Determination of Rainfall with the ESOC Precipitation Index

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ABSTRACT

A validation of the ESOC (European Space Operations Centre) Precipitation Index (EPI) is carried out by comparing satellite data with observed rainfall in five African countries to determine the possibility of estimating accumulated precipitation independently of the area considered. In the formulation of the EPI it is assumed that most of the tropical rain originates from deep and cold clouds. The scheme is a cloud indexing method based on the infrared channel, additionally including a stratification of data into three classes according to the Upper Tropospheric Humidity (UTH) obtained from METEOSAT 6.3 μm channel.

The results indicate that rainfall can be well estimated in the tropical area while more sophisticated methods are required for the subtropics. The stratification of the data according to the UTH constitutes an improvement which is particularly significant away from the Intertropical Convergence Zone (ITCZ).

1. Introduction

Knowledge of the accumulation and distribution of precipitation is of vital importance to agriculture worldwide. Its significance has been clearly demonstrated in Africa, where prolonged dry spells have severely damaged the crop yield during recent years.

The precipitation is an essential parameter in a number of meteorological fields. Climatological and general circulation studies and the validation of numerical weather prediction models need accurate information on precipitation. Tropical precipitation is of particular importance to estimate midtropospheric diabatic heating, a major forcing mechanism of the general circulation of the atmosphere. Unfortunately, the coverage of the conventional network of rainfall stations has remained poor in many regions, particularly in the tropical ocean areas, and fresh approaches to determine precipitation have to be sought. Remote sensing seems to be a promising option. Good results could be obtained using radar, but considering its high cost, limited coverage, and the necessity to calibrate it against a high density rain gage network, this solution would only be applicable to limited areas. For global precipitation monitoring, the geostationary satellites appear to be the only well-suited avenue, due to their excellent temporal and spatial coverage.

A number of scientists have already used data from geostationary satellites to estimate precipitation (e.g., Arkin, 1979; Stout et al., 1979; Griffith et al., 1981). Many of their schemes are, however, based on the individual tracking of cloud entities throughout their lifetimes, which requires substantial computing resources. Therefore, they are feasible for use only in deriving rainfall estimates over limited areas and time periods. The scheme has to be relatively simple if the coverage is semi-global and the sampling is made frequently for a long period of time. The approach proposed by Arkin (1979) constitutes a feasible solution for the global scale. He has shown that the fractional cloud cover colder than a certain temperature threshold is proportional to the accumulated precipitation. The scheme is proved to be reliable if it is integrated over an area larger than 150 × 150 km and over a time longer than 24 hours (Richards and Arkin, 1981).

There are, however, some limitations in the study by Arkin. First, the scheme has been tested only for the limited area of the GATE experiment. Second, the cloud top temperature is the only parameter considered, although two clouds with the same temperature can result in varying precipitation accumulations depending on the orography, wind shear and moisture conditions. The role of the humidity has been emphasized by Adler and Mack (1984), and the upper tropospheric humidity (UTH), readily available from the METEOSAT 6.3 μm channel, is included in the European Space Operations Centre (ESOC) Precipitation Index (EPI). The METEOSAT Exploitation Project (MEP) is described in detail in a paper by de Waard et al. (1984).

The purpose of this paper is twofold:

1) To validate the EPI, i.e. to convert the fractional cloud cover into rainfall, in five geographical locations and to find out whether the precipitation can be esti-

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mated with an identical method, independently of the area considered. This is crucial if precipitation mapping over the whole tropical zone is envisaged.

2) To investigate the importance of humidity in the determination of the accumulated precipitation.

The inclusion of the humidity (UTH) in the EPI is a unique feature of any precipitation index produced so far.

This paper consists of three main sections: the description of satellite and ground truth data, the presentation of the results from the validation process, and the conclusions.

2. Data

Both satellite and ground truth data have been collected for the test period from 3 October until 26 December 1985, with a gap between 22 and 26 November due to the nonavailability of the precipitation index. The data originates from five African countries: Ivory Coast, Kenya, Senegal, Morocco and Tunisia. The location of each country is displayed in Fig. 1. Ivory Coast and Kenya lie in the equatorial region, influenced by the fluctuations of the intertropical convergence zone (ITCZ), where most of the precipitation is convective. Morocco and Tunisia are situated in the subtropical zone where convection is supplemented by occasional frontal passages. Senegal has a semi-arid climate, which is only tempered by convective rains from the ITCZ in late summer.

a. Satellite data

For ease of processing, the METEOSAT image is divided into segments, fixed in space, consisting of 32 × 32 IR pixels. Most of the meteorological products extracted are determined on segment basis (de Waard et al., 1984). Similarly, the EPI was calculated on segment basis and stored for the whole test period for those segments that fitted wholly into the five aforementioned African countries.

