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## On the Capture of Fog Particles by a Forest (I)

By Hirobumi ÔURA

The amounts of fog water entering and leaving the forest in a horizontal direction were measured by the use of vertical wire screens set in front of and in the rear of the forest, respectively, while that carried into the forest in a downward direction was determined by making use of a horizontal screen set above the tree crowns which was fitted with a mosquito curtain hung from its frame.

Three kinds of forests were compared with one another in respect of the capability of capturing fog particles. The most effective forest was found to be the one grown comparatively sparsely with needle-leaved trees having no lower branches. The forest next to this was thickly grown with needle-leaved trees with dense lower branches, and the last one was that which consisted of needle-leaved trees mixed with broad-leaved and whose density was intermediate between those of the other two.

It was further ascertained that the front surface of the forest was about three times as effective as the top surface.

### §1. Introduction

The capture of fog particles by the forest near the coast performs an important function in protecting the land against the invasion of sea fogs.

It has been pointed out by many observers that the amount of fog water caught by the forest is not at all negligible. Marloth [1] noted that the forest on the summit of *Table Mountain* near *Cape Town* grew luxuriantly without any rain but solely with fog, and using his instrument "Nebelfänger" (a rain gauge with a bundle of grasses which was enclosed with metal gauze and so arranged that the fog deposited on it would run into the gauge) he ascertained that the forest arrested a number of fog particles even when none was collected on the ground. Linke [2] called attention to the fact that a rain gauge put for one year in the forest of *Picea* at *Frankfurt on Main* indicated the amount of water about twice as much as in the

open, and used after *Süring* the term "horizontaler Niederschlag" for the precipitation caused by the presence of the forest. Similarly he observed, from four years' records at 2,500 ft elevation in the *Taunus* Mountains, where there are some 200 foggy days each year, that the rain gauge caught near the edge of the forest the amount of water averaging 157% of that in the open, and toward the interior 123%. The maxima were 300 and 260%, respectively. More recently, *Diekmann* [3] also emphasized, through his experience at Mt. *Brocken*, the importance of the precipitation of fog within the forest as the source of water in the district. (As to the work by *Rubner* [4], see "General Survey" written by *Yosida*.)

Now, in order to inquire into the fog-preventing function of a forest in the case of sea fogs, in which we are interested, we have tried to determine the amount of fog water captured by the forest by measuring the amount of fog entering the forest, on the one hand, and that leaving it, on the other hand, at the same time to see how the capturing function depends on the structure of the forest. It is to be assumed that at the windward margin of the forest there exist only fogs that enter the forest, since the windward component of turbulent motion of air does not exceed the mean wind velocity. At the leeward margin there exist, for the same reason, only fogs that escape from the forest. As regards the upper surface of the forest, we have to take into account both the inflow and outflow of fogs, because there comes the vertical component of turbulent motion into question.

Aside from the direct measurement, in which we were engaged and which we shall describe in detail below, the amounts of inflow and outflow at the margins can be determined, if the wind velocity and the fog water content in unit volume are known, while those at the upper surface can be calculated with the help of the expression

$$K \frac{\partial q}{\partial z} + \sum w_r f(r),$$

where

- $K$ : eddy diffusivity;  
 $\varphi$ : liquid water content of fog in unit volume of air;  
 $z$ : vertical coordinate directing upward;  
 $w_r$ : falling velocity of a particle with radius  $r$ ;  
 $f(r)$ : number of fog particles with radius  $r$  in unit volume of air.

The first term represents the turbulent diffusion and the second term the falling effect of fog particles. Accordingly, if we can obtain the amounts of  $K$ ,  $\varphi$ ,  $w$ , and  $f(r)$  experimentally, we shall be able to calculate the net amount of inflow through the upper surface of the forest. *Tabata* and others [5] carried out the measurement along this line, and their results were compared with those obtained from our direct measurement, a tolerable agreement having been found.

From our experiments it was also observed that the amount of captured fog was largely affected by the conditions of the forest such as thickness or kind of trees.

