Zeitschrift: Ingénieurs et architectes suisses
Band: 116 (1990)
Heft: 18

Artikel: A modular watershed-modelling system for use in mountainous regions
Autor: Leavesley, G.H. / Stannard, L.G.
DOI: https://doi.org/10.5169/seals-77291

geable dans les écoulements de cette zone de moyenne altitude subdésertique.

BIBLIOGRAPHIE

BAKALOWICZ M. (1979) *Contribution de la géochimie des eaux à la connaissance de l'aquifère karstique et de la karstification.* Thèse Doct. ès Sci., Université Paris 6, Paris.

BLACK R., JAUJOU M., PELLATON C. (1967) *Carte géologique de l'Aïr au 1/500 000e et notice explicative.* République du Niger, Ministère des Travaux Publics et des Transports, des Mines et de l'Urbanisme. Direction des Mines et de la Géologie.

BLAVOUX B. (1978) *Etude du cycle de l'eau au moyen de l'oxygène 18 et du tritium. Possibilité et limites de la méthode des isotopes du milieu en hydrologie de la zone tempérée.* Thèse Doct. ès Sci., Université Paris 6, Paris.

FONTES J.Ch. (1980) Environmental isotopes in groundwater hydrology. In : P. Fritz and J.Ch. Fontes (eds), *Handbook of Environmental Isotope Geochemistry,* vol. 1, The Terrestrial Environment, A. Elsevier, Amsterdam, 75-140.

FRITZ P., CHERRY J.A., WEYER K. U., SKLASH M. (1976) Storm runoff analyses using environmental isotopes and major ions. In : *Interpretation of Environmental Isotope and Hydrochemical Data in Groundwater Hydrology,* IAEA, Vienne, 111-130.

HUBERT P., MARCE A., OLIVE P., SIWERTZ E. (1970) Etude par le tritium de la dynamique des eaux souterraines. *C. R. Acad. Sci., Paris, 270,* 908-911.

LEROUX M. (1983) *Le climat de l'Afrique* Champion ed., Paris, 2 vol.

MOOK W. G., GROENVELD D. J., BROWN A. E. & VAN GANSWIJK A. J. (1974) Analysis of a runoff hydrograph by means of natural 180. Proc. IAEA Symp. Isot. Tech. Groundwater Hydrol., Vienna, 145-153.

ORSTOM (1960 puis 1976 à 1989) Rapports de campagne sur le bassin du Teloua. Niamey, NIGER.

ROUSSIN-BARIAC M. (1985) *Etude hydrochimique et isotopique d'une nappe alluviale sous climat semi-aride (cuvette d'Agadez Niger).* Thèse Doct. 3e Cycle, Université Paris-Sud, Orsay.

SKLASH M. K., FARVOLDEN R. N. and FRITZ P. (1976) A conceptual model of watershed response to rainfall, developed through the use of oxygen-18 as a natural tracer. Can. J. *Earth Sci., 13,* 271-283.

A MODULAR WATERSHED-MODELING SYSTEM FOR USE IN MOUNTAINOUS REGIONS

G.H. LEAVESLEY & L.G. STANNARD
U.S. Geological Survey, MS 412, Denver Federal Center, Lakewood, Colorado 80225, USA.

ABSTRACT A modular watershed-modeling system that provides a range of hydrologic-simulation and dataanalysis capabilities has been developed for use in mountainous regions. The watershed-model component is the U.S. Geological Survey's Precipitation-Runoff Modeling System (PRMS). PRMS is a modular-design, physical-process based, distributed-parameter watershed model. Data-management and analysis components are provided by the U.S. Geological Survey's datamanagement program ANNIE (not an acronym). Hydrologicforecasting capabilities are provided by a modified version of the National Weather Service's Extended Streamflow Prediction (ESP) program. Other components include a digital-terrain-analysis module for use in basin characterization and parameter estimation, and a remote-sensing-applications module for incorporating remotely sensed snow-covered-area data in watershed simulations.

INTRODUCTION

A modular watershed-modeling system is being developed and tested in a variety of mountainous regions to provide improved modeling tools and procedures that address current problems in mountain-watershed simulation. Problems in the use of distributed-parameter models in mountainous regions include : optimal subdivision and characterization of watersheds to account for the effects of slope, aspect, elevation, soils, and other watershed features on hydrologic response ; extrapolation of point data to areal-value estimates in complex, high-relief terrain ; verification of the simulated hydrologic response of delineated subwatershed areas ; and updating of simulated watershed conditions using measured values when forecasting streamflow.

