

## **Multisource monitoring of rainfall and surface water balance over the humid tropical zone of West Africa**

**ERIC BARRETT, MICHAEL BEAUMONT,  
MALCOLM TABERNER & ANDREA WILMSHURST**

*Centre for Remote Sensing, School of Geographical Sciences, University of Bristol,  
Bristol BS8 1SS, UK*

c-mail: e.c.barrett@bris.ac.uk

**Abstract** Water is vital for life, and for many human activities. Rainfall is the pre-eminent source of water as a renewable resource, and surface water balance (as a surrogate for soil moisture) is a key measure of moisture availability at least for the hydrological and agroclimatological communities. Recognizing that both these parameters are so poorly observed and/or reported from many regions, a set of satellite-based techniques have been prepared and extensively tested for the real-time monitoring of rainfall, shortwave solar radiation, evapotranspiration, and surface water balance. This paper describes the B4 approaches to rainfall and surface water balance, and provides examples of results and validations obtained from more than five years of investigations over the West African humid and sub-humid zone from Ivory Coast through Ghana, Togo, Benin and Nigeria to western Cameroon.

### **INTRODUCTION**

Unfortunately, although both rainfall and surface water balances are parameters of such importance to the hydrological and agroclimatological communities, they both vary significantly in both space and time, and neither is measured adequately at the surface, particularly if information is required rapidly, e.g. for real-time monitoring and/or short-term prediction.

In 1992 the Centre for Remote Sensing at the University of Bristol initiated its B4 (Bristol/Barrett, Beaumont, Bellerby) programme of quasi-operational monitoring of these and other parameters over the humid tropical zone of West Africa, based on visible and infrared data from the Meteosat satellite family, and calibrated by both conventional climatological datasets, and daily weather observations from surface meteorological stations (Barrett *et al.*, 1993).

In B4, rainfall is monitored using 12 Meteosat infrared images per day. These are analysed for the optimum rain: no-rain infrared threshold temperature or temperatures, the subsequent durations of identified rain cloud, and rain rates, adjusted to take account of both the long-term average for each pixel and surface-observed short-term weather variations. Surface water balance is evaluated, again uniquely for each pixel, using the rainfall calculations from the method summarized above, counterbalanced by estimates of evapotranspiration moisture losses derived from a specially-modified version of a model used by the Agrometeorological

Service of Ivory Coast. This modification invokes, wherever possible, satellite assessments of relevant parameters, including shortwave received solar radiation, surface albedo, and temperature, plus selected information from surface meteorological stations. The whole methodology is run in near-real time, with outputs generated for  $25 \times 25$  km, or  $5 \times 5$  km. grid squares, including daily, 10-daily, and monthly digital estimate maps and related hard copy, plus monthly anomalies also in the case of rainfall.

Implementation of the methodology over a period now in excess of five years (rainfall) and three years (SWB) has revealed much concerning the variability of the parameters monitored, their meteorological causation, and the optimum forms of the multisource models themselves.

## THE B4 METHODOLOGY: RAINFALL

In the B4 method:

$$R = f(C_T, RC_D, M_{CLI}, S_W)$$

where:  $R$  is daily accumulated rainfall;  $C_T$  is cloud-top temperature;  $RC_D$  is (probably precipitating) cloud (i.e. rain cloud) duration;  $M_{CLI}$  is a "morphoclimatic weight", specifically mean monthly rainfall per rain day; and  $S_W$  is synoptically-reported weather, specifically 24-h rainfall totals.

Effectively, therefore, over West Africa B4 is used to map and monitor probable rain areas from the combined evidence of 2-hourly geostationary Meteosat satellite infrared images, and weather station data obtained via the Global Telecommunication System (GTS) of the World Meteorological Organization (WMO); to apply initial rain-rates derived from "background fields" of surface climate data which also take account of terrain (especially altitude and aspect); and to calculate and apply improved intensity/duration functions to the initial daily rainfall estimates using satellite surface data together; and to do all this in near real-time (typically within 90 minutes of the end of any 24-h estimation period).

