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FOG PRECIPITATION MEASUREMENTS ON AFRICA'S SOUTHWEST COAST

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ABSTRACT Precipitation amounts from radiation and advection fogs at Swakopmund and from rain and fair weather clouds on Table Mountain, as well as from a mountain saddle near Stellenbosch are studied. For the evaluation of fog precipitation during rainfall a special formula was developed in which account is taken of both the rainfall and wind speed. It is found that in certain places the contribution from fog precipitation to the water supply can be much larger than from rainfall.

1. INTRODUCTION

Deposits of cloud or fog droplets, commonly named "Fog precipitation", contribute substantially to the water supply in many parts of the world, especially on mountains. Marloth (1904, 1907) noticed that an amount of water is deposited from the "Table Cloth" on the vegetation of Table Mountain at Cape Town. He exposed two raingauges on this mountain plateau, one covered with a bundle of reeds and the other open on top. After the occurrence of cloud on the plateau in the absence of rain he observed a considerable amount of water in the first instrument, while the ordinary raingauge only collected a negligible quantity. As cloud and fog droplets have a very low fall speed, they move practically with the air and can therefore only enter a raingauge through eddy motion. Evidently, the amount of fog precipitation is directly proportional to the liquid water content of the air and also to the wind speed. For example, while the wind facing side of a forest can collect a large amount of fog droplets, the wind speed is rather low within the forest but the top foliage still catches a large number of cloud droplets. The deposited droplets will increase in size by coalescence with newly arriving droplets and will eventually either drop from the leaves or trickle down the twigs and trunks.

Many efforts have been made by various investigators to measure fog precipitation. Dieckmann (1931) used a gauze cylinder mounted over a raingauge. With this arrangement, called a fog catcher, the measurement is independent of the wind direction. The object of the gauze cylinder is to replace or simulate vegetation, and the measurements made with such a fog catcher refer to species of plants which would collect amounts of water corresponding to those of the instrument. Grunow (1952) followed Dieckmann's principle and made the height of the gauze cylinder equal to twice its diameter and so that the effective area (height x diameter) was equal to the catching area of the raingauge. This enabled him to compare fog precipitation and rainfall amounts. However, while raingauges measure the rainfall more or less accurately (generally with a negative error), a gauze cylinder can only catch a certain percentage of the cloud droplets passing through an equal area in the free air. The deficiency is due to the fact that the wind speed is reduced by the cylinder and by the deflection of the air around and over it, and also because drops are blown off the sides of the gauze cylinder in strong winds. Nagel (1956), following Grunow's method, estimated that this deficiency is 25% in light winds and more than this percentage in strong winds. Owing to the uncertainty introduced by this factor no allowance was made for it.

In order to ascertain whether a station is within cloud, or otherwise, in any particular case a hygrograph is required. Therefore the equipment necessary for the measurement of fog precipitation should consist of the following four instruments:

(i) an automatic raingauge,
(ii) an automatic fog catcher,
(iii) a recording anemometer (giving wind speed only) and
(iv) a hygrograph.

Fog precipitation was measured during 1954 and 1955 near the western end of the Table Mountain plateau (Nagel 1956). Continuous measurement of this element at Table Mountain House ($\phi = 33^{\circ}59'S$, $\lambda = 18^{\circ}24'E$, $H = 761$ m) in March 1956 and at Maclear's Beacon ($\phi = 33^{\circ}58'S$, $\lambda = 18^{\circ}26'E$, $H = 107$ m, near the highest point on Table Mountain) in November 1956. In June 1959 precipitation from radiation and advection fogs was measured on a number of occasions on the west coast of South-West Africa At Swakopmund ($\phi = 22^{o}41'S$, $\lambda = 14^{o}31'E$. H = 5 to 10 m). Fog precipitation measurements were also made from August 1960 to September 1961 on a saddle in the Jonkershoek mountains near Stelenbosch ($\phi = 33^{o}57'S$, $\lambda = 18^{o}57'E$, H = $\pm$ 840 m).

