21°09'-22°33'$ N, $99°58'-101°34'$ E) is situated on the northern edge of the tropical zone in the South-East Asia contiguous to Laos to the South and

Myanmar to the Southwest. With direct impacts of the East Asian Monsoon, Xishuangbanna is dominated by warm-wet air masses from the Indian Ocean in summer and continental air masses of subtropical origin in winter, which results in a rainy season between May-October, and a dry season between November-April. The mean annual rainfall is 1487 mm, which is considerably lower than other rain forest in other parts of the world. Due to its unique geographical location and climatic features, this area supports a tropical rain forest with a small proportion of deciduous tree species (Cao et al., 1996). A large proportion of the forest in this region is tropical seasonal rain forest. The seasonal rain forest is primarily formed in wet valleys, lowlands and on low hills (less than 1000 m above sea level) where heavy radiation fogs frequently occur (Cao et al., 1996). Radiation fogs are formed during the night when cooling effect caused by long-wave radiation reduces the air temperature to or below its dew-point.

Fog precipitation has long been recognized as an important hydrological and chemical input in many mountainous and coastal environments (Azevedo and Morgan, 1974; Bruijnzeel et al., 1993; Cavelier et al., 1996; Clark et al., 1998; Dawson, 1998). It has been speculated that fog might play an important role in the water relations of plants and in the hydrology of the tropical seasonal rain forest in SW China (Cao et al., 1996). However, there are few quantitative data on fog precipitation, and no general picture about radiation fog as a contributor to fluxes of chemical substances in this forest can be drawn so far.

In this study, a more direct procedure is used to determine the net water input to the forest floor as throughfall (or canopy drip) during fog immersion and absence of rainfall (Lovett et al., 1982). Daily fog drip, rainfall and other related climate data were measured between January 1999 and December 2002. In addition, to study the influence of forest canopy on fogwater

chemistry, fogwater collection was performed on a 72 m high meteorological tower at 38 m during November 2001 to October 2002.

2. STUDY AREA

This study was conducted at a tropical seasonal rain-forest location (21°55'39" N, 101°15'55" E, 750 m) in the Menglun Forest Reserve in Mengla County, Yunnan province. The study site is located on a small flat area between two hills extending from east to west, and is a permanent plot dedicated to long-term ecological research managed by the Xishuangbanna Tropical Rainforest Ecosystem Station, Chinese Academy of Sciences. A stream (about 1 m wide) winds through the site. The width of the flat is approximately 40 m. Slopes to the south and north of the site are about 15°. The soil under the forest is yellow latosol developed from purple sandstone. This valley is a typical site for the occurrence of tropical seasonal rain forest in this area. The forest flora is closely related to Malesian forests and is different from tropical lowland rain forest (Cao *et al.*, 1996). A substantial proportion of tree species is deciduous under the monsoon climate, although they do not shed leaves in the same season. The species composition is comparable with Sarawak lowland rain forests. The species number is less than Malesian rain forests, but higher than those of Australian and African rain forests, or tropical forest on Barro Colorado Island, Panama (Cao *et al.*, 1996). The canopy is uneven and consists principally of megaphanerophytes over 40 m, and the canopy trees usually develop strong buttresses (for example, *Terminalia myriocarpa, Pometia tomentosa*). The tree stratum is subdivided into three layers represented by different species. More than 70% of the trees occur under the canopy in the tree layer C (below 16 m). Cauliflorous trees occur frequently under canopy (such as *Baccaurea ramiflora, Ficus auriculata, Saurauia* spp.). Many species of algae,

lichens, mosses and ferns comprise the epiphytes and stranglers. The woody climbers such as *Byttneria integrifolia*, *Gnetum montanum*, *Tetracera scandens*, *Tetrastigma planicaule*, are very common. Some of woody climbers reach the forest canopy.

