

西双版纳热带季节雨林林冠穿透雾水的观测研究

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摘要 利用4年(1999~2002年)的林冠穿透雾水观测资料,对西双版纳热带季节雨林林冠穿透雾水进行了研究。全年林冠穿透雾水达 (89.4 ± 13.5) mm(平均值 \pm 标准差)(雾季和干热季共占 $85.9\% \pm 6.6\%$),为全年降水量(穿透雾水+雨水)的 $4.9\% \pm 1.7\%$ 。全年水平降水(穿透雾水+截留雾水)共 (337.9 ± 18.3) mm,占总降水(穿透雾水+截留雾水+雨水)的 $16.4\% \pm 1.0\%$ 。年林冠穿透雾水与年降雨量呈负相关关系。月林冠穿透雾水与月均最低气温呈显著的负相关,与月均相对湿度、月均0:00~10:00风速及月雾日数呈显著的正相关。全年 $68\% \pm 5\%$ 的有雾天气里可以收集到林冠穿透雾水((0.38 ± 0.27) mm \cdot d⁻¹),且日穿透雾水量、穿透雾水强度与气温和风速呈显著的相关,即气温越低、风速越大,日穿透雾水量、穿透雾水强度越大。对本地区热带雨林生态系统的健康生长和维持而言,雾及雾水极大地弥补了降雨量的不足,且降雨量少的年份,雾的这种作用似乎更为重要。

关键词 水平降水 穿透雾水 截留雾水 热带季节雨林 西双版纳

FOG THROUGHFALL AT A SEASONAL RAIN FOREST IN XISHUANGBANNA, SOUTHWEST CHINA

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Abstract Fog throughfall and related microclimatic factors were measured between November 1998 and February 2003 at a tropical seasonal rain forest in Xishuangbanna, Southwest China. Twelve bottle-funnel collectors were set in a random pattern on the forest floor to determine the daily amount of fog throughfall, and two funnel collectors connected with polyethylene tubing to a mechanical recording siphon-raingauge were used to determine fog throughfall intensity and temporal character. Related microclimatic variables including air temperature, relative humidity, wind speed, solar radiation and rainfall were also recorded by a meteorological observation system mounted on a 72 m meteorological tower in the study site. During the study period, absolute amounts of mean annual fog throughfall were up to (89.4 ± 13.5) mm (mean \pm SD), contributing $4.9\% \pm 1.7\%$ of the annual precipitation, with $85.9\% \pm 6.6\%$ of the fog throughfall collected in the foggy season (November-February) and dry-hot season (March-April). The amounts of annual fog throughfall plus fog interception accounted for $16.4\% \pm 1.0\%$ of total annual precipitation which includes fog throughfall, fog interception and rainfall. The annual fog throughfall was negatively correlated with annual rainfall, demonstrating that the dependence on fog as an additional water input was highest in the year when rainfall was lowest but fog throughfall was high. Monthly variation in fog throughfall was different from rainfall patterns and negative correlation was found between monthly average minimum air temperature and monthly fog throughfall while positive correlations were found between monthly fog throughfall and monthly average relative humidity, monthly average wind speed during 0:00–10:00, and monthly sum of fog-days. In fog-drip occurring days, the average fog throughfall was (0.38 ± 0.27) mm \cdot d⁻¹ and the amounts of fog throughfall per day and throughfall intensity were negatively correlated with air temperature and positively correlated with wind speed. The results suggest that fog, which not only inputs water into the forest but also partly reduces the evapotranspiration of the forest, plays an important role in the hydrology of the forest, especially in the foggy and dry-hot seasons. Therefore, neglect of the contribution from horizontal precipitation (fog throughfall plus fog interception) will make calculations of the water balance inaccurate in the forest. These results also demonstrate the importance of understanding the impacts of climate factors, and have important implications for ecologists and hydrologists interested in fog-inundated ecosystems and the plants that inhabit them.

