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# Salt Particles and Haze in the Indian Monsoon Air*

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ABSTRACT. During the International Indian Ocean Expedition, an extensive series of time-lapse motion pictures of clouds was taken from aircraft over the Arabian Sea. An unusual feature revealed by these pictures is the occurrence, during the monsoon season, of cumulus clouds immersed in a dense haze, which frequently cut down the visibility to less than 10 km. In this paper, an attempt is made to explain the occurrence of the haze, over the eastern portions of the Arabian Sea, in terms of condensation of water vapour on sea-salt particles.

## 1. Introduction

During the International Indian Ocean Expedition, the Woods Hole Oceanographic Institution flew an instrumented aircraft over the Indian Ocean and the Arabian Sea during the three periods (*i*) early southwest monsoon season 1963, (*ii*) northeast monsoon 1964 and (*iii*) middle and late southwest monsoon 1964. These flights were generally made at a height below 4 km above sea level. Besides making measurements of various meteorological variables, time-lapse motion pictures of clouds were taken from the aircraft. The pictures taken during the southwest monsoon season showed the rather unusual feature that cumulus clouds often occurred embedded in a general dense haze which frequently cut down the visibility to less than 10 km. The presence of a dense haze layer over India, during the premonsoon months, March to June, has been noted in the literature (Trewartha 1961). Bryson, Wilson and Kuhn (1964) observed a dense haze layer extending from Libya to Burma as an almost unbroken layer during the month of April in 1962 and 1963. The top of the haze layer varied from 5 to 10 km in altitude above sea-level, the maximum height being attained over the Rajasthan desert. This haze was apparently a result of the dust mixed up by the hot, unstable, dry continental air. The observations of haze during the southwest monsoon season over the Arabian Sea, reported here, do not, however, appear to admit of such an explanation, since the air in question had a trajectory of considerable length over the ocean away from sources of pollution. In this note it is shown that, over the eastern portions of the ocean, there is a strong association between the occurrence of haze and high relative humidity, and that the transition from a non-hazy to hazy condition takes place near the phase-transition point for salt, namely, near a relative humidity of about 80 per cent. On this basis it is suggested that the haze is due to the condensation of water vapour on sea-salt particles.

## 2. Haze and relative humidity

The haze was generally absent in the very lowest layers extending from the sea surface to an altitude of a few hundred metres as shown by photographic shots taken from the aircraft at low levels, and by reports of excellent visibility received from ships in the area. When the airplane climbed to higher levels, the atmosphere was often found to be hazy. This is shown by Fig. 1, which gives two pairs of pictures taken within a few minutes of each other on 16 (Fig. 1a) and 18 August 1964 (Fig. 1b).

The incidence of and increase in haziness with ascent on these days was associated with an increase in relative humidity wth increasing altitude above sea-level. Fig. 2 shows the profiles of relative humidity on these two days as deduced from measurements made from the aircraft. The altitudes at which the photographs of Fig. 1 were taken are indicated by the arrows. On 16 August, the relative humidity at the lower level (no haze) was 74 per cent while that at the upper level (hazy) was 81 per cent. On 18 August, the relative humidity at the lower level (no haze) was 77 per cent, while that at the upper level (hazy) was 82 per cent. It was, therefore, at a relative humidity near 80 per cent that the transition from a condition of no haze to one of haziness took place. Incidentally, it may be remarked that the increase of relative humidity with height in the lowest layers of the atmosphere is what is to be expected in a well-mixed layer.

Variations in haziness were encountered not only in the vertical but also in the horizontal. The variations in the horizontal also appeared to be associated with corresponding variations in the relative humidity. To illustrate this point and in order to better demonstrate the transition from no-haze to haze conditions with increasing relative humidity, data for three flights (30 June 1963, 20 August 1964 and 28 August 1964), amounting

