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LD CLIMATE PROGRAMME

RESEARCH

WORLD CLIMATE PROGRAMME

VALIDATION OF SATELLITE PRECIPITATION MEASUREMENTS
for the
GLOBAL PRECIPITATION CLIMATOLOGY PROJECT

(Report of an International Workshop, Washington, D.C., 17-21 November 1986)

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Report of the International Workshop On The VALIDATION OF SATELLITE PRECIPITATION MEASUREMENTS For The Global Precipitation Climatology Project

Edited By

J.C. Wilkerson

NOAA/NESDIS
U.S.A.

Organized By

World Climate Research Programme

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EXECUTIVE SUMMARY

1. INTRODUCTION

The International Workshop on the Validation of Satellite Precipitation Measurements for the Global Precipitation Climatology Project (GPCP) was organized by the World Climate Research Programme (WCRP), following recommendations made at a previous workshop held in July 1985 on global large-scale precipitation data sets, which addressed the problem of validating climate model outputs with global observations. The objectives of the present workshop were:

(i) To develop a plan for validating large-scale estimates of monthly precipitation, derived from a combination of geostationary satellite observations, polar satellite observations and ground-based raingauge measurements, summarized over approximately 250 x 250 km^2 areas over the globe.

(ii) To document locations globally where radar/raingauge precipitation estimates are routinely compiled, with raingauge densities of one or more gauges per 50 x 50 km^2 area.

(iii) To establish the usefulness of current ground-based measurements of precipitation amounts on these scales and to document how and in what form these measurements are being recorded.

(iv) To define the procedures and responsibilities of the "collecting country" and the "receiving country" and the benefits which might accrue to each.

(v) To document the status of other potential ground-based measurement techniques, such as microwave attenuation and acoustic methods, which might be developed should funds become available.

It is clear that, at the present time, no single type of measurement could be used as a standard for comparison with space-based measurements of rainfall amount over large areas and long time periods. An optimum reference comparison data set would require a combination of data from raingauges, radar and other instruments, either currently available or under development. The workshop considered the problem of implementing a validation effort with existing instrumentation and facilities, with the provision that improved systems could be added later as they become available.

Forty participants, representing 13 countries and one multinational organization, met in Washington, D.C. during 17-21 November 1986 to consider the problem of organizing a programme to validate the GPCP global precipitation fields. Following two days of background presentations, the participants were organized into four panels to discuss the following subjects and to prepare recommendations.

(i) Satellite precipitation validation requirements.

(ii) Existing rainfall data sources and validation strategy.

(iii) Role of models in the estimation and validation of rainfall.

(iv) Rainfall measurement technology.

The following sections summarize the major conclusions and recommendations of the workshop.

2. SATELLITE PRECIPITATION VALIDATION REQUIREMENTS

The requirements for validation of large-scale precipitation fields fall into two categories. The first includes requirements describing the institutional structure which is needed in order for the GPCP to proceed. The second includes requirements describing the technical characteristics of the reference data sets and the associated data processing.

2.1 Institutional Requirements

(i) An international advisory group should be constituted, or an existing group identified, to provide the scientific guidance to the GPCP. This group should oversee research activity on the problem of estimating area-averaged rainfall, and should act as an advocate to persuade national research programmes and funding agencies to actively participate in finding solutions to the problems.

(ii) A Surface Reference Data Centre(SRDC) should be established to serve as the focal point within the GPCP for the collection and archiving of reference data sets for the validation of large-scale precipitation estimates.

(iii) An ad hoc committee of scientists, who are actively involved in research on the estimation of area-averaged rainfall, should be established to provide scientific and technical guidance to the SRDC, recommend strategy for both the operational and research activities of the SRDC, and promote collaborative research projects among workers in the field.

(iv) At least one rainfall calibration site should be established and equipped with state-of-the-art instrumentation, which would permit the testing and application of conventional and experimental rainfall measuring techniques to obtain high-quality, long-term rainfall data sets.

2.2 Technical Requirements

(i) Quality standards for reference data sets should be established, in terms of network density, record length, calibration, proper exposure of sensors, and quality control procedures.

(ii) Standards should be established in terms of contents and formats in which data should be submitted from calibration sites to the SRDC.

3. EXISTING RAINFALL DATA SOURCES AND VALIDATION STRATEGY

The GPCP requirement calls for rainfall estimates over areas of 2.5° latitude x 2.5° longitude and time scales of 5 days to one month. The optimum number of validation sites required is not very large but there should be at least one site for each major climatic type. Sites, which normally include stations which record both radar and rainfall estimates could be termed primary sites and data should be collected from these sites beginning in the near future. The validation of simple geostationary satellite-based techniques could make use of daily rainfall estimates from several parts of the tropics, even without radar data, as long as raingauge networks are fairly dense. These sites are referred to as secondary sites. The following were recommended:

(i) Primary sites should be established in Thailand, north Australia, Japan, Florida, the Caribbean Basin, south Brazil, Canada, UK, Sweden and Israel.

(ii) Secondary sites should be established in Indonesia, Thailand, south Japan, north Australia, Florida, Honduras, Puerto Rico, south Brazil, Ivory Coast, Nigeria, Kenya and India.

(iii) Statistical studies on raingauge data sets from the above sites should be conducted to establish confidence limits to be placed on these data sets.

(iv) Additional sites in several important tropical areas, which do not have sufficient instrumentation, should be established with the addition of equipment. These are the Amazon Basin of Brazil, oceanic regions near Indonesia and the region around the South Pacific Islands.

4. ROLE OF MODELS IN THE ESTIMATION AND VALIDATION OF RAINFALL

Models can serve a useful purpose in evaluating satellite estimates of rainfall, but they may not be able to serve as unequivocal ground truth due to uncertainties in the estimates of rainfall contained in them. However, models do reflect the fact that rainfall is a product of the many thermodynamic and dynamic processes in the atmosphere that generate precipitation and as such serve as an aid to understanding these processes. Thus, models must be used to interpret satellite estimates of rainfall from a broader perspective than simply as tools for estimating the validity of these estimates. Models provide the means to carry out sensitivity tests of satellite rainfall estimates and may place bounds on them. Differences between model and satellite estimates may not always be resolvable but an examination of them may yield useful insight into both the satellite estimation technique as well as the model.

The workshop recommended that a specific number of modelling methods and specific models be selected for use to provide comparisons for satellite rainfall estimates. These are described in the following subsections.

4.1 Dynamic Models

4.1.1 Large-Scale General Circulation Models

(i) Attention should be focussed on the ECMWF model, which has a number of attributes qualifying it as the best model currently available for comparison with satellite rainfall estimates or procedures.

(ii) Comparisons should be made between model calculations and satellite estimates of global precipitation, specifically for processes in the Pacific Ocean Basin and adjacent maritime continent of Australasia, which are central to understanding the relationship between global precipitation and short-term climate change.

4.1.2 Mesoscale Models

(i) Mesoscale models, with spatial resolutions of 10 to a few 100 km, should be used in specific areas and cases to generate comparisons of rain volume over domains comparable to those observed by satellites.

4.1.3 Convective Cloud Models

(i) A substantial effort should be made to apply and extend the work of Adler and colleagues (Convective Stratiform Technique) to other cases and convective regions.

(ii) Support of modelling work at government and university laboratories, related to rainfall research concerned with remote sensing and its validation, should be encouraged.

4.2 Statistical and Empirical Models

(i) Statistical studies of rainfall distributions and estimations over the GATE area should be extended to other areas.

(ii) Models of the spatial variability of rainfall on scales ranging from tens of centimetres to kilometres should be developed to help with the interpretation of raingauge measurements as estimates of area-averaged rainfall and calibration sources for radar.

4.3 Budget Methods

(i) Methods, based on vertical soundings of the horizontal velocity and thermodynamic fields, should be used in specific locations to evaluate evaporation minus precipitation over substantial areas and time periods.

5. RAINFALL MEASUREMENT TECHNOLOGY

The measurement of precipitation, either near the surface or aloft, is in a primitive state. With minor exception, this technology has not advanced for almost five decades. There is virtually no established and generally accepted set of methods for calibrating and validating rainfall observations. Thus, the development of suitable calibration and validation techniques and systems need to be approached as a problem of the utmost importance.

A clear distinction was made between calibration and validation functions. Calibration refers to instantaneous measurements or those taken in a time comparable to the spaceborne sensor averaging time. Validation, on the other hand, refers to the comparison of time/space averages of rainfall by spaceborne methods with those made by a system of ground-based instruments of known accuracy for the same areas and time periods.

Primary standards were defined to be instruments/methods of the highest achievable and known accuracy and precision. Transfer standards were defined to be those instruments/methods whose accuracy and precision were determined by comparison with the primary standards and these would be transportable to validation sites for either calibration of other instruments or for use in long-term validation exercises. There is an urgent need for the development of accurate instruments which could be used both as primary standards or transfer standards.

5.1 Basic Calibration and Validation Facility (BCVF)

(i) A BCVF should be established with the following functions:

- act as a world centre for the development and evaluation of the full spectrum of rainfall measuring instruments and methods.
- conduct evaluations of the performance of existing and new technologies.
- operate a rainfall test facility capable of generating "standard" rainfalls of varying intensity and drop-size distribution.
- maintain and operate calibrated raingauges of various types and other direct and remote sensors.
- act as host to all interested in bringing instruments for calibration and validation.
- Maintain a repository of a reasonable number of transfer standards for loan to prospective users.
- Provide expertise on rainfall measurements.
- operate network of raingauges and other systems on time scales of up to one year and space scales up to 5° latitude x 5° longitude.

(ii) The BCVF should be established in a stepwise fashion, starting with the most important and reliable instruments and progressively adding newer and more sophisticated ones.

(iii) The BCVF should be supported and operated as an international facility, open to scientists and organizations from all over the world.

5.2 Primary and Transfer Standards

(i) The following should be used as primary standards:

- large collecting area, low turbulence raingauges
- pit gauges
- optical scintillation gauge
- momentum disdrometers
- 10 cm radar of NEXRAD class
- 0.9 cm wavelength, dual polarization microwave link
- underwater ambient sound technique
- microwave attenuation tomography.

(ii) The following should be used as transfer standards:

- aircraft equipped with microwave beacons
- attenuation measured on a space-to-ground microwave link
- microwave radiometry in conjunction with radar.

Report of the International Workshop on the

Validation of Satellite Precipitation Measurements

for the

Global Precipitation Climatology Project

1. INTRODUCTION

The International Workshop on the Validation of Satellite Precipitation Measurements for the Global Precipitation Climatology Project (GPCP) was opened at 9:00 a.m. on 17 November 1986 at the Department of Commerce Building in Washington, D.C., U.S.A., by J. Wilkerson of NOAA, the chairman of the workshop. He noted that the goal of the GPCP is to produce a 10-year data set of global rainfall estimates for the World Climate Research Programme (WCRP). The agenda for the workshop is included in Appendix A and a list of participants in Appendix B.

The objectives of the workshop were:

(i) To develop a plan for validating large-scale estimates of monthly precipitation derived from a combination of geostationary satellite observations, polar satellite observations and ground-based raingauge measurements, summarized over approximately 250 x 250 km^2 areas over the globe.

(ii) To document locations globally where radar/raingauge precipitation estimates are routinely compiled, with raingauge densities of one or more gauges per 50 x 50 km^2 area.

(iii) To establish the usefulness of current ground-based measurements of precipitation amounts on these scales and to document how and in what form these measurements are recorded.

(iv) To define the procedures and responsibilities of the "collecting country" and the "receiving country" and the benefits which might accrue to each.

(v) To document the status of other potential ground-based measurement techniques, such as microwave attenuation and acoustic methods, which might be developed should funds become available.

Global and regional water balances and the measurement of precipitation have been a major concern of meteorologists, climatologists, hydrologists and others for many years. Of the large number of meetings held in the past on this subject, three workshops had specific relevance to this meeting. Two were sponsored by the USA National Aeronautics and Space Administration (NASA) and one by the WCRP.

(i) Precipitation Measurements from Space (Greenbelt, Maryland, USA, 28 April - 1 May 1981).

(ii) Tropical Rainfall Measuring Mission (Greenbelt, Maryland, USA, 18-20 November 1985).

(iii) Global Large Scale Precipitation Data Sets for the World Climate Research Programme (Washington, D.C., USA, 24-26 July 1985.

Among the conclusions reached was that it was clear that, at the present time, no single type of measurement could be used as a validation standard for comparison with space-based measurements of rainfall amount over large areas and long time periods. An optimum reference comparison data set would require a combination of data from raingauges, radar and other instruments.

For the near-term, there is a need within the WCRP to answer the following questions:

(i) What is the best that could be done with existing instrumented networks and techniques to begin a programme of validation of global precipitation for the GPCP in 1987?

(ii) What precipitation monitoring test sites exist worldwide and how might they contribute to the GPCP validation needs?

(iii) Where are there radar/raingauge networks of sufficient size, resolution and continuity of observations, which could be used as reference sites?

(iv) Which of these sites need equipment, which could make them acceptable as validation sites for the GPCP validation programme?

(v) What would be the strategy for implementing a validation programme, which would utilize test site data from such diverse sources as exist worldwide?

(vi) How could quality control of these data sources be maintained?

(vii) What national and international experiments, planned for implementation in 1987 or beyond, could provide test site data for GPCP use?

(viii) What instrument development would be needed to improve measurements of precipitation over the oceans and what development approaches should be taken at this time?

The workshop was organized to provide answers to the above questions and to provide the guidance needed to prepare a plan for validating global large-scale monthly rainfall fields to be produced by the GPCP.

Three keynote presentations were made to introduce the major topics for discussion by the workshop:

(i) Validation requirements for the GPCP (P. Arkin)

(ii) Indirect measurements and strategy for validation of satellite precipitation measurement (G. Austin)

(iii) Modelling and direct ground-based techniques for in situ measurements of precipitation (M. Garstang).

Presentations on possible sources of ground-based rainfall measurements were given by representatives of 12 countries. All of the above presentations are included in Appendix D.

Three sessions were then held to provide background information (see Appendix D) for the four panels, constituted from the workshop participants, which discussed in some detail the following subjects and prepared recommendations for a GPCP validation plan.

(i) Panel 1: Satellite precipitation validation requirements

(ii) Panel 2: Existing rainfall data sources and validation strategy

(iii) Panel 3: Role of models in the estimation and validation of rainfall

(iv) Panel 4: Rainfall measurement technology

The reports of the four panels have been summarized in sections 2-5 of this report. A summary of the recommendations agreed upon by the workshop is included in section 6.

2. SATELLITE PRECIPITATION VALIDATION REQUIREMENTS

2.1 Introduction

The measurement of large-scale precipitation is of great importance to a wide variety of climate modelling and diagnostic studies. The release of latent heat associated with tropical convection is one of the principal driving mechanisms of the general circulation and interannual variations in the spatial and temporal distribution of that heating are central to the El Niño/ Southern Oscillation (ENSO) phenomenon. Knowledge of the large-scale precipitation field has important potential applications in the generation of initial conditions for numerical weather prediction models and in the validation of climate general circulation models.

Each of these applications requires measurements, or estimates, of the area-averaged rainfall for regions of 10^5-10^6 km^2, integrated over periods of 12 hours to 1 month. The only possible source for such data, particularly over oceanic regions, is satellite observations. While many methods of using satellite visible, infrared and microwave radiances have been shown to yield useful estimates of area-averaged rainfall, none of these techniques are capable of providing the quantitative measurements needed without some independent estimate of the rainfall to calibrate and validate the satellite information.

The Global Precipitation Climatology Project (GPCP) has been organized by the World Climate Research Programme (WCRP) to produce a 10-year global data set, beginning in January 1987, of monthly rainfall for 2.5° latitude x 2.5° longitude areas. In regions of sparse in situ rainfall measurements, such as the tropical oceans, simple satellite estimates based on geosynchronous satellite infrared radiances will have to be used initially, while passive microwave estimates will be used to estimate rainfall over extratropical oceans. These estimates must be compared with independent measurements to assure prospective users of their validity. The data flow proposed for the GPCP is shown in Figure 2.1. The component labelled Surface Reference Data Centres represents the source of calibration/validation measurements for the Geostationary Satellite Precipitation Data Centre and the Polar Satellite Precipitation Data Centre.

A point deserving strong emphasis is that the "measurement" (really an estimation) of rainfall on any scale and from any measuring device is very much a research problem. The focus of the workshop was on the aspects required to enable the GPCP to accomplish its objectives, but there should be a constant awareness of the need for research as well.

2.2 Satellite Precipitation Validation Requirements

The requirements for validation of large-scale precipitation fields, to be produced by the GPCP, fall into two categories. The first includes requirements describing the institutional structure which is needed in order for the GPCP to proceed. The second includes requirements describing the technical characteristics of the reference data sets and the associated data processing.

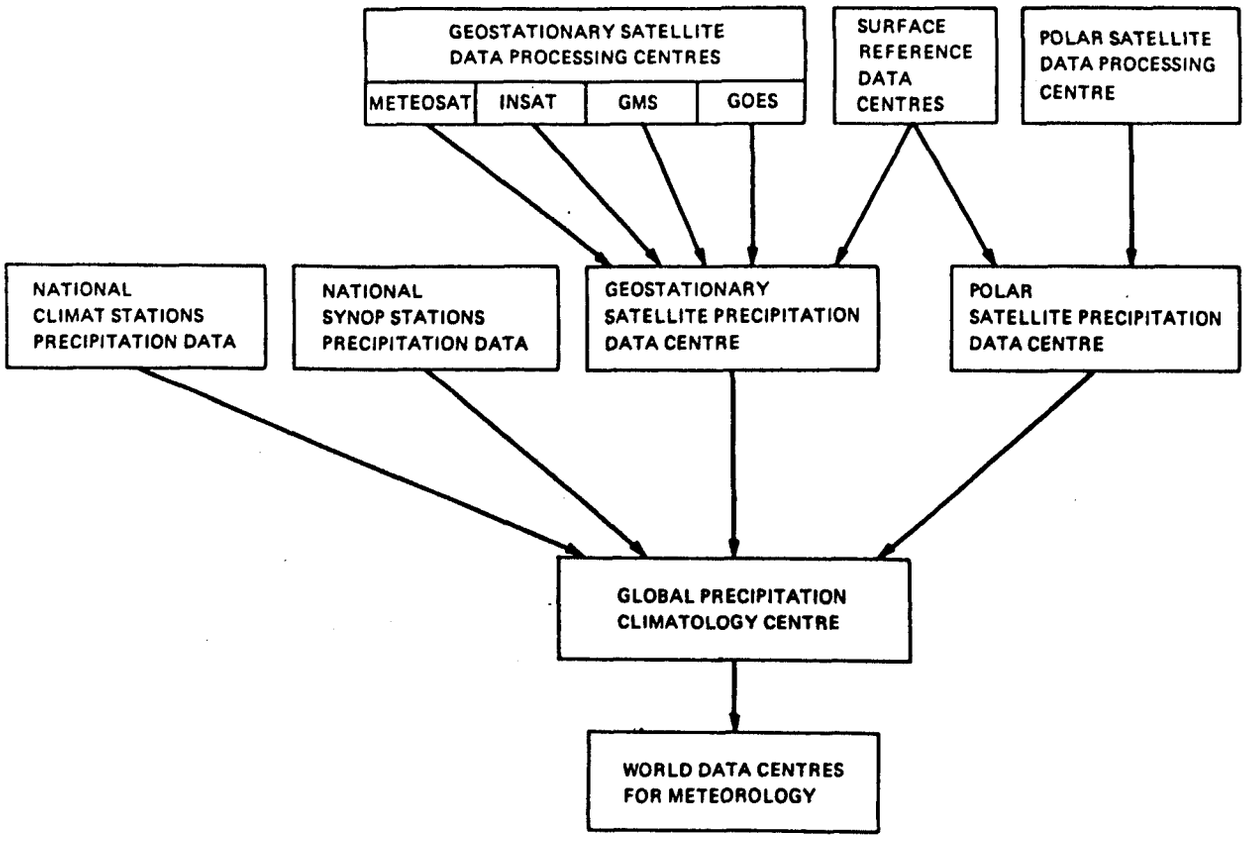

Figure 2.1. Global Precipitation Climatology Project Data Flow

2.2.1 Institutional Requirements

The workshop recommended that an international group be constituted, or an existing group be identified, to provide the scientific guidance to the GPCP with respect to the task of estimating global large-scale precipitation fields. The model for this group should be the Ad hoc Working Group on Clouds and Radiation of the IAMAP International Radiation Commission, which provides advice and guidance for the International Satellite Cloud Climatology Project. This group should be briefed periodically on the progress of the GPCP; it should oversee research activity on the problem of estimating area-averaged rainfall; and it should act as an advocate to persuade national research programmes and funding agencies to actively participate in finding solutions to the problems.

A Surface Reference Data Centre (SRDC) should be established within the GPCP. The functions proposed for the SRDC are described in Section 2.3.

An ad hoc committee should be formed to provide scientific and technical guidance to the SRDC. This committee should be constituted from scientists actively involved in research on the estimation of area-averaged rainfall. It should recommend strategy for both the operational and research activities of the SRDC and promote collaborative research projects among workers in the field.

The validation and calibration of rainfall estimates is of great importance. Accordingly, rainfall calibration sites should be established. At least one site should be equipped with state-of-the-art instrumentation which would permit testing and application of conventional and experimental rainfall measuring techniques and the acquisition of a high quality, long-term rainfall data set for the development and validation of satellite-based rainfall estimating schemes. Of equal importance is the establishment of additional validation sites, located in climatologically important rainfall regimes, which would provide long-term rainfall data sets of high quality.

2.2.2 Technical Requirements

It is recognized that although the scale of interest for GPCP is 2.5° latitude x 2.5° longitude monthly (global) and 5-day (tropics) totals, there may exist data sets containing rainfall estimates at smaller scales ($\geq 10^4$ km^2, daily), which could provide an opportunity to validate satellite-based rainfall estimates for these scales with high confidence. It is therefore a requirement to identify and obtain reference data sets of area-averaged rainfall for areas $\geq 10^4$ km^2 for periods ranging from daily to monthly. Successful validation of any technique at smaller scales should guarantee good performance of the technique at larger scales. Identification of such data sets would also provide opportunities for the future validation of techniques adapted towards other than GPCP goals.

Minimum levels of quality for inputs to reference data sets should be established. Since any reference data set has errors which depend on many factors often difficult to account for, and ranging from sensor calibration to climatic variability, it is recommended that certain minimum standards of quality be established in terms of network density (number of gauges per unit area), record length, calibration and proper exposure of the sensors, and quality control steps.

(i) Network density

The requirement for a minimum network density stems from the effects it can have on the performance of any of the techniques used to produce an areal estimate. Special studies may be required to determine this density. Some insight into this question may be found in Creutin and Obled (1982) and Tabios and Salas (1986).

(ii) Record length

The requirement for a minimum record length ensures that there is sufficient experience with the network providing the reference data set to identify potential problems, if any, of that network. If a new network is established, this requirement could be relaxed.

(iii) Calibration and proper exposure of sensors

The calibration requirement simply means that all sensors should be well-calibrated and properly situated.

(iv) Quality control

The quality control requirement ensures that bad data (or outliers) do not enter the validation process. Quality control methods are not well established at present and should be left to the group responsible for collecting the data.

The form in which data are to be submitted to the Surface Reference Data Centre should be standardized, in terms of contents and formats. It is fairly easy to establish such standards for raingauge data. It is recommended that information on gauge location (latitude, longitude, elevation), sensor type (collector, tipping bucket, etc.), sensor sensitivity, resolution, reporting procedure, and accuracy be provided along with the data. Due to the small volumes of raingauge data, even reports in documentation form should be acceptable. The task of establishing standards for radar data is much more complex because of the large volume of data involved. These data should be provided in summarized form and could include the accumulation of data over specific time periods (e.g., daily) and for a rectangular grid with a certain resolution. In some cases, it may be possible to trace back the "raw" radar data (e.g., USA RADAP-II data are archived at the National Climatic Data Center).

2.3. Surface Reference Data Centre

The Surface Reference Data Centre is a vital component of the GPCP. The SRDC should be the focal point for the validation of large-scale precipitation estimates and provide selected reference data sets to the Geostationary Satellite Precipitation Data Centre and the Polar Satellite Precipitation Data Centre. The SRDC should compile selected reference data sets and deliver them to the World Data Centres (WDC) for Meteorology for archiving and distribution.

The estimation of large-scale precipitation from many data sources is an extremely difficult scientific problem and requires a significantly augmented effort. New techniques for estimating large-scale precipitation fields should be investigated. These techniques should include those using satellite sensors, surface and aircraft based sensors, and models, or combinations of these. It is vital that research, development and testing of these techniques be promoted.

The workshop emphasized that the study of the error structures of estimates of large-scale precipitation from all sources should be encouraged. In particular, little is known of the spatial distribution of errors in rainfall fields estimated from various measurement systems.

The SRDC should have both operational and research responsibilities. Its functions in support of operations are:

(i) Publish a catalogue containing descriptions of available reference data sets, satellite estimation techniques, and model-based estimation techniques. The catalogue should have three sections (i.e., surface reference data sets, satellite estimation techniques, and model-based estimation techniques). Within each, attention should be given to the classification of types of input, compositing and estimation

procedures, and resulting products. As an example, the section on precipitation reference data sets should indicate whether or not gridded fields are available, the methods used in producing such fields, the numbers and locations of raingauges, the type of radar used and some of its key characteristics, and any other sources or special characteristics utilized.

(ii) Collect reference data sets with appropriate documentation from each of the participating validation sites.

(iii) Assess the quality and composition of the reference data sets and accept those which meet the agreed-upon standards.

(iv) Produce selected gridded reference data sets, using an agreed-upon composite estimation technique and ship them to the satellite precipitation data centres.

(v) Ship copies of all gridded reference data sets, with appropriate documentation, to the WDCs for Meteorology.

(vi) Encourage and sponsor frequent communication and dissemination of relevant information on validation and estimation results, through the following means: newsletters, publication lists, special journal editions, sessions at professional meetings, workshops, etc.

Its functions in support of research are:

(i) Compare selected smaller-scale precipitation reference data sets with satellite precipitation fields to improve the performance of each.

(ii) Investigate the feasibility of acquiring and archiving full resolution satellite data for selected time periods to aid in the development and testing of other satellite estimation techniques.

3. EXISTING RAINFALL DATA SOURCES AND VALIDATION STRATEGY

3.1. Validation Strategy

The GPCP requirement calls for rainfall estimates over areas of 2.5° latitude and 2.5° longitude and time scales of 5 days to one month. The need for tropical data sets is greater than for extratropical data sets. The optimum number of validation sites is not very large but it does seem desirable to have at least one for each major climatic type.

The validation of polar orbiting satellite rainfall estimation techniques is rather different than for geostationary satellite techniques in that it requires both instantaneous rainfall patterns at the time of passage of the satellite and also monthly amounts. This would allow for both the validation of the instantaneous rainfall estimates and the assumptions which have to be made to convert these estimates into totals on climatological time scales.

3.2 Existing Rainfall Data Sources

Sites, which normally include stations which record both radar and rainfall estimates, could be termed primary sites and are areas where data should be collected in the near future, i.e., Thailand, north Australia, Japan, Florida, the Caribbean Basin, south Brazil, Canada, UK, Sweden and Israel (see Figure 3.1). In addition, it is believed that some sites could be upgraded primarily by the addition of a relatively low cost digitizer to an existing radar. A particular location where this would be possible is the island of Barbados.

The validation of simple geostationary satellite-based techniques could make use of daily rainfall estimates from several parts of the tropical region without the additional information provided by radar if the raingauge networks are fairly dense. A set of appropriate locations for secondary sites is also shown in Figure 3.1. The sites suggested are Indonesia, Thailand, south Japan, north Australia, Florida, Honduras, Puerto Rico, south Brazil, Ivory Coast and/or Nigeria, Kenya and India. These suggestions were based on the availability of networks of the highest raingauge density for the climatic type. The reports required from these sites are daily totals for each raingauge in the region. Reports should be submitted as soon as possible and certainly within one year of the collection of the data. Local quality control of data is essential.

In general, the accuracy with which these raingauge networks represent the rainfall in these regions is not well known. The workshop suggested that statistical studies be conducted on the data sets from the regions in order to establish confidence limits which may be placed on the raingauge estimates. These data and analyses should be made available to the world community.

3.3 Deficiencies in Existing Networks

The workshop expressed serious concern over the fact that several important tropical areas did not have available sufficient data meeting the primary requirements. These areas are:

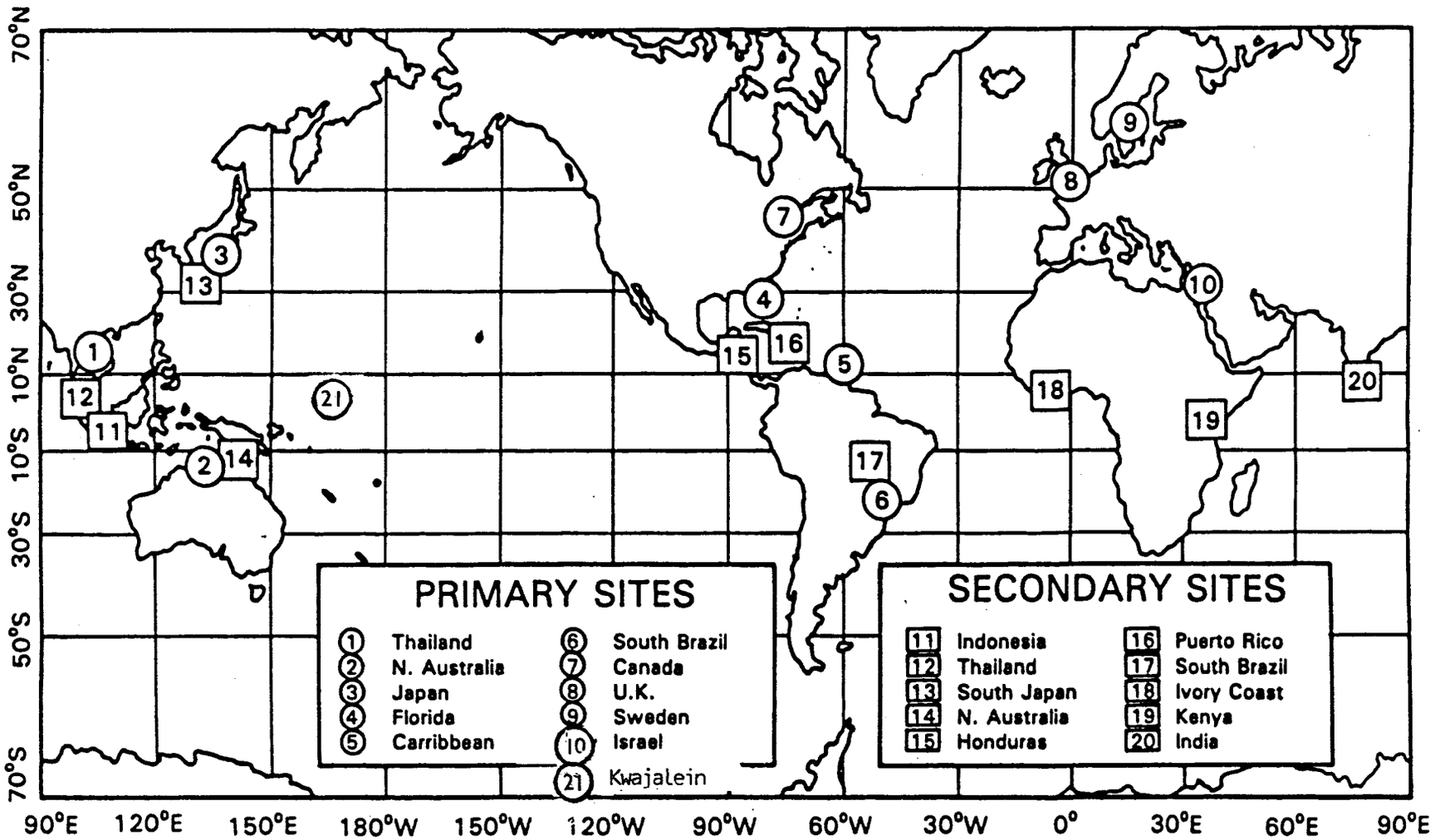

Figure 3-1. Proposed Primary (Radar and Raingauge Networks) and Secondary (Raingauge Only Networks) Sites for the Global Precipitation Climatology Project

(i) Amazon Basin of Brazil. This area is of major importance due to the extremely intense convection over the region during most of the year. The role of the rain forest in atmospheric chemistry and the role of the atmosphere in distributing these chemical products are important. The region near Manaus is flat and although the vegetation makes extensive raingauge installations expensive (towers are needed), a combination of weather radar and microwave attenuation raingauges could provide the data coverage needed.

(ii) Oceanic rainfall near Indonesia. While there is an array of raingauges in the region, the extreme topography in the region makes it difficult to obtain a representative network. The importance of convection over the region to the El Niño phenomenon is probably significant. The location of a radar on one of the islands should be considered a priority requirement.

(iii) The South Pacific islands. The South Pacific contains many small islands and it would be useful to include a radar/raingauge system in that area.

3.4 Other Considerations

In the longer term, in addition to the calibration site proposed (see Section 5.4), it is also necessary to maintain at least a few other high quality validation sites over several years in order to establish how different climatologies and rainfall systems affect the accuracy with which both in situ and remotely-sensed techniques estimate rainfall amounts. This is not a trivial matter and should be the subject of an on-going research effort.

Since the Tropical Rainfall Measuring Mission (TRMM) and other rainfall measurement projects, yet to be organized, would have similar data requirements as for the GPCP, it is believed that the objectives for these projects should be combined. In particular, the present effort to establish both primary and secondary validation sites could be used to support the TRMM concept without significantly damaging or complicating the GPCP objectives.

4. ROLE OF MODELS IN THE ESTIMATION AND VALIDATION OF RAINFALL

4.1. Introduction

Models can serve a useful purpose in evaluating satellite estimates of rainfall on a scale of 250 x 250 km^2 and over time periods ranging from days to 100's of days. It is stressed, however, that models may not be able to serve as unequivocal ground truth due to uncertainties in the estimates of rainfall contained in the models. However, models reflect the fact that rainfall is a product of the many thermodynamic and dynamic processes in the atmosphere that generate precipitation and as such serve as an aid to understanding these processes. Models therefore must be used to interpret satellite estimates of rainfall from a broader perspective than as simple tools for attempting to estimate the validity of these estimates. Models provide the means to carry out sensitivity tests of satellite rainfall estimates and as such may place bounds upon them. Differences between model and satellite estimates may not always be resolvable. Examination of these differences, however, may yield useful insight into both the satellite estimation technique as well as the model.

In viewing modelling of rainfall in the broadest sense, it is believed that many modelling efforts could be carried out on small computers and at very low cost in man-hours and money. Specific models and modelling approaches are recommended below because the modelling comparison effort must be focused and not allowed to stray into diffuse avenues not directed at the central problem of evaluating existing satellite rainfall measurements. Models must therefore be applied to address specific aspects of the problem for which they are particularly suited. Modelling tools could be applied in particular to the following aspects of rainfall estimation.

(i) Models can cover large areas (250 x 250 km^2) and many days (1 to n).

(ii) Models can be run for remote areas of the globe, over both the oceans and the continents.

(iii) Models can be combined with other meteorological observations, including direct (raingauge) and indirect (e.g. radar) estimates of rainfall.

(iv) Models can evaluate spatial and temporal variability of rainfall thereby assisting in the design of observing networks, and the determination of how well rainfall is measured on different scales.

The workshop recommended that a specific number of modelling methods and specific models be selected in order that useful comparisons could be made with satellite rainfall estimates. The modelling efforts are divided into three categories as described in sections 4.2-4.4.

4.2 Dynamic Models

4.2.1 Large-scale General Circulation Models

It is recommended that attention be focused on the European Centre for Medium-Range Weather Forecasts (ECMWF) model, which has a number of attributes

which, in our opinion, qualify it as the best model currently available for comparison with satellite rainfall estimates or procedures. ECMWF products are widely available on an operational basis. The model has excellent spatial resolution and is being updated to include surface water budget physics.

The isopleths of satellite-inferred outgoing long-wave radiation (OLR) have been used by climate modellers and ENSO investigators (see, for example, Rasmussen and Arkin, 1985) as a proxy variable for rainfall from tropical convective systems. They assume that positive rain anomalies are associated with cold OLR anomalies and vice versa. These anomalies over the Pacific Basin have an important annual variability which can occasionally be masked or overcome by a strong ENSO event. When the latter occurs, the OLR cold anomalies move from their normal position over the Indonesian maritime continent into the central and eastern Pacific, resulting in drought conditions over Australia and impacting the entire circulation pattern over North America and other distant areas. Up to the present, researchers have had to assume that the proxy variable OLR (cold cloud top temperature) represents precipitation and that OLR anomalies represent anomalies in precipitation. To check the range of validity of this assumption in the important Pacific Basin area, the ECMWF model could be used to interpolate between and supplement rainfall data collected at key reference stations such as Kwajalein, Darwin and stations in southeast Asia. Not only could the rainfall products of the model be compared directly with the estimates by the Arkin (OLR) method, but also the comparison could be made in the context of the evolving circulation patterns, either normal seasonal evolution or even more definitively in the case of the strong ENSO events.

Such an analytical effort should be mounted as a high priority task among the on-going estimates of global precipitation by research groups involved in determining methods for use in global precipitation estimates (e.g., those at the Cooperative Institute for Climate Studies).

It is recognized that other comparisons between global precipitation calculations and satellite estimates could be made. Such comparisons are encouraged but it is stressed that the process in the Pacific Ocean Basin and adjacent maritime continents of Australasia are central to the problem of the relationship between global precipitation and short-term climate changes, so that these should have the highest priority in the context of the WCRP.

4.2.2 Mesoscale Models

Mesoscale models, with spatial resolutions of 10 to a few 100 km, should be used in specific areas and cases to generate comparisons of rain volume over domains comparable to those observed by satellites. Mesoscale models should be used in two ways:

(i) In realtime, for direct comparison between the mesoscale model estimate of rain volume and the satellite estimate of rainfall.

(ii) Diagnostically, to generate a library of mesoscale convective/stratiform rainfall cases, which could serve as guidance to satellite rainfall estimates under different rain producing conditions.

It should be noted that the mesoscale model products could and should be usefully compared with direct (raingauge) and indirect (radar) estimates of rainfall.

It is recommended that comparisons with mesoscale model products and satellite rainfall estimates be carried out selectively for specific geographical locations. At present, the most promising regions for comparisons are:

(i) U.K., where an operational mesoscale model with a spatial resolution of 15 x 15 km^2 is being used.

(ii) Southeastern USA including the Florida Peninsula, where mesoscale models have been applied.

Attempts should be made to carry out mesoscale model rainfall estimates in other areas such as Israel and the more tropical regions of northern Australia and southern Japan.

4.2.3 Convective Cloud Models

One-dimensional convective cloud models (time dependent or non-time dependent) have been shown to contain useful diagnostic information which could be used to "calibrate" or fine tune estimates of convective rainfall from satellite infrared or visible radiances (Adler and Mack, 1984). These models are simple and most economical to run on minicomputers and some personal computers.

A substantial effort should be made to apply and extend the work of Adler and colleagues (see Simpson et al, this volume; Adler et al, 1985; Adler and Negri, 1987; Negri et al, 1984) to other cases and particularly to other convective rain regimes. The one-dimensional model is used to take into account the effects of environmental stability, humidity and (very roughly) wind shear (via an entrainment coefficient) to make infrared estimates of convective rain locations with different cloud environments. Its application has so far been made only in Florida and in the midwestern USA in summer, where clouds grow in a fairly humid tropical air mass. To translate the infrared calibration technique for use in convective rainfall estimates in semi-arid areas, evaporation below cloud bases would have to be included or parameterized. It is particularly important to note that this approach applies only to the actively convective portion of the cloud system and that some technique must simultaneously be employed to screen out non-raining cirrus and stratiform precipitation occurring from convectively produced anvils. The Convective Stratiform Technique (CST) of Adler and Negri (1987) is recommended for use for this purpose, first for cloud systems in tropical air masses and later in semi-arid areas. In the latter case, considerable research and comparisons with observations would be required to estimate the evaporation, which would probably differ between the convective and stratiform portions of the system. In young systems, evaporation is likely to be greater from the higher stratiform clouds than from the lower-based more heavily raining convective portions. The relative evaporation would clearly vary with the initial sounding and the life cycle of the cloud systems of interest. Extension and testing of the method to a few selected tropical areas should not require more than about 1 man-year of effort by a masters' level

meteorologist and negligible computer cost. The major part of such an effort would be the careful selection of areas and the necessary data acquisition. Judicious use should be made of 2-D and 3-D cloud models and particularly a cloud population model, such as that of Tao (Tao and Simpson, 1984) to determine rain volumes, infrared brightness in convective/stratiform systems, and estimates of other radiative properties.

Modelling work being carried out at such laboratories as the Goddard Laboratory for Atmospheres and the Department of Atmospheric Science at the South Dakota School of Mining and Technology (see for example, Chen and Cotton, 1986) should be encouraged and expanded to other centres of cloud modelling and rainfall research concerned with remote sensing and its validation. The South Dakota School of Mines group has concentrated mainly on two-dimensional approaches to orographically-induced precipitating systems with highly sophisticated cloud microphysics. Two-dimensional models, where justified, are relatively inexpensive to run on medium to large size main frame computers. Fully three dimensional single cloud and cloud population models with adequate resolution and adequately sophisticated cloud microphysics for satellite validation are presently expensive to run and require main frame computers as large or larger than a CYBER 205. These models must therefore be used judiciously, but they are essential components of satellite rainfall algorithm development and validation, They are also needed for advancing the basic understanding of cloud interactions, which is essential if satellite rain sensing and validation is to progress at an optimum rate.

4.3 Statistical And Empirical Models

Statistical studies of rainfall distributions and estimations, such as those carried out by North and others on the GATE data set, should be extended to other areas. Models (e.g., Krajewski, this report) of the spatial variability of rainfall on scales ranging from tens of centimeters (raingauge diameters) to kilometers (radar resolution) need to be developed to help with the interpretation of raingauge measurements as estimates of area-averaged rainfall and as calibration sources for radar. These studies together with computer models developed by hydrologists and based upon measured rainfall distributions in convective storms should be used to design ground-based rainfall measuring networks, and to estimate the magnitude of the error in measuring rainfall under a wide range of sampling protocols. There is also a need to evaluate the usefulness of rainfall measurement on ships-of-opportunity by numerical simulation and statistical analysis.

4.4 Budget Methods

Budget methods, based on vertical soundings of the horizontal velocity and thermodynamic fields, should be used in special locations to evaluate evaporation minus precipitation over substantial areas and time periods, as was done over the Global Atmospheric Research Programme (GARP) Atlantic Tropical Experiment (GATE) area by Brummer (1978), Frank (1978) and others, and over Texas by Matthews (1983). In particular, opportunities to accurately evaluate moisture and precipitation budgets exist over Florida, northern Australia and the Amazon Basin.

Efforts should be made to evaluate the use of indirect sounding techniques, now being used in the Pacific Ocean, and indirect soundings from satellites as input to budget calculations over remote ocean areas.

5. RAINFALL MEASUREMENT TECHNOLOGY

5.1 Introduction

The measurement of precipitation, either near the surface or aloft, is in a primitive state. With minor exceptions, this technology has not advanced for almost five decades. The workshop noted that there is virtually no established and generally accepted set of methods for calibrating and validating rainfall observations. Even the densest existing network of raingauges (about 1 per km^2) is questionable for various reasons. Moreover, the establishment of suitable methods for the "accurate" measurement of point rainfall and of raingauge networks or remote sensors for area-wide rainfall is a fundamental problem which confronts a very broad range of disciplines and applications including meteorology, climatology, hydrology, agriculture, aviation and others. Thus, it was felt that the development of suitable calibration and validation techniques and systems needed to be approached as a problem of the utmost importance. Indeed, as we begin to tackle the problem of the earth as a system and recognize that water is the quintessential element on which life depends, it is evident that the measurement of the global water budget and the hydrological cycle can no longer be neglected.

It should be noted, however, that this problem is being addressed in a number of forums, most recently in workshops on TRMM. The October 1986 draft of the TRMM workshop and the subsequent report of the TRMM Sciences Steering Group deal with the "ground truth" problem very well. Indeed, whatever ground truth systems, which may be established for TRMM, would be directly applicable to the GPCP and conversely. Therefore, this section expands upon, or takes exception to, portions of the TRMM workshop report.

5.2 Comparison of Needs of TRMM and GPCP

(i) The overall requirements are essentially the same except that in addition to the validation of total monthly rainfall over 5° latitude x 5° longitude regions, the GPCP has an additional requirement for validation over 5 days and 2.5° latitude x 2.5° longitude regions.

(ii) TRMM proposes the use of a low-orbiting, low-inclination satellite which would sample a given area no more than twice per day but would cover the diurnal cycle by precessing so as to cross the equator at a given longitude at a variety of clock hours during the month. GPCP, which requires global coverage, will utilize infrared observations from geosynchronous satellites and available microwave observations from polar satellites in sun-synchronous orbits.

(iii) TRMM aims to determine the vertical structure of precipitation for use in improving geophysical algorithms and establishing the vertical profile of latent heating. GPCP is concerned mainly with rainfall at the surface.

(iv) Both projects consider existing methods to be inadequate and regard the development of ground truth instruments and systems as a critical problem for research and development.

(v) Both projects approach the design of ground truth systems in essentially similar ways with the need for a central site having raingauge networks of various sizes and raingauge densities imbedded in one another, and where a spectrum of different in situ and remote sensors could be intercompared and calibrated.

5.3 Definitions

The workshop made a clear distinction between calibration and validation functions. Calibration refers to both the calibration of instruments and methods used for the measurement of rainfall at a point and over various size areas up to the size of the resolution or footprint of a spaceborne sensor. Generally, it also refers to instantaneous measurements or those taken in a time comparable to the spaceborne sensor averaging time. Validation, on the other hand, refers to the comparison of time/space averages of rainfall by spaceborne methods with those made by a system of ground-based instruments of known accuracy for the same areas and time periods.

Primary standards refer to instruments/methods of the highest achievable and known accuracy and precision. These would generally reside at a main calibration site. Transfer standards refer to those instruments/methods whose accuracy/precision have been determined by comparison with the primary standards and are then transportable to validation sites for either calibration of other instruments or for use in long-term validation exercises. There is an urgent need for the development of accurate instruments which may be used both as primary calibration standards and transfer standards.

5.4 Basic Calibration and Validation Facility

The workshop proposed the establishment of a Basic Calibration and Validation Facility (BCVF), which is somewhat more ambitious and far reaching than a corresponding facility proposed by TRMM, although it appears that the intentions are essentially similar. The most accurate primary calibration standard would reside in the BCVF. The raingauge network should have three station densities, with areas of about 100, 2500 and 40000 km^2, with spacing of 1 km, 5 km, and 15 km respectively. The raingauges should be state-of-the-art telemetered instruments, interspersed with pit gauges, optical scintillation gauges and disdrometers. The BCVF would have the following functions:

(i) Act as a world centre for the development and evaluation of the full spectrum of rainfall measuring instruments and methods, both primary and secondary.

(ii) Conduct evaluations of the performance of existing and new technologies by comparison with the best available standards.

(iii) Operate a rainfall test facility capable of generating "standard" rainfalls of varying intensity and drop-size distribution.

(iv) Maintain and operate calibrated raingauges of various types and other direct and remote sensors for rainfall measurement and act as host to all organizations interested in bringing their instruments to the BCVF for calibration and evaluation.

(v) Maintain a repository of a reasonable number of transfer standards for loan to prospective users throughout the world for calibration of rain measuring systems.

(vi) Provide expertise to all users concerned with rainfall measurements.

(vii) Operate a network of raingauges and other rain sensing systems capable of measuring rainfall with the utmost accuracy on time scales up to one year and space scales up to 5° latitude x 5° longitude, for use in validating spaceborne methods.

The BCVF should be implemented in a stepwise fashion starting with the most important and reliable instruments and progressively adding newer and more sophisticated ones. The following priority phasing is suggested:

(i) Phase 1: Instrumentation would include a raingauge network, a well-calibrated, narrow-beam 10 cm radar which is implemented for measurements of polarization diversity or can be upgraded for such later, a dual wavelength, dual polarization microwave link, optical scintillation gauges, and disdrometers.

(ii) Phase 2: Instrumentation would include the addition of vertically-pointing microwave radiometers, underwater hydrophones for rain rate and drop-size, laser optical drop-size instruments, an optical, or infrared, extinction link, an artificial rain generator for producing "standard" rains with controlled drop size distributions, and vertically pointing CW Doppler radar.

(iii) Phase 3: Instrumentation would include further additions of an air-to-ground multi-wavelength microwave link using attenuation by a storm between ground-based receivers and airborne beacons, a satellite beacon receiver in the 1 to 2 cm band, areal rainfall measurements by microwave attenuation tomography, a humidity convergence system surrounding a fine mesh raingauge network for water budget studies, and standard meteorological observing systems.

The BCVF should be supported and operated as an international facility open to scientists and organizations from all over the world. If operated by a single nation, reasonable user fees may be charged for access. The locale of the BCVF should include the following characteristics:

- plentiful rainfall, both convective and stratiform;
- access to both ocean and land;
- uniform topography;
- an existing climatological record;
- a good road network; and
- an existing organizational infrastructure for logistic support.

5.5 Instruments and Methods for Measuring Precipitation

The following instruments and methods are recommended for use as potential primary standards:

(i) Large collecting area, low turbulence raingauges.
(ii) Pit gauges.
(iii) Optical scintillation gauge (Wang).
(iv) Momentum disdrometers, such as that of Joss (with larger collecting area).
(v) 10 cm radar of the NEXRAD class.
(vi) 0.9 cm wavelength, dual polarization microwave link (a second wavelength at about 2 cm would provide greater dynamic range).

Other new technologies which deserve serious attention are the underwater ambient sound technique (Nystuen, 1986) and microwave attenuation tomography using an array of links,

Methods which have performed well in the past and which deserve to be implemented as calibration transfer standards are:

- an aircraft equipped with microwave beacons, circling behind a storm and transmitting to a central receiver site,
- attenuation measured on a space-to-ground microwave link, and
- microwave radiometry in conjunction with radar.

A potentially very simple and economical raingauge and disdrometer is a small vertically pointing CW Doppler radar. This should be investigated promptly.

5.6 Use of Radar

5.6.1 Conventional Radar

The workshop was considerably less confident than the TRMM report that conventional radar could be used to measure rainfall. Although the biases which often characterize short-term or individual storm measurements are often averaged down in long-term/large-area averages, this effect cannot be relied upon in many cases (e.g., where rain in a specified time/area domain is dominated by only a few storms).

5.6.2 Differential Polarization Radar

The use of a high performance differential polarization radar was recommended for further testing at the BCVF, but it cannot yet be regarded as either a primary or transfer standard. Also, even with a narrow beam system, it should not be expected that such a radar will perform well beyond a range of about 50 km, or the range at which the beam intercepts the melting level. When such radars are used with smaller antennas and larger beams, the range to which they may be useful decreases even further.

The concept of calibrating either conventional or differential polarization radars by either raingauges or disdrometers is fraught with

hazards. Unless the rain is very uniform in space and time and little evaporation or growth occurs during its fall, such surface measurements may not be representative of the volumes observed by the radar.

5.6.3 Doppler Radar

The workshop was less optimistic than the TRMM report about the utility of Doppler radar measurements. It is believed that useful measurements of updraft velocities in convective storms cannot be obtained by the Velocity-Azimuth Display (VAD) method and those in stratiform storms are often close to the effective noise limit of the method. The only way to determine the vertical velocities in convective storms is to use a dual or tri-Doppler system, but this does not appear justified for present purposes alone. However, the Doppler system might be useful in the following ways:

(i) When located near the centre of a surface raingauge network, it could provide divergence measurements for use in water budget methods of estimating rainfall.

(ii) In stratiform situations, the VAD method could provide wind profiles which might help in determining where the rain aloft reaches the ground.

(iii) Small and economical vertically pointing CW Doppler radars could provide improved measurements of drop-size distribution and rain rate because of the larger sampling volumes relative to raingauges or momentum disdrometers.

5.7 Vertical Profiling of Diabatic Heating

The TRMM report refers to the estimation of the vertical profile of diabatic heating from either the vertical velocity field (from Doppler radar) or the reflectivity field (with non-Doppler radar). The temperature field, which is consistent with the three dimensional field of motion, could in fact be retrieved with a multi-Doppler system. Otherwise, the reflectivity field alone provides little information on the heat profile unless it is parameterized with the use of some storm model.

From time to time, it would be useful and efficient to conduct studies of the dynamics and microphysics of storms at the BCVF. However, a permanent multi-Doppler system would not be warranted for present purposes.

5.8 Other Methods and Approaches

5.8.1 Vertically Pointing Radiometer

Adjustment procedures required for the interpretation of spaceborne microwave radiometer data depend on the intensity and vertical depth of the liquid water in a region of rain. Radar provides information about the scattering properties of the precipitation but cannot provide an unambiguous estimate of the phase of the precipitation. Vertically pointing microwave radiometers could supply the additional information needed to reduce the ambiguity of the radar measurements.

Long-term vertically pointing radiometer observations, made in conjunction with co-located surface raingauge data, would provide the statistical information on rain layer thickness needed to optimize the adjustment of downward-pointing microwave radiometer measurements for the estimation of rainfall. Such measurements should begin as soon as possible at each validation site.

Microwave radiometers have a limited dynamic range. Multiple co-located radiometers operating at different frequencies are needed to span the wide range of precipitation intensities. At a minimum, these frequencies should be selected in the 10-40 GHz range and two frequencies in the 50-60 GHz band.

5.8.2 Microwave Attenuation

Microwave attenuation in the 1 to 3 cm band is essentially linear with the path-averaged rainfall rate and is largely independent of the Drop Size Distribution (DSD). Thus, the use of a microwave link, with a transmitter at one end and a retroreflector at the other, would be an excellent means of measuring the average rain rate over the path. A variety of configurations are possible to provide area wide coverage. Path lengths ranging from 1 to 10 km are visualized. It is particularly important that such a system is implemented over a fine mesh raingauge network with dimensions on the order of 10 x 10 km^2.

Because the attenuation is sensitive to the polarization of the radiation relative to the essentially horizontal orientation of the oblate raindrops, the measurements should be made with alternating horizontal and vertical polarization, or with circular polarization.

The best wavelength for such a link is 0.9 cm where the attenuation is almost perfectly linear with rain rate and is independent of the DSD and is largely independent of temperature. With a 10 km path, the system should have a dynamic range of 80 db in order to measure path average rain rates up to 200 mm/hr. For longer paths and rain rates, it would be necessary to use a second (longer) wavelength to extend the dynamic range.

Microwave attenuation links are especially important for use at validation sites on islands or coasts where it is not possible to deploy raingauges over water. In such cases, one could consider the use of a microwave link between oil drilling platforms or from the ground to an aircraft carrying one or more beacon transmitters. The aircraft would be tracked by a ground-based tracking radar which is slewed to the nearby receiving antennas. In this way, it would be possible to measure a circumferential profile of the integrated attenuation through a storm as the aircraft flies a path behind the storm with respect to the ground-based receivers. Of course, the aircraft must repeat its track beyond the storm at intervals of 5 to 10 minutes in order to estimate the total rainfall as the storm moves and evolves. It should be noted that this method may be viewed more for calibration rather than validation purposes because it is unlikely that aircraft measurements would be available for long durations and over large areas.

In order to obtain longer duration measurements, it would be worth considering the release of standard chaff packets to act as "pseudo-standard" targets behind the storms. The difference between the chaff echo intensity viewed directly and that seen through the storm is the attenuation.

5.8.3 Satellite Beacon Attenuation

Satellite beacons of opportunity provide a means of sampling the attenuation on a slant path with a larger dynamic range than is possible with a microwave radiometer. Unfortunately, the number of geostationary satellites available for such observations are limited and the slant path to an available satellite may be at a low elevation angle. Radar data should be obtained in conjunction with such measurements to facilitate the separation of the effects of vertical variations in rain from those produced by horizontal variations. Information on vertical variations is needed to optimize the adjustment of downward-looking microwave radiometer observations.

5.8.4 Microwave Attenuation Tomography

Microwave attenuation links are attractive for the reasons noted in section 5.7.2. If a number (three or more) of microwave attenuation links could be set up to "criss-cross" a given region, then tomographic inverse techniques could be used to estimate the spatial distribution of rainfall rate. This would be an improvement over single microwave links as such measurements produce only line integrals of rainfall rate. It might also improve radar calibration (over the same region) since it measures the same moment of the drop-size distribution as rainfall rate whereas radars do not.

5.8.5 Airborne Doppler Radar

For purposes of intermittent calibration over the oceans, the workshop recommended the use of a method proposed by Atlas and Matejka, in which a vertically-scanning Doppler radar, such as that installed in the National Oceanic and Atmospheric Administration (NOAA) P-3 aircraft, would be employed. This method involves the viewing of precipitation both directly and indirectly via mirror image reflection from the sea surface. It would then be possible to separate the two components which control the vector velocity, the windspeed (u) and the mean Doppler fallspeed (v). The combination of v with the radar reflectivity (Z), in the same pulse volume, would thus provide a two parameter estimate of the rain rate (R). Simulations with real drop-size data indicate that such measurements could be made with RMS errors of about 8%, excluding instrumental errors. Also, the measurements could be made with acceptable accuracy out to horizontal distances, on either side of the aircraft, equal to the aircraft height. In order to avoid excess attenuation associated with the Bright Band, it would be desirable to fly just below the melting level.

The above method is still experimental and it is not known whether or not suitable mirror reflections could be received from the sea at high windspeeds. However, this should be readily determined because the aircraft is flown regularly within storms and hurricanes. Assuming that this method works successfully, it would be possible to fly long tracks along and across precipitation bands to obtain measurements of rain intensity. Moreover, since

the aircraft is fitted with Knollenberg probes, one could obtain excellent DSD data for further validation of the method and the determination of appropriate Z-R resolutions.

5.8.6 Underwater Acoustic Technique

This is an experimental technique which shows promise as a means of monitoring rainfall over oceanic regions. It depends on the fact that rain striking a flat water surface is a very effective underwater sound source and that the intensity of the sound produced appears to be related to rainfall rate (Nystuen, 1986).

At the present time, there is no proposed algorithm for inferring rainfall rate from underwater ambient noise , since the currently-available data set for developing such an algorithm is not large enough. There are also some important questions which need to be addressed, such as:

(i) Are there times (or places) where other sound sources obscure the sound generated by rain?

(ii) How does wind affect the sound generated by rain?

(iii) How does the drop-size distribution in the rain affect the sound generated?

These questions are the subject of active research.

Observations have shown that, when present, rain is usually the dominant underwater sound source. Furthermore the spectral characteristics of the rain-generated sound are distinctive and therefore this technique should detect the presence of rain even when the rainfall rate is very light, i.e. 1 mm/hr. On the other hand, there have been times when local shipping, boating or biological activity (e.g. snapping shrimp) has contaminated the data. There will be locations where this technique is not very effective.

Recently, Nystuen and Farmer (1987) have examined the influence of wind on the sound generated by light rain (rainfall rate 1 mm/hr and no drops with diameter >2 mm). Their conclusion was that wind modifies both the shape of the spectrum of underwater sound produced by light rain and the intensity of that sound. This result casts some doubt on the ability of this technique to quantitatively measure the light rain which may be typical of some mid-latitutde stratiform rain systems. Clearly, more measurements are needed. Larger drops (>2 mm diameter) are less affected by wind and so this problem might not be as critical for convective rain. The observation that sound intensity is proportional to rainfall rate (Nystuen, 1986) was based on data from a heavy convective storm. More data would be needed to verify that observation.

While this is not an operational technique, it should be included as a Phase II instrument system at the BCVF. This technique has the potential of being an extremely useful way to monitor rainfall. The basic sensor, a hydrophone, is readily available, inexpensive and durable. Hydrophones could be deployed almost anywhere there is water, and, in particular, in remote ocean regions where no other surface rainfall measurement systems are

available. Furthermore, the BCVF would be the best facility at which the underwater acoustic technique could be developed, calibrated and tested.

5.8.7 Ships as Instrument Platforms

There are a number of techniques which provide hope for useful rainfall measurements from ships of opportunity. Such measurements would be valuable in allowing at least partial validation over much wider geographical areas than would be possible with fixed sites. The processing scheme for these data would be designed to compare near instantaneous rain rate estimates from ships and satellites, wherever time and space coincidence allows. Sufficiently dense measurements along major shipping lanes should also be used to give average climatologies in these areas. For this purpose, various types of measuring instruments could be used:

(i) Standard raingauges. The problem of siting gauges on ships, and the large errors that could result from airflow distortions by the hull or superstructure are well known. However, the main data set from which the geostationary satellite visible/infrared techniques have been derived was raingauge measurements taken on GATE research vessels. These ships were nearly stationary at the times of observation, but ship speeds constitute less of a problem than wind speeds in causing major errors. Also, modern cargo vessels tend to have flat, relatively uncluttered, upper decks that allow reasonable gauge siting. Experiments are being conducted on trans-Pacific vessels to explore siting problems (WCRP, 1986). Preliminary results indicate that reliable data could be derived, particularly if data from high relative wind conditions are edited out.

