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Precipitation estimation with AVHRR data: a review

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Abstract

A review of remote sensing techniques using AVHRR data to obtain information about precipitation is presented. Each technique is described and discussed, particularly from the point of view of the original contribution of using AVHRR data rather than other radiometric VIS/IR data. Other applications of AVHRR or similar data to study clouds are reported and their utility in the precipitation problem is discussed.

1. INTRODUCTION

In the past few years several algorithms have been developed to estimate precipitation from satellite Visible (VIS) and/or Infrared (IR) radiometric measurements (see for example: Arkin 1979, Garand 1989, Griffith et al. 1978, Adler and Negri 1988, Wu et al. 1985). The majority of such algorithms make use of data from geostationary satellite; this is mostly due to the good time and space coverage of such data compared to other satellite systems, for example the NOAA polar satellites.
The data from the Advanced Very High Resolution Radiometer (AVHRR), on board of NOAA series polar satellites, differ from the radiometric data from geostationary satellite in their better space resolution as well as in the number and wavelength of the channels (see Tab.1). There are reasons to believe that those qualities can improve the estimation of precipitation from VIS/IR passive radiometry.
As part of a study to establish whether or not the AVHRR data can give a significant contribution to the remote sensing of precipitation, a review of AVHRR studies on precipitation is presented. Moreover, because of the planned channels for the Meteosat Second Generation (MSG) Radiometer are very similar to those on the AVHRR, the results of such a study are expected to be useful also for MSG algorithm development.
Generally speaking, the estimation of rain amounts from satellite basically depends on both the delineation of raining areas and the estimation of rainfall rates. Hence, studies concerning not only the quantitative but also qualitative description of raining areas are considered. Each study is described briefly and discussed particularly in terms of: origin, data used, products, validation process and results and limits of validity.

2. PRECIPITATION STUDIES

Inoue. The method (Inoue 1987) is based on the intuitive idea that optically thick clouds have a large probability of rainfall: rainfall areas are defined as those covered by classified optically thick clouds (cumulus or cumulonimbus).

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The cloud classification method is based on a threshold technique in the two-dimensional space whose axes are the brightness temperature of the 11 μm channel (T4) and the difference between the brightness temperature in this channel and in the 12 μm one (T4-T5). To avoid the ambiguity due to any misregistration present between the window channel, the average of a 2x2 pixels box is used in the classification.
Fig.1 shows an example of a classification diagram: the area referred as "non-classified" is described as due to either low-level black cloud overlaid by very thin cirrus cloud, or low-level cloud not sufficiently thick to be considered as black cloud, or low level black cloud which partially fills the field of view of the instrument.
Two external parameters are needed in this scheme: the temperatures at 400 (T_{400}) and 700 hPa (T_{700}). The last one has been demonstrate (Inoue 1987) to be useful in the detection of warm rain over the Pacific Ocean. The climatological T_{400} is used for high/low level discrimination, while the maximum T4, in a subarea, assumed to be a SST (Sea Surface Temperature) estimate, minus 5 K, is used as the low level threshold (T_{700}). It can be observed that the delineation of the precipitating area, as well as the area covered by non-precipitating cirrus, are strongly dependent on the definition of those temperatures.
The technique has been developed and validated during the summer over the Western Pacific Ocean. Because of the area of interest of the study (tropical oceans) no middle-layer clouds, such as altocumulus, were considered.
The technique does not give quantitative values of rain-rate but only a delineation of raining or non-raining areas.
A quantitative comparison with radar data (six single image cases), in terms of success indexes is presented in the paper (Inoue 1987). Also a comparison with the results obtained with a simple IR threshold technique, applied to the same cases, is reported in order to discuss the improvement due to the use of the proposed technique.

Kakane and Imbernon. This study (Kakane and Imbernon 1992) is based on the assumption that precipitation affects the land surface temperature through evapotranspiration.
Therefore, a linear relationship between surface temperature (T_s) and the accumulated precipitation (P) measured at the ground to produce rainfall maps was sought.
The technique uses the AVHRR data because it assume the possibility to compute the surface temperature corrected for atmospheric effect.
The algorithm consists of three parts:

- Computation of the surface temperature using the equation:
$$T_s = 2.84 + T4 + 2.77 \cdot (T4 - T5)$$
- Synthesis of a map of the maximum surface temperature, for each pixel, occurring in a 15-day period, in order to eliminate cloud-contaminated measurements and minimize the effects of atmospheric absorption from water vapour.
- Linear regression between T_s (accumulated) and P (accumulated) to determine the regression equation.