Key words Horizontal precipitation, Fog throughfall, Fog interception, Tropical seasonal rain forest, Xishuangbanna

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多雾的山地和沿海森林生态系统中,雾降水(Fogwater, Occult precipitation, and Horizontal precipitation)一直被认为是一种极其重要的水文和化学输入项,其生态效应是多方面的(Dallard *et al.*, 1983; Unsworth & Crossley, 1987; Asbury *et al.*, 1994; Ishibashi & Terashima, 1995; Monteith & Unsworth, 1990; Ingraham & Matthews, 1988)。雾的形成不仅凝结水汽(Ingraham & Matthews, 1988)、沉降养分(Weathers & Likens, 1997)进入森林,同时也释放了凝结潜热而减弱了降温强度(刘文杰等, 2001a),还缩短了日照时数而消减蒸发散,这对缓解植物干旱、补充养分不足、减弱因低温加剧的光抑制等方面具有重要作用(Ishibashi & Terashima, 1995)。由于雾水作为森林水文、化学循环的关键环节而影响养分循环模式(Weathers & Likens, 1997),因而频繁的雾是决定某些山地和沿海森林分布及特征的重要因子,尤其是在热带森林分布地区(Gordon *et al.*, 1994a)。例如,低地山地雨林(Lower montane rainforest)总是被频繁的雾弥漫,而高地山地雨林(Upper montane rainforest)则更多地被频繁、持久的雾所笼罩,这两种森林均被称为热带山地多雾林(Tropical montane cloud forest)(Grubb & Whitmore, 1966)。这些热带山地多雾林林冠穿透雾水可达全年降水量(雨水+雾水)的2.4%~60.6%(Cavelier & Goldstein, 1989; Cavelier *et al.*, 1996),而雾水中化学离子浓度为雨水中相应离子的2~24倍(Asbury *et al.*, 1994; Clark *et al.*, 1998a; Gordon *et al.*, 1994a; 1994b; Weathers & Likens, 1988),可提供全年养分输入(雨水+雾水)的8%~30%(Asbury *et al.*, 1994)。

西双版纳热带雨林是在水分、热量、海拔均达到极限条件下的热带北缘季节雨林群落,由于地处山原地貌和季风气候特点的热带北缘,热带雨林受到了季节干旱和冬季低温的影响(朱华, 1992)。本区属西南季风气候区,年降雨量1 500~1 600 mm,但雾季(11~2月)和干热季(3~4月)雨量偏少,不足全年的13%。尤其是3~4月,气温升至全年最高,植物需水量大为增加。但本区是有名的静风(年均风速 $0.5 \text{ m} \cdot \text{s}^{-1}$)、多雾(年雾日 $>170 \text{ d}$)区,雾季和干热季多有辐射雾出现,雾的总持续时间占雾季和干热季时间的40%以上(刘文杰等, 1996),尤其是在热带雨林覆盖区,辐射雾更是频繁出现。因而,雾所塑造的温湿环境必然对热带雨林的生存和发展起到一定的作用。然而,有关西双版纳地区热带雨林林

内水平降水的研究几乎为空白。刘文杰等(2001b)对本区热带季节雨林林冠穿透雾水的研究结果表明:在干热季有雾的夜间,林下穿透雾水可达 $0.39 \text{ mm} \cdot \text{d}^{-1}$,但并未对全年林冠穿透雾水状况进行研究。本文利用1999年11月至2003年2月在热带季节雨林内观测的林冠穿透雾水和环境因子的资料,研究林冠穿透雾水特征及其影响因子,为热带森林内雾水的水文和化学效应及水分和养分循环规律的深入研究提供参考。

1 样地自然环境及群落特征

观测点设在中国生态系统研究网络西双版纳热带季节雨林定位观测样地(热带季节雨林面积约 3 km^2)内($21^{\circ}56' \text{ N}$, $101^{\circ}15' \text{ E}$),海拔750 m,观测点与雨林边缘平坝区相对高差约150 m。本区属热带北缘西南季风气候,一年中有干季(包括雾季(11~2月)、干热季(3~4月)、雨季(5~10月)之分(张克映, 1963)。年均气温 21.7° C ,年均风速 $0.7 \text{ m} \cdot \text{s}^{-1}$,相对湿度86%,年降雨量1 700 mm,其中雨季占83%~87%,干季占13%~17%。