(ii) Wang Optical Raingauge. This instrument has evolved from previous designs (Wang and Lawrence, 1981). It measures variations in light from a near-infrared laser diode along a short (1m) path. The light beam is in the form of a horizontally-oriented strip measuring about 30mm x 1mm x 1000mm, so that drops falling with a vertical component of velocity through the strip give a rapid fluctuation in received light. Horizontal motions result in slower fluctuations which are rejected by the detector electronics. The variations are band-pass filtered at about 700 $\pm$ 300 Hz and an output analogue voltage is provided which is proportional to the log of the averaged (10 second time constant) fluctuating power in this band. The manufacturer shows a linear relation between this voltage and the log of the rain rate. Performance of the raingauge under at-sea conditions remains to be evaluated. It must still be sensitive to flow distortions due to the ship, but should not itself affect the flow near the collecting volume. The gauge is relatively cheap and simple to handle. An Automatic Gain Control (AGC) system corrects for slow laser diode power changes or for dirt or salt deposition on the optics. It therefore appears to be suitable for unattended operation on a ship.

(iii) Microwave Attenuation. For this technique, (Atlas and Ulbrich, 1977), an unobstructed path of 50-100 m could probably be found on an average-sized cargo vessel, with folding to increase this by a factor of 2-4, (say to 200 m). At 90 GHz, equipment is expensive, but at 30 GHz the attenuation would be reduced to 1/3 in db, causing problems with lighter rain. Systematic drifts in attenuation must be compensated for. Those that are not a function of rain rate could be monitored using the baseline observed between rain events.

(iv) Optical Attenuation. This technique (Ulbrich and Atlas, 1985, Nedvidek, et.al, 1986) has been demonstrated to provide measurements of rain rate accurate to about ±25%. Attenuation for a 200 m path varies from 0.2 db at 1 mm/hr to 2 db at 100 mm/hr. These values could be increased by greater folding of the path, so that accurate measurements over this range should be feasible. However, the system would be strongly affected by fog and snow.

6. SUMMARY OF RECOMMENDATIONS

(1) Establish an international advisory group, or identify an existing group, to provide scientific guidance to the GPCP on the estimation of global large-scale precipitation fields. (This group should oversee research activity on the problem of estimating area-averaged rainfall and serve as an advocate in persuading national research programmes and funding agencies to actively participate in finding solutions to the problems involved.)

(2) Establish a Surface Reference Data Centre to act as the focal point within the GPCP for the collection and archiving of reference data sets for the validation of large-scale precipitation estimates.

(3) Promote research, development and testing of new techniques for estimating large-scale precipitation fields.

(4) Encourage the study of error structures of large-scale precipitation estimates from all sources.

(5) Establish an ad hoc committee of scientists actively involved in research on the estimation of area-averaged rainfall to provide scientific and technical guidance to the SRDC, recommend strategy for both the operational and research activities of the SRDC, and promote collaborative research projects among workers in the field.

(6) Establish at least one rainfall calibration site, equipped with state-of-the-art instrumentation, which would permit the testing and application of conventional and experimental rainfall measuring techniques to obtain high-quality, long-term rainfall data sets.

(7) Establish other validation sites located in climatologically important rainfall regimes, which could provide additional high-quality, long-term rainfall data sets.

(8) Identify and obtain reference data sets of area-averaged rainfall for areas 10^3 km^2, for periods ranging from daily to monthly.

(9) Establish quality standards for reference data sets, in terms of network density, record length, calibration, proper exposure of sensors, and quality control procedures.

(10) Establish standards, in terms of contents and formats, in which data should be submitted to the Surface Reference Data Centre:

(a) Information on gauge location, sensor type, sensor sensitivity, resolution, reporting procedure and accuracy should be provided along with the data.

(b) Radar data should be provided in summarized form.

(11) Establish rainfall validation data sites around the globe to provide radar/raingauge measurements for at least one site for each major climate type:

(a) Primary sites are those areas in which stations normally record both radar and rainfall data and could provide them in the near future. A first estimate of available locations are Australia (northern part), Brazil (southern part), Canada, Caribbean Basin, Florida, Israel, Japan, Sweden, Thailand and UK. (It should be noted that some areas could easily be upgraded by the addition of a relatively low cost digitizer to an existing radar, e.g., Barbados.)

(b) Secondary sites are those areas in which stations have reasonably dense raingauge networks but no radar coverage is available. A first estimate of available locations are Australia (northern part), Brazil (southern part), Florida, Honduras, India, Indonesia, Ivory Coast, Japan (southern part), Kenya, Nigeria, Puerto Rico and Thailand.

(12) Conduct statistical studies on raingauge data sets to establish the confidence limits which may be placed on these rainfall estimates.

(13) Establish rainfall measurement sites in several important areas in the tropics which do not have available any data meeting GPCP requirements,

(a) Amazon Basin of Brazil: combination of weather radar and microwave attenuation raingauges.

(b) Oceanic region near Indonesia: radar on one of the islands.

(c) South Pacific islands: radar/raingauge system.

(14) Maintain at least a few high-quality validation sites over several years to establish how different climatologies and rainfall systems affect the accuracy with which both in situ and remotely-sensed techniques estimate rainfall.

(15) Combine the needs of GPCP with those for TRMM and other projects for calibrating and validating rainfall measurement techniques.

(16) Select a specific number of modelling methods and models so that useful comparisons could be made between model outputs and satellite rainfall estimates.

(17) Focus attention on the ECMWF model, which has a number of attributes qualifying it as the best model currently available for comparison with satellite rainfall estimates or procedures.

(18) Make comparisons between model calculations of global precipitation and satellite estimates, specifically for processes in the Pacific Ocean Basin and adjacent maritime continent of Australasia, which are central to the relationship between global precipitation and short-term climate changes.

(19) Make selective comparisons of rain volume produced by mesoscale models and satellite rainfall estimates, over domains of 10 to a few 100 km, in the following specific locations:

(a) UK, where an operational mesoscale model with a spatial resolution of 15 x 15 km^2 is being used.

(b) Southeastern USA, including the Florida Peninsula, where mesoscale models have been applied.

(c) Whole of Israel.

(d) More tropical regions of northern Australia or southern Japan.

(20) Make a substantial effort to apply and extend the work of Adler and colleagues (Convective Stratiform Technique) to other cases and other convective rain regions.

(21) Make judicious use of 2-D and 3-D cloud models, particularly a cloud population model (e.g., Tao), to determine rain volumes, infrared brightness in convective/stratiform systems, and estimates of other radiative properties.

(22) Encourage support of modelling work being carried out at laboratories, such as the NASA Goddard Laboratory for Atmospheres and the Department of Atmospheric Science at the South Dakota School of Mining and Technology, and expansion to other centres of cloud modelling and rainfall research concerned with remote sensing and its validation.

(23) Extend statistical studies of rainfall distributions and estimations to other areas (besides the GATE area).

(24) Develop models of the spatial variability of rainfall on scales ranging from tens of centimeters to kilometers to help with interpreting raingauge measurements as estimates of area-averaged rainfall and as calibration sources for radar.

(25) Evaluate the usefulness of measurement of rainfall on ships of opportunity by numerical simulation and statistical analysis.

(26) Utilize budget methods, based on vertical soundings of the horizontal velocity and thermodynamic fields, in special locations to evaluate evaporation minus precipitation over substantial areas and time periods.

(27) Evaluate the use of indirect sounding techniques now being used in the Pacific Ocean and indirect soundings from satellite as input to budget calculations over remote ocean areas.

(28) Develop accurate instruments which may be used as both primary calibration standards and transfer standards.

(29) Establish a Basic Calibration and Validation Facility with the following functions:

(a) Act as a world centre for the development and evaluation of the full spectrum of rainfall measuring instruments and methods.

(b) Conduct evaluations of the performance of existing and new technologies.

(c) Operate a rainfall test facility capable of generating "standard" rainfalls of varying intensity and drop-size distribution.

(d) Maintain and operate calibrated raingauges of various types and other direct and remote sensors.

(e) Act as host to all interested in bringing instruments for calibration and validation.

(f) Maintain a repository of a reasonable number of transfer standards for loan to prospective users.

(g) Provide expertise on rainfall measurements.

(h) Operate network of raingauges and other systems on time scales up to one year and space scales up to 5° latitude x 5° longitude.

(30) Establish a Basic Calibration and Validation Facility, where the most accurate calibration standards reside, in a stepwise fashion starting with the most reliable and important instruments and progressively adding newer and more sophisticated ones;

(a) Phase 1: Instruments to include a raingauge network, a well-calibrated narrowbeam 10 cm radar (implemented for measurements of polarization diversity or capable of being upgraded later for such measurements), a dual-wavelength dual-polarization microwave link, optical scintillation gauges and disdrometers.

(b) Phase 2: Instruments to include the addition of vertically-pointing microwave radiometers, underwater hydrophones for rainrate and drop-size measurements, laser optical drop-size instruments, an optical or infrared extinction link, an artificial rain generator for producing "standard" rains with controlled drop-size distributions, and vertically-pointing CW doppler radar.

(c) Phase 3: Instruments to include further additions of an air-to-ground multi-wavelength microwave link (using attenuation by a storm between the ground-based receivers and airborne beacons), a satellite beacon receiver in the 1-2 cm band, areal rainfall measurements by microwave attenuation

tomography, a humidity convergence system surrounding a fine mesh raingauge network for water budget studies and standard meteorological observing systems.

(31) Operate the BCVF as an international facility, open to scientists from all nations. (If operated by a single nation, reasonable user fees may be charged for access to the facility.)

(32) Utilize the following instruments and methods as potential primary standards:

(a) Large collecting area, low turbulence raingauges
(b) Pit gauges
(c) WANG laser scintillation gauge
(d) Momentum disdrometers
(e) 10 cm radar of the NEXRAD class
(f) 0.9 cm wavelength dual polarization microwave link (second wavelength of about 2 cm would provide greater dynamic range).

(33) Develop and test other new technologies, such as the underwater ambient sound technique (Nystuen, 1986) and the microwave attenuation tomography using an array of links.

(34) Implement the following calibration transfer standards:

(a) Aircraft, equipped with microwave beacons, circling behind a storm and transmitting to a central receiver site.

(b) Attenuation measured on a space-to-ground microwave link.

(c) Microwave radiometry, in conjunction with radar.

(35) Investigate the use of a small vertically-pointing CW Doppler radar as a potentially very simple and economical raingauge and disdrometer.

(36) Establish an artificial rain-generating facility for the calibration of rainrate and drop-size measuring instruments.

(37) Develop and test instruments which could be deployed on ships of opportunity.

(38) Investigate the applicability of the two-parameter method of using an Airborne Doppler Radar over the ocean for calibration or short-term validation measurements.

(39) Record, archive and process, in a standardized manner, the data from instruments used in either the BCVF or any other validation site.

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APPENDIX A

INTERNATIONAL WORKSHOP ON THE VALIDATION OF SATELLITE PRECIPITATION MEASUREMENTS FOR THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT

(Washington, D.C., 17-21 November 1986)

AGENDA

MONDAY, 17 NOVEMBER 1986

0830	Registration	
0900	Welcome	T. Kaneshige
0905	Welcome	G. Ohring (COSPAR)
0915	Validation Requirements for the Global Precipitation Climatology Project	P. Arkin
0945	Indirect Measurements and Strategy for Validation of Satellite Precipitation Measurements	G. Austin
1015	Modelling and Direct Ground-based Techniques for In Situ Measurements of Precipitation	M. Garstang
1045-1100	Break	
1100	Rainfall Measurements in Kenya	R. Okoola
1120	Australian Bureau of Meteorology Rainfall Network	T. Keenan
1140	Rainfall Measurements in Brazil: A Survey	R. Calheiros
1200-1320	Break	
1320	Ground Truth Data Available for the UK Area for Validation of Precipitation Measurements from Satellite Data (by M.W. Wilson)	K. Browning
1340	Precipitation Observation Network in Japan	K. Matsubara
1400	Validation of Satellite-derived Precipitation Measurements in Canada	J. Nystuen
1420	The Caribbean Countries - Rainfall and Radar Stations	C. Depardine
1440	Israel	A. Gagin

1500-1520	Break	
1520	Raingauge Network in India	A. Krishna Rao
1540	A Brief Introduction on Raingauge Networks and Hydrologic Application of Meteorological Satellites in China	J. Yang
1600	Rainfall Measurements in Thailand	S. Sangmit
1620	Rainfall Network in Tanzania	P. Kato
1640	General Discussion	
1700	Adjourn	

TUESDAY, 18 NOVEMBER 1986

SESSION 1 - Rainfall Regimes and Measurements		Chairman M. Garstang
0845	On Improved Validation of Rainfall Estimates from Geosynchronous IR Products	J. Simpson
0920	Precipitation Climatology	J. Griffiths
0940	Precipitation Measurements: Agricultural Concerns	R. McArdle
1000	Advances in Raingauge Technology: An Optical Rain/Snow Gauge	T. Wang
1020-1100	Break	
SESSION 2 - Direct and Indirect Measurements of Rainfall		Chairman G. Austin
1100	USA Raingauge and Radar Network Data Bases	K. Hadeen
1120	Hydrology-related Observations and Their Application to Validation of Satellite-derived Rainfall Estimates	R. Gurney
1140	Radar Reflectivity and Related Measurements of Rainfall	D. Atlas
1220-1400	Break	
SESSION 3 - Sampling and Statistics of Rainfall		Chairman J. Vogel
1400	Some Selected Results from Dense Raingauge Networks	J. Vogel

1420	Multiple Sensor Rainfall Estimation	W. Krajewski
1440	Some Problems and Prospects in Sampling Precipitation	J. Flueck
1500	A Statistical Model of Rainfall for Remote Sensing Studies	T. Bell
1520-1540	Break	
1540	Statistical Variations of Precipitation on Spatial Scales Smaller than 256 km	R. Crane
1600	Precipitation Statistics Using Model Output	W. Tao
1620	Summaries and Discussions	Session Chairman
1700	Adjourn	

WEDNESDAY-THURSDAY, 19-20 NOVEMBER 1986

0830	Panel Meetings
1100	Plenary Session for Interaction and Feedback
1200-1330	Break
1330	Panel Meetings
1600	Plenary Session for Interaction and Feedback
1700	Adjourn

FRIDAY, 21 November 1986

0830	Panel 1 Report
0900	Panel 2 Report
0930	Panel 3 Report
1000	Panel 4 Report
1030-1100	Break
1100	Discussion of Implementation Plan
1200-1330	Break
1330	Wrap-up Session
	Action Items

APPENDIX B

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APPENDIX C

LIST OF ACRONYMS

AGC	-	Automatic Gain Control
BCVF	-	Basic Calibration and Validation Facility
CST	-	Convective-Stratiform Technique
CW	-	Continuous Wave
DSD	-	Drop-Size Distribution
ECMWF	-	European Centre for Medium-Range Weather Forecasts
ENSO	-	El Niño/Southern Oscillation
GARP	-	Global Atmospheric Research Programme
GATE	-	GARP Atlantic Tropical Experiment
GCM	-	General Circulation Model
GPCP	-	Global Precipitation Climatology Project
IAMAP	-	International Association of Meteorology and Atmospheric Physics
ICSU	-	International Council of Scientific Unions
NASA	-	National Aeronautics and Space Administration (USA)
NOAA	-	National Oceanic and Atmospheric Administration (USA)
OLR	-	Outgoing Long-wave Radiation
SRDC	-	Surface Reference Data Centre
TRMM	-	Tropical Rainfall Measuring Mission
VAD	-	Velocity Azimuth Display
WCRP	-	World Climate Research Programme
WDC	-	World Data Centre
WMO	-	World Meteorological Organization

APPENDIX D

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A Brief Introduction to Ráingauge Networks and Hydrologic Applications of Meteorological Satellites in China (J. Yang) D-65

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VALIDATION REQUIREMENTS FOR THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT

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1. INTRODUCTION

The measurement of large-scale precipitation is of great importance to a wide variety of climate modeling and diagnostic studies. The release of latent heat associated with tropical convection is one of the principal driving mechanisms of the general circulation, and interannual variations in the spatial and temporal distribution of that heating are central to the El Niño/Southern Oscillation (ENSO) phenomenon. Knowledge of the large-scale precipitation field has important potential applications in the generation of initial conditions for numerical weather prediction models, and in the validation of climate general circulation models.

Each of these applications requires measurements, or estimates, of the areally-averaged rainfall for regions of 10^5- $10^6 km^2$ integrated over periods of 12 hours to 1 month. The only possible source for such data in many regions is provided by satellite observations. While many methods of using satellite observations of visible, infrared, and microwave radiances have been shown to yield useful estimates of areally-averaged rainfall, none of them are capable of doing so without some independent estimate of the rainfall to serve as validation/calibration information. The problem of obtaining such validation/calibration measurements is the subject of this workshop.

2. THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT

The Global Precipitation Climatology Project (GPCP) has been established by the World Climate Research Programme to produce a 10-year data set, beginning January 1987, of monthly rainfall for areas of 2.5° latitude x 2.5° longitude for the globe. In regions such as the tropical oceans, it is expected that simple satellite estimates based on IR data from geosynchronous satellites will have to be used, while passive microwave estimates will have to be used over the extratropical oceans. Estimates based on either must be compared with independent measurements to assure prospective users of their validity. The data flow proposed for the GPCP is given in Figure 1, in which an element labeled "Surface Reference Data Centres" is shown. This element, as yet undefined, is expected to be the source of the calibration/validation measurements for the Geostationary Satellite Precipitation Data Centre and the Polar Satellite Precipitation Data Centre.

3. EXAMPLES

The simple IR histogram-based estimates of large-scale precipitation proposed for the initial stages of the GPCP have been available for the region viewed by the U.S.A. Geosynchronous Operational Environmental Satellites (GOES) since December 1981. Validation of these estimates for certain areas has been attempted using available station observations. These examples make

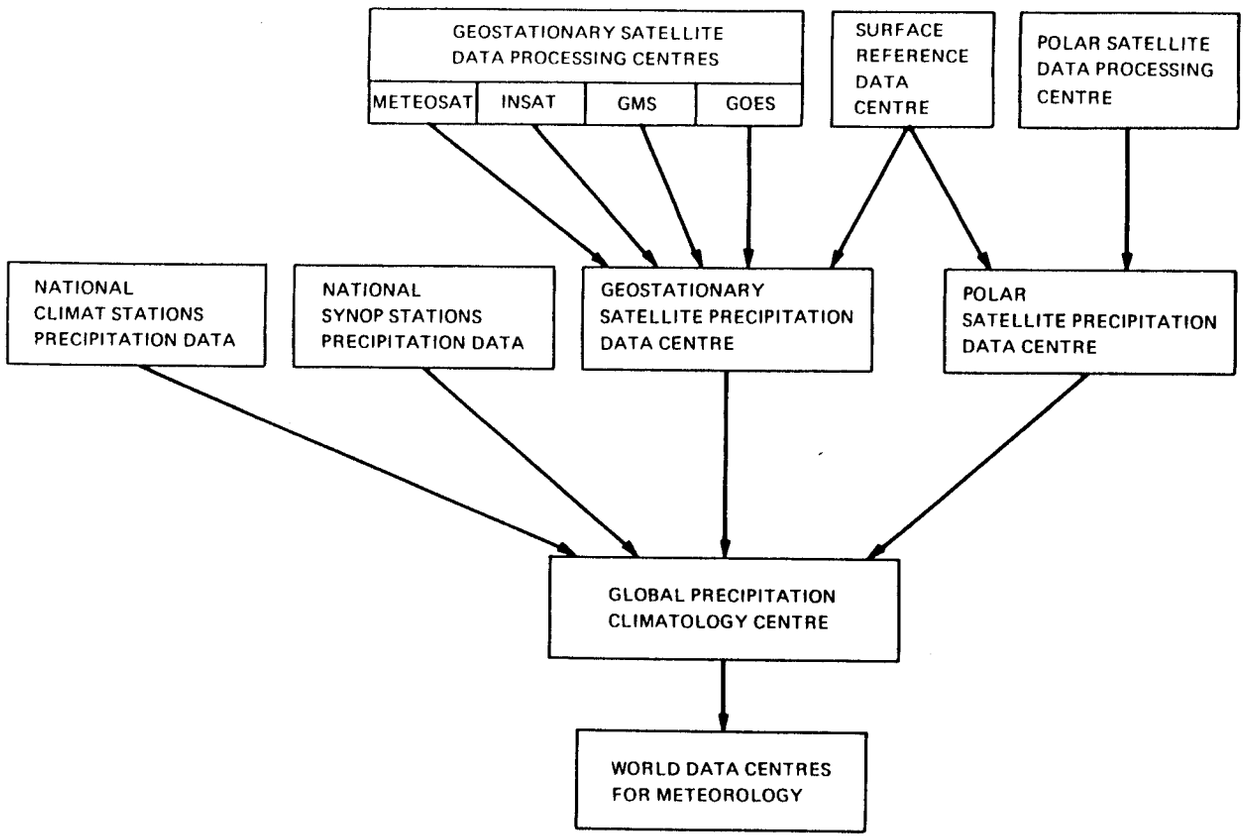

Figure 1. Global Precipitation Climatology Project Data Flow

it quite clear that either denser networks of gauges or integrated radar/gauge analyses in some areas would be highly desirable for the validation of such rainfall estimates.

The difficulty in using routinely reported station observations of rainfall for such validation is illustrated by Figure 2, which shows the maximum number of observations available on the Global Telecommunication System in each 2.5° latitude x 2.5° longitude area viewed by the GOES satellite during the period December 1981-November 1983. Eighty-seven percent (87%) of the areas had no observations, while only 14 had more than three. Spatial correlations of these data with the IR estimates (Figure 3) for this period show that one can have some confidence that the two estimates are of similar parameters, but one would hesitate to claim that they are identical.

A somewhat more reasonable data set with which to attempt such studies is provided by the monthly rainfall for the U.S.A. Climate Divisions (CDs), a set of 344 climatically homogeneous regions for which station rainfalls are averaged each month. Spatial correlations between the IR estimates and the CD rainfall over the U.S.A. (Figure 4) are highest (0.7) during the warm season, when the rainfall is presumably most convective in nature and, thus, most amenable to estimation by such a technique. Temporal correlations during this period (Figure 5) are highest east of the Rocky Mountains and during the warm season. However, areas of relatively high correlation in the upper Midwest are found to exhibit large biases, indicating that the temporal variability is being captured but that the quantitative estimate is inaccurate. This information, however, is the bare minimum which a validation study should yield. One would not feel confident in modifying the estimation algorithm on the basis of these results.

4. WORKSHOP GOALS

It is clear that, in order to meet its goal of constructing a 10-year set of global large-scale fields of monthly precipitation, the GPCP must obtain independent estimates of rainfall over temporal and spatial scales which would allow comparisons with various satellite estimates to be made. Determination of the means of obtaining such estimates/measurements is the objective of this workshop.

It is hoped that the final report of the meeting will contain the following:

(i) A plan describing how to acquire and integrate existing rainfall measurements so they can be used to validate/calibrate satellite estimates and to bring about the development of new methods to measure rain over ocean areas.

(ii) A description of the institutional structure necessary to achieve the validation requirements of the GPCP.

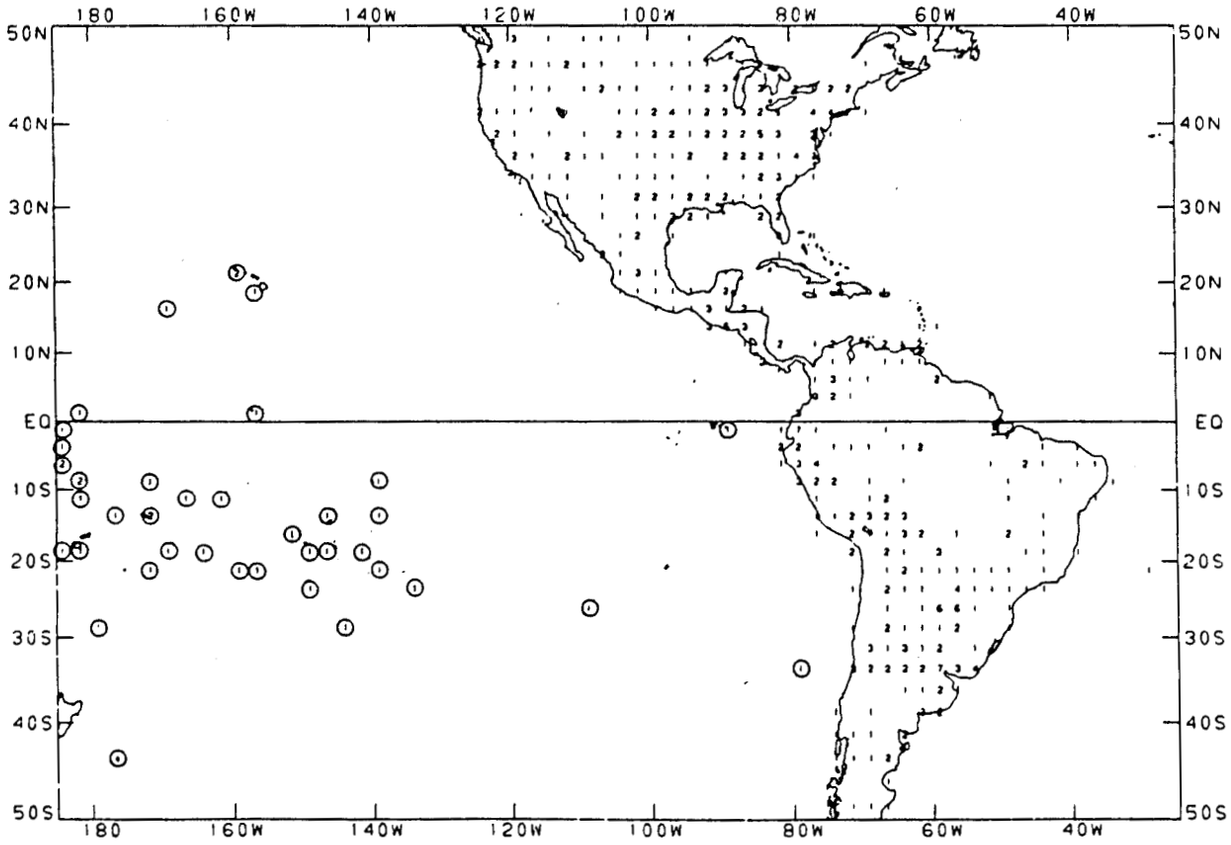

Figure 2. Number of rainfall observing stations in each 2.5° latitude x 2.5° longitude area used in the comparison of observed rainfall and GPI. The numbers represent the maximum number of stations available in each area in any month during the study period. The numbers representing Pacific Ocean island stations are circled.

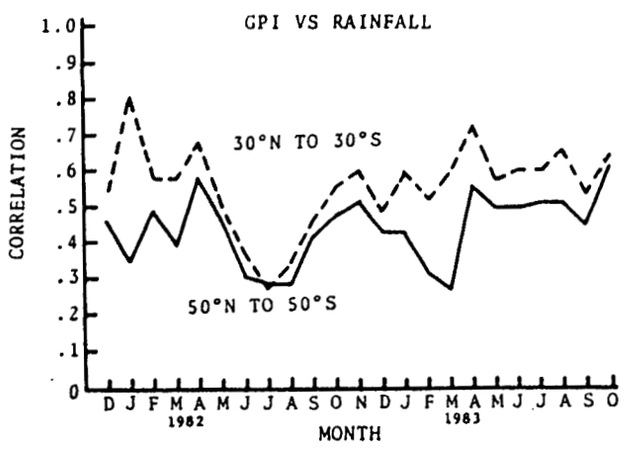

Figure 3. Time series of the spatial correlation between monthly rainfall observed at the stations identified in figure 2 and GPI for the region from 30°N-30°S and for the entire 50°N-50°S region.

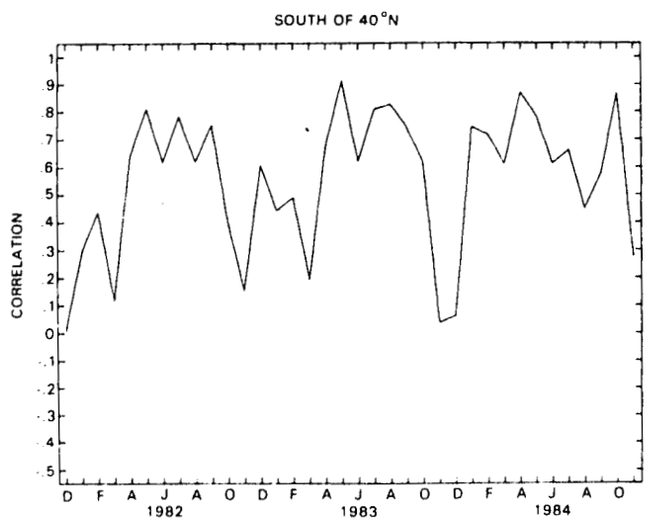

Figure 4. Time series of the spatial correlation between monthly GPI and Climate Division (CD) rainfall for the United States south of 40°N.

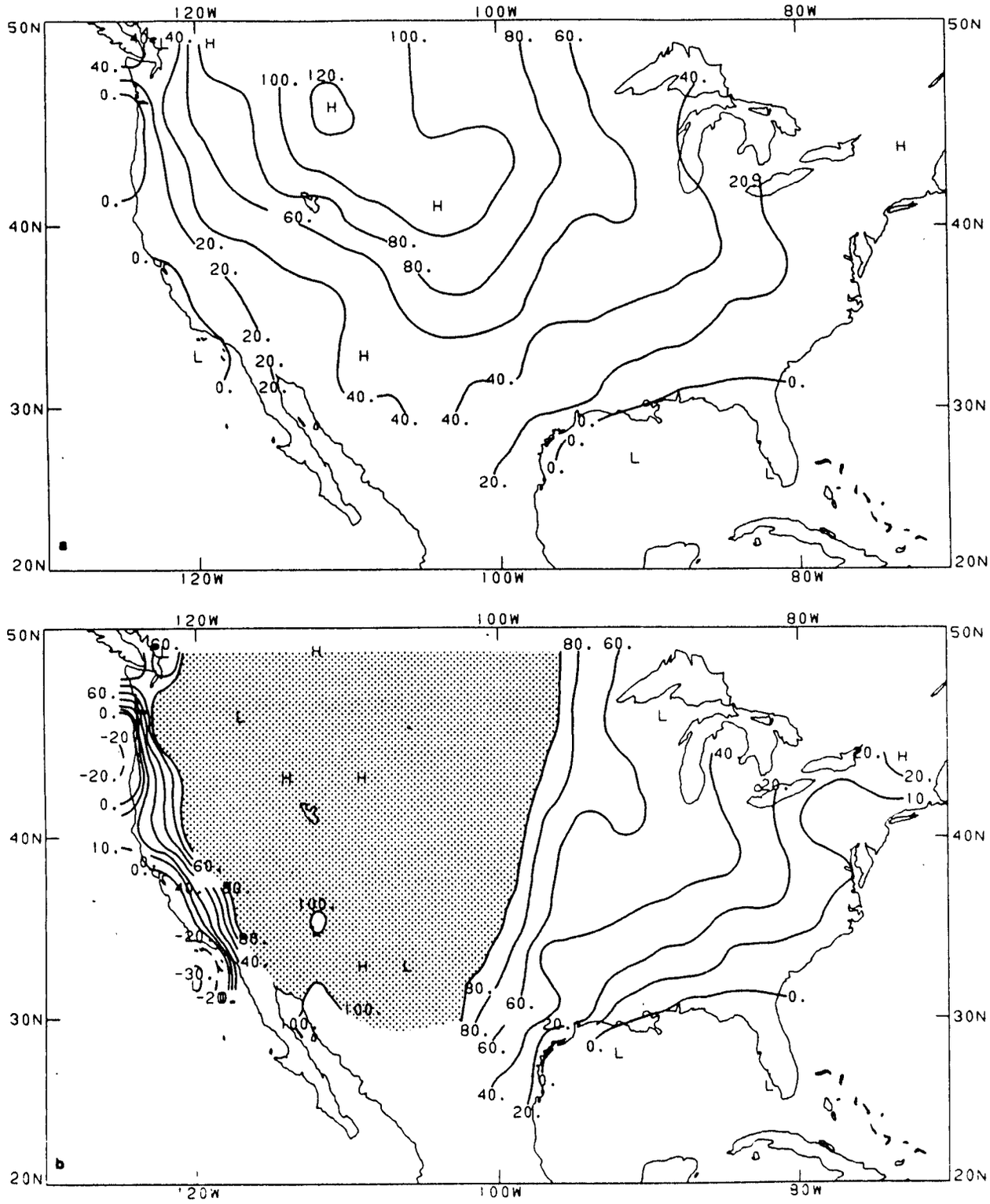

Figure 5. The temporal correlation (multiplied by 100) between monthly CD rainfall and GPI over (a) the full 3-yr period used in the study and (b) over the warm season (April–September) only. Contour interval is 10 with negative contours dashed.

INDIRECT MEASUREMENTS AND STRATEGY FOR VALIDATION OF SATELLITE PRECIPITATION MEASUREMENTS

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1. INTRODUCTION

The indirect measurement techniques for precipitation discussed here are weather radar (ground-based and space-based), microwave attenuation (ground links and radiometers), and satellite visible and IR techniques (IR only and bispectral/classification).

2. WEATHER RADAR

The major advantages of weather radars are that the reflection is directly from raindrops and that a complete three-dimensional structure of the precipitation may be obtained with good spatial (1 km) and temporal (5 minutes) resolution. A large number of systems of this type already exist around the world.

The major theoretical difficulty is that the reflection is proportional to the sixth power of the drop diameters whereas rainfall depends on the cube of the drop diameter multiplied by the drop fall speed. The net effect of this is that there is a non-linear and potentially unstable relationship between the radar measurement and the rainfall rate. Much work has been done on this problem over the years. In the author's personal opinion, too much of the observed discrepancy between gauge and radar measurements has been attributed to this Z-R relationship problem and too little to the sources of error including:

(i) Updrafts.

(ii) Presence of hail/snow/melting layer.

(iii) Attenuation in heavy rain.

(iv) Geometrical problems associated with the horizontal drift and modification of the rainfall pattern between the height of the radar beam and the ground.

The techniques for the adjustment of radar estimates of precipitation using rain gauges and other more advanced techniques, including dual polarization and dual wavelengths, have been studied. If greater effort is given to the calibration and the elimination of instrumental artifacts, then the accuracy which might be achieved with a simple radar would be of the order of 30% for a 100 km x 100 km area over a one hour period. It is not likely that remote sensing techniques will exceed this accuracy in the near future.

3. MICROWAVE ATTENUATION METHODS

The major advantage of these techniques is that the attenuation of microwaves depends on the rainfall rate in an almost linear manner. This means that path averaged attenuation may be used directly as path averaged rainfall. The most direct way to use this technique is to measure the

attenuation between an array of transmitter-receiver pairs over an area of the order 20 km x 20 km. This would simulate a large raingauge. The region could have significantly less sampling error than arrays of gauges (2).

An alternative use is in the form of radiometers located either on the ground looking up or in space looking down. The ground-based systems at low frequencies measure thermal emission from rain drops against the cold space background (3). The distinction of emissions from rain, snow cloud and water vapour is aided somewhat by operating the system at multiple wavelengths. From space the precipitation is observed as attenuation of the signal from the sea surface or land surface temperature background. At higher frequencies cold space is observed in the ice-filled cloud tops by a scattering mechanism (5).

4. VIS AND IR SATELLITE METHODS

The IR sensor measures the cloud top temperature and the reflected sunlight measured by the visible sensor can be used to estimate the optical thickness of clouds. The inference of rainfall amount from these characteristics of clouds is at best indirect or statistical. However, the data are available from geostationary satellites with high spatial (4 km) and temporal (30 minutes) resolution. An interesting but largely unresolved problem is to assess the relative contribution to rainfall accumulation measurement errors from the error due to poor spatial and temporal resolution.

The validation of IR satellite estimates of global rainfall amounts can probably be accomplished by data sets from a worldwide network of raingauge arrays with a density on the order of 50 gauges per 200 km x 200 km areas. However, consideration of extratropical areas suggests that, as large areas of cirrus become much more common, the simple IR thresholding techniques become very inaccurate (6). Other techniques using IR gradients or textures or the visible data set to eliminate such clouds may do better (7,8).

5. CONCLUSIONS

It is now a good time to collect global rainfall measurements in a few areas of the world in an attempt to validate remotely sensed techniques for rainfall estimates, even if the presently available techniques have rather large errors. This subject is clearly going to be a major area of research in the next decade. The sooner we get more quality-controlled verification data sets, the more rapid the scientific and operational progress will be.

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MODELLING AND DIRECT GROUND-BASED TECHNIQUES FOR IN-SITU MEASUREMENTS OF PRECIPITATION

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1. INTRODUCTION

Validation of global estimates of rainfall on a 2.5° latitude x 2.5° longitude space and a 30-day time scale must be based upon:

- direct measurements of the variable itself (raingauges),
- indirect measurements of rainfall (radar),
- indirect estimates based upon atmospheric dynamics (models), and
- consideration of the nature of rainfall.

I will highlight the last two, starting with the "nature" of rainfall.

2. NATURE OF RAINFALL

Much of our difficulties in estimating or measuring rainfall at the ground stem from the discontinuous nature of rainfall and the resulting high variability of rainfall in time and space. To deal with this variability, it is helpful to recognize how rainfall is produced and distributed on various time and space scales.

2.1 Convective Versus Stratiform

Cloud fields (Sadler, 1970) give a global view (Figure 1). Sellers (1965) provides a latitudinal view (Figure 2) which suggests that much of the globe's rainfall is generated from convective systems. There is no precise breakdown in terms of the relative contribution of each type of rainfall on this scale. However, a pervasive result is that 50 per cent or more of the rainfall falls about 10 per cent of the time, whether this is applied to days with rain (Figure 3) or hours with rain. A point of interest in Figure 3 is that this result is true for both dry and wet years.

The amount of rain received in a year (Figure 4) is a function of atmospheric systems with high rain rates, but the systems with the high rain rates, which produce the large amounts of rainfall, occur only rarely (Figures 5 and 6) and therein lies much of our difficulties. We must have the capability of adequately estimating the rainfall of these systems. This means that we must measure the high rainfall rates accurately and must be able to delineate the organized synoptic-meso-convective scales. How do we recognize the rate/space problem?

2.1.1 Mesoscale

The distinction between convective and stratiform rainfall does not, however, lie only on the synoptic scale. Convective systems may produce up to one-half of their rainfall from stratiform clouds (Figure 7). Sixty percent convective and forty percent stratiform may be a more reasonable result.

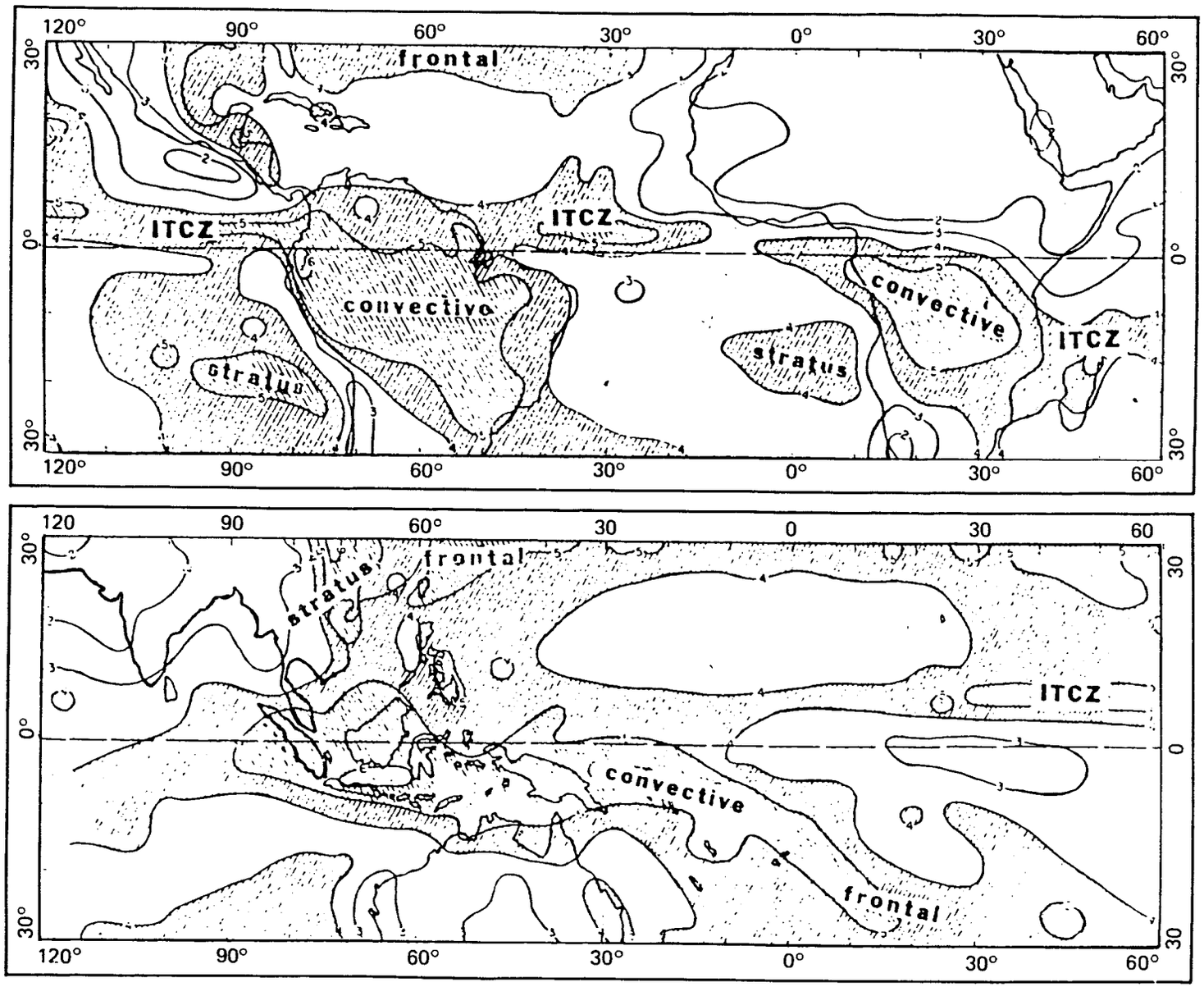

Figure 1a. Climatological Cloud Cover For January. (After Sadler, 1970.)

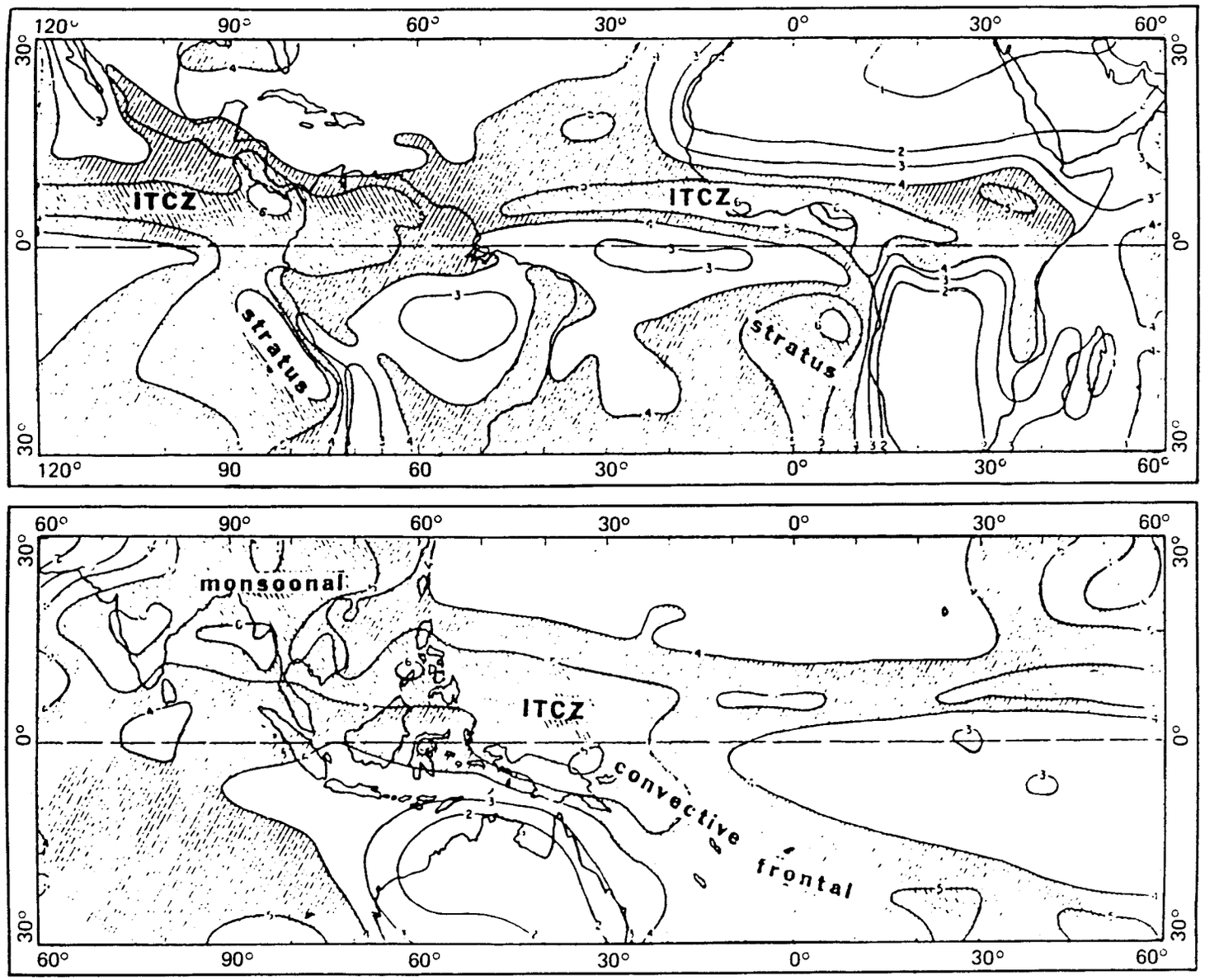

Figure 1b. Climatological Cloud Cover For July. (After Sadler, 1970.)

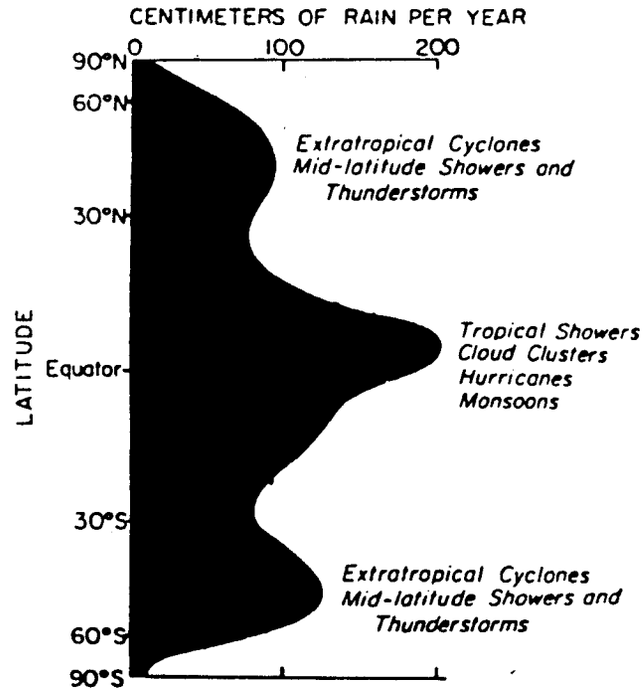

Figure 2. Globally Averaged Annual Precipitation and Associated Rain-Producing Weather Systems. (After Sellers, 1965; as noted by Houze, 1980.)

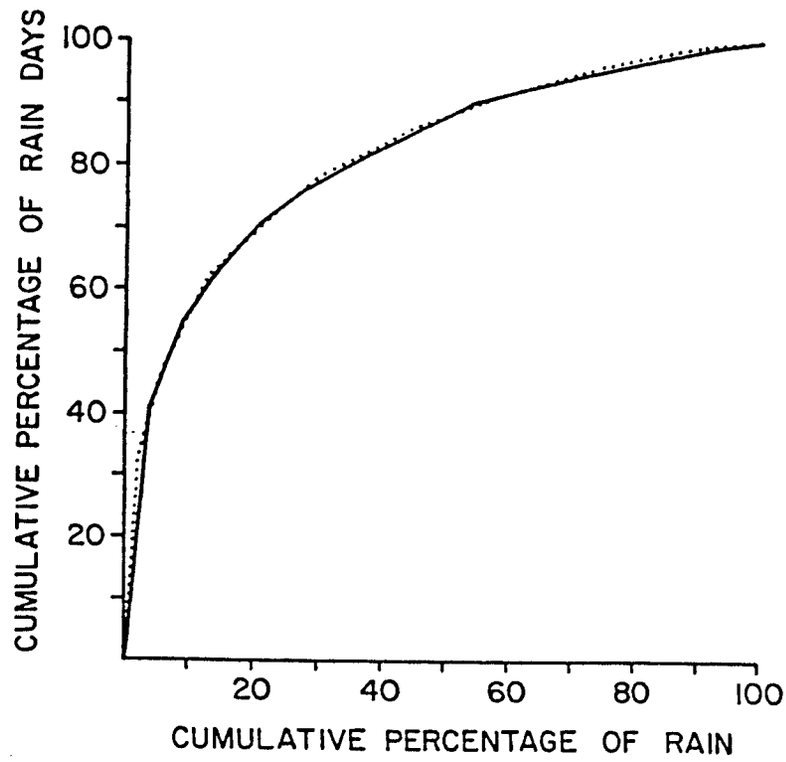

Figure 3. Cumulative Percentage Rain Days and Amount of Rain for Wet Years (Mean Summer Season Rainfall > 800 mm, Solid) and Dry Years (Mean Summer Season Rainfall < 600 mm, Dotted) Over Northeastern South Africa. (After Garstang and Emmitt, 1983.)

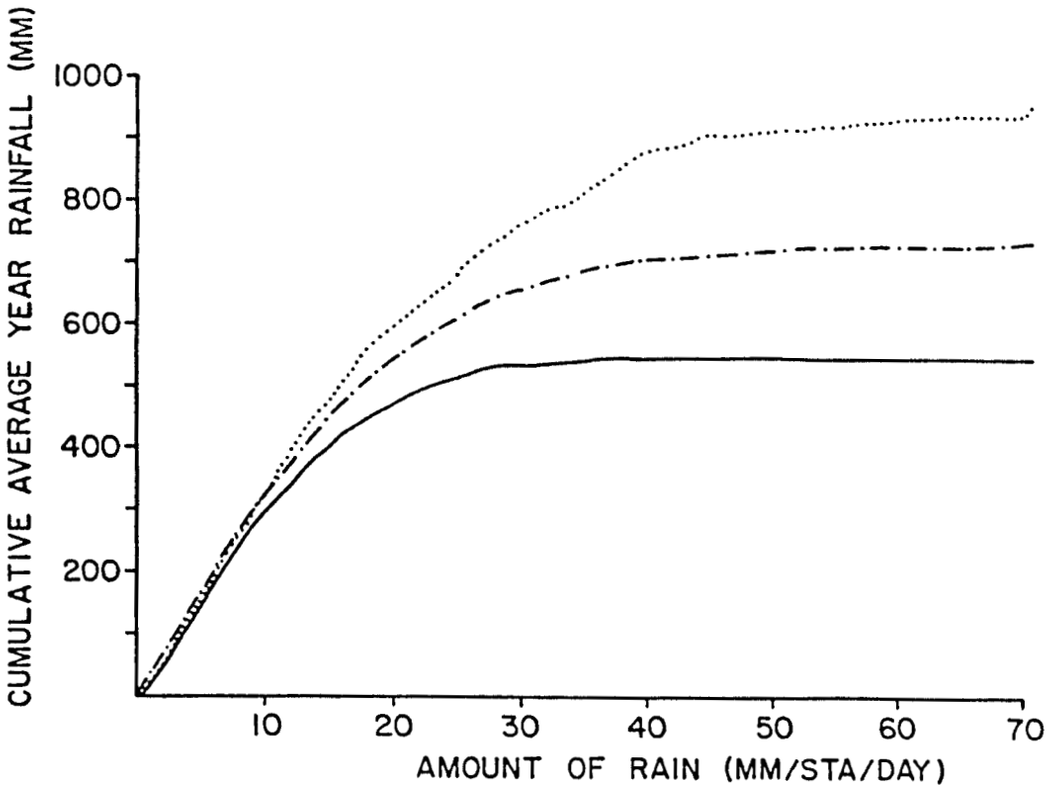

Figure 4. Cumulative Average Summer Season Rainfall Over Northeastern South Africa in 1 mm Classes of Average Amount of Rain Per Station Per Day for Wet Years (Dotted), Dry Years (Solid) and Average Years (Dash-Dot). (After Garstang and Emmitt, 1983.)

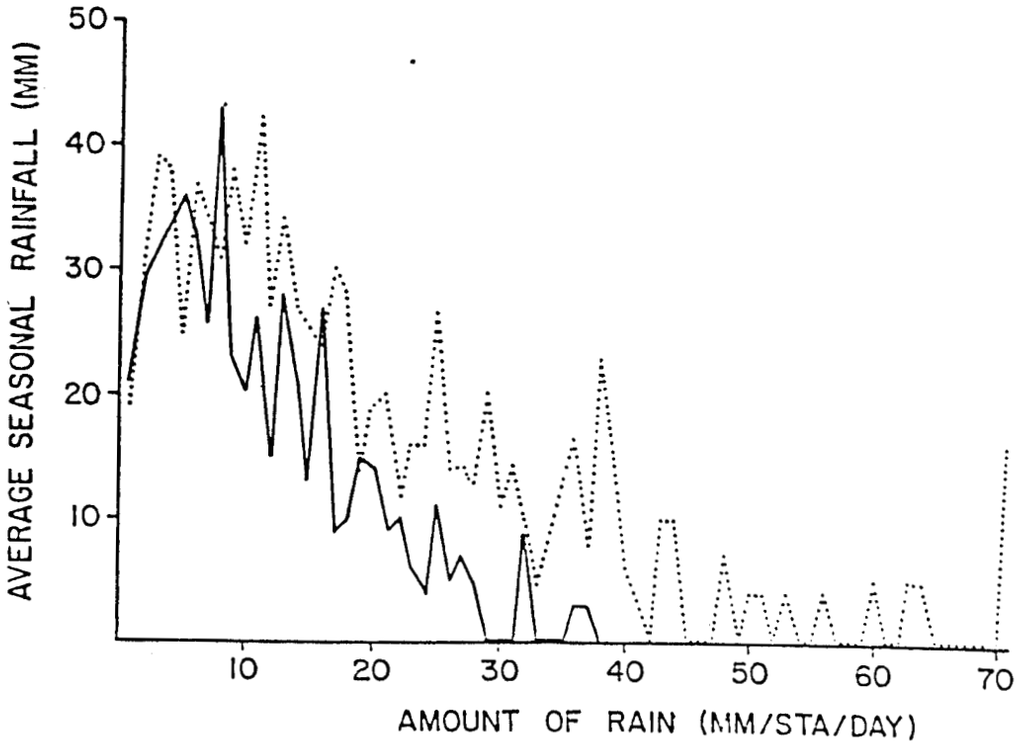

Figure 5. Average Amount of Seasonal Northeastern South African Rainfall Contributed in Each Station Daily Rate Class for Dry (Solid) and Wet (Dotted) Years. (After Garstang and Emmitt, 1983.)

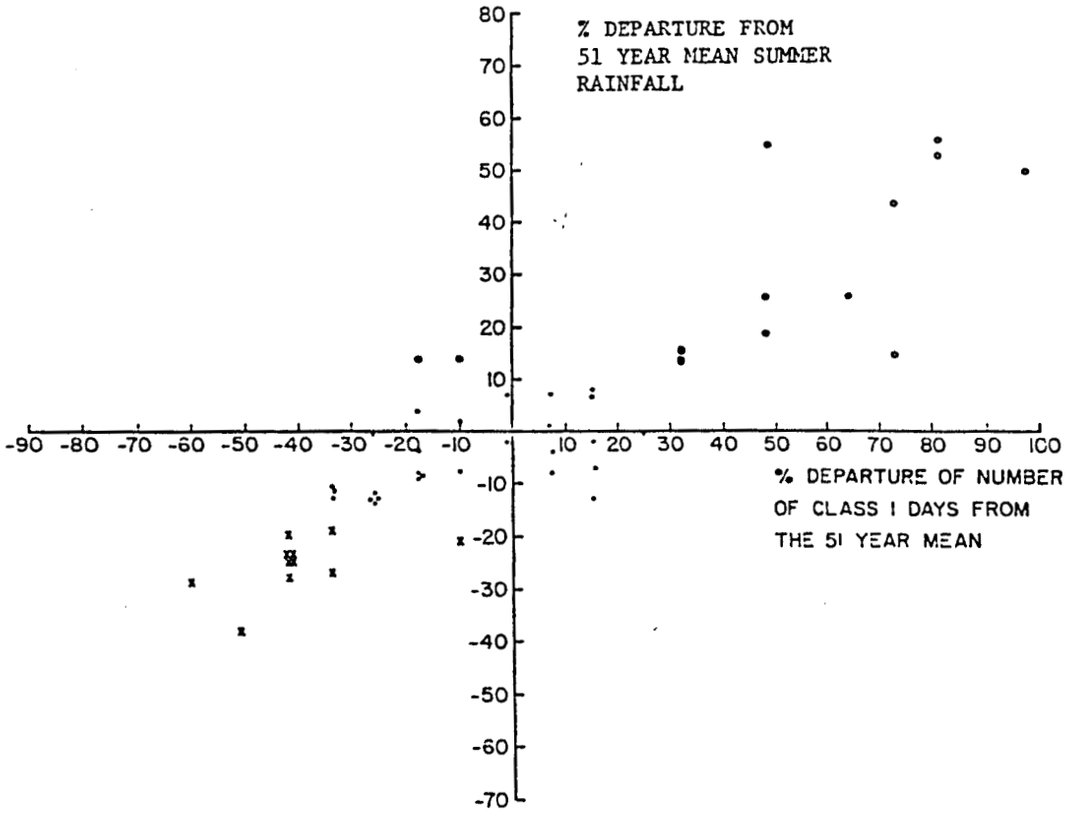

Figure 6. Percent Departure of Northeastern South African Summer Rainfall from the 51 Year Annual Mean Rainfall and the Percent Departure of the Number of Class I (Rainfall > 15 mm) Days from the 51 Year Mean Number for Dry (Crosses), Wet (Circles) and Normal (Dots) of Class I Days. (After Garstang and Emmitt, 1983.)

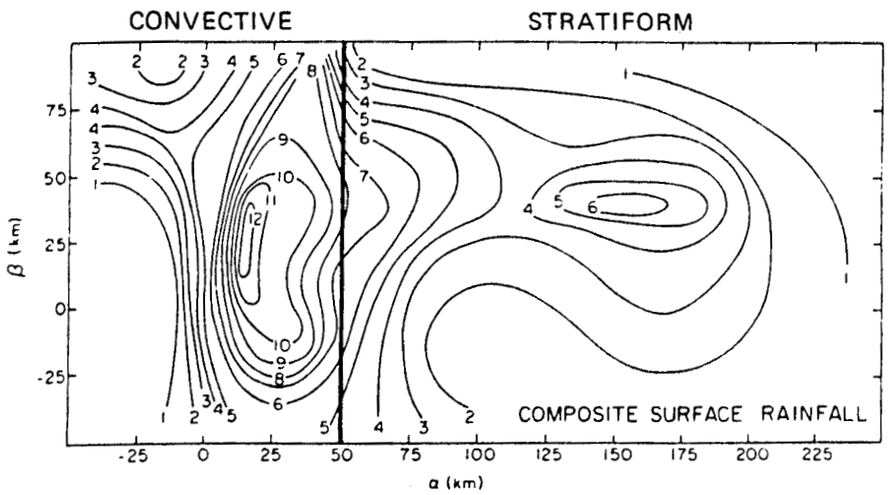

Figure 7a. Composite Surface Rainfall Rates (mm h^{-1}) for the Convective and Stratiform Regions of a Mesoscale Convective System in the Tropics as Determined from Hourly Radar Observations. (After Gamache and Houze, 1983.)