The scientific strategy outlined above differs from that followed by most previous workers in this field in that it considers all the parameters as spatial and temporal variables, and seeks to identify the most suitable values for them for each unit estimation period, and for each pixel. (Fig. 1). For example, most rainfall estimation techniques based on satellite data critically depend upon a fixed IR rain:no-rain threshold temperature to define cold cloud areas from which rainfall estimates are derived. One of the most widely used IR based methods rests on the work of Richards & Arkin (1981) who found that over the GATE region of the tropical Atlantic Ocean, rainfall accumulated over some large area or time is strongly correlated with the fraction of cold cloud below 235 K. From this, Arkin & Meisner (1987) defined a GOES Precipitation Index (GPI) for estimating the accumulation of rainfall over large areas. However, simple threshold methods such as the GPI, although useful for estimates of rainfall in some areas, have proved to be prone to error over other areas of the world. Indeed, one basic premise of the B4 method is that fixed thresholds are often inaccurate; another is that the IR rain:no-rain threshold temperature is much better treated as variable than as a constant, as identified by

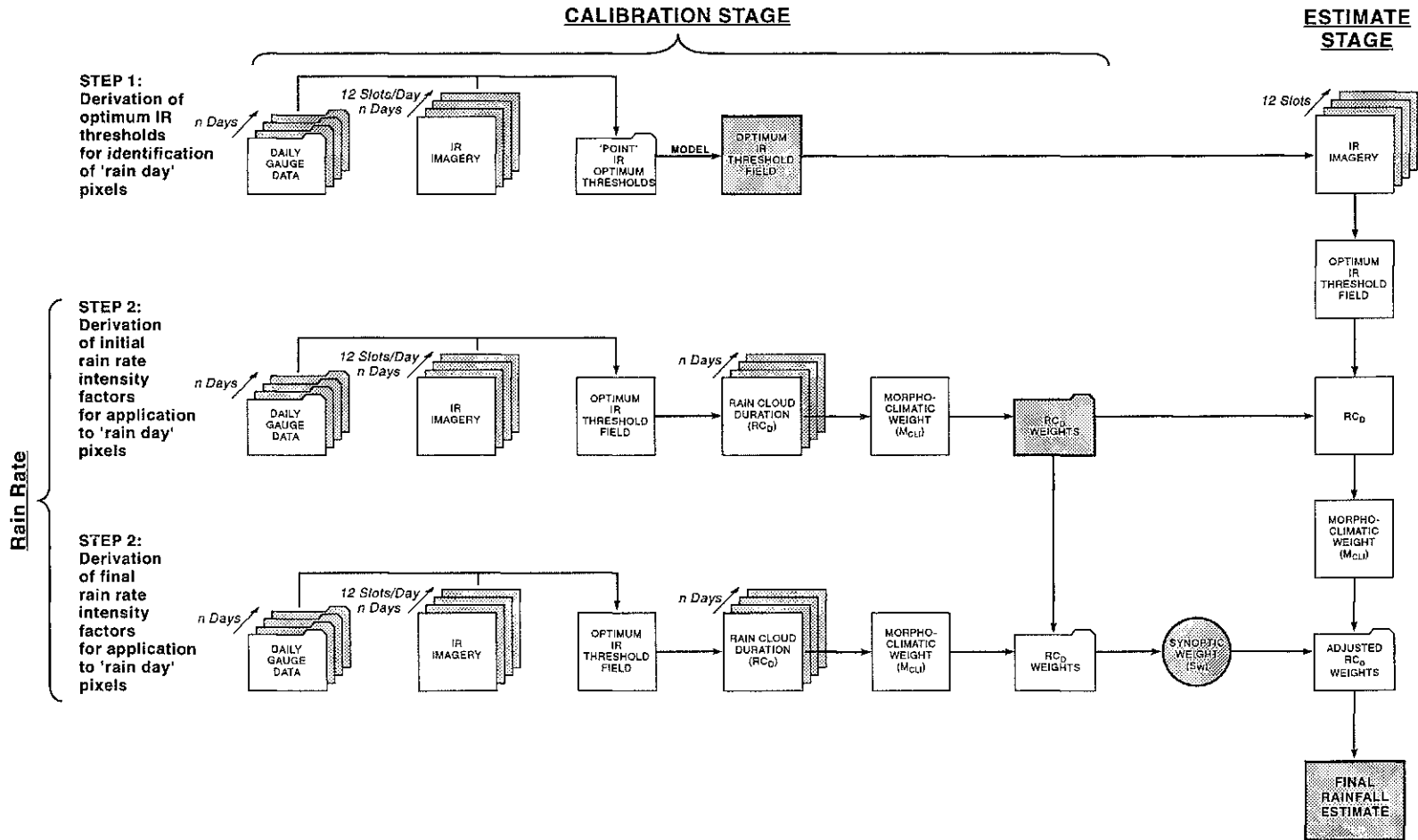


Fig. 1 Flow diagram for the B4 rainfall estimation method as currently configured.