Fig.2 shows an example of scatterplot and regressed line between accumulated T_s and accumulated P.
The technique has been developed using meteorological data (83 stations) and associated AVHRR images over Senegal. The period analysed was from 15 June to 15 October. No validation of the method is given. Regression equations are computed for different interval length (15 days to 3.5 months) but the stability of the regression coefficients is not discussed.
The use of the AVHRR data it is not really justified: there is no need for an *exact* measurement of T_s for such a regression approach, moreover such a measurement is not probably taking into account the spectral emissivity of the land surfaces.

The results are interpreted only in terms of the effect of evapotranspiration in diminishing the surface temperature: the impact of changes in surface emissivity, for example due to vegetation coverage changes, is not mentioned.

Karlsson. This precipitation estimate is a by-product of a more complex image classification scheme operational at the Swedish Meteorological and Hydrological Institute (SMHI), developed between 1984 and 1988 in a systematic long term study of multispectral signatures (Karlsson and Liljas 1990, Karlsson 1989).
The scheme is based on 6 features including all the channels, used as single value or combined with other channel measurements, plus the texture (for the definition see: Karlsson and Liljas 1990) of channel 4 for a 5x5 pixels box (see tab.4). The classification scheme also need the appropriate sun elevation and season classes (respectively 12 and 4 in total) and the values of the temperature at 700 and 500 hPa (those value are obtained from the latest available objective analysis).
Although a maximum likelihood classifier was initially considered, the actual classifier technique is a thresholding algorithm. It was found that the probability distributions of many objects were not gaussian and therefore can be better treated with a thresholding algorithm, as long as the class distribution is described by a number of sub-classes. Furthermore, thresholding algorithms are found to be more suitable for operational use.
The final product is a classified image with 23 classes, some of which are also subdivided in subclasses (see tab.3). An example of cloud classes definition, in the $(T_3 - T_4)$ versus $(T_4 - T_5)$ feature space, valid for winter night is shown in Fig.3.
Some of those classes/subclasses are associated with three qualitative precipitation categories: 'light, moderate and heavy'. This association is based on the U.K. Met. Office Obs. Guide 1982. Then, from a scheme developed at SMHI to interpret synoptic surface observations, the following quantitative estimates of rainfall rate are associated with the precipitation intensity classes: light=3, moderate=10, heavy=20 mm/3hr (Karlsson 1992, personal communication).
In Tab.2, the 23 defined object classes are reported with their relative precipitation intensities.
The method has been developed over the Scandinavian Region for all the seasons.
A qualitative comparison of the AVHRR precipitation products with an analysis of surface observations, has been presented for one case (Karlsson 1989).
The algorithm requires a period of training.

Kerr et al. The intuitive concept on which the technique (Kerr et al. 1989) is based is that vegetation change is due to the availability of water. This concept is limited to particular geographical regions and assumes no irrigation.
The parameter used is the Global Vegetation Index (GVI), defined as the time composite of the Normalized Difference Vegetation Index (NDVI) (Schneider et al. 1981). Therefore the AVHRR channels used by this technique are CH1, CH2 and CH4 (for cloud screening purposes).
For a number of selected locations (59) where rainfall measurements were available, monthly values of GVI have been related, with a simple linear relationship, with the corresponding rainfall measurements. The same was done using accumulated values (up to 4 months). An example is shown in Fig.4.
The technique was developed for use in Senegal and the data were collected during the period May-October.
Two different linear relationships are reported corresponding to the different accumulation periods, i.e. 1 and 4 months. The coefficients are very different.
The final product is a map of accumulated (over a given period) rainfall over land and therefore, assuming a validity of the algorithm, can be only used for climatological applications.
No validation is reported.

Due to the nature of the approach the method is limited, not only to land surface areas, but to limited geographical regions where a well-defined vegetation cycle, together with absence of irrigation, can be found.