The original feature of the EPI is the incorporation of the UTH, which is determined on the basis of the radiance in the METEOSAT 6.3 μm channel. The average value of the radiances is first determined for each segment. The value is then converted into the UTH, calibrated against all the available humidities from radiosondes. The UTH represents the mean humidity in the layer between 70 and 30 kPa (Fischer et al., 1981).

The EPI is a cloud coverage index, counted every three hours and summed over five days. The averaging interval (5 days) and the area (160 × 160 km^2) are well in line with the findings of Richards and Arkin (1981). The determination of the EPI is performed in two stages:

1) The fractions of pixels (5 × 5 km over the subsatellite point) with the effective blackbody temperature colder than 235 K in each METEOSAT segment are first counted as suggested by Arkin (1979). Forty numbers are obtained, each ranging between 0 and 1.

2) A class of UTH is determined for each three hours. The UTH ranges of 75%–100%, 40%–75% and 0%–40% are used. The fractions are segregated into the three classes according to what the UTH is each time. If the 6.3 μm channel is contaminated by clouds, the UTH is considered saturated. Thus the EPI consists of three indices, called EPI-moist (UTH: 75%–100%), EPI-normal (UTH: 40%–75%) and EPI-dry (UTH: 0%–40%). The index used by Arkin (1979), called EPI-all,

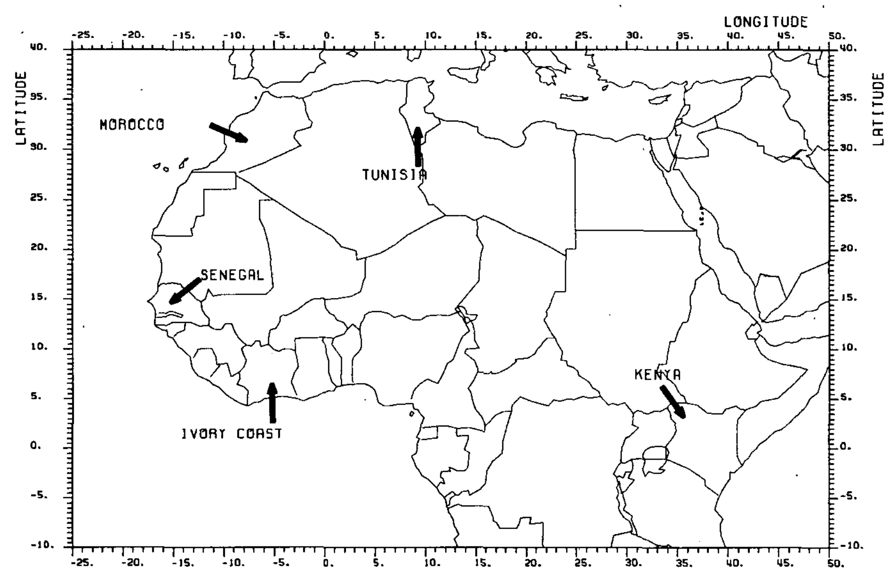

FIG. 1. The location of the five African countries studied.

is simply the sum of all the three indices, ranging from 0 to 40 for each five-day interval.

The same UTH ranges are used for all the five countries in spite of the highly variable climates, so it is important to explore whether all the UTH classes are well represented in each country. Clouds colder than 235 K are indeed occurring in an almost equal frequency in the three classes. In Kenya, for example, the contribution of the moist, normal and dry indices is 23, 41 and 36%, respectively. The corresponding values for Ivory Coast are 21%, 37%, 42%. Towards the subtropics the contribution of EPI-moist becomes dominant.

b. Ground truth data

Daily records from all regularly operating raingages from the five African countries were collected, amounting to 48 raingages from Ivory Coast, 38 gauges from Kenya, 34 gauges from Senegal, 44 gauges from Morocco, and 18 gauges from Tunisia.