Long-term climate records as measured at a weather station (600 m asl) 5 km SE from the study site between 1959 and 2002 show that the mean annual air temperature is 21.7 °C with a maximum monthly temperature of 25.7 °C for the hottest month (June) and a minimum monthly temperature of 15.9 °C for the coldest month (January). There are two distinct seasons, each with their distinctive characteristics. A dry season occurs between November to April, which includes a cool sub-season from November to February and a hot sub-season from March to April. The cool-dry sub-season is characterized by highest frequency of heavy radiation fog during the night and morning. The hot-dry sub-season is characterized by dry and hot weather during the afternoon and with heavy radiation fog during the morning only. A rainy season occurs between May to October, and is characterized by high rainfall, which is mainly brought by the southwestern summer monsoon. The mean annual rainfall over the past 40 y is 1487 mm, of which 1294 mm (87%) occurs in the rainy season vs. 193 mm (13%) in the dry season. Radiation fog occurs almost every day from November to April (Table 1) and is heaviest from midnight (23h00-02h00) until mid-morning (09h00-11h00) (Liu *et al.*, 2004). The mean monthly relative humidity is 87%. The prevailing wind direction is SW all year around, with mean annual wind speed of 0.7 m s^{-1} and frequency of calm days of 75%.

3. METHODS

Plastic funnel collectors (80 cm in diameter), each connected with a 1000-m*l* plastic bottle, were specially designed, fabricated, and mounted at 0.7 m above the forest floor to collect fog

dripping from the canopy. Litter fall was excluded from the bottle by a nylon mesh (1 mm square). Each 503-mℓ of water collected in the bottle was equivalent to 1 mm of net precipitation. Twelve of these collectors were placed in a fixed but random pattern on the forest floor to collect fog drip. The collectors were read in the morning after fog drip had stopped, and were leveled and cleaned of any litter present. At each fog drip sampling for chemical analysis, funnels and bottles in the field were replaced with clean ones. To reduce the number of samples for chemical analysis, a volume of water proportional to the volume collected by each collector for each collection event were combined after separate measurement of the volumes collected.

Fogwater samples were collected on an event basis, by using passive cylindrical string collectors (Schmitt, 1987). Two of these collectors mounted on a 72 m high meteorological tower at 38 m (0.5 m above the canopy) in the study site were used to collect sufficient fogwater. Each was connected to 1 cm plastic pipe that was interconnected so that all fogwater drained into a 1000-mℓ watertight plastic container. Each collector was covered by a plastic bag when not in use and was cleaned with distilled water before each sample collection period.

Rainwater samples were collected with a collector consisting of a stainless steel funnel (314 cm^2) connected to a 2000-mℓ plastic bottle. The funnel was mounted on top of the tower to avoid obstacles from trees and the tower itself. The duration of each sample was 24 h. The funnel was washed twice daily in the morning and evening to avoid dry deposition. However, contamination due to dry deposition cannot be completely ruled out.

Seventeen fog episodes were sampled, eleven in cool-dry season, four in hot-dry season and two in rainy season. The fog episodes occurred predominantly from the middle of the night through mid morning, lasting from 8 to 13 h. Meanwhile, nine rainwater samples were collected, two in cool-dry season, two in hot-dry season and five in rainy season.

A tipping bucket raingauge (Model SL-3; Changchun Institute of Meteorological

Instruments, China) was used to determine rainfall intensity and event duration. The raingauge was mounted on top of the tower. Wind distortion of rainguage readings should be small as wind speed is generally low in this region.

Fogwater, fog drip, and rainwater samples were collected in the 250-mℓ precleaned polyethylene bottles, and transported to the laboratory. The pH of samples was measured immediately with a digital pH meter. Thereafter, these samples were filtered (0.45-μm) and refrigerated at 4℃ until chemical analysis could be conducted, approximately seven days later. Chemical analysis was performed by the Xishuangbanna Water Extension Laboratory, Water Environment Monitoring Center of Yunnan, China. The samples were analyzed for major ionic components (for details see Xie and Wang, 1998).