various authors, including Arkin *et al.* (1989) who reported seasonal variations over an area of coastal India, where the best threshold in the summer monsoon season was 265 or 270 K, Joyce & Arkin (1994) who reported spatial variations over the USA, and Barrett & Beaumont (1994) and Todd *et al.* (1995) who discuss the problem more roundly.

In the B4 work over West Africa the optimum rain:no-rain temperature threshold was initially considered to be a spatial constant, but a temporal variable. Figure 2 shows that large variations occur in the optimum rain:no-rain temperatures on a seasonal basis, and that significant variations—particularly in the timing of changes—occur inter-annually. It was then found that significant variations occur on a station-to-station basis in a north-south direction, particularly in the spring and autumn (transition) periods (Dewhurst *et al.*, 1996). The current operational B4 method for West Africa implements meridionally-sloping rain:no-rain thresholds when the surface calibration stations in Ivory Coast indicate the need. Thus, at certain times of the year, the rain:no-rain threshold is treated as a simple spatial variable, as well as a temporal variable. Work continues, with the aim of developing a routine whereby the optimum rain:no-rain threshold over West Africa may be treated fully as a complex spatial and temporal variable.

In some areas of the world (including West Africa), earlier versions of B4 are being run in parallel with the more recent, more highly-developed, versions so that time-series of results relating to key parameters (e.g. the sensitivity analyses performed for model “refinements”) can be built up.

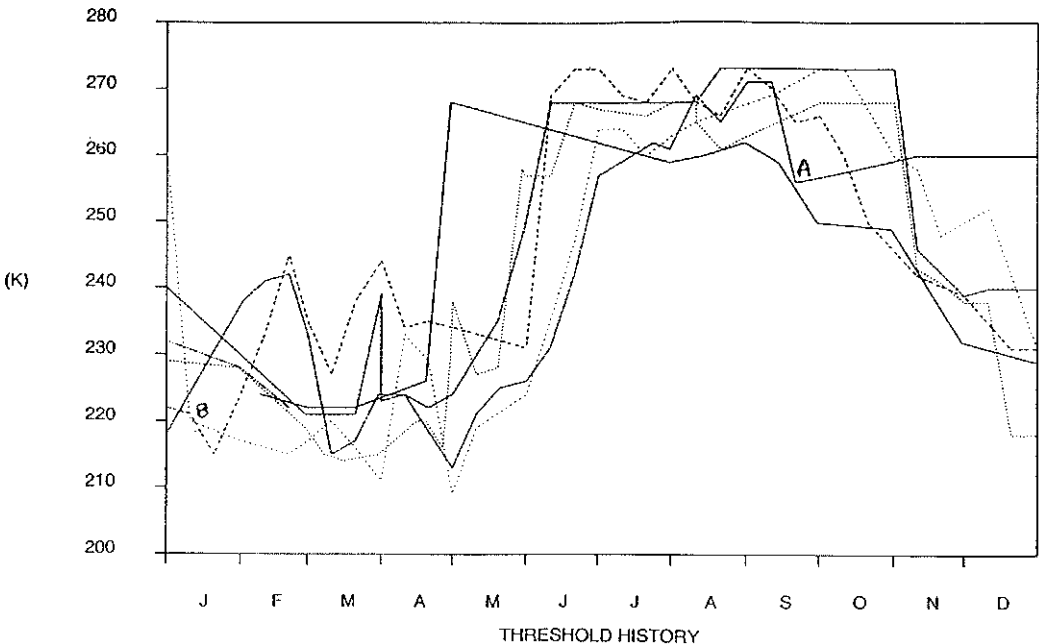


Fig. 2 Temporal variation of the optimum rain:no-rain IR threshold temperature over West Africa, February 1992 to February 1998. Note that from September 1995 to January 1996 (A to B) the curve is unreliable because of Meteosat encryption-related problems, now solved.

