RAINFALL ESTIMATION FROM COLD CLOUD DURATION: EXPERIENCE OF THE TAMSAT GROUP IN WEST AFRICA

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1 - INTRODUCTION

It is now more than ten years since the initiation of rainfall estimates over West Africa which use the duration of cold cloud as the main observed variable. Since then, these estimates have been put to a number of operational uses, and the results of several different algorithms have been compared, for example during the 1993 workshop held in Niamey (AGRHYMET, 1994). However, there has been little advance in the scientific basis for the methods used, and their empirical nature means that they have not improved systematically over the years. It is appropriate at this stage to review the results, and consider the way forward. This paper presents a contribution to this process based on the experience of the TAMSAT group.

The obvious gains in the last few years have included the increasing amount of data which is available to provide calibrations, and these are now based on a variety of wetter and drier years. The stability of the calibrations is discussed in section 5. Another major advance has been in understanding the limitations of the rainfall estimates which result from any of the regressions, and hence the realism with which they can be used in operational decision making. In spite of the substantial scatter which is inherent in the methods, the estimates can indeed be relied upon for a number of important purposes, and some of these are outlined in section 7. First, however, a brief account is given of the detailed procedures which have been used by TAMSAT, knowing that these can have a substantial effect on the outputs from apparently similar processing systems. Some attempts to elaborate and improve the algorithms are reviewed. Compared with the original, simplistic version none of these has yet provided a significant increase in the accuracy of the estimates when tested in an operational mode.

2 - RAINFALL ESTIMATES FROM COLD CLOUD STATISTICS

The basic methodology of the cold cloud statistics procedures is simple. It has been set out more fully elsewhere (Barrett, 1989), and is briefly summarized here. A regular series of thermal infrared (TIR) images of an area is received, pixels with apparent temperatures lower than some predetermined threshold are classified as "cold cloud", and their characteristics accumulated over some period. The resultant map is converted to a rainfall estimate, possibly with the help of information from other sources (which may be other satellite sensors or observations from the Earth's surface). The procedures adopted and the form of the algorithms are regarded as a statistical model, which is calibrated through comparisons between observed cold cloud characteristics and sets of conventional raingauge data. To establish the utility of the method, it must subsequently be validated by comparing estimates and gauge data from some area or period distinct from that used for the calibration. Alternatively, validation may consist of testing the use of the estimates in a quantitative application, such as a catchment runoff model, again using a separate period or area from that used for the calibration.

Within the estimation procedure there are many decisions to be taken and numerical values to be assigned. It is normally assumed that the radiometer is accurately calibrated and that navigation is also accurate. In discussing the limit of spatial resolution it is usual to think of a pixel as a well-defined area but it should be remembered that it is not in fact sharp-edged, and that pixels will always overlap those of other images. Also, even the best co-location leaves a pixel-sized residual uncertainty in a field derived from a sequence of images.

The factors to be considered in comparing methods include the following:

- the type of regression model employed (linear, non-linear, multivariate)
- the interval between images (slots)
- the time averaging period
- the space averaging scale
- the threshold temperature adopted
- data treatment (e.g. linear or temperature weighted accumulation) additional data incorporated (e.g. water vapour channel, visible channel or contemporary surface raingauge measurements)
- localization of calibration (time or space varying TIR features, variation with geographic location, time of year, character of season, topography and local storm climatology).

Many of the choices made by TAMSAT were those judged appropriate for the West African Sahel, and any extension to other areas has to justify these choices afresh because the relation between rainfall and cold cloud duration is climate-specific, depending on average storm characteristics. As an extreme example, threshold temperatures appropriate for the semi-arid regions of Africa are substantially lower than those used over the oceans, or over N. America (GRIFFITHS & WOODLEY, 1973).

Optimization of the factors listed is complex because they are interdependent, and also because the optimum result depends on the user's viewpoint. In addition, to establish even a simple relationship a considerable size of sample is needed, typically a minimum of 100 data pairs.

It is therefore not surprising that not all these factors have been evaluated, even for a small part of Africa.

3 - TAMSAT PROCEDURES

While the procedures used in the TAMSAT rainfall estimation, and the reasons behind them, have been described elsewhere (MILFORD & DUGDALE, 1990a, DUGDALE, 1992), it is useful to summarize them here because they can contribute to the differences between estimates for any given area and time which appear even when different groups process the same data from METEOSAT and use the same algorithms.

The technique is simple. Local seasonally varying temperature thresholds which best discriminate between precipitating and non-precipitating clouds of convective origin are determined. Simple linear regressions of rainfall per hour of "cold cloud" are applied to calculate the period rainfall. The operational details follow.

Firstly, all available Meteosat TIR slots are used. There is little gain in using half-hourly images rather than hourly but, if some are missing the accuracy of the cold cloud duration is materially improved. Within an image, faulty lines, detected by being out of range or discontinuous, are replaced by those on either side. Where more than ten lines are missing the image is rejected. The preceding image is repeated to substitute for a single missing image. Infilling from each side covers longer gaps. If more than six consecutive hours of data are lost no estimate of rainfall is made for that day for operational purposes and the users are advised accordingly. If decadal data are needed for climatological purposes a missing day is represented by the average of the other nine days.

Time and space averaging considerations interact. In TAMSAT, all data processing is carried out on the original METEOSAT pixels at full resolution, with reprojection (which inevitably loses some resolution) left to the last possible stage. Rainfall estimates are made pixel by pixel on a decadal basis: the clouds have already produced a reasonably smooth field so that general smoothing is not necessary. However, to avoid discontinuities smoothing is applied at the boundary between two calibration zones, using linear interpolation across a band of 20 lines or pixels on either side of the boundary. This interpolation is applied to the threshold calibration. This also represents a meteorological/climatological transition zone.