The modular system is based on the concept of a master library that contains compatible subroutines to simulate most components of the hydrologic cycle. Alternative or new simulation procedures for selected process components can be compared directly while keeping the remaining process components the same. The use of a standard set of statistical measures, maintained within the system framework, provides a common basis on which to compare component performance. The modular concept also provides a system with operational and research modeling capabilities. The use of a standard model framework and data structure enables researchers in a variety of disciplines to develop and test model components in their areas of expertise without having to develop the entire model.

The initial system has been developed from existing software. The major components of the system are the U.S. Geological Survey's Precipitation-Runoff Modeling System (PRMS) (Leavesley *et al.*, 1983), the U.S. Geological Survey's interactive data-management and control program ANNIE (Lumb *et al.*, 1989), a modified version of the National Weather Service's Extended Streamflow Prediction (ESP) program (Day, 1985), a set of digital-terrain-analysis programs for use in basin characterization (Jenson & Domingue, 1988), and a set of procedures for applying remotely sensed data to basin characterization and model analysis. Together they form a complete system that enables a user to : reduce, analyze, and prepare data for model application ; simulate and forecast watershed response ; and statistically and graphically analyze model results. The purpose of this paper is to provide an overview of the initial system and its application in addressing the problems of watershed modeling in mountainous regions.

PRECIPITATION-RUNOFF MODELING SYSTEM (PRMS)

PRMS is a modular-design, physical-process based, distributed-parameter watershed model that was developed to evaluate the effects of various combinations of precipitation, climate, and land use on watershed response. Watershed response to normal and extreme rainfall and snowmelt can be simulated to evaluate changes in water-balance relations, flow regimes, flood peaks and volumes, soil-water relations, sediment yields, and ground-water recharge. Parameter-optimization and sensitivity-analysis capabilities are provided to fit selected model parameters and to evaluate their individual and joint effects on model output.

Distributed-parameter capabilities are provided by partitioning a watershed into units using characteristics, such as slope, aspect, elevation, vegetation type, soil type, and precipitation distribution. Each unit is assumed to be homogeneous with respect to its hydrologic response and to the characteristics listed above; each unit is called a hydrologic response unit (HRU). A water balance and an energy balance are computed daily for each HRU. The sum of the responses of all HRU's, weighted on a unit-area basis, produces the daily watershed response.

Watershed response can be simulated at both a daily and a storm time scale. The daily mode simulates hydrologic components as daily average or total values. Streamflow is computed as a mean daily flow. The storm mode simulates selected hydrologic components at time intervals shorter than 1 day. The minimum time interval is 1 min. A second level of partitioning is used for storm-mode computations. The watershed is conceptualized as a series of interconnected flow-plane and channel segments. A HRU can be considered the equivalent of a single flow plane, or it can be delineated into a number of flow planes. The watershed drainage network is characterized as a system of channel, reservoir, and junction segments that jointly describe the drainage pattern.

Daily Mode Components

Model inputs are daily precipitation, maximum and minimum daily air temperature, and daily solar radiation. Precipitation in the form of rain, snow, or both is reduced by interception, and the remainder becomes net precipitation delivered to the watershed surface. If daily solar-radiation data are unavailable, estimates of daily solar radiation are made using air temperature, precipitation, and computed potential-solar-radiation data. The energy inputs of air temperature and solar radiation drive the processes of evaporation, transpiration, sublimation, and snowmelt.

A watershed is conceptualized as a series of reservoirs whose outputs combine to produce the total watershed response. A soil-zone reservoir is defined for each HRU and represents that part of the soil mantle that can lose water through the processes of evaporation and transpiration. Average rooting depth of the predominant vegetation covering the HRU defines the depth of this zone. Water storage in the soil zone is increased by infiltration of rainfall and snowmelt, and decreased by evapotranspiration. The soil zone is treated as a two-layered system. Losses from the upper zone, termed the recharge zone, occur from evaporation and transpiration; losses from the lower zone occur only through transpiration.