The networks of the rain stations are well-suited for this study due to their fairly even distribution over the territories considered. To eliminate the local variation of the precipitation within each METEOSAT segment, only the segments with four raingages or more are considered. In addition, one segment from Senegal is excluded, since all the four stations are clustered in one corner, the rest of the segment being over the sea. Ivory Coast is represented by three segments (13 stations), Kenya by three segments (21 stations), Morocco by five segments (25 stations), Senegal by two segments (13 stations) and Tunisia by one segment (4 stations). The daily mean of observed precipitation is calculated for all the segments considered and summed over five days.

3. Results

a. General results

The test period consists of 16 five-day intervals. The variation of the precipitation and the EPI-all as a function of time is diaplayed in Figs. 2–6 for Ivory Coast, Kenya, Senegal, Morocco and Tunisia, respectively. The curves represent fluctuations of precipitations and EPI-all values, both of them averaged over all the segments considered. The EPI-all values are multiplied by a scaling factor of seven, arbitrarily chosen, used only for an improved visualization.

The variation of precipitation is depicted by the solid lines. The results from Ivory Coast show the displacement of the ITCZ southwards towards the end of the year. There is a distinct maximum in Kenya in November (intervals 6–11) (Fig. 3). The heavy rainfall can be related to the southward migration of the equatorial trough (Riehl, 1979). The segments from Morocco and Tunisia report light precipitation throughout the test period. In Morocco, however, during the latter part of the period slightly higher values of precipitation are recorded, due to the passages of midlatitude frontal systems. The solid line from Senegal (Fig. 4) indicates little precipitation, since the ITCZ lies well south of the country for the whole time.

The two curves presenting the mean precipitation and EPI-all values bear a close resemblance both in Ivory Coast (Fig. 2) and in Kenya (Fig. 3). The similarity is especially striking during the rainier periods. On the contrary, in Senegal the precipitation and the index seem to have a lesser correspondence (Fig. 4). The EPI-all remains well above zero for a number of five-day periods although no precipitation was then recorded. The cold nonprecipitating clouds can be associated to the subtropical jet, crossing Senegal during winter months (Riehl, 1979). Thick nonprecipitating jet stream clouds cannot be filtered out using the EPI-all only (see Fig. 4). In Morocco and Tunisia (Figs. 5 and 6), the two curves appear to be out of phase most of the time.

b. Overall statistics for each country

It is essential to further investigate the relationship between the observed rainfall and precipitation indices to explore whether the estimation of the precipitation based on the indices is feasible. The relationship can perhaps be best characterized with multiple and partial correlation coefficients. Therefore, they were determined for each country. If the correlation remains modest, it indicates that the precipitation cannot be determined with any linear combination of the indices. For clarity the results from the three tropical countries are discussed together. The same is true for those from the subtropical countries of Morocco and Tunisia. The complete test period and all the segments are considered.

The coefficients of the multiple and partial correlation are shown in Table 1 for the tropical areas (Kenya, Ivory Coast and Senegal). The multiple correlation between the observed precipitation amounts and three indices (EPI-moist, EPI-normal, EPI-dry) is fairly high, superior to the one calculated between the observed precipitation and the EPI-all. Due to the small samples, the difference is significant only at 20% level. This is an indication that the stratification of the EPI into three classes according to the humidity results in an improved correlation in comparison to the method proposed by Arkin (1979).

The values of the partial correlations vary considerably from one country to another and are rather low in certain cases. The partial correlation between the EPI-moist and the precipitation is low (less than 0.2) everywhere. An example is shown in Fig. 7, where the evolution of the EPI-moist and observed precipitation in Kenya through the test period is illustrated. The two curves indeed show little resemblance, except for the periods 11–14. Because the upper troposphere was