## §2. Experimental Method

**Principle of measurement:** Suppose that the forest is completely enclosed with an imaginary surface as shown by broken lines in Fig. 1. The turbulent air carries fog particles in or out through this surface. Thus the difference between the amount of fog water carried in ( $M$ ) and that carried out ( $N$ ) can be regarded as the amount caught by the forest. In front of the forest, where  $N=0$ , a rectangular wire screen (Fig. 2d) was set vertically and the fog particles caught by it were collected into a self-recording rain gauge. The amount of collected water is given by the product: (wind velocity)  $\times$  (liquid water content of fog)  $\times$  (area

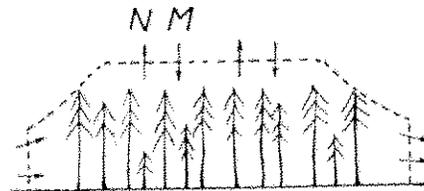


Fig. 1.

of the screen)  $\times$  (collecting efficiency of the screen). In order to estimate the effective height of the forest, the stream lines of wind were traced by the use of smoke or a small balloon with no buoyancy carried freely by the wind. The same sort of measurement was also made on the leeward side of the forest.

The values of  $M$  and  $M+N$ , from which the amount  $M-N$  entering the forest from above can be computed, were obtained in the following way. A pair of wire screens was placed horizontally above the forest, one for  $M+N$  and the other for  $M$ . The one for  $M+N$  was a single screen, which had no preference between upward and downward motions of turbulent air. The one for  $M$  was of such a construction that it kept the fog particles moving upwards from arriving at the screen; namely, it was fitted with a small ordinary mosquito curtain hung down from the frame holding the wire screen (Fig. 2c). The fog water collected by each of the screens was led separately to the self-recording gauges placed on the ground.

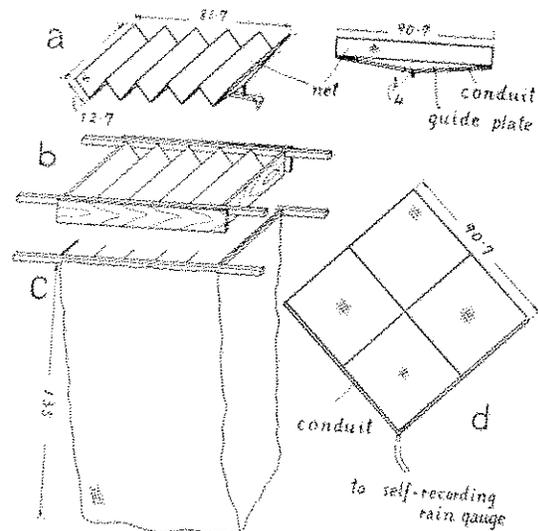


Fig. 2. Horizontal and vertical wire screens.

Posts of observations: Vertical screens were placed in front ( $A_1$ -point\*) and in the rear ( $B_1$ -point) of the forest at the heights of 3 m and 6 m (Figs. 3 and 4), and three pairs of horizontal screens were set at points  $X_1$ ,  $X_2$  and  $X_3$  above the tree crowns (Fig. 5). Another pair set at  $A_1$  in the open at the height of 2.5 m (Fig. 6) was intended for measuring the amount of fog particles captured by the ground surface.

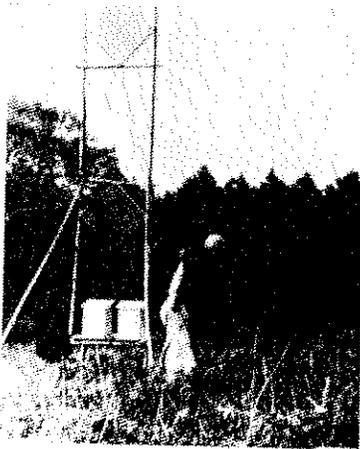


Fig. 3. Experiment by the use of balloon,  $A_1$ -point.