Pylkkö and Aulamo. This study (Pylkkö and Aulamo 1991) consists of the application of the algorithm presented by Garand (1989) using VIS and IR measurements from GOES geostationary data. This is a day-time algorithm with a limit of applicability given from a sun elevation angle $\theta_{\odot} > 8^o$. In the study, the same algorithm was applied to AVHRR and to METEOSAT data.
The AVHRR channels used are CH1 and CH4. Brightness temperature and albedos are calibrated using coefficients provided by NOAA, but the albedo was also corrected using solar zenith angles. A segment size of 11x11 km^2 (50x50 km^2 when using METEOSAT data) is used in order to detect both synoptic and convective rain.
The cloud fraction is calculated by using the albedo value of 0.22 as a threshold for cloudy pixels. The algorithm gives the probability of precipitation (POP %) and rain is assumed for POP > 40 %. The table used is shown in tab.3. Apart for one albedo class, a negative dependence of the POP with cloud top temperature is used.
The results were validated using qualitative comparisons with present weather parameter from 3-hr synoptic observations.
The technique not only does not make use of the multispectral properties of the AVHRR data but also degrades the pixel resolution.

In Tab.4 a summary of the AVHRR precipitation studies is given.

A paper (Sunde and Haga,1991) has been presented, mentioning the use of precipitation information obtained from AVHRR data, but no information about the technique applied are available in either the paper or from several personal enquires.

3. <u>CLOUD STUDIES</u>

Other applications of AVHRR or similar data to study clouds are reported in the following.

- Using radiative transfer theory, several studies have been performed to relate AVHRR multispectral measurements to cloud optical properties (Hunt 1973, Wu 1985, Yamamonouchi et al. 1987, Prabhakara et al. 1988-1990, Parol et al. 1991, Stone et al. 1990). Those studies, often supported by observations, can facilitate the determination of the phase of the cloud or of the optical thickness of the cloud, making *apriori* assumptions about the cloud droplet size distribution and scattering properties. The parameters used are the differences T4-T5 or T3-T4.

- Several empirical cloud classification/detection schemes have been developed using different AVHRR channels/combinations (Ebert 1988, Saunder and Kriebel 1988, Olesen and Grassl 1985, Derrien et al. 1989). The characteristics of the required variables (cloud types) are identified, both in the development and, if present, in the validation phase, using human subjective analysis. However, some of the results from the radiative transfer studies mentioned above, also if is not used in the algorithm development, are generally consistent with empirically developed cloud classification schemes.

- A parameterization scheme to derive both cirrus optical thickness and stratus liquid water path from the reflectance in the AVHRR channel 1 has been presented by Kriebel et al. (1989). The algorithm requires the reflectance to be measured at wavelengths outside the water vapour absorption band ($\lambda < 0.75\mu$m) and therefore could be also applied to some of the VIS data from a geostationary satellite (see Tab.1).

- The emissivity of liquid water clouds in the 3.7 μm window is lower than that at 10 μm: this allows fog or low stratus cloud to be distinguished from the background surface in the channel 3 image or the information to be displayed using an image of the brightness temperature difference between channels 3 and 4 (Eyre et al. 1984, d'Entremont and Thomason 1987, Ellrod 1992).

- Channel 3 brightness temperatures can be used to study cloud properties during day-time, because of the great variation of forward and backward scatter with drop size and because of the difference in reflectivity between cloud water droplets and ice crystals. The observation of convective areas using channel 3 during day-time has been described by several authors (Scorer 1987, Setvak and Doswell 1991). When cloud tops contains drops greater than 20 μm, which begin to grow rapidly into fallout particles, they cease to reflect and, hence, appear darker. The same thing happens when clouds freeze.

  No quantitative algorithms have used this information. However, the presence of precipitation has been inferred from the use of such data.

  It should be noted that the upgraded AVHRR instrument to be launched on NOAA-K (and subsequently) will provide radiance measurement at 1.6 μm, instead of 3.7 μm, during the day-time.

4. CONCLUSION

A review of the use of the AVHRR data to estimate precipitation from satellite has been performed as a starting point for the development of an AVHRR-based algorithm. The result of such a review is that despite an abundant use of AVHRR for cloud discrimination and/or classification, very few applications of AVHRR data to measure precipitation have been done.

The reviewed techniques can be divided into two classes:
- those (Inoue 1987, Karlsson 1989, Pylkkö and Aulamo 1991) using the observation of the *causes* (cloud) of the precipitation to retrieve it;
- those (Kakane and Imbernon 1992, Kerr et al. 1989) using the *effects* (vegetation growth/changes in surface temperature) of precipitation to retrieve it.