This paper aims to explain the method used to determine fog precipitation (especially during the occurrence of rain), to present and discuss the results obtained and to give an indication of the probable amount of water obtainable from this source, exclusive of rainfall, in a given area.

2. MEASUREMENT AND EVALUATION

In the absence of rain, the amount of fog precipitation at a station within cloud is obtainable directly from the readings of a fog catcher. However, when rainfall also occurs the fog catcher collects both cloud and rain drops at the same time. As the total rainfall catching area of a fog catcher is that of the raingauges and the gauze cylinder together, it will collect more rain water than an ordinary raingauge, except during light winds.

If the angle, α, between the vertical and the direction of the falling rain drops exceeds 8^{o}, i.e. the angle which the top rim of the gauze cylinder subtends with the rim of the raingauge funnel, the factor of increase of the catching area is

$$\phi = 1 + \tan \alpha - \tan 8^{o} \quad \text{.........(1)}$$

Considering a median drop size and assuming that the horizontal component of the falling rain drops has the same speed, v, as the air, then

$$\tan \alpha = \frac{v}{o} \quad \text{......................(2)}$$

where o is the fall speed of the median drops, which could be approximated by the rainfall intensity. However, the increase, ϕ, is undoubtedly considerably less than that given by the transformed equation (1), due to the splashing of the rain drops on impact with the gauze cylinder, the blowing away of drops in strong winds and their deflection round the cylinder, in the same way as for cloud droplets.

During the measuring period, rainfall occurred at Table Mountain House on a number of occasions from clouds with bases above the station level. For these cases, the ratios, ψ, of the rain water collected in the fog catcher to the rainfalls measured with the raingauge are entered against the wind speed, v, in Figure 1. For simplicity, the dashed curve representing the mean ψ/v relation is replaced by a straight line with fairly satisfactory accuracy, except for light winds. This line is given by the equation

$$\psi = \frac{v}{15} + 1 \quad \text{....................(3)}$$

For the rainfall, r, as measured with the raingauge, and the precipitation, p, as measured with the fog catcher, this ratio, in the absence of fog, is

$$\psi = \frac{p}{r} \quad \text{.........................(4)}$$

Substituting (3) in (4) it follows that

$$p = r(\frac{v}{15} + 1) \quad \text{...................(5)}$$

When rainfall and fog precipitation, f, occur simultaneously, the fog catcher collects both rainfall and cloud droplets. Equation (5) therefore becomes

$$p = r(\frac{v}{15} + 1) + f$$

or

$$f = p - r(\frac{v}{15} + 1) \quad \text{...............(6)}$$

In this empirically derived formula, millimetre units were chosen for f, p and r, while v and the constant, 15, have the dimension of m sec^{-1}.

For f = 0 the equation (6) of course becomes identical with equation (5). The last term of equation (6) is small for light winds. For v = 0, f must also be zero, as any noticeable fog precipitation cannot occur in calm air. In this case p = r. In the absence of rain r = 0 and therefore f = p

Equation (6) was used for the evaluation of fog precipitation on Table Mountain and at the station near Stellenbosch.