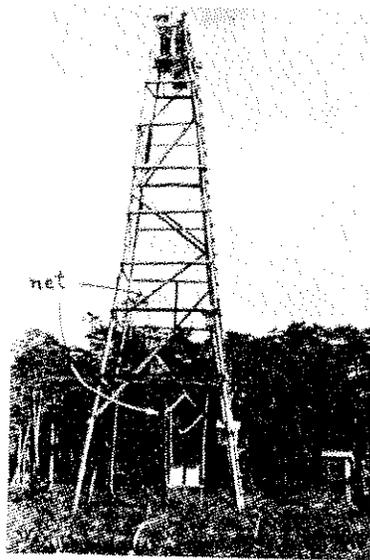


Fig. 4.  $B_1$ -point.

Nearly all the forest area was occupied by needle-leaved trees (*Picea Glehnii*) except in the neighborhood of  $X_1$ -point, where there were some broad-leaved trees (*Sorbus commixta* and *Betula Ermani*) mixed with the needle-leaved (*Abies sachalinensis*).

The forest around  $X_1$ -point was very thick (56 trees within a circle of radius 5 m, that is, 0.71 tree per 1 m<sup>2</sup>) and the trees from 5 to 9 m in height had many lower branches. The level at which the screens were placed was 8.6 m above the ground.

\* As to the designations ( $A_1$ ,  $B_1$ , ...) of the posts of observation, see "General Survey" written by Yosida.

Fig. 5. The screen at  $X_2$ .Fig. 6. A<sub>1</sub>-point.

The vicinity of  $X_2$  was sparsely wooded (58 trees within a circle of radius 10 m, or 0.18 tree per  $1m^2$ ) and the trees had no lower branches, their height being about 12 m. The screens were set at the height of 12.3 m. Around the point  $X_2$ , there were within a circle of 10m radius seventy needle-leaved and fifteen broad-leaved trees—0.27 tree per  $1m^2$ — and the height was 9~10 m. There were only few lower braches, but the broad-leaved trees spread their branches extensively at their crowns. The height of the screens was 9.7 m.

An idea of the features of the forest at each post of observation may be gained from Figs. 7, 8 and 9 (photo. by Matsui [6]).



Fig. 7.  $X_1$ -point.



Fig. 8.  $X_2$ -point.



Fig. 9.  $X_3$ -point.

**Apparatus:** We made our recording apparatus suitable for use in wet sea fogs, which frequently appear at the eastern seacoast of *Hokkaido*. Extremely good sensitivity was not needed, since it was only necessary to estimate the order of amount of the fog water captured by the forest.

All the screens were made of galvanized iron wire with gauze number 30 (about 0.29 mm) and meshes 25 per 3 cm. The size of the vertical screen was  $90.7 \times 90.7 \text{ cm}^2$  and it was set in such a manner that its diagonal line became vertical (see Fig. 2 d). There were two conduits along the lower sides of the rectangular net, and the fog water collected by them was led through a rubber tube to a self-recording rain gauge. The inside diameter of the rubber tube was 9 mm.

The horizontal screen was of zigzag form with five valleys, as shown in Fig. 2 (a, b, c), its effective area being  $90.7 \times 81.7 \text{ cm}^2$ . The angle of inclination of each constituent net to the horizontal plane was  $50^\circ$ . Once the screen was wetted, water drops scarcely fell out of it, inasmuch as the thickness of the wire, the number of meshes, and the angle of inclination of the constituent net had been so chosen as to prevent water from dropping out of the net. To the bottom of each valley a guide plate made of galvanized iron having the shape of obtuse-angled isosceles triangle was attached for guiding the water to a conduit placed just beneath the two equal sides of the guide plate. The water flowing out of each conduit was collected by means of an aqueduct set across under the conduits and was led to the self-recording rain gauge.

The cloth of the mosquito curtain to be hung from the frame of the screen was made of hemp yarn and had a length of about 135 cm and meshes of 25 per 3 cm.