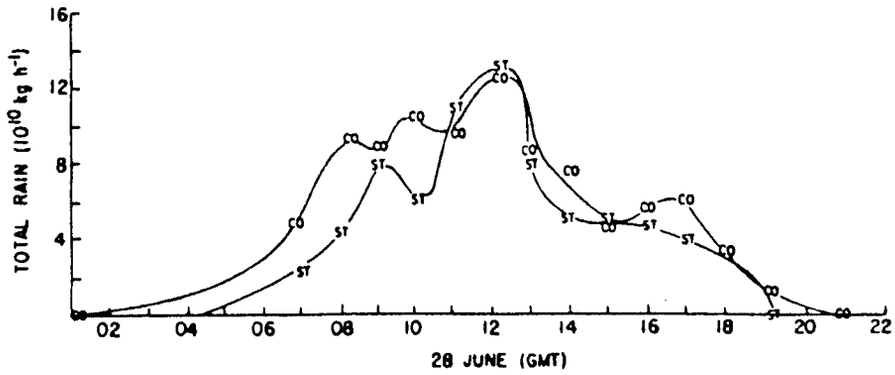

Figure 7b. Variation in Time of Area Integrated Total Rainfall in Both the Convective and Stratiform Regions of a Tropical Squall Line as Determined from Radar Observations. (After Houze and Rappaport, 1984).

2.1.2 Local and Diurnal

Diurnal cycles of convective rainfall are well documented over land. There is much less evidence of diurnal or semi-diurnal variation over the open oceans. What evidence there is suggests that there is a semi-diurnal variation of convective rainfall over the open tropical oceans.

3. NATURE OF CONVECTIVE RAINFALL

The large variations in space and time of convective rainfall must be dealt with. Figure 8 shows a small area in Florida (approximately 600 km^2) with average gauge density of 2.6 km^2 per gauge for two individual summer periods and their combined results. Figure 9 shows results for a single day. Rainfall amounts calculated as a function of distance from the center of the rainfall maximum illustrate the magnitude of the gradients. Rainfall decreases to one-half of the maximum value in three kilometers, with a mean rainfall gradient of about 7.1 mm/km. Fifty percent of rain volume occurs in 17 per cent of the area with rain. Such intense gradients occur with high rainfall rates and diminish with lower rainfall rates.

Similar gradients are found over larger areas as illustrated by radar echoes over Florida (Figure 10). (VIP brightness > 3. VIP = Video Integrator and Processor.)

4. DENSITY OF RAINGAUGE NETWORK

The preceding provides much of the reason why it is so difficult to measure rainfall accurately with raingauges. Studies have been done which attempt to provide a sound basis for the number of raingauges required (Figure 11). If we bear the Florida results in mind (area = 600 km^2), we need about 1 gauge per 10 km^2 to keep within a 10 per cent accuracy. For a 2.5° latitude x 2.5° longitude region, we need approximately 1 gauge per 50-100 km^2. It is unlikely that many raingauge networks exist, which, by themselves, can provide adequate ground truth. The answer will have to come from the combined use of more than one ground truth measurement.

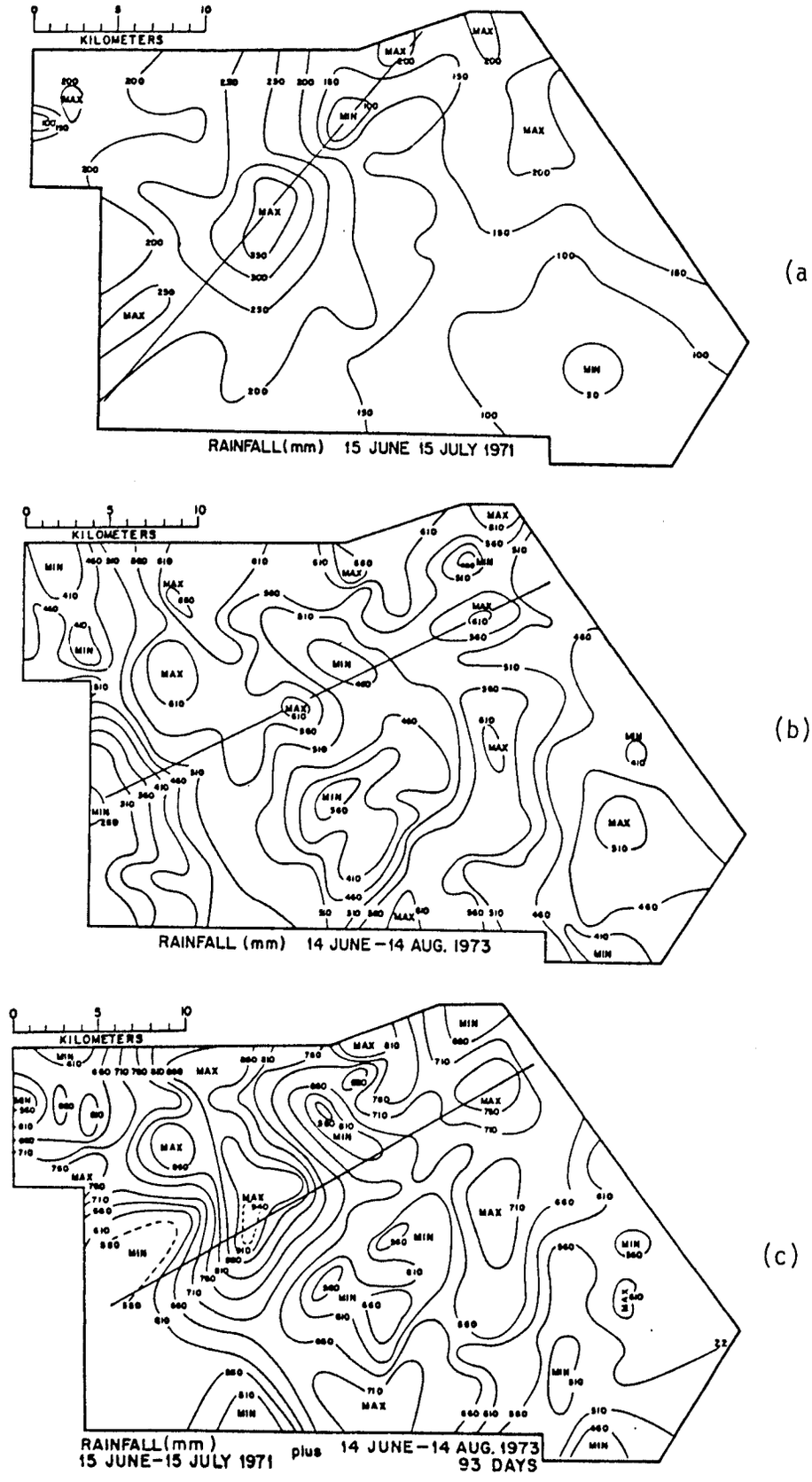

Figure 8. Isohyetal Analysis of Florida Convective Rainfall Determined by Raingauge Networks from the FACE Experiment for (a) 15 June-15 July 1971; (b) 14 June-14 August 1973; and (c) 1971 and 1973 Combined. (After Woodley et al., 1975.)

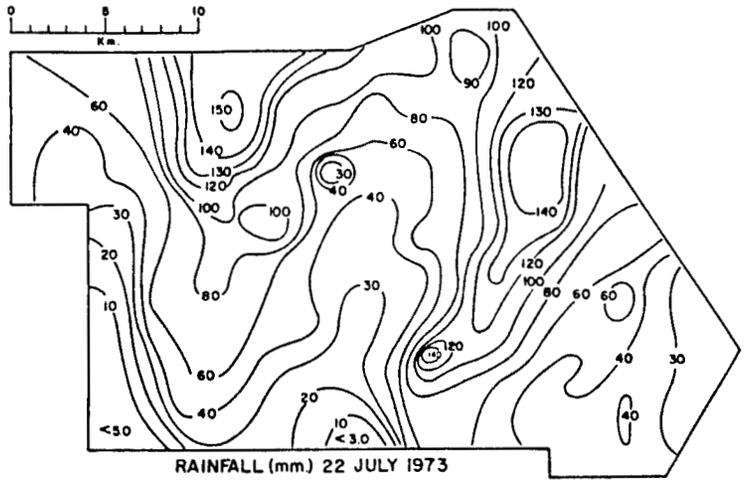

Figure 9a. Same as Figure 8, but for 22 July 1973.

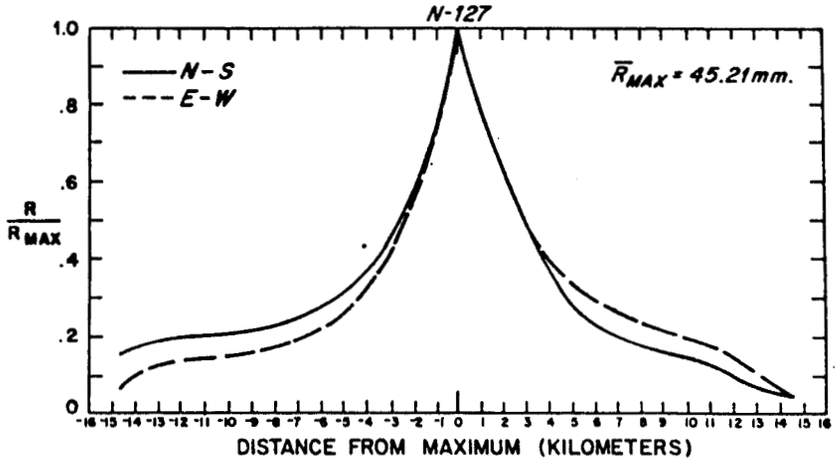

Figure 9b. Mean Normalized Rain Profiles of Two Orthogonal Lines Oriented North-South and East-West of the Individual 24-hr Rain Maxima Found During the FACE Experiment. (After Woodley et al., 1975.)

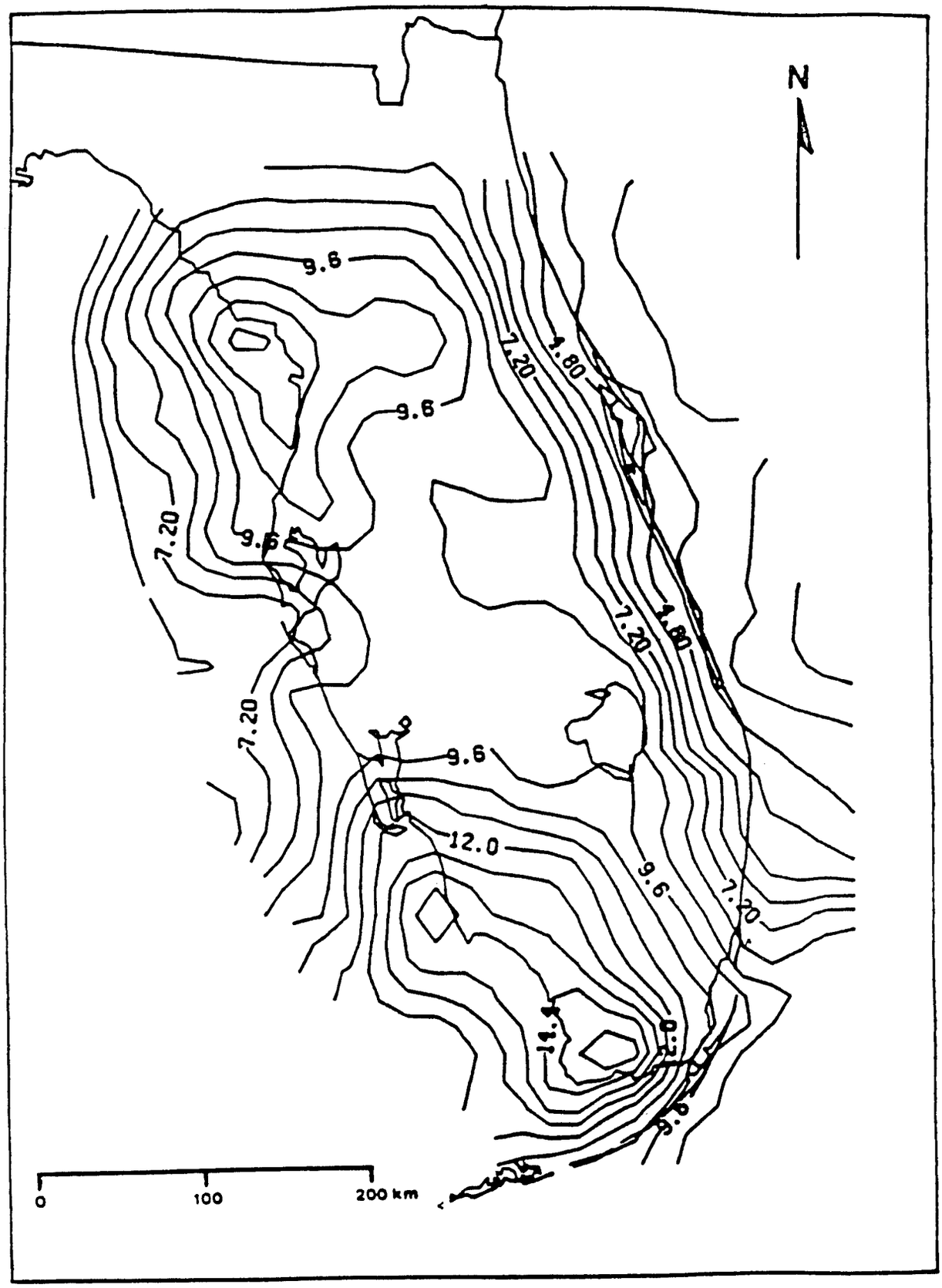

Figure 10. Percentage of Hours Thunderstorm Criteria Was Met (VIP Brightness > 3) Over the State of Florida During the Summers of 1978-82. (After Michaels et al., 1986.)

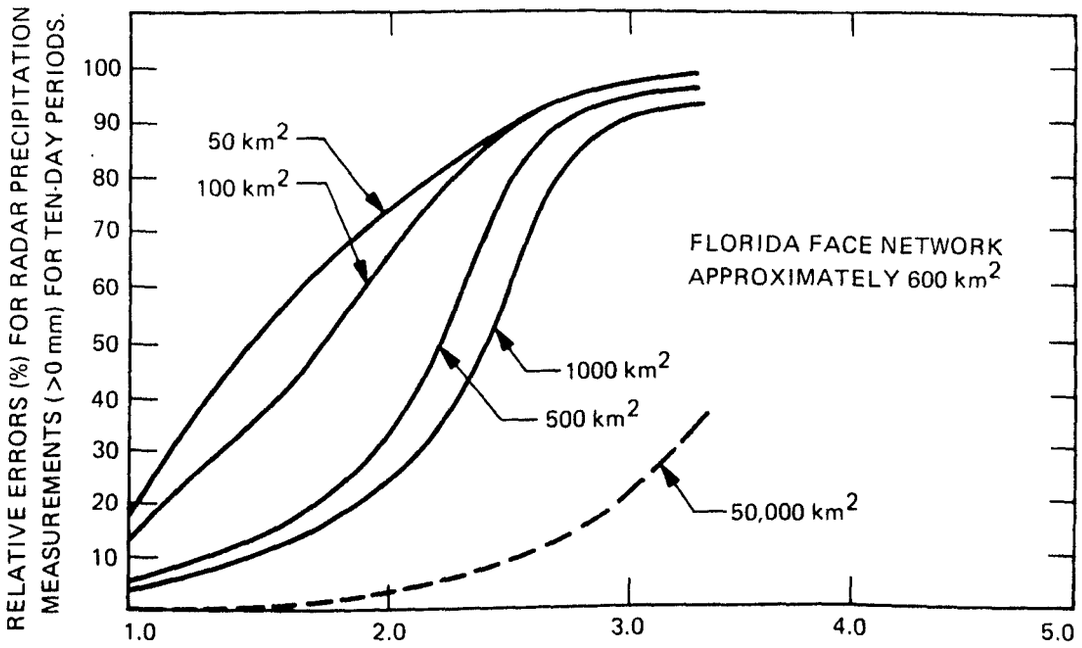

Figure 11. Log of Area of Raingauge Network for 1 Gauge. (Based on Data from Volynets et al.)

5. MODEL CALCULATIONS

Moisture budget calculations yield an estimate of precipitation obtained as a residual to the moisture balance equation. Calculations from special observations have proved to be useful (Figure 12). Calculations from routine observations are unreliable (Figure 13).

A second method of calculation of the moisture balance involves computing the sensible and latent heat budgets and the subsequent condensation rates. Uncertainties are involved in the use of the bulk aerodynamic equations but relatively good agreement has been obtained when special data sets have been used (e.g., Song and Frank, 1983 - using GATE data).

General circulation models (GCM), of which there are now a considerable number, calculate precipitation on a scale of about 400 x 400 km^2. Some models go down to scales as small as approximately 100 x 100 km^2. The large scale precipitation is computed by determining the degree of super-saturation. Convective precipitation is calculated either by the Convective Adjustment Method or by a Cumulus Parameterization Scheme.

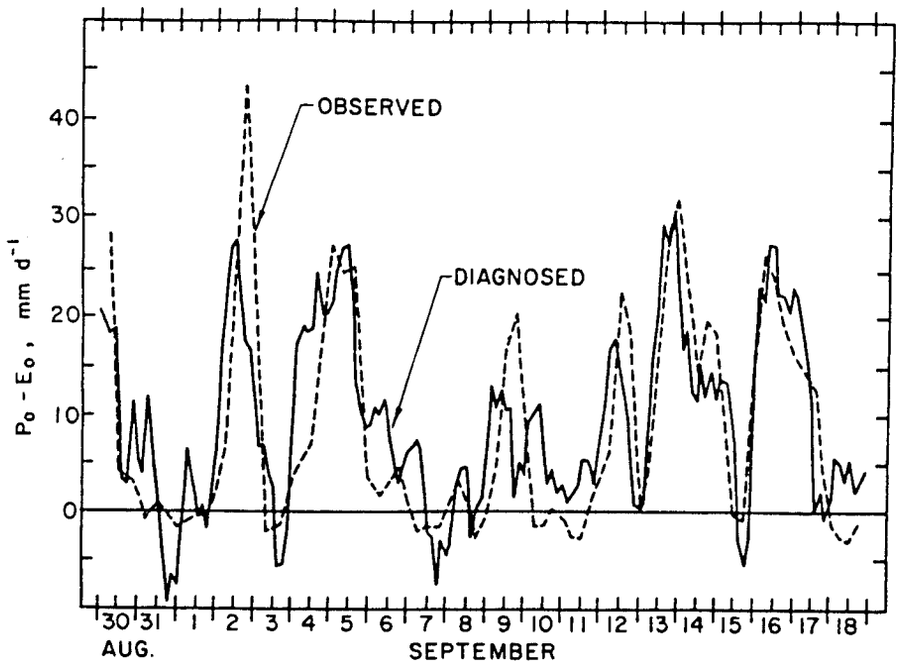

Figure 12. Time Series of Observed (Dashed) and Moisture Budget Calculated (Solid) Values of Precipitation Minus Evaporation for Phase III of the GATE Experiment. (After Thompson et al., 1979.)

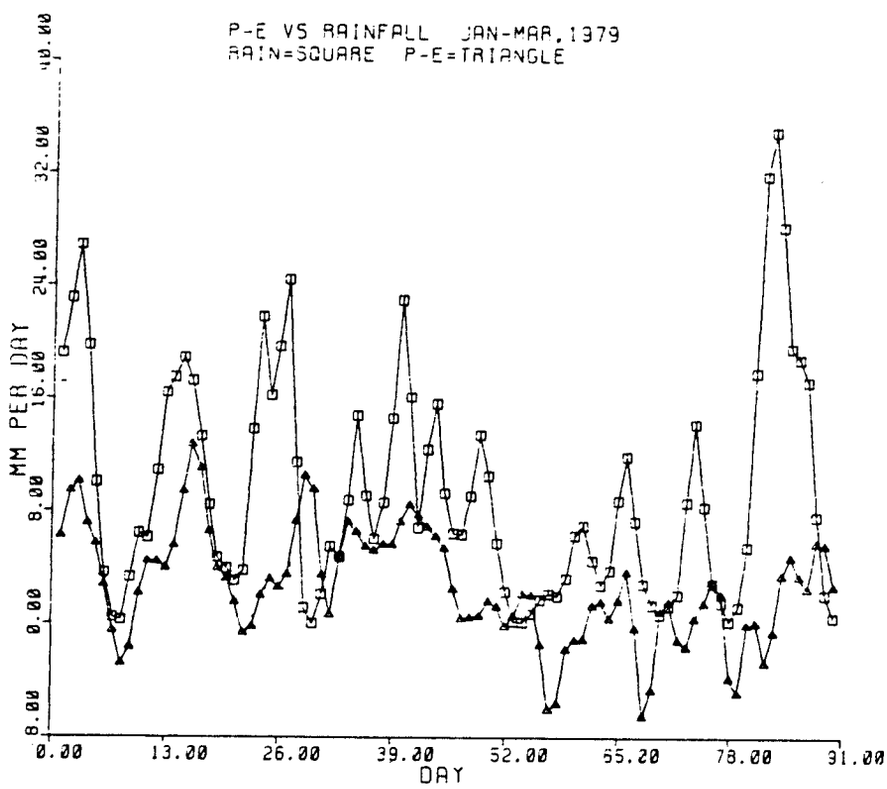

Figure 13. 1 January-31 March 1979 Time Series of Observed Rainfall (Squares) and Budget Calculated Precipitation-Evaporation (Triangles) for a Study Region in the Near-Equatorial Western Pacific. (After Morrisey, 1986.)

Large scale global fields computed over periods of months show qualitative agreement between the computed and observed fields (e.g., Manabe and Holloway (1975) for December-February) (Figure 14).

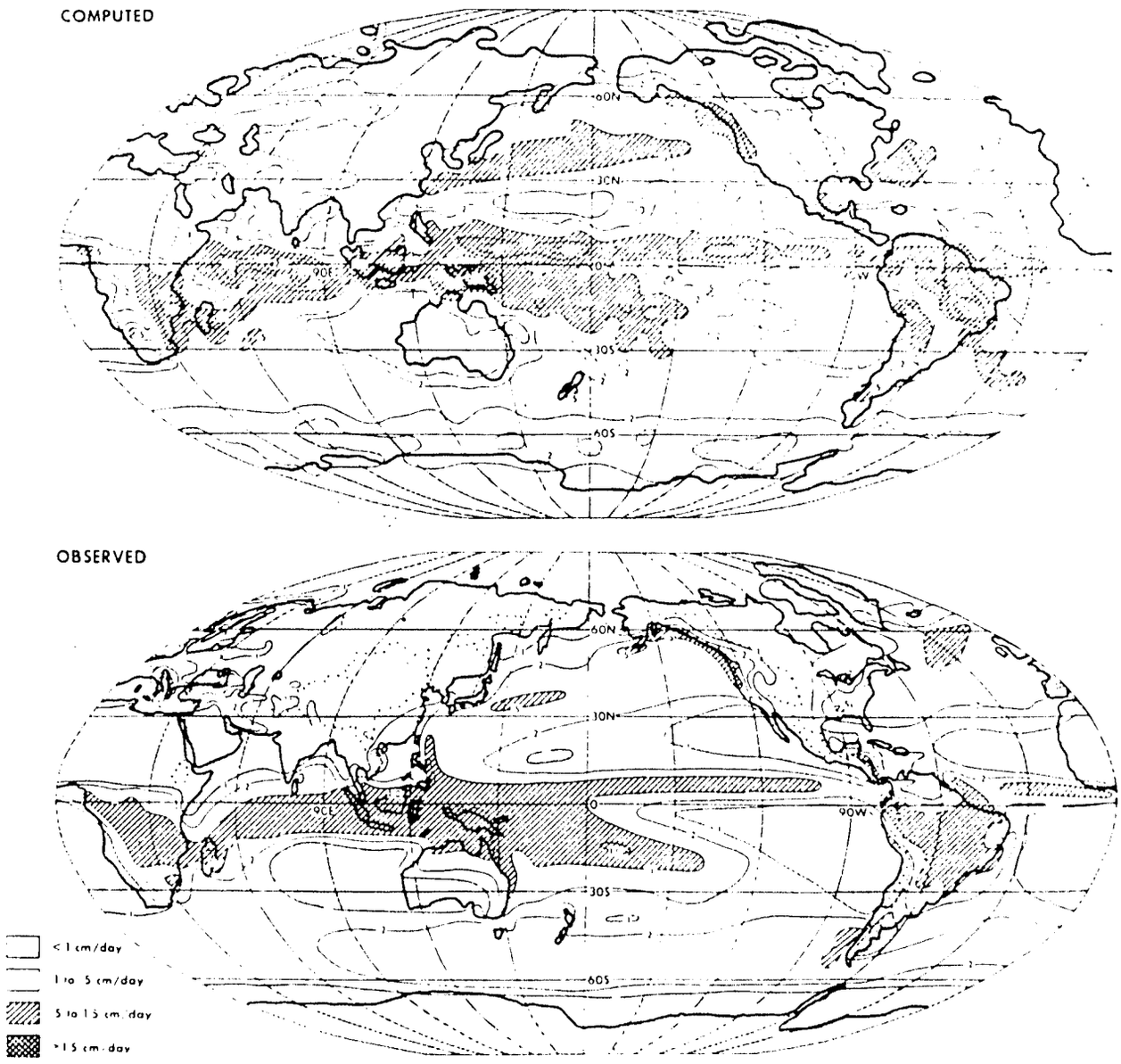

Figure 14. Global Distribution of Mean Precipitation Rate Computed by GFDL General Circulation Model (Top) and Estimated from Observed Data (Bottom) for December, January and February. (After Manabe and Holloway, 1975.)

Figure 15 shows a more quantitative comparison between zonally averaged mean annual precipitation rate and the observed precipitation. Model calculated values in the tropics are much larger than observed. More recent calculations of the same kind of monthly precipitation rates (e.g., Figure 16, McAvaney et al., 1978) shows the same tendency. Model calculations provide useful sensitivity tests but cannot be regarded as ground truth.

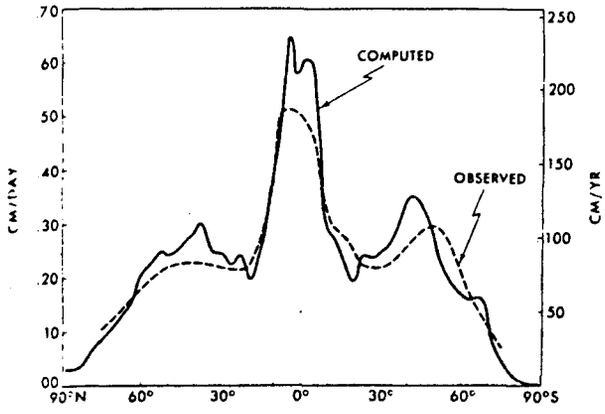

Figure 15. Latitudinal Distribution of Annual Mean Rate of Precipitation Computed by Model (Solid) and Observed (Dashed). (After Manabe and Holloway, 1975.)

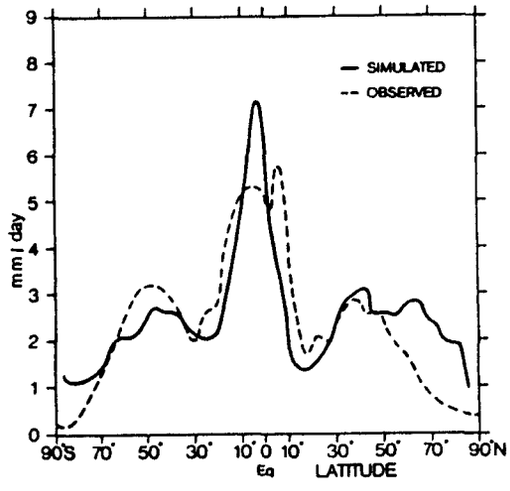

Figure 16. Zonally Averaged Mean Precipitation Rate for January as Estimated from Observations (Dashed) and Computed From a Spectral General Circulation Model (Solid). (After McAvaney et al., 1978.)

6. CONCLUSIONS

We will hear more details on the nature of rainfall and methods which might be used to deal with this important but difficult variable. We need to assimilate much of this information and use it to evaluate our ability to provide ground truth. We should take care to specify what we believe is possible as well as what is not possible given the constraints of existing systems.

We might even conclude at this point that no single method provides adequate ground truth for rainfall on a scale of 2.5° latitude x 2.5° longitude and 30 days. A combination of methods must be used.

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THE AUSTRALIAN BUREAU OF METEOROLOGY RAINFALL NETWORK

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1. INTRODUCTION

The Bureau of Meteorology (BOM) in Australia maintains an extensive rainfall monitoring network and data archive which can supply considerable information to users of water resources data. This report is intended to provide a brief overview of the Australian network and its suitability for the calibration of satellite based precipitation measurements. Data processing and quality control procedures employed with the rainfall data and forms of data availability will be discussed. Also, information will be presented on special observational programs relevant to the workshop. The benefits of this program to Australia and the extent of Australian participation will also be outlined.

2. THE DAILY RAINFALL NETWORK

The standard Bureau rain gauge network consists of about 6875 stations of which about 6155 are manned by volunteer rainfall observers. At about 720 of these stations, other meteorological observations are also recorded. Of the latter, 67 are official BOM stations with the rest run by paid cooperative observers. The number of stations reporting rainfall varies from month to month but the above figures are considered representative of the network over the past five years.

Rainfall measurements are made using both standard rain gauges and pluviographs. The pluviograph network will be discussed later. The daily rainfall measurements made using the rain gauge network are of most relevance and will be discussed in this section. The standard reporting procedure for most rainfall stations for daily rainfall is to obtain accumulated rainfall amounts for the past 24 hours at 0900 LST each working day. Rainfall reports are also available routinely at three hourly intervals at the 480 synoptic observing stations. These data are available but are not subjected to the same quality control procedures as the daily station data.

The daily rain gauge network is shown in Figure 1. It is apparent that gauge density varies considerably throughout Australia. The network has been restricted by many practical limitations such as the availability of observers and the existence of suitable observer sites, especially in the more remote locations. In addition, sub-standard sites have been retained because of the existence of long periods of records. However, its basic design does meet specific hydrological activities within Australia although it is biased significantly to the more populous areas.

The BOM has divided the nation into 107 rainfall districts as shown in Figure 2. Each district is considered to have an approximately uniform rainfall climate. Districts where the density of gauges within these districts falls below WMO minimum network density criteria of 1 station per 3000 sq km (T.O.) in mountainous terrain are indicated. As can be seen from Figure 2, a significant part of Australia does not have a rainfall network of sufficient density to specify accurately the rainfall characteristics.

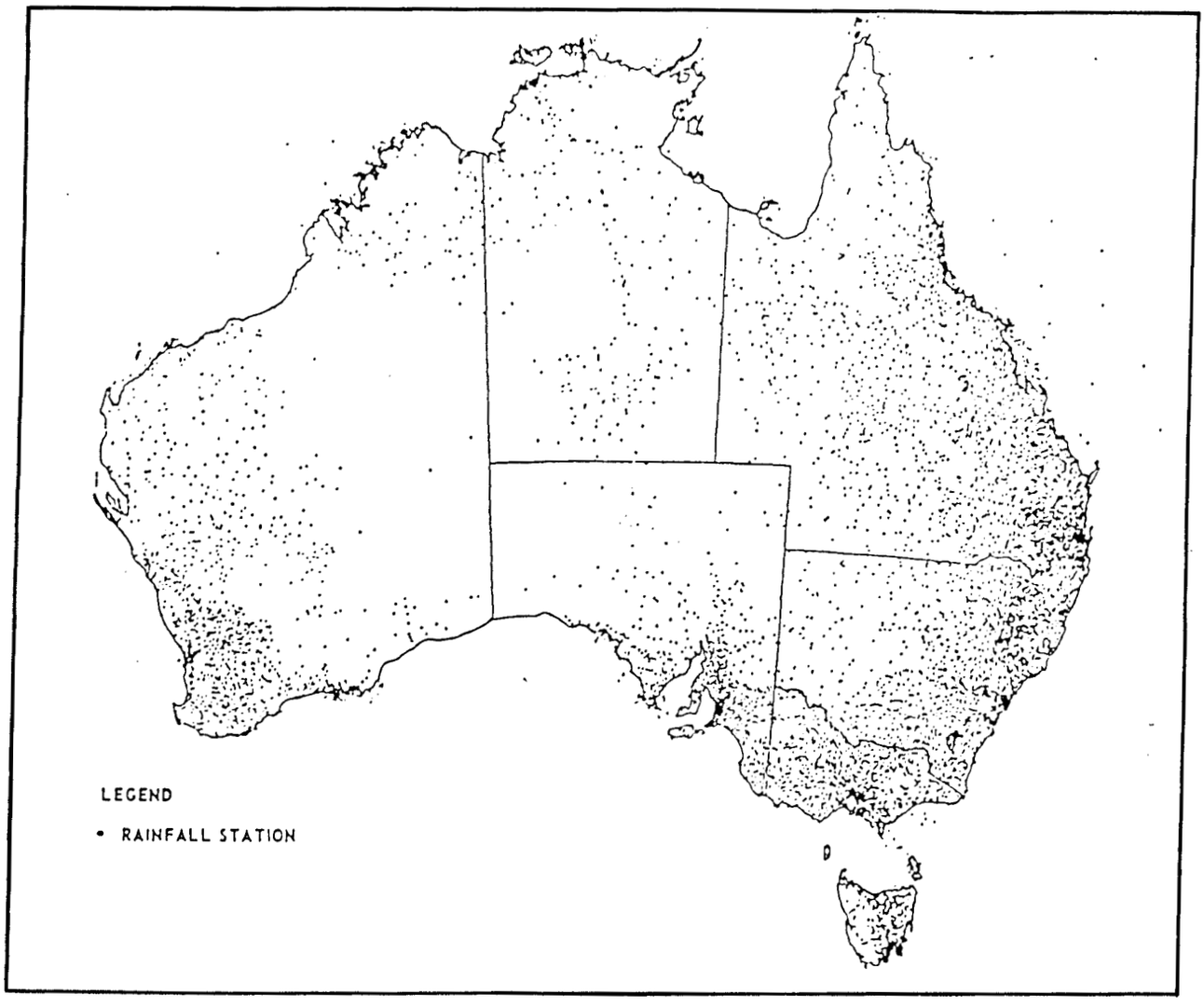

Figure 1. The Daily Rain Gauge Network in Australia as of August 1985

REFERENCE TO DISTRICTS

WESTERN AUSTRALIA

1 North Kimberly
2 East Kimberly
3 West Kimberly
4 De Grey
5 Fortescue
6 West Gascoyne
7 East Gascoyne
7A Murchison
8 North Coast
9 Central Coast
9A South Coast } Southwest
10 North Central
10A South Central
11 Eucla
12 Southeast
13 Northeast

NORTHERN TERRITORY

14GA Darwin – Daly
14BC Arnhem } Northern Rivers
14DE Roper – McArthur
14F Victoria
15A Barkly } Northern Plateau
15B Alice Springs

SOUTH AUSTRALIA

16 Northwest
17 Far North
18 Western Agricultural
19 Upper North
20 Northeast
21 Lower North
22 West Central
23 East Central
24 Murray Valley
25A Murray Mallee
25B Upper Southeast
26 Lower Southeast

QUEENSLAND

27 North Peninsula
28 South Peninsula
29 Lower Carpentaria
30 Upper Carpentaria
31 Barron } North Coast
32 Herbert
33 East Central Coast
34 West Central Coast
35 Central Highlands
36 Central Lowlands
37 Upper Western
38 Lower Western
39 Port Curtis } South Coast
40 Moreton
41 East Darling Downs
42 West Darling Downs
43 Maranoa
44 Warrego
45 Far Southwest

NEW SOUTH WALES

46 Western (Far Northwest)
47 Western (Lower Darling)
48 Western (Upper Darling)
49 Western (Southwest Plains)
50 Central Western Plains (S)
51 Central Western Plains (N)
52 Northwest Plains (W)
53 Northwest Plains (E)
54 Northwest Slopes (N)
55 Northwest Slopes (S)
56 Northern Tablelands (W)
57 Northern Tablelands (E)
58 Upper North Coast
59 Lower North Coast
60 Manning
61 Hunter
62 Central Tablelands (N)
63 Central Tablelands (S)
64 Central Western Slopes (N)
65 Central Western Slopes (S)
66 Metropolitan (E)
67 Metropolitan (W)
68 Illawarra
69 South Coast
70 Southern Tablelands (Goulburn – Monaro)
71 Southern Tablelands (Snowy Mountains)
72 Southwest Slopes (S)
73 Southwest Slopes (N)
74 Riverina (E)
75 Riverina (W)

VICTORIA

76 North Mallee
77 South Mallee
78 North Wimmera
79 South Wimmera
80 Lower North
81 Upper North
82 Lower Northeast
83 Upper Northeast
84 East Gippsland
85 West Gippsland
86 East Central
87 West Central
88 North Central
89 Western Plains
90 West Coast

TASMANIA

91 Northern
92 East Coast
93 Midlands
94 Southeast
95 Derwent Valley
96 Central Plateau
97 West Coast (Mountain Region)
98 King Island
99 Flinders Island

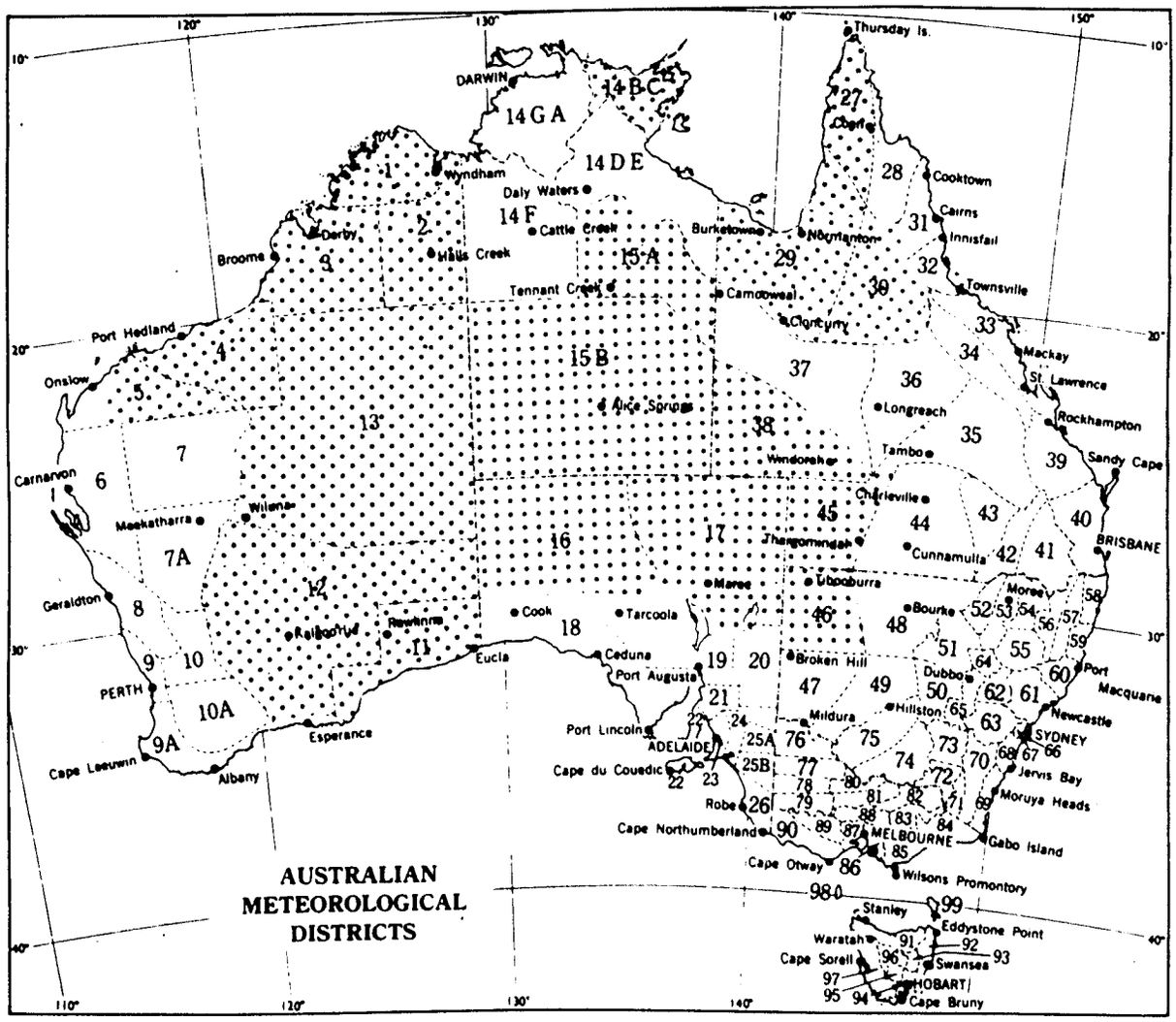

Figure 2. Australian Rainfall Districts. Districts Not Satisfying the WMO Network Density are Stippled.

At 95 per cent of stations, the daily rainfall observations are made with 200/203 mm type rain gauges. This gauge has a 200 mm rainfall capacity and a 203 mm funnel. At locations where the daily rainfall may exceed 200 mm, funnels with a 127 mm diameter are used, e.g., along the coastal fringe of Queensland. Approximately five snow gauges are also maintained by the BOM in the alpine region of southeast Australia.

2.1 Recording Accuracy

The measure for the standard 203 mm gauge is graduated up to 20 mm with 0.2 mm subdivisions. For the 127 mm gauge, it is graduated up to 50 mm. The rainfall is recorded to the nearest 0.2 mm up to 1 mm and to the nearest mm when the amount exceeds 1 mm. Days on which the rainfall is less than 0.1 mm are not counted as days of rain and are indicated by the entry "trace" in the recording log.

All sites are installed according to strict guidelines to minimize observing inaccuracies due to local effects, e.g., interference from obstructions, topographic features such as cliffs, etc. However, errors due to leaky rain gauges, poor site exposure, evaporation and careless observing practices are inevitable. Due to limited resources it is not possible to have frequent inspection of gauge sites and most locations are visited only once every five years.

2.2 Reporting and Quality Control Procedure

Each month, forms containing the daily rainfall for the past month from each station are posted to the BOM. The returns are inspected manually, sorted and then digitized to form a computer-based data set. These data are also subjected to quality control procedures at various stages leading up to the archive process. The quality control includes:

(i) Rainfall range and internal consistency checks, e.g., duplicate day numbers, days out of sequence, sum of daily totals different from monthly total.

(ii) Consistency checks between months and searches for duplicate data.

Data found to be erroneous are flagged or rejected for manual checking. Once the data satisfy the above criteria they are passed to a temporary archive. Additional checks applied to these data at this second stage include:

(i) Areal checks, i.e., a comparison of the daily rainfall with data from surrounding stations.

(ii) Completeness checks that produce a summary print for each station-month processed. Missing months appear as gaps in the display.

(iii) Consistency and station number change checks. This program checks for fictitious stations or stations reporting data outside their open and close dates.

The above list is by no means complete but does give a general indication of the quality control procedures. More details may be found in Bureau of Meteorology (1982). The main problems with the daily rainfall data set are the existence of data gaps due to failure of observers to return monthly summaries and the lack of observations during weekends or public holidays.

The above working validated data set is used to update the final archive. Rainfall data are in tenths of mm and are complemented by comment codes arising from the validation process. This archive data set is used to satisfy requests for rainfall data. Various standard products are also available and some of these will be described in the following sections.

2.3 Data Availability

The Bureau's rainfall archives contain over half a million station-years of rainfall records for the rain gauge stations. One station-year represents one year of rainfall data for a single station. The average length of rainfall data for each rainfall district in Australia is summarized in Figure 3. Only averages are represented and there is considerable variability between individual stations within each district.

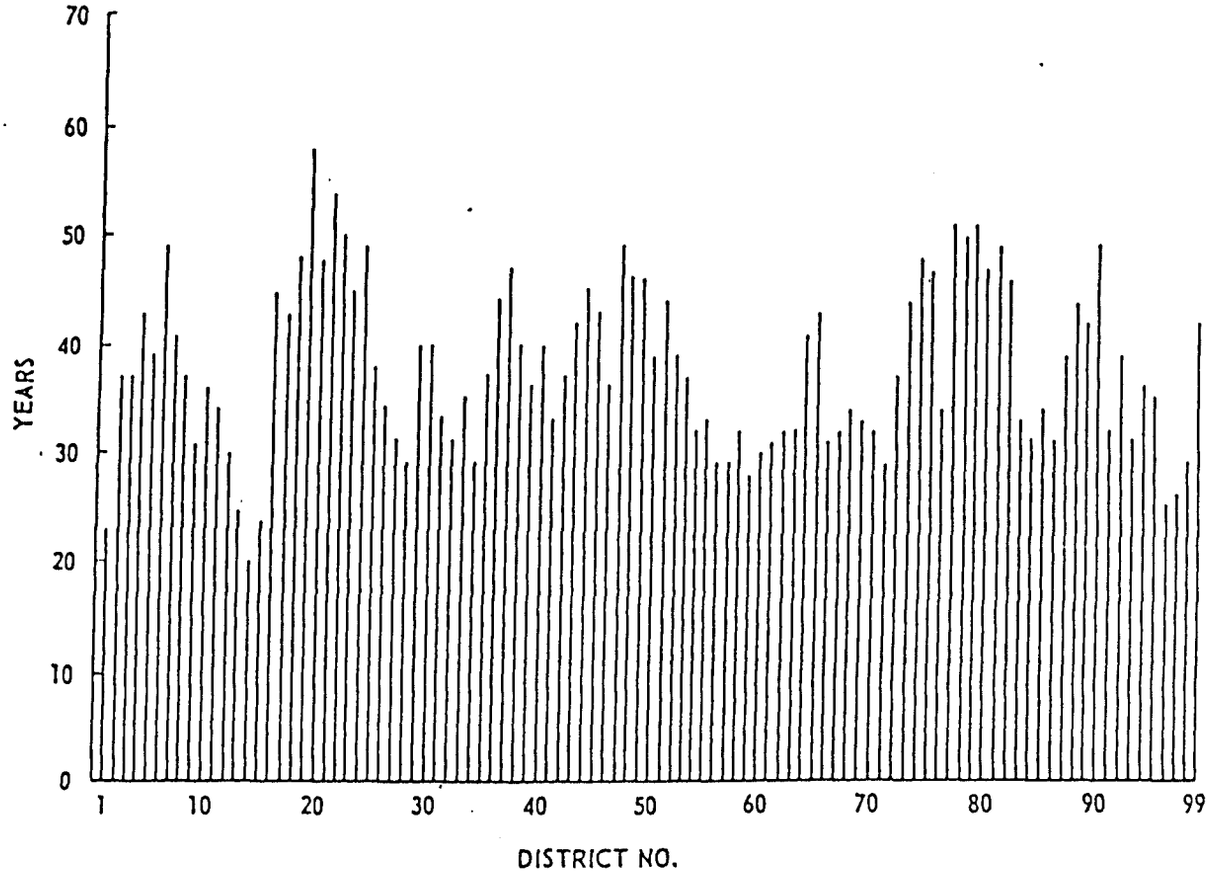

Figure 3. Average Number of Years of Rainfall Data Available for Each Rainfall District

Most station data have been added to the archive by the end of the following month. These data represent 80 per cent of the network returns. A further 7 per cent are added by the following month and the remaining 13 per cent within six months.

Due to the late arrival of some station data in any given month and the lack of a digital archive prior to 1974, "back" data are also processed by the BOM. These data are subject to similar quality control procedures as outlined in the previous section. Processing of this backlog of data is near completion with most states over 95 per cent complete, with the exception of New South Wales. At the present rate of processing the backlog will be completed within five years.

The rainfall data base is available through the National Climate Centre (NCC) of the BOM. A wide variety of products are available which will be described briefly in the following section. Charges for access to the rainfall data vary depending upon the amount of processing necessary and the type of media required. The data are available on computer listings, magnetic tape and microfiche. A charge for 1000 stations covering all available years on magnetic tape would cost typically about $A200.

2.4 General Structure of Archived Station Rainfall Data

Data are available in raw station form and processed in various statistical analyses suitable for climatological and design purposes. All data files contain label or header records for easy reference and manipulation. In the case of station rainfall data, the file would contain a number of monthly sub-files each commencing with a station header followed by a data header. Examples of the types of products available are given in Table 1. Of most interest to this workshop is the monthly mean station and district rainfall averages.

Table 1. Selection of Statistical Analyses for Rainfall Data

(1)	Daily records of rainfall at each station.
(2)	Aggregate and mean rainfall for districts and/or stations for periods from 1 to 12 months.
(3)	Averages, extremes, rankings and deciles of annual and monthly rainfall for districts and/or stations.
(4)	Average, median and number of raindays for districts.

2.5 Pluviograph Data

The BOM maintains a network of about 520 pluviographs. Other pluviographs are also maintained by such institutions as the W.A. Public Works Department, the Department of Water Resources, N.T. Melbourne and Metropolitan Board of Works in Victoria and the Sydney Water Board. Data from these institutions are available to the Bureau but are not processed routinely. The distribution of both Bureau and non-Bureau pluviographs is shown in Figure 4. The main types of Bureau pluviograph instruments include:

(i) Dines daily syphon 5 mm capacity.

(ii) Dines daily syphon 25 mm capacity.

(iii) Leupold and Stevens long-term with a 0.2 mm tipping bucket rain gauge.

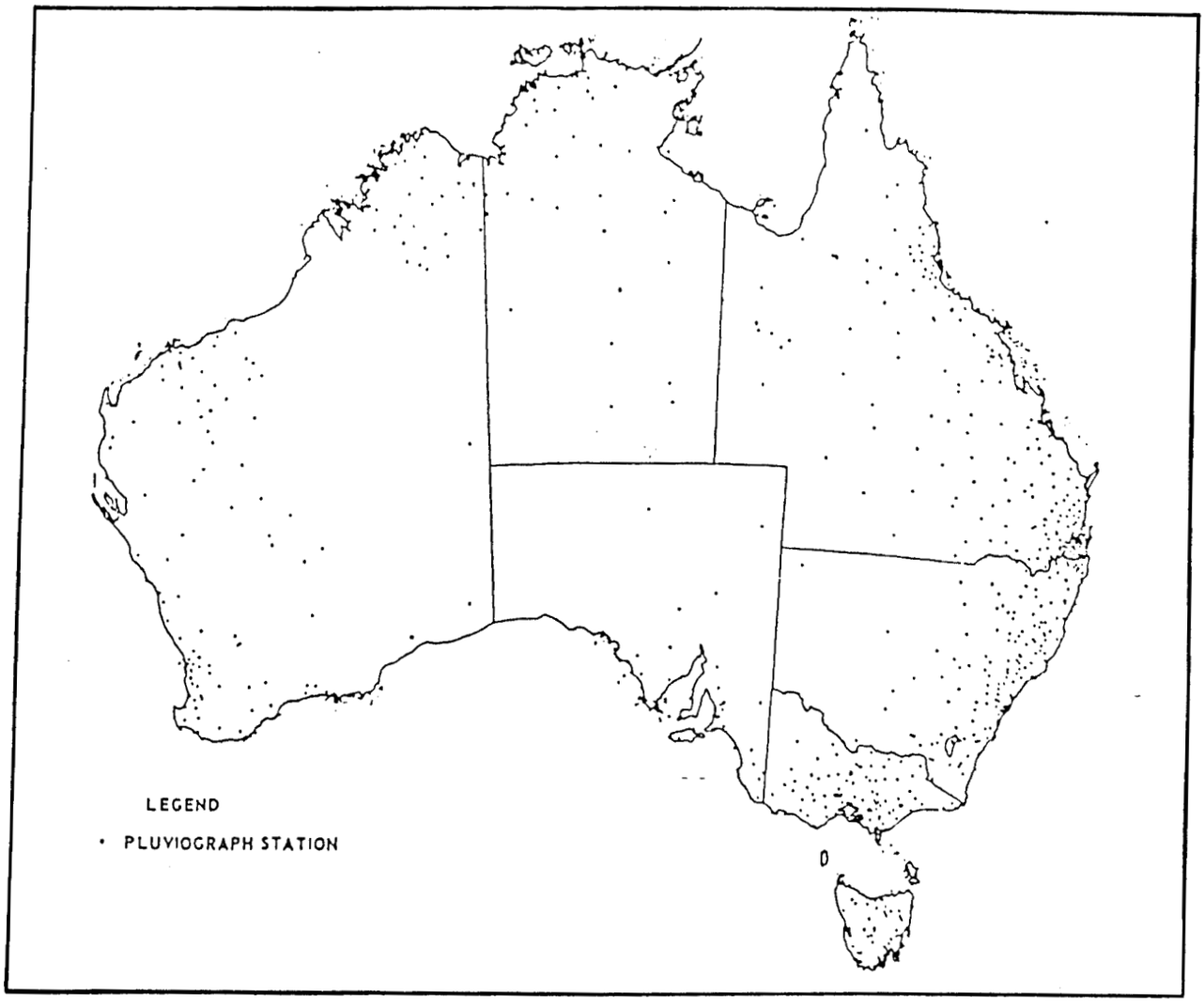

Figure 4. The Australian Pluviograph Network

Daily charts are removed at 0900 LST or DST and time marks on the long-term charts are in LST or DST. The daily charts are forwarded monthly to the Bureau and the long-term charts every six months.

Rainday charts are digitized and data are then fed into a series of quality control programs. The data are archived finally on magnetic tape. The original observer returns and daily charts are held under the control of BOM regional offices responsible for the station. The following accuracies can be expected for rainfall intensities derived from the archive:

Duration (minutes)	Error % (95% confidence)
6	0 to -20
12	±7
18	±6
30	±5
60	±3

Note the six-minute intensities generally have a negative bias of about -10 per cent.

Products available from the pluviograph network through the NCC include:

(i) Monthly rainfall intensity analyses.

(ii) Annual summaries of primary rainfalls at 6, 12, 18, 30, 60, 120, 180, . . . up to 4320 minute intervals.

(iii) Rankings of heavy rainfalls at the above intervals.

(iv) Rainfall/intensity analysis at specified return periods. More detailed analyses are also available through the Hydrology Branch of the BOM.

3. SPECIAL OBSERVATIONAL PROGRAMS

Several programs planned by the BOM have the potential to supply additional ground truth observations for the validation of the satellite derived precipitation estimates. These programs will be described briefly in this section.

3.1 Tropical Field Experiments During 1986/87

The Australian Monsoon Experiment (AMEX) will be conducted in two phases, the first occurring from 20 October 1986 to 4 November 1986. A second phase will be conducted from 10 January 1987 to 15 February 1987, in conjunction with the Equatorial Mesoscale Experiment (EMEX) and the Stratospheric-Tropospheric Exchange Project (STEP). These experiments will undertake detailed monitoring of the tropical convection over Northern Australia using an enhanced radiosonde, surface and radar network. Instrumented aircraft will be deployed for EMEX and STEP.

The basic network for Phase 2 of AMEX is shown in Figure 5. The experiment has been designed to provide both an enhanced network in the area of the Gulf of Carpenteria as well as an upgraded larger scale network over northern Australia. This network will provide radiosonde data every six hours for the duration of Phase 2 whereas the instrumented aircraft will be deployed on specific missions of up to ten hours duration. The land-based radar data are to be archived every ten minutes with volumetric scans occurring every 30 minutes. These data will be recorded at six intensity levels. The ship based radar will be capable of an almost continuous archive at 256 intensity levels. It should be noted that radar data are not archived routinely in

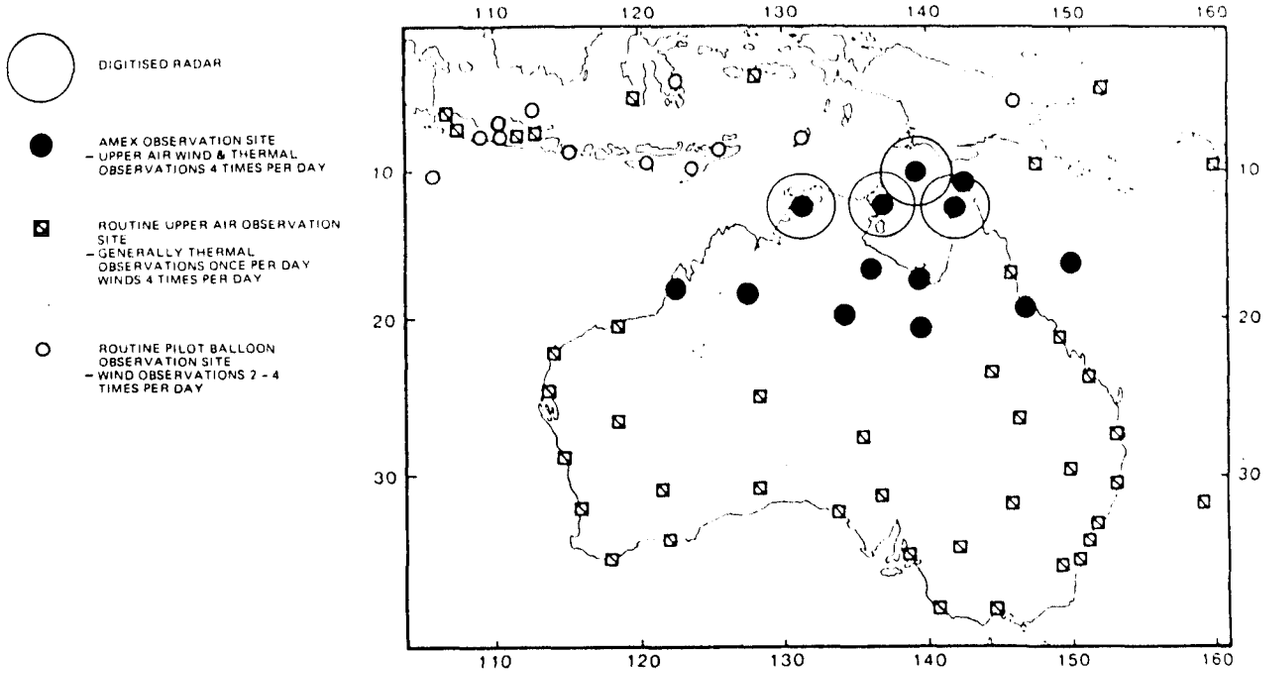

Figure 5. The Basic Observational Network for AMEX

Australia. GMS satellite data will be archived every three hours and hourly for up to four, 10-hour periods during the experiment. All available AVHRR satellite data will also be archived.

These data, in conjunction with the enhanced surface pluviograph network, will offer a unique opportunity for verification of satellite-derived precipitation estimates over tropical Australia and the ocean. Additionally, use of satellite-derived precipitation estimates will be extremely useful and necessary in the derivation of the rainfall over the entire AMEX Gulf of Carpenteria network. These rainfall estimates are required for diagnostic budget studies of the convective activity within the Gulf.

The basic data will be available in various forms within six months of the completion of the experiment.

3.2 Future Plans Associated with the Tropical Rainfall Measuring Mission (TRMM)

The BOM Research Centre (BMRC) has tentative plans to become involved in the TRMM project being proposed by NASA. This involvement would include the establishment of a ground truth station over northern Australia. The most probable location would be Darwin, but Weipa is also under consideration.

The BMRC plans involves the upgrading of an existing radar facility to obtain a system suitable for undertaking quantitative precipitation estimates. A dual-polarization capability on the radar coupled with a high density surface network of pluviographs is under consideration. At present, it is anticipated that action on this system will begin by late 1989 or early

1990 in time for the preliminary testing of TRMM instrumentation. In addition, BOM plans to have an S-band receiver at Darwin by 1987/88. This will enable direct local readout of AVHRR satellite data. The BOM will also have a MCIDAS terminal in Darwin by that time.

This TRMM site would provide a useful station for the additional verification and research relevant to satellite derived precipitation measurements. Unfortunately, it will not be possible to bring this project forward given the present commitments within the BOM.

4. BENEFITS OF SATELLITE-DERIVED MONTHLY PRECIPITATION ESTIMATES TO AUSTRALIA

The strength of the Australian economy is strongly dependent on the health of its rural or agricultural sectors. Production from these sectors is extremely sensitive to fluctuations in rainfall. This is illustrated in Figure 6 taken from Nicholls (1985). A very strong relationship is evident (correlation of 0.7) between the first principal component score of the June to November district average rainfall and the total value of Australian crops. It should be noted that long-term trends have been removed in Figure 6. As the total value of the 1982-83 crop was about 5000 million dollars, the fluctuations of up to plus or minus 1000 million dollars are very important.

The fluctuations in the above rainfall are linked strongly to the El Niño/Southern Oscillation (ENSO) phenomenon. Thus, it is extremely important for Australia to have a proper understanding of its rainfall climate and the link with the ENSO in order to minimize the effects of drought.

