STUDY ON THE PHYSICAL PROCESS OF WINTER VALLEY FOG IN XISHUANGBANNA REGION*

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ABSTRACT

Xishuangbanna of Yunnan Province is a famous tropical foggy region. A field experiment was carried out from November 23 to 30 of 1997 during which fogs occurred regularly every day. In the paper the characteristics of macrostructure of fog are analyzed and the physical processes of formation and dissipation of fog are studied. The results show that the Xishuangbanna valley fog forms firstly in the lower atmosphere with two-layer structures and then develops suddenly in the vertical direction after reaching the ground. Furthermore, the vegetation effect on the formation and dissipation of fog is discussed specially.

Key words: Xishuangbanna, valley fog, physical process, vegetation

I. INTRODUCTION

Xishuangbanna, in the southern Yunnan Province of China, is a famous tropical foggy region, with annual maximum of 208 fog days, and is an important tourism region, with one million tourists every year. Located in the central Xishuangbanna, around 21°27′—22°36′N, 100°25′—101°31′E, Jinghong is the capital of the Dai Autonomous Prefecture of Xishuangbanna. At present, the prominent problem is that fog affects traffic safety. Thus, it is necessary to study the causes and evolution of fog, and predict the formation and dissipation of fog. On the other hand, fog is very sensitive to the change of ecological environment. Especially with development of economics and cities, decreasing of tropical rain-forest, there is a trend that fog decreases evidently. Therefore, studying on fog can reveal the influence of ecological environment on climate and enrich the theory of global warming.

Study of fog was started as far back as the beginning of this century. The field experiment was made to study the formation of fog in 1917 by Taylor (1917).

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Comprehensive field observations of fog were conducted in the early 1970s in Cardington (UK. 1971—1973) by Roach et al. (1976). and in the Elmira Valley (USA, 1970) by Pilie et al. (1970), together with numerical model study. Starting from the end of the 1970s. a program of radiation fog field observation was implemented for years in Albany of New York State. USA (Jiusto et al. 1983). More recently, experiments on valley fog were performed in the Pol Valley of Italy (Fuzzi et al. 1992; Wobrock et al. 1992). Those efforts have basically revealed the physics of genesis/lysis of radiation fog and its affecting factors. In recent years, an intensive research has been undertaken of urban fog in China, revealing many new features of the event over a complicated terrain (Li et al. 1994). However, because of the limited conditions at that time, there was no study on physics of fog in depth and its relation to ecological environment.

Supported by the National Natural Science Foundation of China, a one-week field experiment was done in November, 1997, with focus on the physics-chemistry and genesis/lysis of fog and its relation to the ecological environment. Based on observation of four fog events, the present paper has focus on the fog physics evolution and dominant features, attempting to provide physical interpretation. not for all problems.

Based on observation. it can be found that fog forms in the lower atmosphere, and has a double layered-structure and burst development characteristics. Burst development of Pol Valley fog in the vertical, resulted from higher fog layer advection, not vertical development of fog layer. It is important to understand physics process of valley fog by revealing these main features.

II. DESCRIPTION OF OBSERVATION SITES AND INSTRUMENTS

Xishuangbanna is located in the southern part of the valleys of the Hengduan Mountains. N-S oriented, in the western Wuliang Mountain, in the eastern Nushan ranges. and the middle part is wide valley basin caused by Lanchang River and small Heijiang River.

The observing sites were in Jinghong meteorological station and Mengyang farm station, 13 km apart at 582. 0 and 771. 0 m above msl, respectively, in central Xishuangbanna. Jinghong is in the west of Lanchang River and in the north of Liusa River. The northern and the southern of Jinghong Basin are Sanda Mountain, NW-SE directed, at 1200 m msl. Mengyang is located in valley of northern Sanda Mountain and, in the south Guanping Mountain, 1000—1200 m high. All mountains are covered with primitive tropical rain forests and rubber trees, as tall as 10—15 m. True topography is shown in Fig. 1.

In addition to conventional meteorological observations at these 2 sites, observations of the atmospheric boundary layer (ABL) and the microphysical structure were made together with fog water and aerosol particles sampled, in which the AIR (Atmospheric Instrumentation Research, Inc.)-made ADAS (Automatic Data Acquisition System) was used for ABL soundings and the home-made droplet collector for microphysical purposes, CYQ-60 type of high-volume particulcate sampler for aerosol particles sampled, and home-made active sampler for fog water.

Principle of ADAS is that tethersonde sounds many elements at different levels, such

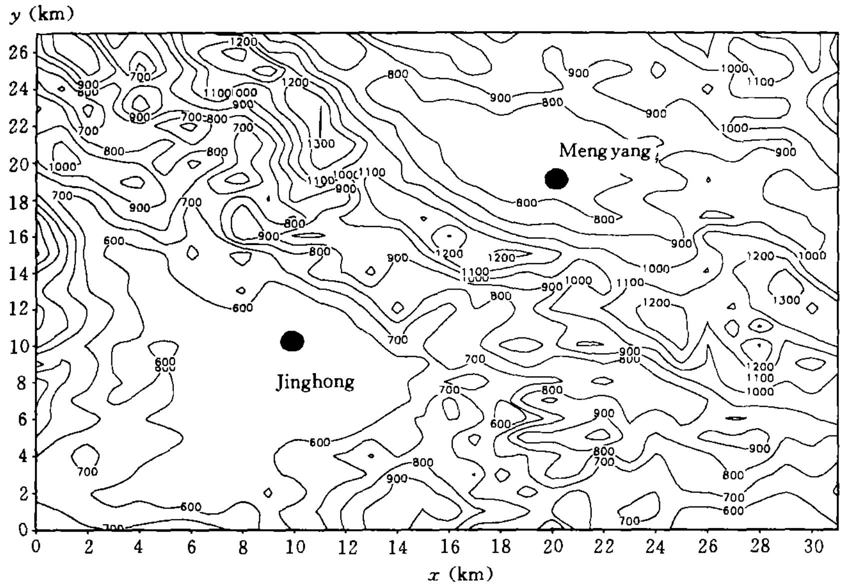


Fig. 1. Topography of Xishuangbanna and observation sites.