Since the mean running distance of water drops slipping down the net is about 20 cm for the vertical and about 5 cm for the horizontal screen, the time lag resulting therefrom is rather trivial, as compared with the time interval in which the water drops grow to such an extent that they start slip-

ping down. This largely depends on the conditions of foggy wind; naturally, the thinner the fog, the larger is the time constant, the time required for the fog to saturate the screen. In the actual observation the time constant was sometimes found to be as long as several hours.

The capturing coefficient of the screen, defined as the ratio of the amount of fog water caught by the screen to that passing across the area covered by the screen, was determined experimentally by blowing known amount of artificial fogs against the screen completely wetted beforehand. It came out 0.40 for the wind velocity  $v=0.7$  m/sec, 0.45 for  $v=2\sim 3$  m/sec and 0.5 for  $v=5\sim 6$  m/sec. Since in most cases of our observation  $v$  was about 3 m/sec, we assumed as the capturing coefficient the value 0.45, apart from the corrections to be mentioned below. Here it is also assumed that the capturing coefficient is approximately independent of the direction of wind.

In the estimation of capturing coefficient, we must further take account of the fact that the stream lines of wind gradually spread out as they get near the screen, or, in other words, the flux of wind across unit effective area of the screen becomes smaller. We placed in the wind flow a square screen (with or without mosquito curtain), whose linear dimension was half that of the screen actually used in the field observation, and made the wind velocity twice as large as that most frequently observed in the field, namely 6 m/sec (according to *Reynolds'* law of similarity). The plane of the screen was made inclined to the wind direction at various angles (from  $20^\circ$  to  $90^\circ$ ). The stream lines were visualized by floating streamers of fine silk threads properly arrayed in the current of air. In this way, we found that the flux of wind across unit effective area was reduced, owing to the presence of the screen with (or without) curtain, to 0.67 (or 0.73),\* which is to be regarded as the correction factor for obtaining the true capturing coef-

\* The decreasing ratio of the flux of wind was found to be approximately independent of the inclination.

ficient. We get thus

0.33 for vertical screen,

0.33 for horizontal screen without curtain,

0.30 for horizontal screen with curtain.

Practically, we may well use the value  $1/3$  as the capturing coefficient for any kind of the screen.\*

Finally, it is to be remarked that, in spite of the large storage capacity of the screen and hence its large time constant in the actual observation, the evaporation of water while retained on the screen could be neglected, since our observation was made at midnight so that the foggy air was saturated with water vapor.

### § 3. Experimental Results

We knew by experience that the horizontal screens yielded from time to time, especially when the wind was strong, some intricate or even contradictory results, such that the amount of fog water  $M$  (entering the forest) came out less than the amount  $N$  (leaving the forest). This is, in all probability, due to the imperfection in the structure of our apparatus; namely, the guide plates attached to the bottom of the horizontal screen must have captured an excessive amount of fog particles when the mosquito curtain was absent. For this reason, and further in view of the fact that, aside from the above-mentioned exceptional cases, the amount  $N$  at  $X_1$ ,  $X_2$ , and  $X_3$  was in general negligibly small, we made use chiefly of the data obtained by the screen fitted with curtain. Expressed in other words, we assumed that the fog particles carried in from above the forest was completely captured by the forest.

In the interpretation of the data it was naturally of great importance to distinguish fog from rain. As the mark on the boundary between rain and fog, we take the radius of water

\* The maximum error inherent in the rain gauge was  $\pm 3$  g, which is equivalent to the error of  $\pm 10$  g/m<sup>2</sup> in the amount of captured fog water.

droplet  $r=0.09$  mm or the falling velocity  $w_r=1$  m/sec which corresponds to drizzle. Let the velocity of wind be denoted by  $v$  m/sec, then the ratio of the amount of water droplets passing through unit vertical area  $V$  to that passing through unit horizontal area  $H$  is equal to  $v/w_r$ , provided the droplet size is considered uniform. We thus discriminate, as a rough approximation, between rain and fog according to the relations

- $V/H < v (w_r > 1)$ : rain,
- $V/H \cong v (w_r \cong 1)$ : drizzle,
- $V/H > v (w_r < 1)$ : fog.