观测样地所在的热带季节雨林,其群落高度35 m左右,乔木层按高度可分为3层:上层优势种为番龙眼(*Pometia tomentosa*)、千果榄仁(*Terminalia myriocarpa*);中层常见种有云南玉蕊(*Barringtonia macrostachya*)、大叶白颜树(*Gironniera subaequalis*)、山蕉(*Mitrephora maingayi*)等;下层树种主要有染木(*Saprosma ternatum*)、狭叶巴戟(*Morinda angustifolia*)、玉叶金花(*Mussaenda* sp.)等,群落结构特征详见文献(Cao & Zhang, 1996)。

2 研究方法

在热带季节雨林林下距地表0.7 m高处水平随机架置12个口径0.8 m的圆形漏斗,各漏斗出水口处悬挂1 000 ml的塑料瓶承接穿透雾水。塑料瓶内503 ml承接水换算到单位面积上等于1 mm的穿透雾水。每日9:00左右(林冠无雾水滴落时)测定穿透雾水量(1998年11月开始),日穿透雾水量取12个漏斗承接水的平均值。1999年1~2月,将两个漏斗承接的穿透雾水用塑料管(口径1 cm)导入虹吸自记雨量计中进行自动记录,测定林冠穿透雾水强度和时间动态变化。采用小气候梯度观测法,将MAOS-1全自动小气候观测系统(包括4层温度、湿度、风速;1层土壤热通量、辐射各分量、管状辐射表、雨量计)(长春气象仪器研究所生产)安装在热带

季节雨林定位样地梯度观测铁塔上(塔高 72 m),观测小气候要素变化特征。针对热带季节雨林 3 个乔木冠层 I、II、III(简称冠层 I、冠层 II、冠层 III,高分分别约 33 m、20 m、5 m),在冠层 I 以上 0.5 m 布设一层温、湿、风传感器及辐射传感器(总辐射、反射辐射、净辐射),在冠层 II、冠层 III 以上 0.5 m 及铁塔顶部各布设一层温、湿、风传感器,翻斗雨量计水平安置在铁塔顶部测定降雨量(采集频度 1 次·h⁻¹,1997 年 11 月开始观测)。雾日定义为水平能见度 < 1 km

及至少持续 15 min (Gordon *et al.*, 1994b)。

3 结 果

3.1 林冠穿透雾水量和降雨量的年变化

热带季节雨林内全年林冠穿透雾水达(89.4 ± 13.5) mm(平均值 ± 标准差),为全年降水量(穿透雾水 + 雨水)的 4.9% ± 1.7%(表 1)。由 4 年观测的年林冠穿透雾水和降雨变化(图 1a)可看出,2002 年的降雨最多(1948.7 mm),其穿透雾水最少

表 1 热带季节雨林内各季节平均穿透雾水量和降雨量分布(1999~2002 年)
Table 1 Seasonal variation of fog throughfall and rainfall in the tropical seasonal rain forest (1999~2002)

| 项目 Items | 雾季 Foggy season | 干热季 Dry-hot season | 雨季 Rainy season | 全年 Whole year |
|--|--------------------|-----------------------|--------------------|------------------|
| 穿透雾水 Fog throughfall (mm) | 56.2 ± 5.2 | 20.6 ± 4.0 | 12.6 ± 2.4 | 89.4 ± 13.5 |
| 降雨量 Rainfall (mm) | 114.7 ± 34.3 | 62.2 ± 18.3 | 1 531.3 ± 182.0 | 1 717.8 ± 206.2 |
| 穿透雾水/(降雨量 + 穿透雾水) | 32.9 ± 4.2 | 24.9 ± 2.7 | 0.8 ± 0.2 | 4.9 ± 1.7 |
| Fog throughfall/(Rainfall + Fog throughfall) (%) | | | | |

表内数据为平均值 ± 标准差,样本数为 4 Entries are means ± standard deviation (SD)(n = 4)