## THE B4 METHODOLOGY: SURFACE WATER BALANCE

The B4 SWB monitoring approach is based on a surface water balance model parameterized solely by surface observations. Meanwhile, the B4 model uses remote sensing to obtain estimations for as many of the parameters as possible. The similarity of the two models allows direct comparison of results, both for purposes of calibration and validation and for assessing the contribution to surface water balance by remotely sensed inputs.

Surface water balance is calculated on a pixel-by-pixel basis at full resolution ( $5 \text{ km} \times 5 \text{ km}$ ) assuming that the:

$$\text{surface water balance} = \text{balance at end of} + \text{daily rainfall} - \text{daily } ETM \\ \text{at end of day} \qquad \qquad \text{previous day}$$

(limited to 0–100 mm), where the maximum evapotranspiration  $ETM$  is calculated from the potential evapotranspiration  $ETP$ , where  $ETM$  is the product of  $ETP$  and  $K$ , a coefficient relating to the state of the crop in question.  $ETP$  is calculated by Penman's formula:

$$ETP = \frac{(\Delta / \gamma L) Rn + C(e_w - e)(1 - cv)}{(1 + \Delta / \gamma)}$$

where  $\Delta$  is the slope of the vapour pressure–temperature curve at  $T_a$ ;  $\gamma$  is the psychrometric constant;  $L$  is the latent heat of evaporation;  $e_w$  and  $e$  are saturated and actual vapour pressures at screen height;  $C$  and  $c$  are aerodynamic coefficients;  $v$  is windspeed at 10 m above ground level;  $Rn$  is net daily radiation. Meanwhile,  $e_w$  and  $Rn$  are estimated for inclusion in the formula for  $ETP$  using:

$$e_w = \frac{6.07 \exp(17.1544T_a)}{(234.7 + T_a)}$$

where  $T_a$  is mean daily air temperature at screen height, and  $Rn$  is the ground incident solar flux:

$$(1 - r) - \sigma T_a^4 (0.56 - 0.08\sqrt{e})(0.1 + 0.9m)$$

where  $r$  is ground reflectivity;  $\sigma$  is Stefan's constant; and  $m$  is the proportion of the sky which is cloud free.

Conventional inputs are used for the coefficient  $K$ , wind speed, and vapour pressure. A table of monthly values is used for the coefficient  $K$ , presently based on relevant indices for a crop of particular interest (e.g. cocoa). Monthly climatological values are used for vapour pressure and windspeed due to a lack of station data. Where meteorological reporting is more reliable, station data could be used.

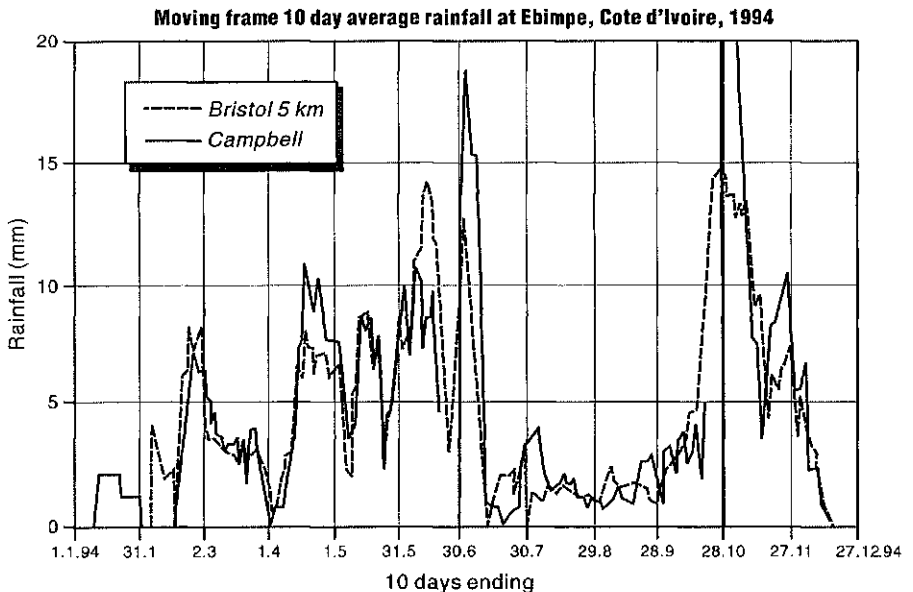
Ground incident solar flux, ground reflectivity, the proportion of the sky which is cloud-free, daily mean air temperature, and rainfall are all estimated using remotely sensed parameters. Further, ground reflectivity and incident solar flux are calculated using data from the visible channel of Meteosat with a radiative transfer model. Thus, cloud-related estimation uses Meteosat visible data, while Meteosat infrared data are used to estimate "thermal" parameters. The Meteosat "thermal" channel in fact detects surface rather than air temperatures, although these are generally not dissimilar in the region of large crops.

