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# On the Conditions for Occurrence of Steam Fog

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### Abstract

The conditions for occurrence of steam fog formed over a relatively warm sea surface in winter were studied observationally and theoretically. Based on the equation of turbulent diffusion for heat and water vapor, the conditions for occurrence of steam fog were studied numerically. As a result, it was shown that the difference between the air and sea surface temperature depends strongly on the relative humidity of a small airmass and slightly on the sea surface temperature. The calculated results are in good agreement with the observed conditions for occurrence of steam fog. The results also are compared with that of other worker.


## 1. Introduction

A modification of a small cold airmass which flowed out over Ishikari Bay from Ishikari plain was observed at Ishikari from 24th January to 6th February 1972, as reported in a previous paper.[1] By the observation, it was intended to measure the diffusion coefficient and vertical flux for heat, utilizing the three-dimensional distribution of steam fog over the sea and vertical distributions of air temperature, relative humidity and wind velocity over the land. Accordingly it was necessary to know the optimal conditions and favorable time for occurrence of steam fog.

Saunders[2] estimated the conditions for occurrence of steam fog theoretically, assuming that the diffusion coefficients for heat and water vapor were everywhere equal. But, he paid no attention to the ratio of mixing of two air masses in the estimation, in spite of the fact that his idea was identical to the mixing law for two air masses. Besides, he estimated the conditions for occurrence under neutral conditions, in spite of the fact that steam fog usually occurred under stable conditions. In this paper, the conditions for occurrence of steam fog will be estimated under stable conditions, based on the equations of turbulent diffusion for heat and water vapor. And the estimated conditions for occurrence will be compared with the meteorological condition when steam fog occurred.

## 2. Observation

Before the observation, the condition for occurrence was studied roughly using available data. Kikuchi[3] found the occurrence of steam fog over Ishikari Bay five times by photographic observation from the top of Mt. Teine (see Fig. 1) during the period of 27th January to 20th February 1964. Fig. 2 shows the relation between the occurrence of steam fog and minimum air temperature. Solid lines and arrow marks indicate minimum air temperature and wind direction at Ishikari, respectively. Solid circles on the solid line show the day when steam fog occurred and a dotted line shows the value of –16°C. It is seen that minimum air temperature is lower than about –16°C on the day when steam fog occurred. On the day, the wind direction is southerly, that is to say, the wind blows over the sea from the

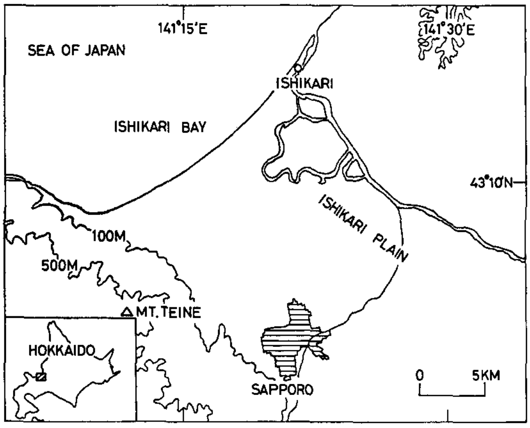


Fig. 1 Map of observation area.

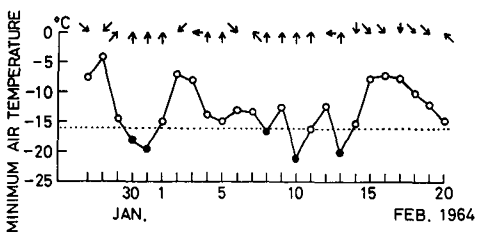


Fig. 2 Relation between the occurrence of steam fog and minimum air temperature. Solid circles, solid lines and arrow marks indicate the day of occurrence of steam fog, minimum air temperature and wind direction, respectively.

land. It is well-known that such a meteorological condition occurs often at Ishikari during the period of January to February.