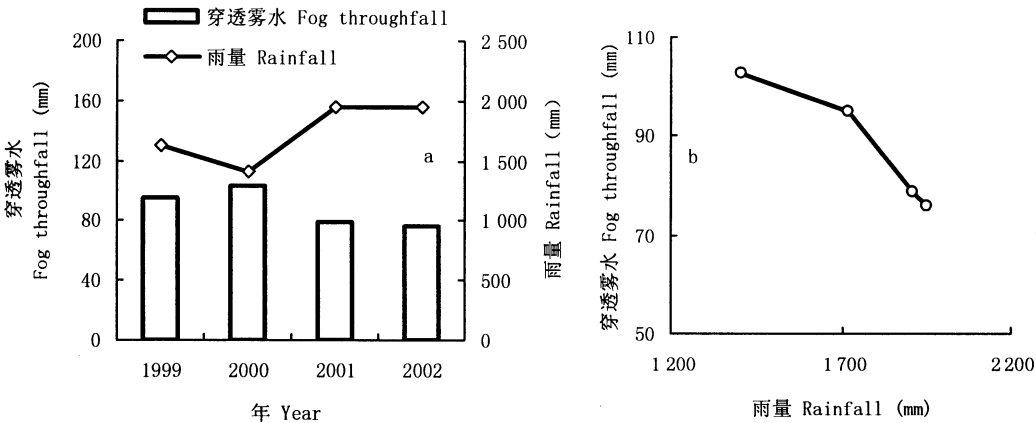


图 1 热带季节雨林内年穿透雾水量和降雨量变化(a)及其关系(b)
Fig.1 Variation (a) and relationship (b) between annual fog throughfall and rainfall for the tropical seasonal rain forest

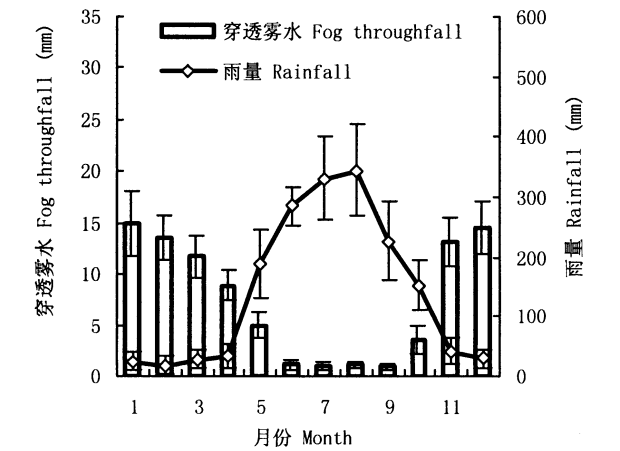


图 2 热带季节雨林内平均各月降雨量和穿透雾水量(1999~2002 年)
Fig.2 Mean rainfall and fog throughfall each month for the tropical seasonal rain forest from 1999 to 2002

(75.9 mm);2000 年降雨最少(1 405.5 mm),其穿透雾水最多(102.9 mm)。年林冠穿透雾水量与降雨量具有负相关关系(图 1b)。因而,对此热带季节雨林而言,雾水在雨水较少的年份可能具有更为重要的意义。

3.2 林冠穿透雾水量和降雨量的季节变化

月降雨量与月穿透雾水量呈相反的分配状况(图 2)。雨季(5~10 月)各月降雨量多,但穿透雾水量较少;雾季(11~2 月)和干热季(3~4 月)各月降雨较少,但穿透雾水量较多。雾季和干热季,林冠穿透雾水量共占全年总穿透雾水量的 85.9% ± 6.6% ((76.8 ± 7.2) mm),而雾季相应就占 62.9% ± 4.8% ((56.2 ± 5.2) mm)(表 1)。由表 1 可看出,雾季的穿透雾水量可占本季节降水量的 32.9% ± 4.2%,而干热季和雨季则依次减小。