When the soil-zone reservoir reaches field capacity, water in excess of field capacity is apportioned between surface runoff and movement to subsurface and ground-water reservoirs. The subsurface reservoir simulates the faster component of flow that might occur in the unsaturated zone during periods of rainfall and snowmelt. The ground-water reservoir simulates the slower component of flow from the saturated zone. The subsurface reservoir can be defined as being linear or nonlinear, whereas the ground-water reservoir is assumed to be linear. Subsurface and ground-water reservoirs can be defined for each HRU, or can be defined as larger areas receiving outflows from several HRU's. Surface, subsurface, and ground-water flows are combined to produce daily streamflow. Storage and routing of daily streamflow in channel reservoirs can be simulated using a linear routing procedure or a modified-Puls procedure (U.S. Soil Conservation Service, 1971).

The snow components simulate the initiation, accumulation, and depletion of a snowpack on each HRU. A snowpack is maintained and modified on both a water-equivalent basis and as a dynamic-heat reservoir. A snowpack water balance is computed daily and an energy balance is computed twice each day. The energy-balance computations are a combination of equations and functional relations obtained or derived from several sources. The conceptual model for the snowpack system and its energy relations is one described by Obled & Rosse (1977). The net-shortwave and net-longwave components of the energy balance are computed for each HRU using equations developed by the U.S. Army (1956). The latent and sensible heat component is computed as a simplified temperature-index value that is adjusted for the presence or absence of forest cover.

Storm-Mode Components

Infiltration is computed using a variation of the Green and Ampt equation (Green & Ampt, 1911). Rainfall excess (net precipitation less infiltration) is then routed as surface runoff over the flow planes into the channel segments using the kinematic-wave approximation to overland flow. Channel flow is routed through the watershed channel system using the kinematic-wave approximation for channel flow.

Sediment detachment and transport from flow planes is computed using a rill-interrill concept (Hjelmfelt *et al.*, 1975). This concept considers rainfall and flow-detachment processes and the subsequent transport and deposition of entrained sediment. Sediment delivered from a flow plane currently (1990) is transported as a conservative substance in the channel system; detachment- and deposition-process algorithms are being developed.

Optimization and Sensitivity-Analysis Components

Optimization components control the automatic adjustment of model parameters to obtain better agreement between measured and simulated runoff. Two optimization techniques are available: one is the Rosenbrock technique (Rosenbrock, 1960); the second is a Gauss-Newton technique similar to the linearization method described by Draper & Smith (1966).

Sensitivity-analysis components allow the user to determine the extent to which uncertainty in the parameters results in uncertainty in the simulated runoff. When sensitivity analysis is coupled with optimization, the user also can assess the magnitude of parameter standard errors and parameter intercorrelations.

ANNIE

ANNIE is a system of software modules designed to help a user interactively create, check, and update input to hydrologic models, and to provide statistical and graphical tools to assist in the analysis of model input and output. A reformat option converts meteorologic and hydrologic time-series data from a number of different sources into the system-compatible, direct-access file structure. A generate option provides the capability to create new data sets by applying a mathematical operation to one, or selected combinations of two, existing data sets. Statistical-analysis capabilities are provided by both internal- and external-application programs. Graphical-analysis options include time-series plots of data sets and model outputs, x-y plots of selected data sets, frequency plots, flow-duration plots, and scatter diagrams.

EXTENDED STREAMFLOW PREDICTION (ESP)

A modified version of the ESP program has been coupled to PRMS to provide forecasting capabilities. The ESP procedure uses historic or synthesized meteorologic data to forecast future streamflow, given the simulated hydrologic conditions for a watershed at a specified point in time. The ESP program performs a frequency analysis on simulated values of maximum and minimum daily flow, flow volume, and the date that the flow decreases to less than a selected threshold value. The Log-Pearson Type III probability distribution is currently (1990) supported, but other distributions can be added. The forecast period can vary from a few days to an entire year.

The ESP component provides a valuable tool for a variety of hydrologic forecasting and analysis applications. These applications include short-term or seasonal forecasting for floods and water supply, evaluation of the effects of land-use changes on streamflow characteristics under a variety of meteorologic and watershed conditions, and the evaluation of the potential effects of climatic changes on streamflow under existing or future watershed conditions.

BASIN CHARACTERIZATION

Basin characterization is the discretization of a basin into HRU's on the basis of topography, vegetation, soils, and other basin features for application in distributed-parameter models. Historically, this procedure has been a labor-intensive, manual operation that involved a great deal of subjectivity. Resulting watershed characterizations reflected the interpretations and biases of the model user. A set of programs and procedures has been developed for use with PRMS to provide a more objective watershed-characterization process.