Where the estimates are used for hydrology on a daily basis, a minimum catchment area is specified for averaging. In practice the minimum size may depend on the density of raingauges available for calibration in the area, but a sample of less than 400 pixels (i.e. a minimum area of 10 km) is not recommended in any case.

The type of regression used by TAMSAT has so far simply been linear in rainfall against CCD, considering non-zero CCD values only. It is an important proviso that zero CCD is always equated to zero rainfall. During calibration, the rainfall values are grouped according to 2.5-hour bands of CCD and the regression performed on the median rainfall in each class (see MILFORD & DUGDALE, 1990a for more detail). To provide a significant number of classes each containing a sensible population, a minimum of 100 data pairs has been recommended. As more become available they can be used to improve the statistical significance of existing calibrations or to subdivide the calibration areas. This criterion is now easily met in the current zones with 116 in October for zone 8 to 2 425 in August for zone 2 data points contributing. (May and October have only been included since 1990).

The next consideration is the way in which an area should be divided up for calibration purposes. The much published map of Africa (e.g. MILFORD & DUGDALE, 1990a, fig. 1) shows the zones recommended in 1988 for the first FAO ARTEMIS operations. These were based on a limited data base, and a radical revision would now use more zones, maintaining a broadly E-W pattern but taking more account of topography. An example of the subdivision of an area using data from southern Africa is

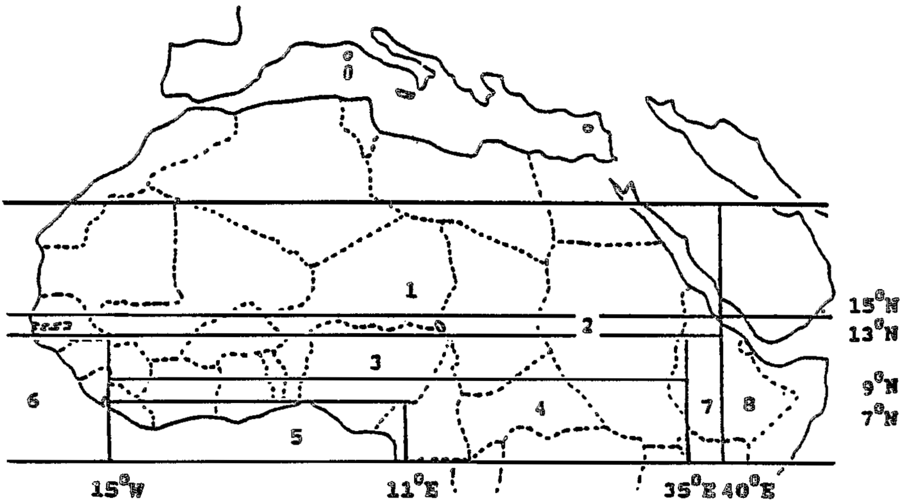

Figure 1 - Calibration zones.

shown below (fig. 6b), where the importance of taking account of the final use of the information before deciding on an "optimum" zonation is stressed. The calibrations are also time-dependent, and those from TAMSAT have so far been related to individual months of the year. An attempt to relate the calibrations to the vagaries of the climate rather than to the calendar is referred to in section 4.

Finally, some reference should be made to the raingauge data which are essential to the whole procedure. For the majority of purposes such as drought and agricultural monitoring, decadal rainfall data are suitable, and any sources available have been used, including FAO and national records. Daily data, as required for hydrological purposes, may come from data transmitted over the WMO Global Telecommunications System, or from national meteorological services. It should be noted that few of these data sets have been subjected to serious quality control procedures - not that these are very reliable in the case of daily rainfalls because of the huge inherent variability. Some reservations over the accuracy of measured rainfall are justified when, for instance, decadal rainfall from two sources show only 38 % of the decades in agreement with 8 % having a difference greater than 10 mm. Quality control of the data at Reading has been minimal except to compare supposedly identical sets reaching here by different routes, and, very occasionally, to shift daily records by one day where a station shows a consistent displacement of major rainfalls either from neighbouring stations or from satellite records of cloud.

4 - ALTERNATIVE ALGORITHMS

In this section a number of attempts to increase the information content of the rainfall estimates is mentioned briefly, particularly those for heavy daily falls which have always been underestimated. The philosophy has still been to provide algorithms