夜间或清晨,气温越低、相对湿度越高,雾越容易形成、越浓重。风速越大,则随风携带的雾滴被林冠截留的量将越多(Oke, 1978; Unsworth & Crossley, 1987)。因而,在干季(雾季和干热季),月穿透雾水量与月均最低气温呈明显的负相关,与月均相对湿度、月均 0:00 ~ 10:00 风速及月总雾日数呈明显的正相关(图 3, $p < 0.001$)。雨季同样有此相关性($p < 0.001$),但雨季和干季的相对湿度与穿透雾水量的关系是无法同时比较的,因为对干季而言,雨季高的相对湿度并不能导致多的穿透雾水量。

3.3 林冠穿透雾水量的日变化

雾季, $92\% \pm 6\%$ 的有雾天气里能够收集到林冠穿透雾水,平均可达 $(0.52 \pm 0.37) \text{ mm} \cdot \text{d}^{-1}$,而干热季和雨季的相应值则依次减小(表 2)。就全年能够收集到穿透雾水的次数而言,其平均值为 $(0.38 \pm 0.27) \text{ mm} \cdot \text{d}^{-1}$ 。日穿透雾水与当日最低气温呈明显的负相关($p < 0.001$)与当日 0:00 ~ 10:00 的平均风速呈明显的正相关(图 4, $p < 0.001$)。穿透雾水强度与当时的气温和风速同样具有这种明显的相关性(图 5, $p < 0.001$),即气温越低、风速越大,日穿透雾

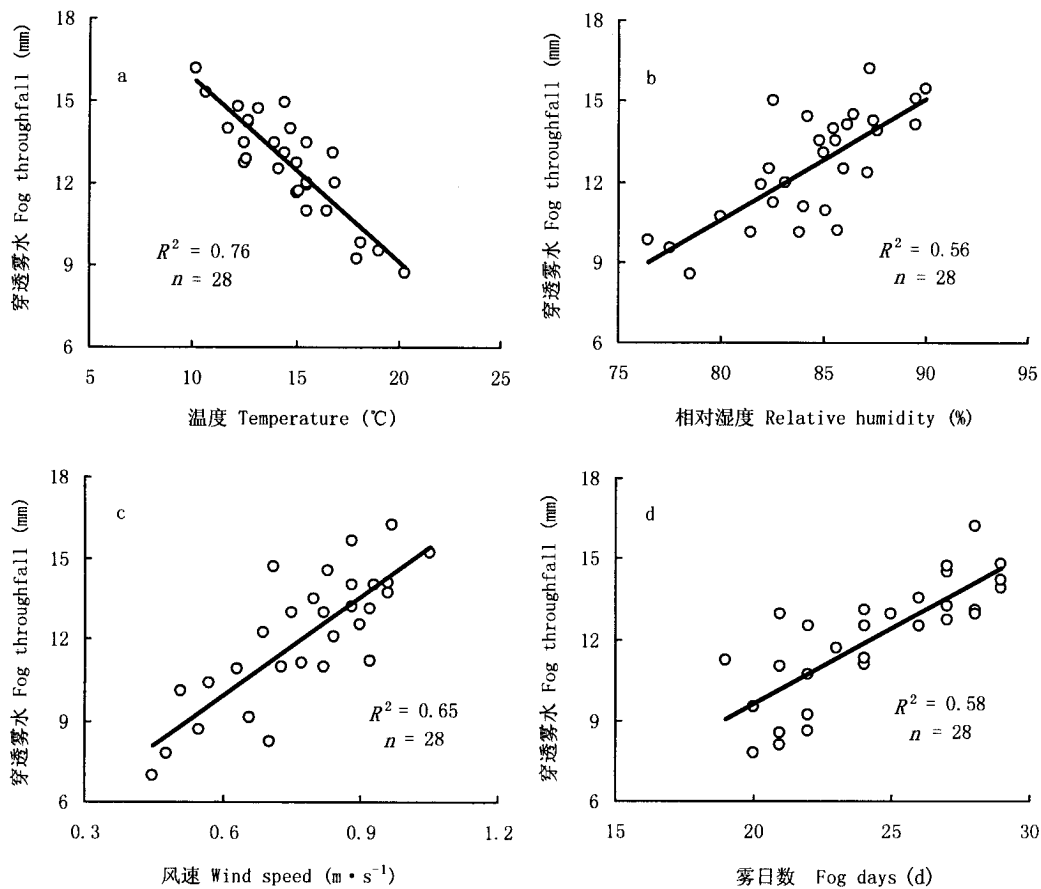


图 3 月穿透雾水量与月均最低气温(a)、月均相对湿度(b)、月均 0:00 ~ 10:00 风速(c)及月雾日数(d)的关系

Fig.3 Relationships between monthly fog throughfall and monthly average minimum air temperature (a), monthly average relative humidity (b), monthly average wind speed during 0:00 ~ 10:00 (c) and, monthly sum of fog-days (d)

