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The relationship between extratropical rainfall and satellite cloud-top temperatures

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An initial study was made in the Victorian region of the possible relationships between rainfall totals for 30 and 60-minute intervals and cloud-top temperature data derived from the polar orbiting NOAA-5 satellite. Results indicate potentially useful relationships in cases where the cloud is chiefly cumuliform and where sub-cloud evaporation effects are small.

Introduction

The first impact of satellite imagery on meteorological analysis has been the identification and location of synoptic systems by the subjective interpretation of cloud patterns. Eventually, the availability of imagery in digital form, and the introduction of the eleven micron 'window' radiation channel which enabled estimation of specific cloud parameters such as cloud-top temperature, have permitted more objective treatments of satellite data. The requirements for objective estimates of variables such as rainfall have led to the development of various methods which are based on digital satellite data.

For tropical regions in particular, considerable work was done with temporally frequent data from geostationary satellites, which enable the growth of deep convective clouds to be monitored on the diurnal scale. This approach is discussed for example by Scofield and Oliver (1977). However, in mid-latitude regions comparatively little work has been done on rain and cloud imagery on an objective basis. One recent work is a study of six summer days' data near Montreal, Canada by Wylie (1979). In that interesting study rainfall was estimated from convective clouds identified among layer clouds in each mid-latitude system. The approach was then basically an extension of the tropical techniques referred to above.

With the availability of locally received digital infrared data it became practicable to examine coincident cloud-top temperature (CTT) and rainfall data for mid-latitude systems. This paper considers 21 such data sets and the results of a first, basic investigation into any relationship between CTT and rainfall.

Data

Cloud imagery in the form of equivalent blackbody temperature maps was obtained by processing locally received NOAA-5 satellite infrared data, as described by Del Beato et al. (1979). This temperature is not strictly equivalent to cloud-top temperature as the emitting cloud tops are not always radiating as black bodies, particularly in the case of the more tenuous layer clouds. Further, the infrared radiation approaching the satellite sensor is reduced by the intervening moist atmosphere, producing an apparently colder CTT. In this initial study, however, the latter effect was ignored because its inclusion would have presented additional problems which would outweigh the possible gain in accuracy of a few degrees K at most. The former effect is potentially more serious as cirrus layers with emissivities from 0 to 1 have been observed (Allen 1971). No adequate method of dealing with cases of low and variable emissivity are known, but based on experience with satellite photographs and climatology of conventional cloud observations, the occurrence of transparent cirrus is limited to a minority of cases.

The data have a maximum resolution of about 60 km^2 at the sub-satellite point. Averaging was performed to produce regular arrays of temperatures on a Mercator projection, with a resolution of 200 km^2. This did not adversely affect results with cumulus cloud, as such cloud occurred in clusters which were much larger than 200 km^2. This averaging served to minimise the effects of location errors, which were estimated to be of the order of a picture element, (= 8 × 8 km) and served also to provide data with a spatial resolution compatible with the temporal resolution of the rainfall observations for a representative speed of translation of the cloud elements. Thus, optimum resolution values probably vary with each case, but this is not investigated further here.

Rainfall totals reported were generally light to moderate, with the heaviest totals for 60 minutes below 8 mm and most cases below 3 mm. They were obtained from up to 139 pluviograph recorders within the study area which is located within 36.2°S, 38.6°S, and 142.16°E, 148°E as shown in Fig. 1. The area comprises a variety of terrain ranging from flat grasslands with an annual rainfall of about 400 mm, to mountain ranges with an annual rainfall exceeding 2400 mm. Although orography plays an important part in the distribution of the rain within the area, it has not been considered explicitly here as all calculations have been performed on the pooled data of all stations.