as temperature, air pressure, moisture, wind and so on, then sends them to ground-based receiver. The ascending velocity of tethered balloon is adjusted according to profiles obtained. For example, the balloon would slow down to obtain the fog height as it is going out from a fog region. Generally, the whole process takes 20—30 minutes or so, with an interval of 5—10 m for obtaining a group of data. Observation for each event was from 1900 BT when fog did not form yet, to 1300 BT of the next day when the fog dissipated, at a 2-h interval, but hourly for formation and dissipation stages. Droplet collector is that fog droplets deposit on an oiled-glass sampler under inertial force, then taking photos to read data of density and size, with minimum of 3. 2 μm. A coefficient for capture correction is used in processing data. Fog water can be measured directly by using droplet collector and filtered-paper.

III. CHARACTERISTICS OF MENGYANG FOG

During the experiment, observation was made for four fog events, occurring on November 25, 26, 28 and 29, 1997. During the period, Xishuangbanna region was controlled by a subtropical high at 500 hPa, which includes a number of anticyclones. One high was from the Southeast India, through the Bay of Bengal to the Indo-China Peninsula (the India-Burma high), and another was from the longitude of 100°E to the South China Sea. Xishuangbanna is in the southeast of the India-Burma high and in the northwestly air stream in front of the weak ridge of Yunnan-Guizhou, when weak ridge around Tibetan Plateau moves toward the south Yunnan-Guizhou Plateau, and followed by the India-Burma high extending to the northeast, and is in the westly and southwestly air stream of the north and northwest of the South China Sea high, when the shallow trough moves to east over Tibetan Plateau and the India-Burma high moves to south and withdraw from west. No matter which case it is, the air in this region is stable, clear, and wind is weak. All these are favorable for the formation of radiation fog.

The genesis/lysis of the fog at Mengyang happened in the following fashion: starting from 1700 BT, surface temperature dropped, temperature inversion occurred, and after sunset (1820 BT), air temperature decreased to 16°C from 25°C until 2000 BT. After then, it dropped slowly until sunrise, and began to rise gradually at about 0900 BT and to increase rapidly since 1100 BT. Meanwhile, relative humidity increased suddenly from 40% to 90% from 1700 BT to 2000 BT, and then increased slowly and attained saturation about 0100 BT, which resulted in fog formation. AT 0900 BT, relative humidity began to decrease and surface visibility increased and fog dissipated completely until 1100 BT. It lasted for 10 hours from fog formation to dissipation (see Fig. 2).

Depths and temperature of fog layer during these four fog events are shown in Table 1, based on the radiosonde observation. According to the droplet collector observation, the appearing time of liquid water content is defined as surface fog formation, and the disappearing of mark of filter paper is defined as dissipation of fog. It can be found that fog firstly occurred in the lower atmosphere about midnight and then touched the surface, with non-uniform development in vertical and had a double layered-structure which was merged as development or dissipation. And also, it can be found that fog developed explosively in vertical from 0130 BT to 0300 BT. During this period, the depth of fog increased explosively from 160—250 m to about 300 m. Surface temperature was generally from 13°C to 17°C during formation and temperature of the fog layer was usually above 12°C, even though the minimum of fog top temperature observed was 10. 9°C on November 26. These exhibit the characteristics of radiation fog in tropical region.

Main microphysics parameters of 3 fog events are given in Table 2 together with observations at Mengyang (1986) and Chongqing (winter, 1989). Data on November 26 and 28 are from the whole process, respectively, and the data on 29 are only from formation and development. Mean number density, mean diameter and calculation of mean liquid content are shown in Table 2. They vary from 81 to 315 cm^{-3}, from 7. 6 to 9. 2 μm and from 0. 082 to 0. 174 g cm^{-3}, respectively. Compared to the results of 11 years ago, number density increases to some extent, droplet diameter decreases evidently and liquid water content decreases by 3 times or so, which may be related to decreasing of tropical rain-forest and development of town and factory. Same phenomena have also been found in Chongqing.

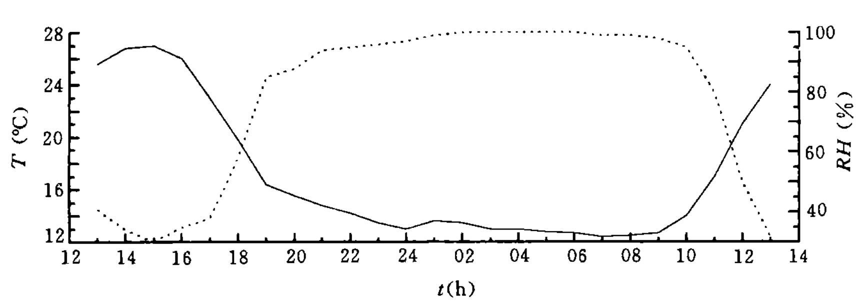


Fig. 2. Daily variation of the surface temperature (°C, solid line) and relative humidity (%, dotted line).