4. RESULTS AND DISCUSSION

4.1. Fog drip amount

During the study period, the average annual fog drip collected by the funnel collectors beneath the forest canopy was 89.4 ± 13.5 mm (mean ± 1SD, $n = 4$), accounting for about 5% of the annual rainfall (Table 1). The maximum amounts of fog drip (102.9 mm) was observed in 2000, the year of lowest rainfall (1405.5 mm). The lowest amounts of total annual fog drip (75.9 mm) were recorded in 2002, the year of highest rainfall (1948.7 mm). Annual fog drips were negatively correlated with annual rainfall (Annual_Fog = 105 − 0.0021 e $^{0.0049\ Rain}$; $R^2 =$ 0.99).

Monthly fog drip data for four complete years are shown in Fig. 1. The monthly fog drip shows a clear seasonal pattern during the period of measurement. Maximum fog drip and minimum rainfall occur in the cool-dry season (November-February; rainfall = 28.7 ± 8.6 mm mo^{-1}; fog drip = 14.1 ± 2.7 mm mo^{-1}), while the minimum fog drip and maximum rainfall were

observed during the rainy season (May-October; rainfall = 255.2 ± 74.3 mm mo^{-1}; fog drip = 2.1 ± 1.3 mm mo^{-1}). Fog input to the forest floor over the entire dry season (November-April) accounted for 86% of the annual fog drip. Monthly fog drip varied more than 40-fold, with a maximum of 19.8 mm in February 1999 and a minimum of 0.5 mm in July 2001. Monthly fog drip was negatively correlated with monthly rainfall according to the following relationship:

$$\text{Fog} = \frac{K_f}{1 + (Rain / K_r)^{3/2}}$$

Where the average maximum fog drip K_f = 17.89 ± 0.65 mm. The constant K_r = 62.33 ± 4.86, and R^2 = 0.92.

Fog occurs more frequently in cool-dry and hot-dry season (90% and 79%) and less frequent in rainy season (57%). The collectors recorded fog drip during heavy fogs only, which accounted for 68% of all the fog events (Table 1). The remaining light fog events were completely intercepted by the tree foliage before the water could reach the ground. The mean daily amounts of fog drip during a typical day was 0.52 ± 0.17 mm in the dry season, and 0.22 ± 0.15 mm in rainy season (Table 1).

Annual fog drip at this site accounted for about 5% of the annual rainfall, which falls within the lower range of values compared to other tropical montane forests (Bruijnzeel, 2001). The overall mean daily fog drip of 0.38 mm (Table 1) in this study falls in the lower range reported by previous studies. Bruijnzeel (2001) suggested typical cloud water deposition rates is 1–2 mm d^{-1} (range 0.2–4.0 mm d^{-1}). The low fog drip observed in our study compared with some other studies may be partially attributed to the low wind speeds prevailing at our site (< 2 m s^{-1}, Liu et al., 2004). For the low wind speeds that are typical for radiation fog, sedimentation is the dominant process of fog deposition (Glasow and Bott, 1999).

In this site, both rainfall and fog deposition presented a highly seasonal pattern with the fog drip as the main water source during the dry season. For example, only 10% of the annual rainfall occurs during the dry season from a relatively few storms (Fig. 1). Because the fog drip is at a maximum during this period, it constitutes an important additional source of moisture, especially during the hot-dry season from March to April.

4.2. Fog chemistry

The pH values in fog drip on 5 occasions in 2001 and on 12 occasions in 2002 and their corresponding values in fogwater are given in Fig. 2. It can be seen from this figure that pH values in fog drip samples were, by and large, higher than those in fogwater samples. The pH was highly variable in both of the sample types, and both lowest in January, which was the foggiest month in which the average fog duration reached 12.8 h per day (Liu, 2004). Fog- and rainwater were considerably more acidic during the middle of the dry season (January and February) compared to the early dry season (November and December) and rainy season.