Rain was considered in the form of short-period totals rather than instantaneous rates. Although the rain rate is more meaningful when considering the microscale aspects of the rain production, it is not applicable to hydrological or many meteorological applications without accompanying duration or frequency statistics. All rain totals were centred on the time the polar-orbiting satellite crossed latitude 38°S. Some inaccuracies occurred in the rainfall data due to the occasional misalignment of the recording chart on the revolving drum of the pluviograph. For this and other reasons relating to the resolution of the imagery, it was decided not to use rainfall intervals shorter than 30 minutes.

The synoptic cases are listed in Table 1. They comprise seven cold frontal bands, eight low pressure systems and six post-frontal southwesterly streams. Three of the fronts (nos 1, 2 and 21) had secondary low pressure centres developing on them. The remaining four were of simpler structure with the parent lows to the south of the study area. Five of the lows (nos 3, 16, 17, 19 and 20) were closed circulations at the surface and aloft. Three of the southwesterly stream cases (nos 5, 11 and 15) were post-frontal cellular convection cases in cyclonically curved flow, while two (nos 4 and 6) were secondary developments termed 'comma' clouds or 'PVA masses' by Guymer (1978, p. 14). The ratio of stations reporting rain to all stations, during a 60-minute period centred on the time of the satellite imagery, is shown as the ratio F in Table 1. All available cases in the study period were used but because the recording

Fig. 1 Location of the study area within the State of Victoria, Australia. Within the dashed region there is an additional network of gauges which is not shown for clarity. Contours of ground elevation are shown for 300 m, 600 m and 900 m.