During the observation period of 24th January to 6th February 1972 at Ishikari, steam fog occurred three times. Fig. 3 shows the appearance of steam fog at 0828, 24th January. It is seen that steam fog scarcely occurs at the right side and steam fog generally occurs at the left side, judging from black and white grade on the photograph. The occurrence or non occurrence of steam fog and meteorological variables at 0700 hours when the occurrence or non occurrence of steam fog can be found with the naked eye after dawn are summarized in Table 1. It is seen that air temperature is lower than −11°C on 24th January, 27th January and 5th February when steam fog occurred, and steam fog did not occur on the day when air temperature is higher than −11°C. On the day of occurrence, the wind direction is southerly, that is to say, the wind blows over the sea from the land.

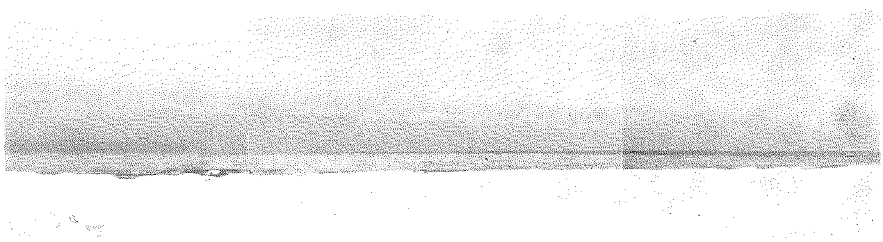

Fig. 3 Steam fog at Ishikari shore, 0828 24th January 1972.

Table 1. Meteorological variables for 0700 hours during observation period.

| DATE | AIR TEMPERATURE | RELATIVE HUMIDITY | WIND DIRECTION | WIND SPEED | CHARACTER OF STEAM FOG |
|---|---|---|---|---|---|
| 24 JAN. | −12.9 °C | 69 % | SE | 3 M/S | DENSE |
| 25 | − 2.1 | | ENE | 3 | NONE |
| 26 | − 7.0 | 81 | NNE | 10 | NONE |
| 27 | −11.6 | 79 | SE | 3 | MODERATE |
| 28 | − 5.2 | | WNW | 14 | NONE |
| 29 | − 7.5 | | W | 11 | NONE |
| 30 | − 5.1 | 94 | | | NONE |
| 31 | − 5.5 | 82 | | | NONE |
| 1 FEB. | −10.4 | 74 | E | 2 | NONE |
| 2 | − 9.1 | 98 | ESE | 7 | NONE |
| 3 | − 7.0 | 72 | WNW | 16 | NONE |
| 4 | − 6.1 | 87 | NNE | 2 | NONE |
| 5 | −11.3 | 84 | S | 3 | MODERATE |
| 6 | −10.6 | 83 | SE | 3 | NONE |

It is found out that threshold of minimum air temperature for occurrence of steam fog in 1964 does not agree with that of air temperature in 1972. This may be due to fact that it is difficult to observe small-scale steam fog over Ishikari Bay from the top of Mt. Teine which is far from Ishikari Bay and the time of observation of steam fog does not always agree with that of occurrence of minimum air temperature of the day. Besides, it is considered that the condition for occurrence depends also on the relative humidity of air mass and sea surface temperature in addition to air temperature of air mass, and that their effects are fairly large. These effects will be discussed in next section.

## 3. A condition for onset of steaming

A small cold airmass flows over a warm sea from the cold land and is modified by the supply of heat and water vapor from the warm sea surface. If the mixing ratio in the air mass is more than the saturation mixing ratio corresponding to the temperature at a point, the water vapor in the air mass condenses and steaming takes place. If we assume a steady state of air flowing with a constant speed $u$ along the $x$-axis and a constant diffusion coefficient $K$ for heat everywhere, the following equation is obtained,

$$u\frac{\partial\theta}{\partial x}=K\frac{\partial^2\theta}{\partial z^2}, \tag{1}$$

where $\theta$ is the potential temperature and $z$ is the vertical coordinate. If the diffusion coefficients for heat and water vapor are assumed to be equal, the following equation is obtained,

$$u\frac{\partial r}{\partial x}=K\frac{\partial^2 r}{\partial z^2}, \tag{2}$$

where $r$ is the mixing ratio.