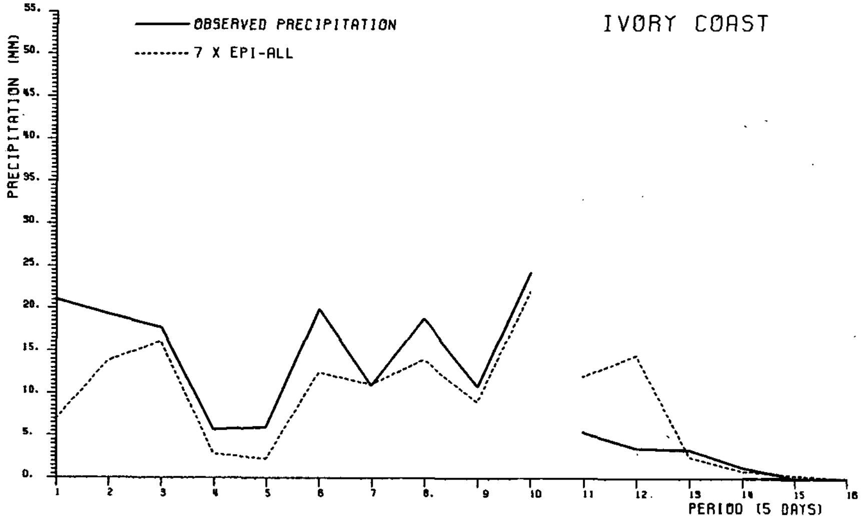

FIG. 2. The variation of the mean precipitation in mm (solid line) and EPI-all, multiplied by a scaling factor of 7 (dashed line) in Ivory Coast during the test period. Each time interval represents a 5-day period. The periods 1–6 correspond to the month of October, the periods 7–11 to November and the periods 12–16 to December, respectively. One 5-day period between 10 and 11 is missing.

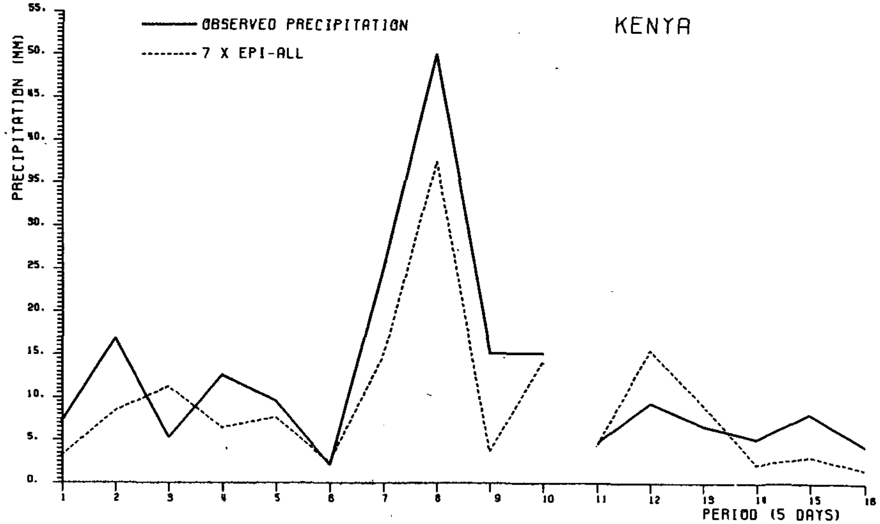

FIG. 3. As in Fig. 2 except for Kenya.

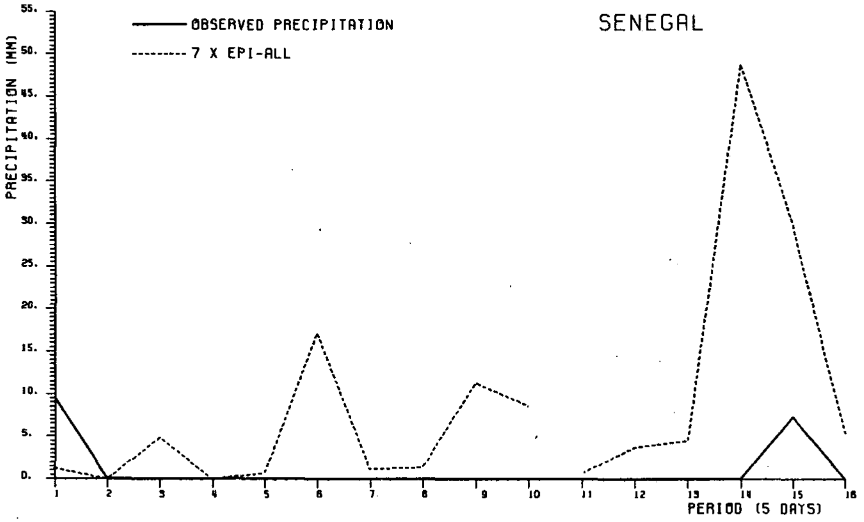

FIG. 4. As in Fig. 2 except for Senegal.