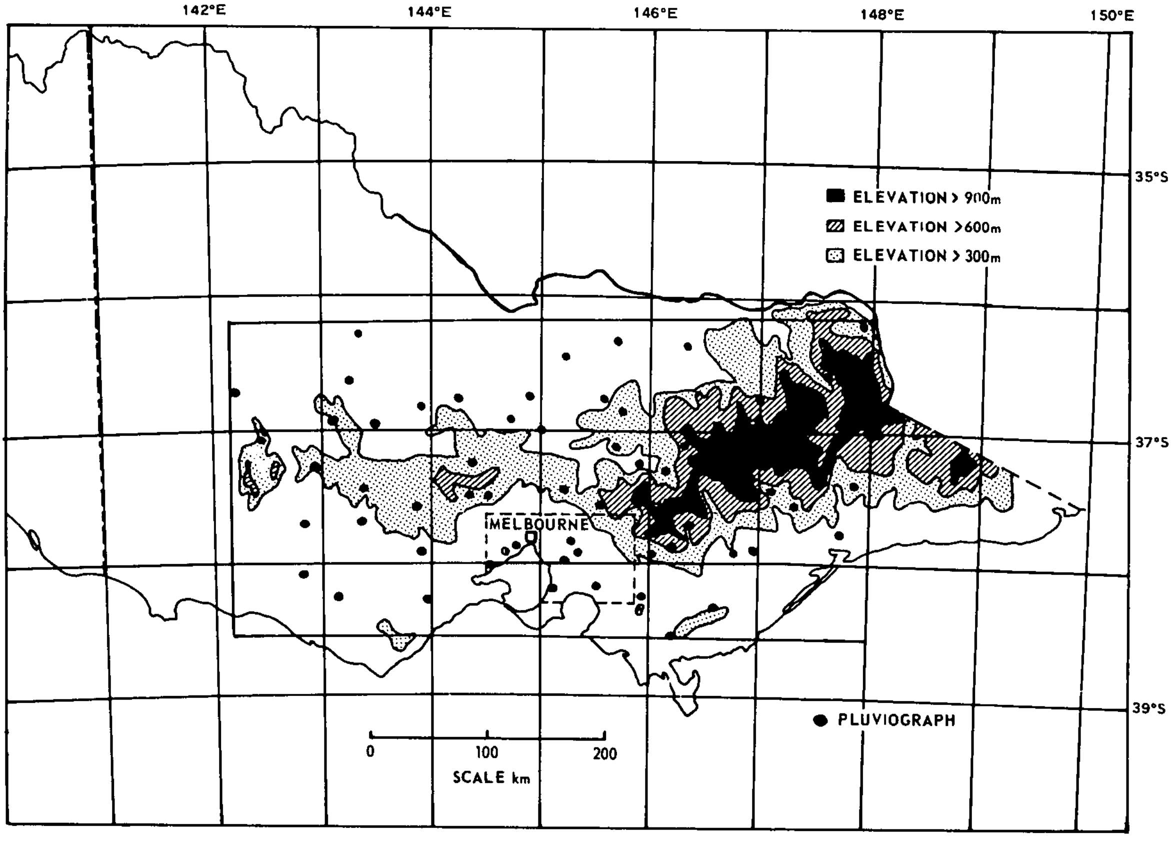


Table 1. List of synoptic cases. Data and time are in GMT. $\overline{CTT}$ signifies the mean cloud-top temperature over the pluviograph stations in °C. $\bar{R}_{60}$ is the mean 60-minute rainfall, calculated for stations which received some rain only. F is the ratio of stations which received rain in the 60-minute period to the total number of stations operating. The synoptic category refers to the system producing the rain. 'SW' refers to post-frontal southwesterly showers (see text for details).

Case No.	*Date (GMT)*	*Time (GMT)*	*Synoptic Classification*	$\overline{CTT}$ *(°C)*	$\bar{R}_{60}$ *(mm)*	*F*
1	14.12.76	2256	front	−25	1.6	41/122
2	20. 5.77	2115	front	−15	1.7	47/122
3	23. 5.77	1058	low	−15	0.8	73/115
4	25. 7.77	1122	comma	−25	1.7	72/106
5	''	2225	SW	−9	0.9	48/103
6	26. 7.77	1037	comma	−31	1.7	82/102
7	12.10.77	2244	front	−37	0.3	1/135
8	13.10.77	1054	front	−13	0.4	3/135
9	8.11.77	2218	front	−15	1.0	2/123
10	9.11.77	1227	front	−50	1.0	55/127
11	10.11.77	2251	SW	+ 2	1.2	34/ 98
12	28.11.77	1205	low	−28	0.4	27/129
13	24.12.77	2137	low	−34	0.6	62/130
14	25.12.77	1143	low	− 7	1.2	22/128
15	27.12.77	1210	SW	− 4	1.4	52/118
16	5. 1.78	1125	low	−10	1.1	79/122
17	,,	2229	low	− 5	1.2	35/118
18	26. 1.78	2235	front	− 3	1.1	36/127
19	29. 1.78	1137	low	−16	1.5	99/132
20	,,	2221	low	− 3	0.8	36/121
21	27. 2.78	1121	front	−15	1.5	59/116

of the satellite data had to be activated manually and in real time, only a fraction of all the possible situations was successfully recorded.

Rain and cloud-top temperature

In each case the study area was synoptically homogeneous, that is, nearly all the stations within it were located within the same synoptic system. Thus initially, the rainfall-CTT data sets were classified by synoptic type although it was recognised that such a grouping was only a first approximation to grouping by more relevant criteria, such as cloud type, droplet spectra, air mass trajectory etc. Tabulations were constructed of the 30-minute and 60-minute totals with the corresponding CTT values and a typical example is shown in Table 2.

The rain observations in each tabulation appeared bounded by an upper limit which was dependent on CTT, as typified in Table 2. Thus the data suggested that an effectively maximum rainfall total exists for a cloud mass with a given CTT, and that this maximum increases as the CTT decreases. A method for illustrating this upper limit will be discussed later. However, to test for any quantitative relationship a linear correlation coefficient was evaluated for each set of observations using 30-minute and 60-minute rain totals (R_{30} and R_{60}) and also the maximum total observed in each CTT interval. Before testing the correlation between the frequency of 30-minute and 60-minute totals with CTT, these frequencies (including those corresponding to **no rain**) were normalised to total 100 for each CTT class, or column as in Table 2. This was necessary to remove the effect of uneven sampling of CTT in each case, which would significantly bias the results. Then the correlations were performed on the normalised **rain** cases only, providing a much more sensitive test. The significance of these correlations at the 95 per cent confidence level is shown in Table 3.