In order to appreciate the impact of such planetary scale phenomena on the Australian climate it is first necessary to have an accurate climatology of Australian rainfall including its variability. As shown in Figure 2, over much of the Australian continent the density of observations within the present rainfall network falls below minimum acceptable levels. It is also interesting that it is in these regions that the linkages with ENSO appear less significant. Is this a real effect or a reflection of the inadequate

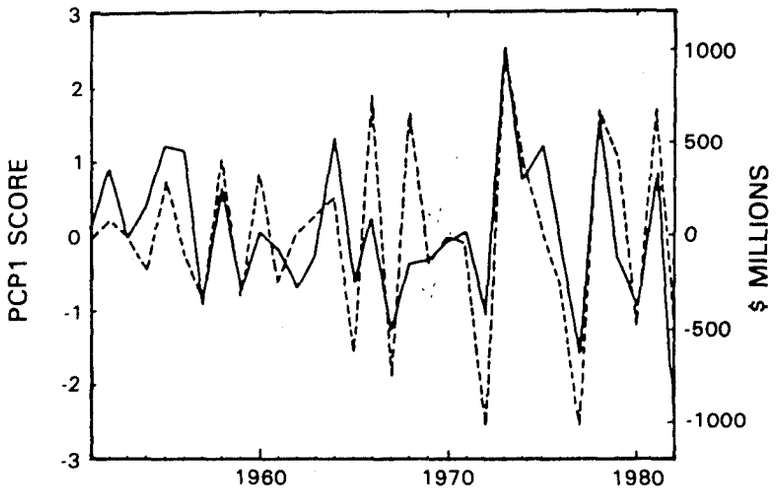

Figure 6. Time Series of Factor Pattern (Correlation) of First Principal Component of June to November District Average Rainfall (Full Line) and Anomalies of the Total Value of Australian Crops in $Millions (Broken Line). Taken from Nicholls (1985).

data base? At present this question cannot be answered. In this context, accurate long term rainfall estimation from satellite techniques may provide an answer by improving the overall quality of the Australian network.

Apart from improving our understanding of the effect of ENSO on Australian rainfall, it is also imperative that ENSO be forecast to minimize the consequences of drought. This requires a complete understanding of the physical mechanisms involved in ENSO. The limited rainfall data obtained over the tropical oceans and such places as New Guinea and Africa presently restrict our ability to understand and model this phenomenon. Global estimates of rainfall data, obtained for instance by satellite techniques, are therefore equally important to Australia. These data would be used in a research mode for diagnostic studies and to initialize GCM climate models for improved understanding of ENSO. Forecasts of the onset of ENSO might then be made more reliably.

Because of the importance of climate anomalies to the Australian economy, the NCC has an objective to promote projects related to improving our understanding of their occurrence and predictability. NCC also has the responsibility to produce climate advisories, diagnostic bulletins and drought watches. Incorporation of routine satellite-derived precipitation estimates into their standard archives would assist these functions. In addition, BMRC has an interest in long-range weather forecasting research. These data would also be useful for such research.

5. BUREAU OF METEOROLOGY INVOLVEMENT IN VALIDATION PROCESS

The BOM would participate in the following areas associated with the suggested program:

(i) Supplying validated rainfall data for the project. The Bureau is not in a position to process rainfall data from other countries. Similarly, the Bureau is not equipped to undertake direct validation of the satellite-derived rainfall measurements on a routine basis. Any such involvement would have to be on specific research-oriented projects relevant to ongoing projects, e.g. AMEX.

(ii) The Bureau has a keen interest in TRMM and in this context is planning to develop a ground truth station in the tropical areas of Australia. This station is planned to be in operation by 1990 and any data gathered would be available to this particular program at that time.

(iii) The AMEX data sources will be available for this program. Radar and associated rainfall data will be available by December 1987. In the context of AMEX, BMRC would become involved in collaborative research projects involving the use of satellite, radar and surface observations for estimation of rainfall. In addition, the Hydrology Branch of the Bureau has an interest in participating in projects directed at obtaining areal precipitation estimates remotely.

(iv) The NCC would routinely archive satellite-derived precipitation measurements if they were made available to Australia in a standard and recognizable form. This is seen to be in the

long-term interest of Australia, given its susceptibility to climate anomalies and the subsequent need for relevant research data bases. Development of a standard format for transmitting satellite-derived precipitation estimates over the Global Telecommunication System is seen as an appropriate means of communicating these data. In this way data could be monitored and archived in a routine manner.

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RAINFALL MEASUREMENTS IN BRAZIL: A SURVEY

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1. INTRODUCTION

The two rainfall measurement systems presently in operation in Brazil (rain gauge and radar) are described and expansions of the respective networks considered. The rain gauge network for each state and territory is characterized in terms of spatial distribution, average density, type of gauging, data availability and tape and disk files. The network density for areas of about 200 x 200 km^2, centered approximately 100 km apart and covering the whole country, is shown. Radar locations and ranges are indicated, as well as gauge densities for areas of 200 x 200 km^2 centered at the radar site. Programs in development or planned, implying digital radar data recording, are mentioned. Comments are made on the limitations of the measurement networks and improvements to them are discussed. Considerations on the usefulness for the country of monthly rainfall estimates for 200 x 200 km^2 are discussed.

2. RAIN GAUGE NETWORK

The national network is composed presently of some 8000 rain gauges, of which approximately 1200 are of the recording type. Recording gauges are of the syphon or tipping bucket type with catching areas of 200 cm^2 . There are also tipping bucket gauges situated mostly in the Amazonic region with an 800 cm^2 catching area. These are telemetering gauges located in remote areas, where recordings are made on six-month charts and used for control purposes. In general, daily and monthly charts are employed. Non-recording gauges are of the Ville de Paris type, with a 400 cm^2 catching area and readings are made on a graduated measuring glass. There is also another type, the Paulista, used in the State of Sao Paulo with a 500 cm^2 catching area.

The DNAEE (National Department of Water and Electrical Energy) maintains a national inventory of the rain gauge network. In addition to operating its own network, it receives data from about 100 organizations distributed throughout the country. In the case of data from its own network, there is an average interval of 3-4 months between the time observations are made and the time data are available at the DNAEE central office (the Central Directory of Hydric Resources - DCRH). For data from other organizations, this average delay increases to 6-8 months.

In the DNAEE network, readings are registered in a notebook in three copies by the observer. One copy is filed, The second is collected by personnel maintaining the gauges and sent to the respective DNAEE District. The third is sent by mail, in places where this is possible, to the central

office at the end of each month. In the District, a preliminary analysis is made and data are sent via internal mail to the central office. Recorded charts are collected and sent to the central office for digitization.

In Table 1, the state and territory networks as registered in the DNAEE inventory published in 1983, is shown. With respect to the updated network, only the number of gauges is available. Modifications that have occurred do not alter significantly the overall picture, but in specific cases there were considerable improvements. The updated density numbers are shown in parenthesis in Table 1.

The INEMET (National Institute of Meteorology) operates a network of about 370 non-recording and 330 recording rain gauges, spread throughout its eight districts. Data are received in the districts within approximately two months after observations are made.

Table 1. State and Territory Rain Gauge Network

State or Territory	Recording Gauges	Non-Recording Gauges	State or Territory Areas(km^2)	Average Density ($km^2.gauge^{-1}$)	Density 86
AC	7	27	152,589	4 487.	(4487)
AL	11	97	27,731	256.	(259)
AM	39	106	1,564,445	10 789.	(11017)
AP	6	15	140,276	6 679.	(5010)
BA	108	741	561,026	660.	(637)
CE	47	344	148,016	378.	(400)
DF	15	11	5,814	223.	(208)
ES	17	99	45,597	393.	(407)
GO	29	190	642,092	2 931.	(2732)
MA	20	128	328,663	2 220.	(1816)
MG	198	562	587,172	772.	(732)
MT	53	121	881,001	5 063.	(4298)
MS	8	46	350,548	6 491.	(3339)
PA	41	112	1,248,042	8 157.	(7385)
PB	16	163	56,372	314.	(320)
PE	49	458	98,281	194.	(191)
PI	30	186	250,934	1 161.	(1173)
PR	90	786	199,554	227.	(226)
RJ	58	181	44,268	185.	(185)
RN	10	141	53,015	351.	(351)
RO	7	29	243,044	6 751.	(4586)
RR	7	11	230,104	12 784.	(7423)
RS	55	378	282,184	652.	(633)
SC	30	158	95,985	510.	(482)
SE	4	67	21,994	310.	(310)
SP	246	1644	247,898	131.	(130)

Consistency analyses are performed routinely at DNAEE and data are finally stored on tape or disk.

Table 2 shows the situation for each state or territory of the form in which data are available at DNAEE and their storage on tape or disk. The data for the Sao Paulo State network are especially pertinent because of their potential use for the calibration of the only operational radar recording digital data at the moment. There, the State Department of Water and Electrical Energy operates a network of about 1050 non-recording and 150 recording gauges. Of these, about 230 are within a 200 x 200 km^2 area centered at the radar location, as shown in Figure 4.

For the network, daily rainfall data from 1982 are available on tape.

Table 2. Form In Which Data are Available and Existence of Storage on Tape or Disk

	Data Availability				
State or Territory	"in natura"	Preliminary Data*	Data Partially or Fully Consisted	Existing Data, Not Available at DNAEE	Tape and Disk Files
AC	11	20	-	3	29
AL	99	2	-	7	101
AM	1	127	-	17	105
AP	-	14	-	7	7
BA	716	27	-	106	707
CE	382	-	-	9	379
DF	2	13	11	-	21
ES	96	2	-	18	16
GO	163	29	-	27	37
MA	130	9	-	9	123
MG	464	70	28	220	270
MT	30	44	112	22	179
MS	12	35	1	6	38
PA	26	113	1	13	92
PB	168	-	-	11	154
PE	330	5	-	172	349
PI	204	1	-	11	209
PR	86	4	-	786	78
RJ	34	54	52	99	137
RN	146	-	-	5	147
RO	-	29	-	7	25
RR	4	12	-	2	14
RS	194	6	-	233	192
SC	125	3	-	60	122
SE	69	1	-	1	64
SP	15	236	766	873	1708

(*) Preliminary data is a classification meaning that a initial verification was performed at the DNAEE districts.

A period of 45-75 days, after observations have been made, is required before the data can be made available to users. A consistency check is performed, taking generally a recording gauge as a standard for comparison for a group of gauges and comparing daily accumulations.

In Figure 1, network densities for the whole country are presented, as computed for approximate areas of 200 x 200 km^2. The computation was made for about every 100 km in latitude, running the 200 x 200 km^2 windows in roughly 100 km steps in longitude. Regions where densities of 1 gauge/ 2500 km^2, or greater are reached, in 200 x 200 km^2 areas, can be localized with these curves. The spatial distribution of the network for each state and territory is given in Figure 2. The DNAEE inventory for 1983 was used for both Figures 1 and 2.

3. RADAR SYSTEM

Figure 3 shows the sites of both existing and planned meteorological radar systems. Presently the only radar recording digital data is the one located at Bauru, Sao Paulo (22°21'S, 49°01'W), operated by the Meteorological Research Institute, University of Bauru. It is shown in Figure 4 where a dedicated calibration rain gauge network and radar resolution are also presented. The equipment is an EEC WR-100-5, C-band, and recording is performed with a digital system supplied by the Alberta Research Council of Canada.

Basic data are reflectivities in bins of 1° x 1.05 km, from 3, 15 to 157.5 km generated in antenna cycles of about 5 minutes, composed of sweeps for elevations from 0° to 14° in 1° steps. Reflectivity values are quantified with a precision of 1 dB. There is a post facto generation of 3.5 km CAPPIs in which the elementary cell is an average of the reflectivity for a 4 x 4 km^2. Data available from 1982 is listed in Table 3.

The Bauru radar is the first of a planned three-set network for the State of Sao Paulo, as shown in Figure 3. This network is the basic data acquisition system for the RADASP II (Radar in Sao Paulo) Project, a research program (2) involving many operational aspects.

The Ponte Nova Radar (23°35'S, 45°59'W) will be supplied by McGill University and should start operations before the 1987 Southern Hemisphere summer. It is an S-band system with digital data recording capability. Intensity resolution is 6 bits, bins are 1° wide in azimuth and 0.5 km, 1 km and 2 km in length, for the range intervals of 0-60, 60-120 and 120-240 km respectively.

The third radar of the project will cover the western part of the State (20°22'S, 51°20'W), and will have specifications similar to the one at Ponte Nova. Installation has not yet been defined.

The Sao Roque (23°30'S, 47°W), Rio de Janeiro (22°30'S, 43°W) and Brasilia (16°S, 48°W) radars are Air Force OMERA radars DLM 10-E in operation for aviation purposes and are integrated in CINDACTA I (Integrated Center of Air Defense and Air Traffic Control I). The one at Sao Roque is just being equipped with a DATANAV CMM-250 interface which permits data recording and computer processing, if the required hardware is coupled to it and proper software is implanted. Intensity resolution is 7 bits and bin size is 0.3 to 1.2 km in range and 1.7° in azimuth. Similar interfaces are programmed to be installed in the Rio de Janeiro and Brasilia radars.

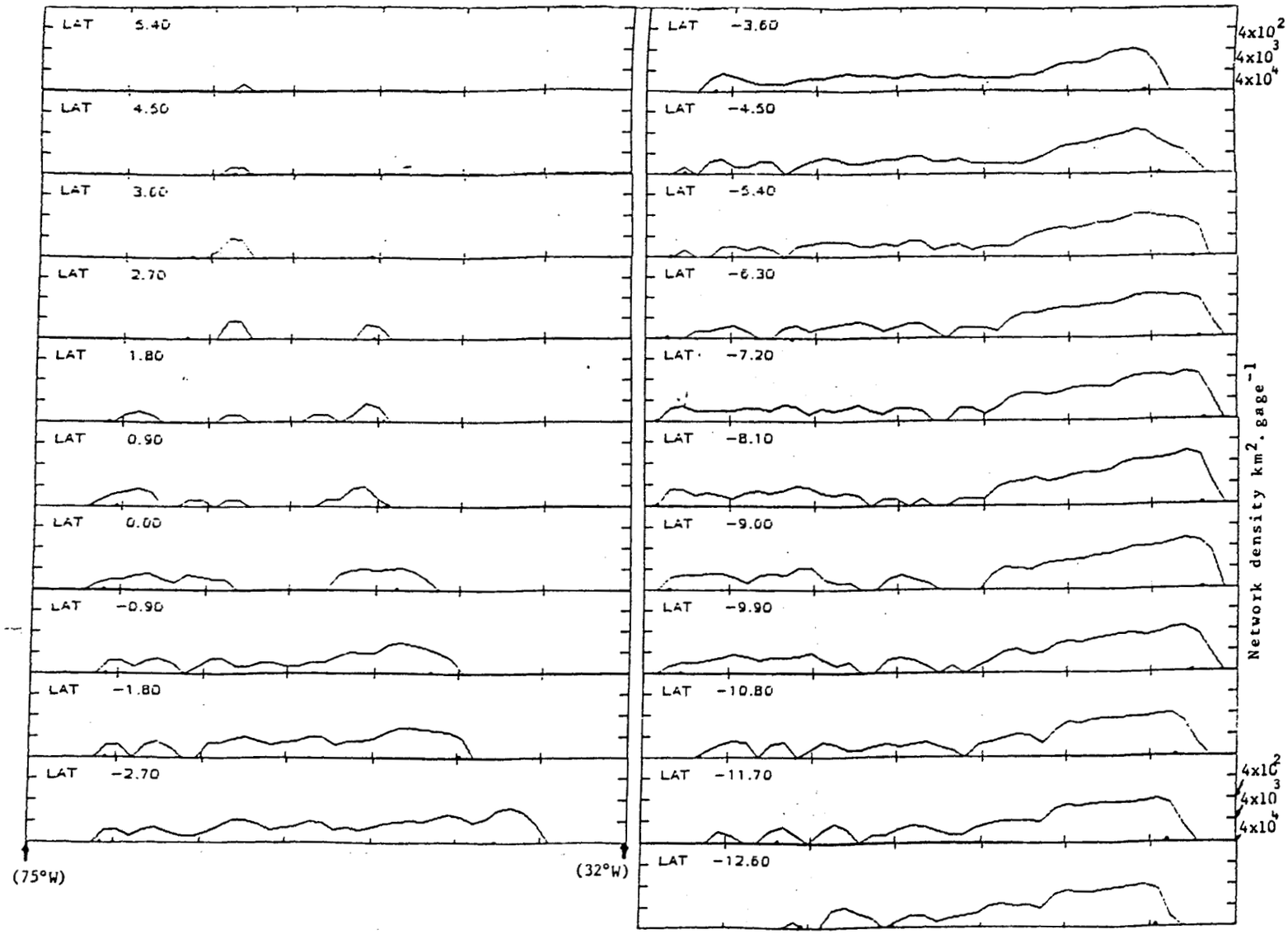

Figure 1. Gauge Densities for Areas of Approximately 200 x 200 km^2 Running in Steps of 100km Apart (Dots are references for geographical limits of the Country.)

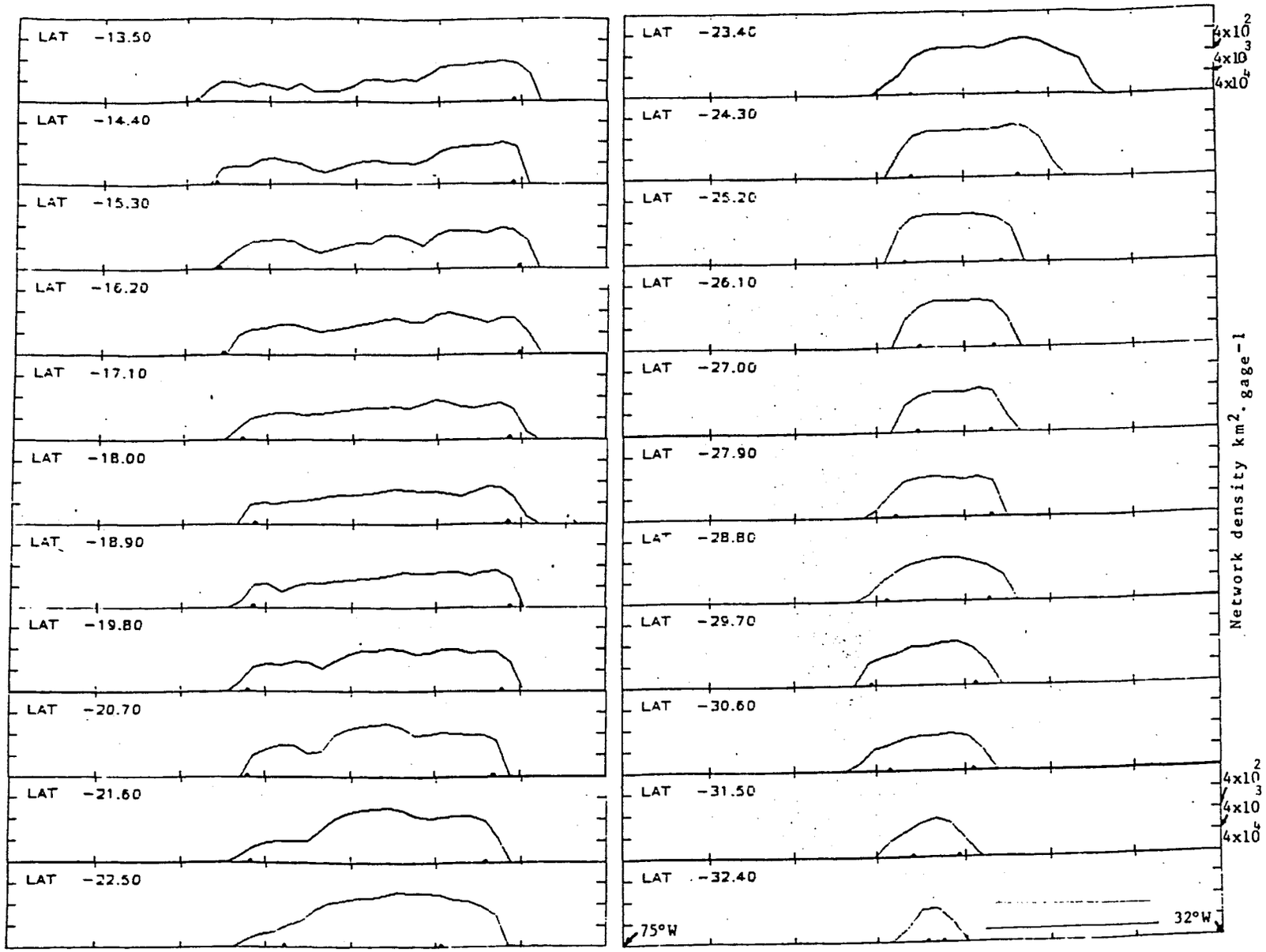

Figure 1. Gauge Densities for Areas of Approximately 200 x 200 km^2 Running in Steps of 100km Apart (Dots are references for geographical limits of the Country.) (Continued)

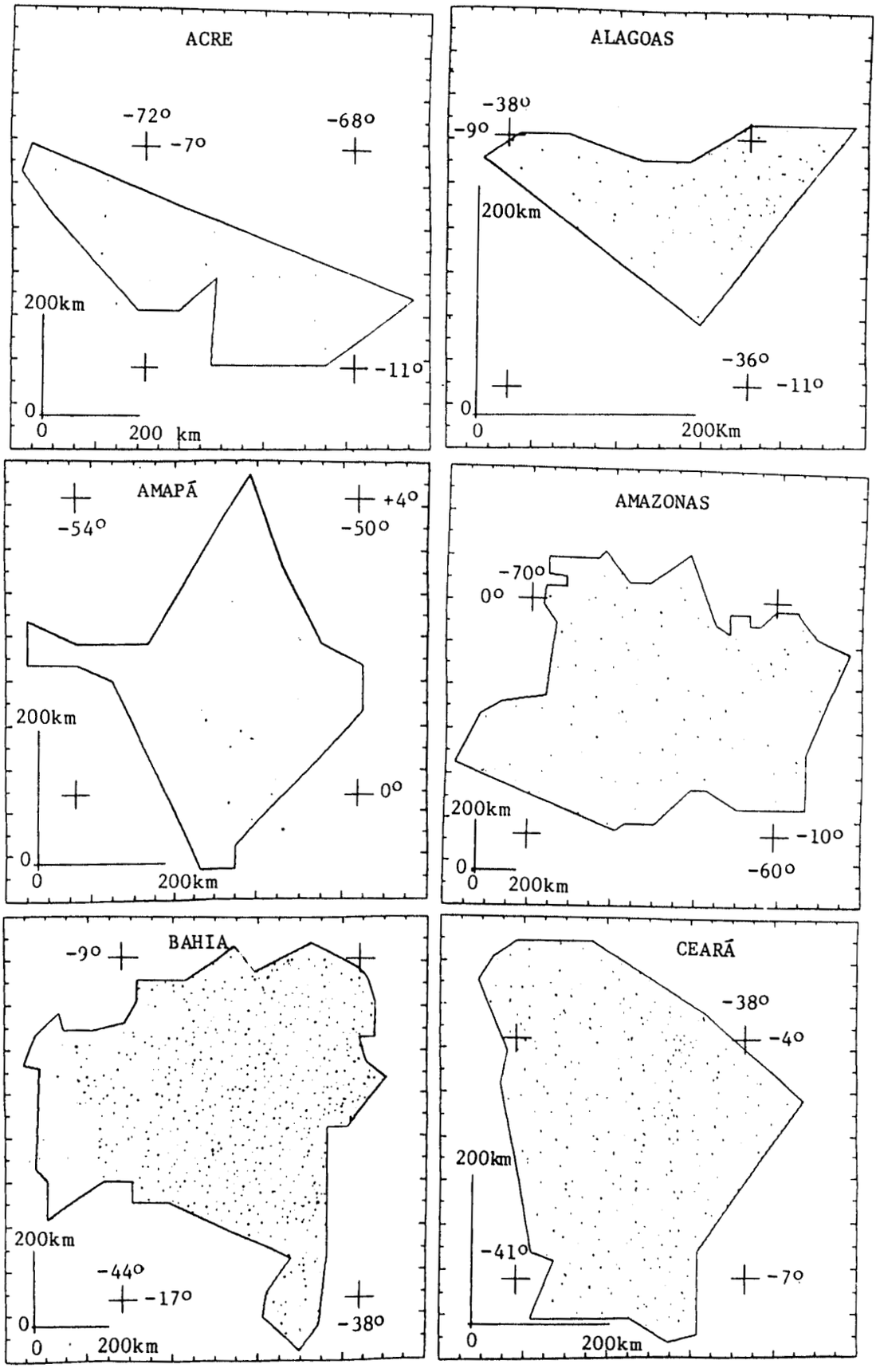

Figure 2. Spatial Distribution of the Gauges Within the States and Territories

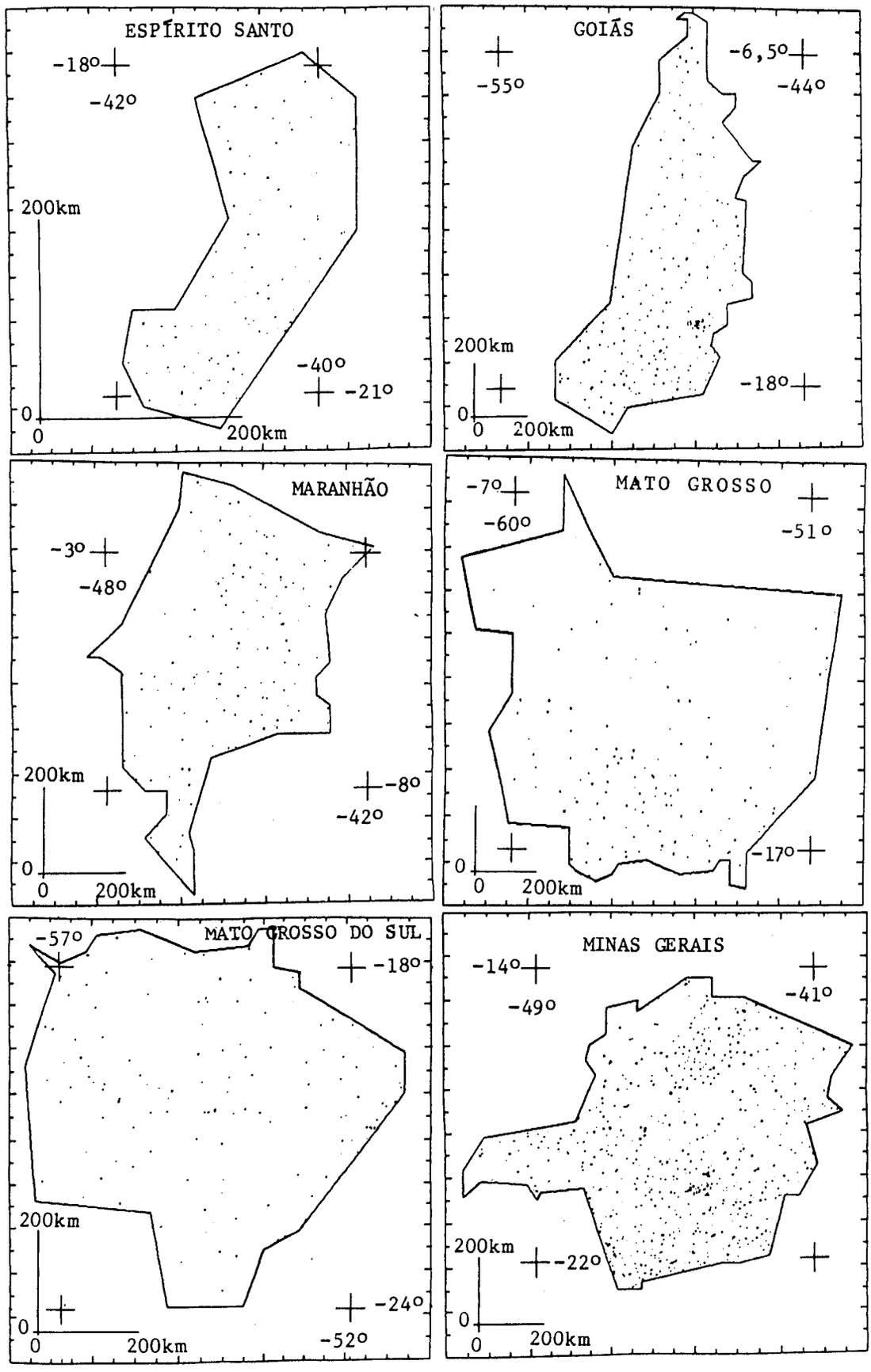

Figure 2. Spatial Distribution of the Gauges Within the States and Territories (Continued)

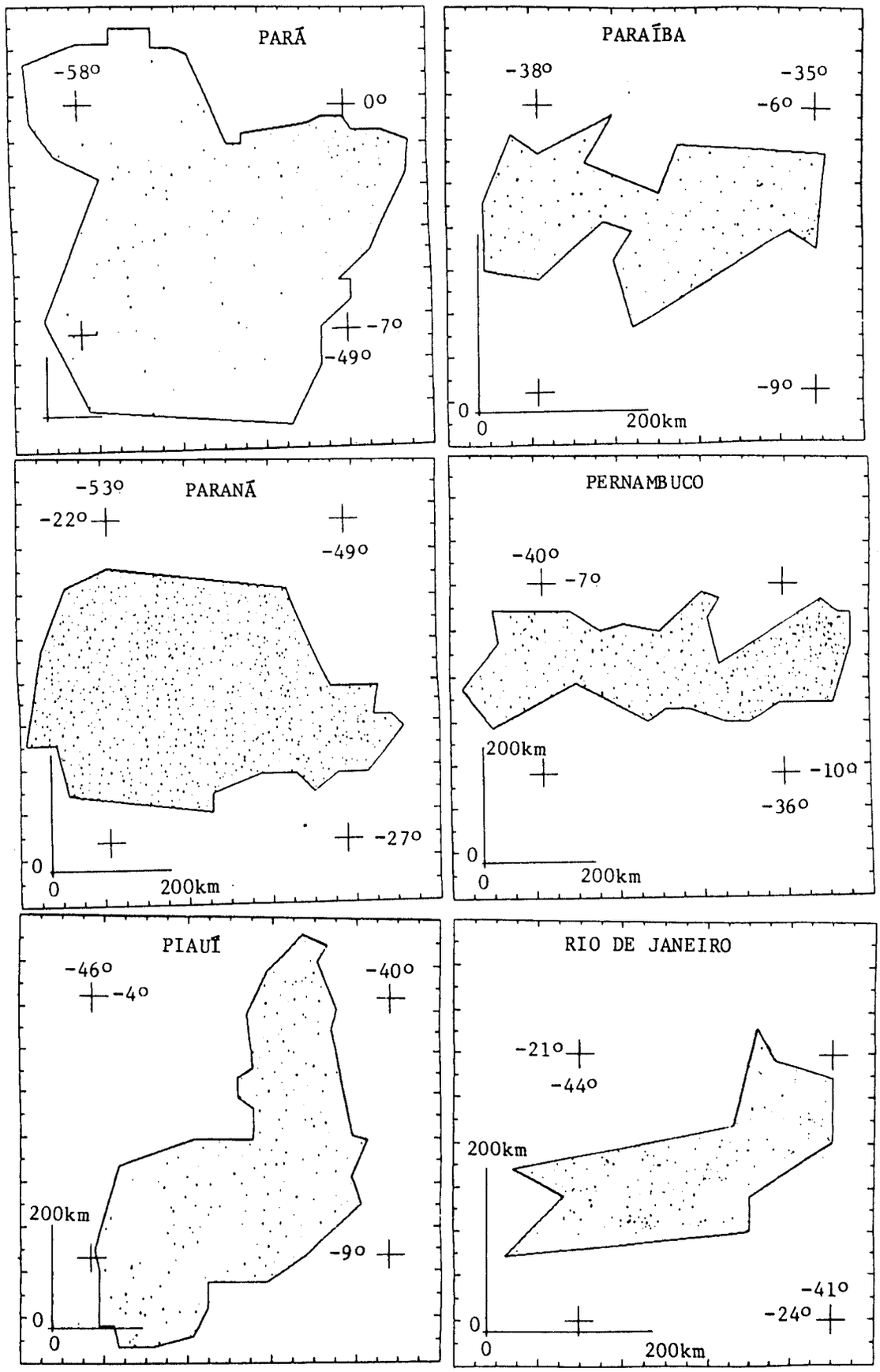

Figure 2. Spatial Distribution of the Gauges Within the States and Territories (Continued)

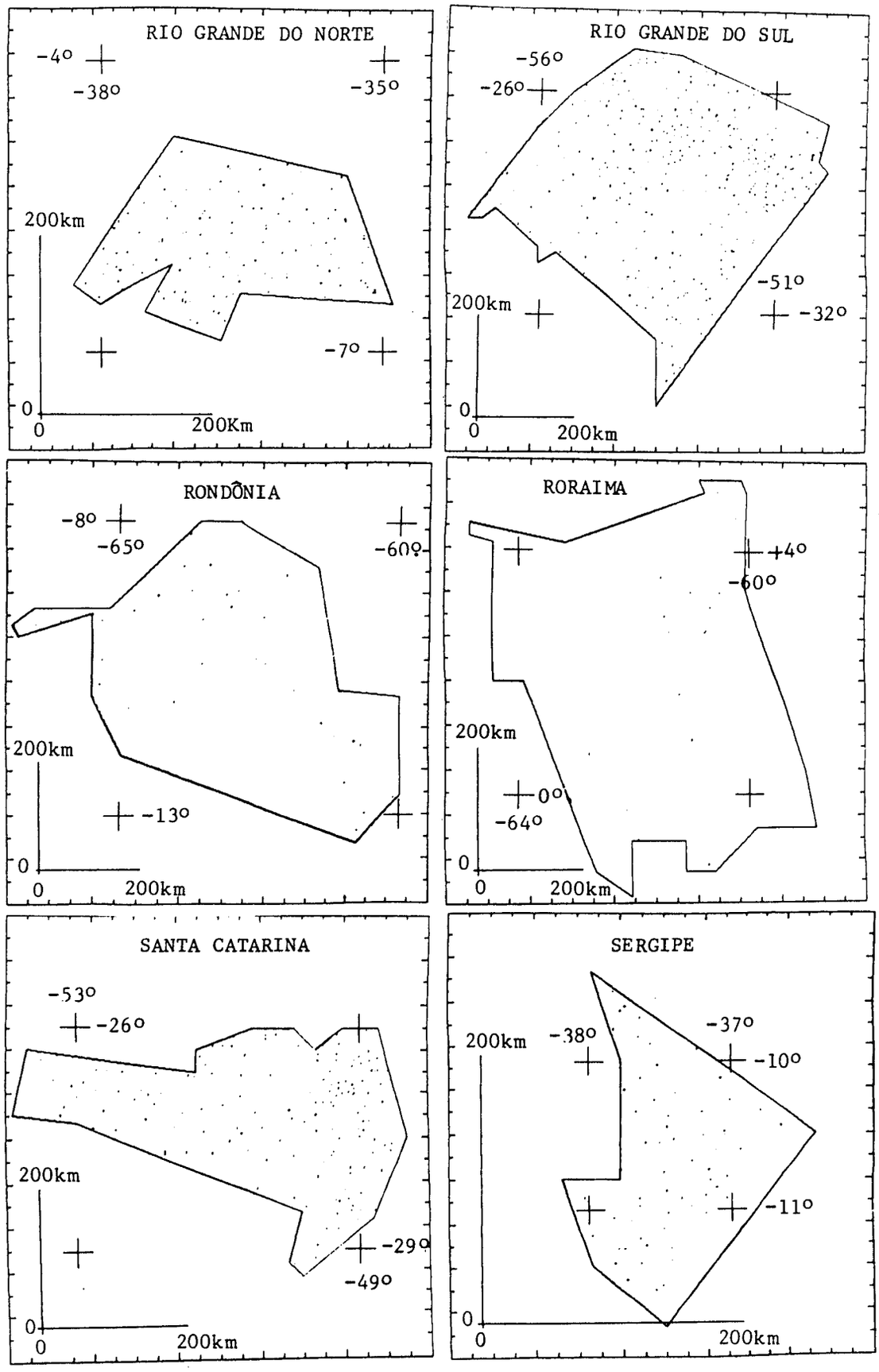

Figure 2. Spatial Distribution of the Gauges Within the States and Territories (Continued)

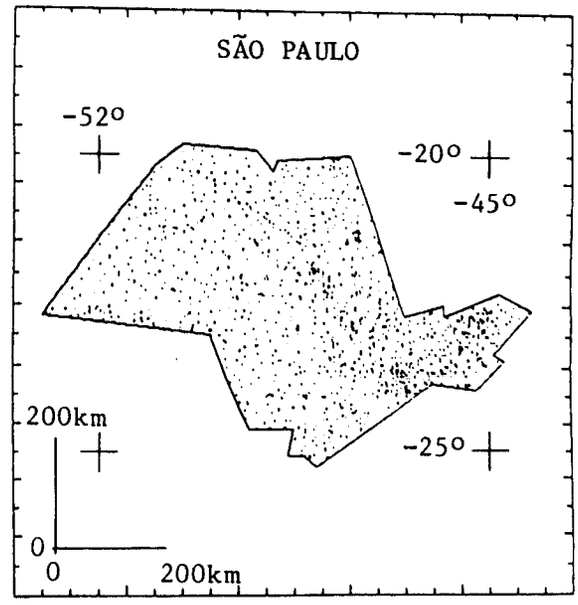

Figure 2. Spatial Distribution of the Gauges Within the States and Territories (Continued)

Table 3. Monthly Periods (hours) of Recorded Data for the Bauru Radar from 1982.

YEAR Month	1982	1983	1984	1985	1986	(1)
JAN	306.33	394.93	------	330.23	384.63	
FEB	359.05	348.00	5.70	374.28	283.22	
MAR	429.73	291.92	364.33	430.03	186.10	
APR	89.92	260.93	86.70	299.00	------	
MAY	113.87	181.63	46.52	56.48	126.13	
JUN	306.60	134.28	34.93	23.32	5.27	
JUL	99.17	------	65.27	21.52	5.77	
AUG	198.23	------	132.87	27.90	58.87	
SEP	99.97	------	165.22	105.37	32.45	
OCT	323.93	------	152.45	183.18	65.18	
NOV	327.78	------	357.95	293.20	27.55	(2)
DEC	359.15	------	349.33	272.53		

(1) There are about 60 hours of recording to be added to the last 6 month period.

(2) Updated to November 13.

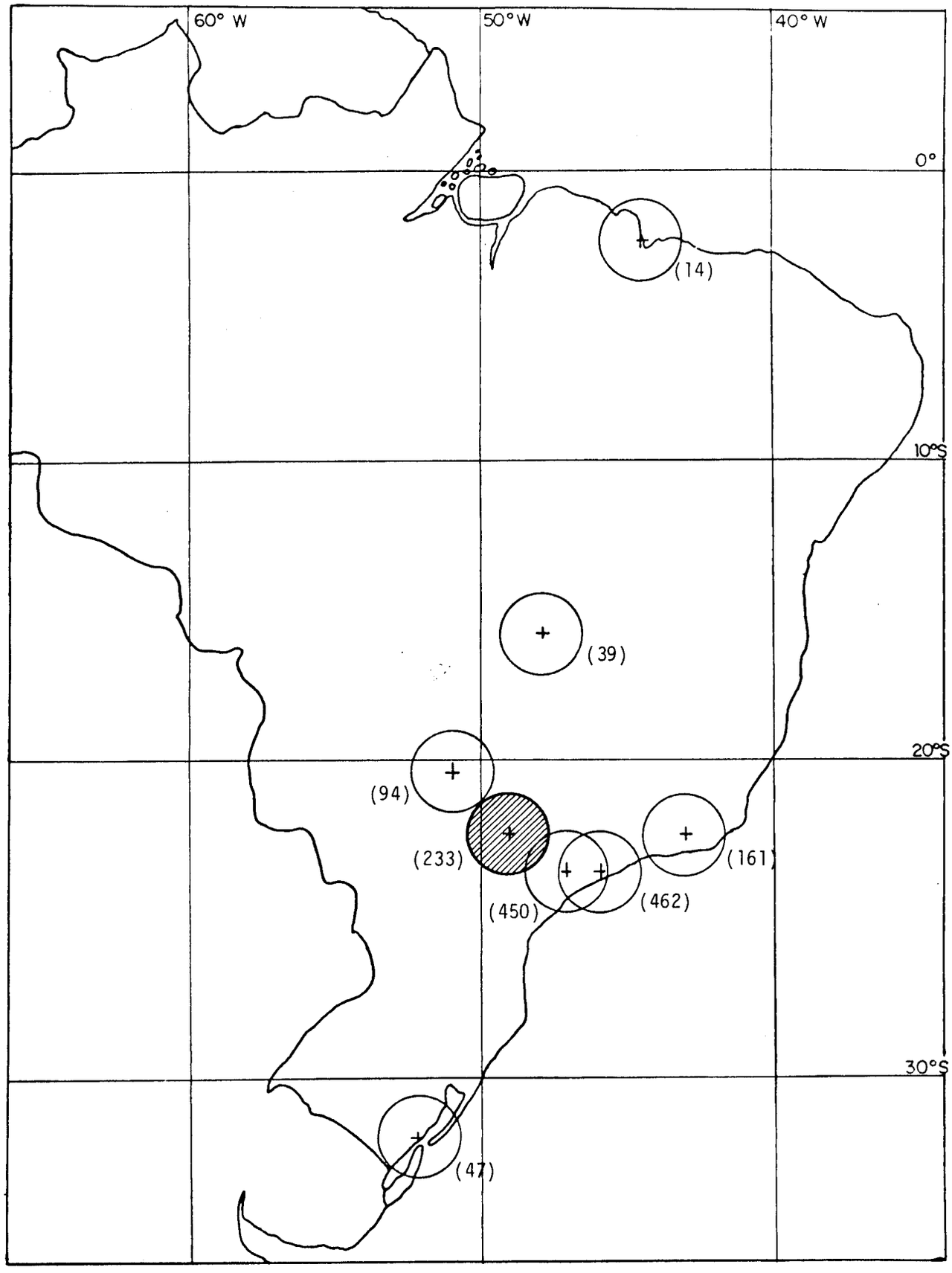

Figure 3. Existing and Planned Radar Network. Numbers in Parenthesis are Gauges Within Areas of About (200 x 200) km^2 Centered at the Respective Radar Sites. Ranges Indicated are 150 km. Hatched Area Indicates the Bauru Radar.

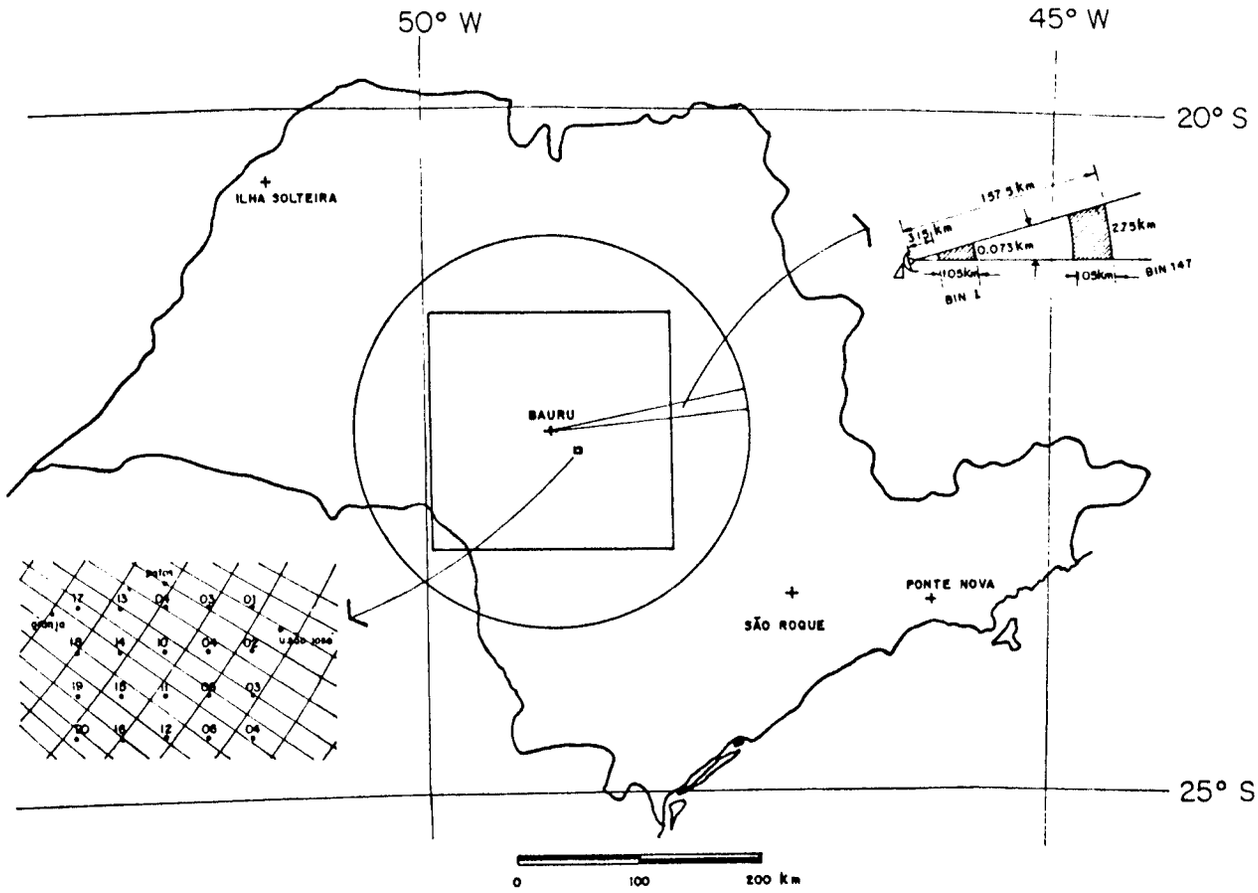

Figure 4. The Bauru Radar Location with Digital Coverage and Space Resolution. Also Shown is a Dedicated Network, Used for Calibration Purposes (Not Operating Presently; Undergoing a Change of Recording System). The Square Centered in the Radar is a 200 x 200 km^2 Area.

Alcântara, in the North (2°24S, 44°23'W), is a possible site for the installation of an existing Air Force Plessey 45C, C-band radar equipped with a Plessey Colourscan Display System. Digital data recording should be possible with the proper interfacing and computing facility.

A project keeping many similarities with the before mentioned RADASP II is being planned by the Federal University of Pelotas (31°44'S, 52°20'W). Basic data for the project will be collected by an S-band radar with digital data recording capability. As of now, radar installation is planned for 1990.

4. COMMENTS AND DISCUSSIONS

Problems regarding the spatial distribution of the gauges are noticed in Figure 2. There are areas of high concentration of gauges, like in portions of the eastern part of the state of Sao Paulo, with adjacent relatively sparse data areas. A striking example is the strip in the western most part of Bahia, which is clearly distinct from the rest of the state.

Figure 1 shows details of distributions of average densities for 200 x 200 km^2 areas. Table 1 shows that in approximately 65 per cent of the country, network density is poorer than 1 gauge/2500 km^2. In the states of Amazonas and Para, the existing number of gauges would have to be increased by a factor of 3 to 4 to reach the required density. In Table 1 it is seen that recording gauges, which are considered more reliable, represent only 15 per cent of the total number.

For the Amazonic region, there are plans to install approximately 30 telemetering rain gauges in a joint INEMET/DNAEE project. These will add to the present set of 20 already in operation in the area. Availability of estimates of monthly rainfall for 200 x 200 km^2 areas would have potential applications for the Amazonic region. Applications in southern regions would require finer space and time scales.

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[1] Ministry of Mines and Energy, National Department of Water and Electrical Energy: "Inventario Das Estacoes Pluviometricas" (updated to June, 1983), 1983.

[2] Calheiros, R.V.; "Meteorologia com Radar em Sao Paulo - Project RADASP II", 2 vols., presented to the Foundation for the Support to the Research in the State of Sao Paulo, February, 1982.

THE CARIBBEAN COUNTRIES RAINFALL AND RADAR STATIONS

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1. INTRODUCTION

The countries of the Caribbean Basin vary in size from some of the small islands of the eastern Caribbean to the large South American country, Venezuela, and the countries of Central America and Mexico. Figure 1 is a map of the Caribbean Region. All of the countries have orographic features which play an important role in the variation of rainfall. This is evident even on the smaller islands and will pose the major problem in any attempt to use the precipitation data for validation of the satellite-derived estimates.

Although the emphasis of this project is expected to be on monthly estimates, it may be useful to describe briefly a project which is aimed at the validation of storm rainfall estimates, but which is not yet fully operational. The RA-IV Hurricane Committee, which is comprised of the directors of the Meteorological Services of the Caribbean Islands, the Central American countries, Venezuela, Mexico and the National Hurricane Center in Miami, established a study group on storm rainfall estimation in 1982. The group, along with invited scientists, met at the RMC Miami and discussed the various techniques in use. The Hurricane Committee, acting on the recommendations of the study group, proposed a project in 1984 in which the RMC would provide estimates of rainfall for storms which are expected to make landfall within 36 hours and ground truth would be provided by the meteorological centres at Barbados, Martinique and Mexico.

The Committee also appointed a representative from Costa Rica to determine a method to correct for topographic effects. It was anticipated that in the long run, all of the regional meteorological centres would be in a position to use the method to adjust satellite estimated values. Because there were an insufficient number of opportunities due to a lack of active systems in the southern part of the region, no work was possible in 1985. It was hoped that 1986 would have shown an improvement, but this has not been the case.

2. THE RAIN GAUGE NETWORK

Table 1 summarizes the areas of the countries and their rain gauge networks.

2.1 Barbados

There is a network of about fifty reliable rain gauges including three recording gauges providing daily totals. With an area of about 425 km^2, this represents a density of about one gauge per 10 km^2. There are no plans for the use of any new measurement techniques. Historical records dating back to 1982 and earlier are available for this network. The data are recorded manually on specially designed forms, but there are plans to transfer the data to diskettes in the future. There are no ongoing hydrological or meteorological programmes which could be of value to the validation project.

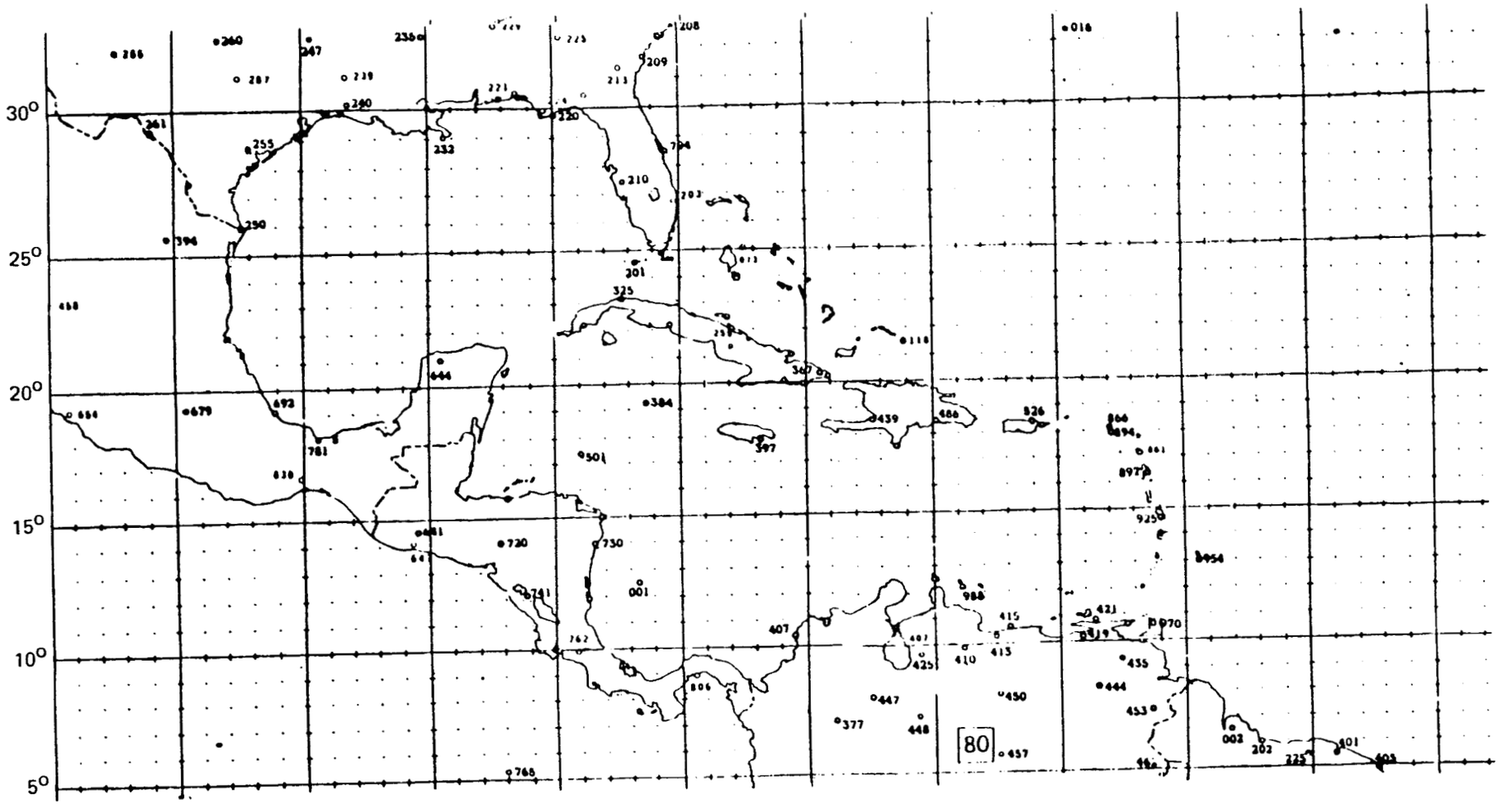

Figure 1. The Caribbean Basin

Table 1.

Country	Area (km^2)	Number of Rain Gauges	Recording Gauges
Barbados	425	50	3
Trinidad	4,765	113	26
Puerto Rico	9,400	140	25
Jamaica	11,292	220	12
Bahamas	14,000	45	-
Santo Domingo	48,480	420	72
Costa Rica	52,000	336	171
Guyana	214,970	250	20
Belize	-	53	-
Netherlands	-	79	5

Because of the small size of the island and the easy accessibility of the rain gauge network, the meteorological office is of the view that satellite-derived monthly estimates would have limited value.

2.2 Trinidad

This island has an area of approximately 4,765 km^2 and a rain gauge network of about 113 gauges of which 26 are recording gauges. This represents a density of about 1 gauge per 42 km^2. Figure 2 shows the location of most of the gauges. Historical records are available for the years dating back to 1982 and earlier. The data are kept in ledgers, but there are plans to transfer them to diskettes in the near future. A computer has recently been installed and work is in progress.

There are no ongoing or planned hydrological or meteorological programmes that would be useful for this project, nor are there any plans to use any newly developed techniques. It is envisaged that the satellite-derived estimates would be useful, but in a limited way.

2.3 Puerto Rico

The area of this island is approximately 9,400 km^2. There is a main rain gauge network of about 85 stations throughout the island that provides 24-hour totals. In addition, there are 25 continuous reading sensors, each providing a paper tape that is processed by computer. The installation of a network of around 30 real-time reporting stations (Sierra-Misco Alert System)

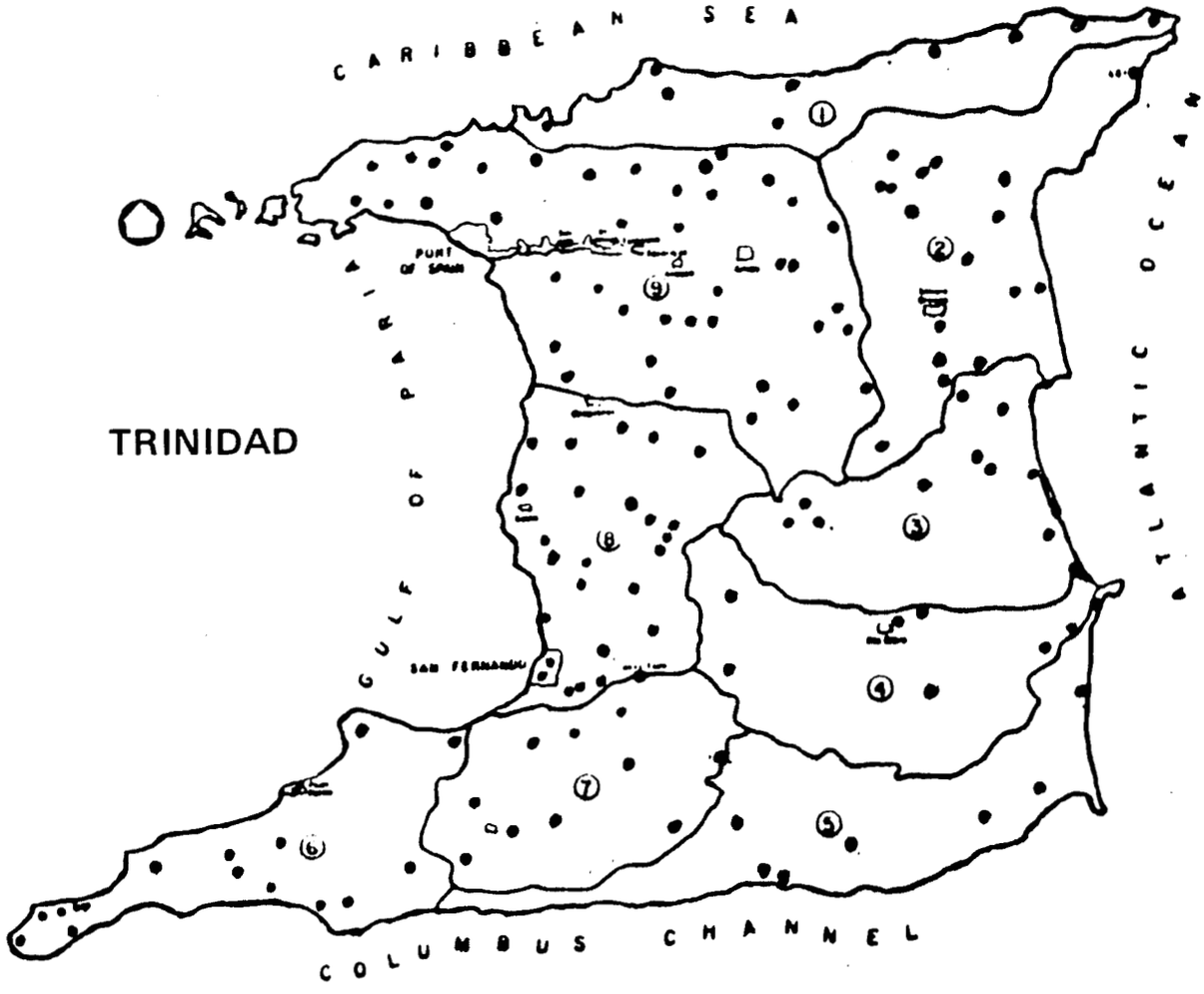

Figure 2. Locations of Rainfall Stations in Trinidad

is in progress and there are plans to increase this number to 55. The data are received in real-time increments of 0.01 inch and are stored on an IBM-PC. There are no plans for the use of any newly developed techniques.

In addition, there are two co-operative networks, one with the Police Department and the other with radio amateurs. These report twice daily to the meteorological office. Historical data from the entire network is available dating back to 1982 and earlier. The meteorological office would welcome any satellite-derived monthly estimates, but is of the view that its usefulness would be questionable, due to the large volume of data that is presently available.

2.4 Guyana

This country has a relatively large area of 214,970 km^2, but a large portion is inaccessible. There is a network of 250 rain gauges including 20 recording gauges operated by the Hydrometeorological Service. Most of these are located along the coastal area of the country where the population density is highest. The rain gauge density is one or more per 50 km^2 in the coastal region, but becomes more sparse further inland where there are few gauges.

These are not easily accessible. Historical data are available for the years dating back to 1982 and earlier. All data are recorded in manuscript form and there are no immediate plans to change this method.

There are water projects planned for the east and west water conservatories in the coastal regions. A number of additional gauges are planned for the area, but there are no plans for the use of any new techniques. The satellite-derived estimates would be of benefit particularly in the areas of Guyana where rain gauge data are limited.

2.5 The Bahamas

If a smooth line were drawn around the Bahamian archipelago, it would contain an area 800 km long and 240 km wide. Most of this area, however, would be ocean. The islands are, in general, long narrow strips of land with a total area of 14,000 km^2. There are about forty-five rainfall stations distributed through the island chain. There are no recording gauges and there are no plans for the use of any new techniques. The data are recorded in manuscript form and are available dating back to 1982 and earlier. It is not anticipated that the satellite-derived monthly estimates would be of great benefit.