Table 1. Depth (H, unit: m) and Temperature (T, unit: ℃) of Fog Layer

			November 25	November 26	November 28	November 29
Ground fog genesis			0050 BT	0135 BT	0045 BT	0010 BT
Fog genesis	Low-level	Time	0100	0100	0000	0000
		T (base)	16.8	13.7	14.9	15.0
		T (top)	15.6	13.5	15.3	15.3
		H (base)	1.5	60	40	29
		H (top)	184	87	119	106
	High-level	T (base)	15.8	13.8	15.5	15.8
		T (top)	15.2	13.7	15.5	16.1
		H (base)	197	107	136	110
		H (top)	226	181	160	251
The most strong development	Low-level	Time	0300	0300	0300	0130
		T (base)	16.1	13.4	14.5	15.4
		T (top)	14.6	12.2	13.8	14.5
		H (base)	1.5	1.5	1.5	1.5
		H (top)	225	191	191	176
	High-level	T (base)		13.1	14.8	15.0
		T (top)		13.0	14.5	15.4
		H (base)		222	261	192
		H (top)		342	381	324
Fog dissipation	Low-level	Time	0900	0900	0900	0900
		T (base)	15.0	12.5	13.9	14.4
		T (top)	13.5	10.9	13.7	12.5
		H (base)	1.5	1.5	1.5	1.5
		H (top)	289	277	273	381
	High-level	T (base)		12.1		13.0
		T (top)		12.0		13.4
		H (base)		360		391
		H (top)		387		430
Ground fog dispersal			0950 BT	0935 BT	0935 BT	0930 BT

Table 2. Microphysical Structure Parameters of Mengyang Fog

Parameters		Mengyang 26 Nov. 1997	Mengyang 28 Nov. 1997	Mengyang 29 Nov. 1997	Mengyang* Dec. 1986—Feb. 1987	Chongqing** Dec. 1989—Jan. 1990
Number density (cm^{-3})	Mean	81.7	313.0	315.2	94.8	529.0
	Maximum	388.5	955.2	2437.7	270.2	2026.0
	Minimum	10.9	2.2	16.4	2.1	35.0
Mean diameter (μm)	Mean	9.2	7.3	7.6	13.1	4.4
	Maximum	27.2	17.6	16.5	22.8	7.5
	Minimum	4.6	4.0	4.0	5.7	3.5
Maximum diameter (μm)	Mean	41.0	40.0	31.5	58.8	21.9
	Maximum	78.4	80.0	60.8	66.5	35.0
	Minimum	19.2	14.4	12.8	42.0	7.0
Peak diameter (μm)	Mean	5.3	3.8	5.4	6.8	3.5
	Maximum	19.2	11.2	19.2	21.0	3.5
	Minimum	3.2	3.2	3.2	3.5	3.5
Liquid water content ($g\ cm^{-3}$)	Mean	0.082	0.116	0.174	0.25	0.02
	Maximum	0.258	0.568	0.667	0.74	0.12
	Minimum	0.003	0.001	0.007	0.02	0.00
Visibility (m)	Mean	165	274	170		
	Maximum	660	800	740		
	Minimum	40	40	15		
Samples		40	44	18	14	

Note: * Li et al. (1992); ** Li and Wu (1995).

IV. PHYSICS PROCESSES IN FORMATION AND DEVELOPMENT OF FOG

Since processes for all the 4 fog events are similar, only one of them is taken as an example to study the main features in formation and development and attempt to give physical interpretation to them. Spatial and temporal distributions of air temperature, specific humidity and relative humidity of the fog on November 26 are shown in Fig. 3, which describes macrophysical characteristics of fog at Mengyang of Xishuangbanna region. From Fig. 3, we see that, starting from 1700 BT, November 25, temperature inversion occurred in the near surface layer, followed by sharp drop of temperature in this layer, and specific humidity and relative humidity increased suddenly against time from