These results show that often there is evidence for a relationship between rainfall and CTT within a particular case. It remains to determine if these cases can be identified by some common property. The first attempt by a simple synoptic classification provides mixed results. Although the number of cases is small the proportion of **yes** cases in the fronts and lows classes is discouraging, although in the southwesterly and comma classes combined it approaches statistical significance. This suggests further investigation with cloud variables which were similar in the southwesterly cases.

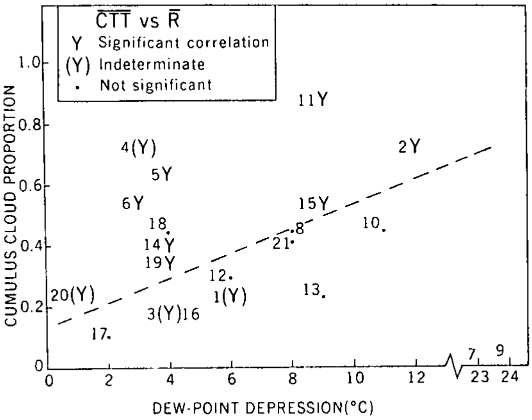
Table 2. Frequency diagram showing distribution of 30-minute falls in cloud-top temperature classes and in rainfall classes for case no. 4 of 25 July 1977. Note the trend to heavier totals with decreasing cloud-top temperature.

	Cloud-top temperature(°C)													
	10	*5*	*0*	*−5*	*−10*	*−15*	*−20*	*−25*	*−30*	*−35*	*−40*	*−45*	*−50*	*−55*
No rain	3	3	10	3	6	3	1	1		3	3	2	2	
Rainfall (mm)														
0.00					4			1		6	1	4		
0.25			1	1	1	1	1	1		3		2	2	
0.50				1		1					1			
0.75		1		1		1				1	3	2		1
1.00						1		1		1	1	1	1	
1.25						1				1	1	2		
1.50														
1.75						1				1	2	1		
2.00								1		1	1			
2.25														
2.50											1			
2.75										1	2			
3.00										1				
3.25														

The lack of microphysical data precluded the consideration of several variables which would be expected to be relevant. However, examination of the surface and radiosonde observations in each case prompted consideration of the cloud type and sub-cloud layer humidity. It is characteristic of mid-latitude systems to contain a mixture of low (cumuliform), middle (stratiform cloud such as altostratus) and high cloud (cirriform), so that cloud type was expressed as the proportion of cumuliform cloud reports to all cloud reports, based on surface observations. This cloud type was chosen since it was assumed that in these cases the cloud-top temperature would be more indicative of cloud thickness, and hence its capacity to precipitate, than in cases of stratiform cloud. Sub-cloud layer humidity can be a particularly relevant factor as exemplified by cases nos 7 and 9. In both there was almost no report of rain while satellite imagery showed frontal cloudbands with mean CTT of −37°C and −15°C. Surface reports and radiosonde data indicated deep altostratus cloud decks but with bases at about 3 km and sub-cloud humidities between 20 and 30 per cent. The evaporation of rain in such conditions was estimated (see Appendix) and results suggest it is capable of explaining the lack of surface rain. Sub-cloud layer humidity in these 21 cases was expressed in terms of the mean dew-point depression for the layer as determined from the radiosonde data from Laverton (see Melbourne, Fig. 1) and, when applicable, from Mt Gambier (37°49′S, 140°46′E) and Wagga (35°06′S, 147°30′E), together with surface dew-point data and cloud base heights.