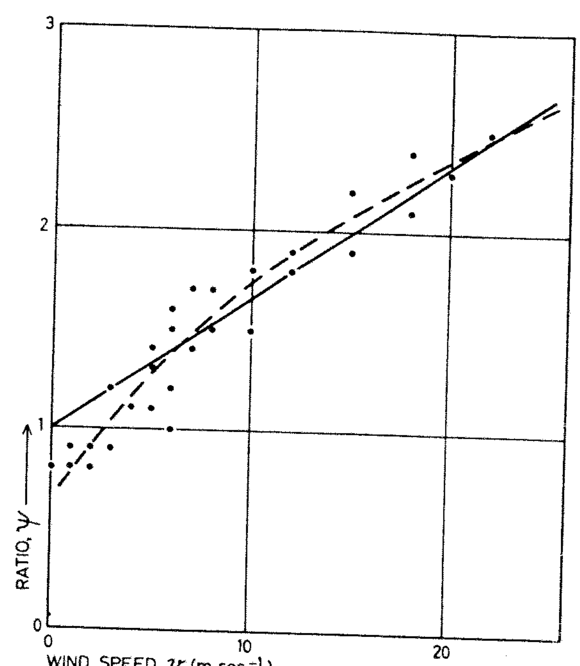

FIG. 1

Ratio, ψ, of rainfall catch of fog catcher to that of the raingauge, as a function of the wind speed, v.

3. RESULTS

(a) On Table Mountain. The mean three-hourly and daily values of fog precipitation, f, and of rainfall, r, at Table Mountain House over a 5-year period (1957-61) are given in Table 1 for the individual months, for the summer (October-March) and winter (April-September) seasons and for the year. It is apparent that fog precipitation contributes considerably more than rainfall to the total precipitation at this station. Only in June is r higher than f. This can be attributed to the fact that during the occurrence of rain in May, July and August the winds were stronger than in June. The ratio between fog precipitation and rainfall is 2.40 in summer, 1.25 in winter and 1.55 for the year.

For convenience, the diurnal variations of fog precipitation in summer, winter and

TABLE 1. Monthly and seasonal mean three-hourly and daily values of fog precipitation, f, (mm) and of rainfall, r, (mm) over the 5-year period 1957-61 at Table Mountain House.

month season		hours of day 00-03	03-06	06-09	09-12	12-15	15-18	18-21	21-24	00-24
Jan	f	26	25	26	17	9	11	18	28	160
	r	5	8	11	7	5	4	5	5	50
Feb	f	27	20	28	11	12	10	23	22	153
	r	9	7	11	22	10	8	7	7	81
Mar	f	22	28	29	26	16	18	22	21	182
	r	11	13	7	5	9	11	7	8	71
Apr	f	29	26	22	17	17	18	27	25	181
	r	17	13	19	14	20	14	11	15	123
May	f	48	55	54	44	33	43	39	44	360
	r	40	39	46	42	37	39	30	35	308
Jun	f	26	29	28	21	17	16	19	21	177
	r	25	38	40	26	29	26	31	29	244
Jul	f	31	33	33	28	21	24	29	33	232
	r	16	26	19	8	7	11	10	9	106
Aug	f	29	47	42	37	25	30	24	29	263
	r	20	46	40	28	24	26	20	29	233
Sep	f	31	29	35	28	22	22	28	26	221
	r	17	17	21	19	17	19	13	8	131
Oct	f	30	41	37	20	10	20	24	26	208
	r	21	23	27	17	11	8	6	7	120
Nov	f	20	33	24	15	13	11	14	19	149
	r	3	5	6	8	5	2	2	2	33
Dec	f	21	15	14	9	6	8	17	22	112
	r	5	6	6	5	9	6	4	3	44
summer	f	146	162	158	98	66	78	118	138	964
	r	54	62	68	64	49	39	31	32	399
winter	f	194	219	214	175	135	153	166	178	1,434
	r	135	179	185	137	134	135	115	125	1,145
year	f	340	381	372	273	201	231	284	316	2,398
	r	189	241	253	201	183	174	146	157	1,544

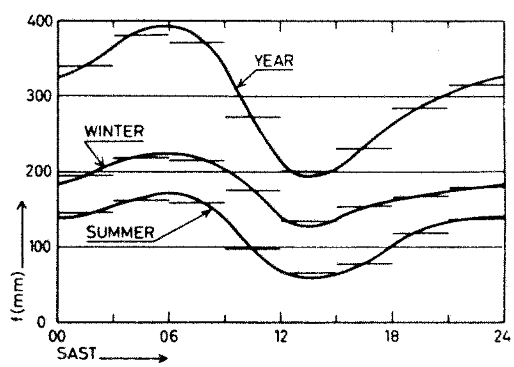

FIG. 2 Mean diurnal variations of fog precipitation, f, (mm) over the 5 year-period 1957-61 in summer, winter and over the year at Table Mountain House. The short horizontal lines indicate values of three-hourly averages.