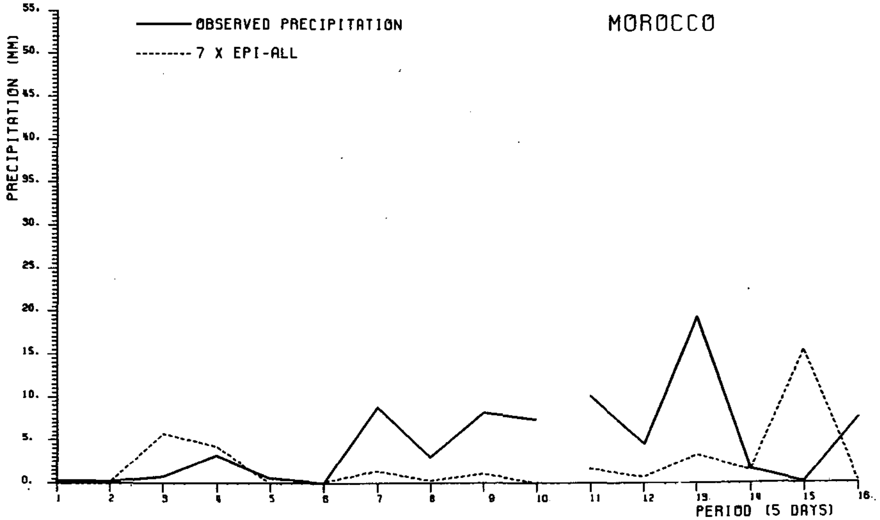

FIG. 5. As in Fig. 2 except for Morocco.

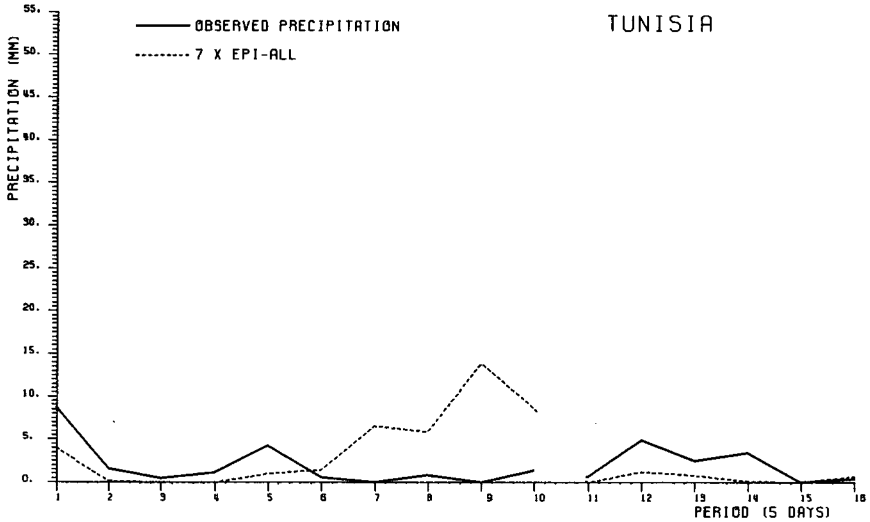

FIG. 6. As in Fig. 2 except for Tunisia.

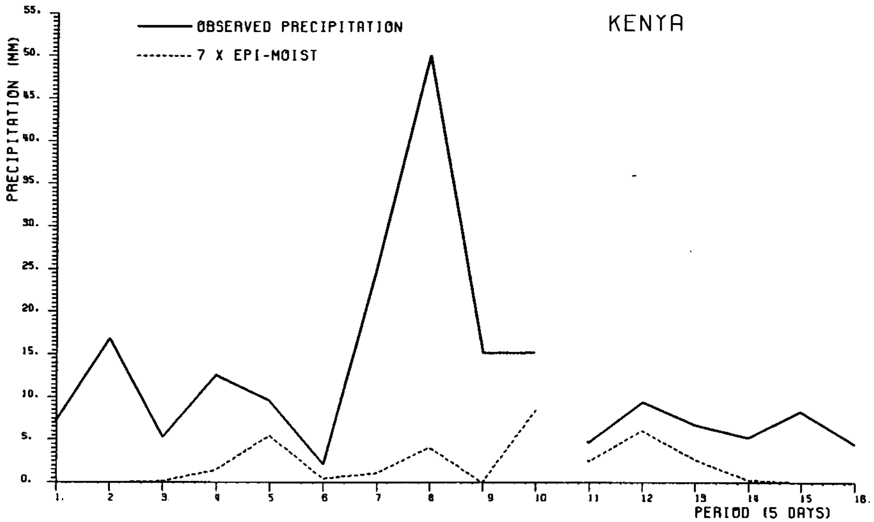

FIG. 7. The variation of the mean precipitation in mm (solid line) and EPI-moist, multiplied by a scaling factor of 7 (dashed line) in Kenya during the test period. Each time interval represents a 5-day period.