The ion concentrations in fog- and rainwater were generally very low (Table 2). The ion with the highest concentration for fog- and rainwater was HCO_3^-, which amounted to 85.2 and 37.3 $\mu eq \; \ell^{-1}$, respectively. The HCO_3^- has been shown to be a very important ion in some tropical fogs, particularly at high pHs (Schemenauer and Cereceda, 1992; Subramanian and Saxena, 1980). The HCO_3^- concentration for fogwater was 2.3 times that for the rainwater. The other anions, NO_3^-, SO_4^{2-} and Cl^-, were less concentrated in fog- and rainwater than HCO_3^-. The NO_3^- concentration in fogwater was 2.1 times that in rainwater, the SO_4^{2-} concentration 2.7 times, and the Cl^- concentration 1.6 times. The dominant cation in fog water was Ca^{2+} followed by Mg^{2+}, NH_4^+, K^+, Na^+ and H^+. The cation in rainwater generally had the same order except

that Na^+ had the fourth highest concentration. Like the anions, the cation concentrations in the fogwater were usually higher than those in the rainwater. There is a better chemical balance between cations and anions in the fogwater and in the rainwater, with the ratio of the sum of the cations to the sum of the anions 1.35 and 1.26, respectively. It further appears that there may be some other missing anions such as formic and acetic, which were not analysed in fog- and rainwater at our study site.

The quality of fog droplets falling on the forest is altered during a brief but significant interaction with the surfaces of the plants, resulting in a transfer of additional mineral matter to the forest floor. The mean concentrations of all the ionic components in fog drip were usually higher than those in fogwater except NH_4^+ and H^+. Among all ions, K^+ and Mg^{2+} were substantially increased in fog drip (Table 2).

Fogwater samples collected during the middle to end dry season (February to April) had greater concentrations of NO_3^-, HCO_3^-, NH_4^+, Ca^{2+}, and K^+ when compared to those collected in the early dry season (November and December) ($P < 0.05$; Fig. 3). Ion concentration in fog drip and rainwater also showed similar pattern during the two sampling periods mentioned above, coinciding with obvious atmospheric haze layers, presumably due to agricultural activities and biomass burning.

The pH of fogwater at Xishuangbanna ranged between 5.71 and 7.92, and rainwater between 5.69 and 7.25 indicating an alkaline nature as compared to the reference level of 5.65. Higher pH values (average pH exceeded 6.0) were also observed in the San Joaquin Valley and Sacramento Valley radiation fogs in central California (Collett *et al.*, 2002; Zhang and Anastasio, 2001). Kapoor *et al.* (1992) and Schemenauer and Cereceda (1992) found the pH of

fogwater varied between 6.2 and 6.9 at Delhi, North India, and between 7.0 and 7.9 on the Arabian Peninsula, respectively. The high pH values of fog- and rainwater in our study site may be attributed to high concentrations of NH_4^+, Ca^{2+} and Mg^{2+} compared to low concentrations of SO_4^{2-} and NO_3^-. In general, NH_4^+ is attributed mostly to bacterial production from agricultural activities and partly to man-made pollutants, and is thought to neutralize the cloud or fog water acidity (Saxena and Lin, 1990). Sources of NH_3 may be anthropogenic, from agricultural activities (livestock and fertilizing) (Thalmann et al., 2002) and large amounts of smallholder industry of rubber processing using NH_3 within the Xishuangbanna region. In addition, during the dry season, NH_3 may be emitted through biomass burning, which very commonly occurs in the Xishuangbanna area. With further chemical reactions in the atmosphere, this could produce NH_4^+ (Crutzen and Andreae, 1990).