For real-time applications, the techniques using observation of the *effects* of precipitation are not suitable. Moreover, it can be observed that the two *effects-based* techniques reviewed are:
- not sufficiently validated;
- limited to land surface only;
- based on assumptions that are in conflict, namely, for the same area and same season, the technique presented by Kerr et al. assumes a change in vegetation, presumably resulting with a change in surface emissivity, but Kakane and Imbernon seem to assume a constant surface emissivity in interpreting the surface temperature variation only in terms of evapotranspiration.

Because no available visible channel data are currently absolutely calibrated and because of the inadequate knowledge on the bidirectional reflectance of clouds, the quantitative use (for example, applying results derived from radiative transfer models) of the visible data is limited. A discussion on the sources of error in using AVHRR visible data is given in Kriebel et al. (1989).

Several authors (Inoue 1987, Karlsson and Liljas 1990, Prabhakara et al. 1988, Derrien et al. 1989) agree in using split window data for the discrimination of optically thin ice clouds. Even the threshold values, despite the very different geographical areas and seasons of validity, seem to agree.

The advantages of AVHRR data compared with geostationary data due to multispectral properties of the radiometer are therefore:
- better discrimination between water and ice clouds
- information about the optical thickness.

Such information is obtainable, mostly, from combinations of the AVHRR channels 3, 4 and 5. On the other hand, the full use of multispectral properties from geostationary radiometric data, as, for example, the use of the METEOSAT WV channel in precipitation studies has not been widely investigated (Papadakis et al. 1992, Cheng 1990).

An advantage of AVHRR data compared with geostationary data should arise also from the higher spatial resolution. However, very limited use of spatial information (Karlsson and Liljas 1990, Ebert 1988, Lovejoy 1992) has been made. This could be related to the difficulty in preserving spatial information through the distortions introduced by the scanning geometry, as well as to the difficulty of observing large scale structure (eg cyclones) because of the limited width of each scan. The possibility of applying the results from studies carried out using geostationary satellite data (see for example: Burnfeind et al. 1987, Seze and Desbois 1987, Garand and Weinman 1986, Wu et al. 1985) should be considered.

The use of temporal information (see eg Griffith et al., 1978) is limited by the poor time sampling but it will be solved once the instrument will flies on geostationary platforms.

Due to the opacity of clouds, particularly when precipitating, in the VIS/IR spectrum, there are theoretical limitations to the information about precipitation that can be obtained from satellite radiometric measurements at those wavelengths. Nevertheless, much other information about the cloud (eg phase, space/time evolution, optical thickness) can be retrieved from multispectral VIS/IR radiometric data.
Such information is only indirectly related to eventual precipitation, however, together with a better knowledge of physical precipitation processes can be used to infer precipitation.
For example it is expected different algorithm depending upon the precipitation type (convective, stratiform, etc.).

The lack of indirect information of the VIS/IR radiometric data about the precipitation can be improved by the use of external sources of data, for example numerical weather analysis/prediction model products. The use of such data has, however, been limited to the use of temperature at different levels to tune thresholds.
Other application should be investigated. For example, because of the expected correlation between the water vapour vertical distribution and the location of precipitating areas, within a cloud system, investigations should be done about algorithms using products from numerical weather models together with satellite radiometric data.

As demonstrated from this study, the ability of AVHRR-like data to infer precipitation has been investigated only superficially: further research is, therefore, needed to establish the effective potential of the use of such data.
The interest in using AVHRR data for precipitation estimates comes mostly from Scandinavian countries, due to the poor quality of geostationary data at their latitude and the number of orbits available from polar orbiting satellites (eg Pylkkö and Aulamo (1991) used the AVHRR data simply as a substitute to geostationary data, not taking full advantage of the multispectral properties of the radiometer). This makes the validity of the algorithms developed locally limited; in addition, the extension of such algorithms to different areas was not considered.
Nevertheless, the technique developed at the SMHI (Karlsson 1989) can be considered to sub-

sume the approach used in Inoue (1987) and Pylkkö and Aulamo (1991) as well as most of the concepts underlying the AVHRR-based cloud studies reviewed previously (See Section 3). Validation studies of such a technique should, therefore, be extended to different areas and climatological conditions. The stability of boundaries between the classes should also be studied. Of the investigated techniques, only one (Inoue, 1987) was presented with a quantitative validation, albeit, one limited in area and season. This is due to the lack of good validation data sets and techniques.
The GPCP-AIP/2 Campaign (WMO 1989) first introduced the AVHRR as potential satellite radiometric data for precipitation estimate. The results of the campaign will be the first quantitative comparison of AVHRR-estimated precipitation against ground truth data as well as against other radiometer based algorithms and will provide a complete and documented data set for further studies.