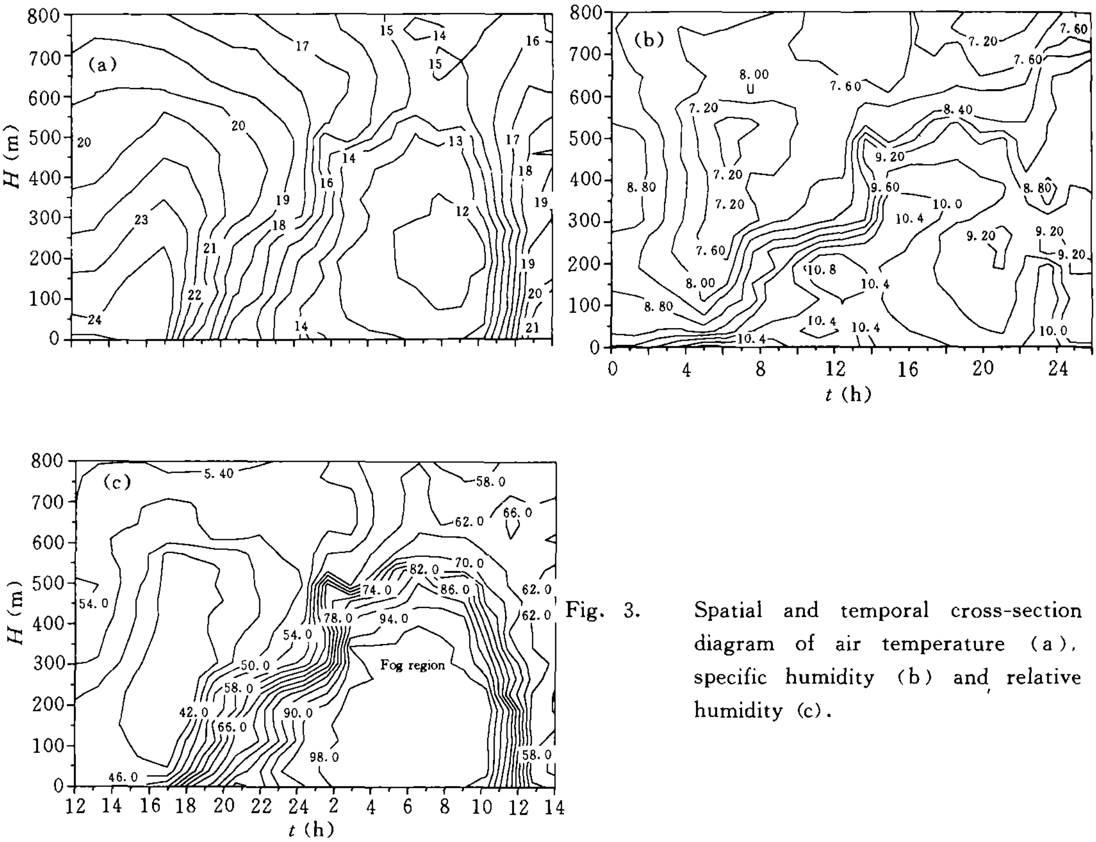


Fig. 3. Spatial and temporal cross-section diagram of air temperature (a), specific humidity (b) and relative humidity (c).

lower layer to upper layer. When relative humidity of the atmosphere at 200 m height rose from 50% of surface relative humidity at 1700 BT to 95% at 0100 BT of next day, fog was generated at 0135 BT. After formation, fog layer happened explosively to 342 m at 0300 BT, because air temperature dropped sharply between 200 m and 500 m height, specific humidity and relative humidity increased abruptly. In mature period, located in cold center, change of temperature of fog layer was small and vertical distribution was uniform, and consuming of water vapor by fog layer resulted in decrease of specific humidity. From relative humidity, change in height of fog was small. Beginning at 0900 BT, air temperature rose rapidly from fog base to middle. Meanwhile, fog dissipation started from fog base and top and did not end completely until 1100 BT.

Evolution of fog region on 26, November was shown in Fig. 4 in order to describe the evolution process clearly. From Fig. 4, it can be found that process of fog is divided into four stages as the following: (1) The stage of fog formation. Fog occurred firstly at low layer and then touched surface about midnight. (2) The explosive development stage (0300—0500 BT). Fog developed rapidly in vertical direction during the period. (3) The mature stage (0500 — 0900 BT) with relative stable development. (4) The stage of dissipation (0900—1100 BT). Surface fog disappeared and changed into low cloud and disappeared completely.

Basic characteristics and main affecting factors at every stage are analyzed as follows.

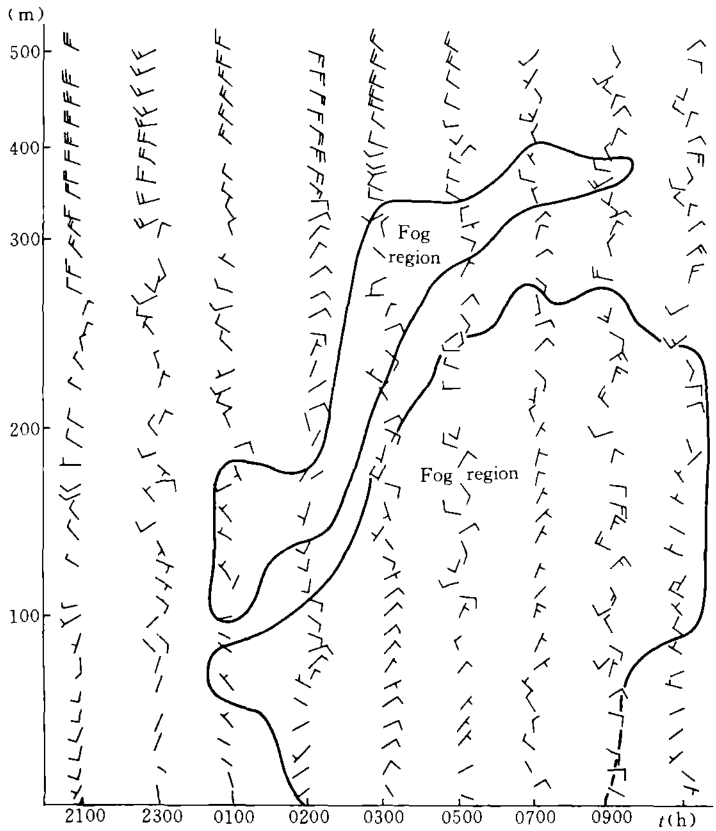


Fig. 4. Diagram of evolution of fog region on 26, November.

1. *Fog Genesis*

On November 25, after sunset, drop of temperature happened, and starting from 1700 BT, temperature inversion occurred in the near surface layer (Fig. 5a), followed by sharp drop of temperature in this layer and maximum of detemperature rate existed in the surface with 7.3°C in two hours. The inversion height reached 265 m at 1900 BT, displaying two strong centers, one being 5.5°C/100 m under 60 m and the other being 2.7°C/100 m between 110—154 m. The inversion lifted beyond 400 m at 2300 BT, when two centers rose to 100—154 m and 220—310 m, respectively, and being 6.7°C/100 m and 3.0°C/100 m. Meanwhile, surface specific humidity increased rapidly with maximum of 0.5 g kg^{-1}, accompanied by two high-value regions of specific humidity as a result of accumulation of a large amount of moisture near the layer base, which formed and located under the inversion base and lifted with rising of the inversion. AT 0100 BT, two layer fog regions occurred firstly in the maximum specific humidity layer at 50—87 m and 100—118 m height, and then lower fog layer extending downward and reaching ground about 0135 BT.