2.6 Jamaica

This island has a land area of approximately 11,292 km^2 and there are 220 rainfall stations, including 12 recording gauges distributed throughout the island. The density is about one gauge per 50 km^2. Historical data exist for the period dating back to 1982 and earlier. The data are recorded mainly in manuscript form, but there are plans to transfer to diskettes in the near future. A flood plain mapping project is currently in progress. As a part of the project it is planned to have data transmitted using a telemetering system on a daily basis to provide accurate real-time data from several stations. There are no plans for the use of any new rainfall measurement techniques. It is anticipated that the satellite-derived estimates will be useful in the more remote areas of the island, if such estimates are available on a small scale.

2.7 Santo Domingo

The area of this country is approximately 48,480 km^2. There are about 240 rain gauges, including 72 recording gauges, operated by different agencies. In addition, there are several private institutions that take rainfall measurements. The data are recorded manually at synoptic, climatological, hydrological and agrometeorological stations. Daily and monthly totals are recorded and historical data exist dating back to 1982 and earlier. However, there are no plans for the use of any newly developed measuring techniques.

The hydrological institute has embarked upon a project for hydrological prediction in which they are using 15 remote control stations via satellite to obtain real-time data. It is anticipated that the monthly satellite-derived estimates would be beneficial.

2.8 Costa Rica

This country has an area of 52,000 km^2 and there is a rain gauge network of 336 gauges and 171 recording gauges. This provides a density of

one or more per 50 km by 50 km area. Data are recorded on diskettes and are available dating back to 1982 and earlier. There are no plans for the use of any new measurement techniques in the near future. It is anticipated that the satellite estimates would be useful.

2.9 Belize

There are 53 rainfall stations in Belize operated by the Weather Bureau and other Government Departments. All data are collected and stored in manuscript form, but data for 12 stations are stored on diskettes within six weeks of measurement. There is a density of one or more gauges per 50 km x 50 km in the lowlands part of the country. Historical records dating back to 1982 and earlier are available. There are no plans for the use of any newly developed techniques, but the meteorological service would welcome information on any such techniques.

A programme for the development of hydrological basins commenced in August 1986. There are plans to deploy ten digital recording gauges before June 1987 as part of this programme. The satellite-derived estimates are expected to be of some value particularly to the hydrological and engineering services in their investigations.

2.10 Netherlands Antilles and Aruba

Daily rainfall totals are available from a rain gauge network of 79 stations on the islands of Aruba, Bonaire, Curacao, Saba, St. Eustatius and St. Martin. In addition six hourly measurements are available from five stations where recording gauges are available. The islands are all small in area. Data are available for the period going back to 1982 and earlier. The data are recorded in manuscript form and reported by means of basic statistical tables. There are no specific on-going or planned hydrological or meteorological programmes in the Netherlands Antilles that would be relevant to this project. It is expected that the results of this project would yield practical benefits to these islands, particularly in the area of water management.

2.11 Venezuela

No information on the number of rain gauges in use was available in time for this report, but it is expected to be obtained at some future date. However, it may be useful to mention that an experiment in the derivation of rainfall estimates from satellite pictures and subsequent attempts at validation has been in progress during the past five years. The method used is based on the Schofield/Oliver technique, but various difficulties have been encountered particularly with respect to orographic effects. However, work in this area is progressing.

3. THE RADAR NETWORK

There are several weather radars available in the region, as summarized in Table 2. In the english-speaking countries, these are located in Guyana, Tobago, Barbados, Antigua, Jamaica and Belize. These are all 10 cm Mitsubishi RC-32B radars with a maximum range of 500 km. Figure 3 shows the overlapping beams in the eastern Caribbean at 6 km height and zero elevation, as well as the location of other weather radars. Apart from Guyana, all of the others have areas blocked by hilly terrain and consequently the useful

Table 2. The Radar Network

Caribbean Meteorological Organization Radars	
Belize International Airport	RC32B (Mitsubishi) 10 cm 500 km
Jamaica	RC32B
Antigua	RC32B
Tobago	RC32B
Barbados	RC32B
Guyana	RC32B
Cuban Radars	
Havana	
Camaguey	
La Bayada	
Punta Del Este	
Gran Piedra	
French Radars	
Martinique	Omera ORP 330 3 cm 200 km
Guadeloupe	Omera ORP 330
French Guiana	Omera ORP 330
Netherlands Radars	
Curacao	Texas Instr. 10 cm 144 km
Curacao	WSR-745 10 cm 400 km
Surinam Radar	
Zanderij Airport	

range is reduced. There are two radars of 3 cm wavelength, located in the French islands of Guadeloupe and Martinique which overlap with the Barbados and Antigua radars. In addition, several weather radars are located in Cuba and one in Puerto Rico. The Dutch island of Curacao has two weather radars, one of which has a range of 144 km and the other which has a 10 cm wavelength, and a range of 400 km. Venezuela has indicated its intention to install three weather radars in the near future and Santo Domingo has also proposed a project to WMO for a radar to be located on its southern coast.

4. DISCUSSION

The countries of the Caribbean Basin vary in size from the very small islands less than 500 km^2 in area to the very large countries on the central and south American coasts. Most of the countries, including the islands, are mountainous and there is therefore a considerable orographic effect on

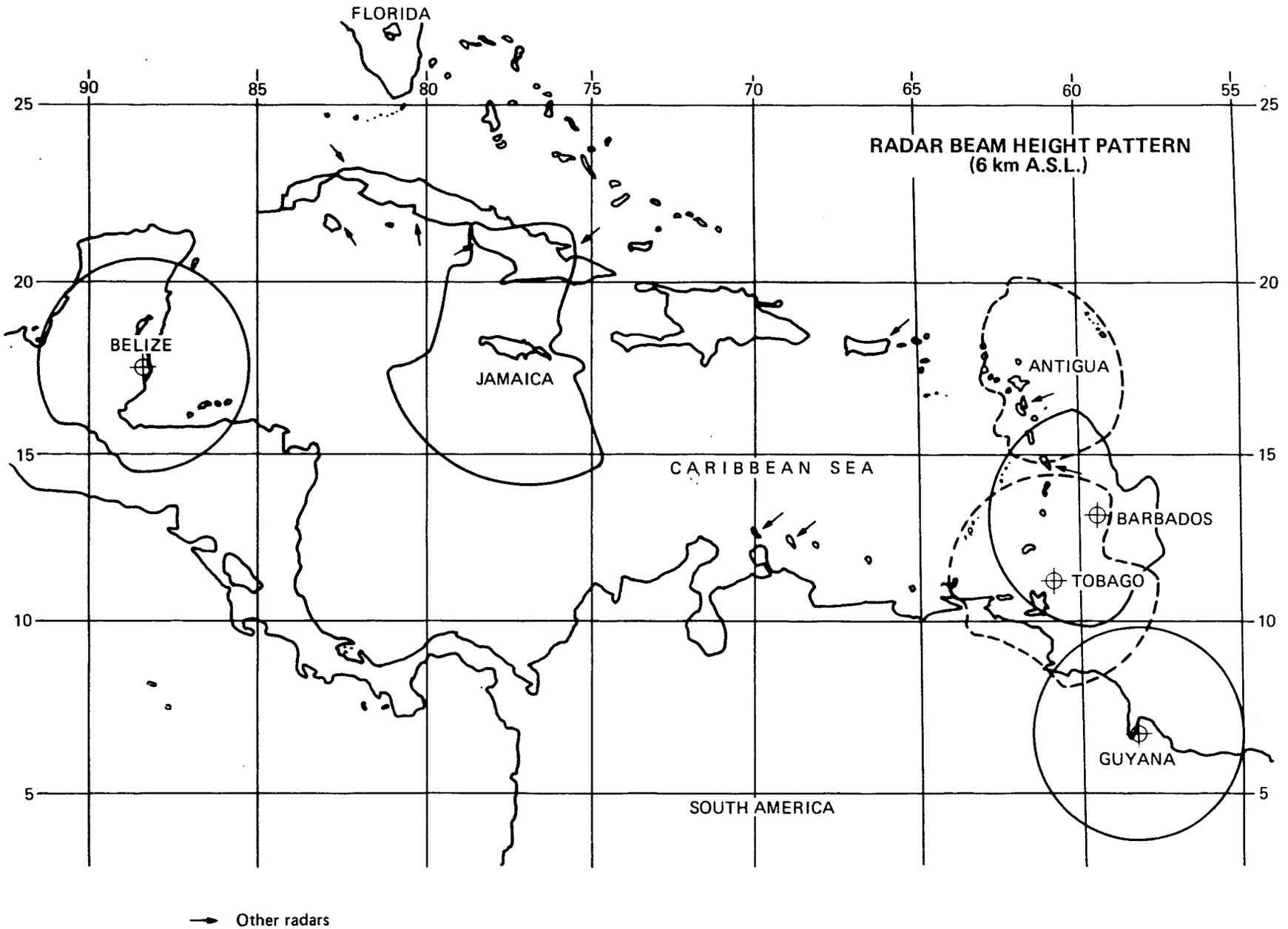

Figure 3. Locations of Weather Radars ⟶ Other Radars

precipitation. Even on islands such as Barbados which is relatively flat, there is a distinct variation of rainfall from the coastal regions to the centre of the island as illustrated in Figure 4. The mountainous island of Dominica which is 781 km^2 in area has an annual rainfall variation of 1,270 mm on the leeward coast to 7,620 mm at an inland area.

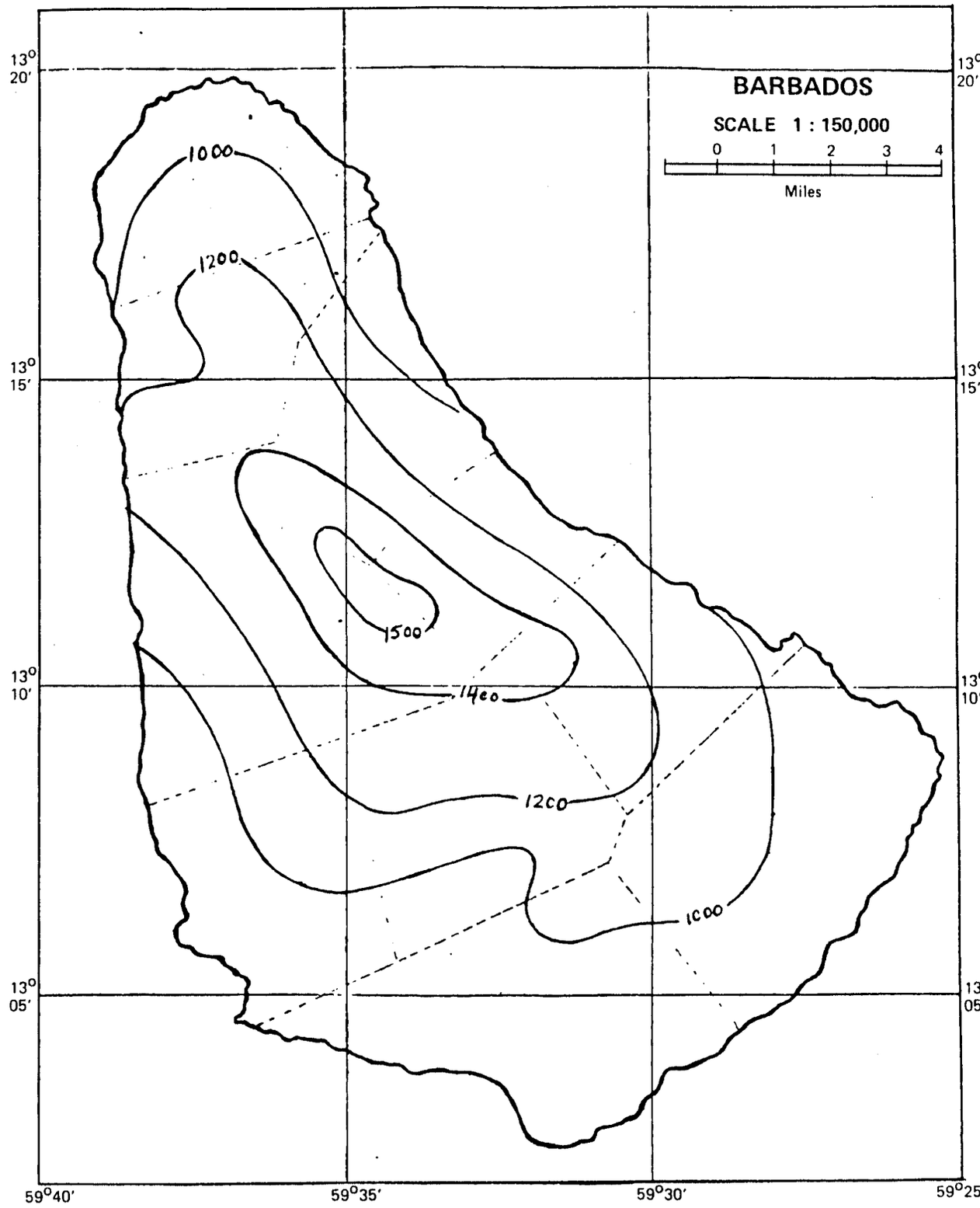

Figure 4. Average Summer Rainfall (mm) in Barbados

The rain gauge network throughout the region is fairly extensive and those in the larger territories will be useful to the validation project. On the smaller islands the available information could perhaps be used to validate estimates derived over the oceans, but a method would first have to be determined to correct for the orographic effects. The usefulness of the monthly satellite-derived estimates will vary from country to country. In the smaller islands, the ease of accessibility to the rain gauge network would result in such estimates having limited use. However, in the larger territories, parts of which are usually inaccessible and the rain gauge network sparse, such estimates may provide the only useful data.

VALIDATION OF SATELLITE-DERIVED PRECIPITATION MEASUREMENTS IN CANADA

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Canada has several programs underway which are of interest to this workshop. These include two programs in which satellite rainfall data are being used to make precipitation measurements and three programs which might provide surface truth for other satellite programs. The first one of interest is an operational system, called RAINSAT, which uses satellite-derived precipitation measurements as a real-time forecast aid in Quebec. This is an example of a system which might be the prototype of a larger or even global-scale satellite-derived precipitation measurement program. The satellite data used are the visible and infrared imagery from the GOES satellite covering eastern Canada (at 75°W). The calibration for this system comes from a seasonal comparison of visible and IR imagery with ground-based weather radar which is then used to generate a climatological relationship between visible and IR brightness and the probability of rainfall. The 1985 summer season was used to generate the algorithm base that was used during the 1986 summer. The output of this program is the probability of rainfall, not rainfall amount. The forecasting ability comes from pattern recognition between successive satellite images and works reasonably well when defined patterns are present. The analysis has proven most useful for the sparsely populated regions of Quebec. One of the conclusions is that the visible data are most useful in mid-latitudes. This is because the climatology of the region often includes stratiform rain and high altitude winds when convective storms are present. At night, when only IR data are available, results are noticeably poorer.

There is also a climatological program comparing several satellite rainfall techniques for the southern Ontario region with the goal of providing rainfall measurements at longer time scales (several days to months). The satellite techniques considered included RAINSAT along with two other methods, one proposed by Negri and Adler using IR data and another in which cloud cover is assigned a climatological rainrate. The ground truth for this work comes from accumulated ground based weather radar combined with data from a rain gauge network on which an objective analysis procedure is applied.

Canada does have an extensive automatically recording rain gauge network (approximately 3000 instruments), primarily in the more densely populated parts of the country. These are available for satellite ground truth studies, although RAINSAT and the subsequent climatological program have relied heavily on ground-based weather radars, which also exist and can be used for verifying other techniques.

Another area of active research in Canada is how to provide rainfall measurements at sea. This is a critical problem since, at present, there are few, if any, methods for making reliable precipitation measurements over the ocean and yet a major portion of the global precipitation falls over the ocean. Various satellite techniques should work over the ocean but the problem of lack of surface truth for these methods is acute. One idea that has been pursued recently is to set up a ship of opportunity program to provide at least qualitative information about rainfall. It is well known that shipboard rainrate measurements are quantitatively unreliable. However, even qualitative assessment of rainfall conditions (no rain, light rain, heavy rain) would be of value for oceanic rainfall climatology studies.

Another method, which has the potential of providing quantitative measurements of rainfall in oceanic areas or in any other region where large bodies of water, such as lakes or reservoirs are present, is to simply monitor the underwater ambient noise levels. Precipitation striking the sea surface produces large amounts of underwater sound which has distinctive spectral characteristics which allow it to be identified from other sound sources. The shape of the sound spectrum identifies that rain is present, while the spectral levels may be used to estimate quantitative rainfall rates. There are a number of exciting advantages for this technique. Hydrophones are relatively inexpensive and durable and, in fact, a commercial instrument has been recently developed in Canada. They can be deployed anywhere so measurements need not be fair weather biased. The instrument would be deployed below the surface. This eliminates surface platform stability problems and means that the instrument does not interfere with the processes being measured nor is it subject to the stress of being in the surface boundary layer. Finally, the depth of deployment determines the water surface area that is monitored, thus underwater sound measurements provide natural spatial averaging which is very important for precipitation studies. This may be particularly useful from the point of view of calibrating satellite techniques since satellites also provide spatial averaging. Of course, the area monitored using underwater sound will be much smaller than the minimum area monitored by a satellite method. Useful climatological information is still obtainable.

This technique is still in the development stage. The physics is fairly well understood although there is still some question of how wind modifies the sound generated by rain and vice versa. At present, it is possible to identify whether or not it is raining and whether it is light rain (i.e., no large drops) or heavy rain. If it is heavy rain, then a quantitative estimate may also be possible. The data set on which an algorithm might be based is still too small to attempt to formulate the algorithm, however, work is underway in Canada to collect that data set. One program that provides part of this data set is the Canadian Atlantic Storm Program. This project monitored a series of storms off the coast of Nova Scotia during the 1985-86 winter. Sources included rain gauges, ground based weather radar and underwater ambient sound measurements. Analysis is just underway but does look promising. The underwater acoustic techniques for measuring precipitation will need to be developed in coastal regions where more conventional measurements can be made from nearby land locations. More experiments should be planned where this combination of instruments is present. Eventually acoustic devices can be deployed at deep water moorings or from drifting buoys which would then provide information about the climatology of open ocean areas.

In conclusion, a number of research activities in Canada are applicable to the problem of how to provide for validation of satellite-derived precipitation measurements. There is an existing operational program called RAINSAT, which uses satellite visible and infrared imagery to assign rainfall probabilities which are then used in real-time weather forecasting. RAINSAT was calibrated using ground-based weather radar. Secondly RAINSAT, and two other satellite methods are being used to derive climatological rainfall at longer time scales. This study uses a rain gauge network as well as weather radar for verification. A large rain gauge data set does exist in Canada which could be used for other validation efforts. Fourth, over the ocean rainfall measurements are particularly difficult. A ship of opportunity program is being considered to provide at least qualitative information of

precipitation in oceanic areas. Finally, the techniques of rainfall measurements by monitoring the underwater sound produced by precipitation striking the surface is under active development. This technique shows promise as a means of providing quantitative measurements of rainfall at sea. At present the data set needed to propose an algorithm for inferring precipitation from underwater sound is not large enough. Experiments in coastal regions where more conventional rainfall rate measurements are possible need to be planned and carried out. Doing so should provide a data base from which open ocean sound measurements can be interpreted in terms of rainfall climatology. This could then be compared with various satellite-derived precipitation measurements.

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A BRIEF INTRODUCTION TO RAIN GAUGE NETWORKS AND HYDROLOGIC APPLICATIONS OF METEOROLOGICAL SATELLITES IN CHINA

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China is a country with a vast territory. There are many large rivers, lakes and high mountains. Of the total territory, plateaus and mountainous areas cover 59 per cent, hilly areas 10 per cent, plains 12 per cent, and basins 19 per cent. The whole country has an area of 9.6 million square kilometers. The topography of the country consists of high altitudes in the western part and low altitudes in the eastern part. One hundred million hectares of cultivated lands are concentrated in the three main plains of the country (the Northeast Plain, the North China Plain and the Middle and Lower Yangtze River Plain) and in the Pearl River Delta, as well as some island plains.

China's climate is strongly influenced by the monsoon. It is wet in summer and dry in winter. Annual mean precipitation decreases from more than 1500-2000 mm in the southeast region to less than 200 mm in the northwest region. In the deserts of Xingjiang, there is often no rainfall at all during the entire year. The annual mean precipitation for all of China is about 630 mm. Due to the effect of monsoons in summer in north and northeast China, 70-80 per cent of the rainfall is concentrated in a few months of the year. Meanwhile, due to different intensities of monsoons in different years, precipitation also shows great differences from year to year.

China has a large number of rivers. Among the longer ones are the Yangtze River, Yellow River, Huai River, Hai River, Pearl River, Liao River, Heilong River, Songhua River, Yaluzangbu River, Lancang River and the Nu River. Moreover, there are also some inland rivers in the arid areas of the northwest. These inland rivers originate in the snow-covered mountainous areas, so the runoff often disappears and they become seasonal rivers. There are also some rivers flowing out of our national boundaries in the southwest, northeast and northwest of the country (Table 1). In China, most of the river runoff comes directly from precipitation. The Yangtze River basin has the most abundant water supply, up to 40 per cent of the national total.

In summer and autumn, the wet currents from the Pacific Ocean and Indian Ocean bring abundant rains, while in winter and spring, the dry and cold currents from the central part of the Eurasian Continent and the Mongolian Plateau bring less rain. The coastal areas in the eastern and southern parts of China have a humid climate and are rich in rainfall, while the northwestern inland areas have a dry climate, with less rainfall, because of the blockage of monsoon penetration by the mountains. This is the basic climate difference between the south and the north, the former is rich and the latter is poor in water. This difference in climate is the main factor for the uneven distribution of water resources in China, either in space or in time. Although the total amount of water resources of China is 2,700 billion m^3, which ranks sixth in the world, per capita is 2,700 m^3 which is about one-fourth of the world mean. So it is not as abundant when compared with other countries.

Table 1. The Amount of Water Resources of Rivers

Name of Rivers	Length (Km)	Catchment Area (1,000km^2)	Annual Precipitation (mm/year)	Annual Runoff Yield (Hundred Million m^3) Normal Year (A)	Annual Runoff Yield (Hundred Million m^3) Drought Year (B)	(B)/(A) %	Amount of Annual Runoff Per Capita (m^3) Normal Year	Amount of Annual Runoff Per Capita (m^3) Drought Year
Heilongjiang	3,101	897	486	1,192	890	73	1,617	1,180
Liaohe	1,390	345	555	486	370	76	541	411
Hai	1,090	319	556	292	196	67	298	200
Yellow	5,460	795	468	688	584	85	683	580
Huaihe	1,000	327	867	766	514	67	400	268
Yangtze	6,300	1,809	1,060	9,600	8,736	91	2,840	2,584
Pearl	2,210	578	1,547	4,739	4,170	88	4,487	3,949
National Total		9,600	628	26,380	24,533	93	2,638	2,453

The amount of water resources is very unevenly distributed from region to region. According to annual mean precipitation figures, China can be divided into five different regions, i.e., much rain, humid, semihumid, semiarid and arid. The distribution of surface runoff in China is basically similar to that of precipitation, but at an even higher degree. The criteria for these classifications are given in Table 2, and the map of classifications is shown in Figure 1.

Table 2. Regions classified according to precipitation and runoff in China

Serial No.	Classification According to Precipitation	Annual Mean Precipitation (mm)	Classification According to Runoff	Annual Mean Runoff Depth (mm)
I	Much rain	>1600	Abundant water	>900
II	Humid	800 - 1600	More water	200 - 900
III	Semi-humid	400 - 800	Intermediate	50 - 200
IV	Semi-arid	200 - 400	Less water	10 - 50
V	Arid	<200	Arid	<10

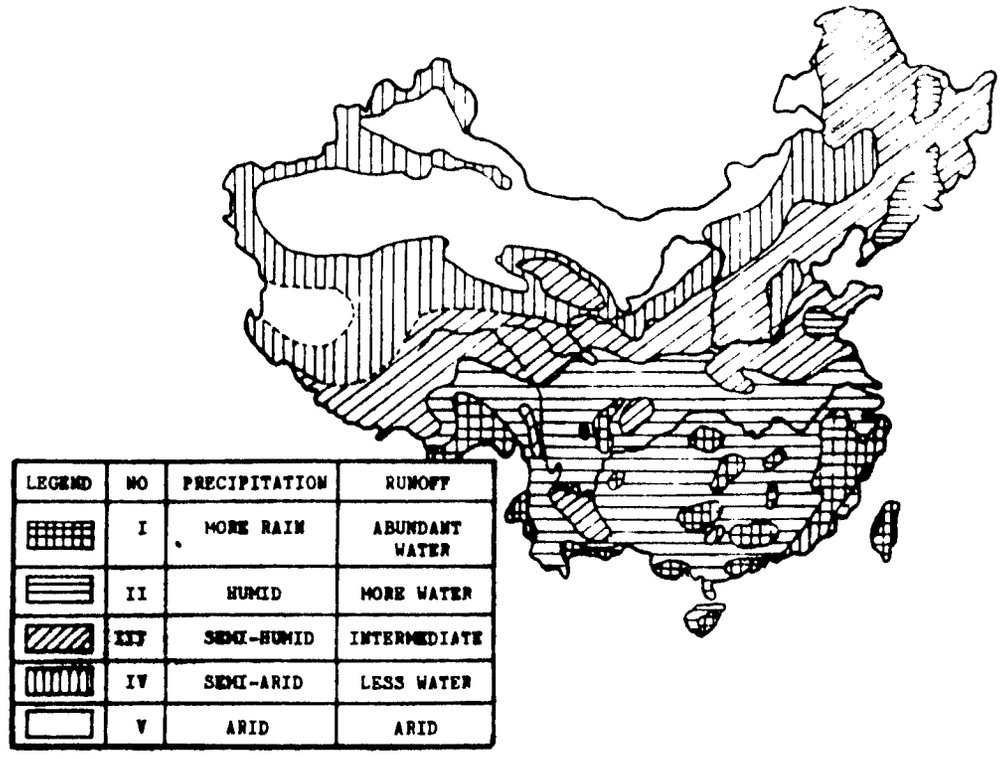

Figure 1. Map Showing the Regional Classification of Precipitation and Runoff in China

China is a country with many rainstorms. Due to the strong intensities and short durations of these storms, the runoff from catchment areas concentrates very rapidly. As a result, the flood stage of a river rises and falls rapidly. For this reason, flood damage occurs frequently, especially in the middle and lower reaches of rivers. Most rivers get sudden peak floods during the flood season as the intensity of rainstorm is very high. Some of the rivers carry huge amounts of sediments downstream. All of these conditions have produced complicated problems of hydrology (see Figure 2).

Gauging stations are classified as basic stations and special stations. Basic stations form a basic hydrological network. The task of the basic hydrological network is to provide data for water resource assessment, hydrological analysis and scientific research. This hydrological information is also used for forecasting for major water control projects and major areas of large rivers. Special stations are set up for special investigations.

The present state of the basic station network is elaborated in Table 3. The precipitation and evaporation station network is evenly distributed in the main. On the upper reaches of medium and small size rivers, there must be adequate precipitation gauging stations to meet the requirements of the stream gauging stations in the analysis of storm floods. Equipment in common use is employed for measuring the water level and precipitation. Stations using precipitation or water level recorders now account for more than half of the total number. Most of them are "daily" recorders and the creation of 3-monthly recorders is under way.

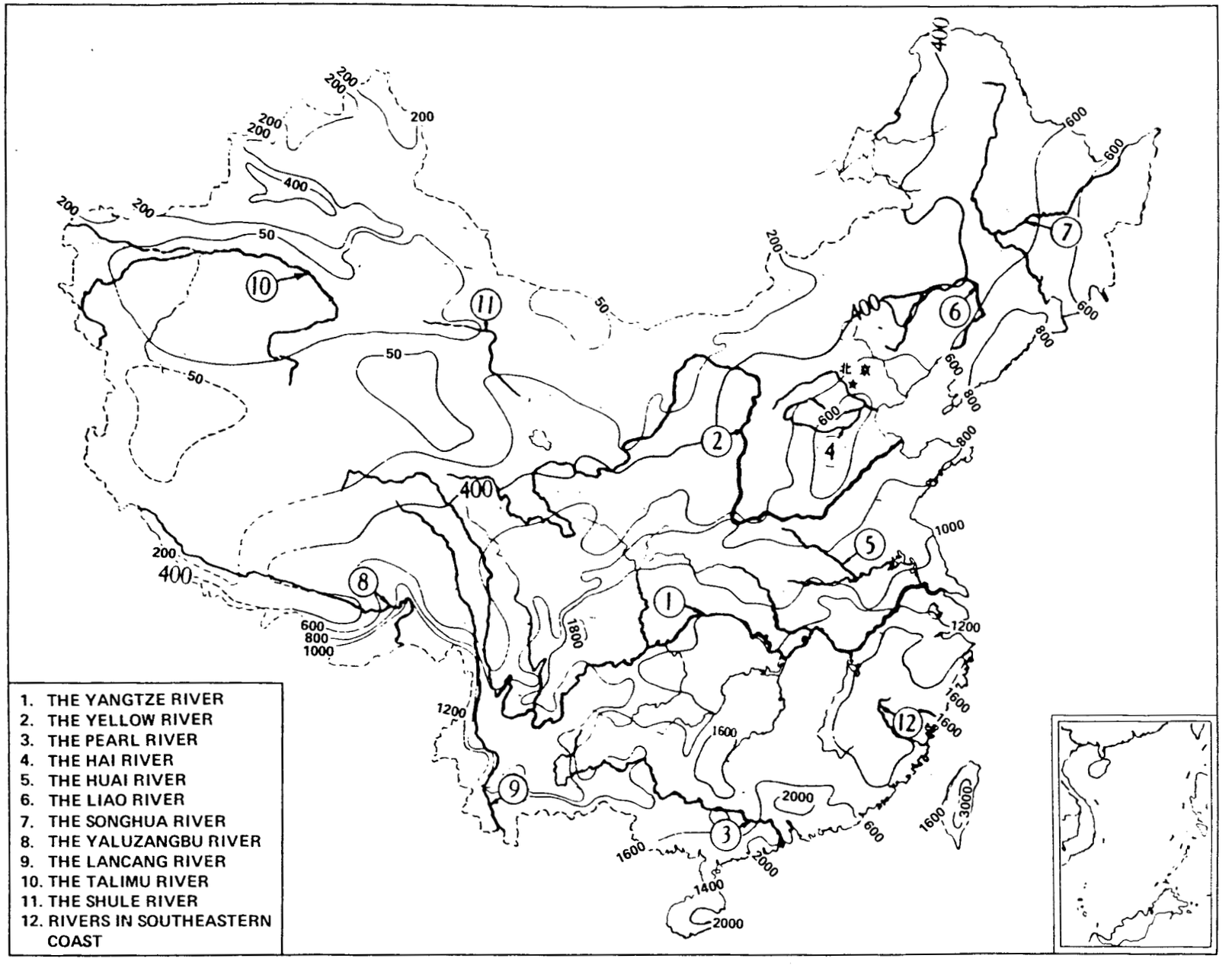

Figure 2. River Systems and Mean Annual Precipitation of China

Table 3. Present State of the Basic Hydrological Network in China (figures as of early 1984)

Types	Stream Gauging Station	Stage Station	Precipitation Gauging Station	Experimental Station
Number	3,396	1,425	16,734	63

Item	Water Level Gauging Station	Discharge Station	Sediment Station	Hydrochemistry Station	Precipitation Station	Evaporation Station
Number	4,821	3,396	1,583	977	20,566	1.431

Note: The numbers of precipitation and evaporation stations do not include meteorological observatories and stations.

We use GMS and NOAA imagery for investigation of flooded areas and cloud cover for:

(i) Rapid mapping of flooded areas and flood hazard (monitoring of flood). Investigations have been made on the flooded areas and flood hazard in the Hefei Region in Anhui Province in 1984 and the Liao River in northeastern China in 1985, by using NOAA-7 satellite imagery.

(ii) Enlarging the cloud atlas, and classifying clouds into 16 different types, according to different gray scales (later checked by ground truth). These are correlated with the rainfall depth contour. We are very interested in rainfall estimates from IR histograms of geostationary satellite observations.

Scientists and engineers of water resources and electric power of China are fully aware of the urgency of finding solutions for the above problems and of the necessity of employing the latest, most satisfactory and most effective techniques. We must learn the advanced science and technology from other countries.

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RAIN GAUGE NETWORK IN INDIA

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1. INTRODUCTION

For meteorological homogeneity, India is divided into 35 meteorological subdivisions. The mainstay of the Indian economy is agriculture. India is influenced by two monsoons, namely the southwest or summer monsoon and northeast monsoon. Of these, the southwest monsoon is important since most regions of the country receive their maximum rainfall during this season. In its 120-day duration, the summer monsoon influences the entire country while the northeast monsoon affects only the southern portions of India. Northwest India also receives rain and snow during the winter months. Tropical cyclones affect India during the months of April-May and October-November.

Since over most of the regions the crops are fed by rain, the success or failure of the summer monsoon spells prosperity or disaster for the Indian population. It is therefore imperative that the rainfall distribution needs to be monitored closely.

2. NETWORK OF RAIN GAUGES

Meteorological observatories in India are classified into six classes, depending on the number of instruments provided, the types of observation required to be taken, and the frequency of such observations.

The India Meteorological Department maintains 560 rain gauge stations. In addition, rain gauges are maintained by different authorities like states, agricultural institutions, etc.

3. MODE OF COLLECTION

All of the rainfall data are transmitted either by telephone, (wherever they exist), telegram or radio-telephone. Certain categories of stations do not send their reports on a real-time basis but do so on a weekly or monthly basis.

4. ARCHIVING

Rainfall data are archived on magnetic tapes in the India Meteorological Department.

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CLOUD AND RAINFALL OBSERVATIONS IN ISRAEL

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1. INTRODUCTION

Israel is located between latitudes 28°30'N and 33°30'N. Its northern parts, north of latitude 31°30', have a rainfall regime which is subtropical in nature. It is sometimes defined as "Mediterranean", since its moderate seasonal rainfall amounts occur primarily in wintertime, i.e., during the period October - April (see Figures 1 and 2).

The primary observational network of rainfall stations has been organized and maintained since 1948 by the Israel Meteorological Service of the Israel Ministry of Transport. Being the national and official organizational framework for all meteorological services, it has collected, checked and archived all available rainfall data to form a most efficient, fully computerized rainfall data center. Daily rainfall amounts are now available from as early as the late 1800's. In fact, there is now a unique and continuous daily rainfall record for Jerusalem which has its beginning in 1860.

Following the initiation of the Israeli Rainfall Enhancement Project in 1960, additional rainfall and cloud observational facilities have been established. These comprise two fully computerized radar systems (one of which is mobile), a dense network of recording raingauges, and a recently established geostationary satellite receiving facility. All later systems are operated and maintained by Israel's National Water Company (Mekorot) and the Department of Atmospheric Sciences of the Hebrew University of Jerusalem.

2. PRESENT STATUS OF RAINFALL DATA IN ISRAEL

Figure 3, which is a reproduction of an official Meteorological Services map, depicts the distribution of over 650 daily read rainfall stations. The average spacing between stations is about 20 km. Figure 3 also outlines the area covered by the C-band 250 kw peak power radar located at Ben-Gurion airport in central Israel.

Gagin et. al., (1985) described a technique which identifies and tracks individual rain cells which compose the above mentioned cloud rain producing systems. The gross rainfall properties of rain cells, such as their maximum rain areas, intensities (or reflectivities), their durations as precipitating entities and the total rainfall they produce during their total lifetime as they grow, have been found to be correlated with the maximum heights attained by these rain cells. Figure 4 depicts this relationship for Israel's rain cells. Similar ralationships have been established by Rosenfeld (1986) for northern Texas, Bethlehem, south Africa, and central Illinois. Gagin et. al. (1985) have also obtained these relationships for south Florida.

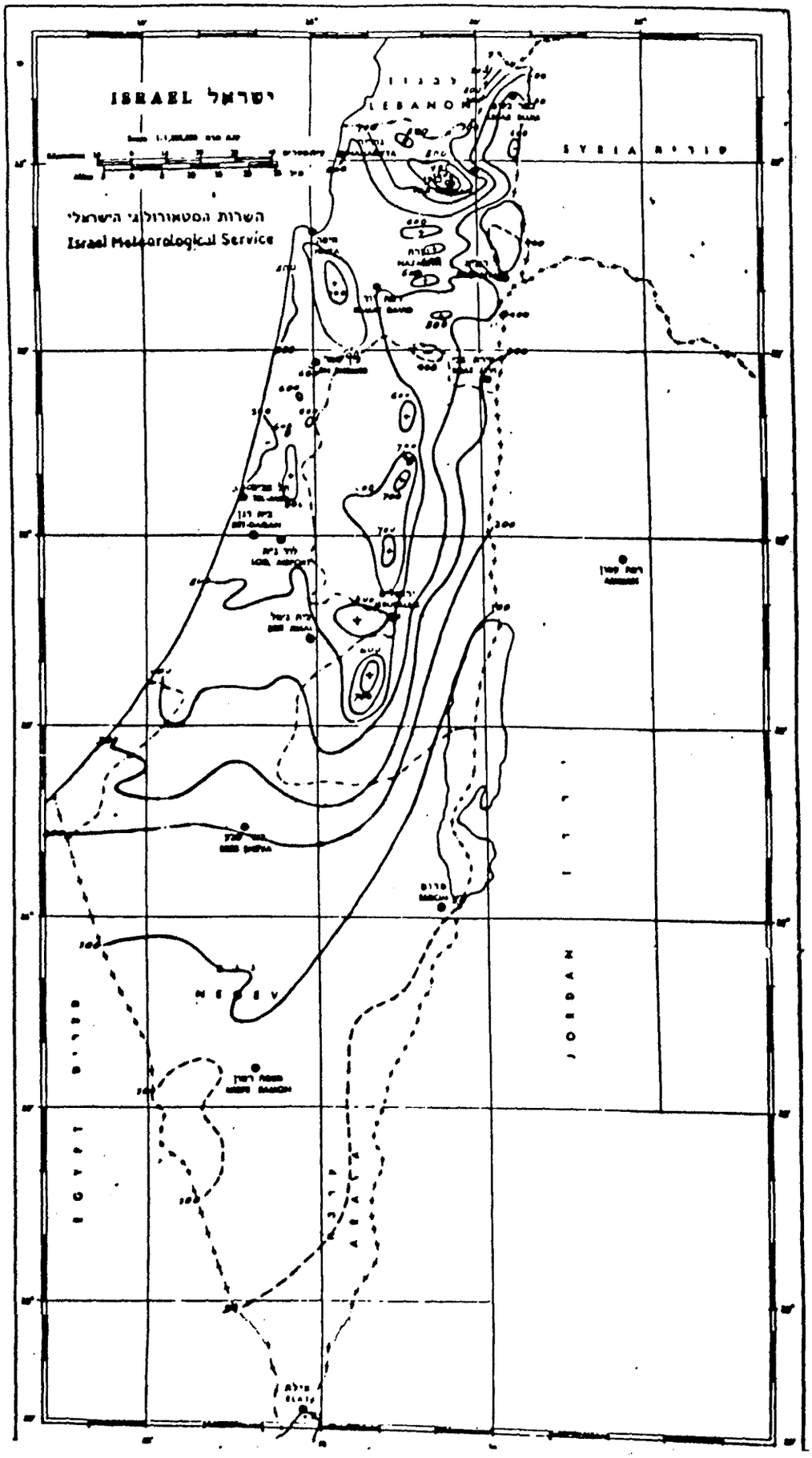

Figure 1. Average Annual Rainfall Amounts (mm) (1951-1960)

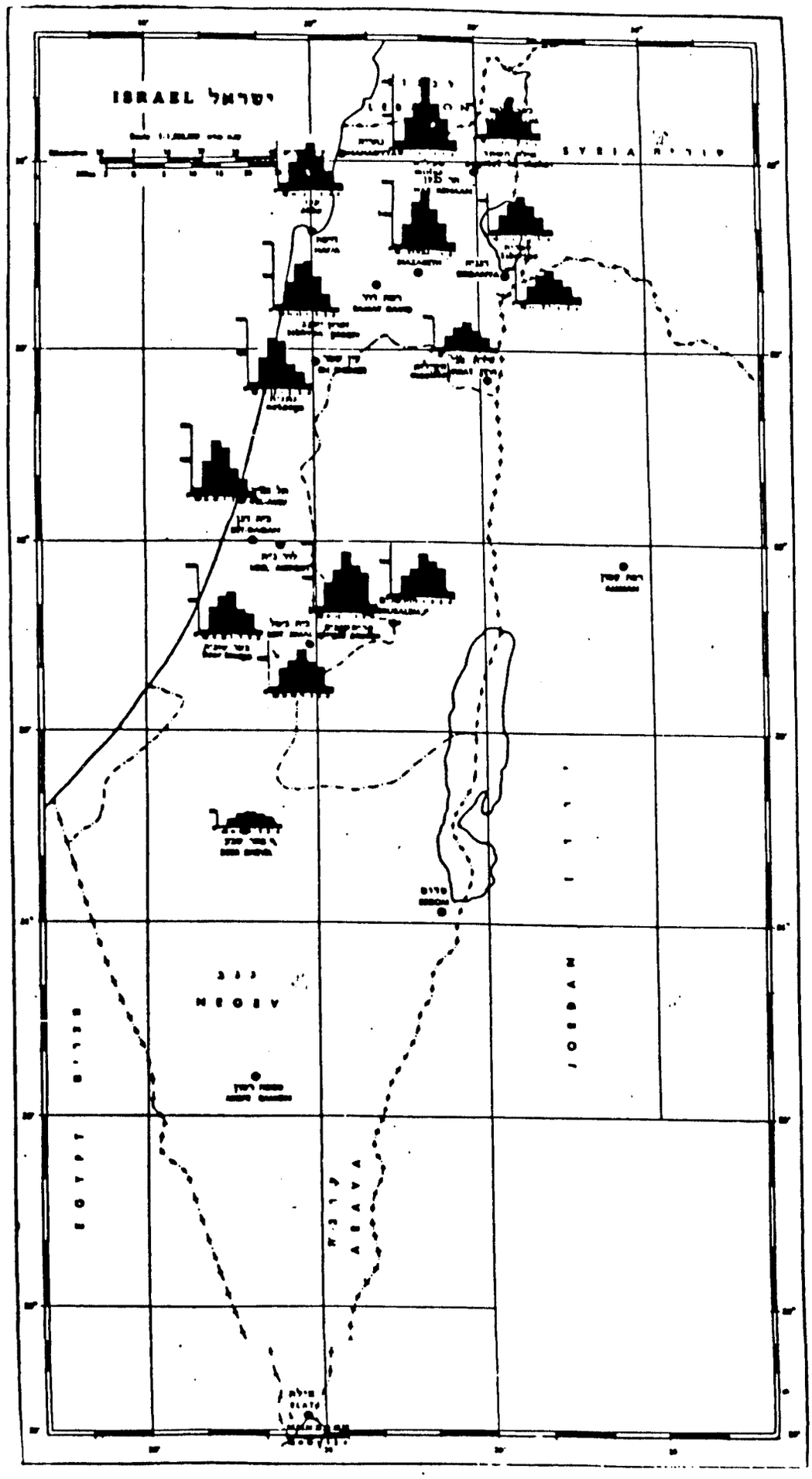

Figure 2. Average Monthly Rainfall Amounts (mm) (1951-1960)

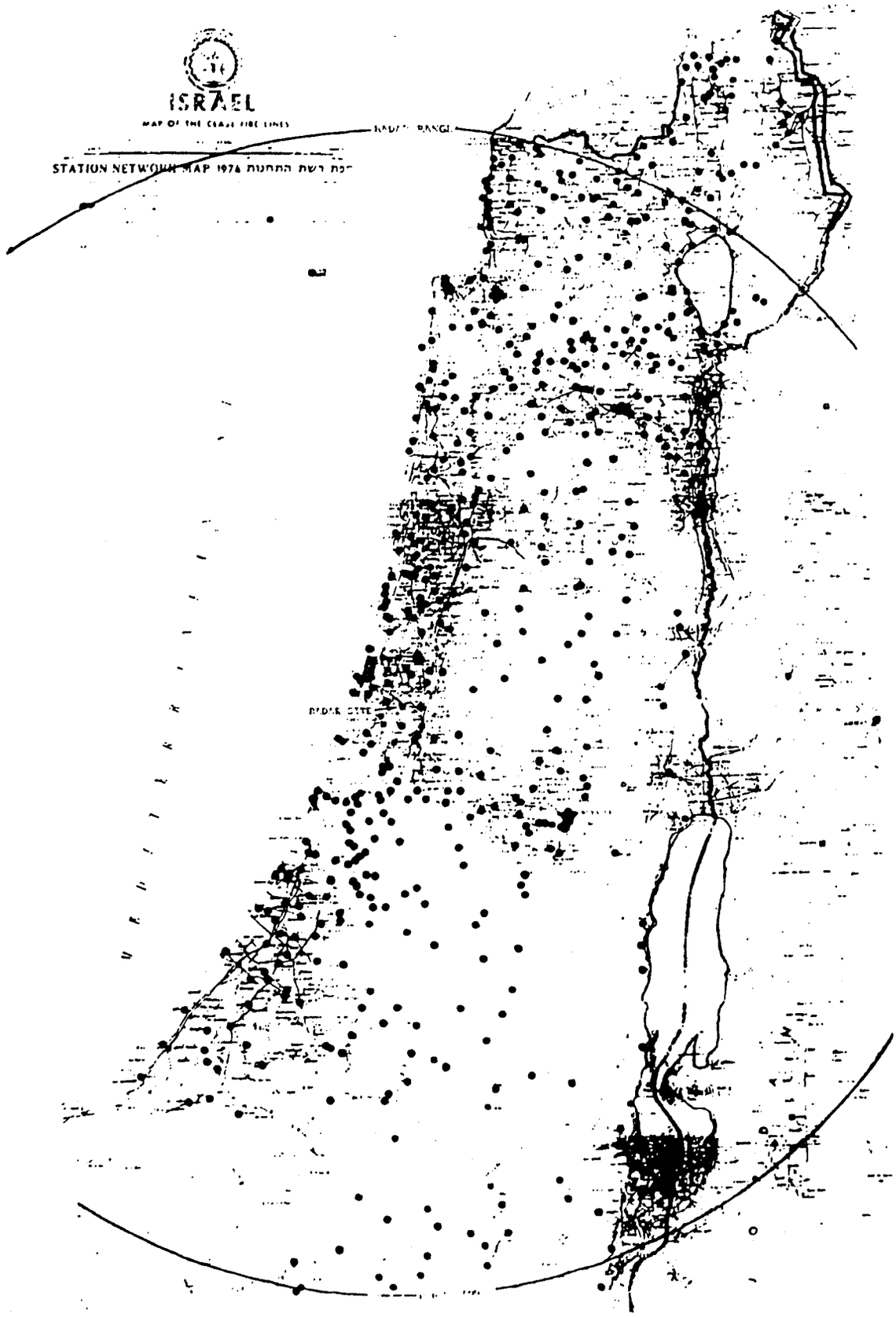

Figure 3. The Distribution of Daily Measuring Rain Gauges in Israel

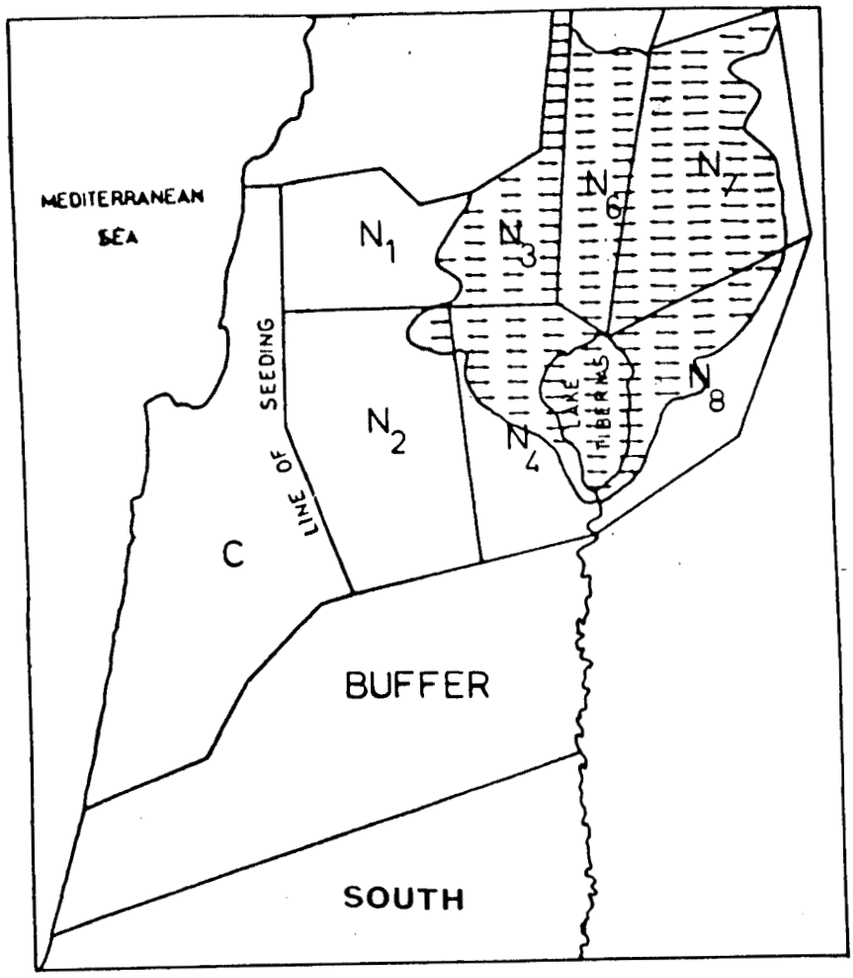

Figure 4. Map Showing the Areas and Sub-areas of the Israeli Experiment II (1969-1975). Hatched Area Defines the Lake Kinneret (Tiberias) Catchment.

2.1 Satellite Data

A study is underway now in which an attempt has been made to relate echo top temperatures, measured by radar and radiosonde, to cloud top temperatures obtained from Meteosat geostationary satellite data. This study is the first step in a series of studies aimed at obtaining estimates of rainfall over the eastern Mediterranean. Figure 5 depicts the relationship between the mean daily echo-top height and temperature distributions and daily rainfall over Northern Israel. Such radar data together with satellite derived cloud top height coverage and relationships of the type given in Figure 6 are expected to provide some estimate of rainfall over the eastern Mediterranean basin.

2.2 Rain Gauge Data

Data collected by the Meteorological Service are carefully checked, digitized and stored on magnetic tapes. Routine procedures for data quality control result in a delay of a few months of the availability of the full data

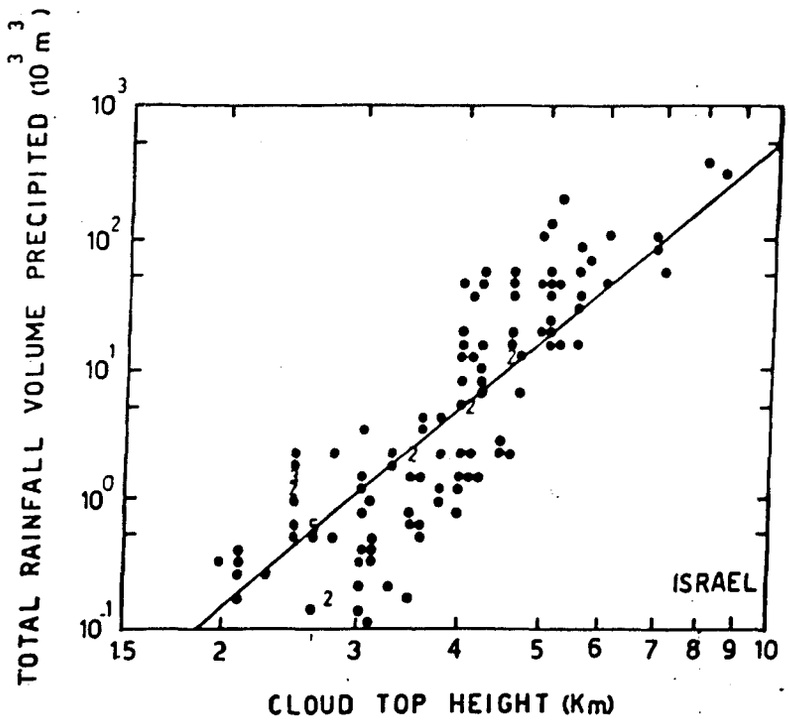

Figure 5. The Dependence of the Total Rain Volume, Precipitated by Rain Cells over Israel, on their Maximum Echo-Top Height.

base for the totality of Israel. A smaller fraction of the total number of stations is of immediate availability.

Since most of the rainfall occurring in Israel is associated with the passage of surface low pressure systems, accompanied by upper-air troughs, it has been shown by Gagin and Neumann (1981) that area rainfall correlations are exceptionally high. Gagin (1981) has attributed this to the fact that the rain-bearing cloud systems in Israel are predominately those of convective clouds organized in bands or lines forming in the cold sectors of low pressure systems.

Table 1 gives the correlation coefficients between the various sub-areas defined in Figure 4. The rainfall means of these sub-areas, as given in Gagin and Neumann (1981), have been found to be practically the same if calculated from a data base of 10 rainfall stations per sub-area, or from all available stations for this sub-area.

2.3 Radar Data

The C-band, fully-computerized radar, located at Ben-Gurion International Airport, is operated continuously on a 24-hour basis as long as there is any rain cloud within the range of the radar. The operational mode is that of volume scan (1° elevation steps up to 21° above the horizon). Real time display of echo-top heights and reflectivity, within the 125 km range of the radar, is given every five minutes.

Two tape drives record the output digital data. One records the raw data directly from the digitizer while the other records the data in a compressed form after processing by the computer. Extensive work has been

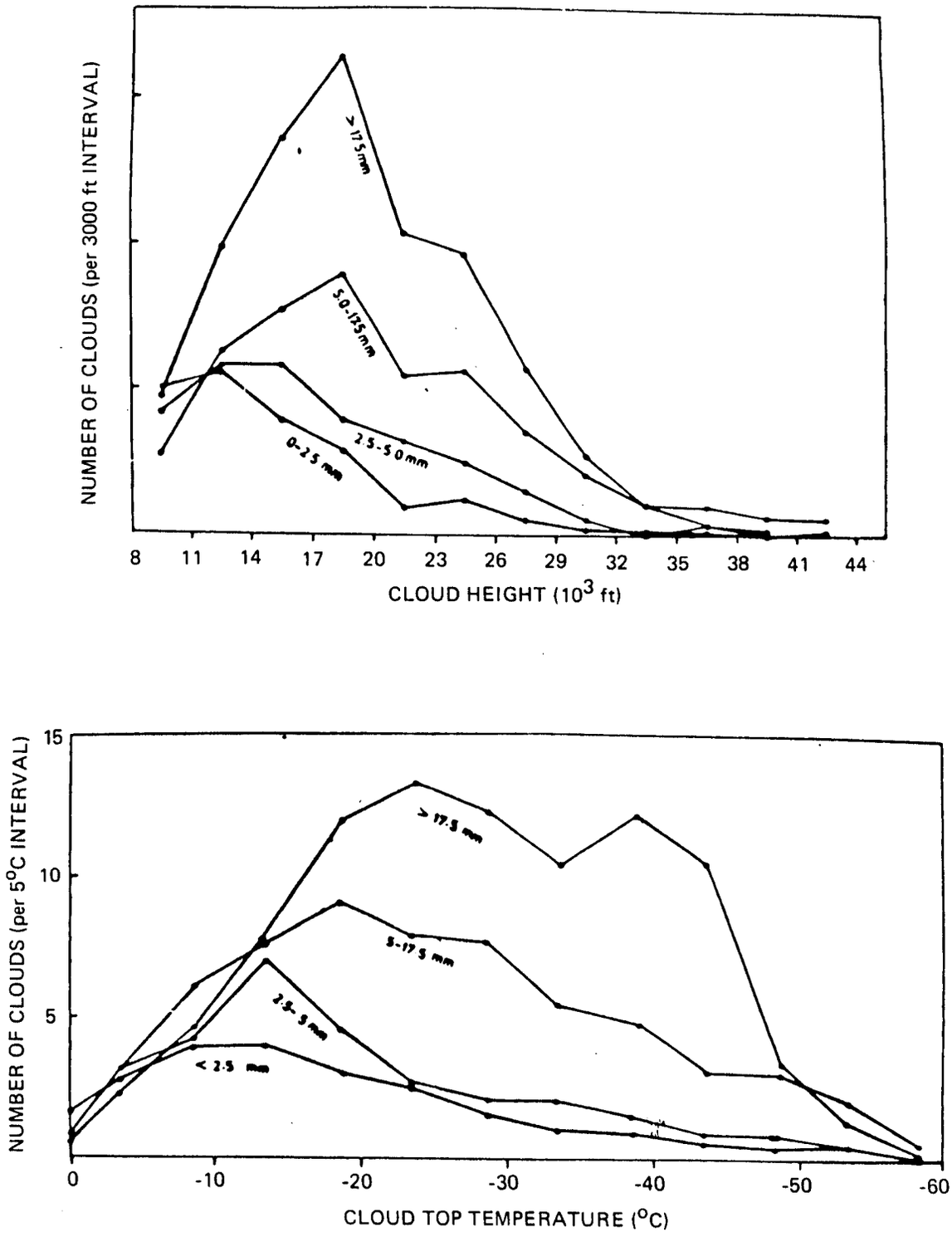

Figure 6. Frequency Distributions of Cloud Top Heights and Temperatures on Days with Different Amounts of Rainfall.

Table 1. Correlation of Daily Precipitation in Different Areas and Sub-areas

AREA	NORTH	LKC*	N1	N2	N3	N4	N6	N7	N8	CONTROL	BUFFER	SOUTH
NORTH TOTAL	1.000	.9815	.9438	.9460	.9571	.9567	.9183	.8824	.8954	.9066	.8544	.6908
CATCHMENT		1.000	.8991	.8977	.9724	.9332	.9493	.9141	.8891	.8533	.8283	.6595
N1			1.000	.8747	.8945	.8786	.8382	.7826	.8291	.9172	.7811	.6230
N2				1.000	.8670	.9411	.8190	.7929	.8533	.9082	.8736	.7178
N3					1.000	.8966	.9108	.8839	.8424	.8380	.7955	.6488
N4						1.000	.8441	.8153	.9042	.8744	.8583	.6702
N6							1.000	.8637	.7967	.7985	.7646	.5835
N7								1.000	.7803	.7298	.7240	.5973
N8									1.000	.8198	.8129	6447
CONTROL										1.000	.8437	.7024
BUFFER											1.000	.8076
SOUTH												1.000

*LKC - abbreviation for Catchment

carried out to establish a Z-R relationship, which, at best gave ± 30 per cent accuracy of point, 24 hour integrated rainfall. The real time software is capable of producing colour display maps of accumulated rainfall for any period of time within the duration of a rainy spell.

3. CONCLUDING REMARKS

We regard participation in the WCRP 10-year project of validating satellite-derived precipitation measurements a unique opportunity to advance our studies of this topic. We will be glad to participate in the exchange of data and techniques.

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PRECIPITATION OBSERVATION NETWORK IN JAPAN

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1. INTRODUCTION

The Japan Meteorological Agency (JMA) has been implementing a National Weather Watch (NWW) project to modernize the JMA weather forecasting and warning system, in order to improve meteorological services. Under this project, two fully-automated precipitation observation networks of rain gauges and radar have been designed and combined to obtain precise precipitation patterns.

The Japanese Islands have been almost completely covered by two different types of precipitation observation networks. One, which consists of surface observation stations, started its operation in 1974. The other, a radar network, was started in 1953. These systems are major tools for observing precipitation phenomena in Japan. The features of these two systems are briefly described in the present paper. The spatial resolution of the precipitation observation networks is:

(i) AMeDAS (Automated Meteorological Data Acquisition System) - about 1300 observation posts to monitor amount of precipitation (average spacing 17 km) and about 840 observation posts to observe surface wind, temperature and sunshine (average spacing 21 km).

(ii) Weather radar network - 20 sites (average spacing about 300 km).

2. PRESENT STATUS

2.1 AMeDAS

This system consists of the automated operation center (AMeDAS center) and automatic observation posts installed all over Japan and linked through commercial telephone lines. An overall schematic representation of the AMeDAS system is presented in Figure 1. The AMeDAS center automatically calls all weather observation posts every hour and collects data from each. Data collection and dissemination are completed within 20 minutes. Figure 2 shows the observation posts of the AMeDAS network of Japan. At the time of the collection, these data have been received by the Center's on-line computer, which checks whether or not the data are correct and then stores them in the Center's data files.

The voluminous amounts of meteorological data gathered by the Center's on-line computer are processed via batch operations by another off-line computer for the preparation of various types of meteorological statistics. These statistics are then compiled into daily, bi-weekly, monthly and yearly reports respectively. They are stored on magnetic tape on a monthly basis. These data are used by JMA for climatic analysis and also loaned out to interested organizations for research purposes.