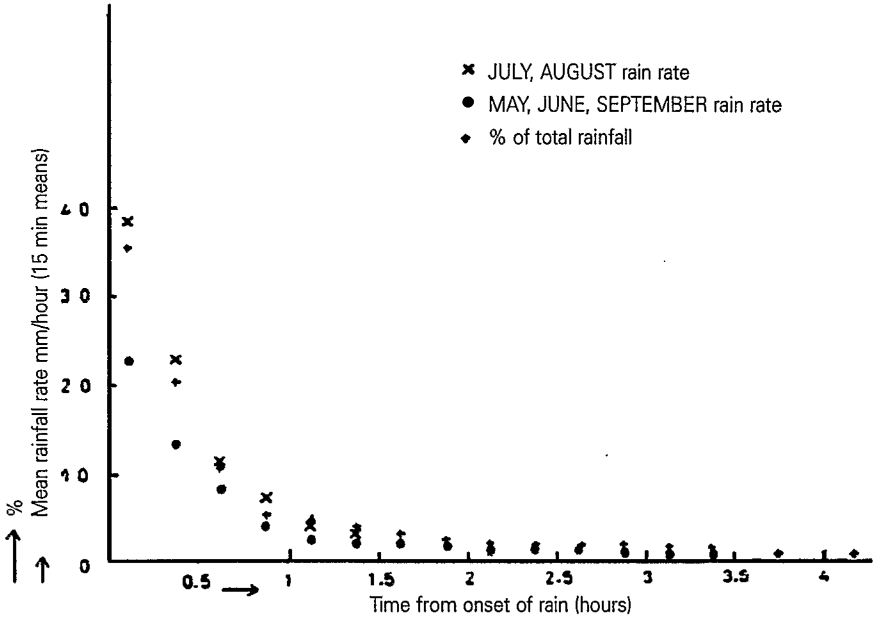

Figure 2 - Rainfall patterns from squall lines.

always been underestimated. The philosophy has still been to provide algorithms which can be applied automatically, and which are fully pre-calibrated. If a method is to be adopted, evidence is required that it gives a significant increase in the correlation or contingency score over the simplest, linear regression, and so far this goal has proved elusive.

A first step, based on the knowledge that much of the rainfall in the West African climate comes in a heavy burst close to the leading edge of the squall lines (fig. 2), was to include the number of rain days as well as the CCD in a multiple regression. A single storm under six hours of "cold cloud" would be expected to give less rain than the total from three smaller storms each showing two hours of cold cloud. No improvement in the validation scores was found over the sample tested. The use of a quadratic instead of a linear regression between decadal rainfall and CCD (expected to show upward curvature because of the general underprediction of heavy falls) was similarly unprofitable as was a logarithmic regression.

Another possibility, related to the intense burst of rain at a squall front, is to identify the level of activity, observing the structure of the leading edge of the storm cloud. The typical signature of a storm passage, as recorded by the temperature of the pixel covering a raingauge station, is shown in figure 3. For a substantial data sample, the sharpness of the front, its speed of advance and its rate of growth (among other characteristics expected to show the vigour of a storm) are evaluated. Again, these variables, singly or in combination, did not improve the rainfall estimation statistics.

Having CCD data for several different temperature thresholds, it is tempting to expect a multiple regression to improve on that from a single threshold. Where the

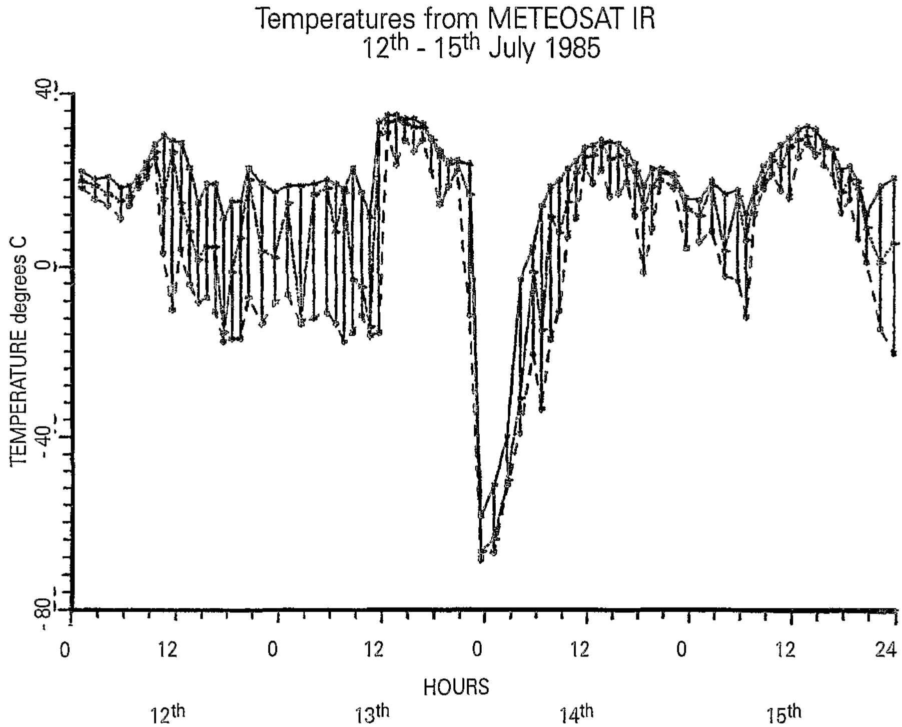

Figure 3 - Satellite observed temperatures, Niamey 12-16 July 1985. The figure shows the range of uncorrected temperatures from Meteosat TIR observed over a 9 x 9 pixel square centred on Niamey Airport. The temperatures on the central pixel are also shown. Note the passage of a well marked squall line during the late evening on the 13th, when 11 mm of rain was recorded at the Airport, with very narrow temperature bands at midday before and after the storm, indicating clear skies.

ratio of cloud areas at - 60, - 50, - 40 °C etc. remains constant, as is the tendency to the north of our study area, minimal extra information content is to be expected. The situation further south is more complex, as illustrated by figure 4 (DUGDALE, 1994). For a typical decade, observed rain is constant over a wide range of latitude, where the CCD at both - 40 °C and - 60 °C is falling away to the south of the maximum, and where the ratio of the two quantities is also changing rapidly.