Based on above results of analysis, it follows that contributing factors consist of radiation cooling and upward transport of ample moisture from ground, especially

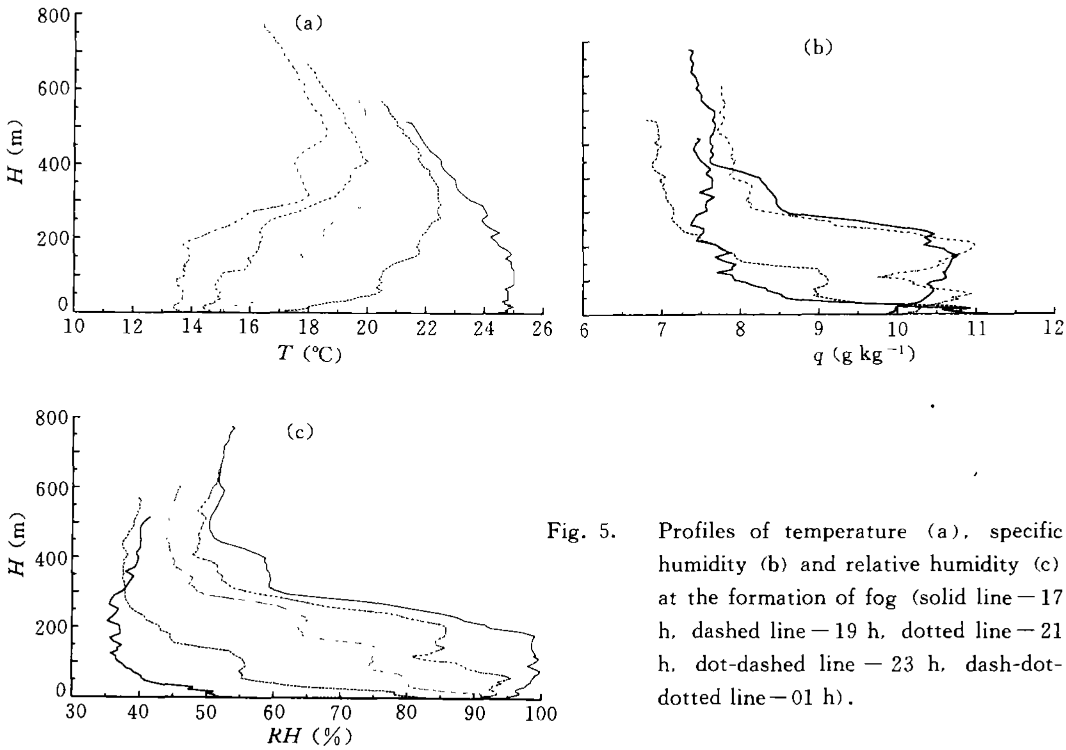


Fig. 5. Profiles of temperature (a), specific humidity (b) and relative humidity (c) at the formation of fog (solid line—17 h, dashed line—19 h, dotted line—21 h, dot-dashed line — 23 h, dash-dot-dotted line—01 h).

accumulation of ample moisture under inversion base through evapotranspiration of tropical rain forests. From this point of view, fog of Mengyang is radiation fog, but its formation is related to cold air coming downward from the mountains. Our simulation of the mountain-valley breezes has demonstrated that the mountain wind happens after 2000 BT at Mengyang and gets intensified in midnight hours, forming a vigorous mountain breeze circulation, centered at 200—300 m.

In Fig. 5a, after 1900 BT, detemperature was not most rapidly on the ground, but sharp drop of temperature occurred between 50—250 m, which may be related to cold air coming downward reaching to the height. In order to prove cold air coming downward, change of wind at different level is analyzed. Results show that W-SE wind occurred between 20—120 m and eastly wind between 130—170 m, which demonstrate air coming downward from the mountain existed at the low layer and air stream upward the mountain at upper layer, forming anticlockwise circulation. About 0100 BT of midnight, the down running cold air increased to 180 m high and circulation rose to 240 m, which gave rise not only to the deepening of the temperature inversion layer but to fog generation at the two levels due to its mixing with moist air underneath the two centers of intense temperature inversion just over the valley. In conclusion, characteristics of fog formation are that, after sunset, radiation inversion gradually increases, displaying two strong centers, moisture accumulates under two centers by upward transport from ground, and cold air coming downward from mountain strengthens the inversion and fog forms at moisture accumulation layer.

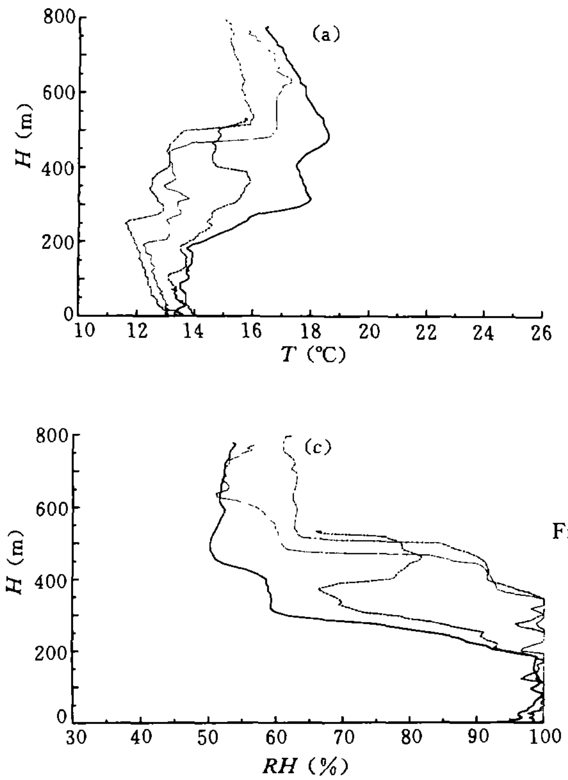


Fig. 6. Profiles of temperature (a), specific humidity (b) and relative humidity (c) at the development stage (solid line—01 h, dashed line—02 h, dotted line—03 h, dot-dashed line—05 h).