## B4 RESULTS VALIDATION, AND PLANS FOR FURTHER WORK

Two examples of validations of B4 results may be debated here. Most existing rainfall station data are used at some stage in the B4 process, and therefore cannot be used for validation of its results. However, Fig. 3 shows an intercomparison between B4 rainfall estimates and data from an independent raingauge operated privately for such purposes for one location in the humid tropical region of Ivory Coast, showing a very good correlation between the decadal estimates plotted. Meanwhile, over East Africa a more comprehensive study has been made of both spatially uniform but temporally variable (B4a), and spatially and temporally variable (B4b), B4 method results, plus outputs from an infrared method which treats both the rain:no-rain thresholds, and rain rates as temporal and spatial constants (the GOES Precipitation Index, GPI: see Arkin & Meisner, 1987), and the Nile Climatological Method (NCM: Shaake & Newby, 1993), which is essentially a GPI with rain rate treated as a local variable (see Table 1). As reported by Todd *et al.* (1995), and despite the fact that the B4 results were obtained using 2-hourly Meteosat imagery, as compared with hourly Meteosat imagery by the GPI and NCM, results from the B4 methods almost always improved upon the statistics of the other methods, often considerably, giving confidence in B4 results elsewhere too.

Validation of surface water balance is more difficult, because this is a parameter even less well-monitored than rainfall by *in situ* means. We have not yet secured independent data with which to validate point estimates of B4 SWB. However, the spatial patterns of results obtained, and their temporal variations, are clearly realistic, and give us confidence in them.

Further work in hand, or planned for the future, focuses on the following:



**Fig. 3** Comparisons between B4 decadal estimates of rainfall at 5-km resolutions, and raingauge measurements at Ebimpe, Ivory Coast.

**Table 1** Examples of Ethiopian highlands rainfall estimation statistics for selected IR techniques, validated against WMO gauge reports.

Period	Rainfall total bias (mm)				Estimate total percentage of gauge total (%)				Point-by-point RMS errors (mm)			
	B4a	B4b	GPI	NCM	B4a	B4b	GPI	NCM	B4a	B4b	GPI	NCM
July 1992	-36.4	-25	59.0	-350.9	99	99	102	86	7.9	7.5	8.2	7.9
Aug. 1992	586.0	314	1063.0	264.2	116	105	129	107	10.2	8.9	10.8	9.7
Sept. 1992	239.0	-200	470.0	303.0	86	88	127	82	6.7	5.6	7.5	7.6

- Ways of incorporating radar data into the multisource dataset, for further improvements in rainfall and SWB results.
- Use of passive microwave satellite data, e.g. from the DMSP-SSM/I, for similar purposes. These data provide good estimates of instantaneous rain rates on a spatially continuous basis at least once daily near the equator, using a single satellite of this polar-orbiting family. At present, three such satellites are in operation, significantly increasing the temporal sampling frequency.
- A study of geographical and seasonal influences on Meteosat ground temperatures to modify the temperature inputs to the SWB model.
- A sensitivity analysis to investigate the importance of the various parameters (especially rainfall) in the SWB model. The results of the analysis will be used to aid decisions regarding which parts of the model to refine.
- Experimentation with alternative approaches to SWB modelling, including use of a pure energy budget equation instead of a semi-empirical formula to estimate evapotranspiration; and utilization of a soil moisture deficit model and "runoff" models to better account for the interaction of the ground with moisture.
- Developing forecasting criteria, as the dataset time series lengthen.

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