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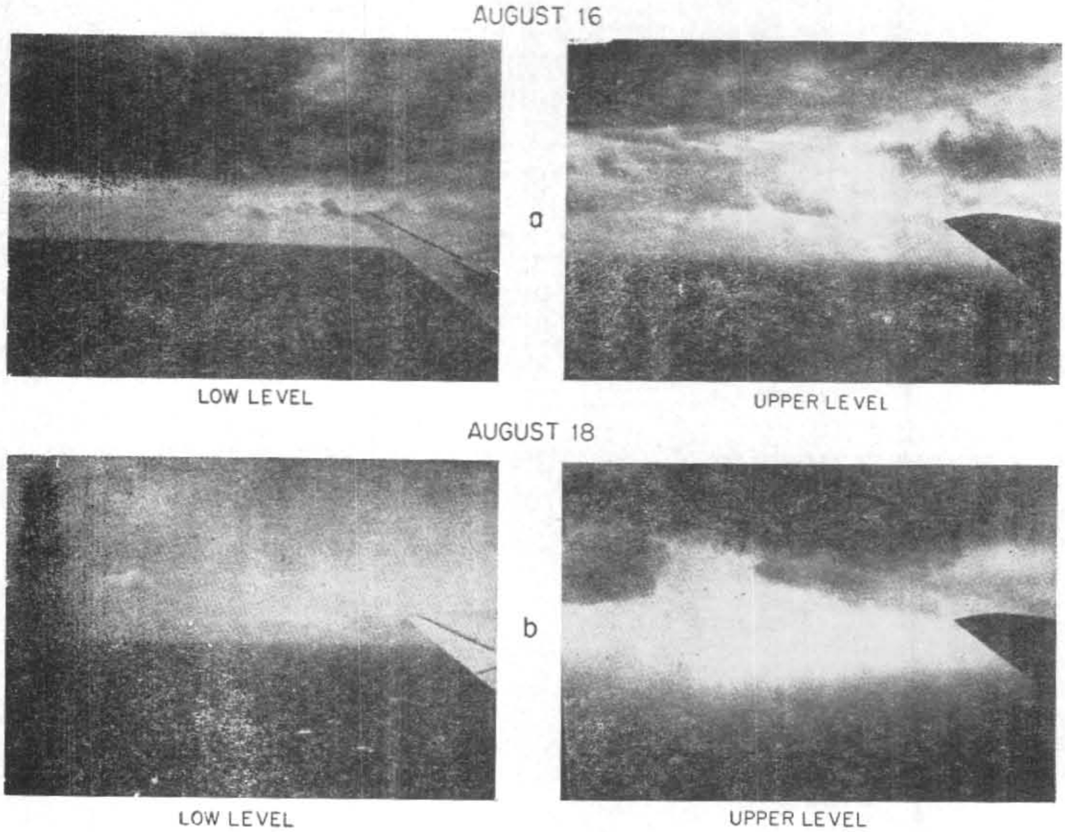


**Fig. 1.** (a) — upper — Shows no haze at a low level, about 100 m a.s.l., (left photograph), and haze at a higher level, about 400 m a.s.l., (right photograph), on 16 August 1964
(b) — lower — Similar to (a). The left photograph was taken at a height of about 100 m, and the right photograph at a height of about 270 m, on 18 August 1964

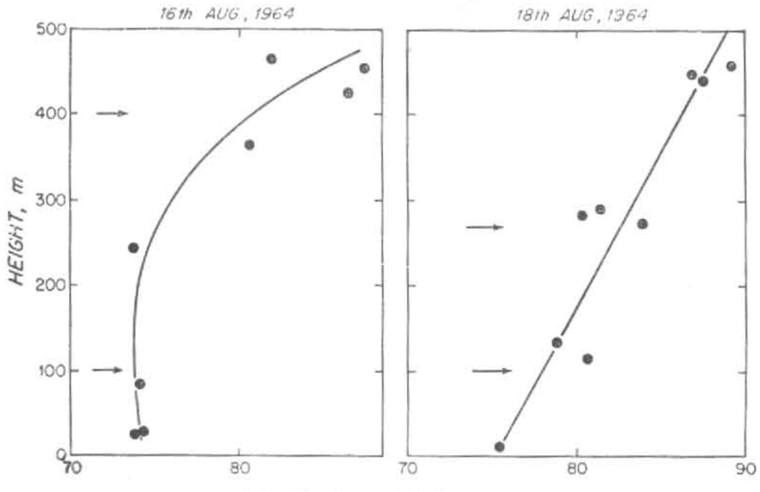


**Fig. 2. Profiles of relative humidity on 16th (left) and 18th (right) August 1964**
The arrows indicate the heights at which the photographs of Fig. 1 were taken

to a total of nineteen flight hours, have been assembled in Fig. 3. The tracks of the three flights are shown at the top of the figure. The circles and crosses on the graphs were obtained as follows — The entire duration of each flight was divided into hazy and non-hazy sections with the help of the time-lapse pictures. For the purposes of this division, segments of the flights during which rain was observed, or the plane was passing in and out of clouds were omitted from consideration. The average duration of a section was of the order of 15 minutes (about 70 km). For each section the average relative humidity was deduced from the psychrograph records obtained during the