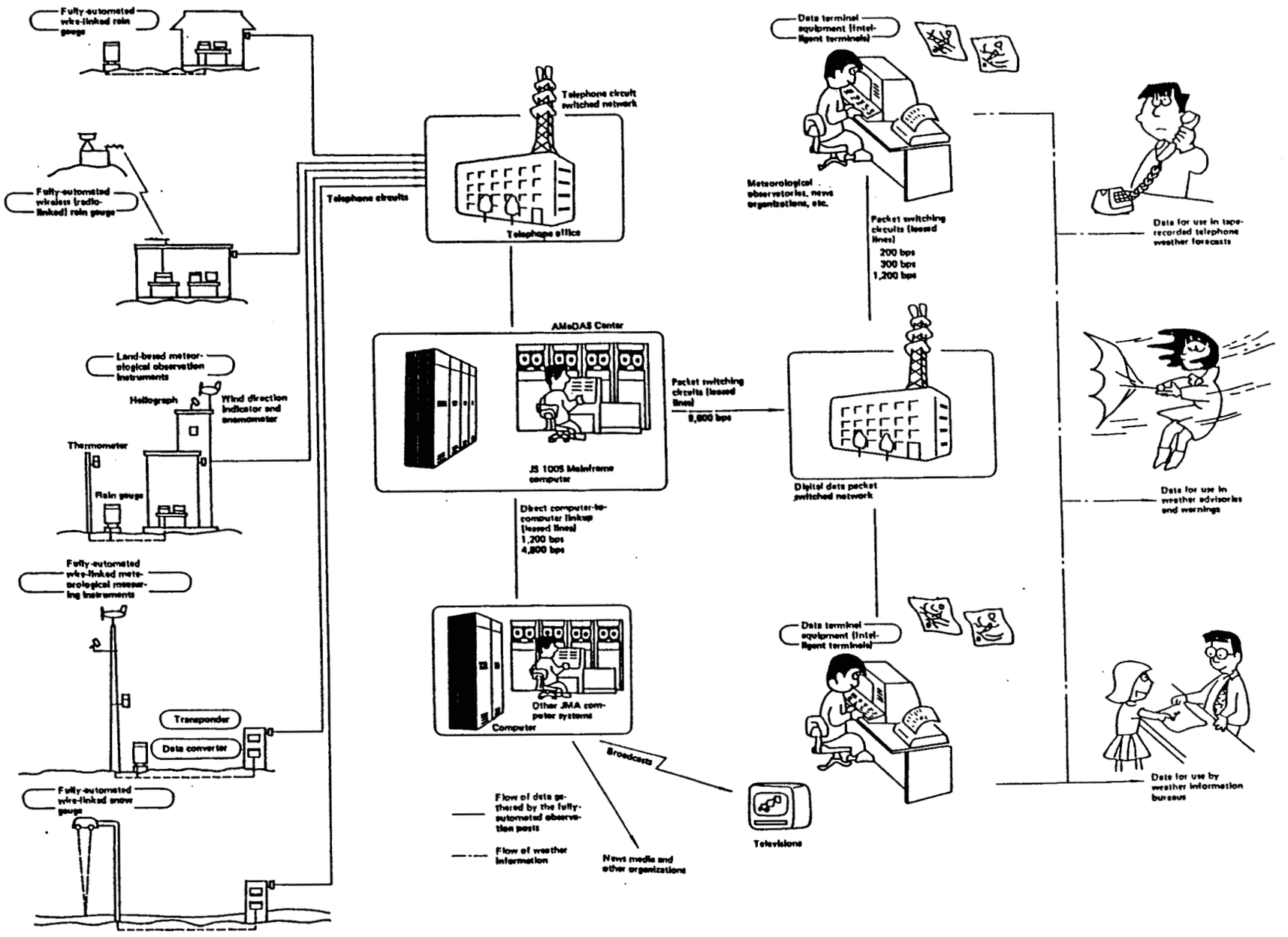

Figure 1. Schematic Representation of the AMeDAS System

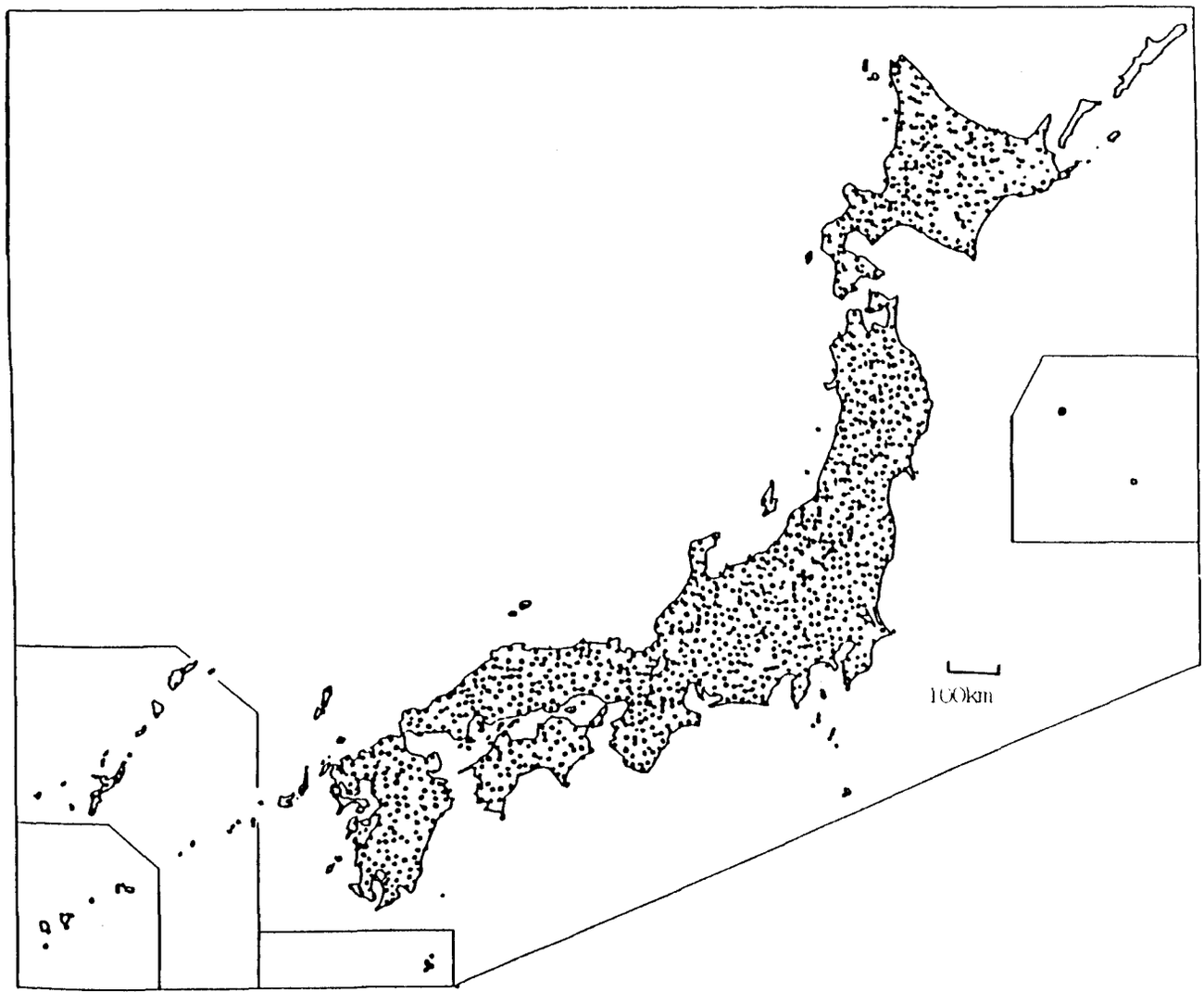

Figure 2. AMeDAS Network of JMA

2.2 Radar Network

The radar observation network in JMA consists of 20 radar observatories (all are 5 cm wavelength radars, except Fujisan which is 10 cm) and covers nearly the entire Japanese Archipelago. An overall radar observation network is presented in Figure 3.

Before the National Weather Watch project was implemented, radar observations had been made by expert meteorologists who sketched radar echoes on a tracing sheet covering the radar scope, and these sketched echo maps were then disseminated to users at forecast centers through telefax. Since 1980, JMA has installed an automatic data processing system, called REDIS (Radar Echo Digitizing and Disseminating System), to conventional radar systems which had already been in operation. Eight weather radars have already been equipped with REDIS. Two more are to be automated by March 1987.

An overall schematic representation of REDIS is presented in Figure 4. The main features of REDIS are as follows:

(i) Suppression of ground clutter with MTI.

(ii) Digitization of echo patterns from PPI scans at three different elevation angles, eight times an hour, and derivation of an approximately constant-altitude PPI (CAPPI) echo pattern from them (2000m above sea level).

(iii) Integration of the above CAPPI echo patterns over periods of one hour, which represent hourly precipitation amounts from radar information.

(iv) Digitization of echo patterns from PPI scans at 10 elevation angles, once every hour, and calculation of echo top height.

(v) Hourly telecommunication of the data from (ii), (iii) and (iv), with a spatial resolution of 5 km, to the high-speed computer at JMA for use in data processing.

(vi) Dissemination of color graphics display to appropriate regional forecast centers for operational weather watch.

2.3 Composite Map Of Precipitation Of Weather Radar Data and AMeDAS Data

In 1983, JMA developed a scheme for combining radar and rain gauge data. Under the NWW project, automation of radar observations has been promoted and information obtained by the AMeDAS network has become available to the JMA processing center after the direct linkage of the AMeDAS center to the JMA telecommunication center. As a result, composition of radar observation with rainfall data of AMeDAS has been realized. This composite map, RAAMAP (composite Radar-AMeDAS precipitation map), contributes to severe weather watch by presenting detailed precipitation features. The RAAMAP is better than either the individual information from AMeDAS or radar in the detection of precipitation. The composition scheme is as follows:

(i) Estimation of precipitation amount by compositing individual radar images.

(ii) Correction of the radar data using statistical calibration data between radar precipitation information and rain gauge information, taking into consideration the individual radar observational performance. (Calibration data represent overall effects of observational errors such as beam blocking by mountains, incomplete beam filling, etc. Effects of difference of rainfall types by seasons are also included in the calibration data. Utilization of statistical calibration values are also effective in arriving at stable results, especially in surface data sparse areas such as in mountainous areas or over seas.)

(iii) Correction of precipitation amounts, estimated by (i) and (ii), using hourly AMeDAS data.

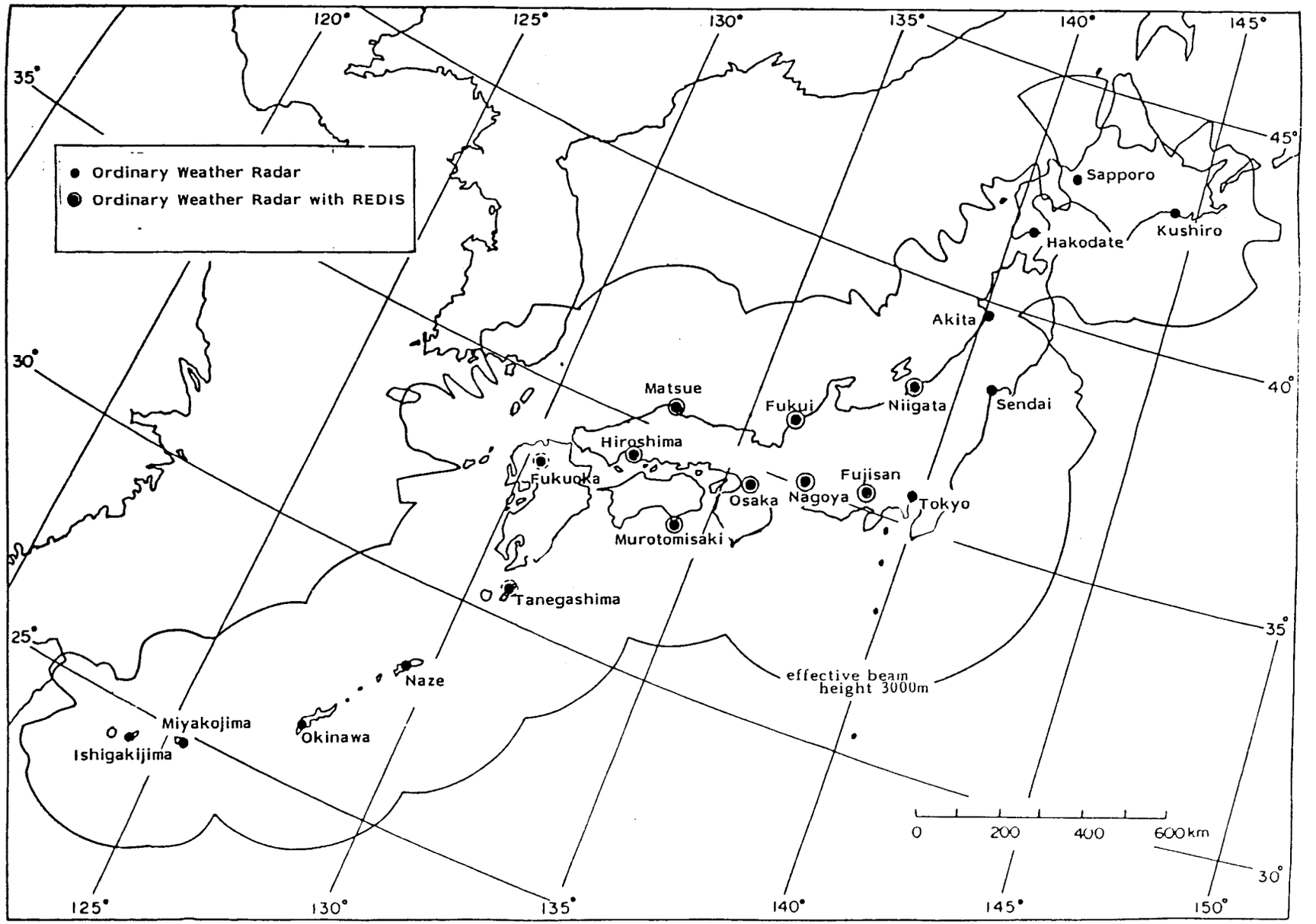

Figure 3. Weather Radar Network of JMA

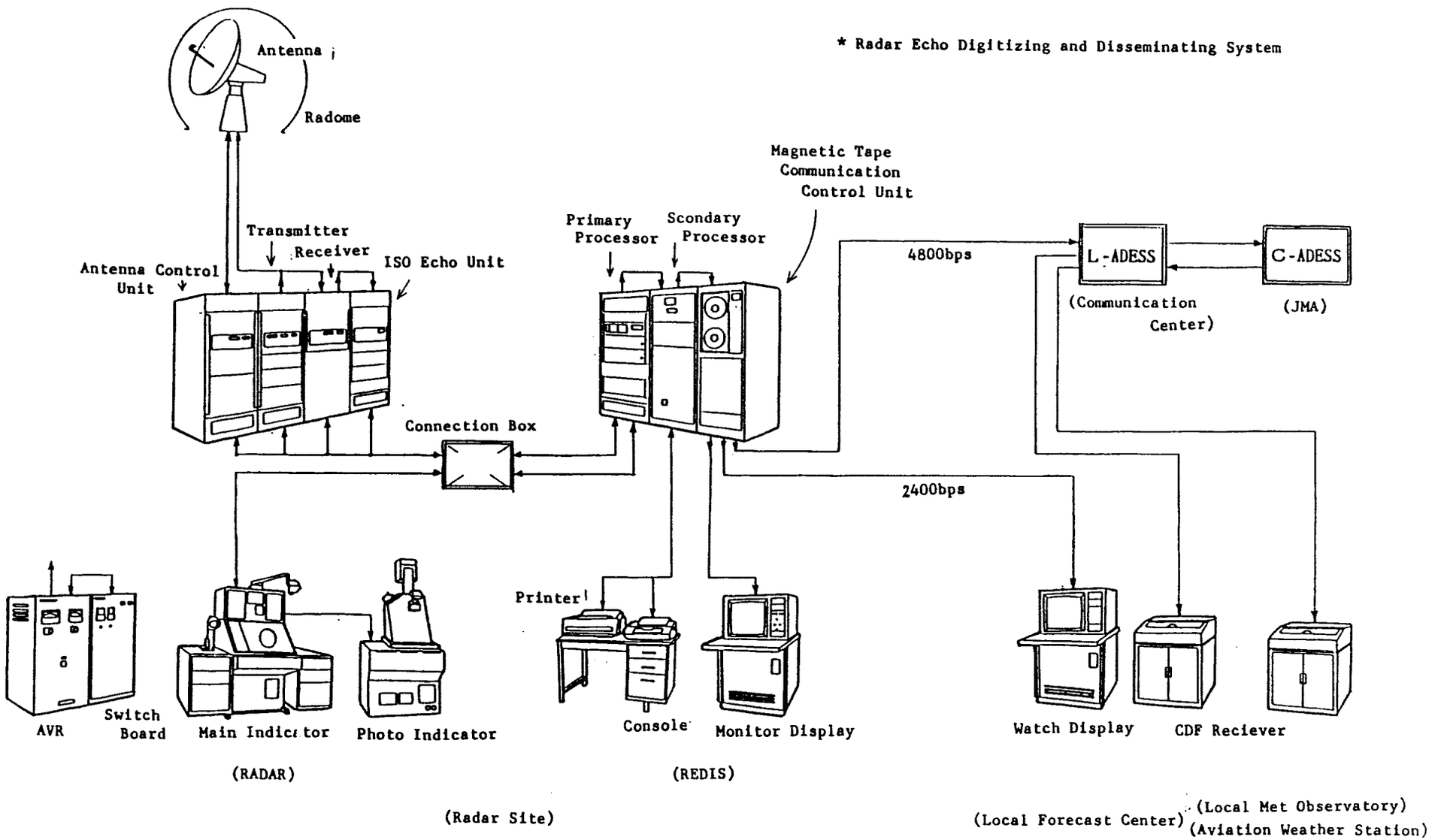

Figure 4. System Diagram of Weather Radar and REDIS

Precipitation information determined by the above procedure, is disseminated in facsimile format at present and utilization of original grid point values in forecast offices is planned. Figure 5 shows an example of RAAMAP.

3. FUTURE PLANS

Automation of radar observation will continue to be promoted to cover all over Japan. In the JMA radar network, eleven radar stations have not been equipped with REDIS. These will be equipped in the near future.

A radar on a ship is one of the most powerful tools to observe the amount of rainfall over the ocean. Two of the meteorological observing ships of the JMA, the Ryofu-maru and Keifu-maru, are equipped with weather radars. However, the observations are made by manually sketching echoes, so these ship-borne radars will have to be equipped with digitizing equipment in the near future.

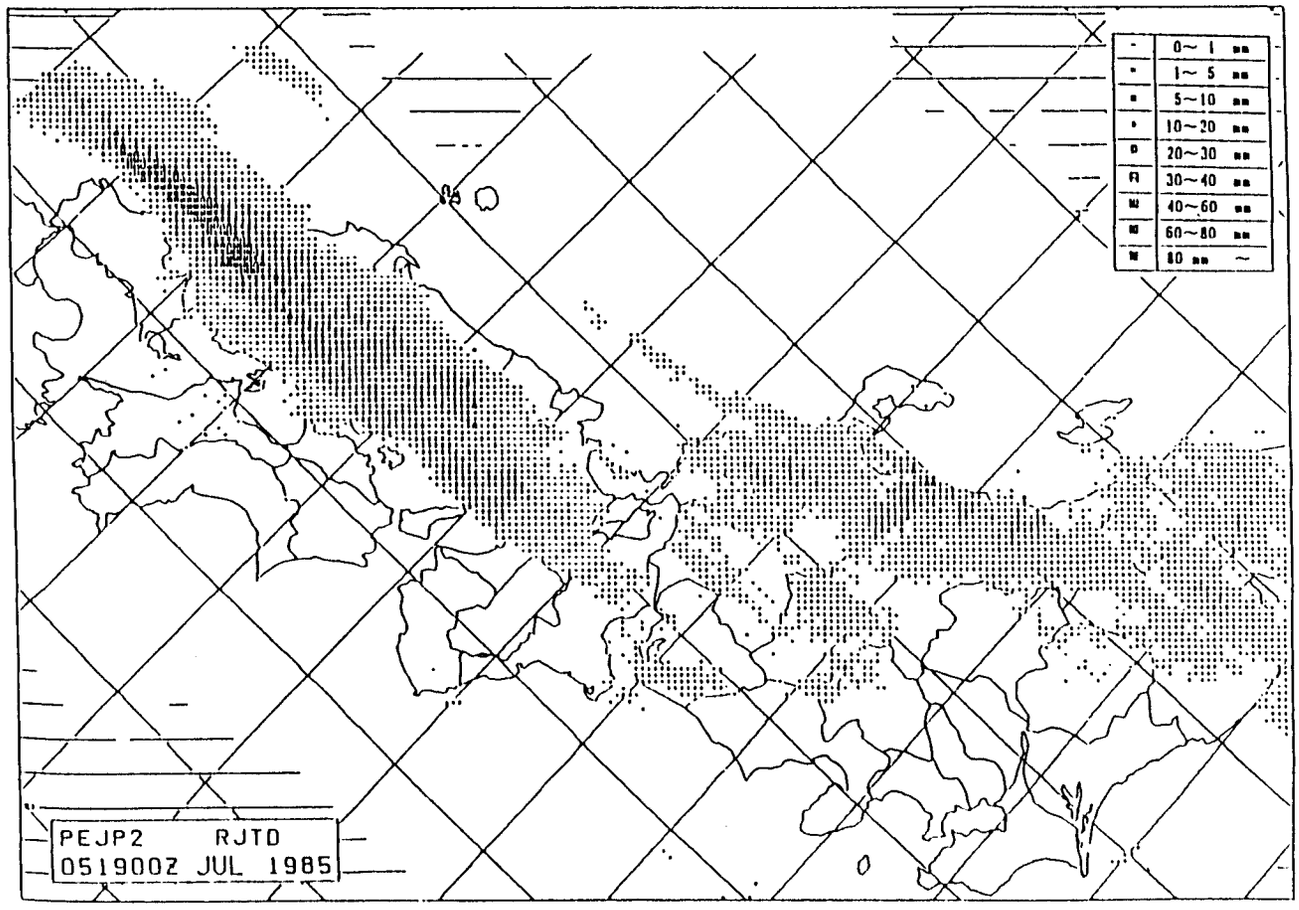

Figure 5. An Example of RAAMAP (Radar-AMeDAS Precipitation Map)

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RAINFALL MEASUREMENTS IN KENYA

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1. INTRODUCTION

The climatic factor of greatest economic significance in Kenya is rainfall. Thus, efforts have been made to measure rainfall at a large number of sites (about 1700 rain gauges altogether). The majority of these rain gauges are operated by volunteers and record only total daily rainfall amounts. For certain studies there is a need to know the hourly rainfall totals, rainfall intensities or even the number of showers in a day and these can only be obtained from recording rain gauges. The recording rain gauges are few in the country (about 30 in number). The rainfall stations are relatively fewer in the semiarid and arid regions of the country and this is where we need more rainfall data if we are to extend our arable lands and combat desertification successfully. It is therefore hoped that satellite-derived data will assist in obtaining good temporal and spatial estimates of rainfall in these areas, but these satellite-derived estimates need to be validated using ground truth measurements.

2. RAINFALL DATA

2.1 Measurements Using Ordinary Rain Gauges

Kenya has a dense network of rain gauges of this category. However, only a few stations have operated for a long enough period to give good statistical estimates (e.g., mean, variation studies). Table 1 and Figure 1 give some of the stations in the country with good daily rainfall records. These daily rainfall totals have or are being used in studies of:

(i) Spatial autocorrelations to reveal possible cellular structures in long term rainfall patterns.

(ii) Trends of rainfall in East Africa.

(iii) Regional classification of East African rainfall stations into homogeneous groups using the method of principal component analysis.

(iv) A technique for determining pentad (five-day) rainfall probabilities.

(v) Seasonal droughts in East Africa.

(vi) Determining dates for sowing of cotton through water requirement rainfall model.

(vii) Principal component analysis and factor analysis to give information on the seasonal shift in homogenous rainfall patterns.

Table 1. Selected Rainfall Stations in Kenya

STATION NUMBER	STATION NAME	LOCATION	PERIOD OF RECORD	ELEVATION feet	(metres)
8534000	LOKICHOGGIO (MOGILLA) Police Post	4°15'N 34°21'E	1949 -	3400	
8535000	LOKITAUNG D.O.'s OFFICE	4°15'N 35°45'E	1932 -	2400	
*8635000	LODWAR MET. STN.	3°07'N 35°37'E	1919 -	1660	(506)
8735005	KAPUTIR IRR. SCHEME	2°06'N 35°28'E	1970 -	2300	
8637000	NORTH HORR POLICE POST	3°19'N 37°04'E	1959 -		
8736000	SOUTH HORR CATHOLIC MISSION	2°06'N 36°54'E	1959 -	3600	
8536001	ILLERET POLICE POST	4°19'N 36°14'E	1956 -	1400	
*8639000	MOYALE MET. STN.	3°32'N 39°03'E	1915 -	3650	(1097)
*8641000	MANDERA MET. STN.	3°56'N 41°52'E	1936 -	755	(230)
8938000	GARBA TULLA POLICE STATION	0°32'N 38°31'E	1950	1500	
8740000	EL WAK, MANDERA	2°47'N 40°57'E	1948	1200	
8940003	LIBOI POLICE POST	0°22'N 40°52'E	1960 -	300	
*8737000	MARSABIT MET.	2°19'N 37°59'E	1918 -	4413	(1219)
8739000	BUNA POLICE POST	2°48'N 39°01'E	1959 -	2000	
8834000	SUAM ESTATE, KITALE	1°14'N 34°51'E	1920 -	6180	
8939000	MUDDO GASHI P.P.	0°45'N 39°11'E	1962 -	800	
8835005	KIPKOITET CHERANGANI	1°02'N 35°16'E	1922 -	6300	
8934177	BUKURA INSTITUTE	0°13'N 34°37'E	1977		(1480)
8835036	KITALE, SHIRIKA (THE LEYS)	1°05'N 34°58'E	1926	6100	
8835024	KITALE MET. STN.	01°00'N 35°00'E		6221	
8840000	WAJIR MET. STN.	1°45'N 40°04'E	1917 -		
8934002	BUKURA F.T.C.	0°13'N 34°37'E	1924 -	4800	
8934001	KAKAMEGA D.C.'s OFFICE	0°17'N 34°46'E	1896 -	5100	
8935001	KABNGENDUI KIBET FARM	0°02'N 35°18'E	1914 -	6200	
8935014	TAMBACH D.O.'s OFFICE	0°36'N 35°32'E	1925 -	6000	
8935018	KAPSABET D.C.'s OFFICE	0°12'N 35°06'E	1904 -	6556	
8935020	KABARNET D.O.'s OFFICE	0°30'N 35°45'E	1915 -	6700	
8935086	ELDORET MUNICIPAL COUNCIL	0°31'N 35°16'E	1947-1973	6836	
8935007	ELDAMA RAVINE D.O.'s OFFICE	0°03'N 35°43'E	1903 -	7200	
8936001	RUMURUTI D.O.'s OFFICE	0°16'N 36°34'E	1907 -	6090	
8937000	MERU D.C.'s OFFICE	0°03'N 37°39'E	1910 - 1972	5150	

*Stations with a recording rain gauge.

Table 1. Selected Rainfall Stations in Kenya (Cont'd)

STATION NUMBER	STATION NAME	LOCATION	PERIOD OF RECORD	ELEVATION feet	(metres)
9035069					
8937002	TIMAU MARANIA	0°05'N 37°27'E	1925 -	8450	
8934040	BUTERE HEALTH CENTRE	0°13'N 34°30'E	1939 -	4700	
8937018	MARALAL WAMBA	0°59'N 37°20'E	1938 -	6000	
8836000	MARALAL D.O.'s OFFICE	1°06'N 36°42'E	1935 -	6400	
*8935086	ELDORET MET. STN.	0°31'N 35°17'E		6836	(2084)
8937043	NANYUKI KALALU SFT. FARM	0°05'N 37°10'E	1926 -	6900	
*9034001	KISII DISTRICT OFFICE	0°41'S 34°46'E	1911 -	5800	(1768)
9034004	KISUMU P.C.'s OFFICE	0°06'S 34°45'E	1903 -	3759	
*9034025	KISUMU MET. STN.	0°06'S 34°45'E	1938 -	3795	(1157)
9035000	NJORO OGILGEI FARM	0°18'S 35°57'E	1922	7100	
9035002	LONDIANI FOREST	0°09'S 35°36'E	1908	7600	
9035003	KERICHO D.C.'s OFFICE	0°23'S 35°17'E	1904 -	6500	(1981)
9035013	SOTIK, MONIERI TEA ESTATE	0°39'S 35°04'E	1911 -	5984	
9035018	MOLO STATION	0°15'S 35°44'E	1904 -	8064	
*9035117	ELBURGON, FOREST STN.	0°22'S 35°49'E		8800	(2682)
9337000	TAVETA DISTRICT OFFICE	3°26'S 37°40'E	1905 - 1971	2370	
9337110	TAVETA WATER DEV. STN.	3°24'S 37°40'E	1968 -	2525	
*9035093	MOLO PYRETHRUM EXP. STN.	0°14'S 35°44'E		8200	(2499)
*9338001	VOI MET. STN.	3°24'S 38°34'E	1904	1837	
9393000	MAZERAS STATION	3°58'S 39°33'E	1904	534	
9339004	KILIFI DISTRICT OFFICE	3°38'S 39°51'E	1918	10	
9340000	MALINDI D.O.'s OFFICE	3°13'S 40°07'E	1891 -	10	
*9340009	MALINDI MET.	3°14'S 40°06'E	1961 -	65	(20)
9439001	KWALE AGRIC. DEPT.	4°11'S 39°28'E	1908 -	1294	
*9439002	MOMBASA OLD OBS.	4°04'S 39°41'E	1890 -	53	(16)
*9439021	MOMBASA MOI AIR PORT	4°02'S 39°30'E	1946 -	186	(57)
9439004	GAZI SUGAR WORKS	4°25'S 39°30'E	1912 -	150	
9035028	MAJI MAZURI FOREST STATION	0°01'S 35°42'E	1925 -	7680	
*9035069	EQUATOR CD CULLEN (EQUATOR MET. STN.)	0°00'S 35°33'E	1938 - 1976	9062	(2762)
9035073	RONGAI, GOGAR FARMS	0°11'S 35°51'E	1931 -	6200	
9036002	NAIVASHA DO OFFICE	0°43'S 36°26'E	1910 -		
9036010	SOLAI OL BONATA OL PUNYATA	0°07'S 36°06'E	1915 -	6000	

*Stations with a recording rain gauge.

Table 1. Selected Rainfall Stations in Kenya (Cont'd)

STATION NUMBER	STATION NAME	LOCATION	PERIOD OF RECORD	ELEVATION feet	(metres)
9036017	NYERI M.O.W.	0°25'S 36°57'E	1904 -	6000	
*9036020	NAKURU RALWAYS STN.	0°17'S 36°04'E	1904 -	6024	(1836)
9036025	NORTH KINANGOP FOREST STN.	0°35'S 36°38'E	1915 -	8630	
9136026	ATHI RIVER RAILWAY STN.	1°27'S 36°58'E	1905 -		
9037001	MAKUYU SISAL LTD.	0°54'S 37°11'E	1920 -	4600	
9037007	MURANG'A DC's OFFICE	0°43'S 37°10'E	1901 -	4200	
9037008	EMBU DC'S OFFICE	0°32'S 37°27'E	1908 - 1977	4700	
*9030000	GARISSA MET. OFFICE	0°29'S 39°38'E	1932 -	452	(138)
*9135001	NAROK MET STN.	1°06'S 35°52'E	1913 -	5200	
9136013	NGONG DO's OFFICE	1°22'S 36°39'E	1910 -	6700	
9136015	RIARA COFFEE ESTATE	1°11'S 36°50'E	1920 -	5600	
9136030	NAIROBI KABETE OBSERVATORY	1°16'S 36°45'E		5971	(1820)
9136024	KABETE VET. LAB.	1°16'S 36°44'E	1915 -	6203	
*9136164	DAGORETTI CORNER (MET. STN.)	1°18'S 36°45'E	1954 -	5900	(1798)
9136039	KAJIADO DC's OFFICE	1°50'S 36°48'E	1930 -	5700	(1798)
9136167	MAGADI SODA WORKS LAB.	1°53'S 36°17'E	1925 -	2010	(613)
9137001	KONZA RAILWAY STN.	1°44'S 37°08'E	1915 -	5427	
9137010	MACHAKOS DC's OFFICE	1°31'S 37°16'E	1894	5400	
9138000	KITUI AGRIC OFFICE	1°22'S 38°01'E	1904	3860	
9139000	BURA POLICE STN.	1°06'S 39°57'E	1920	370	
9139001	WAYU CHIEF'S CAMP TANA RIVER	1°32'S 39°34'E	1954	500	
9140005	TANA RIVER IRR. SCHEME	1°31'S 40°00'E	1957	300	
*9237000	MAKINDU MET. STN.	2°17'S 37°50'E	1904 -	3280	(1000)
9237002	KIBWEZI DWA PLANTATIONS	2°24'S 37°59'E	1913 -	3000	
9237004	LOITOKITOK D.O.'s OFFICE	2°56'S 37°30'E	1933 - 1964	6500	
*9240001	LAMU MET. STN.	2°16'S 40°54'E	1906 -	98	(30)

*Stations with a recorded rain gauge.

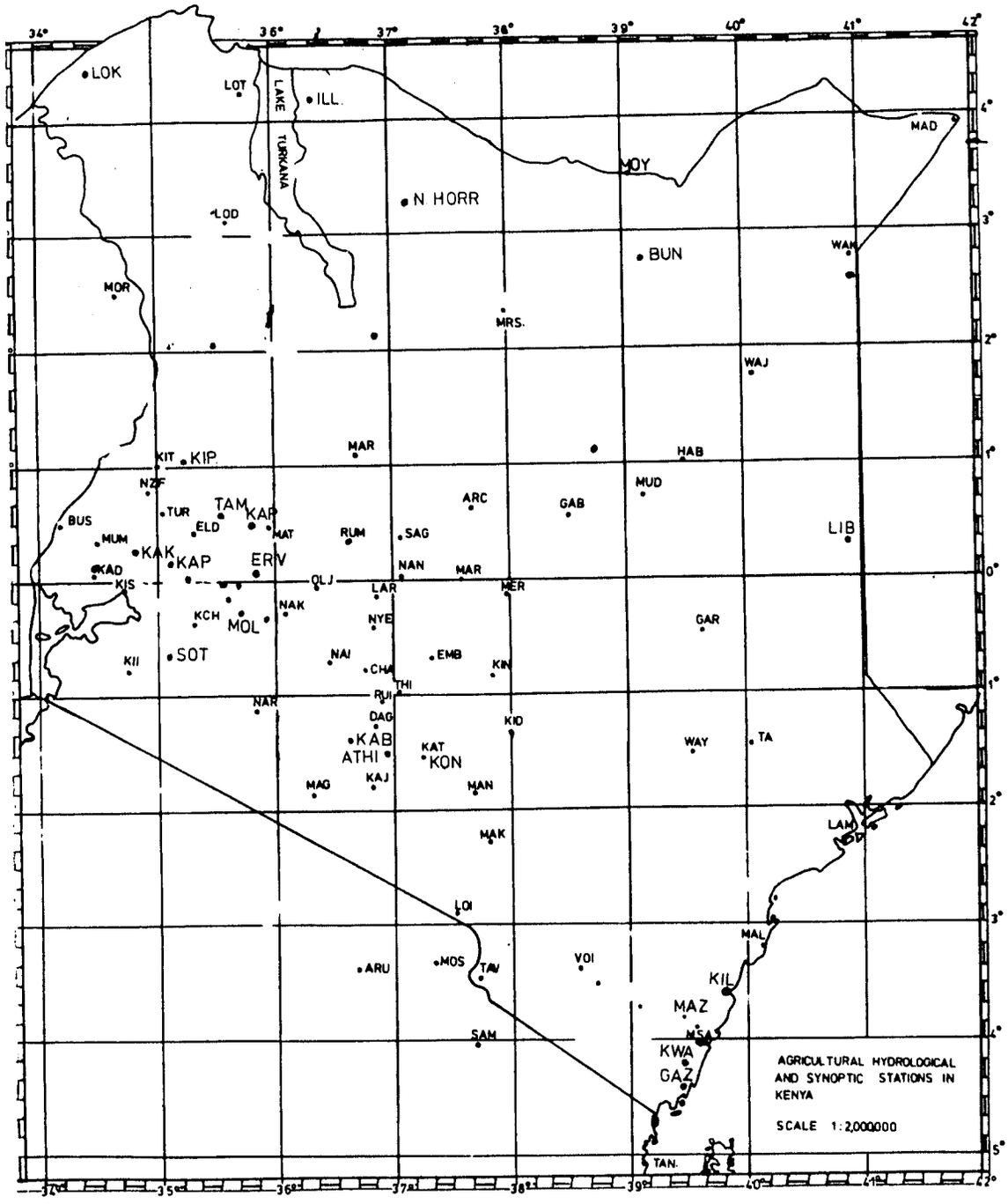

Figure 1. Agricultural Hydrological and Synoptic Stations in Kenya

It is clear that there are relatively fewer stations (Figure 1) in the semi arid/arid regions of Kenya. Also, at many of the stations, we have voluntary observers who are not trained to make these observations. Both of these considerations suggest that satellite-derived daily rainfall totals can be very useful in obtaining better rainfall patterns.

Thus, daily rainfall totals will be correlated with cloud distribution with empirical weights for different cloud types as taken from satellites. This will give a detailed picture of the rainfall pattern for a specific day. However, it has to be done for a number of days, in order to obtain information of a more general character. One problem is that the satellite image represents the situation at a specific time, while the daily sums represent totals over 24 hours. One therefore needs to use satellite images at different times of the day and sum these up, recognizing the strong diurnal variation of precipitation observed in different regions of Kenya. Thus, validation of daily rainfall data derived from satellite estimates relies on empirical relationships derived from fits between weighted cloud type and cloud amount estimates from satellite data and rainfall of nearby ground stations.

2.2 Rainfall Measurement by Recording Rain Gauges

The network of recording rain gauges (about 30 stations) is much too sparse to be used alone. Thus, for homogeneous regions, it is important to correlate rainfall intensity with daily totals. A high correlation will to a great extent improve the accurate interpolation of rainfall intensity. The intensity will also be correlated with data from satellite images noting that high rainfall intensities will come from deep convective clouds which appear "white" on the infrared image of the satellite.

The data from recording rain gauges help us answer the following questions:

(i) How many showers appear on an average day?

(ii) What does an average shower "look like" regarding its time - intensity relationship?

(iii) What is the average duration of an average shower?

(iv) What is the average intensity during a shower and what is the maximum intensity?

Answers to these questions have important applications, for instance in the "erosivity" of a given rainfall intensity. Validation using recording rain gauges will use hourly rainfall data compared with the hourly satellite cloud type and amount data. The hourly RMS difference for hourly mean values are computed. Some studies have been or are being carried out in East Africa using these data:

(i) The diurnal variation of precipitation in East Africa.

(ii) Flash flood studies in the major cities.

(iii) Develop a simple method for rainfall erosivity mapping using Meteosat data.

(iv) Use of visible and infrared satellite images to estimate daily rainfall totals in Kenya.

There is need for further research into the relationships (physical or statistical) between the daily rainfall totals at recording rain gauge sites and cloud amount and type from satellites. These studies will benefit from the use of digital satellite data. These data are easier to handle and enable objective estimates of precipitation to be made. Therefore, there is a need to upgrade the analogue satellite station available in Kenya so that digital values can be received.

3. KENYA'S PARTICIPATION IN THE VALIDATION PROCESS

Kenya already has a lot of daily rainfall data, observed at ordinary rain gauge stations, on magnetic tapes. Kenya also has agreed to host the Drought Monitoring Centre (DMC) for Eastern and Southern Africa. As such, there will be, in time, more data coming to this Centre from within the region. These data will give the mean rainfall state and its temporal variations (mean and standard deviation). Studies using recording rain gauges will assist in finding rainfall intensities and the numbers of showers on a given day, and these results will assist in mapping fields of rainfall intensity, which should be useful in rainfall erosivity studies. It is noted that some of these programmes are of immense economic value to Kenya. Kenya would therefore be interested in research efforts whose object would be to develop methods of determining daily rainfall totals and rainfall intensities over defined regions in the country.

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RAINFALL NETWORK IN TANZANIA

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1. INTRODUCTION

Rainfall in Tanzania varies from place to place due to different physical features found in the country. In coastal areas of the Indian Ocean, annual rainfall is about 1,000 mm. In regions surrounding the mountains, annual rainfall is about 1,500 mm. Over Lake Victoria, especially on the west side of the lake, annual rainfall is more than 2,000 mm. Over the interior, rainfall ranges between 500 mm to 1,000 mm. North coastal, north and northwestern areas experience two rainfall seasons, i.e., March to May and October to December. Southern regions of the country have a single rainfall season from November to April.

2. RAINFALL NETWORK

At the present time, there are about 1,500 active rainfall stations in Tanzania. Most of these are 24-hour rainfall stations and are operated by voluntary observers. The rainfall data from these stations are sent through the Post Office to the headquarters of the Meteorological Department for quality control and archiving at the end of each month. About 50 stations have rainfall recorders and these are operated directly by the Meteorological and Water Departments. Figure 1 shows some of the rainfall stations and most of these have a standard rain gauge as well as a recorder rain gauge.

Tanzania has the following 21 synoptic stations: Dar es Salaam, Zanzibar, Pemba, Tange, Mtwara, Lindi, Songea, Morogoro, Iringa, Mbeya, Same, Moshi, Kilimanjaro Airport, Arusha, Shinyanga, Dodoma, Talsora, Kigoma, Mwanza, Musoma, Bukoba. Rainfall data from synoptic stations are transmitted to Dar es Salaam (the headquarters of the Directorate of Meteorology) by telephone and radio-telephone. The rainfall data are in manuscript form, but the program of putting this data on magnetic tape and diskettes has recently been started.

3. SATELLITE GROUND STATION

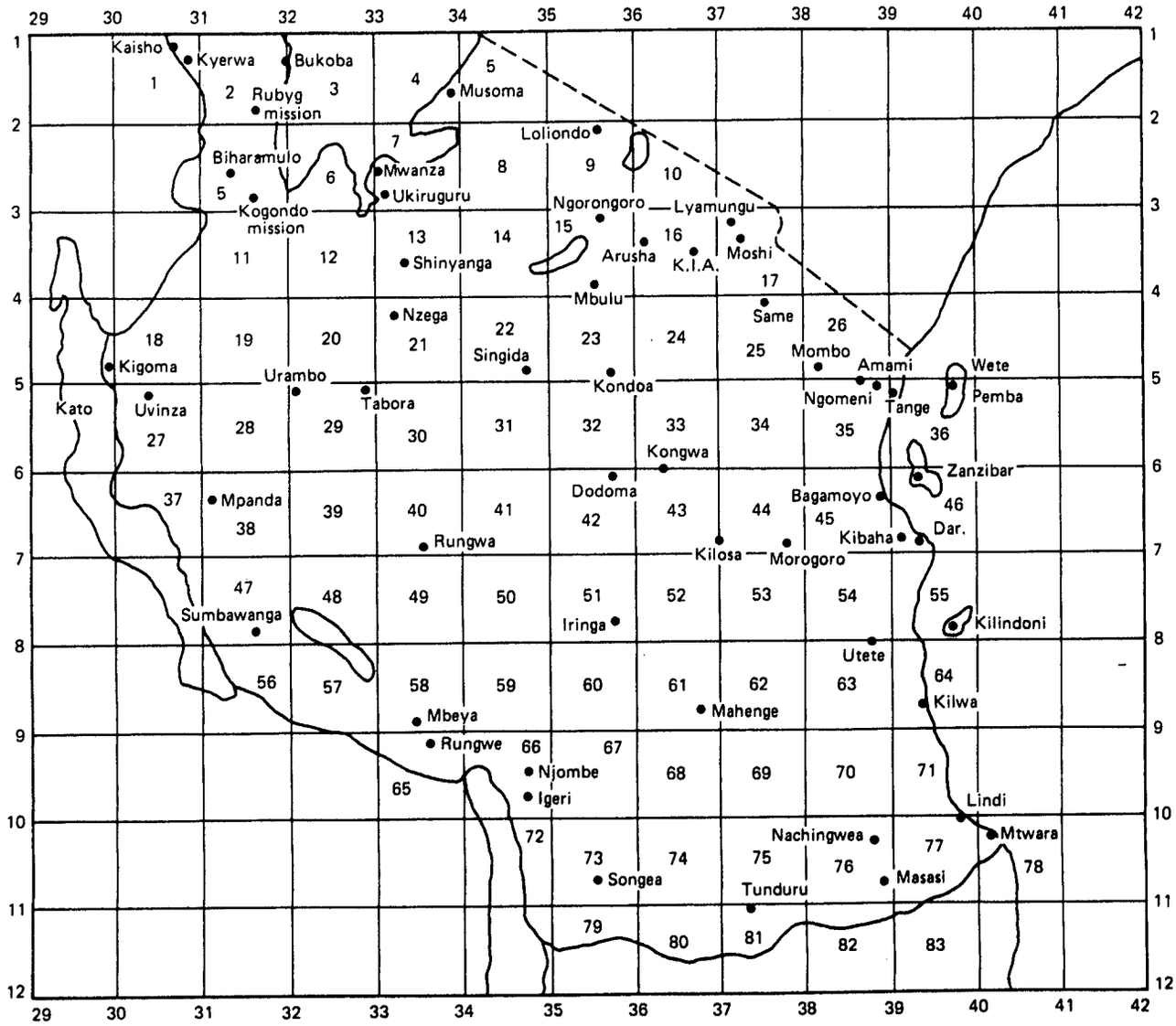
There is an APT/WEFAX ground station located at Dar es Salaam, which receives analogue pictures from NOAA and METEOSAT satellites.

4. RADARS

There are two radar stations, one located at Dar es Salaam and the other at Kilimanjaro International Airport. They are Plessey, 10 cm radars. The two radars are not working because of technical problems.

5. VALIDATION/CALIBRATION OF SATELLITE-DERIVED RAINFALL DATA

At the present time, there is no on-going hydrological or meteorological program of validation of satellite-derived rainfall data. This is because there is no facility for obtaining digital rainfall data from satellites. Tanzania is willing to participate in this program of validation if satellite-derived monthly estimates of rainfall could be received.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K.I.A.
Moshi
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Mbulu
Same
Nzega
Singida
Mombo
Amami
Wete
Pemba
Kigoma
Urambo
Kondoa
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Uvinza
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Dodoma
Bagamoyo
Mpanda
Kibaha
Dar.
Rungwa
Kilosa
Morogoro
Sumbawanga
Iringa
Kilindoni
Utete
Kilwa
Mbeya
Mahenge
Rungwe
Njombe
Igeri
Lindi
Mtwara
Nachingwea
Songea
Masasi
Tunduru

Figure 1

RAINFALL MEASUREMENTS IN THAILAND

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1. INTRODUCTION

Thailand, with an area of 514,000 km^2 (see figure 1), is a member of the World Meteorological Organization (WMO) and the methods of weather observations follow the regulations of WMO. Most of the precipitation that occurs in Thailand is of the convective type from the ITCZ and the southwest monsoon. Each year 2-3 tropical cyclones, in the form of weak depressions, move over the country and cause flooding.

2. DAILY RAINFALL NETWORK

Forty-six recording rain gauge stations that can be used as ground truth for the validation project are listed in Table 1. Rainfall data at these synoptic stations have been recorded for a long period of time and are reliable for the most part. Daily rainfall totals are collected and transmitted shortly after the observation time at 0700 LST. The data obtained from these stations are manually checked and recorded on 8-inch floppy disks for processing on an IBM S/34 minicomputer and archiving in digital form for retrieval. Also, there are about 545 non-recording rain gauge stations, which are manned by volunteer rainfall observers, and daily rainfall totals from these stations are available on a routine basis. Figure 2 shows the network for rainfall observations.

3. WEATHER RADAR

The radar network of the Thai Meteorological Department is listed in Table 2 and is shown in Figure 3. In routine radar operations, only a few significant features of the three-dimensional echo patterns are examined. The features usually extracted are echo coverage and movement, type of echo patterns, and reflectivity factor and echo top height. These features are all represented in a form of an echo sketch, while some significant features are recorded in photographic form for paper work or research.

4. ON-GOING PROGRAMS

There is no significant on-going program except a plan to set up 5 meteorological observation stations in the next few years. In the field of hydrology, the Meteorological Department will act as the National Rainfall Data Center in a national program on hydrology.

5. CONTRIBUTION TO THE PROJECT

As a developing country with a limited budget, the major contribution of Thailand to the project would be in the form of providing supporting ground truth data for validating satellite measurements. However, Thailand is willing to participate in the analysis of data if our personnel could be trained and the necessary facilities implemented.

6. BENEFITS FROM THE PROJECT

As an agricultural country, Thailand would gain a great benefit from the project for long range precipitation forecasting. Another important aspect would be the application of techniques learned from the project to improve the utilization of satellite information for meteorological activities in the country.

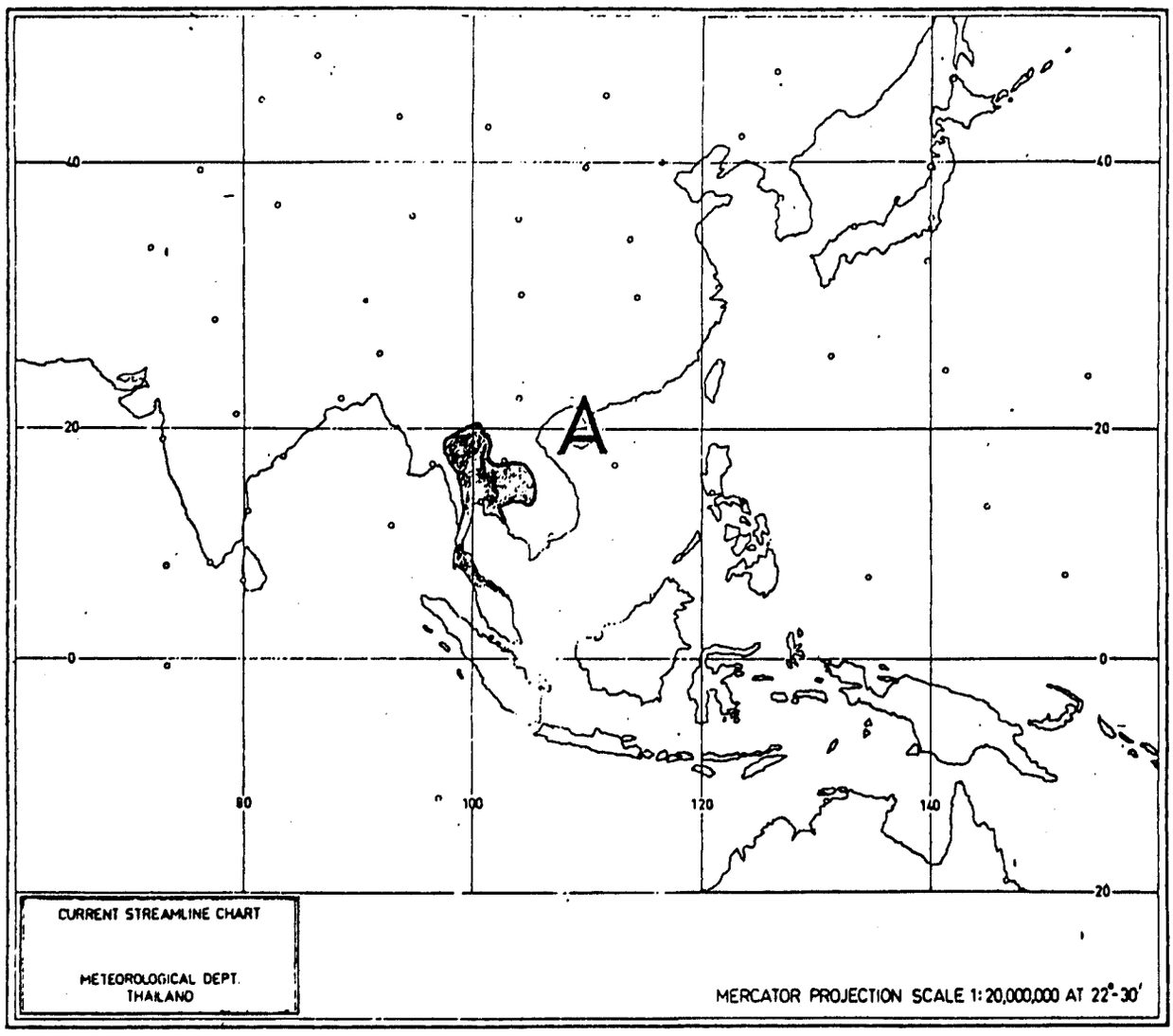

Figure 1. Area Coverage Chart

Table 1. Recording Rain Gauge Network

Station	Latitude (N)	Longitude (E)
Chiangrai	19°53'	99°50'
Mae Hong Son	19°18'	98°05'
Cheang Mai	18°47'	98°59'
Nan	18°46'	100°46'
Lampang	18°17'	99°31'
Mae Sariang	18°10'	97°56'
Phrae	18°10'	100°10'
Uttaradit	17°37'	100°06'
Phumipol Dam	17°14'	99°03'
Tak	16°53'	99°09'
Phitsanulok	16°49'	100°16'
Mae Sot	16°40'	98°33'
Phetchabun	16°26'	101°09'
Nakhon Sawan	15°48'	100°10'
Nong Khai	17°52'	102°43'
Loei	17°27'	101°44'
Udon Thani	17°23'	102°48'
Nakhon Phanom	17°25'	104°47'
Sakon Nakhon	17°09'	104°08'
Mukdahan	16°32'	104°43'
Khon Kaen	16°26'	102°50'
Roi Et	16°03'	103°41'
Chaiyaphum	15°48'	102°02'
Ubon Ratchathani	15°15'	104°52'
Nakhon Ratchasima	14°58'	102°05'
Surin	14°53'	103°30'
Rpachin Buri	14°03'	101°22'
Aranyaprathet	13°42'	102°35'
Lop Buri	14°48'	100°37'
Suphan Brui	14°29'	100°08'
Kanchanaburi	14°01'	99°32'

Table 1. Recording Rain Gauge Network (Cont'd)

Station	Latitude (N)	Longitude (E)
Bangkok Metropolis	13°44'	100°34'
Chon Buri	13°22'	100°59'
Chanthaburi	12°36'	102°07'
Khlong Yai	11°47'	102°53'
Hua Hin	12°35'	99°57'
Prachuap Khiri Khan	11°48'	99°48'
Chumphon	10°29'	99°11'
Ranong	09°58'	98°38'
Surat Thani	09°07'	99°21'
Nakhon Si Thammarat	08°28'	99°58'
Phuket	07°53'	98°24'
Trang	07°31'	99°38'
Songkhla	07°12'	100°36'
Pattani	06°47'	101°10'
Narathiwat	06°25'	101°49'

Table 2. Summary of Thai Meteorological Radars

Radar Station	Location Lat.(N)	Long.(E)	Wave Length (cm)	Antenna Elevation (m)	Max Range (km)	Radar Type	Year of Installation
1. Bangna	13°40'	100°37'	10	24	450	WRS-745	1976
2. Bangkok Airport	13°55'	100°36'	5	25	450	WRS-74c	1981
3. Chiangmai	18°47'	98°59'	5	337	450	WRS-74c	1982
4. Hatyai	6°55'	100°26'	5	50	450	WSR-74c	1982
5. Songkla	7°12'	100°36'	5.6	29	300	WTR-2	1969
6. Sakon Nakhon	7° 9'	104°8'	5.6	187	300	WTR-2	1977
7. Chumphon	10°20'	99°11'	10	28	500	JRC	1978

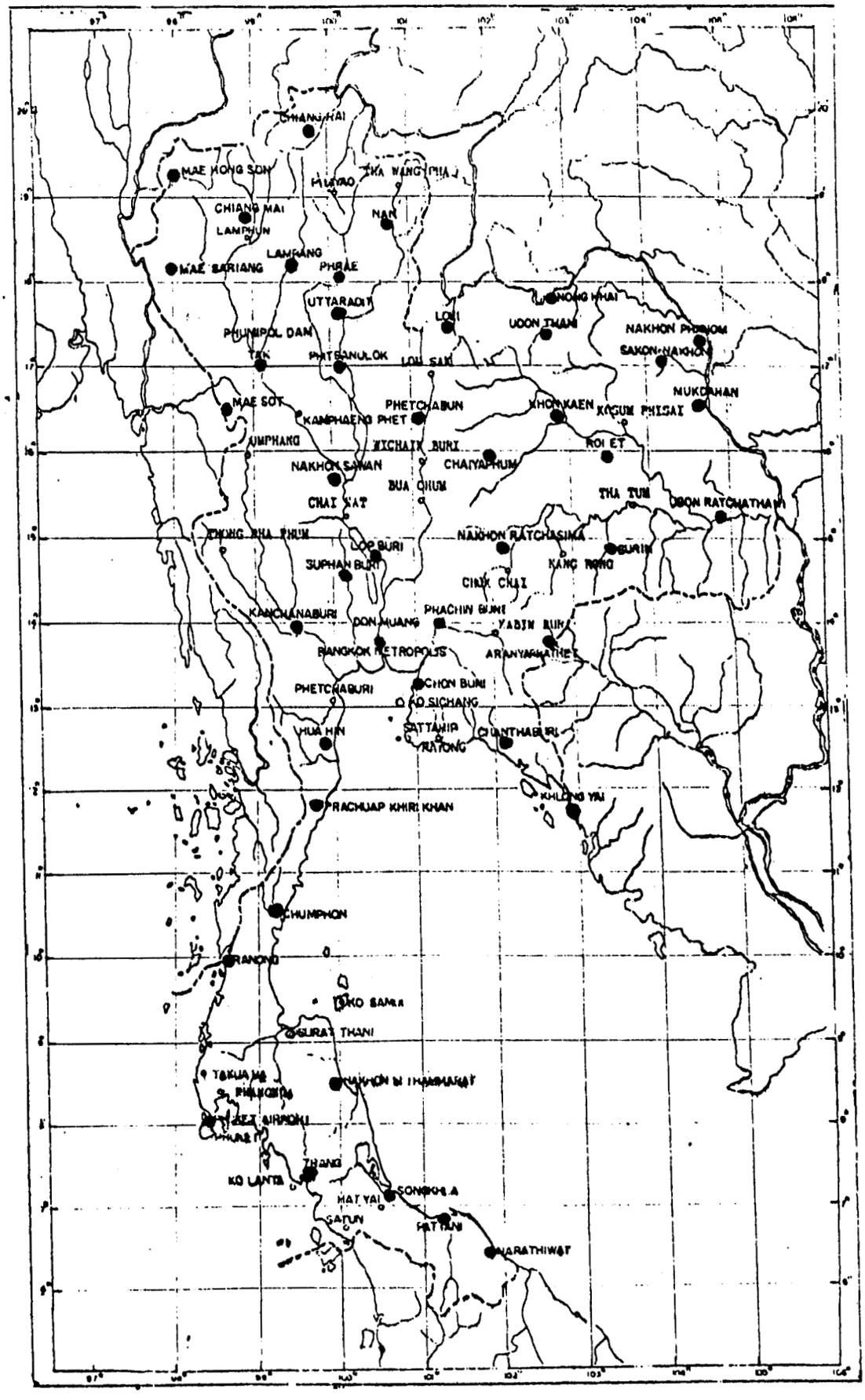

Figure 2. Network of Rainfall Observation Stations

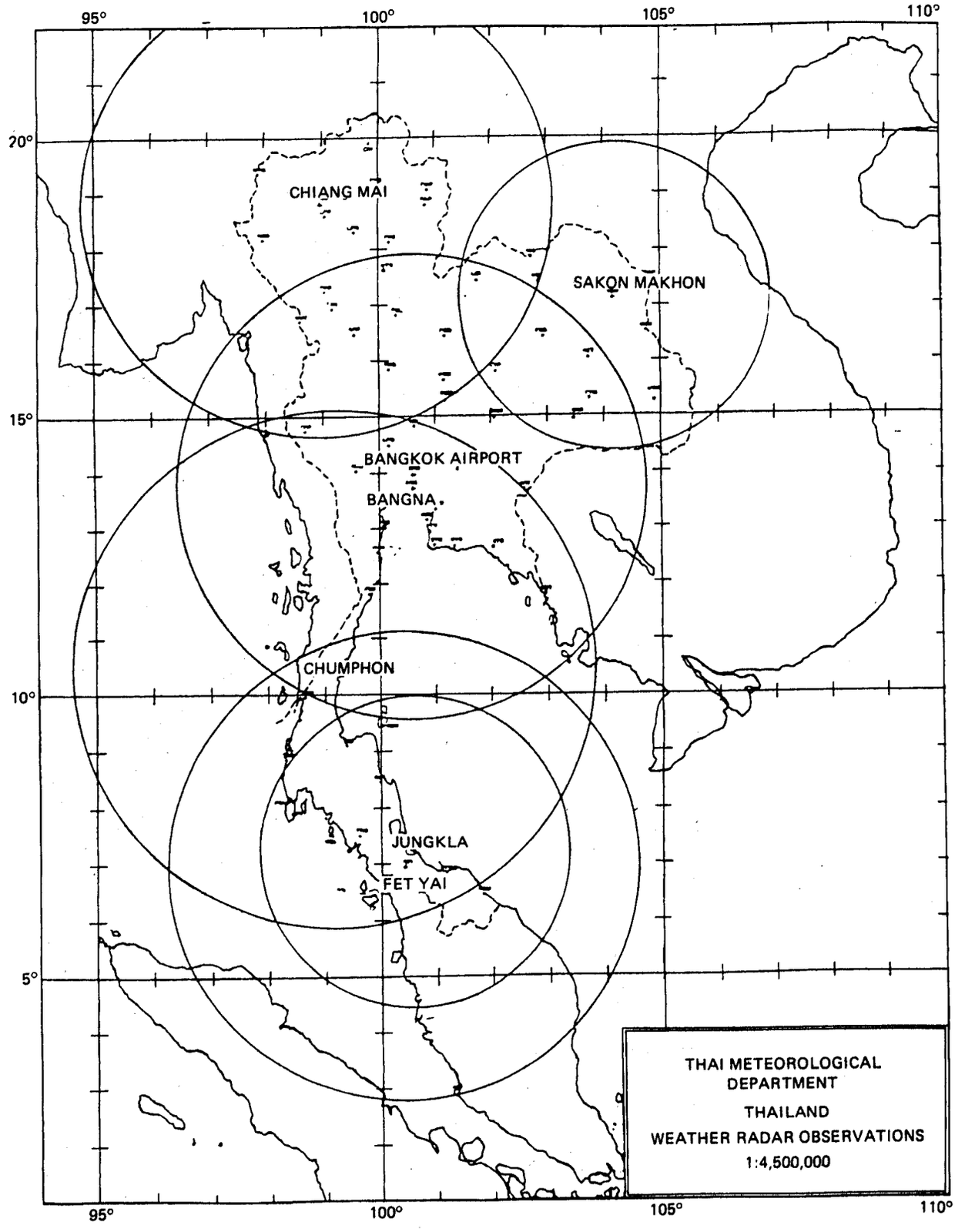

Figure 3. Thai Meteorological Department Weather Radar Stations

GROUND TRUTH DATA AVAILABLE FOR THE UK AREA FOR VALIDATION OF PRECIPITATION MEASUREMENTS DERIVED FROM SATELLITE DATA

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1. INTRODUCTION

The Meteorological Office undertakes research into methods of observing and archiving precipitation amount at a variety of temporal and spatial scales. In near-real time, rainfall estimates are available from a sparse network of gauges, a weather radar network and the so-called FRONTIERS system. FRONTIERS is a rainfall forecasting system which involves combining radar, satellite, and gauge estimates of rainfall with the additional facility for forecaster intervention. Near-real time estimates of sub-daily and daily rainfall totals will also be available soon from the PARAGON system which is a fully automated system for routinely processing radar data, adjusting it by gauge observations, and storing the data. The PARAGON system already produces offline estimates of daily rainfall totals by post-event adjustment of radar data by gauge data. With 5-6 months delay, gauge-only measurements are also available from a dense network of about 6000 rain gauges.