The ion with the highest concentration for fog- and rainwater in our study site was HCO_3^-. Eckardt and Schemenauer (1998) and Schemenauer and Cereceda (1992) also found that the HCO_3^- is a very important ion in some tropical fogs. Similar results were reported for fogs and dews in Indianapolis, Indiana, where HCO_3^- accounted for, on average, 61% of total anion equivalents (Foster et al., 1990).

The pH rose significantly from fogwater to fog drip in the tropical seasonal rain forest. The increase in pH could be caused by the washout of the soil- and ash-oriented ions deposited on the leaves and the alkaline ionic emissions by the leaves. H^+ ion loss and pH increase in throughfall is generally believed to be due to ion exchange of H^+ with other cations on canopy exchange sites (Rao et al., 1995). The depletion of NH_4^+ in fog drip in our study was consistent with the results of previous studies of throughfall (Parker, 1983).

5. ACKNOWLEDGEMENT

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Table 1. Seasonal distribution of fog events, fog drip, daily fog drip and rainfall in the tropical seasonal rain forest at Xishuangbanna, SW China during 1999-2002. Values are means ± 1SD. Daily fog drip is the average of fog day. Percent of days with fog drip is calculated by the day with fog drip divided by total days with fog.

Season	Number of fog events	Fog drip (mm)	Daily fog drip (mm d^{-1})	Rainfall (mm)	Frequency of days with fog (%)	Fog / Rain (%)	Percent of days with fog drip (%)
Cool-dry	108 ± 12	56.2 ± 5.2	0.52 ± 0.17	115 ± 34	90	49	92
Hot-dry	48 ± 6	20.6 ± 4.0	0.41 ± 0.18	62 ± 18	79	33	82
Rainy	102 ± 25	12.6 ± 2.4	0.22 ± 0.15	1531 ± 182	57	<1	36
Annual	258 ± 58	89.4 ± 13.5	0.38 ± 0.27	1718 ± 206	71	5	68

Cool-dry (Nov.-Feb.); Hot-dry (Mar.-Apr.); Rainy (May-Oct.).

Table 2. Volume-weighted mean ion concentrations (μeq ℓ^{-1}) with minimum and maximum values along with their pH values in fogwater, fog drip and rainwater in the tropical seasonal rain forest at Xishuangbanna, SW China during 2001-2002. (n.d.: not detectable)