表 2 热带季节雨林各季节平均日穿透雾水量及可收集到雾水的雾日比率(1999 ~ 2002 年)

Table 2 Seasonal average fog throughfall per day in fog-drip occurring days and average percentage of fog-drip occurring days of total fog-days in the tropical seasonal rain forest (1999 - 2002)

| 项目 Items | 雾季 Foggy season | 干热季 Dry-hot season | 雨季 Rainy season | 全年 Whole year |
|--|--------------------|-----------------------|--------------------|------------------|
| 穿透雾水 Fog throughfall ($\text{mm} \cdot \text{d}^{-1}$) | 0.52 ± 0.37 | 0.41 ± 0.38 | 0.22 ± 0.15 | 0.38 ± 0.27 |
| FD (%) | 92 ± 6 | 82 ± 4 | 36 ± 5 | 68 ± 5 |

FD 为收集到雾水的雾日占季节总雾日的比率 FD represents average percentage of fog-drip occurring days of total fog days 表内数据为平均值 ± 标准差,样本数为 4 Entries are means ± standard deviation (SD) (n = 4)

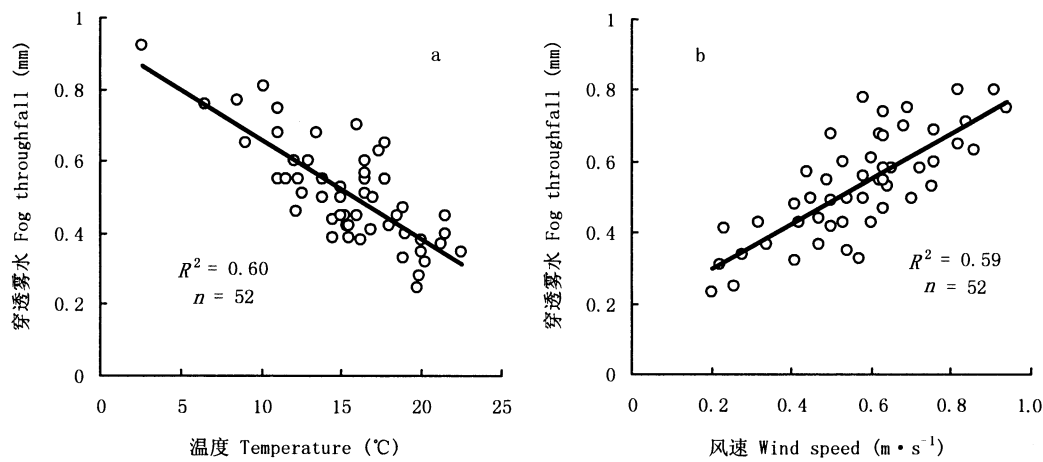


图 4 日穿透雾水量与日最低气温(a)和 0:00~10:00 平均风速(b)的关系

Fig.4 Relationships between diurnal fog throughfall and minimum air temperature (a) and, average wind speed during 0:00~10:00 (b)