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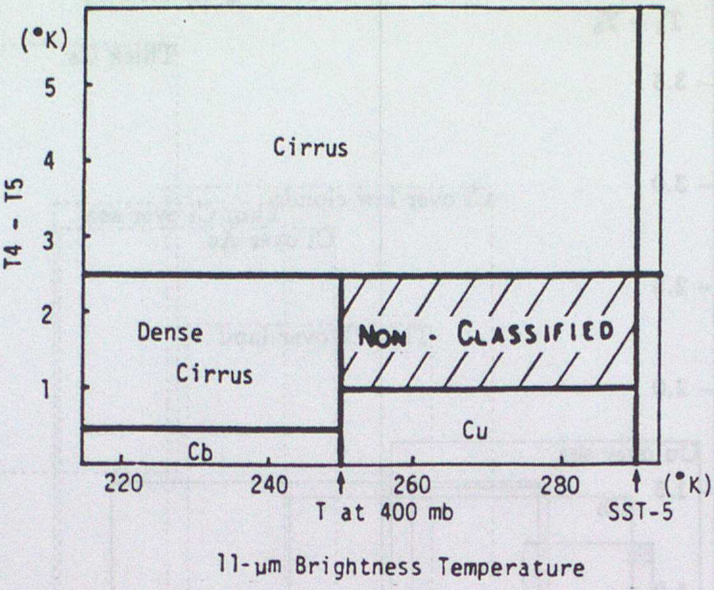

Figure 1: Schematic two-dimensional diagram for type cloud classification (from Inoue 1987).

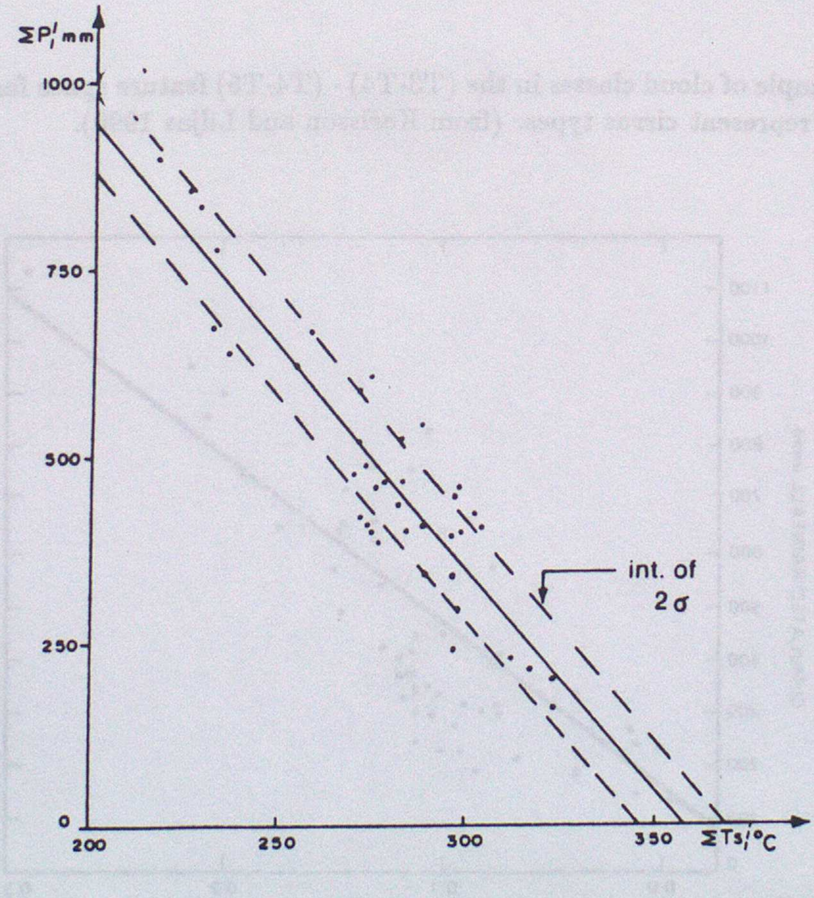

Figure 2: Example of relation between accumulated rainfall and accumulated Ts in Senegal for the period 15 Jun. - 30 Sep. 1987 (from Kakane and Imbernon 1992).