5 - CALIBRATION AND VALIDATION

In the TAMSAT calibration procedure for decadal rainfall areas are first demarcated which have reasonably uniform climate, and which should contain a minimum number of raingauges - 35 if a single month is to be used, but fewer if data from seve-

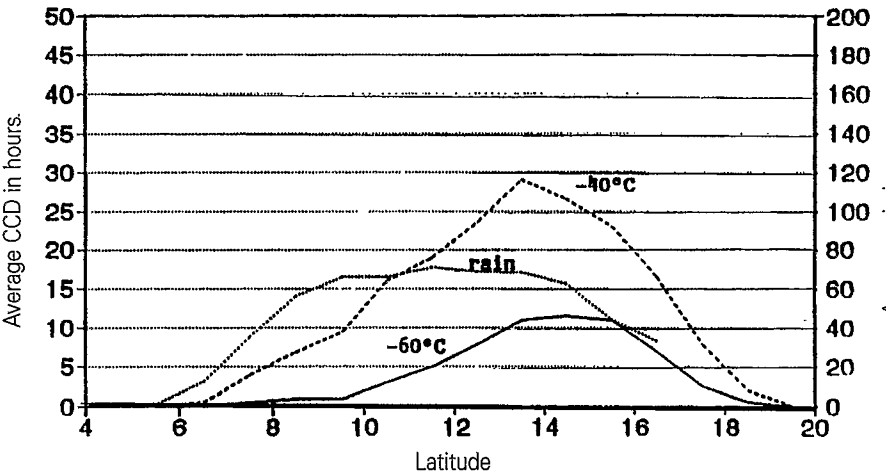

Figure 4 - A north-south cross section from 5 N to 20 N through the ITCZ showing the duration of cold cloud at two temperature thresholds and the rainfall averaged over a strip from 0 to 5 ° E in the period August 1st-10th 1988. (Private communication from Dr V. THORNE).

ral years are already available. Contingency tables of CCD against rain in arbitrarily chosen classes for a number of threshold temperatures are constructed. (For the rainfall class limits, see Table 2 below.) A subdivision of the contingency tables shows which threshold discriminates best between days with and without significant rain: note that the minimum amount of rain which is significant may vary according to the use which will be made of the information. Table 1a shows an example used to choose the best threshold temperature to discriminate between rain over ten-day periods and no rain. A lower value would be used to distinguish significant rain, e.g. above 10 mm (Table 1b).

Table 1a - Decade contingency tables for zone 2 (see fig. 1) using three temperature thresholds. For - 50 °C occasions with rain and no cloud are almost equal in number to those with cloud and no ain. The sum is close to a minimum so - 50 °C is therefore used as the threshold.

	No cloud	Cloud		No cloud	Cloud		No cloud	Cloud
No rain	4	18	No rain	7	15	No rain	11	11
Rain	7	295	Rain	16	286	Rain	30	272
T_t	- 40 °C			- 50 °C			- 60 °C	

Table 1b - As table 1a but for discrimination between rainfall amounts above and below 10 mm. Here a threshold of - 60 °C is indicated.

	Cloud			Cloud			Cloud	
Rain	< 5 h	> 5 h	Rain	< 5 h	> 5 h	Rain	< 5 h	> 5 h
< 10 mm	27	68	< 10 mm	47	48	< 10 mm	68	27
> 10 mm	22	207	> 10 mm	9	220	> 10 mm	26	203
T_t	- 40 °C			- 50 °C			- 60 °C	

When the optimum threshold has been chosen for a given area, ten-day rainfalls are regressed against CCD, omitting periods with zero cold cloud, and an equation of the form: - R = a + a D is produced where R = rain, D is the amount of CCD and a and a are coefficients dependent on threshold. The best discriminating threshold also tends to give the smallest intercept on these regressions. In practice, because of the skewness of the data we prefer to regress the median values of the data grouped into classes. Table 2a shows an example of a contingency table and table 2b the corresponding median values.

When a calibration has been carried out, based on one or more years, it is tested with independent data. Contingency tables are used, as shown in table 3 for July 1994 zone 2, or the estimated rainfall may be regressed against the gauge rainfall. The stability of a

Table 2a - Contingency table: cold cloud duration against rainfall classes.
Threshold = - 60 ° C. Data for July 1985-1990 for zone 2 (see fig. 1).

	COLD CLOUD DURATION (HRS)												
ACTUAL RAINFALL (mm)	0.0 - 0.0	0.5 - 2.0	2.5 - 4.5	5.0 - 7.0	7.5 - 9.5	10.0 - 12.0	12.5 - 14.5	15.0 - 17.0	17.5 - 19.5	20.0 - 22.0	22.5 - 24.5	25.0 - 27.0	27.5 +
0- 0	42	24	17	18	8	6	2		3				
1- 10	53	79	80	73	39	25	7	4		1			
11- 20	13	39	57	85	64	30	24	9	1	1			
21- 30	8	32	39	61	61	39	12	5	3	1		1	
31- 40	2	21	35	54	46	46	16	12	4			1	
41- 60	3	17	40	92	66	71	33	14	18	5	2		
61- 80		5	12	39	47	38	21	17	4	2	1		
81-100	1	3	1	23	19	28	21	17	3	5	4	1	
101-120		2	2	2	8	13	10	9	4				
121-140		2		1	7	4	2	2	3	1		1	
141-160						1	3	2				1	
161-180					1	1		1	1				
181-200				2	1		1						
201-220								1					
221-240													
241-260													
261-280													
281-300						2							
301-320													
321+													

Table 2b - Interpolated quartile values from data in table 2a.