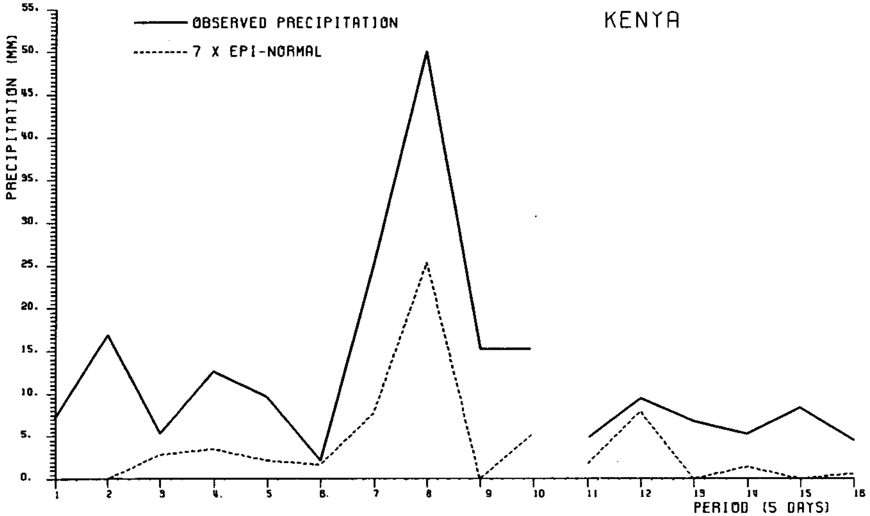

FIG. 8. As in Fig. 7 except for EPI-normal.

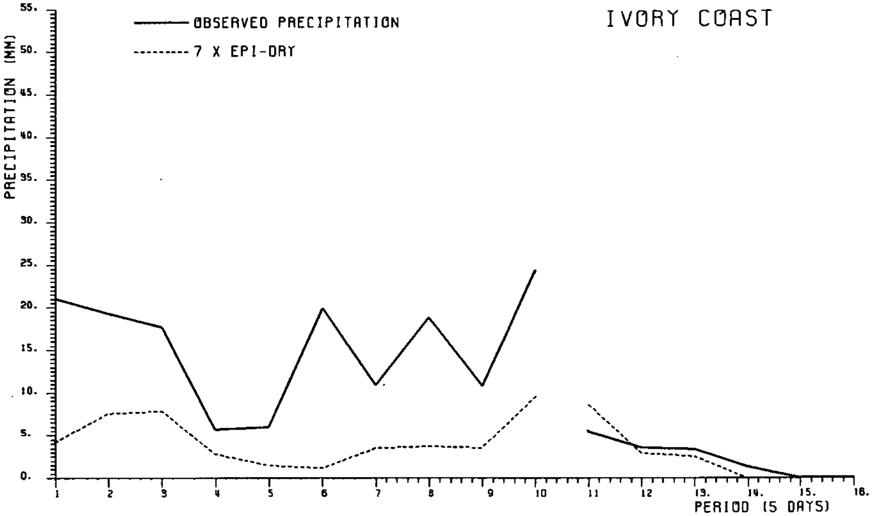

FIG. 9. As in Fig. 7 except for EPI-dry in Ivory Coast.

TABLE 1. Multiple (R) and partial (r) correlations between the observed precipitation (1) and EPI-moist (2), EPI-normal (3), EPI-dry (4) and EPI-all (5) in Kenya, Ivory Coast and Senegal. The notations conform to those by Spiegel (1961). The size of the sample is indicated in parentheses.

		Kenya (48)	Ivory Coast (48)	Senegal (32)
1	R 1.234	0.76	0.76	0.57
2	r 12	0.08	0.20	0.14
3	r 13	0.71	0.46	0.03
4	r 14	0.45	0.67	0.53
5	r 15	0.68	0.68	0.24

considered moist when the 6.3 μm channel results were contaminated by clouds, the poor correlation could be explained by the frequency of high nonprecipitating cirrus, contaminating the results from the 6.3 μm channel. The low correlation implies that the EPI-moist could be excluded, since it provides little information on precipitation.