The archived data from the various sources are used both externally and within the Meteorological Office for purposes ranging from the assessment of water resources on a daily basis (e.g., MORECS (Thompson et al, 1981)) to the identification of climatic trends and variations. Rainfall data are also used in the validation of numerical weather prediction and atmospheric general circulation models and in the development of new observations and processing systems. It is within the context of this latter role that we present here an overview of the rain data available (gauge, radar and radar adjusted by gauge data) for the UK at spatial resolution upwards of five kilometers for periods of one hour to one month. The data are classified according to the time scale upon which data become available, the source of data and the extent to which data have been processed. Monthly values may provide suitable validation data for gross rainfall amounts derived from geostationary satellites, but sub-daily data will be required if any physical insight into deficiencies of the system is to be gained.

2. GAUGE-ONLY DATA SETS AVAILABLE FOR VALIDATION OF DAILY AND LONGER PERIOD RAINFALL TOTALS

2.1 Near Real Time Validation

With any satellite monitoring system a real time validation data set provides a useful check for detection of errors in the data collection or processing systems.

2.1.1 Synoptic Station Data

Daily rainfall totals are available shortly after the end of the rainfall day from the synoptic network of gauges. The network of stations which supply daily totals of rainfall to the synoptic data bank for forecasting purposes is shown in Figure 1. There are about 150 stations, with an average gauge spacing of about 40 km, giving a density of about 25 per 200 x 200 km^2 region. Most of the gauges are standard Met Office 5-inch gauges which are

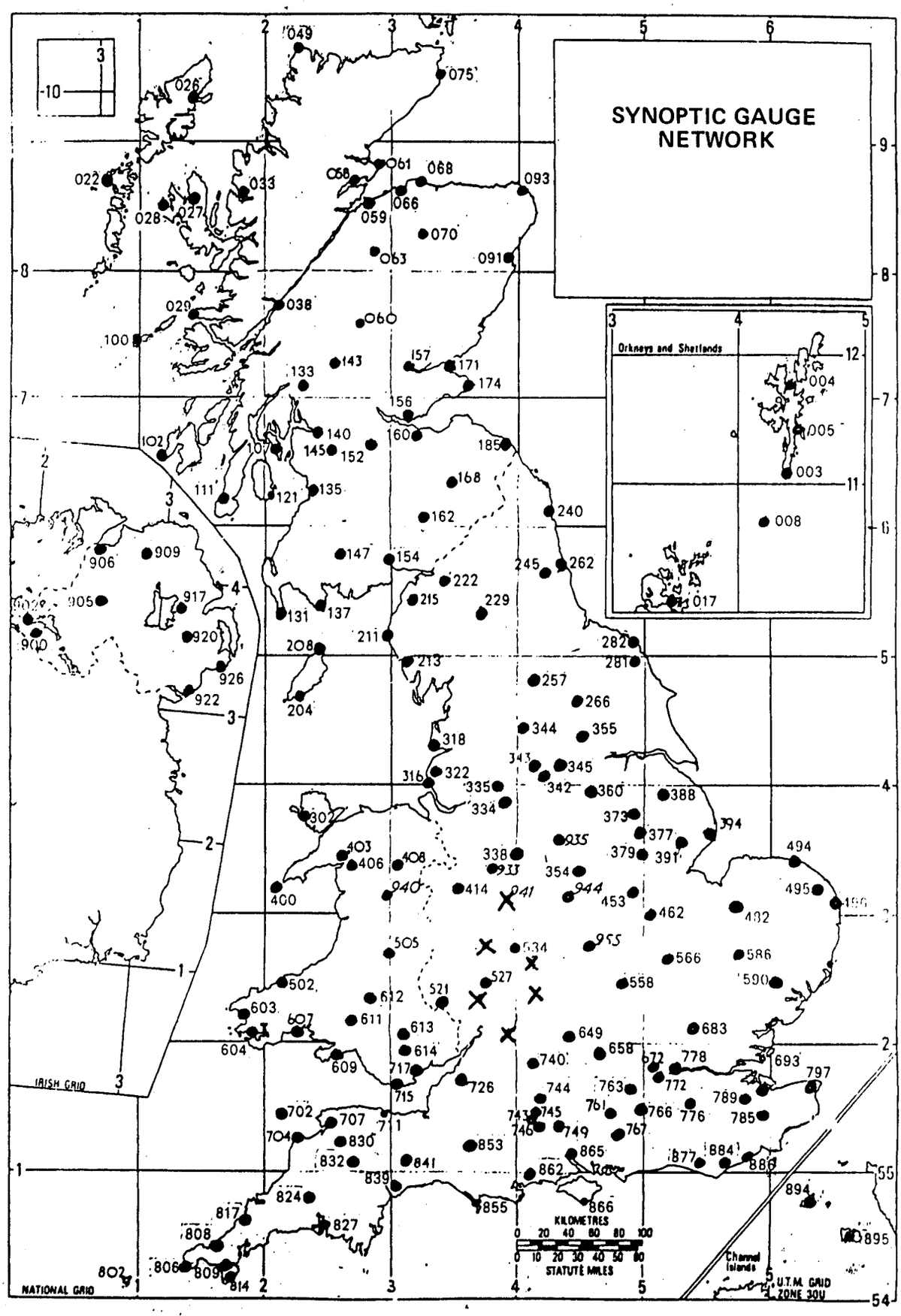

Figure 1. Synoptic Gauge Network

read manually daily. The information is transmitted to Bracknell daily. After an initial quality control procedure by which data are automatically checked for internal consistency within the reported code, the data are available on the synoptic data bank almost immediately after 0900 UT.

2.1.2 MORECS Data Set

On time scales of up to one week the synoptic network data are further quality controlled by visual inspection and data from about 150 of the gauges are used to form the Meteorological Office Rainfall and Evaporation Calculation System (MORECS) data set. MORECS has been designed to provide estimates of weekly and monthly evaporation and soil moisture deficit in the form of averages over 40 x 40 km^2 grid squares (Figure 2) using daily synoptic weather data as its inputs (Thompson et al, 1981). Part of the calculations involve averaging and interpolating selected synoptic gauge data to the required spatial and temporal scale. To interpolate these data onto a 40 km grid, the individual rainfall totals are first expressed as a percentage of the gauge mean annual average (1941-1970). If there is a station within 0.5 km of the centre of the 40 km square, then its total is taken to be representative of the square. Otherwise the nine nearest gauges within a radius of 100 km of the centre of the square are identified. From these nine, the nearest six with data are selected but with the proviso that there are no more than two stations in each octant. A planar surface (after Shearman and Salter, 1975) is fitted to the data if more than three stations meet the specified range and distribution criteria. If there are less than three stations available, an inverse distance squared weighted mean value is calculated for the centre of the square. The grid square rainfall total is then obtained by multiplying the interpolated percentage of annual average rainfall by the climatological (1941-1970) annual average rainfall for the square.

It is not possible to capture the large spatial variation of rainfall fields by interpolation from such a sparse network of stations. The representativeness of the 40 x 40 km^2 averages should improve with the length of averaging period.

2.2 Historical Validation

Two gauge data sets are available for validation of historical data, the MORECS climatology and the dense climatological gauge network.

2.2.1 MORECS Climatology

Although the MORECS system currently in operation was extensively revised in 1980/81, the suite of programs has been run retrospectively on data from 1960 onwards. The MORECS climatology data set, thus constructed, contains daily and mean monthly estimates for each MORECS square for each year. The distribution of gauges used in MORECS is of inferior resolution to that of the dense climatological gauge network. The advantage of the MORECS data is that they are archived and retrievable as areal average estimates whereas the dense gauge data require further processing before it is possible to compare satellite data directly with them.

2.2.2 Dense Climatological Gauge Network

For validation of daily or longer period rainfall totals, well after (six months) the date of rainfall, observations are available from the dense

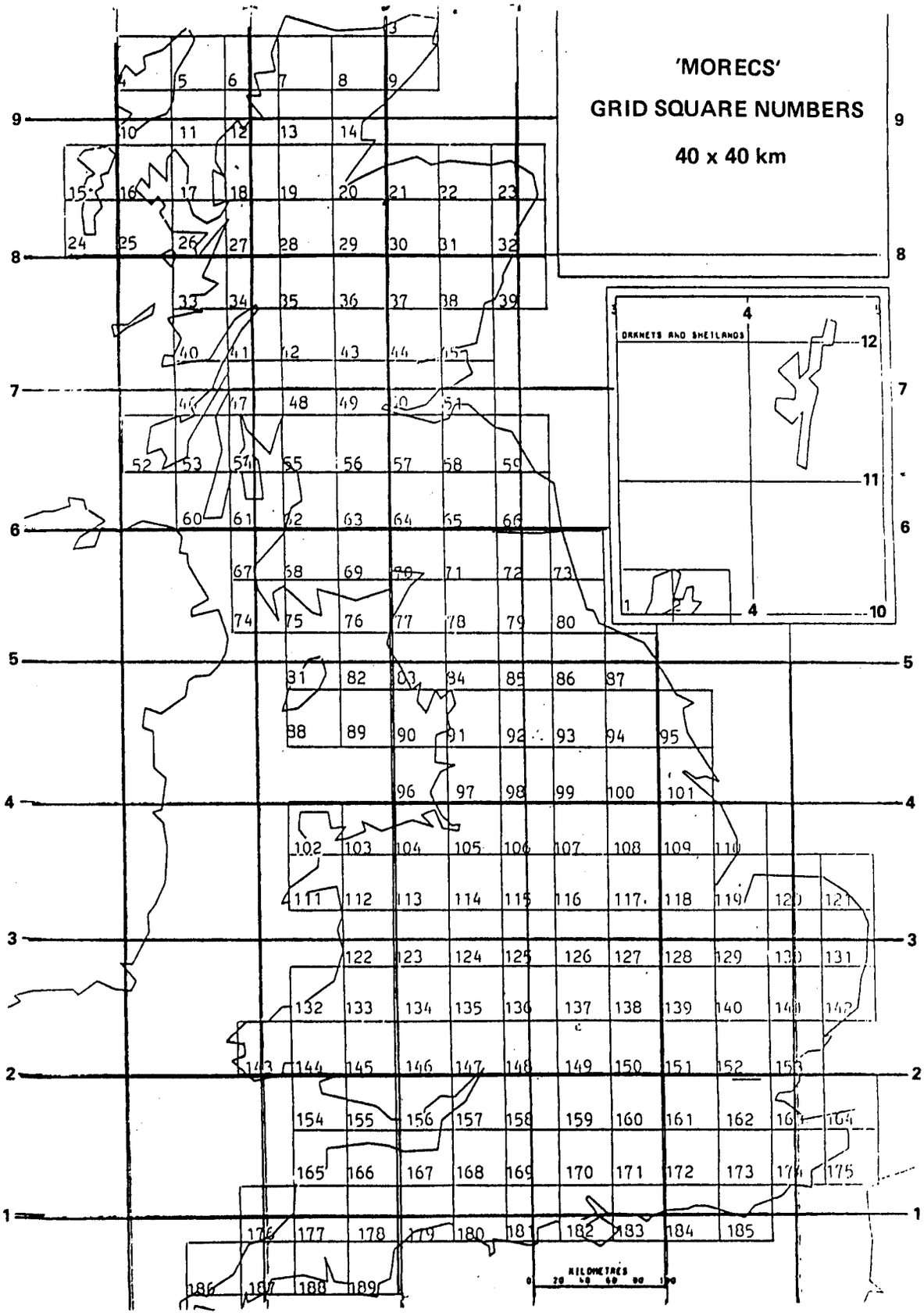

Figure 2. 'MORECS' Grid Square Numbers (40 x 40 km^2 areas)

climatological gauge network. The distribution of about 6000 stations in this network is shown in Figure 3. Gauge spacing ranges from 3 to 30 km with an average density of one gauge per 8 x 8 km^2. Software exists to fit inverse distance squared weighted surfaces of differing complexity (biquadratic biplanar or mean according to the number and distribution of gauges within 100 km radius of a grid point) to these data to map them to a regular 5 km grid. Areal averages at resolution coarser than or equal to 5 x 5 km^2 can then be produced.

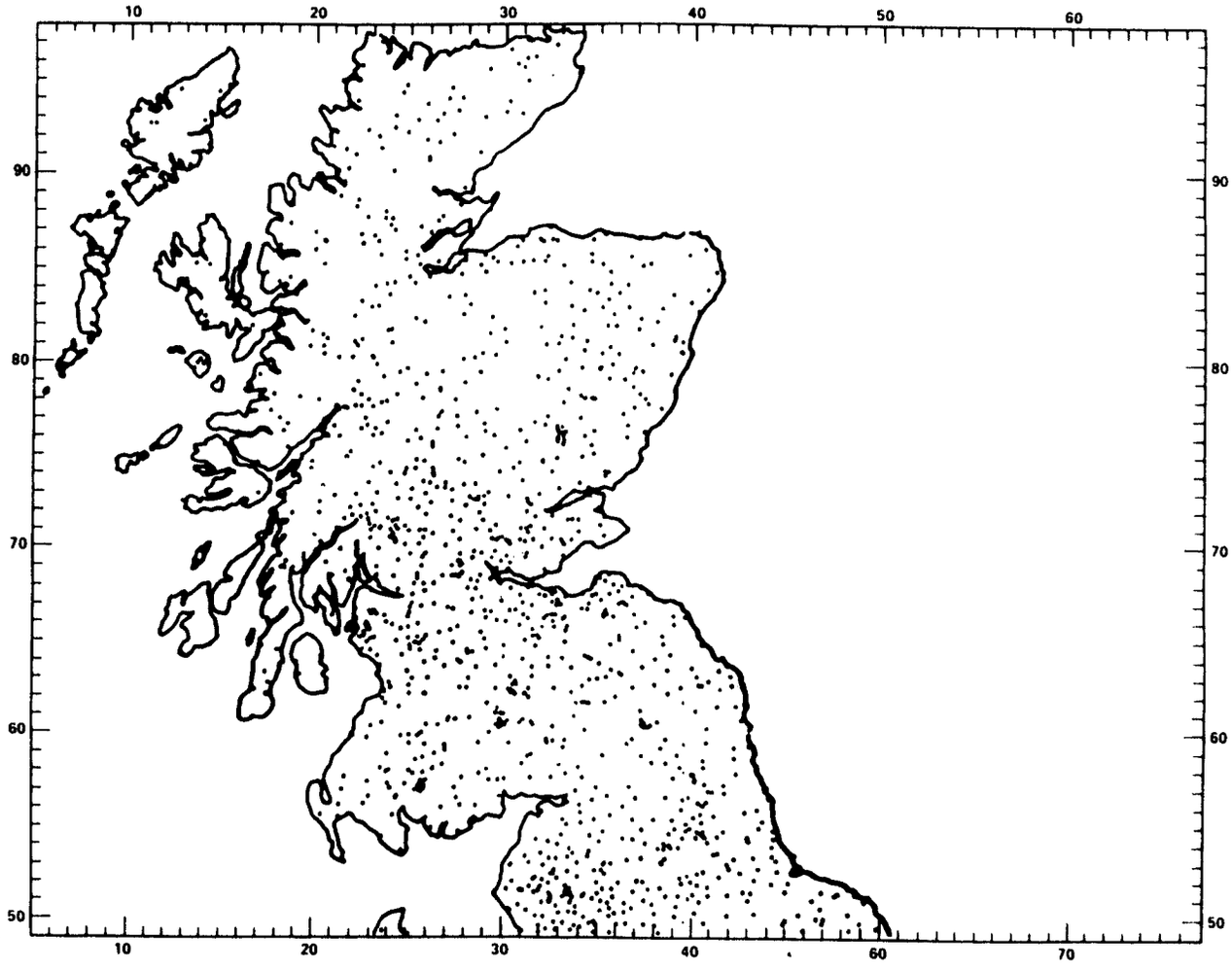

Figure 3. Dense Climatological Gauge Network

Most data are received as rainfall postcards and climatological returns. After brief manual scrutiny the data are entered into the rainfall archive. Once the data for an entire month have been transcribed, an ensemble of quality control subroutines is run to identify and correct common errors. Errors that are accounted for include reporting of date as one day ahead or behind the authentic rainfall day, incomplete data due to inaccurate reporting of the length of a dry period, unidentified or identified accumulations over periods longer than one day which must be apportioned between the days within the period and persistent reading of the gauge at the incorrect time. The compatibility of values between a gauge and its nearest neighbours within a

specified range is also scrutinized. Altitude effects are accounted for by comparing percentage of annual average rainfall rather than absolute magnitude. Whenever a quality control correction is made, the value is flagged and the original values are archived in a quality control data set. All automatic adjustments are available to a manual scrutineer. It is with this person that the final choice of values rests. It is generally accepted that gauges underestimate by up to 5 per cent due to wind effects. No attempt is made to correct for this deficiency. Quality controlled daily rainfall totals from the climatological network are archived in machineable form from 1961 onwards.

3. GAUGE-ONLY DATA AVAILABLE FOR VALIDATION OF SUB DAILY RAINFALL TOTALS

Although the dense climatological network can be used to validate daily and longer period satellite derived rainfall totals, it may provide little useful contribution to understanding why particular rainfall characteristics are inadequately monitored by satellite. Comparison of satellite and gauge data on a finer time scale may provide insight into the precipitation processes and the underlying physical cause for the errors.

3.1 SREWS Network

Hourly rainfall totals are available on the synoptic data bank within a few minutes of the hour from the SREWS network of stations reporting in near real time, as shown in Figure 4. Approximately 60 stations provide these data. It is apparent from Figure 4 that the density of gauges is very sparse and uneven throughout the country.

3.2 TSE, TBR and MTER Data

Within several months, data are available from about 200 stations (Figure 5). These recorders are often coincident with daily-read gauges. Their average spacing is 40 km, although a large range of separations exists. There are large gaps in the network especially in Scotland. The recorders are primarily of two types: the tilting syphon autographic gauge (TSR) of which there are about 130 providing hourly data and the tipping bucket (TBR) and magnetic tape event recorders (MTER) which identify the numbers of time a given mass of water accumulates in the gauge within specified time limits. There are 70 TBRs and MTERs providing data at time intervals of 1 minute and rainfall totals to the nearest 0.2 mm.

All available hourly data since 1980 have been archived. The distribution of sub-daily gauges has varied considerably in recent years. Future numbers of sub-daily gauges are expected to increase.

4. RADAR-ONLY DATA SETS AVAILABLE FOR VALIDATION OF RAINFALL TOTALS

The current network of weather radars is shown in Figure 6. The range to which the UK radars can detect the rainfall signal is 210 km, although as a rule of thumb values are considered quantitatively reliable only within a 75 km radius. The 210 km range extends beyond the coast of much of England and Wales and thus is probably useful for validation of satellite estimates of coastal rainfall.

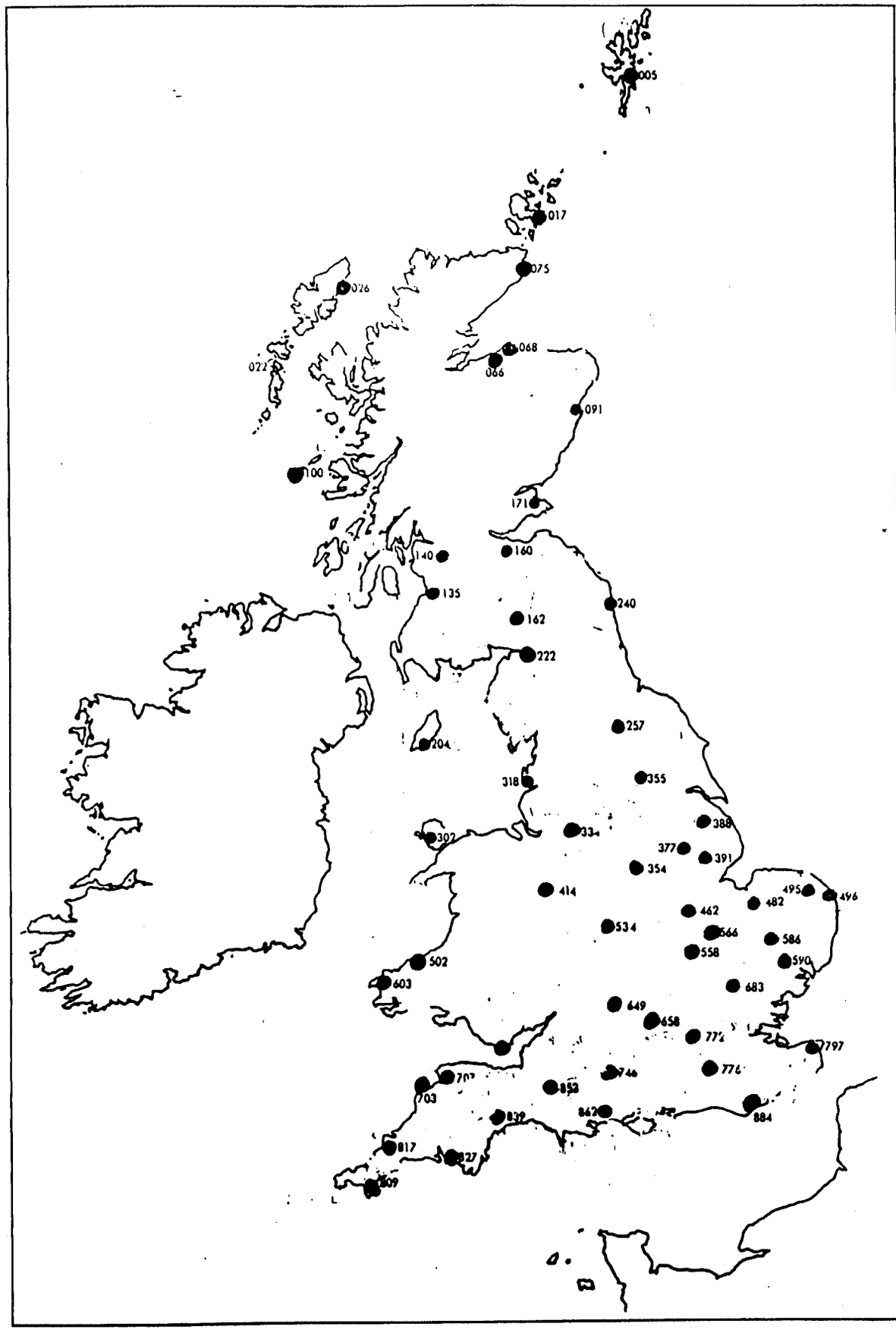

Figure 4. SREWS Network

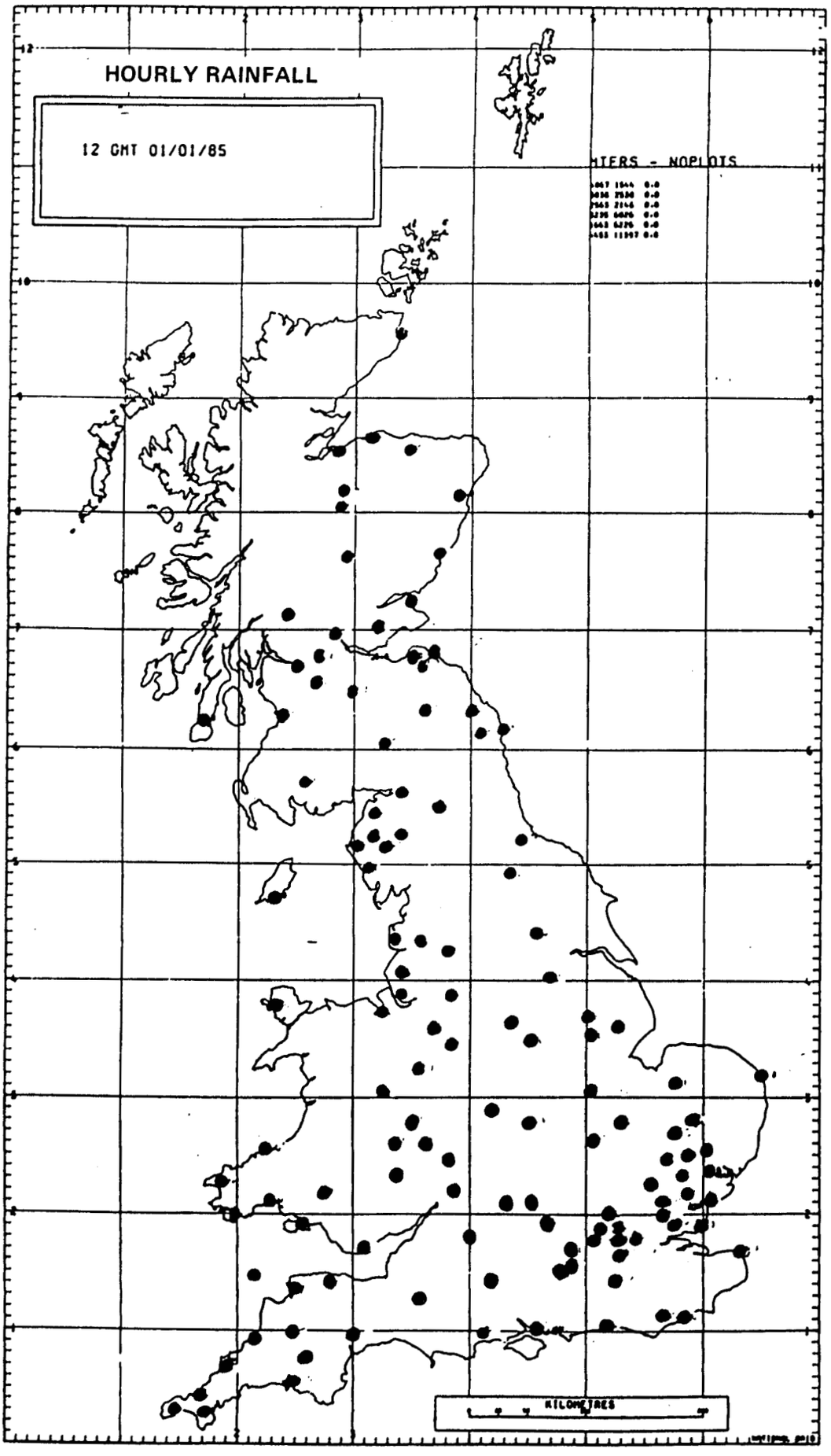

Figure 5. Hourly Gauge Network

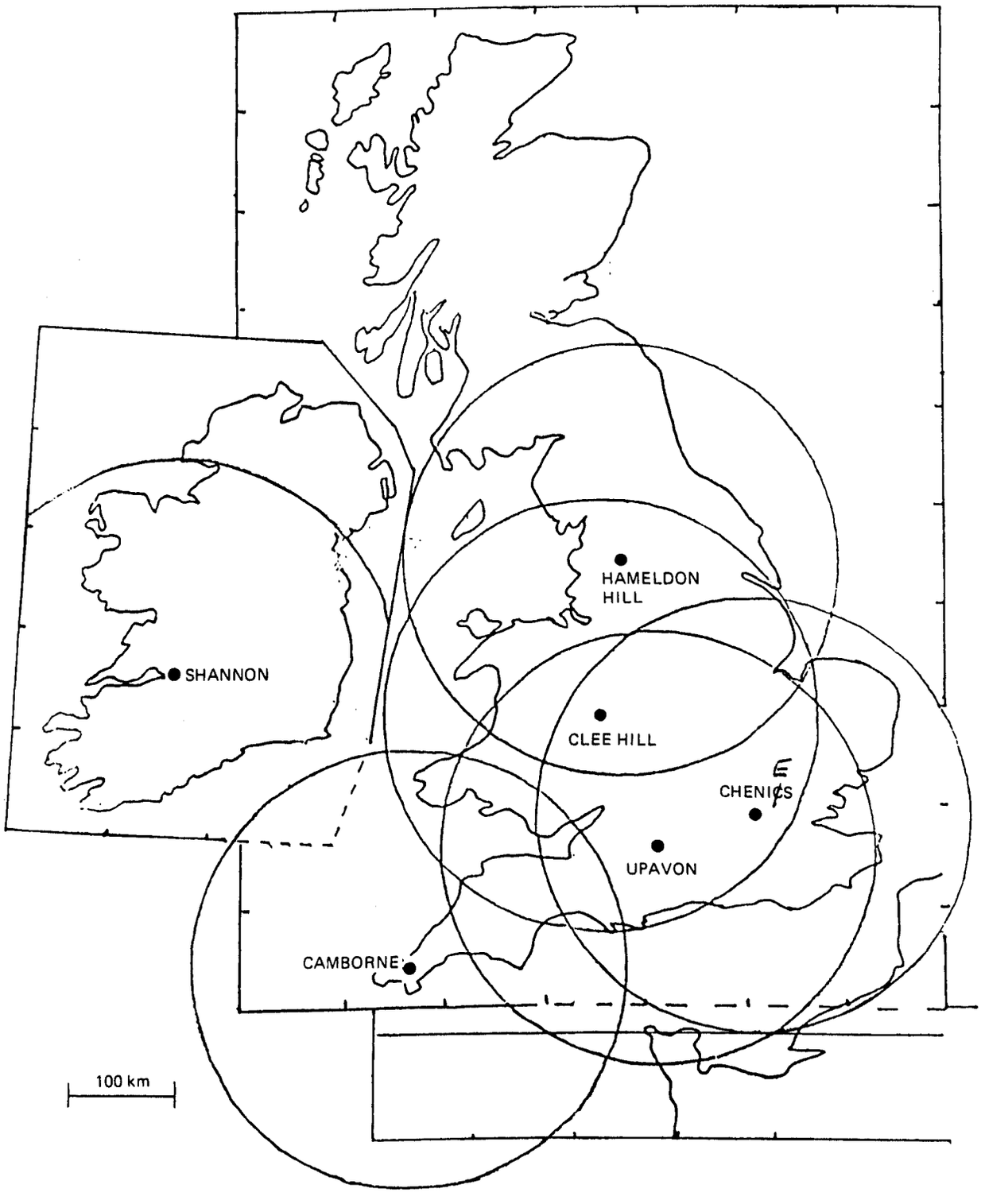

Figure 6. Weather Radar Network

The radar signal is archived as an estimate of rainfall intensity averaged over 5 x 5 km^2 areas. It is calibrated on-site using between three and five dedicated gauges. These estimates are made and recorded every five minutes (off-line data) and transmitted to Bracknell every 15 minutes. Hourly and daily totals are available from May 1981 onwards for all except the Chenies radar which became operational in January 1985. Additional weather radars are to be installed in Northern Ireland (Castor Bay), SW England (Devon) and SW Wales (Dyfed). The Camborne and Upavon radars are to be replaced by new radars at Predannack (Cornwall) and Portland (Dorset), and further plans exist for a radar in East Anglia. Initial discussions between the Meteorological Office and appropriate Scottish Authorities have resulted in a proposed extension of the weather radar network to include three radars in Scotland.

Radar data provide almost the only rainfall information over the sea. Radar data also provide the only high resolution sub-daily and near-real time rainfall estimate over land. Under these circumstances radar provides the best observations available against which satellite data can be compared. However, for two reasons, caution is recommended when data from these two sources are compared. First, use of one remote sensing technique to validate another, when neither senses the required surface rainfall directly, requires great care and individual attention in the interpretation of signals from both sources. Second, current investigation (Advisory Services Branch of Research and Development) of the quality of radar rainfall estimates compared with data from the dense gauge network shows that site-calibrated radar data sometimes contain substantial errors. For example Figure 7a shows the daily rainfall pattern derived from the dense gauge network and Figure 7b from radar for a limited area within 75 km of the Hameldon Hill radar for 21 June 1982. The gauge spacing was mostly 10 km. The synoptic situation was an occluded front, lying across England from Merseyside to the Wash, moving slowly southwards to central Wales and East Anglia by midnight with light easterly winds. The radar recorded excessively low values just east of the area centre. The double feature evident in the gauge field was for the most part missed by radar and the magnitude of the peak in the northwest was grossly overestimated. It is suggested that an underlying cause for these errors is the site calibration technique which is inappropriate for this particular synoptic situation. The Hameldon calibration gauges all lie on the west of the Pennines. For frontal rainfall a westerly/southwesterly air flow is assumed in the automatic calibration procedure and this decreases the estimates of surface rainfall slightly in the eastern rain shadow. On this day the unstable air flow was easterly, promoting orographic enhancement in the east i.e., in the opposite sense to that assumed in the radar site calibration.

Over land where the dense UK gauge network can provide good, high resolution daily rainfall estimates, the use of radar data in validation studies of daily rainfall amount is not recommended. However, locally where daily gauge data are sparse and especially in coastal regions where the area comparison is likely to extend over the sea and for sub-daily validation, then radar data can supplement gauge data, provided that caution is applied in interpreting the radar signal.

Figure 7a. Daily Rainfall Pattern Derived from Dense Gauge Network, for 21 June 1982.

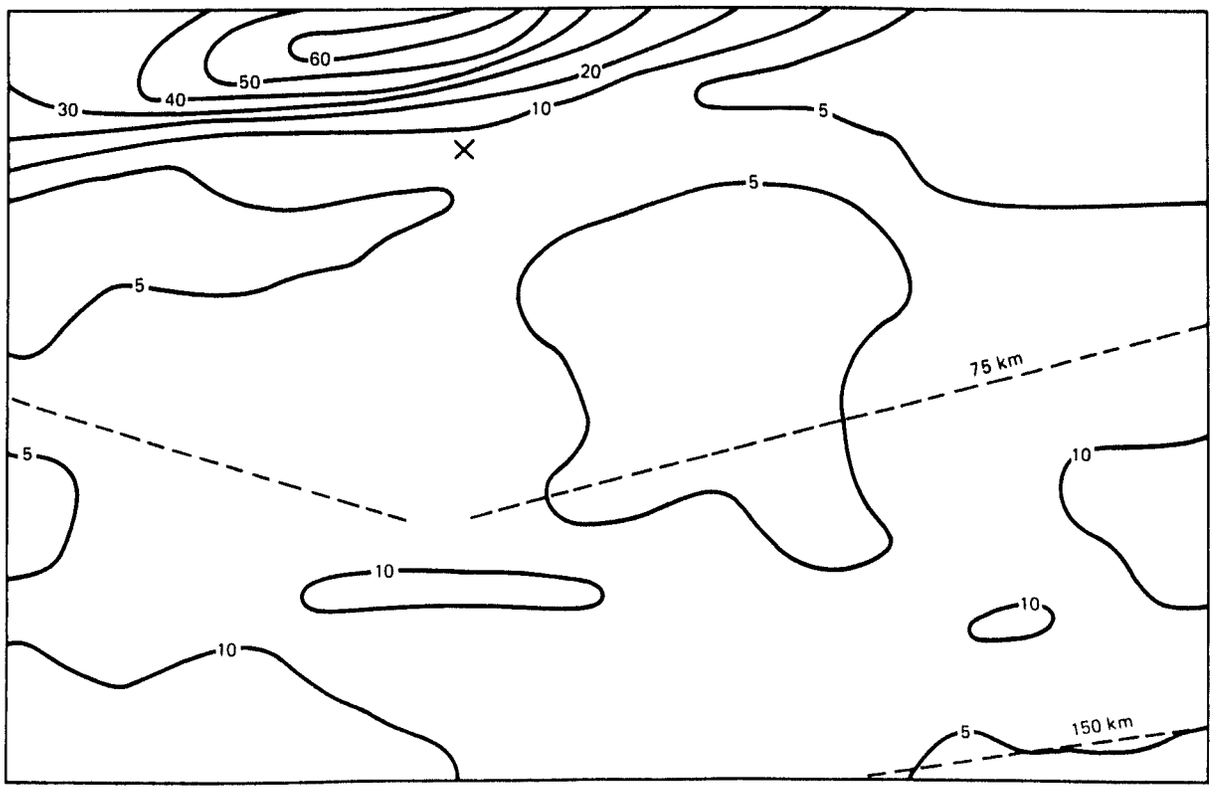

Figure 7b. Daily Rainfall Pattern Derived from Radar, for 21 June 1982, (Hameldon Hill Radar Position Marked by X)

5. CURRENT WORK ON COMBINING RADAR AND GAUGE RAINFALL ESTIMATES

5.1 The PARAGON System

Radar data have a regular and dense spatial coverage (5 km grid). Because of this they can be used for interpolation between observations from more widely spaced gauges. PARAGON (Processing and Archiving of Radar and Gauges Off-line and in Near-real time) is a system designed to process, adjust by gauge observations, and store radar data. The combined radar/gauge estimate should provide a better representation of rainfall patterns than is possible by gauges only and a better representation of the magnitude of rainfall than is possible by radar only. The data flow diagram for the PARAGON system is shown in Figure 8. At present only the off-line system is operational. On-line daily and sub-daily processing is under development.

In the PARAGON system, areas of partial or complete occultation are detected from the site-calibrated radar data. Areas of anaprop are corrected after detection by distinguishing between stationary anaprop signal and moving rainfalls. These quality controlled hourly data are stored. The hourly totals are also integrated to provide single site unadjusted daily radar rainfall totals.

The daily radar data are next adjusted by gauge observations, to bring the general level of radar rainfalls into agreement with those indicated by gauges. In near-real time, the adjustment is made by using the synoptic network of gauges. 5-6 months after the event, adjustment is made by the dense gauge data (May, 1986a). Adjustment involves:

(i) Interpolating the 5 km radar estimates to give a radar estimate (r_e) at each gauge.

(ii) Calculating the gauge/radar estimate (g/r_e) at each gauge.

(iii) Fitting a surface to the g/r_e values to give a g/r_e value at each 5 km grid point.

(iv) Multiplying the actual radar measurement at each 5 km grid point by the interpolated g/r_e adjustment factor.

The adjustment procedure for sub-daily data is still under development. Sub-daily gauge data are thought to have too large a variability to be applied in the same manner as the daily adjustment procedure. The feasibility of using daily gauge data to adjust sub-daily radar data is being considered. When developed, the sub-daily adjustment will permit much better representation of the between-gauge rainfall which is excessively smooth when only gauge data are available. Sub-daily rainfall patterns can be highly variable and cannot be adequately monitored by a sparse network of gauges alone.

5.2 Future Plans for Daily PARAGON Estimates

Clearly, if the rainfall is characterized by large-scale uniform distribution, then radar can add little useful additional information to the smooth interpolated gauge field. When rainfall is spatially variable, e.g., under highly convective conditions or for short periods of sub-daily duration, or where gauge spacing is large, then the potential benefit of combining gauge

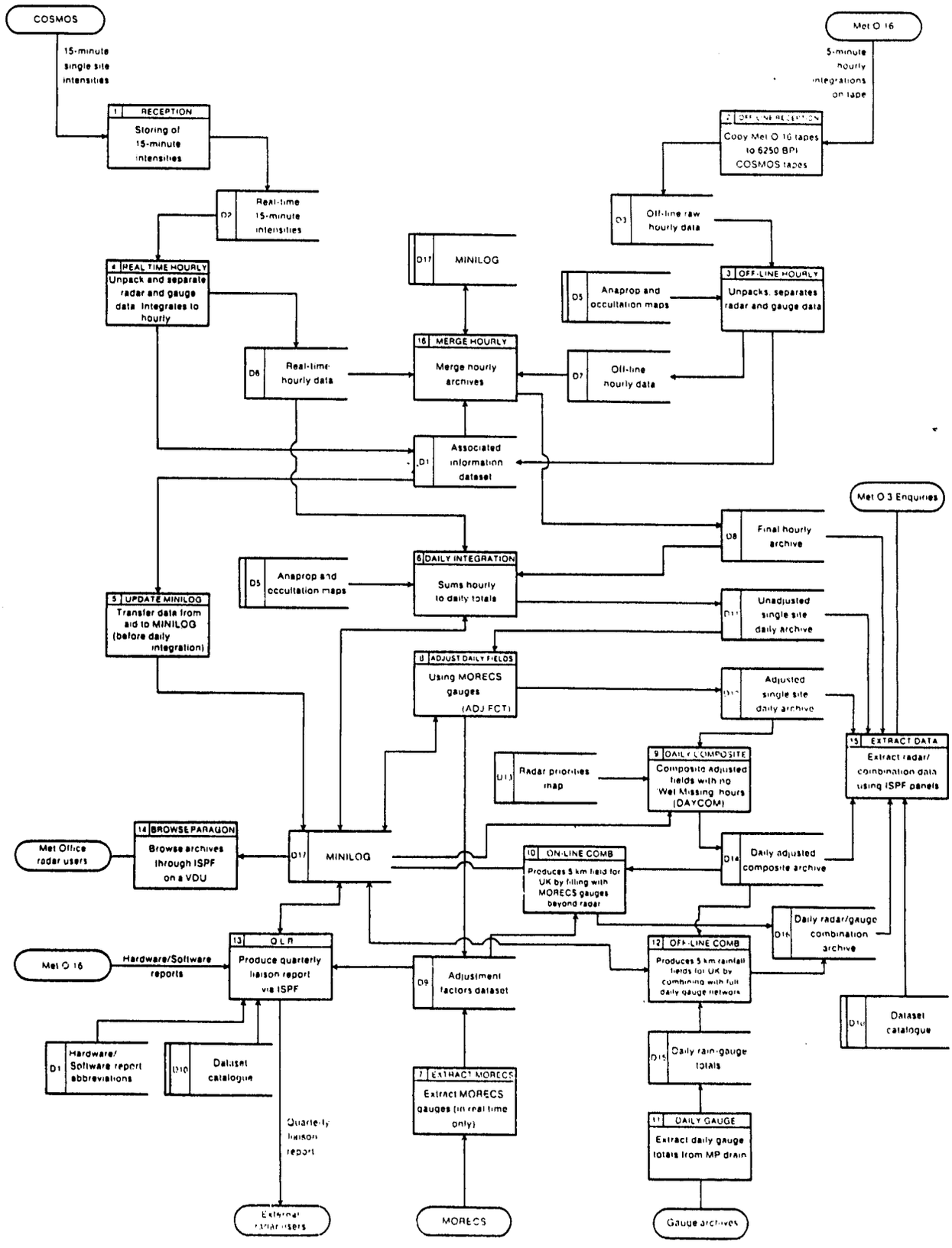

Figure 8. Data Flow Diagram for the PARAGON System

and radar estimates is greatest. Work has begun on the development of an automatic algorithm, based on the variability of radar and gauge estimates (May 1986b) to identify, in real time, points at which addition of radar data is beneficial.

6. SUMMARY

A variety of rainfall data sets are available for the UK that may be used to validate rainfall estimates derived from satellites. The main relevant characteristics of each source are summarized in Table 1.

Table 1. Sources of Data for the UK for Validation of Areal Precipitation Estimates from Satellite

Period	Available in Real Time and/or Historical	Spatial Resolution	Source	Availability
Daily	Real time	40 km	Synoptic gauge network	Daily or monthly gauge averages each year since 1960
	Historical	40 km x 40 km areal average	Synoptic gauge network	Daily or monthly areal averages each year since 1961
	Historical	5 km x 5 km	Adjusted (by sparse and dense gauges) & unadjusted radar	Most of England and Wales + extension over coastal waters 1982 onwards
Sub-daily	Real time	60 km	SREWS	Within a few minutes of the hour every hour from 1981
	Historical	40 km	TSR, TBR & MTER rainfall recorders	Every hour from 1980
	Real time	5 km x 5 km	Site calibrated radar	May 1981

For historical validation of daily or monthly rainfall totals over the mainland UK, the best data available are those from the quality controlled dense gauge network available with 5-6 months delay. Software exists to map these data to a 5 km grid from which areal averages can be calculated.

In near-real time, or historically in coastal and remote upland regions, available gauge-only data are sparse. Particularly in convective situations these gauge-only estimates cannot adequately capture the spatial

variability of rainfall. Judicious use of radar data to supplement gauge data should improve estimates under such circumstances. To understand why certain discrepancies exist between satellite and gauge estimates, it will be necessary to exploit sub-daily process-orientated studies. Although there are many sources of error inherent in a radar monitoring system it is necessary and desirable to use radar in some situations and its merit must be considered on an individual event basis.

The PARAGON system, designed to combine the favourable features of radar and gauge networks, is still being improved. The system is designed to provide an estimate whose magnitude is determined by the gauge data but with between-gauge pattern being determined increasingly by radar, as gauge spacing or spatial variability of rainfall increases. A discrimination algorithm designed to automatically identify where and when addition of radar data to gauge data will improve the measurements is being developed. Radar is of greatest benefit when the quality of radar data are good and the spatial variability of the rainfall high relative to the gauge spacing.

If the algorithm is developed successfully, PARAGON rainfall estimates will improve near-real time rainfall assessment and possibly also provide beneficial additional information to the historical dense climatological network measurements.

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U.S.A. RAINGAUGE AND RADAR NETWORK DATA BASES

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1. INTRODUCTION

Precipitation data are included in many different types of data bases (e.g. agriculture, hydrology, aerospace, weather forecasting, climatology). The following presentation describes several climatological data bases that are particularly suitable as data sources to validate satellite-derived precipitation for the Global Precipitation Climatology Project (GPCP).

2. U.S. NATIONAL COOPERATIVE PROGRAM

The largest nationwide climatological data base, that contains raingauge data, is compiled under the U.S. National Cooperative Program. Daily precipitation is recorded from 8-inch rain gauges by a network of about 10,000 observers located throughout all 50 states (Figure 1), several Pacific islands and Puerto Rico. A 2.5° latitude x 2.5° longitude grid area, envisioned for the GPCP, would contain approximately 35 Cooperative stations.

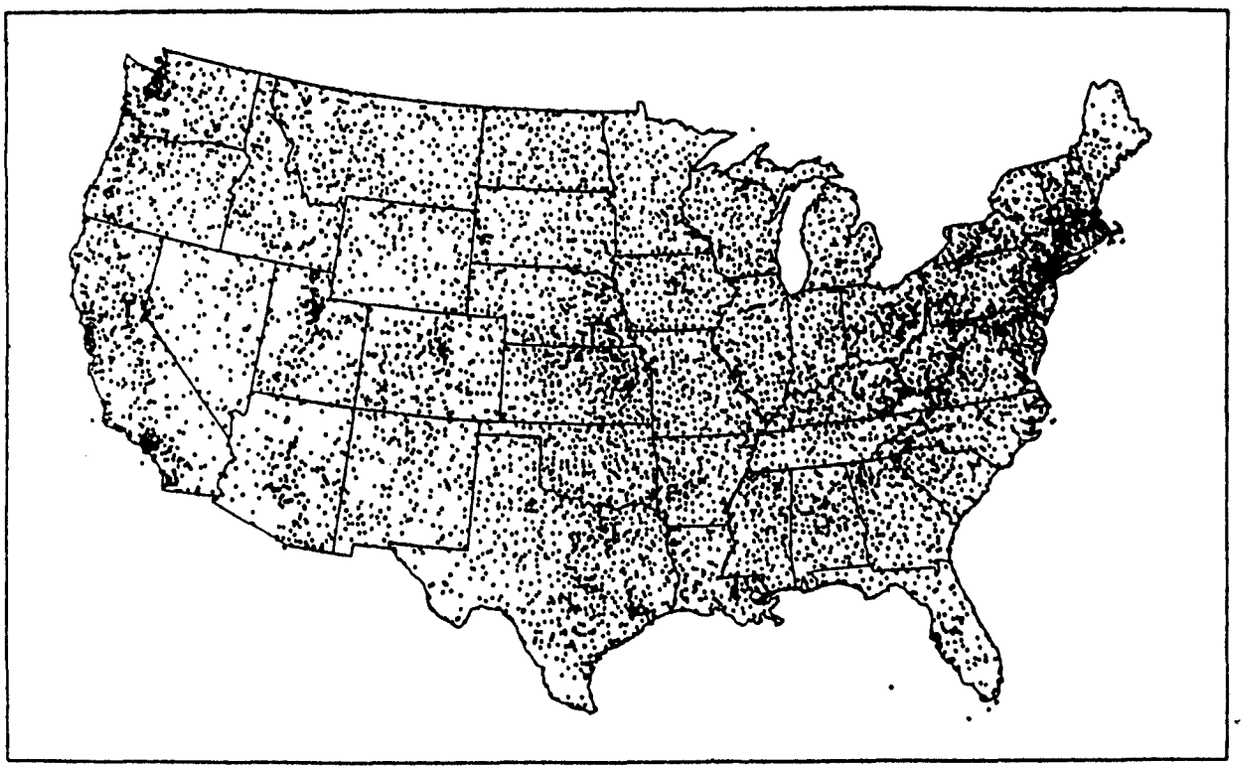

Figure 1. U.S. National Cooperative Data Stations

Although basically established as a climatological network, many of the Cooperative data are input to agricultural, hydrologic and other service programs and regional data bases. These near-real time uses of the data are often on a seasonal or as-needed basis. At the end of every month, data from all 10,000 stations are sent to the National Climatic Data Center (NCDC) where daily and monthly totals and summary statistics are compiled into a digital data base. Several error checks are performed during the compilation and summary process.

3. HOURLY PRECIPITATION DATA NETWORK

The Cooperative data base's very high density, relatively homogeneous national coverage and continuity throughout all seasons provide an opportunity for extensive validation of satellite-derived monthly precipitation totals. However, the usefulness of this data set can be increased by using the Cooperative data in conjunction with higher time resolution data. Higher time resolution data provide the opportunity to identify the large-scale grid areas in which short duration, high intensity precipitation has contributed significantly to daily and monthly totals. These heavy rainfall cases are an important source of error in estimating precipitation from satellite data.

The Hourly Precipitation Data (HPD) network is composed of about 3,000 rain gauges (Figure 2) that automatically record a month's data on paper tapes and charts. Two thousand of these gauges are collocated with Cooperative stations. At the end of every month, the data are sent to the NCDC where 15-minute, hourly, daily and monthly accumulations are compiled into a digital data base. Several error checks are performed during the compilation and summary process.

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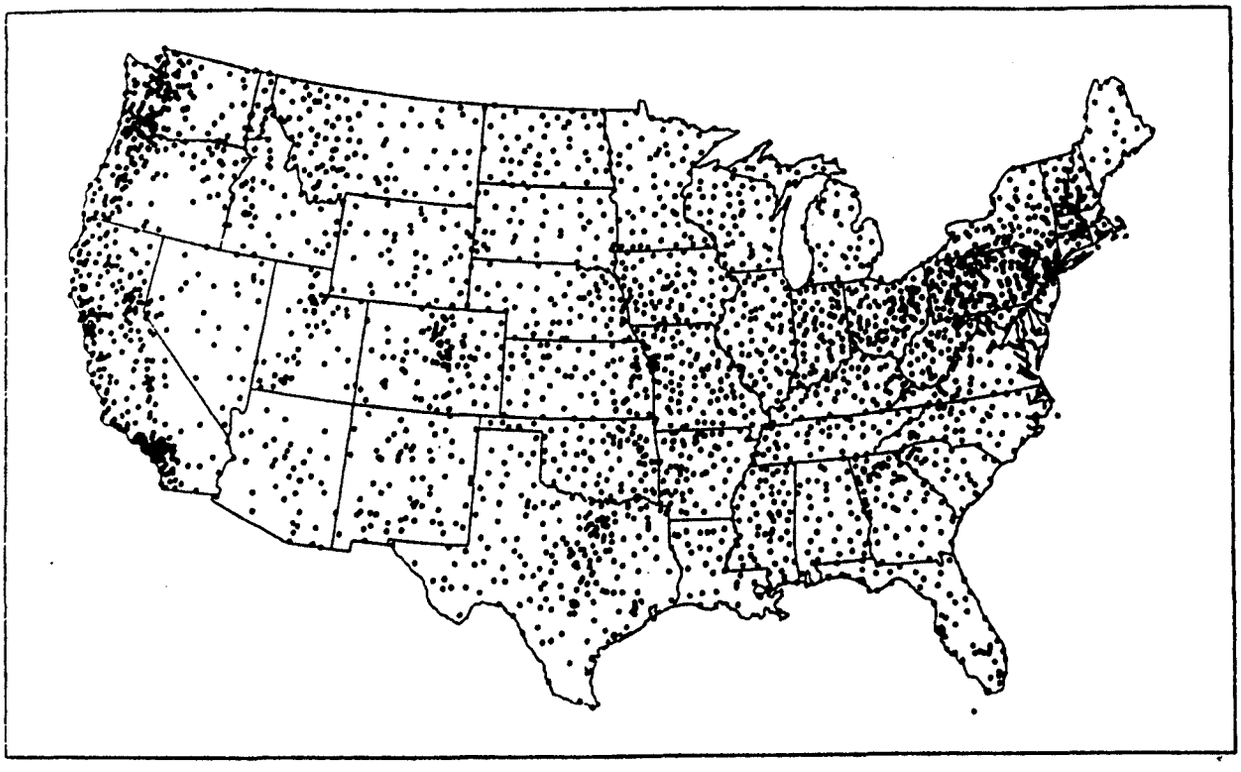

Figure 2. U.S. Hourly Precipitation Stations

The HPD stations are distributed relatively homogeneously throughout 49 states, several Pacific islands and Puerto Rico (Alaska is not in the HPD network) and data are recorded throughout all seasons. In addition to the high time resolution, the HPD network can be used to add daily and monthly data for about 1,000 stations to the Cooperative network data base (i.e., additional data are obtained from the HPD stations that are not collocated with Cooperative stations).

4. U.S. WEATHER RADAR NETWORK

The U.S. weather radar network is another source of high resolution data that can be used in conjunction with the basic Cooperative data. This network consists of 128 radars that cover about three-fourths of the U.S. (Figure 3). The data are disseminated via the Automation of Field Operations System (AFOS) and consequently are loaded, along with all other AFOS products, into daily digital data base files maintained for 5 years at the NCDC under the Service Records Retention System (SRRS) program.

The basic radar observations transmitted over the AFOS and retained in the SRRS data base consist of coded digital values of precipitation type, intensity, and trend for an array of grid boxes surrounding each radar. The grid boxes range from approximately 36 to 48 km on a side. A 2.5° latitude x 2.5° longitude square contains approximately 25 grid boxes (compared to 35 Cooperative stations and 10 HPD stations).

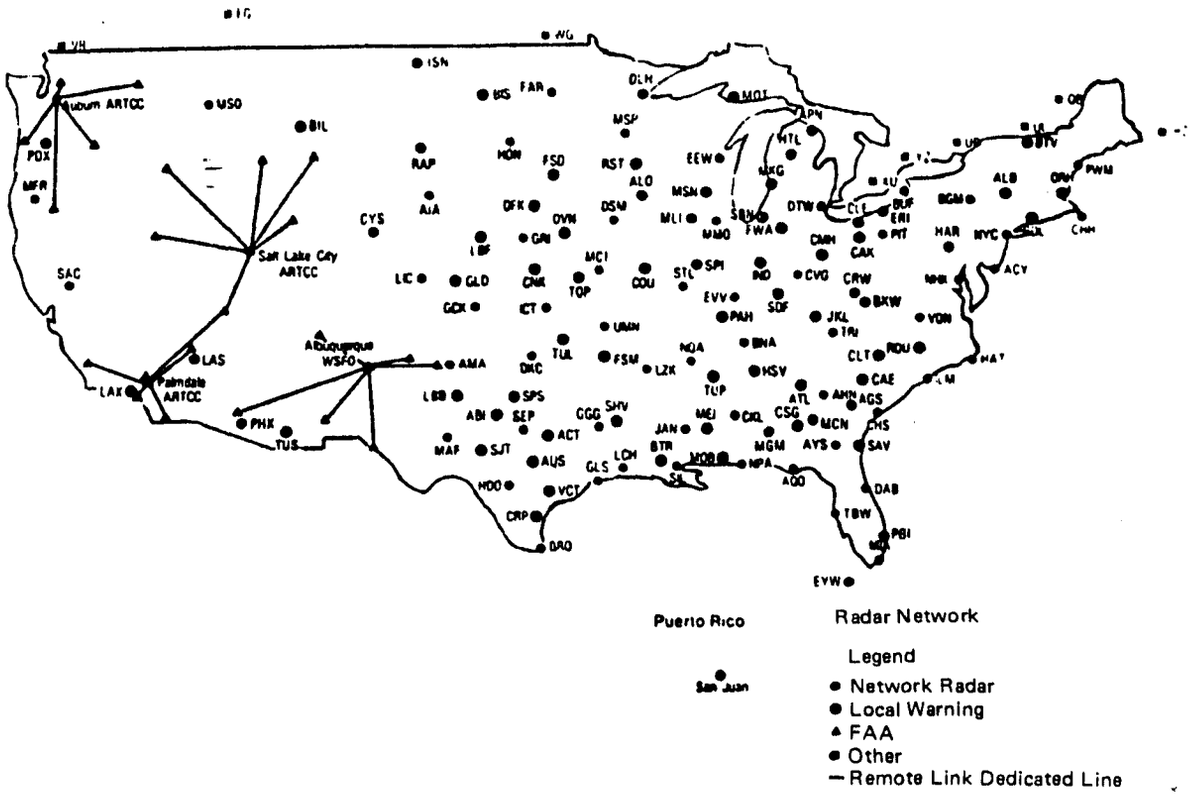

Figure 3. U.S. Radar Network

5. SUMMARY

The above data bases provide high density, nationwide precipitation information throughout all seasons of the year. This wide coverage provides extensive opportunities to validate satellite derived precipitation under many different meteorological conditions. The very high time resolution of the HPD and radar data bases offer the possibility of identifying the occurence of high intensity, short duration precipitation for use in studies to improve the satellite precipitation algorithms.