The programs use digital-elevation data in a gridded format to determine watershed boundaries, stream-drainage location and network configuration, and subwatershed boundaries based on a user-defined minimum subwatershed area. Resulting subwatershed areas are divided by their major drainage channel into two opposing hillslopes. ARC/INFO (Environmental Systems Research Institute, Inc., 1989), a vector-based geographic information system, is used to process, analyze, and display these data. An ARC/INFO data layer, or coverage, is created from the topographic characterization and computed values of slope, aspect, and elevation are added to the coverage as attributes for each hillslope. Hillslope boundaries can be overlain by additional coverages for vegetation, soils, geology, or other watershed characteristics and further subdivided or aggregated to form HRU's, based on the additional information provided in the data overlays. Data overlays also contain information needed to estimate selected parameters for each HRU. An example of this characterization process is presented by Leavesley & Stannard (1990).

REMOTE-SENSING APPLICATIONS

Remotely sensed data provide a range of qualitative and quantitative information about the spatial and temporal variation in physical and hydrologic characteristics of watersheds. This information provides a set of measures to address some of the simulation problems related to mountainous regions. Overlays of these data can be incorporated in the watershed-characterization process, and can be used to extrapolate point and small-area ground-based data to areal estimates of selected HRU parameters.

Estimation of the available-water-holding-capacity parameter (SMAX) of the soil-zone reservoir on each HRU is one example. SMAX is defined as a function of soil physical properties and the average rooting depth of the dominant vegetation on the HRU. Ground-based measures of soil physical properties can be coupled with measures of vegetation type defined from remotely sensed data and knowledge of the rooting characteristics of these vegetation types to estimate SMAX for each HRU. Where little or no soil data are available, the occurrence and type of vegetation can be combined with topographic data, such as slope and aspect, to infer soil physical properties and estimate SMAX.

Remotely sensed data also provide the opportunity to evaluate and verify some of the simulated storages and fluxes of a watershed and individual HRU's. Snow-covered area is the HRU state variable for which remotely sensed data currently are the most readily available. Measured and simulated snow-covered area on the East Fork Carson River watershed in the Sierra Nevada for two dates in 1986 are shown in Figure 1. Measured data for this type of comparison are available every 5-8 days during the snowmelt season.

The ability to jointly analyze measured and simulated streamflow, and snow-covered area decreases the uncertainty in defining sources of model error as compared to an analysis that is limited to the hydrograph alone. Underprediction of late-season snowmelt by PRMS, which had been attributed to inadequate snow cover based on a hydrograph analysis, was determined to be more closely related to errors in model assumptions regarding the rate and distribution of snowmelt during periods of patchy snow cover when snow-covered area was included in the analysis (Leavesley & Stannard, 1990).

The opportunity to use remotely sensed data to update simulated watershed conditions also is evident in Figure 1. Measured and simulated snow-covered area are easily compared by HRU and the simulated value could be periodically updated. The strength of currently available, remotely sensed, snow-covered-area data is that they can be used to identify temporal and spatial differences in the distribution of selected model parameters. The limitation of these data, however, is that they do not provide a quantitative measure of the snowpack water equivalent associated with the areas covered. To overcome this limitation, methodologies are being investigated to couple point measures of precipitation and snowpack water equivalent with remotely sensed measures of areal snow cover to provide an estimate of the spatial distribution of snowpack water equivalent.

INTERACTIVE SYSTEM

The modular system as described above operates on mainframe, mini, and micro computers. ANNIE, PRMS, ESP, and the basin-characterization and remote-sensing components currently are stand-alone programs that run sequentially in a typical application. To provide more flexibility and to decrease the complexity of operation as more capabilities are added, an interactive version of the system is being developed for application on a 32-bit, Unix-based workstation. The interactive system uses a graphical user interface to display system options, data, basin characterizations, and model results and analyses. Expert-system technologies will be used to assist users in system operations, model selection, parameter estimation, model calibration, and the display, comparison, and analysis of model results.