The partial correlation between the EPI-normal and the precipitation is highly variable. An example is shown for Kenya in Fig. 8, where the value of the correlation coefficient is as high as 0.71, the largest contribution to the multiple correlation. In contrast to Kenya, the partial correlation remains low in Ivory Coast (0.46) and poor in Senegal (0.03).

The values of the correlation between the EPI-dry and the precipitation are fair over the three countries. Figure 9 illustrates the behavior of the EPI-dry and precipitation in Ivory Coast, where a reasonable agreement between the two curves prevails.

In Tunisia and Morocco, the linear multiple correlation between the three indices and the observed precipitation is rather low: 0.32 and 0.07 respectively. Similarly, the EPI-all and observed precipitation show little correlation. The poor results from Northern Africa are probably due to the predominance of midlatitude systems during the test period. In late fall the precipitation tends to be more frontal than convective. In frontal situations the cloud tops are often considerably warmer than the threshold considered (235 K). In these circumstances the method used fails to indicate any precipitation.

c. Estimation of the monthly accumulated precipitation

The estimation of the monthly precipitation is the final goal of the project. The statistical analysis has revealed the existence of a fairly good correlation between the precipitation and the satellite data only in Kenya, Ivory Coast and Senegal. The existence of a good multiple correlation is prerequisite to the successful estimation of the precipitation, so the estimation is restricted to these three countries. In Morocco and Tunisia the estimation of precipitation with a regression line is not justified due to the poor correlation between the indices and the observed precipitation during the test period. The method used in this study might yield acceptable results even in the subtropical areas if another season were considered.

To estimate the precipitation, the line of best fit has to be determined using the least-squares method. In this study three lines, in fact, are calculated:

i) The observed precipitation and the three indices,

$$P = (a \times \text{EPI-moist}) + (b \times \text{EPI-normal}) + (c \times \text{EPI-dry})$$

ii) The observed precipitation and the two indices, excluding the EPI-moist which seemed to contribute little into the multiple correlation,

$$P = (bb \times \text{EPI-normal}) + (cc \times \text{EPI-dry})$$

iii) The observed precipitation and the EPI-all,

$$P = s \times \text{EPI-all}$$

where a, b, c, bb, cc and s are the coefficients of the line of best fit and P the estimated precipitation.

In the formulation of the second equation it is supposed that the clouds from the moist and contaminated upper tropospheres contribute little to the total rainfall and that they can be ignored. This may be a way to filter out nonprecipitating cirri, a major problem in all the infrared cloud indexing schemes.

The regression coefficients relating the EPI to rainfall are depicted in Table 2. The values shown for Kenya, however, include only two segments, since in one segment the precipitation would have been strongly underestimated. This segment is located on the upwind side of the Kenyan mountains, a major arographic barrier in Africa (tops higher than 5000 m). Due to the predominance of the easterly flow, the ascending winds form precipitating orographic clouds, often warmer than 235 K; therefore this segment was excluded. Table 2 indicates that the values of the coefficients in Kenya and Ivory Coast are fairly similar, whereas in Senegal they deviate substantially from their

TABLE 2. The regression coefficients of the three lines of best-fit. The coefficients a, b, and c refer to the regression line between the observed precipitation and EPI-moist, EPI-normal and EPI-dry; bb and cc between the observed precipitation and EPI-normal and EPI-dry; and s between the observed precipitation and EPI-all. The size of the sample is indicated in parentheses.

	Kenya (48)	Ivory Coast (48)	Senegal (32)
a	1.2	1.2	0.0
b	8.5	6.6	−2.6
c	9.4	11.5	6.0
bb	8.8	6.9	−2.6
cc	9.3	11.7	5.9
s	7.1	7.3	0.7

counterparts. The coefficients also vary substantially with the UTH, being particularly small in moist upper tropospheres.

The important objective of this study is the estimation of precipitation with a unique set of coefficients. Even with a good multiple correlation, it is not obvious that the precipitation can be well estimated with universal regression lines. The precipitation could have certainly been better estimated using specific coefficients for each country considered, but to discover the universality of the method, only one set of regression lines was used. Due to the large number of raingages in each segment, the values from Kenya are selected as reference. In climatology, the knowledge of the monthly precipitation is important. Thus, the precipitation amounts are estimated during each month by clustering the appropriate five-day periods.