QUARTILE TABLE AT QUARTILE TABLE AT - 60 °C				
CCD RANGE	Rainfall in mm			
	N	25 %	Median	75 %
0.0- 0.0	122	0.0	1.8	9.0
0.5- 2.0	224	3.0	12.0	27.4
2.5- 4.5	283	7.3	17.9	35.1
5.0- 7.0	450	13.7	29.0	48.9
7.5- 9.5	367	17.4	33.4	58.4
10.0-12.0	304	24.4	41.6	65.4
12.5-14.5	152	23.4	46.0	79.8
15.0-17.0	93	33.7	62.0	88.8
17.5-19.5	44	38.8	47.8	80.5
20.0-22.0	16	43.3	60.8	88.9
22.5-24.5	7	57.0	86.0	92.2
25.0-27.0	5	32.3	83.7	137.5
27.5-29.5	0	-	-	-

Table 3 - Contingency table showing estimated rainfall against gauge rainfall in classes and validation scores for July 1994 for zone 2 (see fig. 1).

corr. coeff. = 0.53 number of observations 517
estimated rainfall (mm)

rainfall gauge (mm)	0-0	1-10	11-20	21-30	31-40	41-60	61-80	81-100	101-120	121-140	141-160	161-180	181-200	200+
0-0		1	3	5	4	4								
1-10	2	4	11	21	8	8								
11-20		1	8	17	18	4								
21-30		2	6	13	22	14								
31-40			2	5	21	17	1							
41-60		1	1	12	42	47	2							
81-80			2	12	19	37	8							
81-100			2	9	9	19	8							
101-120			1	3	2	14	3							
121-140				4	2	11	1							
141-160				2	1	5	1							
161-180					2	2								
181-200						2	4	1						
200+							1	3						

total gauge rain 28 411 mm	total estimated rain 19 895 mm
mean gauge rain 55.0 mm	mean estimated rain 38.5 mm

exact	1 out	2 out	3 out	> 3 out	% < 2 out to all	% < 3 out to all	> 1 out too high	> 1 out too low
101	171	114	54	77	53	75	90	155

Table 4 - Six calibrations for zones 1, 2 and 3 for June and August.
N = number of observations, Thr = threshold, Int = intercept.

Year Month	Zone 1				Zone 2				Zone 3			
	N	Thr	Slope	Int	N	Thr	Slope	Int	N	Thr	Slope	Int
June												
1986-7	252	- 60	2.92	6.9					>			
1988-9	83	- 50	1.70	0.4	583	- 50	1.70	0.4	261	- 50	1.74	10.1
1990	83	- 50	1.70	0.4	583	- 50	1.70	0.4	261	- 50	1.74	10.1
1991	177	- 50	1.25	3.1	901	- 50	1.49	0.7	636	- 50	1.97	6.4
1992	233	- 50	0.78	2.1	709	- 50	1.45	0.5	849	- 50	2.07	6.9
1993-4	398	- 50	1.06	- 0.2	1367	- 50	1.55	0.6	1 199	- 50	2.09	6.9
August												
1986-7	39	- 50	1.78	5.3	231	- 50	1.34	24.4	36	- 50	1.92	43.1
19889	187	- 60	3.20	4.1	832	- 50	2.06	8.3	366	- 50	2.26	15.0
1990	723	- 50	2.14	- 2.8	1679	- 50	2.22	9.3	1 154	- 50	2.18	28.5
1991	949	- 50	2.52	- 4.1	2131	- 50	2.80	0.9	1 171	- 40	1.7	20.4
1992	1 168	- 50	2.60	- 5.1	2406	- 50	2.40	7.6	1 493	- 40	1.57	27.9
19934	1 423	- 50	2.45	- 3.6	2685	- 50	2.35	8.5	1 818	- 40	1.63	22.1

calibration is tested by using the calibration derived from one year in subsequent years. Table 4 shows how the calibrations have changed over three particular zones as data from more years became available. In interpreting the comparisons between gauge measurements and satellite estimates of rainfall the ability of the gauge to represent pixel area rainfall must be considered, see FLITCROFT, MILFORD & DUGDALE, 1989.

6 - SELECTED RESULTS

A complete set of tables for the TAMSAT operation over West Africa during the rainy season of 1994 is shown in Annex I. To help their interpretation, the results for calibration zone 2 (see fig. 1) in July which are shown in table 3 are discussed. Note that both the estimated and actual gauge rainfalls are allocated to 10 and 20 mm wide bands, emphasizing that a gauge can only provide an estimate of the average rainfall over a pixel with this order of accuracy. Various indicators of the success of these pre-calibrated estimates are shown below in table 5.

The indicator to which is attached most weight is the count of the number of occasions when estimated and actual rainfall classes are the same, or one, two or three classes apart. Because of the inherent uncertainty in actual area values, a difference of one class is not significant. The occasions when the difference is less than two classes are therefore as good as may be obtained, while a difference of two classes indicates some useful information in the estimate. Table 5 illustrates the use of this score to show the performance of the TAMSAT method over a six year period for three zones (see fig. 1).

Table 5 - Validation scores for July for six years for three zones.