Initial and boundary conditions were determined by the use of observational values at 0839, 24th January 1972 when steam fog occurred. The vertical distributions of potential temperature and mixing ratio on that day are shown in Fig. 4. It is seen that both vertical distributions increase with height and each have a constant vertical gradient in the layer lower than 180 m. So both vertical distributions are written as follows, respectively.

$$\theta=260.5+0.035z \quad \text{for} \quad z\geqq 0, \quad x=0. \tag{3}$$

$$r=1.05+0.0064z \quad \text{for} \quad z\geqq 0, \quad x=0. \tag{4}$$

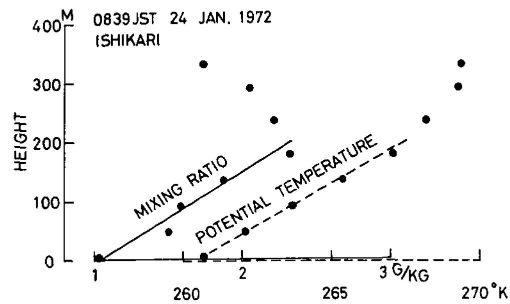


Fig. 4 Vertical distributions of potential temperature and mixing ratio at Ishikari, 0839 24th January 1972.

Equations (3) and (4) can be adopted as initial conditions, because the calculation is carried out in the layer lower than 100 m. The sea surface temperature was measured as constant along $x$-axis by observation, thus potential temperature 273.4°K corresponding to observed sea surface temperature +2.5°C and saturation mixing ratio 4.36 g/kg over sea surface (salinity 35‰) corresponding to the temperature were adopted as boundary conditions. That is,

$$\theta = 273.4 \qquad \text{for} \quad z = 0, \quad x > 0, \tag{5}$$

$$r = 4.36 \qquad \text{for} \quad z = 0, \quad x > 0. \tag{6}$$

Equations (1) and (2) have been solved analytically under the above-mentioned initial and boundary conditions (e.g. Taylor[5]), and the solutions are as follows,

$$\theta = 260.5 + 0.035z + 2.9\left\{1 - E\left(\frac{z}{2}\sqrt{\frac{u}{Kx}}\right)\right\}, \tag{7}$$

$$r = 1.05 + 0.0064z + 3.31\left\{1 - E\left(\frac{z}{2}\sqrt{\frac{u}{Kx}}\right)\right\}, \tag{8}$$

where $E$ represents the error function, that is,

$$E(a) = \frac{2}{\sqrt{\pi}}\int_0^a e^{-t^2}\,dt. \tag{9}$$

An example of the calculated results is shown in Figs. 5 and 6. Fig. 5 shows the change of vertical distributions of potential temperature and mixing ratio with downwind distance under the wind velocity 3 m/sec, based on the observation. In this calculation, diffusion coefficient $K$ was

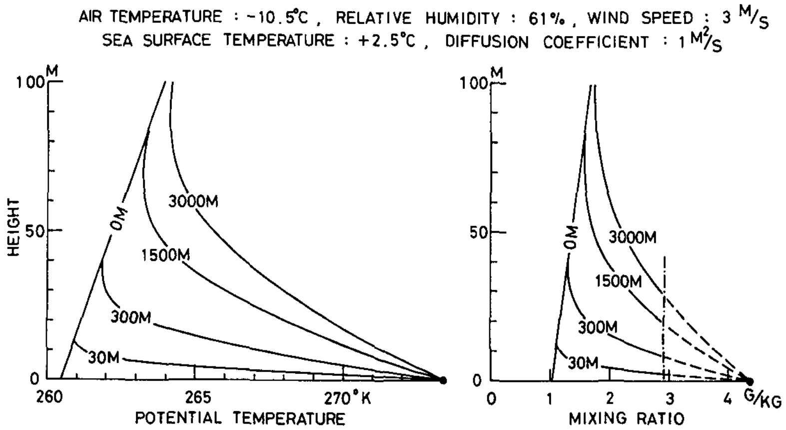


Fig. 5 Change of vertical distributions of potential temperature and mixing ratio with downwind distance. Meteorological variables are indicated in figure.