The interactive system will provide a framework in which to develop and compare models and model-process components, and to identify and apply the optimal approach to selected hydrologic problems. The system also provides a common framework in which to focus multidisciplinary research efforts on the solution of a variety

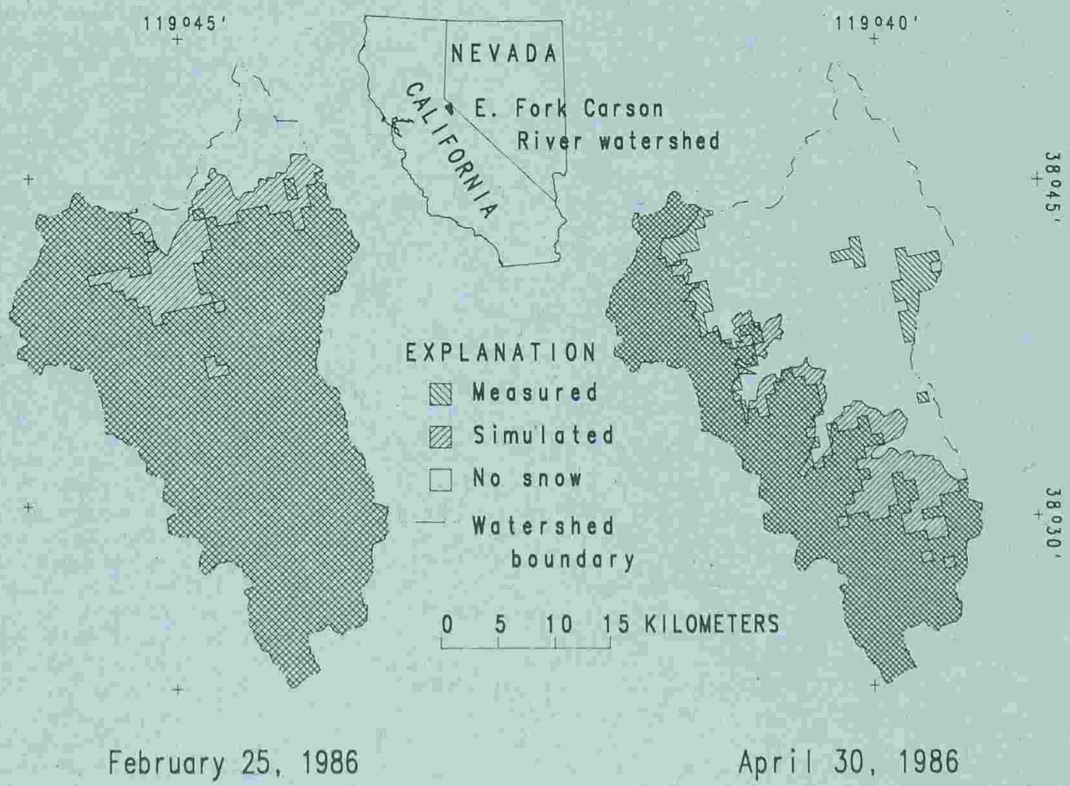

Figure 1. Measured and simulated snow-covered area in the East Fork Carson River watershed, Calif.-Nev., February 25, and April 30, 1986.

of complex watershed-modeling problems, making maximum use of current and future advances in the fields of expert systems, geographic information systems, remote sensing, information management, and computer science. Much work remains to be done to determine which simulation approaches are best for various combinations of application problems and data constraints. As this work is completed, however, the question of which model is best for mountainous regions will be changed to a more appropriate question of which combination of process components is best.

REFERENCES

Day, G.N. (1985) Extended streamflow forecasting using NWSRFS. *J. Wat. Resour. Plan. and Manag. Am. Soc. Civ. Eng. 111* (2), 157-170.

Draper, N.R. & Smith, H. (1966) *Applied Regression Analysis.* John Wiley and Sons, Inc., New York.

Environmental Systems Research Institute, Inc. (1989) *ARC/INFO user's guide-Rev. 5.* Redlands, Calif.

Green, W.H. & Ampt, G.A. (1911) Studies on soil physics, I— Flow of air and water through soils. *J. Agric. Res. 4*, 1-24.

Hjelmfelt, A.T., Piest, R.P. & Saxton, K.E. (1975) Mathematical modeling of erosion on upland areas. In: *Congress of the 16th Int. Assoc. for Hydraul. Res.* (Proc. Symp., Sao Paulo, Brazil), vol. 2, pp. 40-47.

Jenson, S.K. & Domingue,J.O. (1988) Software tools to extract topographic structure from digital elevation data for geographic information system analysis. *Photogram. Eng. and Remote Sensing 54* (11), 1593-1600.