Cumuliform cloud content and mean dew-points are plotted jointly for each of the 21 cases in Fig. 2. Where a case scored at least two significant tests (Table 3) it is plotted as a 'Y', where only one significant test as a '(Y)', otherwise as '.'. By inspection it is evident that higher cumuliform content and moister sub-cloud air is associated with the cases where there is a significant rainfall-CTT relationship. The line in Fig. 2 has been subjectively located to illustrate this distinction. It is evident that this criterion of combined cumulus content and sub-cloud humidity is more efficient in distinguishing the

Fig. 2 Mean sub-cloud dew-point depression (approximately proportional to relative humidity) and cumulus cloud content measured as the ratio of cumulus cloud reports to all cloud reports for each case.



significant cases than the previous synoptic categorisation.

Another approach is to examine the mean of the rainfall totals ($\bar{R}$) and the mean of the CTTs ($\overline{CTT}$) in each case. Plots of $\bar{R}_{30}$ and $\overline{CTT}$ are shown in Fig. 3. The linear correlation coefficient between $\bar{R}_{30}$ and $\overline{CTT}$ is only 0.09, but it was re-evaluated with the progressive omission of some of the cases furthest below the separating line in Fig. 2, i.e. those with least cumulus and driest conditions. Thus with the omission only of cases nos 1, 3, 7, 9, 10, 12, 13, 16 and 17, but not cases 8 and 21 which are almost on that line, the coefficient had increased to 0.79, a highly significant value. Joint plots of the cumulus content and sub-cloud layer dew-point depression are shown again in Fig. 4 with dashed lines separating the cases with dew-point depression greater than 6°C and cumulus content less than 0.5. With the omission of these cases, nos 1, 7, 8, 9, 10, 12, 13 and 21, the correlation coefficient increases to 0.90, another highly significant value. Thus, the importance of cumulus content and sub-cloud humidity to a significant rainfall-CTT relationship is demonstrated.

Fig. 3 Mean cloud-top temperature, $\overline{CTT}$, and the mean 30-minute rain total, $\bar{R}_{30}$, for each case.

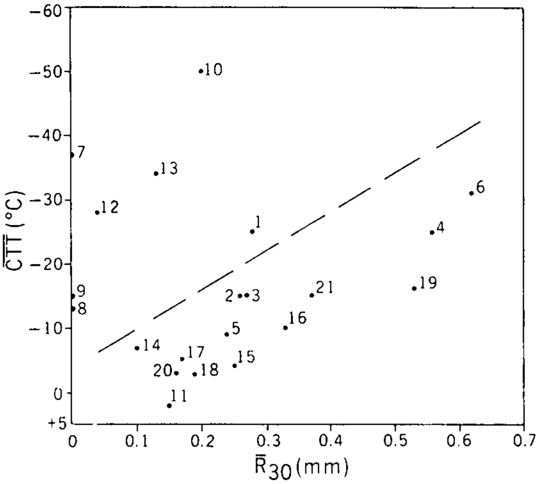
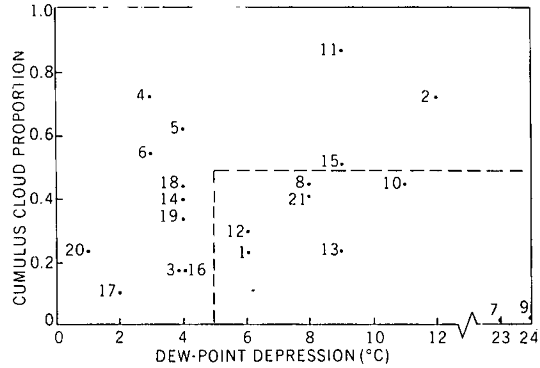


Fig. 4 As for Fig. 2. Cases with cumulus proportion less than 0.5 and dew-point depressions greater than 6°C are enclosed by the dashed lines.