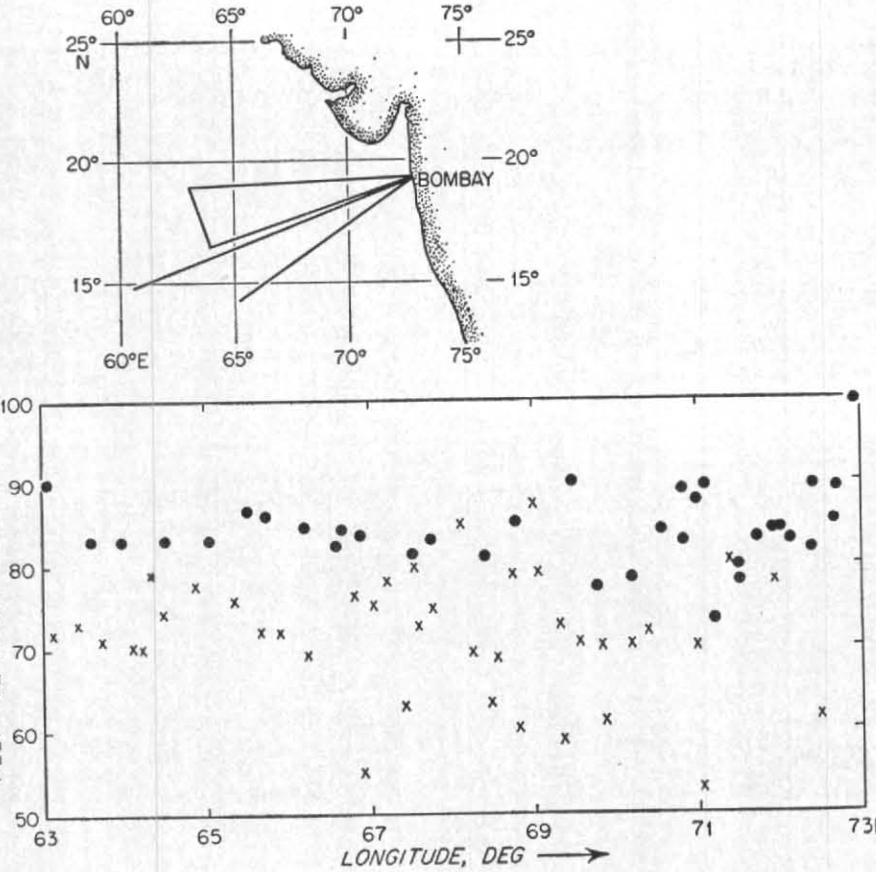


**Fig. 3. The upper portion shows the tracks of the three flights for which average relative humidity is plotted against average longitude in the lower diagram**

The full circles denote hazy conditions, while the crosses indicate the absence of haze

flight. The mean relative humidity has been plotted against the mean longitude of each section, the hazy and non-hazy segments being distinguished by circles and crosses respectively. It is seen that there is a sharp transition from a no-haze to hazy condition at a relative humidity of about 80 per cent. This strongly suggests that the haze is due to the condensation of water vapour on sea-salt particles. In this connection it is interesting to recall the investigations of Wright (1940) based on visibility records for Valentia for a period of five years. Wright found that the opacity of the atmosphere at Valentia depended on the relative humidity when the humidity exceeded 70 per cent, but was independent of it when the humidity was below 70 per cent. He interpreted this to mean that at high humidities, the nuclei were drops of sea-salt solution which increased in radius with increasing humidity, but at humidities below 70 per cent, the droplets crystallized and remained constant in radius.