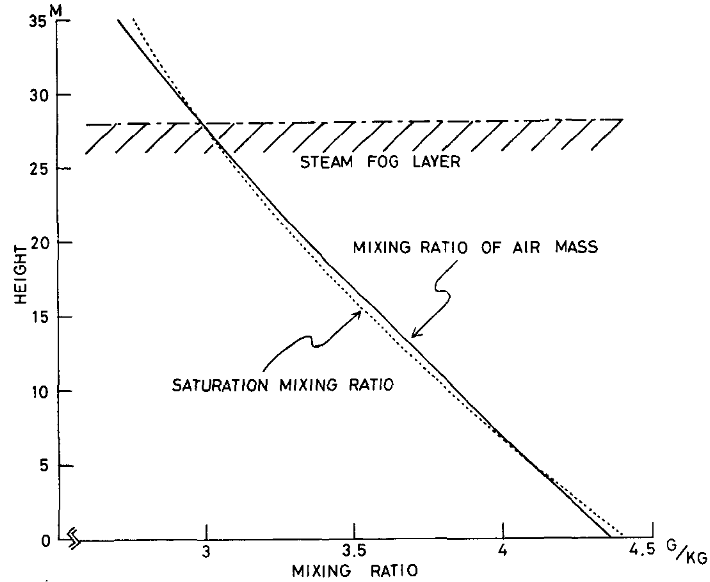


Fig. 6 An example of steam fog layer.

assumed to be 1 $m^2$/sec. The left figure shows the change of vertical distributions of potential temperature with a downwind distance from the shore and solid lines show the vertical distributions at downwind distances of 0, 30, 300, 1500 and 3000 m, respectively. It is seen that air mass is heated from the lower boundary to higher layer in the order of downwind distance.

The right figure shows the change of vertical distributions of mixing ratio with the downwind distance. It is seen that air mass is also moistened from the lower boundary to higher layer in the order of downwind distance.

In order to examine whether the air mass at a point is supersaturated or subsaturated, the vertical distribution of mixing ratio at downwind distance of 3000 m and saturation mixing ratio corresponding to air temperature at the height are shown in Fig. 6 by a solid line and a dotted line, respectively. It is seen that the value of mixing ratio in the air mass exceeds saturation mixing ratio in the layer lower than 28 m. This shows that the air mass is supersaturated, that is to say, steam fog is formed in the layer. Such a steam fog layer is indicated by the part of broken lines in the right figure of Fig. 5. Under this meteorological condition, the occurrence of steam fog is in good agreement with observational fact. It is seen that the height of the top of steam fog layer increases with downwind distance.

In a previous calculation, the diffusion coefficient was assumed to be 1 $m^2$/sec, thus it must be examined whether the condition for occurrence of steam fog depends on diffusion coefficient. Fig. 7 shows the changes of height of steam fog layer with the downwind distance corresponding to the diffusion coefficients of 0.1, 1 and 10 $m^2$/sec. The ordinate and abscissa show the height and downwind distance, respectively. The solid lines indicate the height of steam fog layer. In all cases, the threshold air temperature may be –10°C, because steam fog occurs at air temperatures below –10.5°C and does not occur at air temperatures above –9.5°C. That is to say, it is considered that the value of diffusion coefficient does not affect the condition for occurrence of steam fog. Hence, the value of 1 $m^2$/sec will be adopted as diffusion coefficient for calculations in the future.

As the sea surface temperature changed from +1.0°C to +4.0°C during the observation period, whether the sea surface temperature affects the condition for occurrence of steam fog must be examined. Fig. 8 shows the results of calculations under conditions of sea surface temperature of +1.0, +2.5 and +4.0°C by the same manner as taken in Fig. 7. It is seen that the condition for occurrence of steam fog changes from –10.0°C to –9.0°C when the sea surface temperature changes from +2.5°C to +4.0°C. It is considered that the sea surface temperature affects the condition for occurrence slightly.