the year are shown in Figure 2. In all three curves maxima occur at about 0600 SAST (South African Standard Time which, for the Table Mountain area, is equal to mean solar time plus approximately 45 minutes, on the average) and minima at 1330. It was observed that the diurnal march of these curves is very similar to that of the inverted air temperature curves for Wingfield, near Cape Town, with close coincidence of maxima and minima. Therefore, the air temperature obviously has a marked effect on the diurnal variation of fog precipitation. Owing to insolational heating the clouds are partially dispersed in the afternoon. On the other hand, the wind must be sufficiently strong in order to generate an orographic cloud in fine weather and to increase the density and depth of rain clouds in bad weather on the mountain. The increase of the wind speed during the day, with a maximum shortly after 1500, counteracts the dispersal of the clouds and, therefore, undoubtedly prevents a sharper drop of fog precipitation at this time of the day and also causes a rapid increase of f after the occurrence of the minimum.

Table 2 shows the mean three-hourly and daily values of f and r at Mclear's Beacon over the same 5-year period. This station appears to have the highest fog precipitation and rainfall in the Table Mountain area. As is apparent from the table much less fog precipitation occurs in June than during the preceding and the two following months. Even in September and October the fog precipitation at both stations is higher than in June, which is undoubtedly a result of the comparatively low wind speed during rainfall in the latter month. Fog precipitation at Mclear's Beacon contributes 4.7 times in summer, 2.4 times in winter and 3.0 times as much over the year to the total precipitation as the rainfall does. This is more than twice that at Table Mountain House, where the rainfall is somewhat less.

Figure 3 represents the diurnal variation of fog precipitation at Mclear's Beacon for summer, winter and the year. The curves show a very similar pattern to those of Figure 2 and maxima and minima occur at the same hours as for Table Mountain House.

In Table 3 the contribution to the total precipitation from the Table Cloth, which only appears in fine weather, and from rain clouds in the absence or presence of rain are given separately. From this table it is apparent that the contribution from rain clouds is considerably greater than that from the Table Cloth,

TABLE 2. Monthly and seasonal mean three-hourly and daily values of fog precipitation, f, (mm) and rainfall, r, (mm) over the 5-year period 1957-61 at Mclear's Beacon.

month, season	Type of Precipitation	hours of day 00-03	03-06	06-09	09-12	12-15	15-18	18-21	21-24	00-24
Jan	f	56	59	61	40	20	38	55	64	393
	r	7	12	14	10	8	3	7	5	66
Feb	f	55	53	61	46	30	27	42	38	352
	r	9	11	18	24	13	12	16	10	113
Mar	f	60	66	57	46	45	43	59	62	438
	r	13	15	9	10	8	11	9	12	87
Apr	f	64	54	56	47	28	33	44	49	375
	r	17	13	19	21	22	24	17	16	149
May	f	102	117	112	81	83	82	86	95	758
	r	49	46	59	51	58	44	34	46	387
Jun	f	52	66	65	56	39	54	56	56	444
	r	32	47	45	30	30	26	33	34	277
Jul	f	86	92	82	68	56	61	74	85	604
	r	28	25	18	10	12	16	16	22	147
Aug	f	76	76	80	69	77	70	93	77	618
	r	24	50	53	38	29	28	20	35	277
Sep	f	74	82	82	53	46	56	62	70	525
	r	31	21	26	22	14	23	20	14	171
Oct	f	77	84	71	49	47	54	56	71	509
	r	27	35	29	11	9	7	7	10	135
Nov	f	53	43	47	34	19	29	49	45	319
	r	3	5	10	11	6	3	3	4	45
Dec	f	48	48	38	27	28	37	52	51	329
	r	5	5	6	6	11	9	4	4	50
summer	f	349	353	335	242	189	228	313	331	2,340
	r	64	83	86	72	55	45	46	45	496
winter	f	454	487	477	374	329	356	415	432	3,324
	r	181	202	220	172	165	161	140	167	1,408
year	f	803	840	812	616	518	584	728	763	5,664
	r	245	285	306	244	220	206	186	212	1,904