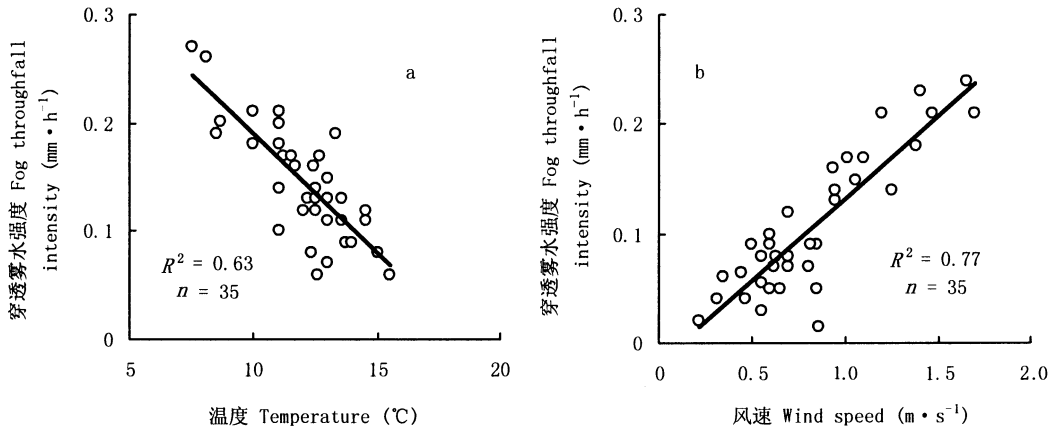


图 5 穿透雾水强度与气温(a)和风速(b)的关系

Fig.5 Relationships between fog throughfall intensity and air temperature (a) and, wind speed (b)

水量、穿透强度越大。

4 结论和讨论

西双版纳热带季节雨林全年林冠穿透雾水达 (89.4 ± 13.5) mm (雾季和干热季共占 $85.9\% \pm 6.6\%$), 占全年降水量(穿透雾水 + 雨水)的 $4.9\% \pm 1.7\%$ 。年穿透雾水量与年降雨量呈负相关关系。月穿透雾水量与月均最低气温呈显著的负相关, 与月均相对湿度、月均 0:00~10:00 风速及月雾日数呈显著的正相关。全年 $68\% \pm 5\%$ 的有雾天气里可以收集到穿透雾水((0.38 ± 0.27) $mm \cdot d^{-1}$), 且日穿透雾水量、穿透雾水强度与气温和风速有显著的相关性, 即气温越低、风速越大, 日穿透雾水量、穿透雾水强度越大。

与世界其它大部分热带森林相比, 本区热带季节雨林林冠穿透雾水平均占降水量 4.9% 的值显然

很小(表 3), 略低于 Baynton(1989)在波多黎哥 Pico Del Oeste 测定的 7.2%、Cavelier 和 Goldstein (1989)在委内瑞拉 Cerro Copey 测定的 9.7% 和在巴拿马 Cordillera Central 测定的 8%, 但高于 Cavelier 和 Goldstein (1989)在委内瑞拉 El Zunmbador 测定的 3.5%。本研究的结果表明, 年林冠穿透雾水量与年降雨量呈负相关关系(图 1b), 这与 Cavelier 和 Goldstein (1989)在委内瑞拉和哥伦比亚热带森林的研究结果相同。然而, Cavelier 和 Zhang (1996)在巴拿马 Cordillera Central 热带森林的研究并没有发现这种显著的相关性。对本地区热带季节雨林而言, 雨水较少的年份, 穿透雾水则较多(图 1b), 较多的林冠穿透雾水似乎是对雨水不足的一种补充, 这可能对热带季节雨林内植物的正常生长具有更为重要的意义。

降雨在林冠层再分配为 3 部分: 林冠截留、穿

表 3 世界部分热带森林内年穿透雾水量和降雨量
Table 3 Annual fog throughfall and rainfall at some tropical forest sites in the world

| 地点 Location | 穿透雾水 Fog throughfall (mm) | 降雨 + 穿透雾水 Rainfall + Fog throughfall (mm) | 穿透雾水/(降雨 + 穿透雾水) Fog throughfall /(Rainfall + Fog throughfall) (%) |
|--|------------------------------|--|---|
| El Zumbador, Venezuela ^a | 72 | 1 983 | 3.5 |
| Xishuangbanna, China ^b | 89 | 1 807 | 4.9 |
| Pico Del Oeste, Puerto Rico ^c | 325 | 4 530 | 7.2 |
| Cordillera Central, Panama ^d | 448 | 5 696 | 8 |
| Cerro Copey, Venezuela ^a | 458 | 4 461 | 9.7 |
| Monteverde, Costa Rica ^e | 886 | 3 191 | 28 |
| Cordillera Central, Panama ^d | 1 130 | 3 630 | 31 |
| Santa Ana, Venezuela ^a | 522 | 1 630 | 32 |
| Serrania de Macuira, Colombia ^a | 796 | 1 649 | 48 |
| Cordillera Central, Panama ^d | 2 295 | 3 790 | 60 |