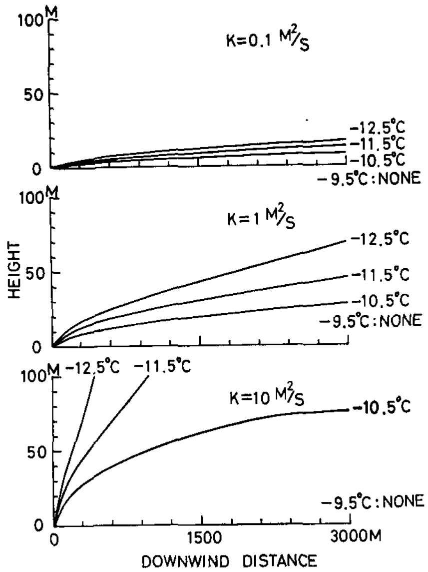


Fig. 7 Relation between diffusion coefficient and the condition for occurrence of steam fog.

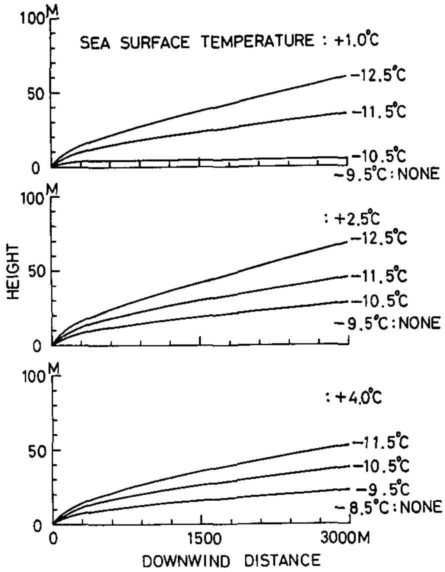


Fig. 8 Relation between sea surface temperature and the condition for occurrence of steam fog.

The effect with which the air temperature and relative humidity of a small airmass and sea surface temperature affect the conditions for occurrence of steam fog is summarized in the next. Fig. 9 shows the results of the calculations in which each parameter is changed over a wide range. The ordinate and abscissa show the difference between air and sea surface temperature and sea surface temperature, respectively. The calculated values are threshold values in the stense that seam fog occurs if air mass is colder or has higher relative humidity than the shown values. It is seen that the difference between air and sea surface temperature depends strongly on the relative humidity of a small airmass and slightly on the sea surface temperature.

The calculated values is about 4°C greater than Saunders' result[2] on an average. This may be explained by the fact that Saunders paid no attention to the ratio of mixing of two air masses in his estimation, in spite of the fact that his idea was identical to the mixing law for two air masses. This is based on the reason that in order that mixed air mass be saturated the air mass must exceed his condition and besides the ratio of mixing must exceed a critical value.

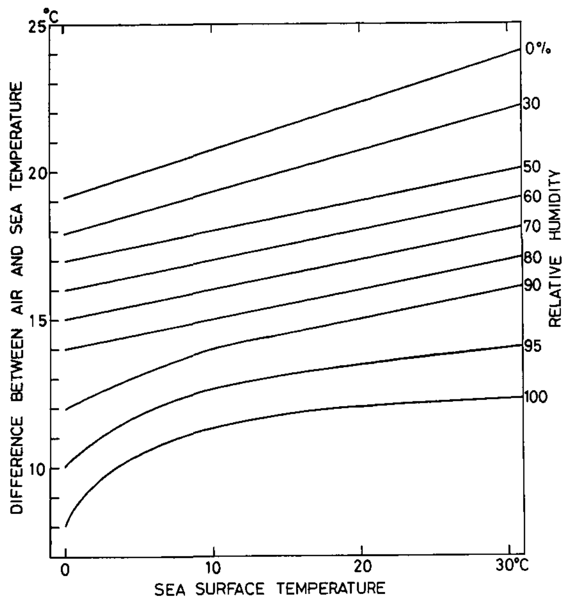


Fig. 9 Conditions for occurrence of steam fog over sea surface (salinity 35‰).

## 4. Consideration

The estimation in a previous section was tested as follows. Fig. 10 shows the relation between calculated values and observed values. The abscissa and ordinate show the air temperature and the difference between air temperatures and threshold air temperatures determined from the relative humidity of air mass and sea surface temperature, respectively. The solid and open circles in the figure correspond to the observed values in Table 1 and show the occasions when the steam fog and non steam fog occur, respectively. As the ordinate shows the difference between the air temperature and threshold air temperature, the open circles and solid circles should be plotted above and below the broken line, respectively. It is seen in Fig. 10 that each value is plotted according to the rule except for two values. Accordingly it may be considered that the estimation in the previous section is right.