especially during winter. This feature is chiefly a result of the high frequency of rain clouds and a low frequency of the fine-weather cloud during winter. But even in summer the frequency of the Table Cloth is lower than that of rain clouds. Comparison between the fog precipitation amounts at the two stations show that the bases of the rain clouds are, on the average, lower than that of the Table Cloth.

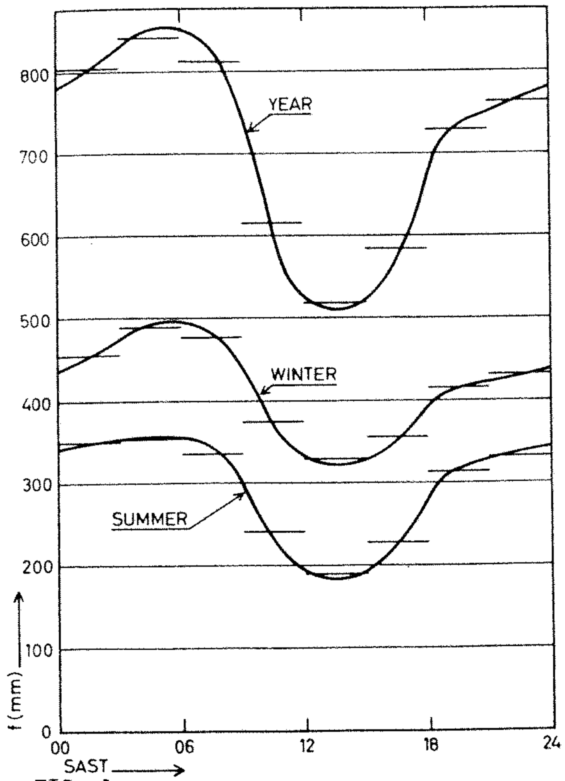

FIG. 3

Mean diurnal variations of fog precipitation, f, (mm) over the 5-year period 1957-61 in summer, winter and over the year at Mclear's Beacon.

Although a relation exists between fog precipitation and rainfall, which is well indicated in the relevant annual variations, it is not apparent in the diurnal variations. In Figure 4 the mean diurnal variation of rainfall over the same 5-year period is shown for Mclear's Beacon only, since that for Table Mountain House is very similar. Maximum and minimum values occur at sunrise and sunset respectively. While the maximum was explained by Nagel /1961/ as being a result of radiational cooling and freezing of drops in the topmost cloud layers, the minimum can be attributed to a considerable decrease of the wind speed and by the still comparatively warm cloud. After sunset the rainfall increase is due to radiational cooling. If the wind had not been strongest in the afternoon, causing additional orographic rain, the rainfall minimum would probably have occurred at about 1500, as indicated by the dotted curves in Figure 4.

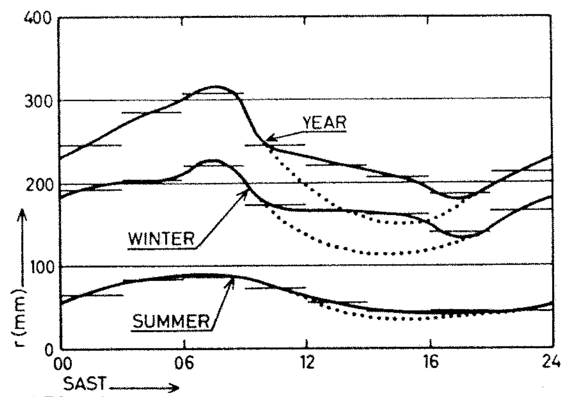

FIG. 4

Mean diurnal variations of rainfall, r, (mm) over the 5-year period 1957-61 for summer, winter and the year at Mclear's Beacon.