Year	N	exact	1 out	2 out	% < 2 out	% < 3 out	high > 1 out	low > 1 out	mean est.	mean gauge
Zone 1										
1987	224	116	62	23	79	90	19	27	11.5	10.9
1988	249	94	91	23	74	84	8	56	19.8	11.5
1989	263	102	86	49	71	90	28	45	16.6	12.9
1990	275	103	93	48	71	89	34	45	17.8	15.5
1991	349	149	112	41	75	87	28	60	14.4	10.4
1992	251	100	83	50	73	93	29	39	14.3	12.7
Zone 2										
1987	389	73	138	93	54	78	127	51	25.2	33.4
1988	424	78	129	101	49	73	62	155	45.7	31.6
1989	433	82	145	101	52	76	144	62	34.1	39.7
1990	409	93	140	92	57	79	86	90	44.9	38.8
1991	389	76	137	86	55	77	52	124	39.6	27.6
1992	263	56	80	78	52	81	44	83	42.6	32.7
Zone 3										
1987	269	47	84	73	49	76	66	72	42.6	39.8
1988	393	69	132	83	51	72	75	117	63.7	53.3
1989	391	65	125	103	49	75	79	122	57.9	50.0
1990	354	71	96	93	47	73	97	90	69.5	64.3
1991	336	63	87	94	45	73	80	106	62.7	49.4
1992	186	35	82	38	52	73	41	48	63.0	53.7

As a further indication of the accuracy of the estimates when averaged over the whole zone, the table compares the total rain measured in the gauges with the total estimated rain for the same sites. The values are also shown as mean values per decade and these are plotted through the season for each zone in figure 5. This shows that the estimates do indeed give good information on the variation through the season, and between years when averaged over these rather large areas.

The final piece of information in table 5 is the count of how many of the departures greater than 1 category out in the estimates are high or low. If the calibration is appropriate, these two classes will be similar in number.

When data from several years are available, a mapping procedure will show how widely a given calibration may be used and we can begin to reduce the area for which each calibration is calculated while maintaining our criterion of a minimum of 100 points to establish any one regression. Figure 6a shows an example where occasions of cold cloud without rain and rain without cold cloud have been plotted, using thresholds of - 40, - 50 and - 60 °C in turn. The need to subdivide the region, and to use different thresholds in different parts is clearly illustrated. Figure 6b shows the calibration zones recommended as a result of this exercise. Within each zone a regression gives the calibration coefficients.

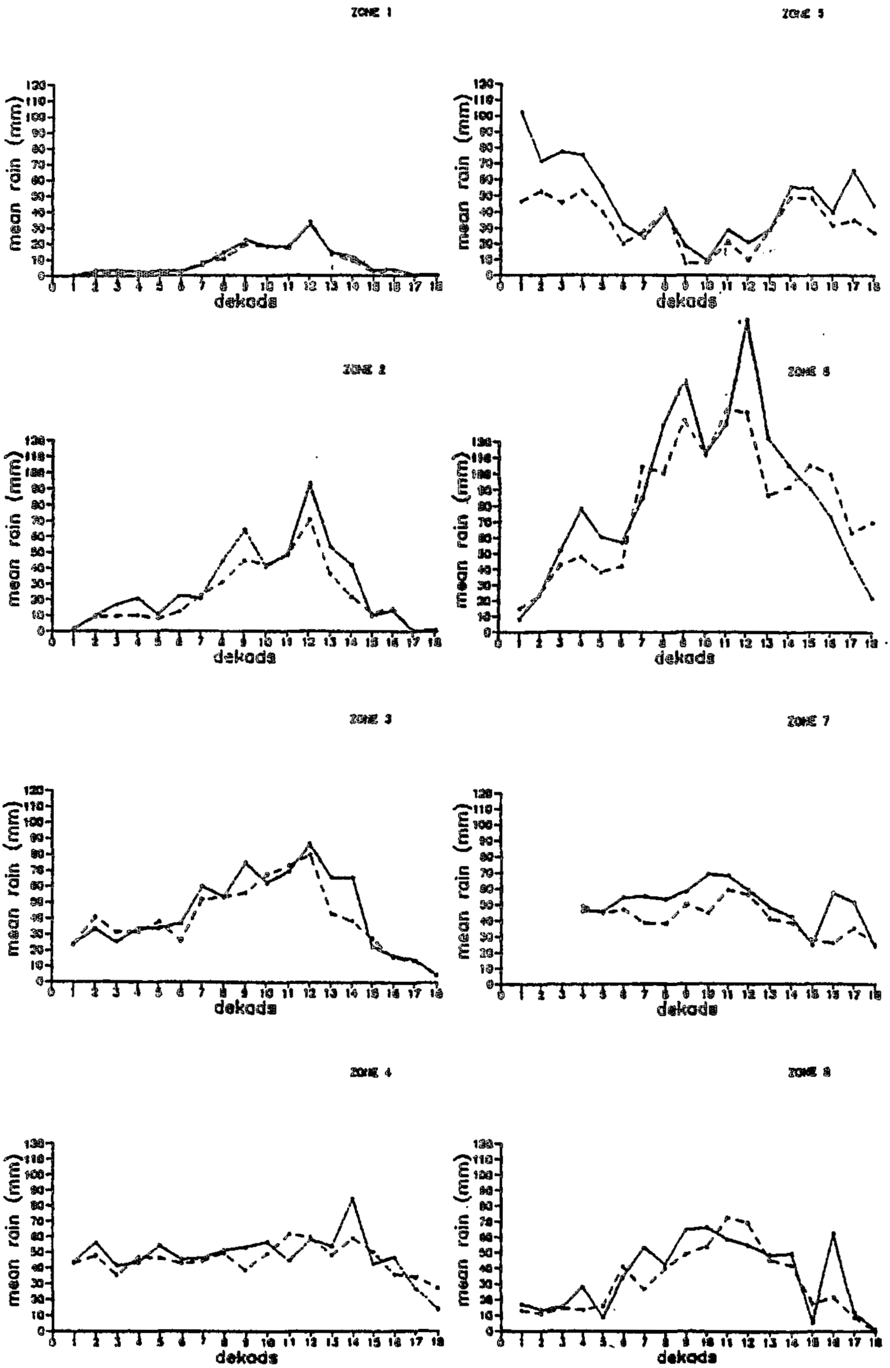

Figure 5 - Graphs of 1992 mean estimated and gauge rainfalls for all eight zones.
Gauge - solid, estimated - dashed, 1 = May 1st decade, 18 = Oct. 3rd decade.