*Handwritten:*  $180 \mu$  rain

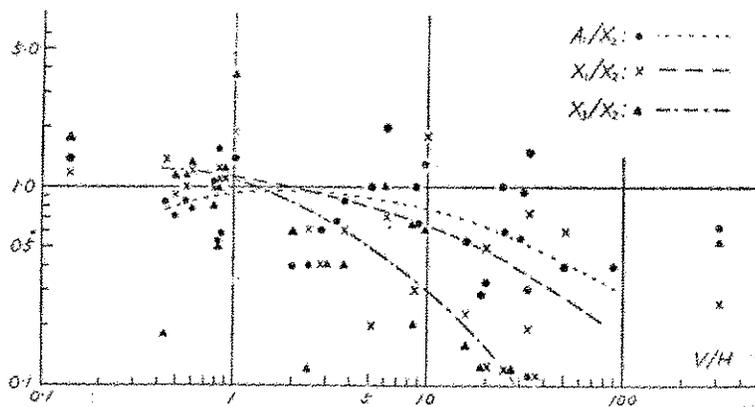


Fig. 10.

Putting together all the data obtained from a long series of measurements, we get the diagrammatic representation in Fig. 10. Here, the amounts of fog water entering the forest from above the crowns at  $X_1$ ,  $X_3$ , and  $X_0$  and that passing through the horizontal screen at  $A$ , downwards are plotted against  $V/H$ , the values at  $X_2$  being taken as unity throughout. The dots are so widely spread that it seems impossible to draw any significant conclusion. But, on careful inspection, it will be found that there is a general tendency that the amount of fog carried downwards (relative to the amount at  $X_2$ ) decreases with increasing  $V/H$ , and that the rate of decrease

varies in the order  $X_2 > A_1 > X_1 > X_3$ . (It must be noticed that the amount of fog water carried upwards at  $A_1$  has not been taken into account, so that the net amount carried downwards must be much smaller. This point will be discussed in detail in the following paper.) Excluding  $A_1$ , in which we are not interested for the moment, we get the order  $X_2 > X_1 > X_3$ , or, expressed in words, the forest grown comparatively sparsely with needle-leaved trees proved to be more effective in capturing fog particles than the forest thickly wooded, which in its turn was found to be more effective than the forest composed of needle- as well as broad-leaved trees with medium density. It must however be noted that careful and thoroughgoing examination is necessary before we can arrive at final conclusion as to the dependency of fog-capturing efficiency on the characteristics of the forest. We are planning on taking up 'microscopic' study of the forest in this respect.

The absolute amount of fog water carried into the forest from above the crowns ranged from scores to hundreds of  $\text{g}/\text{m}^2 \cdot \text{hour}$  for fogs with liquid water contents of several hundred  $\text{mg}/\text{m}^3$ . (In the region where  $V/H$  is less than unity the amount of captured fog water increases so rapidly that it exceeds sometimes  $1,000 \text{ g}/\text{m}^2 \cdot \text{hour}$ .) Some examples of actual data are given in Table 1. The observed values are in harmony with those derived from the measurements of  $K$  and  $dq/dz$  (see [5]). According to the theory of Fukutomi [7], on the other hand, we can roughly estimate the value of  $c/\varphi$  by assuming  $\gamma' = 0.005 \text{ m}^{-1}$  (the rate at which the fog water content above the forest diminishes in the leeward direction),  $s = 7.5 \text{ m}$  (thickness of turbulent layer), and  $v = 5 \text{ m}/\text{sec}$ :

$$c/\varphi = 5 \times 7.5 \times 0.005 = 0.2 (\text{g}/\text{m}^2 \cdot \text{sec}) = 0.7 \times 10^3 (\text{g}/\text{m}^2 \cdot \text{hour})$$

Thus we get the value that also accords with the above-mentioned value.