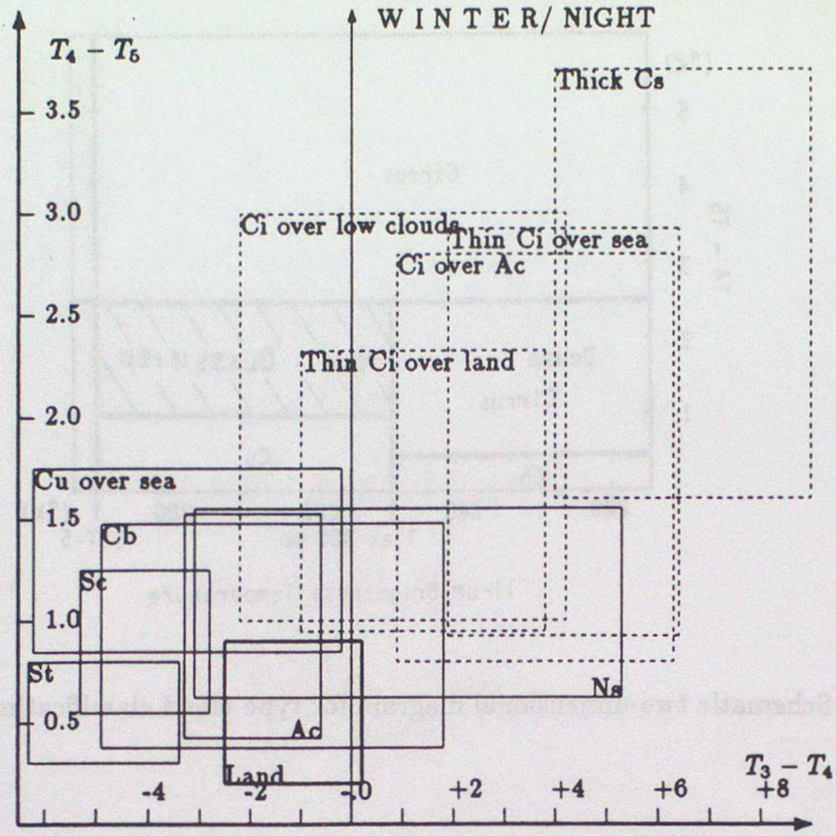

Figure 3: Example of cloud classes in the (T3-T4) - (T4-T5) feature space for winter night cases. Dashed boxes represent cirrus types. (from Karlsson and Liljas 1990).

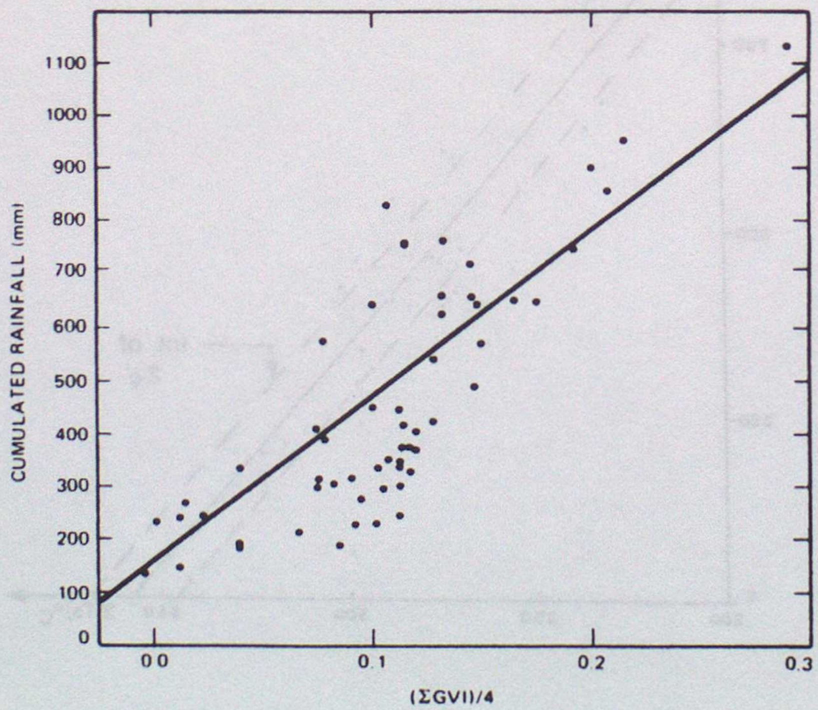

Figure 4: Exaple of scatterplot of cumulative rainfall vs GVI for 59 ground stations in Senegal for the period Jun.-Sep. 1986 (from Kerr et al. 1989).