TABLE 3. Seasonal mean three-hourly and daily values of fog precipitation from the Table Cloth and rain clouds over the 5-year period 1957-61 during summer, winter and the year.

Season and Station	Type of clouds	hours of day 00-03	03-06	06-09	09-12	12-15	15-18	18-21	21-24	00-24
Summer										
Table Mountain	Table Cloth	44	43	31	11	4	10	31	37	211
	rain clouds	102	119	127	87	62	68	87	101	753
Mclear's	Table Cloth	117	120	88	50	37	69	131	123	735
	rain clouds	231	233	247	191	152	160	181	210	1,605
Winter										
Table Mountain House	Table Cloth	14	12	12	9	6	9	12	14	88
	rain clouds	180	207	202	166	129	144	154	164	1,346
Mclear's Beacon	Table Cloth	41	37	30	22	22	30	36	36	254
	rain clouds	413	451	446	352	307	325	380	396	3,070
Year										
Table Mountain House	Table Cloth	58	55	43	20	10	19	43	51	299
	rain clouds	282	326	329	253	191	212	241	265	2,099
Mclear's Beacon	Table Cloth	158	157	118	72	59	99	167	159	989
	rain clouds	644	684	693	543	459	485	561	606	4,675

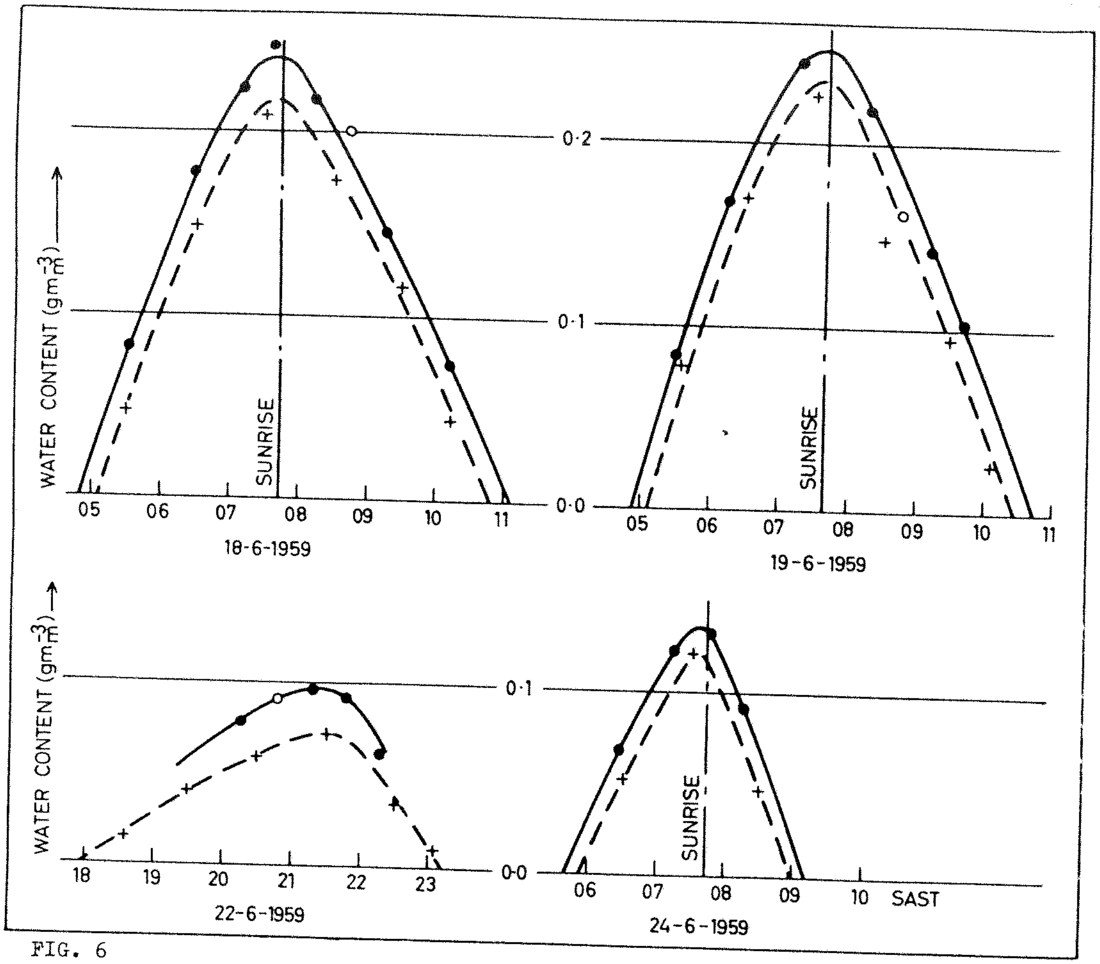

FIG. 6

Graphs of precipitated fog at Swakopmund in gram per cubic metre of air versus time of day. Points marked • refer to measurements with gauze screen on lorry in motion and o when lorry was stationary, whilst + relate to gauze screen in cylinder exposed in town. Radiation fog occurred on 18, 19 and 24 June and advection fog on 22 June, 1959.

culation of the effective area of the screen. On three occasions the lorry was stopped for a while at the terminus with the catching area of the screen exposed normal to the wind direction. The results obtained on the different days are indicated in Figure 6.

This figure also includes the results obtained from another series of observations made by simply drawing air through a double gauze screen inside a metal cylinder of 50 cm diameter. A fan was used to draw the air through the cylinder, and, to exclude possible effects of the actual wind, the cylinder was orientated normal to the wind direction. When the gauze screens were removed the velocity with which the fan drew air through the apparatus