In an attempt to illustrate the fundamental trend between rain and CTT for these cases, a composite frequency distribution was constructed similar to that in Table 2, for CTT intervals of 5°C and R_{30} intervals of 0.5 mm, using the data of the southwesterly stream cases nos 5, 11 and 15. The rainfall frequencies (including the zero rainfalls) were normalised so their sum within each CTT interval, i.e. each column, was unity. That part of the resultant matrix of these frequencies which corresponded to non-zero rainfall, f_{CTT}, was then fitted in the least squares sense by a linear relation, with R_{30} (mm) and CTT (°C) as independent variables and f_{CTT} the dependent variable. The zero-rainfall frequencies were not fitted, but can be estimated as the residual from 1.0 of the estimated column totals. The regression plane is shown as the hatched surface in Fig. 5. The fitted equation was

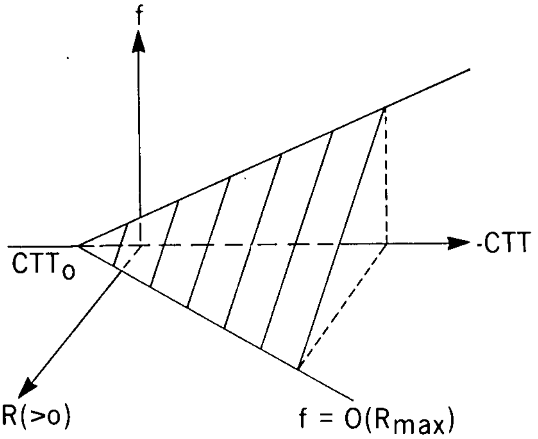
$$f_{CTT} = 0.057 - 0.004\,CTT - 0.054\,R_{30} \qquad \ldots 1$$

and was fitted to 41 independent f_{CTT} values. It has a correlation coefficient of 0.79 which is significant at the 99 per cent confidence level. This equation implies no rain from clouds warmer than about 13°C (see CTT_0 in Fig. 5), and a maximum value of R_{30} (shown as R_{max} in Fig. 5) of

Table 3. Results of significance tests for the correlation coefficients between totals for 30 minute, 60 minute and maximum in each CTT class, and cloud-top temperature in each synoptic case. SW refers to the case of post-frontal showers (see text for details). Significance levels were 95%. '.' refers to a lack of significance. '—' refers to the test not carried out due to lack of rain observations. Note cases nos 7, 8 and 9 produced almost no rain.

	fronts					*lows*											*SW*			*commas*	
Case No.:	*1*	*2*	*10*	*18*	*21*	*7*	*8*	*9*	*12*	*13*	*14*	*3*	*16*	*17*	*19*	*20*	*5*	*11*	*15*	*4*	*6*
Significant for R_{30}	.	Yes	.	.	Yes	—	—	—	.	.	Yes	.	.	.	Yes	.	Yes	Yes	Yes	.	Yes
Significant for R_{60}	.	Yes	.	.	Yes	—	—	—	.	.	Yes	.	Yes	.	Yes	.	Yes	Yes	.	Yes	Yes
Significant for R_{max}	Yes	.	.	—	.	—	—	—	—	.	Yes	.	.	.	.	Yes	Yes	Yes	Yes	.	Yes

Fig. 5 Schematic representation of the regression plane defined by Eqn 1. According to the relation no rain falls from cloud with CTT warmer than CTT_0. For any CTT there is a limiting rainfall value corresponding to the line labelled f=0.



about 2.5 mm for cloud tops of −20°C. The equation illustrates the broad form of the rain-CTT relationship in these cases. A considerably larger data set would be required to provide an accurate formula for practical applications, and it would probably contain additional factors necessarily neglected here. The arrival of geostationary satellites with their frequent imagery readouts will enable this to be done.

Conclusion

Comparisons of 30 and 60-minute rainfall totals with equivalent black-body cloud-top temperatures, as measured by satellite, indicated there were statistically significant relationships in cloud systems where there was a high proportion of cumulus cloud and where there was not severe sub-cloud evaporation. Typical systems meeting these requirements in the Victorian region are the southwesterly stream showers which persist after frontal passages.