Table 1: Meteorological satellite VIS/IR radiometers used for precipitation studies: channel band limits [μm] and maximum resolution [Km].

Mission/Radiometer	VIS		NIR	WV	IR	
METEOSAT	0.5-0.9		-	5.7-7.1	10.5-12.5	
	2.5		-	*5.0*	*5.0*	
GOES/VISSR	0.55-0.70		-	-	10.5-12.6	
	0.9		-	-	*8.0*	
GMS/VISSR	0.50-0.75		-	-	10.5-12.5	
	1.25		-	-	*5.0*	
TIROS-N/AVHRR	0.58-0.68	0.725-1.1	3.55-3.93	-	10.3-11.3	*11.5-12.5*
	1.1	*1.1*	*1.1*	-	*1.1*	*1.1*

Table 2: Defined object classes in the SMHI data base and associated precipitation intensity (N: No rain, L: Light, M: Moderate, H: Heavy).(From Karlsson 1991, personal communication).

CLASS	RAIN	CLASS	RAIN
Open Sea	N	Cu congestus over sea	N
New Ice without snow	N	Small cumulonimbus	M,H
Snowcover	N	Extensive cumulonimbus	M,H
Winterforest	N	Altocumulus/altostratus	N
Land (snow free)	N	Nimbostratus	L,M,H
Mist over land	N	Thin cirrus over land	N
Mist over sea	N	Thin cirrus over sea	N
Fog/stratus	N	Cirrus over low clouds	N
Stratocumulus	N	Cirrus over middle clouds	N
Small Cu over land	N	Thick cirrostratus	N
Small Cu over sea	N	Sunglint	N
Cu congestus over land	N		

Table 3: Probability of precipitation (POP %) as a function of the mean albedo and the cloud top temperature (BT). The average fraction of cloud cover (%) in brackets (from Garand 1989).

	ALBEDO [%]					
BT [K]	0-25	25-40	40-55	55-70	70-85	85-100
205-235	5 (83)	9 (91)	18 (94)	28 (96)	59 (99)	65 (100)
235-255	5 (62)	7 (77)	16 (83)	32 (86)	47 (94)	62 (99)
255-275	0 (46)	3 (44)	14 (58)	20 (74)	35 (90)	49 (98)
275-295	0 (3)	3 (15)	10 (26)	15 (59)	22 (86)	32 (97)

Table 4: Summary of precipitation studies with AVHRR data. [Quantitative, qualitative - Land, Water - A_n/T_n: Channel n Albedo/Temperature - $.^{tx}$: texture - $\theta_\odot$ sun elevation angle -T_{xxx} Temperature at xxx hPa].

AUTHOR	DEVELOPMENT		VALIDATION			INPUT VARIABLES		PRODUCT	COMMENTS
	Area	Time		Area	Time	AVHRR	External		
Inoue	10-30N 120-140E W	Summer	Q	33-39N 135-140E L/W	Summer	$T_4, T_4 - T_5$	T_{700} T_{400}	Precipitating Area	No rainrate Tropical
Kakane & Imbernon	12-17 N 11-18 W L	Jun-Oct				T_4, T_5	No	Cumulative rainfall	No Validation Land only No real-time
Karlsson	54-70 N 8-24 E L/W	Year	q	54-70 N 8-24 E L/W	14.07.1990	$A_1, A_1 - A_2$ $T_3 - T_4, T_4$ $T_4 - T_5, T_4^{tx}$	$\theta_\odot$ Season T_{700}, T_{500}	Rainrate	No Validation Training required
Kerr et al.	12-17 N 11-18 W L	May-Oct				A_1, A_2 T_4	$\theta_\odot$	Cumulative rainfall	No Validation Land only No real-time
Pylkko & Aulamo (*Garand*)	*27-43 N* *57-80 W* *W*	*Winter*	q	40-70 N 20W-40E L/W	16.06.1991	A_1, T_4	$\theta_\odot$	POP %	No Validation Daytime only ($\theta_\odot > 8^o$)

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