2. *Explosive Development of Fog*

After formation of fog, it went into the explosive development at once. The explosive growth is marked by dramatic rise of the fog top, its depth doubling during development. For example, at 0300 BT, 26 November, the top of the lower (upper) fog layer rose to 190 m (340 m) from 90 m (180 m) (see Fig. 4). To make approach to the causes we have constructed a diagram of the profiles of temperature and humidity during the explosive development. One can see that as the fog was generated sharp drop of temperature occurred under 400 m, dropping about 4.0°C from 0100—0300 BT (see Fig. 3 and Fig. 6). With drop of temperature, strong temperature inversion happened above 400 m and vertical distribution of temperature displayed wet adiabatic lapse rate in fog region. The profile of specific humidity changed in such a way that its maximum was at 325 m level, being adjusted to decreasing with height in lower layer of fog. Correspondingly, the fog was experiencing explosive growth in vertical, the upper fog top rose beyond 300 m and displaying uneven multi-layer structures. In order to study the causes of vertical development, it can be found that convergence motion happened under 200 m, which caused vertical development of air and lifting of the fog top during 0100—0300 BT (see Fig. 4a), and was results of combination of air coming downward from Sanda Mountain with that from Guanping Mountain. The upward motion gave rise to expansional cooling of air layer above 200 m, dropping of temperature, and upward transport of moisture from the lower level which made the maximum of specific humidity rise to higher level. It must

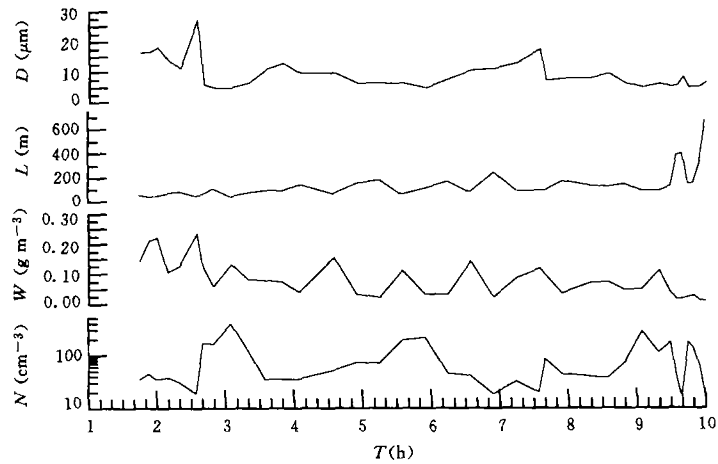


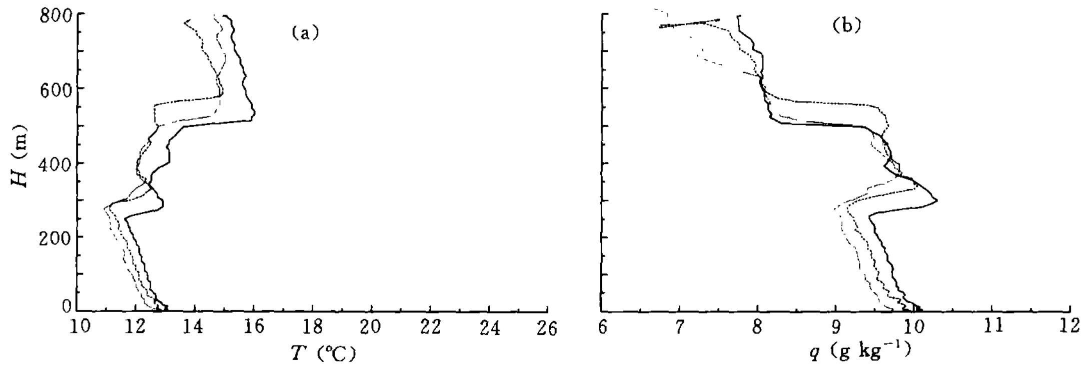
Fig. 7. Temporal variation of number density (N), liquid water content (W), visibility (L) and mean diameter (D) of fog on the surface.

be pointed out that there are some other favorable factors to explosive development of fog, including latent heat of condensation and radiation cooling of fog top.

Evolutions of number density (N), liquid content (W), mean diameter (D) and visibility (L) of the fog on 26. November are presented in Fig. 7. After formation of fog, microphysics developed rapidly in vertical, and variables of N, D and W reached the maximum of the whole process, but parameter of L decreased to the lowest at about 0230 BT. The ground temperature increased by 0. 4°C in an hour as a result of an amount of latent heat released by condensation growth of fog droplets. Dropping of temperature at the fog top and strengthening of the inversion demonstrate that radiation cooling can not be omitted. Heating at the fog base and cooling of fog top give rise to weakening of stability, which is advantageous to the vertical development. Therefore, the explosive development is the results of weakening of the stability of the fog layer and convergent rising of cold air coming downward from two mountains, and simulation demonstrates the maximum of ascending velocity is up to 10—15 cm s^{-1}.