was 4.4 m sec^{-1}. With one screen the air speed was reduced to 3.3 m sec^{-1} (75%) and with the two screens to 2.5 m sec^{-1} (57%). A further reduction to between 1.5 and 2.0 m sec^{-1} (34 to 45%) occurred when the gauze screens were more or less covered with water drops. As the effective catching area of the gauze screen was 0.18 m^2, the air drawn through the wetted gauze amounted to 1100 m^3h^{-1}, on the average. Measurements with this apparatus were made simultaneously with the lorry trips.

From Figure 6 it is apparent that during the early mornings of 18, 19 and 24 June radiation fog occurred with maximum density at sunrise, and the relevant curves are almost symmetrical about on ordinate corresponding to this time of the day. (At Swakopmund SAST is equivalent to mean solar time plus one hour at this time of the year). After the fog dissipated at the ground, low clouds persisted for about an hour. As the cylinder apparatus was installed in town, where the fog was less dense than in the open country, smaller amounts were measured with it than on the lorry trips. This difference in fog density, as indicated in the figure, is in agreement with the corresponding temperatures, being always a few tenths of a degree Celsius higher in town than at the point 3.2 km to the north.

In the afternoon of 22 June advection fog occurred which increased in density during 3 hours to attain a maximum at 2120 SAST and then dissipated in two hours. Incidentally, the advection fog precipitated less water than the radiation fogs, partly due to its low density and also to the low wind speed which did not exceed 2 m sec^{-1}. This low wind speed is very characteristic for Swakopmund as described by Taljaard (1957). The wind velocities at Walvis Bay and Lüderitz, 22 and 400 miles south of Swakopmund, respectively, are much higher so that in the case of advection fog higher amounts of precipitated water should accordingly be obtained at these places. This has been confirmed by a number of fog precipitation measurements with a gauze screen at Lüderitz.