Leavesley, G.H. & Stannard, L.G. (1990) Application of remotely sensed data in a distributed-parameter watershed model. In: *Applications of Remote Sensing in Hydrology* (Proc. Workshop, February, 1990), National Hydrology Research Institute, Saskatoon, Saskatchewan, Canada, in press.

Leavesley, G.H., Lichty, R.W., Troutman, B.M. & Saindon, L.G. (1983) Precipitation-runoff modeling system-User's manual. *USGS Wat. Resour. Invest. Rep.* 83-4238.

Lumb, A.M., Kittle, J.L., Jr., & Flynn, K.M. (1989) Users manual for ANNIE, a computer program for interactive hydrologic analysis and data management. *USGS Wat. Resour. Invest. Rep.* 89-4080.

Obled, Ch. and Rosse, B. (1977) Mathematical models of a melting snowpack at an index plot. *J. Hydrol. 32*, 139-163.

Rosenbrock, H.H. (1960) An automatic method of finding the greatest or least value of a function. *Computer J. 3*, 175-184.

U.S. Army (1956) *Snow Hydrology.* U.S. Army Corps. of Engineers, Portland, Oregon, USA.

U.S. Soil Conservation Service. (1971) *SCS National Engineering Handbook, Sec. 4-Hydrology.* U.S. Govt. Printing Office, Washington, D.C.

«En mémoire à Dominique ROSSIGNOL»

INFLUENCE DU RELIEF SUR LES PRECIPITATIONS EN GUADELOUPE

D. ROSSIGNOL
Centre ORSTOM de Guadeloupe, B.P. 1020, 97178 Pointe-à-Pitre, Guadeloupe

RESUME : les caractéristiques des précipitations journalières et des intensités sont analysées dans le but d'approfondir les mécanismes d'augmentation des précipitations sur le relief de la Basse-Terre. La variation de l'accroissement orographique en fonction du vent et de l'intensité moyenne des précipitations est analysée au pas de temps journalier. L'étude des intensités au pas de temps d'une minute permet de différencier les postes situés sur la pente des postes de crête. La variation diurne distingue les postes influencés préférentiellernent par l'orographie pure de ceux qui subissent le réchauffement diurne.

INTRODUCTION

L'influence des reliefs sur la circulation atmosphérique représente un des phénomènes générateur des précipitations, les deux autres étant les perturbations cycloniques du front polaire et la convection. Les massifs montagneux sont généralement un facteur d'augmentation des précipitations, à tel point qu'ils représentent souvent des résevoirs naturels d'eau, jouant un rôle primordial dans l'économie humaine.
L'évaluation des précipitations sur une surface accidentée n'est pas résolue. Les méthodes d'interpolation courantes à partir de quelques données ponctuelles ne sont pas satisfaisantes, car elle ne représente pas l'effet du relief sur le flux atmosphérique. Seule la modélisation serait capable d'en tenir compte. Avant d'envisager de construire un modèle représentatif des précipitations en montagne, il faut connaître le processus physique responsable de l'augmentation observée.

Différents processus interviennent selon la dimension du massif montagneux par rapport à l'échelle des phénomènes météorologiques étudiés, influencés ou non par la force de Coriolis.

(a) La convergence de frottement de la couche limite augmente en présence de la forte rugosité du relief.
(b) La pente montagneuse favorise l'ascendance de l'air qui subit alors un refroidissement adiabatique qui peut aller jusqu'à la condensation et la formation de nuages. Alpert et Corradini ont développé des modèles numériques basés sur ce phénomène physique.
(c) Le réchauffement diurne des sommets favorise plus particulièrement la convection dans un environnement atmosphérique froid dû à l'altitude.
(d) Certaines influences orographiques trouvent leur origine dans un mécanisme d'ensemencement naturel des nuages inférieurs d'origine orographique par les nuages supérieurs d'origine cyclonique. Ce processus est appelé par les Anglo-Saxons «Bergeron's seeder-feeder» a été mis en evidence lors du passage de front sur les Galles du Sud.

Dans une situation géographique et climatique donnée, il convient d'analyser les données disponibles pour découvrir quel proccssus est susceptible d'avoir l'influence prépondérante. Cette étude traite du cas particulier de la Guadeloupe. Après l'observationde l'existence d'un fort gradient pluviométrique du cumul annuel (près de 10 m sur une distance horizontale de 10 km), sur le massif de la Soufrière, nous avons analysé les précipitations à des pas de temps inférieurs (jour et minute), dans le but d'affiner la connaissance du phénomène.