It may be worth noticing here that the evaluation of  $K$  out of the data of our own and those due to other research

TABLE 1.

- $c$ : Amount of fog water caught by the forest per unit area of its upper surface ( $g/m^2$ , hour);  
 $\varphi$ : Fog water content ( $g/m^3$ );  
 $c/\varphi$ : Amount of fog water to be captured for unit fog water content (m/hour);  
 $v$ : Mean wind velocity (m/sec).

Date	Hour	$X_1$		$X_2$		$X_3$		$V/H$
		$c/\varphi$	$v$	$c/\varphi$	$v$	$c/\varphi$	$v$	
June 22	5~6	$0.14 \times 10^3$	1.5	$0.2 \times 10^3$	2.5	—	—	33
	6~7	0.08 "	1.3	0.4 "	2.2	—	—	"
	7~8	0.08 "	—	0.6 "	2.6	—	—	"
June 25	0~1	0.05 "	1.2	0.56 "	4.8	$0.17 \times 10^3$	5.1	90
	1~2	—	—	0.29 "	4.0	0.18 "	4.8	9.7
	2~3	—	—	2.4 "	3.4	0.86 "	2.0	0.87
June 28	2~3	—	—	1.45 "	5.9	—	—	30
	3~4	—	—	1.99 "	5.6	0.10 "	3.3	19
	6~7	—	—	0.63 "	5.4	—	—	31
	7~8	—	—	0.41 "	4.8	—	—	24

workers concerned in the measurement of  $dq/dz$  always yielded the value of the order  $10^4$  cm<sup>2</sup>/sec.

Next we consider the question as to the amount of fog entering the forest at its front surface and that escaping the forest at its back surface. As can easily be figured out and also as the actual observation by the use of smoke or floating balloon revealed, the wind coming across the forest alters its course more or less to the upward direction, while the wind that has traveled over the tree crowns makes an abrupt turn to the downward direction at the rear edge of the forest. It was estimated that the fog particles are effectively carried into the forest and thereby captured when they have been carried by wind within the region up to 3 m above the ground before they come across the forest.

Supposing that the fog water content increases linearly with height and using the data obtained with the vertical screen set in front of the forest, we came to the finding that for the fog whose  $V/H$  was about 30 the effect of the frontal surface of the forest was equivalent to that of the upper surface of the forest with about 3 times as much depth as its height.

The same sort of consideration yielded the result that the amount of fog water escaping from the forest at its back surface was about one twentieth of that entering at the front.

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#### References

- [1] *Marloth* (introduced by *J. Hann*) (1906): Über die Wassermengen, welche Sträucher und Bäume aus treibendem Nebel und Wolken auffangen. *Met. Zeit.* 23, 547.
- [2] *Linke, F.* (1921): Niederschlagsmessung unter Bäumen. *Met. Zeit.* 33, 141; 38, 277.
- [3] *Diekmann, A.* (1938): Versuch zur Niederschlagsmessung aus treibendem Nebel. *Met. Zeit.* 48, 400.
- [4] *Rubner, K.* (1932): Der Nebelniederschlag im Wald und seine Messung. *Tharandter Forstl. Jahrb.* 83, 121.
- [5] *Huzioka, T., Tabata, T. and Matsumura, N.*: On the Distribution of Fog Water Contents in the Surroundings of a Forest; paper. (15).
- [6] *Matsumi, Z.* (1952): Notes on the Fog-Proof Coefficient of Forest near *Ochiishi* (in Japanese). *Studies on Fog-Preventing Forest II*, p. 301.
- [7] *Fukutomi, T.*: A Theoretical Study on the Changes of Liquid Water Contents of Intruding Stationary Sea Fogs Due to the Capturing Action of a Forest in the Coastal Region; paper (5).

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# STUDIES ON FOGS

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