It should be mentioned that the strong association between high relative humidity and haze shown by Fig. 3 was not found to hold over the north-western portions of the Arabian Sea, where haze was found even though the relative humidity was 50 per cent or even less. The reason for the haze over this part of the Arabian Sea appears to be the same as that for the haze over India during the pre-monsoon months.

### 3. Salt particles, haze and visibility

The rather sharp transition to hazy conditions at a relative humidity of about 80 per cent, shown by Figs. 2 and 3, encouraged us to attempt a quantitative test of the suggestion that the haze is formed by the condensation of water vapour on sea-salt particles. For this purpose, visibilities were estimated from the time-lapse pictures and compared with computed visibilities.

The visibility was estimated from the time-lapse pictures in the following way– The dimensions of a cloud and its distance from the aeroplane were measured by the method described by Ronne (1959) and Bunker (1965). The visibility was taken to be the distance of a cloud which was barely visible in the haze. The visibilities deduced in this way vary from about 5 to over 20 km.

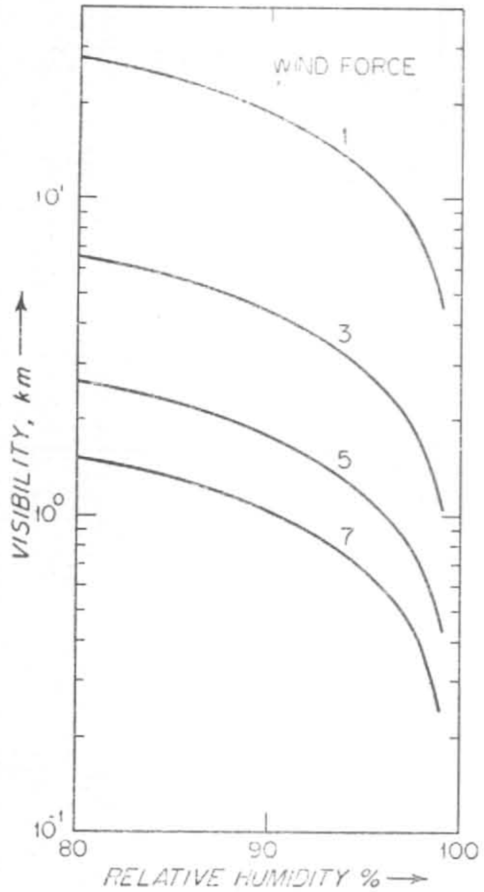


**Fig. 4. Visibility as a function of relative humidity and wind force**

The visibility has been calculated as follows — The sea-salt particle distributions measured by Woodcock (1953) at cloud base level in the vicinity of Hawaii, under various wind conditions, were assumed to be representative of the Arabian Sea region also, since adequate data on sea-salt particles are not available for this area. The size distribution of the haze drops formed by condensation of water vapour on the sea-salt particles was computed using the following equation given by Keith and Arons (1954),

$$r = m^{\frac{1}{3}} \left( \frac{0 \cdot 146}{1 - H} \right)^{0 \cdot 299},$$

which gives the radius $r$ of the solution drop formed on a sea-salt particle of mass $m$, in equilibrium with an atmosphere of relative humidity $H$. From the computed haze-drop size distributions, the visibility, $V$, was obtained by means of the following equation given by aufm Kampe and Weikmann (1952) —

$$V = \frac{2 \cdot 6}{W} \frac{\Sigma n_i \, r_i^{\,3}}{\Sigma n_i \, r_i^{\,2}},$$

where, $n_i$ is the concentration of drops of radius $r_i$, and $W$ is the water content of the haze drops. The visibilities so obtained are shown in Fig. 4 as a function of the prevailing relative humidity and wind force. It is seen from this figure that with relative humidity varying between 80 and 90 per cent and the wind varying between force 1 and 5 — conditions which may be taken as representative of occasions on which haze was observed — the computed visibilities lie between about 2 and 27 km. This range of values is in rather good agreement with the range of visibilities estimated from the time-lapse motion pictures.

**4. Conclusion**

From the evidence presented in the last two sections, we may conclude that the haze observed over the eastern portions of the Arabian Sea during the southwest monsoon season may be explained in terms of condensation of water vapour on sea-salt particles.

**5. Acknowledgements**

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