a: Cavelier & Goldstein (1989) b: This study c: Baynton (1989) d: Cavelier *et al.*, (1996) e: Clark *et al.*, (1998b)

表 4 热带季节雨林平均各季节水平降水量及与总降水量的比率(1999~2002 年)
Table 4 Seasonal average horizontal precipitation and its ratio to total precipitation in the tropical seasonal rain forest (1999–2002)

| 项目 Items | 雾季 Foggy season | 干热季 Dry-hot season | 雨季 Rainy season | 全年 Whole year |
|---|--------------------|-----------------------|--------------------|------------------|
| 截留雾水 Fog interception (mm) | 104.8 ± 7.9 | 46.6 ± 5.5 | 98.9 ± 8.4 | 250.3 ± 16.6 |
| 截留雾水 + 穿透雾水 Fog interception + Fog throughfall (mm) | 161.0 ± 9.7 | 67.2 ± 6.2 | 111.5 ± 9.5 | 337.9 ± 18.3 |
| (截留雾水 + 穿透雾水)/总降水量 (Fog interception + Fog throughfall)/Total precipitation (%) | 58.4 ± 4.6 | 51.9 ± 3.0 | 6.8 ± 0.5 | 16.4 ± 1.0 |

总降水量 = 截留雾水 + 穿透雾水 + 雨水 Total precipitation = Fog interception + Fog throughfall + Rainfall 表内数据为平均值 ± 标准差, 样本数为 4 Entries are means ± standard deviation (SD)(n = 4)

透水 and 树干流。和降雨一样, 水平降水(雾水)同样也应该有这 3 部分的再分配。据作者对该热带季节雨林林冠截留雾水的研究(刘文杰等, 2001b)表明, 干热季林下可收集到雾滴的天气里, 林冠层可截留雾水 $0.97\text{ mm}\cdot\text{d}^{-1}$ 。如果每个雾日(可收集到穿透雾水)以 0.97 mm 的截留雾水量计算, 并忽略雾水的树干流(观测的 4 年间, 并未发现雾水沿树干到达地面, 但仍会浸湿上部树干表面的少部分), 则全年林冠共截留雾水 $(250.3 \pm 16.6)\text{ mm}$ (表 4), 占总降水 (= 穿透雾水 + 截留雾水 + 雨量)的 $12.1\% \pm 0.8\%$, 也即森林内全年水平降水为 $(337.9 \pm 18.3)\text{ mm}$ (占总降水的 $16.4\% \pm 1.0\%$), 平均全年总降水量可达 $2\,055.7\text{ mm}$ 。其中, $(250.3 \pm 16.6)\text{ mm}$ 的林冠截留雾水无疑全部用到了林冠蒸发散中, 这将会极大地改变林冠层的辐射分配和利用状况。因而, 森林内水平降水的研究也不能忽视林冠截留的这部分雾水。另一方面, 本区干热季的降雨多为短时雷阵雨(刘文杰等, 1997), 对植物利用来说, 其有效性无疑远低于缓慢滴落到林下土壤内的雾水。同时, 雾季和干热季白天持续到 11:00 左右的浓雾, 极大地缩短了日照时数, 因而也相对减少了森林的蒸发散量。因此, 雾及雾水导致的水分输入和输入方式

极大地弥补了本区降雨量的不足, 这对本区热带雨林生态系统的健康生长和维持无疑是至关重要的。显然, 进一步的深入研究应该集中在热带雨林内的植物如何利用和利用多少这部分雾水, 雾和雾水如何影响森林蒸发散、光合作用、能量分配, 以及雾水的化学效应上。

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