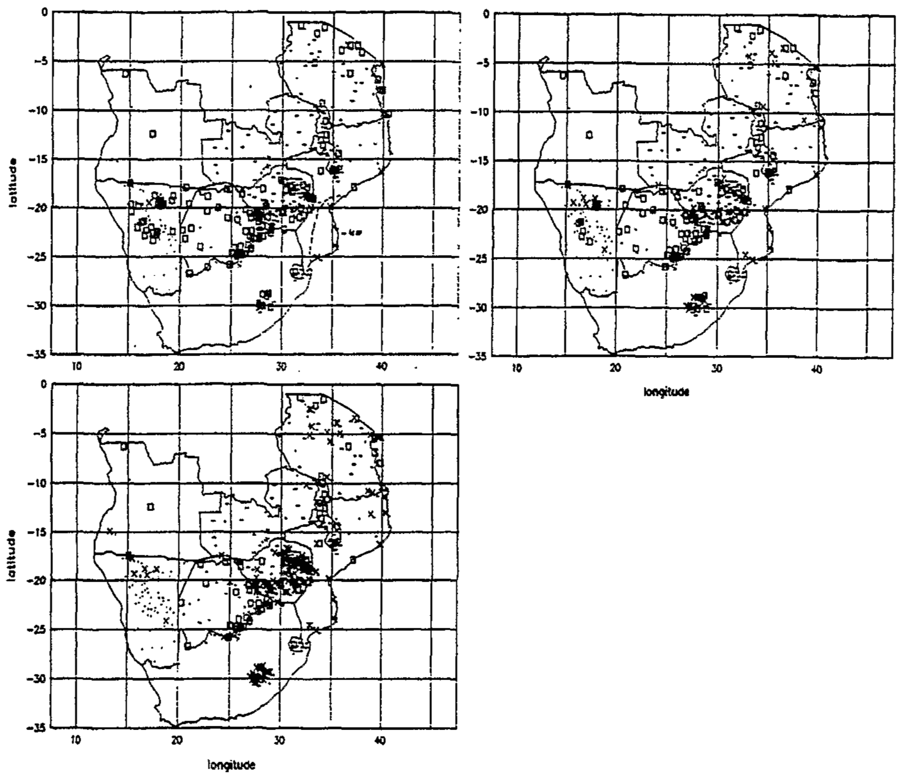

Figure 6a - Southern Africa showing zero/non zero maps from January 1991-1992 data.

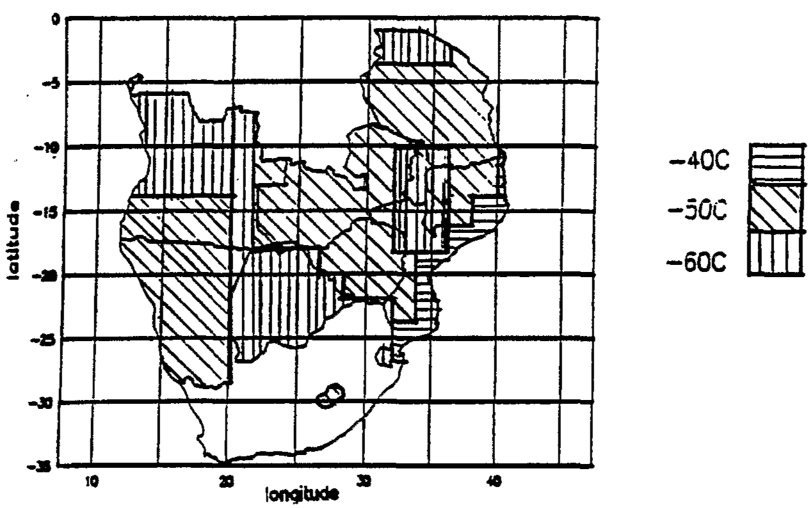

Figure 6b - Calibration zones recommended from maps in fig. 6a.

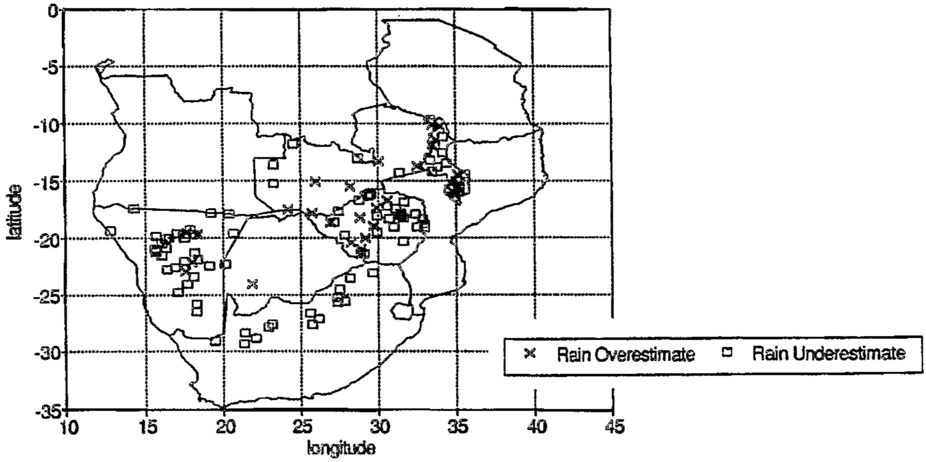

Figure 7 - Southern Africa validation.