The correspondence of amount of fog precipitation at Swakopmund against visibility is presented in Figure 7. The straight line drawn through the scattered points intersects the abscissa at 550 m and the ordinate at 0.27 gm m^{-3}. A relation between liquid water content of the air, w (gm m^{-3}), visibility, η (m) and drop diameter 2r (μ) is given by Trabert's (1901) law viz.

$$w = \frac{2rc}{\eta}$$

where the constant c, is approximately 3. According to Grunow (1960) the most frequent drop size in the two types of fog should be about 12 μ, in the dense sea fogs which occur along the northeast coast of England. Mahrous (1954) found drop diameters are predominantly between 11 and 45 μ, with a mean value of 24 μ. If, owing to the uncertainty of what the drop size is in fogs along the west coast of Southern Africa, a mean value of 18 μ is used in Trabert's equation, a hyperbola is obtained as indicated by the dotted curve in Figure 7. This curve and the straight line show that maximum efficiency of the screen should occur at a visibility of about 300 metres. When the visibility exceeded 550 metres small water drops were observed to form on the screen but did not increase sufficiently in size to trickle down the gauze. On the other hand, in dense fog the gauze became covered with large water drops, so that the wind speed was considerably reduced. This explains the large difference between the hyperbola and the straight line for low visibilities.

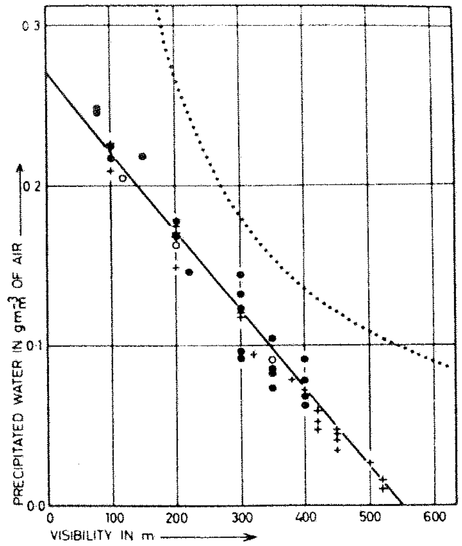

FIG. 7 Precipitated fog water in grams per cubic metre of air as a function of visibility. Straight line represents mean values of fog precipitation as obtained from gauze screen on lorry when travelling •, when stationary o and in cylinder +. Dotted curve represents Trabert's law.

4. CONCLUSIONS

Observations show that precipitation from radiation and advection fogs occurs all along the southwest coast of Africa. Over a coastal strip of at least 3 km width the annual rainfall equivalent from these two types of fog is probably of the order of 150 mm. On mountains, which are higher than the bases of both fine-weather and rain clouds, the rainfall equivalent of fog precipitation appears to exceed the actual rainfall. This is due to the fact that the average fog precipitation and rainfall intensities are roughly the same but that the clouds last much longer than the actual rainfall. Moreover, no rainfall occur from fair-weather clouds.

With sufficient experience the amounts of fog precipitation can be estimated fairly well from the frequency of occurrence and the density of the clouds and from the wind speed. Furthermore, the relation which exists between fog precipitation and rainfall on mountains gives an indication of the precipitable water content of the fog. In the Stellenbosch-Jonkershoek district many mountain tops exceed 2000 metres. Jonkershoek Nek has the highest rainfall on record in South Africa (>3000 mm per annum) and, therefore, fog precipitation there will be at least of the same order of magnitude as that on Table Mountain. On the other hand, the water deposit from clouds rapidly decreases with distance from the sea, unless the heights of mountains increase accordingly. Taking all this into consideration, a cautious calculation of the mean annual fog precipitation over the region between the sea, latitude 32°S and longitude 20°E, covering nearly 50,000 km^2, gives a mean annual fog precipitation equivalent to about 300 mm, i.e. not much less than the average areal rainfall.

This result is certainly of great importance to water engineers, hydrologists and agriculturalists. A climatic atlas not taking account of the fog precipitation in the water household of a country is, therefore, not fully representative of actual conditions.

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