3. *Mature Phase of the Fog Development*

After the development of fog body, it went into its mature phase (from 0500 to 0900 BT) when its top height experienced very small change of approximately 30 m —a phase of relative stationary and the fog layer located in the cold region and low specific humidity region. As seen from Fig. 8a, temperature displays moist adiabatic distribution in vertical with temperature inversion above the fog top. It can be seen from the different curves of temperature that radiation cooling still plays a main role because temperature decreases slowly at this period, and from Fig. 8b one observes that specific humidity decreases evenly as a function of height with humidity inversion above. From the perspective of time, specific humidity decreases slowly at the same rate as temperature, which demonstrates that the condensation consumes the moisture in the fog body. It must be pointed out that after sunrise (0730 BT) dropping of temperature happened from the base



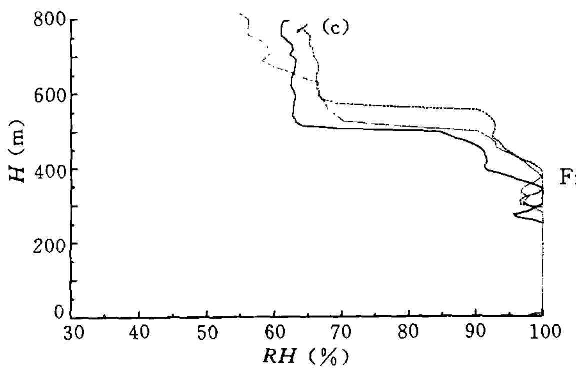


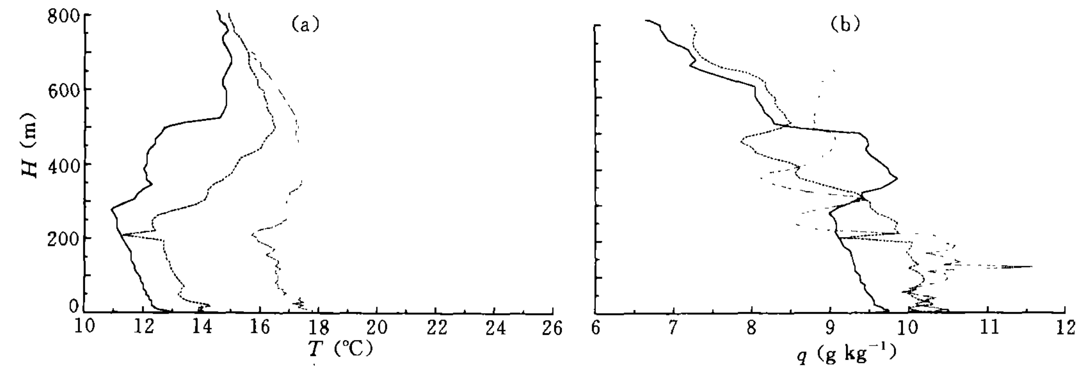
Fig. 8. Profiles of temperature (a), specific humidity (b) and relative humidity (c) at the mature stage (solid line — 05 h, dashed line — 07 h, dotted line — 09 h).

to top in the fog. This demonstrates that during this period the falling of temperature associated with long-wave exceeds the rising due to solar radiation, which is the leading cause of fog maintenance.

4. *Fog Dissipation*

The fog began to dissipate at 0900 BT in such a way that the fog at ground and upper levels attenuated before the top of the lower layer started to drop, changing to low clouds which completely disappeared roughly after 1100 BT. And solar radiation was the decisive factor of the dissipation, which caused rising of the temperature at ground and dissipation of fog. It should be noted that maximum increase in temperature occurred above the fog top, i.e., at 300—500 m level from 0900 to 1100 BT (Fig. 9a), which happened as solar radiation struck firstly the mountain slopes above the top layer, which were heated fast, leading to a valley-breeze circulation with the result that sinking motion happened above the fog top over the valley, producing adiabatic warming. As the sinking continued, the top was lowered. In Fig. 4, divergence field occurred in the low wind field, which is an example of the development of valley circulation.

Under the joint effect of sinking- and radiation-related heating, the dissipation process became fast and covered, in general, a matter of 2 h. After the dissipation of fog, the inversions of temperature and specific humidity had been destroyed, and vertical distributions of temperature, specific humidity and wind speed became even, followed by temperature decreasing with height about 1300 BT.



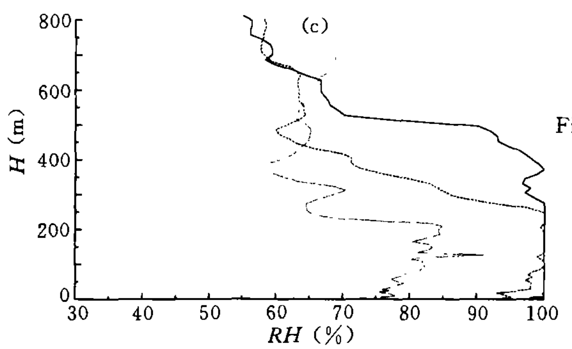


Fig. 9. Profiles of temperature (a), specific humidity (b) and relative humidity (c) at the dissipation stage (solid line — 09 h, dashed line — 11 h, dotted line — 12 h).

V. INFLUENCE OF VEGETATION ON FOG

Xishuangbanna is a state-level nature preservation region of China, where high quality natural forests cover about 77 percent of the area. The surroundings of the Mengyang observing site are mountains covered with natural forests.