| Ion	Fog water (n = 17)			Fog drip (n = 17)			Rainwater (n = 9)		
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
pH	6.78	5.71	7.92	7.30	6.14	8.18	6.13	5.69	7.25
H$^+$	0.39	0.01	2.00	0.12	0.01	0.79	0.80	0.12	2.07
Cl$^-$	22.7	n.d.	59.4	35.4	5.8	85.1	14.5	n.d.	55.5
SO$_4^{2-}$	27.2	n.d.	59.3	31.9	9.3	81.6	10.1	5.2	48.1
NO$_3^-$	30.7	6.7	68.7	79.1	6.6	98.4	15.3	6.3	62.5
HCO$_3^-$	85.2	22.3	172.7	149.9	26.9	192.7	37.3	16.4	79.6
Na$^+$	16.8	11.9	57.4	40.7	14.1	112.6	9.3	3.6	45.2
K$^+$	29.7	8.2	69.8	118.2	16.3	154.3	7.5	2.1	58.2
Ca^{2+}	66.4	9.4	107.1	97.2	12.4	136.4	28.6	4.4	113.7
Mg^{2+}	54.8	7.5	97.6	126.8	8.2	201.8	28.3	3.8	92.5
NH$_4^+$	52.7	n.d.	74.2	27.2	n.d.	59.0	23.2	n.d.	54.8
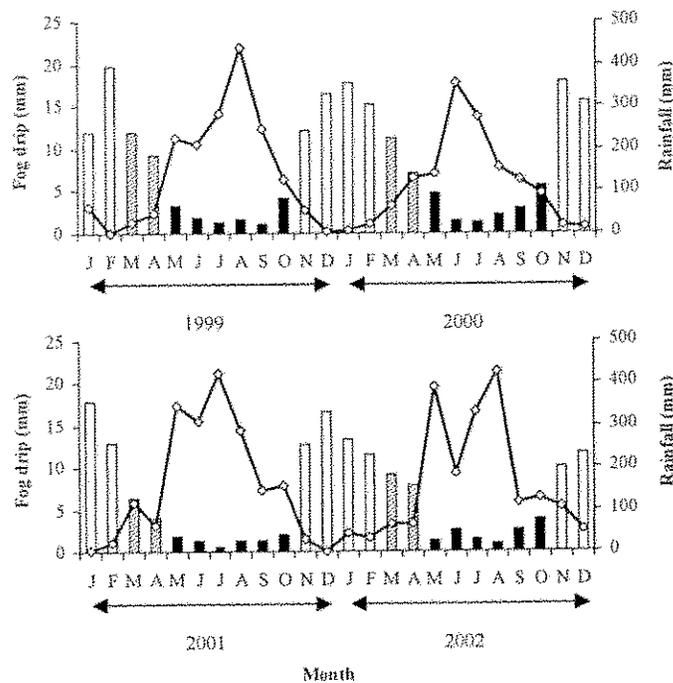
Fig.1. Monthly distribution of fog drip (bars) and rainfall (line) in the tropical seasonal rain forest at Xishuangbanna, SW China during 1999-2002. Open bars represent the cool dry season, shaded bars the hot-dry season and, solid bars the rainy season.
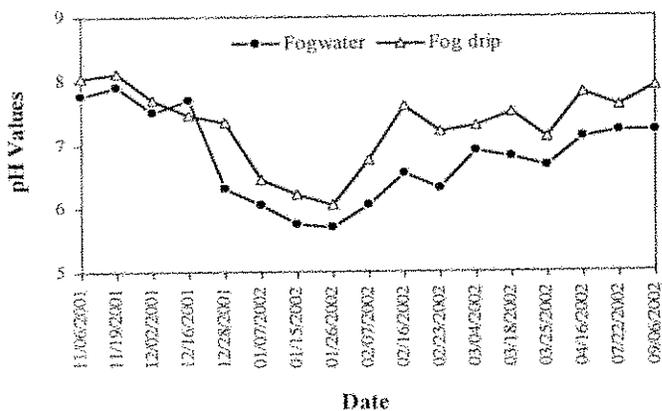

Fig.2. pH values in fogwater and fog drip in the tropical seasonal rain forest at Xishuangbanna, SW China during 2001-2002.
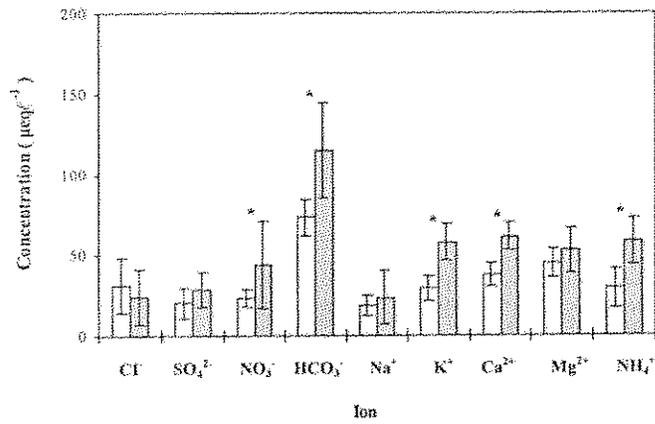
Fig.3. Ion concentrations (mean ± 1 SD) in fogwater collected at the early dry season (November and December, open bars, n = 5) and middle to end dry season (February to April, closed bars, n = 6) in the tropical seasonal rain forest at Xishuangbanna, SW China during 2001-2002. * represent $P < 0.05$, Wilcoxon two-sample nonparametric tests.