Examination of the rain totals in these cases revealed that there is a maximum total which can be associated with a cloud-top temperature, and that this increases as the cloud-top temperature decreases, at least down to about −35°C. The broad form of the relation between the 30-minute rain totals and the cloud-top temperature is suggested by a frequency density function fitted to composite statistics from these synoptic systems.

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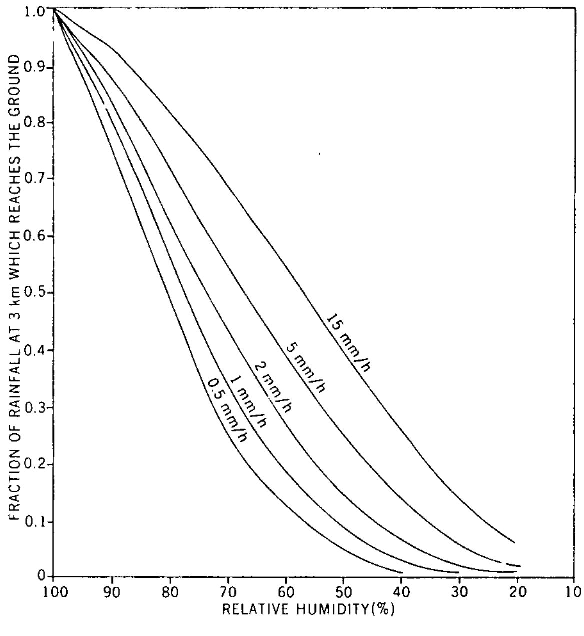
Appendix

Results of a brief calculation are presented in a form which readily shows the quantitative depletion of rain during its fall from cloud base to the ground.

Consider a deep deck of horizontally uniform altostratus cloud of large horizontal extent with base at 3 km (about 700 mb) which is sustained

Fig. A1 Fraction of the rainfall at stratiform cloud base 3 km above ground, which is estimated to survive to the ground after evaporation in falling through the sub-cloud layer of assumed constant relative humidity.



by a flow whose vertical component is of the order of 0.1 m/s. If it is assumed that all the moisture which continues to enter the cloud through the base is eventually precipitated out, then the rainfall rate at the base is dependent on the base temperature.

The rainfall rate measured at the ground is dependent on the evaporation in the sub-cloud layer and is determined by the humidity profile of the layer. The depletion is calculated assuming that the raindrop size distribution is as proposed by Marshall and Palmer (1958), the evaporation of drops during their fall obeys the calculations of Best (1951), and their terminal velocity is as recommended by Mason (1971). The ratio P is defined as

$$P = \frac{\text{rain rate L below cloud base}}{\text{rain rate at cloud base}}$$

where L is the distance of the ground below cloud base. Integrating the spectrum of raindrop sizes leads to

$$P(L) = \frac{\int_0^\infty N(r_l)\, v(r_l)\, r_l^3\, dr_l}{\int_0^\infty N(r_o)\, v(r_o)\, r_o^3\, dr_o} \qquad \ldots A1$$

where $N(r)$ is the Marshall-Palmer dropsize distribution,
$v(r)$ is the drop terminal velocity,
r_l is the radius of a drop after falling to ground through a layer of thickness L,
r_0 is the radius of a drop at cloud base.

Figure A1 shows the dependence of P on relative humidity in the sub-cloud layer (assumed constant here for simplicity) for some rain rates at the cloud base. Thus for a humidity of 70 per cent it is estimated that only a third of 1 mm/h rain which leaves the cloud base survives to the ground, but over half of 5 mm/h rain reaches the ground. However, in the cases of convective showers in a moist maritime stream with bases between 300 m and 1000 m, the evaporation effects are estimated to be very much smaller.