Vegetation plays an important part in the formation and development of fog. As the heat capacity of canopy being small and evapotranspiration consuming large amount of heat of air, the minimum temperature of the canopy is lower than the bare soil. Low-level air humidity is high, because forests evaporate vapor into air through leaves, which are equal to evaporation of the same square of water (Zhou and Shu 1994). Forests make wind speed slow down evidently. All these are advantageous to the formation and development of radiation fog over the canopy.

It should be noted that fog is not very dense under the canopy and we found that the visibility ranges from 200 to 300 m and could drives along the road at the high mountain at moderate speed. In order to study this problem, profiles of temperature and humidity are enlarged and presented in Fig. 10, which gives the changes of temperature and humidity about the canopy. Before the formation of the fog, temperature closing to ground was high and the inversion base of temperature did not touch ground, but at 11 m height, i. e., starting from the canopy, and specific humidity was small under the canopy and increased rapidly with maximum within the inversion layer, which was the cause of fog occurring above the canopy but not the ground.

After the formation of fog, vertical distribution of temperature was not continuous in

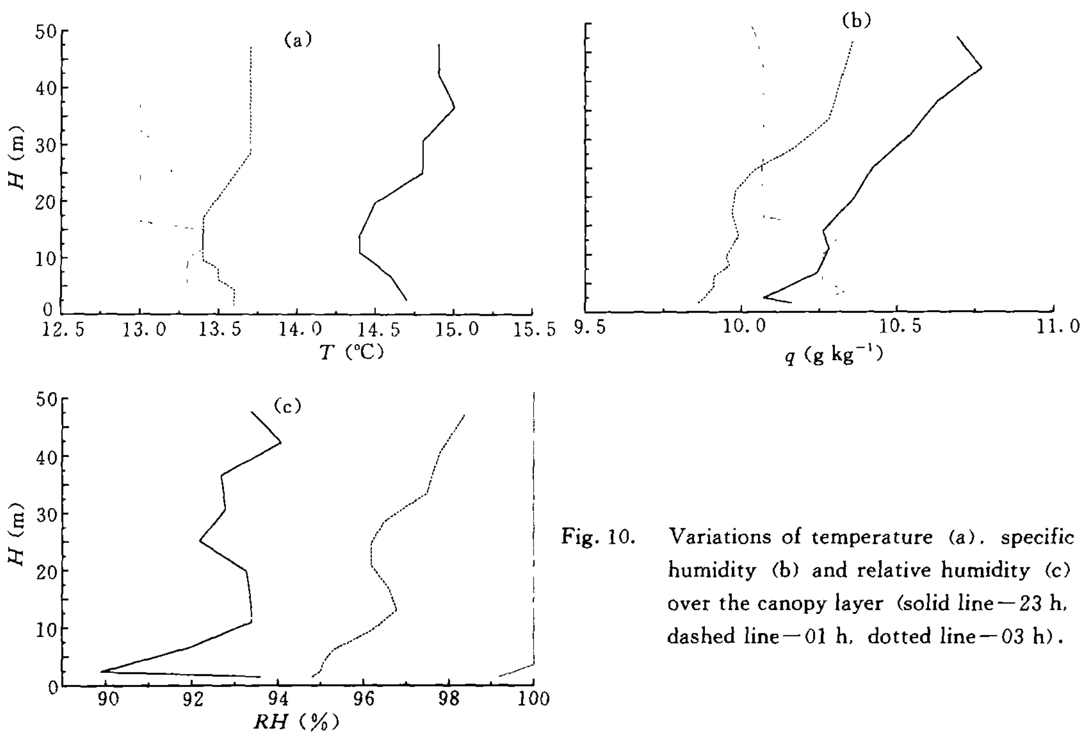


Fig. 10. Variations of temperature (a), specific humidity (b) and relative humidity (c) over the canopy layer (solid line—23 h, dashed line—01 h, dotted line—03 h).

the vicinity of the canopy, with high value of temperature and specific humidity under the canopy. High value of specific humidity is a result of low water content of condensation, which is the cause of good visibility in the forest, and high value of temperature is attributed to the covering of canopy and weakening radiation under forest. The evident weakening of wind speed is due to absorption of turbulent momentum flux by the canopy, which is not good for uptransport of heat from the forests, i. e., canopy acts as a greenhouse. Although cold air comes downward from the mountain, it is confined in the low and middle layers owing to the resisting of canopy.

Furthermore, another cause of high visibility under canopy is that dense leaves of forests can absorb fog droplets owing to the leaves being rough, hairy, grease and juice. Total area of leaves is 60—70 times higher than the area occupied by tree trunks (Zhou and Shu 1994), which results in strong absorption of droplets by leaves. A large number of suspended particles are decreased greatly by the filtering of tree, which results in decreasing of condensation nucleus and droplets under the forest.

VI. CONCLUSIONS

(1) Evolution of each fog event studied is similar, and it is forming at midnight and dissipating at 1100 BT in Xishuangbanna region.

(2) Fog occurs firstly at low-level and is marked by a double-layer structure which is kept till its dissipation.

(3) Shortly after touching surface, as main body, the low-level fog layer experiences explosive growth in vertical, which makes depth of the lower fog layer increasing suddenly

accompanied by lifting of the higher fog layer.

(4) Main contributing factors to fog genesis consist of radiation cooling, evapotranspiration of forest and downslope wind, while dominant elements leading to explosive development include release of latent heat, radiation cooling at fog top and mountain breeze circulation.

(5) The tropical rain forests play an important role in the formation and the development of fog.

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