The observed and estimated precipitation (mm) in Kenya, Ivory Coast and Senegal, using the three regression lines obtained from Kenya, are displayed in Table 3, and the mean difference between the observed and estimated values in Table 4. The results show that the precipitation can be estimated with a good precision in the tropical areas (Kenya and Ivory Coast) using the same set of coefficients. In those regions, the segregation of the index into three classes only marginally improves the estimates. On the contrary, the stratification is crucial in the Sahel area (Senegal), where nonprecipitating cold clouds occur frequently. There the simple use of the EPI-all yields inaccurate results. The use of the three indices constitutes an improvement but acceptable results are obtained only if EPI-moist is disregarded. Excluding the EPI-moist seems to be plausible to solve the problems caused by nonprecipitating cold clouds.

4. Summary and conclusions

A validation of the precipitation index (EPI), recently introduced at the European Space Operations Centre (ESOC), has been carried out by comparing satellite data with observed precipitation. An effort has been made to estimate accumulated rainfall by linear regression, with special emphasis on assessing the dependence of the precipitation on the humidity in the upper troposphere.

The analysis indicated that in the tropical area, exposed mostly to precipitation of convective origin and consisting of Kenya, Ivory Coast and Senegal,

(i) The simple method relating the cold cloud top temperatures to rainfall, refined with the stratification of data into three indices based on the humidity in the upper troposphere, resulted in a good linear multiple correlation between the precipitation and the three precipitation indices. The multiple correlation was significantly higher (at the 20% level) than the simple one relating the sum of the three indices to precipitation. Thus, the stratification did constitute an improvement.

(ii) The partial correlation coefficients between each index and precipitation experienced a considerable variation from one country to another. The correlation between the EPI-moist and the precipitation was, however, constantly rather low. The poor correlation, probably caused by frequent cloud contamination by cold nonprecipitating cirrus, implied that the EPI-moist could be excluded without compromising the accuracy of the precipitation estimates.

Three regression lines were determined based on the data from Kenya using (i) the three indices, (ii) EPI-normal and EPI-dry only and (iii) EPI-all. Utilizing the three lines, monthly precipitation was calculated for each segment in Kenya, Ivory Coast and Senegal. The results indicated that the estimation of the accumulated precipitation was feasible with a considerable precision in Kenya and Ivory Coast using any of the three lines. The use of the segregated data constituted only a marginal improvement over EPI-all. In Senegal, however, the segregation of the index was crucial. The best results were obtained if the EPI-moist was excluded.

In the subtropical regions considered (Tunisia and Morocco) the overall multiple correlation was rather low due to the frequency of frontal precipitation during the test period. In these conditions determining the accumulated precipitation with the present method is not possible. The approach probably has to be space and time dependent.

The results presented have to be considered with some reservations due to certain constraints of the study. First, the sampling has been performed over too

TABLE 3. Observed and estimated precipitation (mm) in Kenya, Ivory Coast and Senegal using the three sets of regression coefficients from Kenya: $a = 1.4$, $b = 8.2$, $c = 8.3$; $bb = 8.5$, $cc = 8.3$ and $s = 6.7$. The number of segments considered is in parentheses.

	Kenya (2)			Ivory Coast (3)			Senegal (2)		
	Oct	Nov	Dec	Oct	Nov	Dec	Oct	Nov	Dec
Observed precipitation, monthly accumulation	57	115	37	89	70	8	13	0	10
Estimated precipitation using:									
a, *b*, and *c*	58	95	41	53	69	15	19	10	38
bb and *cc*	57	93	39	51	68	15	15	6	23
s	56	94	45	52	65	17	29	20	90

TABLE 4. Mean difference (%) between the observed and estimated (using the three regression lines for Kenya) precipitation for Kenya, Ivory Coast and Senegal. The month of November is not considered in Senegal due to the zero precipitation. The number of segments is indicated in parentheses after the name of the country.

	a, *b* and *c*	*bb* and *cc*	*s*
Kenya (2)	10	8	14
Ivory Coast (3)	43	44	54
Senegal (2)	163	73	462

short a period. A full year of data should be used. If the results remain satisfactory, a continuous rainfall mapping over the tropical METEOSAT area could ultimately be carried out. Second, the choice of the countries may not be ideal. Tunisia experiences little convective precipitation in late fall, while many stations in Kenya and Morocco are located at high altitudes where orographic effects play an important role. Third, the Upper Tropospheric Humidity (UTH), retrieved from the water vapor channel and used in the stratification of the index, has a limited accuracy due to its calibration against the radiosonde data. The use of broad intervals, however, compensates the accuracy required.

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