A similar exercise is carried out, again using macros within Lotus or more sophisticated automatic plotting, to show where estimates, based on these calibrations, are consistently too high or too low in relation to observations. Figure 7 illustrates this process, and again shows the need for subdivision of the calibration area originally chosen as uniform, on the basis of threshold. Further subdivision may be needed to improve local calibration. Separate analysis might be carried out according to the user's requirement, i.e. whether the interest was specifically in drought and the occurrence of any rain at all, or whether it was in the amount of rain which had fallen for more general water assessment purposes.

7 - OPERATIONAL APPLICATIONS OF TAMSAT RAINFALL ESTIMATES

The emphasis on the different needs of different users has been a recurrent theme in TAMSAT discussions. The earliest operational application of the rainfall estimates was within Famine Early Warning Systems (FEWS) typified by the FAO ARTEMIS activities (VAN INGEN SCHENAU & VENEMA, 1986), by USAID FEWS and also by national systems in the Sudan and Ethiopia. Where extensive areas are dependent on rainfed agriculture but inaccessible from the capital for monitoring purposes, as in the west of the Sudan, the decadal indications of zero or minimal rainfall are clear indicators of threats to planted crops.

A development of the use of the rainfall estimates from CCD can give quantitative estimates and forecasts of the growth of natural vegetation over extensive grazing areas (such as in the Sahelian pastures). BONIFACIO, DUGDALE & MILFORD (1993) have used a regression model between biomass production, as indicated by standard NDVI maps, and accumulated plant water use, derived from rainfall estimates through a simple soil water budgetting procedure. The regression parameters appear closely related to the nature of the soil (and the resulting vegetation). For this application, which appears to have promise of operational utility over a rather narrow, but important zone in West Africa, the rainfall estimates should be optimized in the lower part of the range, as for Early Warning Systems. This is because the heavy storms, which are not well identified by our procedure, lead to runoff and deep percolation as a result of which the water becomes locally unavailable for subsequent use by local vegetation.

In two other practical applications the requirements for optimizing the information in the rainfall estimates are rather different. In the case of predicting favourable habitats for the desert locust, one criterion is that 20 mm of rain should have fallen. In a typical sandy soil this will penetrate far enough to reach dormant eggs, and lead them to start their development. The same amount is also likely to lead to a vegetative flush, such as is required to sustain the locust long enough to produce the next generation. In this application the likely distribution of falls about the area average is needed as well as the estimate of the average in order to state how much of the area is likely to have received the critical amount of rain (DUGDALE & MILFORD, 1990b). These criteria would have to be adjusted in areas where run-off from impermiable ground may result in accumulated soil moisture of 20 mm in depressions even though the area rainfall may have been only a few mm.

The final example is that of rainfall-runoff modelling where the rainfall over a shorter period, typically a day, is estimated over the area of a hydrological catchment or sub-catchment. Early results from Senegal (HARDY, DUGDALE, MILFORD & SUTCLIFFE, 1989) suggested that similar accuracies in the output from a runoff model may be obtained whether the satellite-derived or raingauge-derived estimates of areal rainfall are used as the input. More recent work (GRIMES, 1992) reinforces this, but also shows that more work has to be done to use recognized storm and catchment characteristics to optimize the method. Better estimates of evaporation will also help the prediction of seasonal flows, but quantification of extreme storms which give rise to the most damaging, local flooding will require a much more substantial meteorological input.

8 - CURRENT DEVELOPMENTS

Figure 6 has already provided examples where homogeneous calibration regions can be identified on a much smaller scale than that required by the international monitoring schemes prevalent to date. This localization of the estimates is best done by national teams which know the local needs and the effects of topography even on the scale of a few pixels. Considering the modest price of a receiver, or of disseminating CCD images from a regional receiver, much more could be done to develop operational information on this "district" scale.

The limited improvement shown by more elaborate regression methods have been mentioned above. In fact, it is hoped that the purely statistical approach is only the first step towards the measurement of rainfall from satellites, and that the application of our knowledge of atmospheric dynamics and thermodynamics will help to improve estimates in future. Considering the synoptic context of the cold clouds would seem appropriate: for this to lead to an operational methodology an objective analysis such as that provided by any global model is required, and we are now starting to explore such an approach.

A word of caution is needed on the evaluation of different methodologies, or of improvements to a procedure. Very often little more than a comparison of correlation coefficients is shown, and these are based on limited data sets. Because of the stochastic element in all aspects of rainfall, differences in correlations, or scoring of "correct" estimates can only be claimed as significant if they persist over a number of similar data sets.

9 - CONCLUSION

To date TAMSAT has concentrated on a single, thermal infrared channel because this has been the only one available on an hourly basis with significant information. While the scientific basis has been admittedly simplistic, the linear regressions between cold cloud duration and gauged rainfall have consistently given information with useful content for a number of operational and decision-making activities. It seems appropriate to continue with the production and dissemination of these estimates at the same time as we try to improve them from current data sources, prepare for the arrival of better data, as from the METEOSAT Second Generation satellites. Discussion of ways in which the estimates can be used, even with a realistic assessment of their accuracy, and continued validation are also activities which have to be continued on as wide a basis as possible.

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