Previous calculations were carried out under stable conditions in which the vertical gradients of potential temperature and mixing ratio are 0.035°K/m and 0.0064 g/kg·m as seen in equations (3) and (4). In order to examine whether the stability of atmosphere affects the condition for occurrence of steam fog,

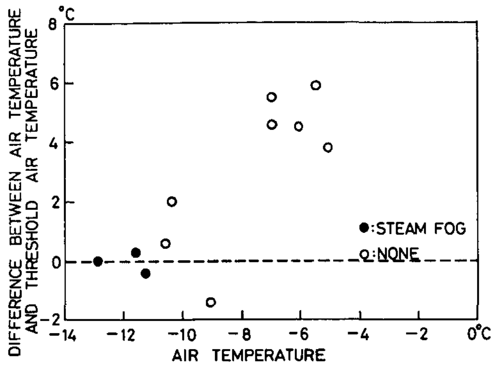


Fig. 10 Relation between calculated values and observed values.

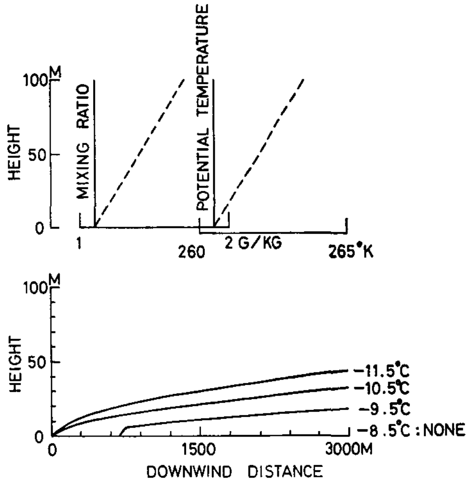


Fig. 11 Condition for occurrence of steam fog under neutral conditions.

the following calculation was carried out under neutral conditions. The initial condition and calculated result are shown in Fig. 11. In the upper part, solid and broken lines indicate the vertical distributions of potential temperature and mixing ratio under neutral conditions and stable conditions, respectively. The other meteorological conditions are the same as the condition of the middle part in Fig. 7. The result calculated under the condition represented by broken lines is shown in the middle part of Fig. 7. In the figure, it is seen that the condition for occurrence is $-10°C$. The result calculated under the condition represented by solid lines is shown in the lower part of Fig. 11. In this case, the condition for occurrence is −9°C. Accordingly it may be considered that the threshold air temperature under neutral conditions is higher than that under stable conditions. It follows that Saunders' estimation[2] is higher than that in this paper. As steam fog occurs when the atmosphere is in a stable condition, it is considered that the estimation under the stable condition is applicable to natural steam fog.

## 5. Conclusion

In winter, a small cold airmass flows over the warm sea from cold land and is modified by the supply of heat and water vapor from warm sea surface. If the mixing ratio in the air mass is more than the saturation mixing ratio corresponding to the temperature at a point, the water vapor in the air mass condenses and steam fog is formed. Based on the equation of turbulent diffusion for heat and water vapor, the condition for occurrence of steam fog was studied numerically. As a result, it was shown that the difference between air and sea surface temperature depends on the relative humidity of a small airmass strongly and on the sea surface temperature slightly. The calculated result was in good agreement with the observed condition for occurrence of steam fog.

Saunders' results[2] were about 4°C less than the value calculated in this paper on an average. This may be explained by the fact that he paid no attention to the ratio of mixing of two air masses in the estimation, in spite of the fact that his idea was identical to the mixing low for two air masses, and that he estimated the condition for occurrence under neutral conditions, in spite of the fact that steam fog occurred usually under stable conditions.

In this paper, it was regarded that the steam fog occurs when the mixing ratio in the air mass exceeds the saturation mixing ratio. But, a certain minimum liquid water content must be condensed out in order for the steam fog to be observed by naked eye. In the future, attention should be paid to this problem.

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