ON IMPROVED VALIDATION OF RAINFALL ESTIMATES FROM GEOSYNCHRONOUS IR PRODUCTS

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Tropical rain systems are a crucial working part of the machinery that makes the climate. Changes in these rain systems are key linkages in climate variability. Furthermore, the water these clouds release gives life to the biosphere, and drastic changes or local shrinkage in rainfall can disrupt the biosphere, including man, sometimes with disastrous consequences. To predict the large-scale circulation of the atmosphere, we need to know the sources and sinks of energy. The atmosphere's main energy source is the latent heat of condensation, released by raining cloud systems. The distribution of the heat release, including its profile in the vertical, is needed to predict the air circulations on all scales, but this is not a one-way prediction process. The cloud heat sources are themselves products of the airflow. Thus, feedback interaction is the key framework in which we wish to address the satellite validation problem.

The aim of this international conference is to organize means to validate rainfall from an "on-top" mapping of IR brightness temperatures, as sensed from geosynchronous platforms, where the present 8 x 8 km^2 pixel area is a substantial fraction of the area of many rain systems. Effectively, we are assuming a relationship between cold pixels as sensed at this resolution and precipitation amount, when averaged over areas about 2.5° latitude x 2.5° longitude for time periods of about 30 days.

A problem we encounter immediately is that within and below the same IR top field, vastly different precipitation amounts and distributions may be occurring. Striking examples are seen by comparing Figure 1 (schematic of tropical marine convective rain system) and Figure 2 (schematic of a convective rain system over semi-arid land), which may have similar distributions of IR cloud-top temperatures.

This comparison begins to make it clear why it is not sufficient, in the validation effort, just to compare mean rainfalls from satellite indices with monthly averaged time series over the available gauge or gauge/radar networks. We must do this, but we must also exert the effort to do more and better for two main reasons (Figure 3). The first reason was illustrated by comparison of Figures 1 and 2. The second and equally important reason is that we need to document and understand precipitating cloud systems better in order to treat their role in global change. There are vital feedback relations among clouds, their forcing (which is dynamic even more than directly thermal), and their impacts on circulations, whose changes result in different cloud forcing and structure. Nowadays, we have the tools to do validation at a much more profound level (Figure 4), if we are determined to muster the required resources and reinforce communications between the diverse research groups needed to do it. We will attempt to outline suggested steps to be undertaken.

First, the Special Sensor Microwave Imager (SSM/I), a multi-channel microwave instrument in polar orbit, will be launched on a military satellite

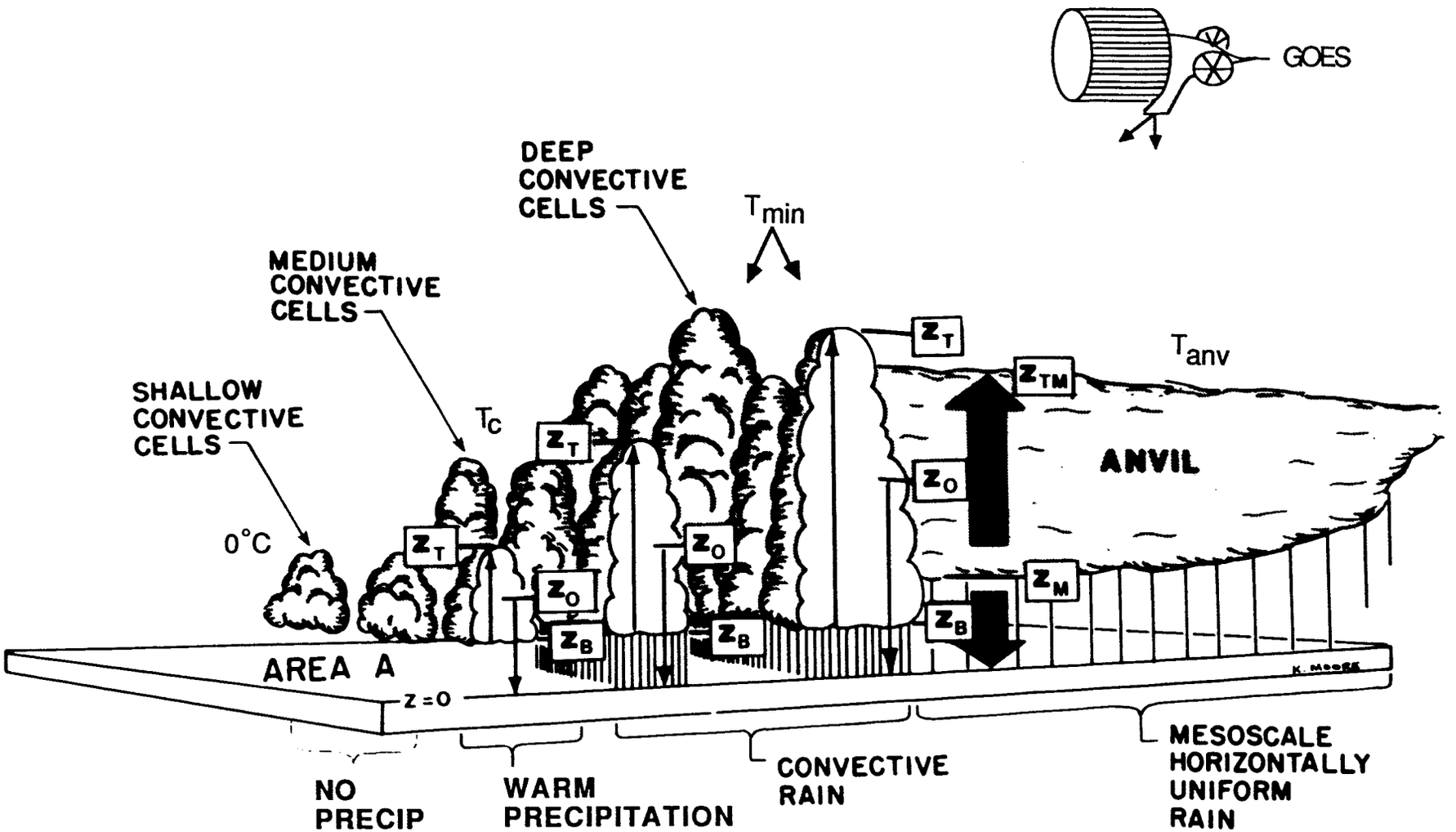


Figure 1. Tropical Maritime Convective Rain System

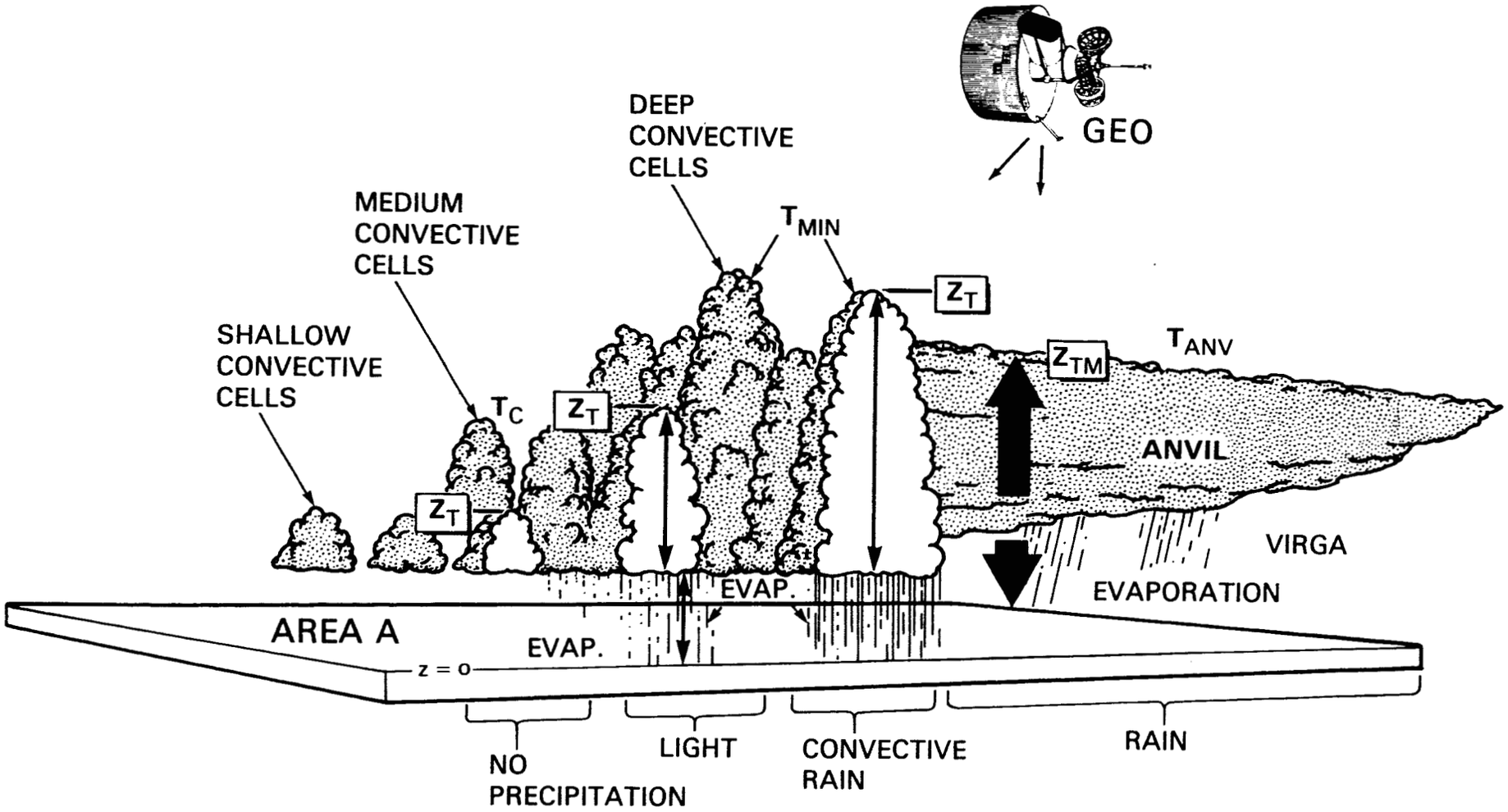


Figure 2. Semi-Arid Continental System Transition to M With Time? Strong Forcing? (Now Subject to Model Simulation)

REASONS WE MUST DO BETTER

(THAN JUST COMPARISONS OF TIME SERIES OF MONTHLY AVERAGES OVER LARGE AREAS)

- WE CANNOT UNDERSTAND CLIMATE LINKAGES, GLOBAL CHANGES INVOLVING PRECIPITATION, CLOUDS, WITHOUT SOME UNDERSTANDING HOW CLOUD AND MESOSCALE PROCESSES WORK

  -- BECAUSE OF FEEDBACK LOOPS BETWEEN

  - CLOUD FORCING BY ENVIRONMENT
  - CLOUD STRUCTURE, DEVELOPMENT
  - CLOUD IMPACTS ON ENVIRONMENT

- MARINE VERSUS ARID CONTINENTAL RAIN: IR TEMPERATURE MAPS MAY BE IDENTICAL BUT PRECIPITATION/EVAPORATION UNDERNEATH MAY DIFFER GREATLY

Figure 3.

REASONS WE CAN DO BETTER

1. SATELLITE MICROWAVE AND ATTENDANT STUDIES

   a. SSM/I launch in 1987
   b. Acceleration of TRMM effort, ground truth

2. PROGRESS IN DISTINGUISHING CONVECTIVE VERSUS ANVIL STRATIFORM RAIN USING GEOSYNCHRONOUS IR IMAGERY

3. PROGRESS IN NUMERICAL MODELLING

   a. Cloud populations, systems (e.g. Tao)
   b. Clouds in mesoscale models (e.g. Cotton, Pielke, Fritsch)

4. DATA SETS CAN IMPROVE UNDERSTANDING, MODELS, MICROWAVE USE TO UPGRADE/CORRECT IR ESTIMATES IN SOME KEY SITES

   a. GATE-Ocean, E. Atlantic ITCZ, 1974 ~3 months
   b. WINTER MONEX-Ocean, Asian monsoon, 1979 ~1 month
   c. AMEX/EMEX-Land/Ocean, Australian Monsoon, 1987 ~2 months
   d. S. Africa & Israel-Semi-arid continents, 10-20 years
   e. Florida-Land and ocean

      Face-S. Florida, 1970-1980, summers. Gage calibrated radar, soundings, aircraft flights, much other data and analyses

      Cape Canaveral networks, N. Central Florida, build up starting now, year round, NEXRAD 1989

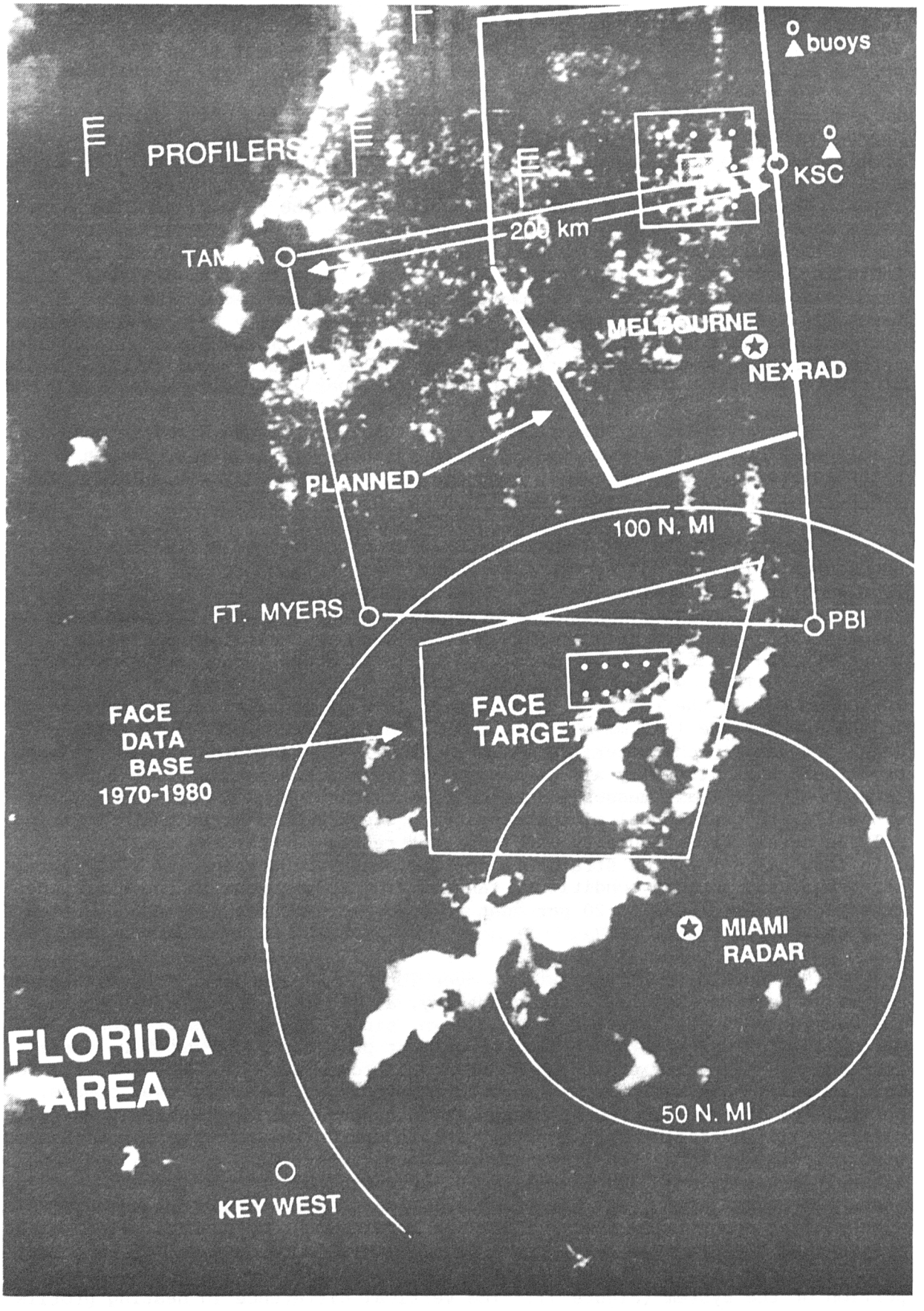
Figure 4

in 1987, providing swaths of underflights at 7 a.m. and 7 p.m. local time. This instrument should be able, using the emission channel at 18 GHz and the dual-polarization feature at 18 and 37 GHz, to give rain rate estimations over oceans which are considerably more accurate than IR alone, despite the 25 x 25 km^2 large footprint of those channels. Over land, the work of Roy Spencer and colleagues (Spencer et al., 1983a,b,c; Spencer, 1984) has shown promise in using the ice-scattering effect both to discriminate rain versus no rain and to recognize high rates by the presence of a strong ice-scattering layer. The better (12.5 x 12.5 km^2) resolution of the 85 GHz channel on the SSM/I should greatly aid in understanding the role and diagnostic use of ice layers in land clouds compared with marine cloud systems. Intensive studies, including modeling, should first concentrate on those key land and ocean sites with calibrated and/or multi-parameter radars, instrumented aircraft, mesoscale networks, etc., to learn how the IR products may be upgraded by the microwave signals over the rest of the SSM/I swaths. These results could then perhaps enable computerized corrections to the IR products even outside the microwave swaths, depending on geography, orography, and climate regime.

The remainder of this talk will be mainly concerned with progress in distinguishing convective versus stratiform (anvil) rain in the context of an existing Florida data set, while emphasizing the value of the Florida area and its present and planned data acquisition to this validation effort (Figure 5).

Beginning with the GATE radar studies of Houze and colleagues (Leary and Houze, 1979), it has become clear that a significant fraction of the rain from cumulus cloud systems falls from stratus layers and the anvils created by the convective activity. Figure 6 presents a schematic vertical section through the right-hand half of Figure 1, showing typical distance scales, radar echo intensities, and rainfall rates in an oceanic convective cluster typical of GATE or winter MONEX. Note that the rain rates are in the range 10-100 mm h^{-1} in the restricted regions of intense updraft, while they are in the lower range 1-10 mm h^{-1} in the much larger stratiform anvil regions, which are usually characterized by a bright melting band. Amazingly, it has been found that virtually all other convective systems examined (in humid ocean or tropical air masses), ranging from tropical squall lines, hurricane eye walls, to continental midwestern severe storms, have structures differing only in detail from Figure 6. An important result is that the fraction of rain that falls from the stratiform portion of the cluster varies with system size, age, and ambient conditions, ranging from 60 per cent in one hurricane case (Jorgensen, 1984) to 20 per cent in four Florida undisturbed convective days (Adler and Negri, 1987).

For satellite IR estimations over long time periods and large areas, one might believe that it is not necessary, at least to first order, to know the convective versus stratiform breakdown, since one might assert that the strong cumulus updrafts are the machines that pump the water vapor up there and condense it, so that just when and how it comes down does not matter. For rain amounts, this may be a marginal first-order approximation over oceans, but surely not over land, where evaporation reduces rainfall directly as fall distance and inversely as rain rate. The importance of anvil processes has been revealed by recent analyses with cloud microphysics, modeling, and aircraft observations. The anvils actually contain mesoscale updrafts, adding their own condensation (and heat release). Mesoscale evaporating downdrafts with cooling occur below them. Thus, the total amount of precipitation may be affected by anvil activity and, moreover, the vertical profile of latent heat release is drastically different in the anvil areas than in the convective portion of the system (Figure 7). The vertical difference in heating profile


buoys
PROFILERS
KSC
200 km
TAMPA
MELBOURNE
NEXRAD
PLANNED
100 N. MI
FT. MYERS
PBI
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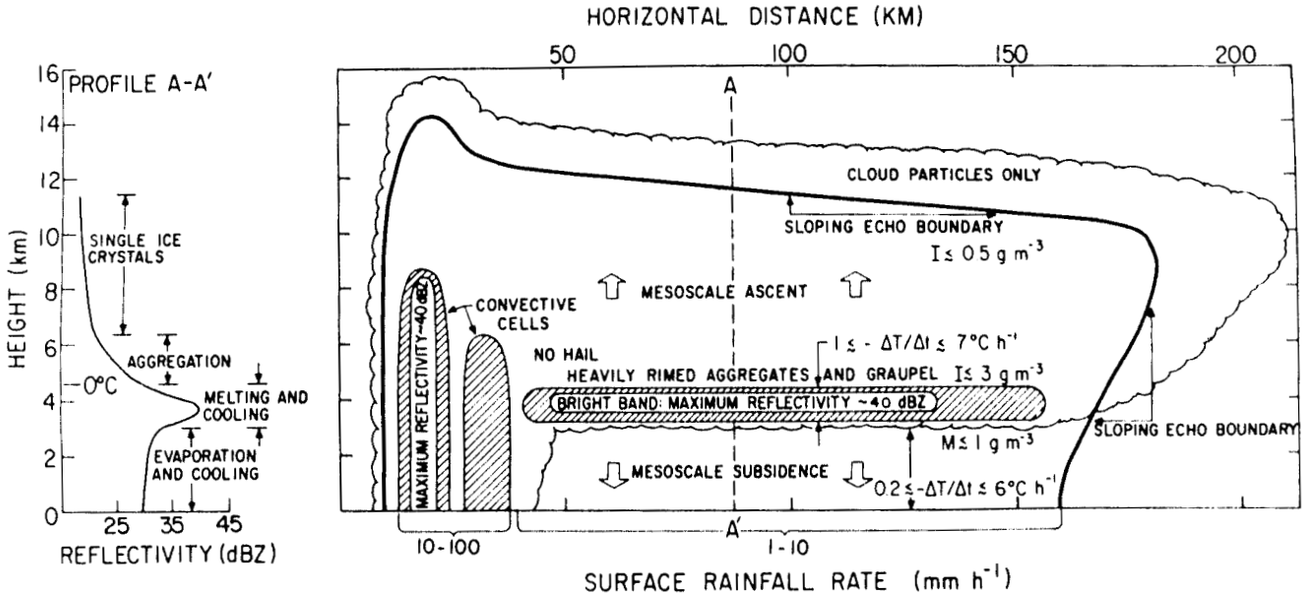
DATA
BASE
1970-1980
FACE
TARGET
MIAMI
RADAR
FLORIDA
AREA
50 N. MI
KEY WEST

Figure 5



SCHEMATIC OF RADAR ECHOES AND RAINFALL RATES IN CONVECTIVE CLOUD SYSTEMS (AFTER LEARY & HOUZE, 1979)

STRATIFORM RAIN IS A SIGNIFICANT PERCENTAGE OF TOTAL RAIN

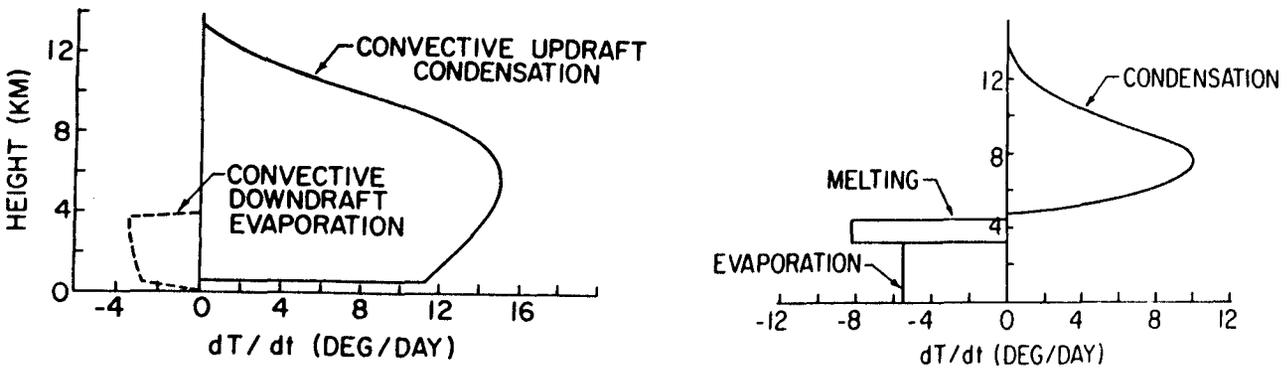
- **GATE + WINTER MONEX ≅ 30%-50% (HOUZE et al.)**
- **HURRICANE ALLEN 1980 ≅ 60% (CHENG & JORGENSEN)**
- **PRE-STORM (MIDWEST U. S.) ≅ 30% (ZIPSER)**
- **S. FLORIDA SUMMER (4 DAYS) ≅ 20% (ADLER & NEGRI)**

FRACTION DEPENDS ON SYSTEM SIZE, AGE, AMBIENT CONDITIONS

Figure 6

LATENT HEAT RELEASE VERTICAL PROFILES DIFFER DEPENDING ON FRACTION OF PRECIP IN

CONVECTIVE VS. STRATIFORM



AFTER HOUZE (1982)

Figure 7

has important implications in large-scale dynamics and climate. The anvil components of rainfall vary with system size and increase as a system ages, it also is a function of environment stability and humidity structure.

One might speculate that an early linkage in the drought onset cycle could be a sharp sensitivity of anvil rain loss to an environment starting to dry out by subsidence. Loss of anvil rain would result in decreased soil moisture and evapotranspiration, leading to weakening of the next generation of convection through a higher evaluation of the condensation level, etc. Before the role of changes in anvil precipitation in droughts can be investigated, however, we need a means to discriminate in IR products between anvil and convective rain. The first steps have been taken by Adler and Negri (1986) in their Convective Stratiform Technique (CST), which will be briefly summarized.

CST was developed in the context of the FACE II (Florida Area Cumulus Experiment II, 1978-1980). This experiment had a gauge-calibrated 10 cm radar (network of 100 gauges), which was digitized and recorded. The radar operated through most of the daylight hours during the months of June through August

for three seasons. The gauge-calibrated radar was used as a primary evaluation tool (Barnston et al., 1981) in a double-blind experiment to evaluate the effects of massive silver iodide seeding on convective rainfall in a 10^4 km^2 target area in southern Florida. The extensive data from networks, soundings, aircraft, and Doppler radars, together with analyses and modeling results from FACE II and its five-season predecessor, FACE I, have been extensively described in the literature (Woodley et al., 1982, Barnston et al., 1983, Barnston and Thomas, 1983, Gagin et al., 1985) as has the Griffith-Woodley IR rain evaluation technique (Griffith et al., 1978, Meitin et al., 1984), which was evolved in FACE I to assess the effects of seeding upon rainfall outside the target area.

The CST locates, in an array of infrared data, all local minima in the brightness temperature field (T_{min}). The local spatial gradient of T_B versus T_B itself (Figure 8) is used to empirically screen out non-raining cirrus. The convective rain area and mean rain rate over that area are assigned to each T_{min} by adapting a series of one-dimensional cloud model results by Adler and Mack (1984), which had already been tested against Florida data. The one-dimensional model is used to take into account the effects of environment stability, humidity, and a rough cut at the effects of wind shear (via an entrainment coefficient) in order to make IR estimates of convective rain in locations with different cloud environments. It has been shown to do well for both Florida and Oklahoma summer (both of these regions also have nearly identical curves separating cirrus from convective rain, as shown in Figure 8), but has not yet been applied to a semi-arid region. Since an environment sounding and some knowledge of cloud-base height are the only local data required for the model runs, extension to arid areas might seem easy. However, sounding selection must be carefully made from a preconvective or early stage convective environment. The climatological mean sounding would be unlikely to produce raining cumuli, while a rainstorm sounding would probably have been greatly modified by cloud activity.

To develop the anvil stratiform algorithm, a T_B threshold, T_S, is used to identify the anvil stratiform region. Since this threshold should coincide with the relatively thick portion of mature anvils, the anvil mode temperature (T_{mode}) is used as an indicator of the anvil background T_B. T_{mode} was used previously by Adler et al. (1985) as such an indicator, with a close correspondence to the near-tropopause neutral buoyancy point (for wet adiabatic ascent). Since it is desirable that the stratiform scheme activate when large cold cirrus anvils are present, T_{mode} is calculated for each T_{min} whose slope is less than or equal to 4 on Figure 8 (this value is chosen empirically). The details are discussed in the paper by Adler and Negri (1987, loc. cit.). The important point for consideration here is that since the CST technique depends only on geosynchronous IR temperatures (minima and gradients), the technique should be transportable to other regions. In semi-arid regions, evaporation would need to be taken into account and tests with gauge-adjusted radars and SSM/I overflights specifically made.

In southern Florida, the CST technique has been tested so far for only four days. Half hourly estimates made in the FACE target area were verified against rain gauges and both unadjusted and gauge-adjusted radar. The results from the CST were compared with the estimates from the Griffith-Woodley technique (Meitin et al., 1981) with results from a simplified version of that technique (Negri et al., 1984) and with the results from the simple cloud threshold scheme of Arkin (1979).

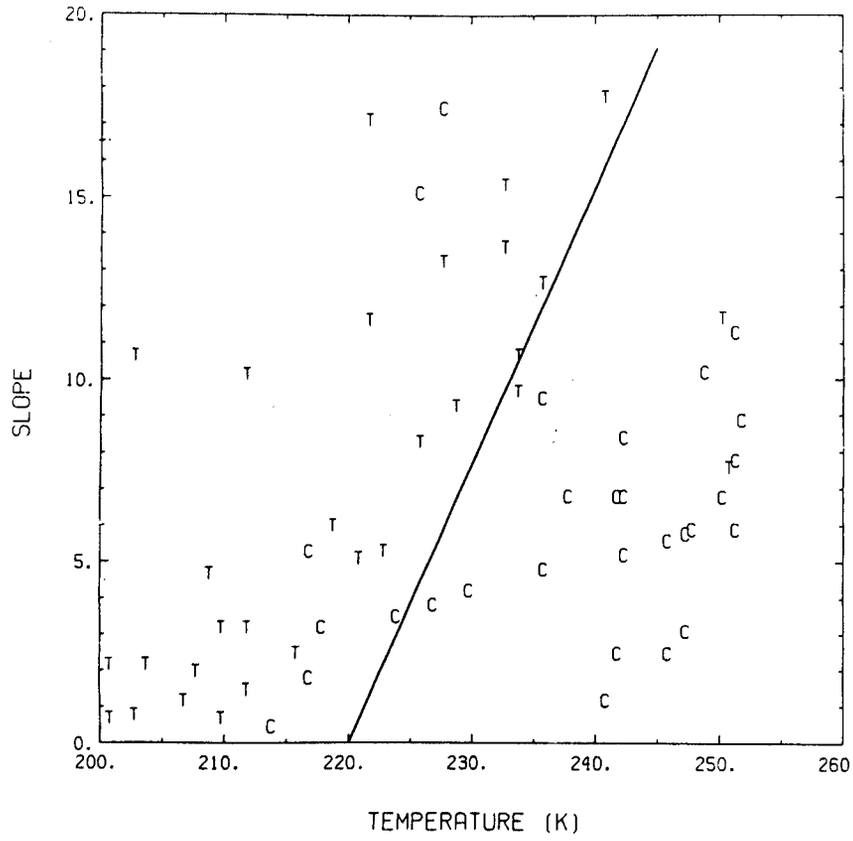
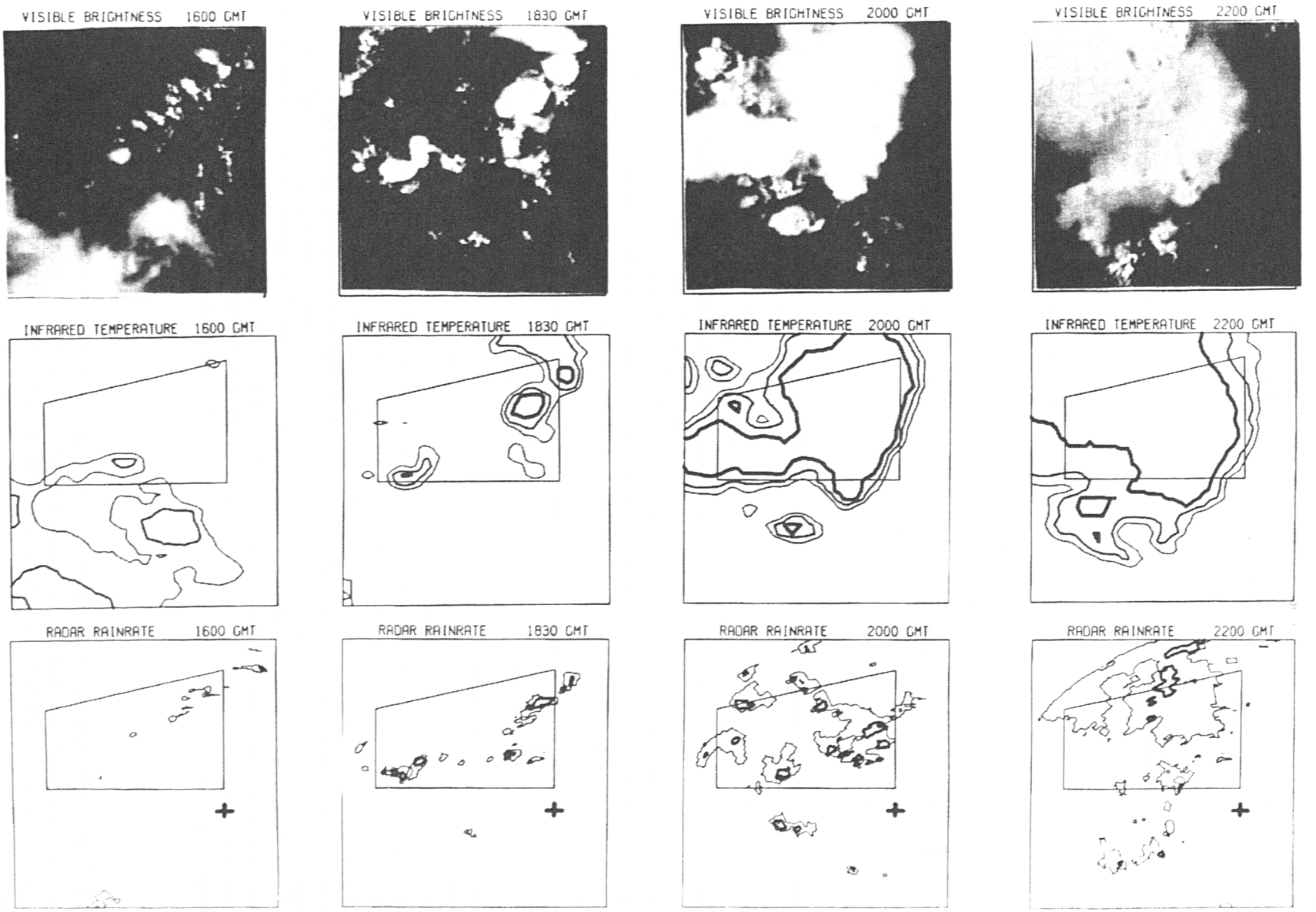


Figure 8

CST rain fields were spatially most similar to the radar for young, isolated storms and poorest in capturing linear features such as squall lines. Some convective features were missed, while other features (generally cirrus debris) were misrepresented as active convection. Stratiform estimates generally corresponded to the radar-derived 1 mm h^{-1} contour. The evolution of the precipitation averaged over the FACE target area (10^4 km^2) was well represented, particularly in capturing peak rainfall and the transition from convective to stratiform rain. Other satellite schemes tested had a tendency to underestimate the rainfall early and overestimate late. Area-averaged stratiform estimates were in good agreement with a modification of a radar-based technique developed by Churchill and Houze (1984) and comprised 10-30 per cent of the total rainfall. An example is shown in Figure 9 for a rather wet convective day.

Statistically, the CST had the lowest bias (-0.02 mm h^{-1}), lowest mean absolute difference (0.28 mm), lowest root mean square difference (0.39 mm), and lowest per cent difference (41.2%) of any satellite technique, when the ground truth was the gauge-adjusted radar. Relative ranking of the techniques remained the same when the ground truth was the gauges alone, although all the above statistics increased. All techniques made daily (8-h) estimates that were reasonable, although the three modes of ground truth were not always in agreement.


VISIBLE BRIGHTNESS 1600 GMT
VISIBLE BRIGHTNESS 1830 GMT
VISIBLE BRIGHTNESS 2000 GMT
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INFRARED TEMPERATURE 1600 GMT
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INFRARED TEMPERATURE 2200 GMT
RADAR RAINRATE 1600 GMT
RADAR RAINRATE 1830 GMT
RADAR RAINRATE 2000 GMT
RADAR RAINRATE 2200 GMT

Figure 9

This new technique seems to do better than previous attempts in estimating the evolution of rainfall in tropical convective systems in a marine or fairly humid environment. The breakdown of rainfall into convective and anvil stratiform components presents the potential to study the structure of tropical convective systems even in the absence of radar or gauge data, and possibly better estimate the vertical heating profiles and vertical motion profiles.

Before summarizing, it is important to point out a class of significant tropical rain systems for which the existing satellite rain estimation techniques based on cold cloud temperatures are not suited. These are the cold lows, kona storms, and other mainly wintertime precipitating systems in the subtropics and that poleward portion of the tropics which is influenced by the westerlies. If convection occurs in these storms, it is usually high based, with no connection down to the CCL or the lower boundary layer. Often, convection is barely present, or exists only in the form of bands of more intense rain in raining altostratus or nimbostratus layers. Clearly, the latent heat release from these systems is important and will have a very different vertical and temporal distribution from those of convectively driven systems. Work has been done on automated cloud pattern recognition from GOES VIS and IR. Relating the patterns to precipitation probability has been done by Weinman and colleagues (Garand, 1986). These methods probably need tuning for regions and seasons, nevertheless, they appear the most promising approach to tropical and extratropical nonconvective rain systems, particularly if developed with microwave retrievals and in strong ground truth areas, such as the planned Cape Canaveral network (with NEXRAD added in 1989) in north-central Florida.[1] As yet, however, microwave cloud radiative models have not been modified for these cloud situations, nor are there any substantial existing data bases (except possibly in Israel, which is not seen by GOES), so that the development of evaluation and validation schemes for these rain systems presents an important and very formidable challenge.

The steps advocated in Conclusions and Recommendations I (Figure 10a) should be relatively modest in cost and human labor. The use of the CST might, in particular, increase the variance accounted for by a substantial increment if first tested and applied in a semi-arid continental region, using and extrapolating the evaporation study of Rosenfeld and Mintz (1986), which was developed for a data base in South Africa. Evaporation rates might then be assigned to convective and anvil rain separately for climatic regimes, based on readily available surface and sounding data. If communications between research groups are systematically organized, the already-planned analyses with SSM/I could possible be torqued slightly to produce the desired comparisons. One-dimensional cloud model runs could be made on a few classes of soundings characteristic of different convective rain regimes rather than making many runs on a short time interval basis. For non-convective wintertime rain, adaptation of microwave models appears to be the best hope of useful supplementation of IR indices.

[1]These plans are being made by NASA to help improve short-range forecasts for the Space Shuttle and as a ground truth site for a planned satellite tropical rainfall measuring mission (TRMM). Field programs in the area are planned, beginning in about 1988.

For the key sites noted in Conclusions and Recommendations II (Figure 10b), there is an extensive FACE bibliography at ERL/NOAA. Contacts to obtain information on the data available and/or planned at the other sites can be provided by the writers, if desired.

CONCLUSIONS AND RECOMMENDATIONS I

- ADAPT CONVECTIVE STRATIFORM TECHNIQUE (CST)
  - In areas where soundings, tests are available
  - To arid areas by devising corrections for evaporation
  - Attempt extrapolation to areas with gauges only (determine whether it can improve relative to IR index)

- ESTABLISH MEANS OF COMMUNICATION BETWEEN KEY RESEARCH GROUPS WORKING ON
  - Satellite rain retrievals
  - Basic physics/dynamics of rain systems
  - Cloud and mesoscale modelling

- INCLUDE MICROWAVE AND MODELS TO CORRECT ESTIMATES
  - Use SSM/I to develop corrections for rain systems in different climatic regions
  - 1-D models help improve convective rain estimates. More sophisticated models relate cloud top IR features to precipitation processes

Figure 10a. Conclusions and Recommendations I

CONCLUSIONS AND RECOMMENDATIONS II

- SELECT A FEW KEY GROUND TRUTH SITES WITH DATA BASE, RESEARCH PRODUCTS

  1. FLORIDA AREA

     A. FACE DIGITIZED RADAR RECORDS, RAIN GAUGES, SUPPLEMENTARY DATA, SATELLITE RAIN ANALYSES, MODELS PROVIDE A GOLD MINE OF SUMMER CONDITIONS, LAND & WATER

     B. CAPE CANAVERAL GROWING NETWORKS WITH PROFILERS, GAUGES, SOUNDING EQUIPMENT, SSM/I OVERFLIGHTS, NEXRAD PROVIDE OPPORTUINITY FOR ALL SEASON VALIDATIONS, TESTS WITH WINTERTIME RAINSTORMS, LAND AND OCEAN, NASA AIRCRAFT EXPERIMENTS PLANNED

  2. SEMI-ARID AREAS (WITH DATA AND RESEARCH)

     A. NORTHWEST AUSTRALIA-MONSOON REGIME AMEX/EMEX 1987. PLANS FOR DARWIN RADAR

     B. ISRAEL-LONG HISTORY OF GAUGE RECORDS RELATED TO PRECIPITATION RESEARCH, SEEDING

     C. SOUTH AFRICA-TWO PRECIPITATION RESEARCH SITES GAUGES, RADAR, HAIL DATA

  3. OCEANIC-IN ADDITION TO GATE, WINTER MONEX

     *A. PACIFIC ATOLLS-MARSHALL ISLANDS, KWAJALEIN RADAR, PROFILER NETWORK

     B. WEST INDIES, ESP. BARBADOS

     *C. TOGA SITES IN EASTERN PACIFIC

*Planned for near future or in early stages

Figure 10b. Conclusions and Recommendations II

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PRECIPITATION CLIMATOLOGY

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1. INTRODUCTION

My own particular field of interest in relation to this proposed study is in the ground truth aspect. The rather frustrating facet of the problem is that we do not know what the ground truth (or rainfall over an area, especially one as large as 2.5° latitude x 2.5° longitude) really is.

Since proxy methods (radar, river flow) have their own inherent inaccuracies, the integration of point measurements (gauges) currently offers the best solution. Clearly the technique involved depends on a number of features. For example:

(i) What rainfall variable is of interest? Over what period?

(ii) For what purpose are the data required?

(iii) What is the accuracy of a raingauge observation?

(iv) What arithmetical/statistical methods should be used to obtain an areal value?

(v) How does the type of rain-causing system affect the estimates?

After addressing these points in turn, I would like to present some information on the unusual data base held at Texas A&M University (TAMU); one that I believe could be used to address some aspects of our initial problem.

2. DEFINITION/HISTORICAL

Precipitation climatology can be defined as the study (presentation) of any aspect of precipitation over a selected period of time.

The first network of raingauges, of which we have record, is that instituted by John Dalton in N.W. England beginning in 1787 and continuing through 1844. The observations were first published in 1793 and in 1840, Joseph Atkinson prepared the world's first map of average rainfall, based on those observations. In 1862, Muhry published a world map of the seasonal distribution of precipitation and during the last 100 years, there has been a multitude of maps and graphs giving rainfall information.

We tend to think of rainfall climatology as being concerned with amounts received during a specific time or incident, but there are actually many other aspects possible. Rain days (above a selected threshold), persistence of rain days, variability of amounts, probability aspects, and extreme falls are but a few of these, as Figures 1 through 9 illustrate.

3. NEED AND ACCURACY

At the root of any collection and presentation of climatological data must be the question "Why are the measurements needed?" In other words, what

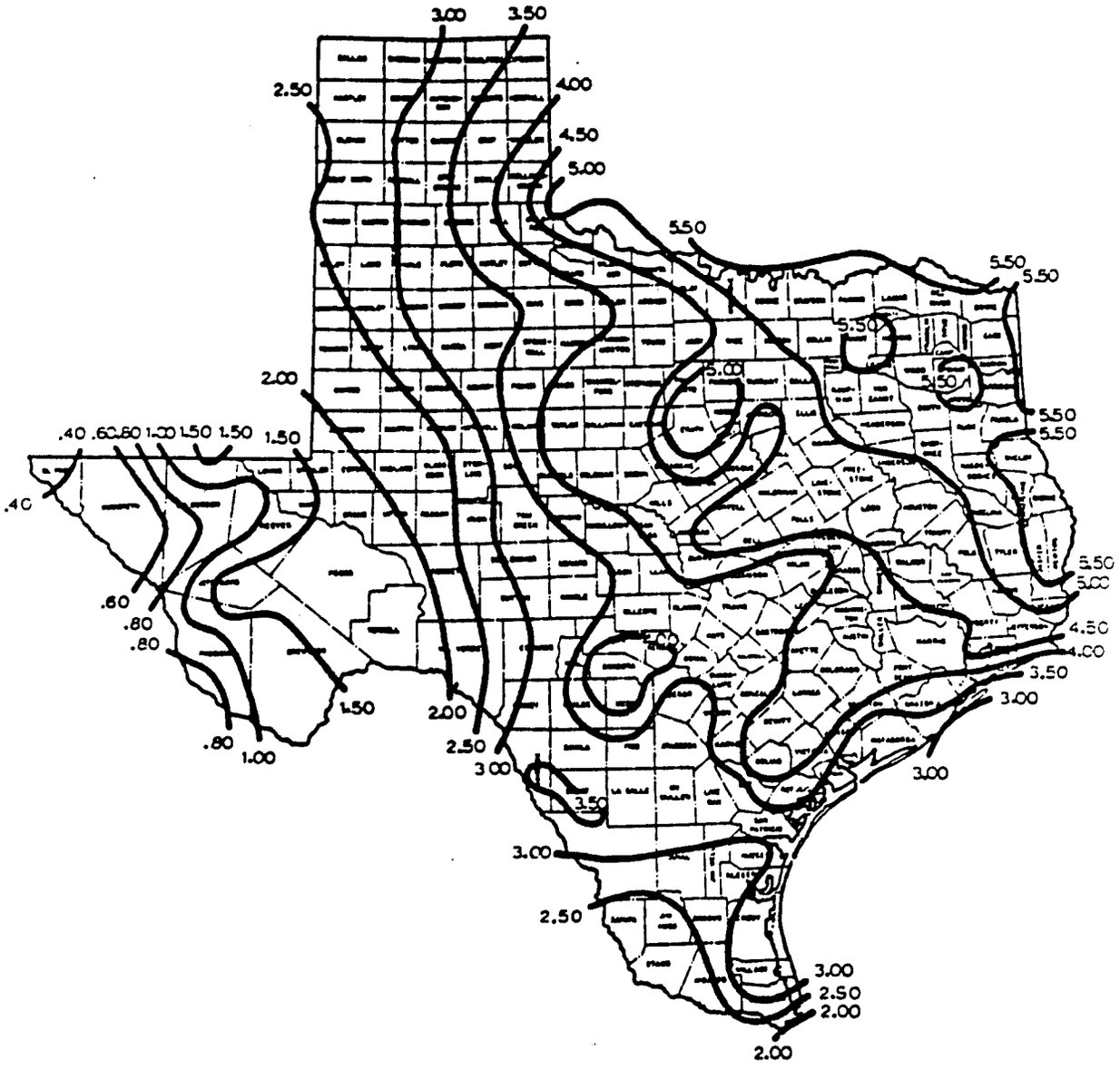


Figure 1. Normal Total Precipitation (Inches) Based on the Period 1931-1960

is the purpose of the operation? In our case, as I interpret it, there are four reasons of prime importance.

(i) To check empirical estimates derived from satellite information.

(ii) To estimate river flows (hydrology).

(iii) To assess soil moisture (agriculture).

(iv) To assist in the science of meteorology by giving a better understanding of the components of diabatic processes, and providing measurements of use in climatic modeling.

It is very likely that the accuracy desirable for each of the aims will be different. In a recent publication, an error value of 1 cm/month (= $10W/m^2$) over a 200 x 200 km^2 box is suggested. This is equivalent,

approximately, to a river flow of 10^4 m^3/min. For soil moisture it is likely that an error of much greater than 1 cm/month would be acceptable in many applications. Incidentally, it cannot be assumed that soil moisture patterns will mirror the rainfall patterns as the example from Kenya in Figure 10 illustrates. It shows that adequate soil moisture is most reliable and prolonged during the short range and not the long range.

4. MEASUREMENT ACCURACY

Historically, precipitation measurements have been made using gauges of about 5" to 8" diameter. Assuming the larger size, all of the raingauges from the National Weather Service (NWS) cooperative station network (12,000) could be fitted into a baseball diamond - not an impressive sample for an area of over three million square miles.

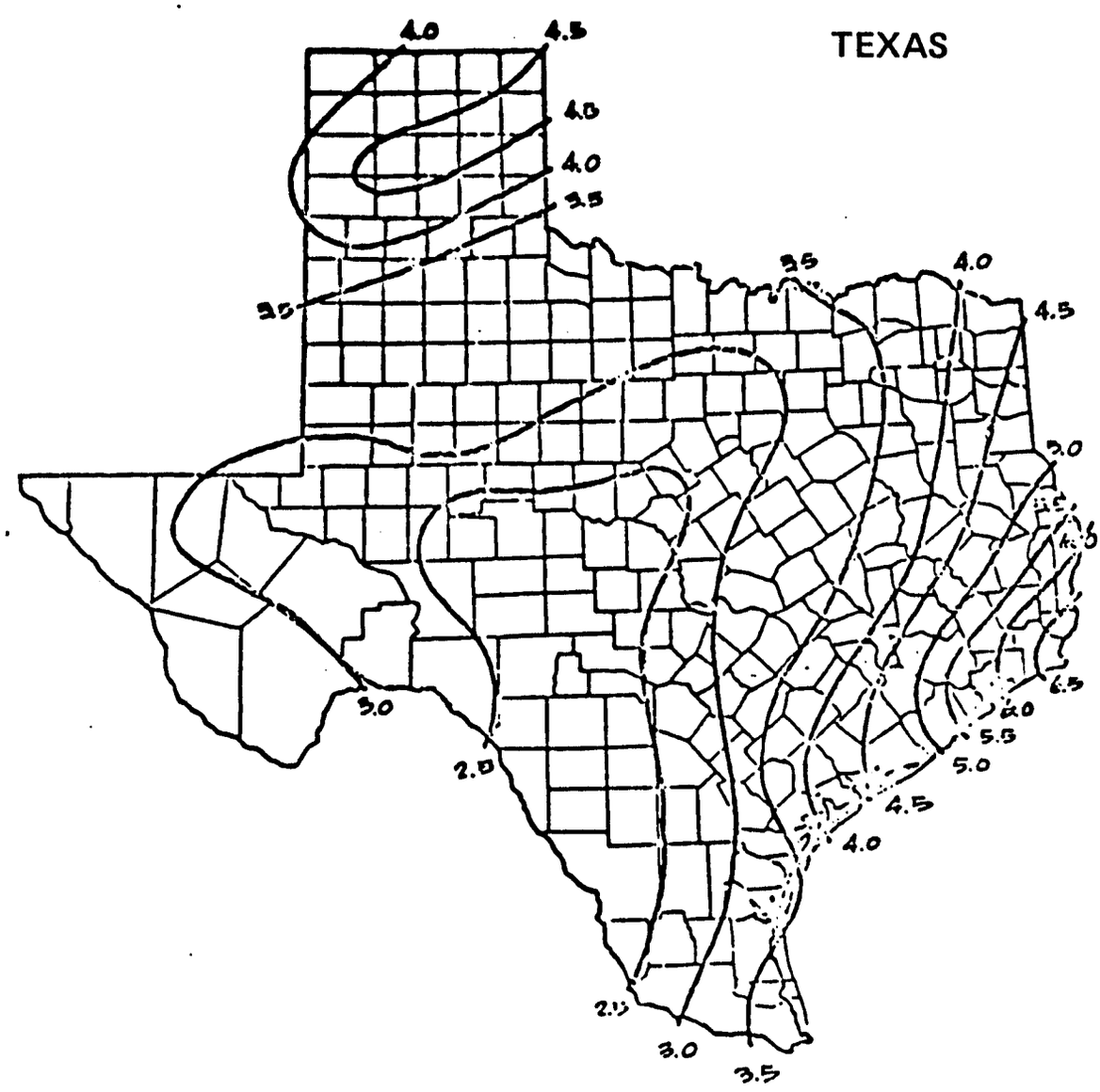


Figure 2. Mean Number of Days of Precipitation Greater Than or Equal to 0.10 inch in August

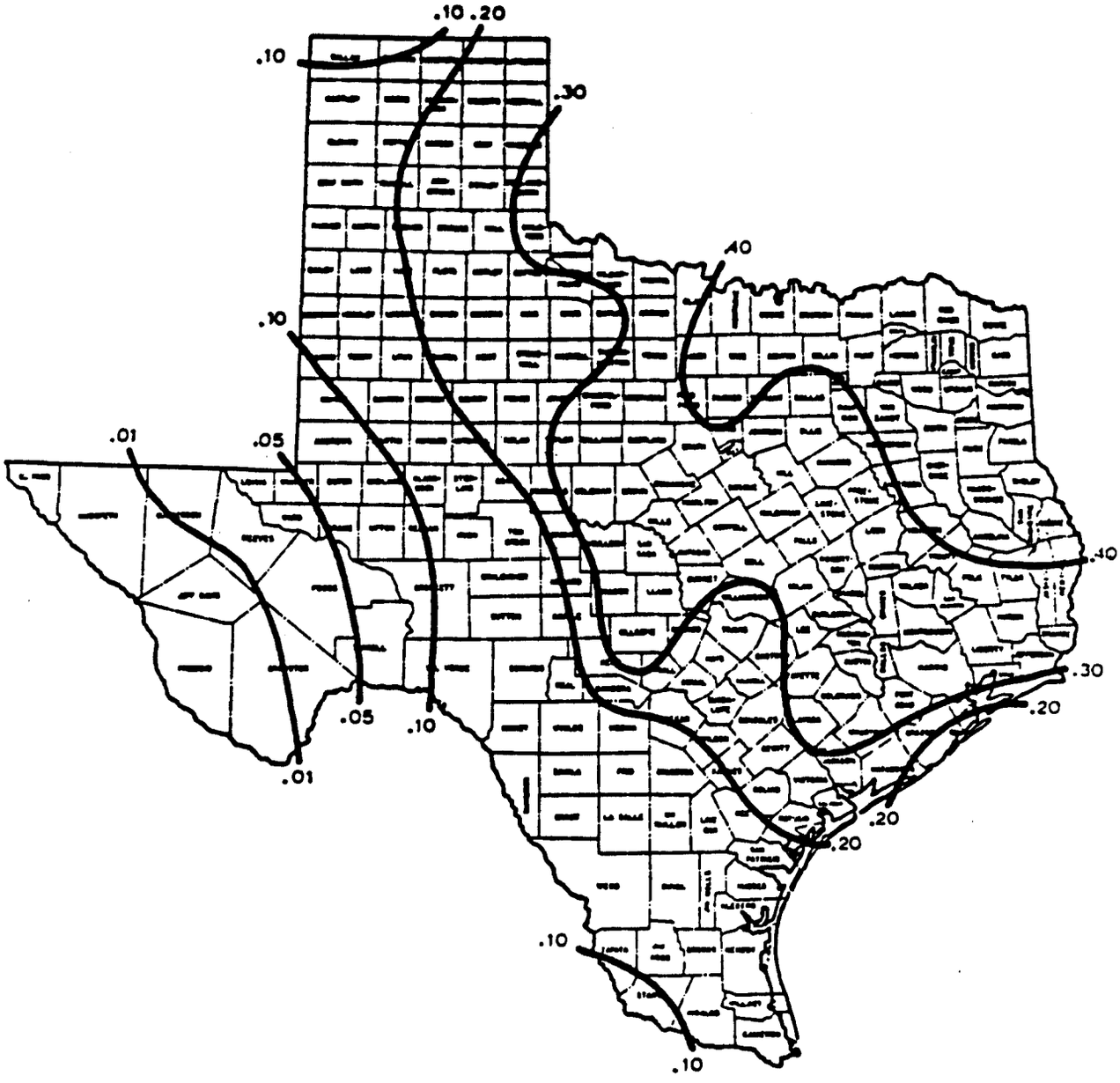


Figure 3. Probability of Receiving 5.00 Inches or More Precipitation During a Month

With regard to instrument accuracy, the impact of air flow upon the earth, evaporation, angle and depth of the funnel, rim size, and exposure, all play important roles in determining the final measurement. Investigations over reasonably uniform, small areas have shown that gauge catches can vary among themselves by as much as ±10 per cent in annual totals. In other words, we do not know the 'true' rainfall over an area.

Studies have shown that gauges with orifices above ground collect 5-15 per cent less than those with orifices at ground level, while from single rainfall events (storms) the discrepancy may range from 0 to 75 per cent. In rainfall (convective) studies, the sampling variation is inversely proportional to the number of gauges and directly proportional to the gradient of rainfall.

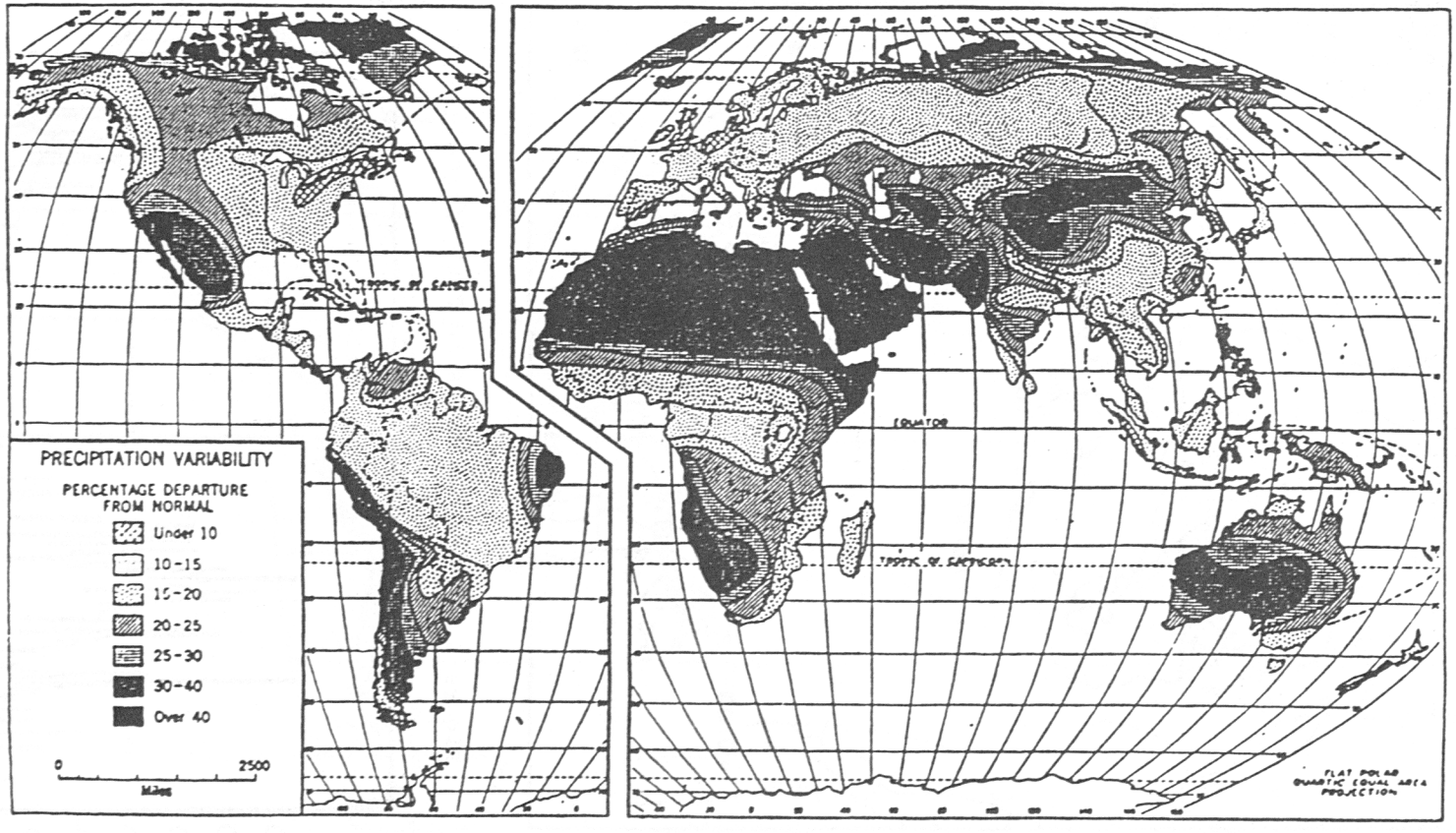


Figure 4. Rainfall Variability Characteristically is at a Maximum in Dry and Subhumid Climates (After Biel, Van Royen, and Others)

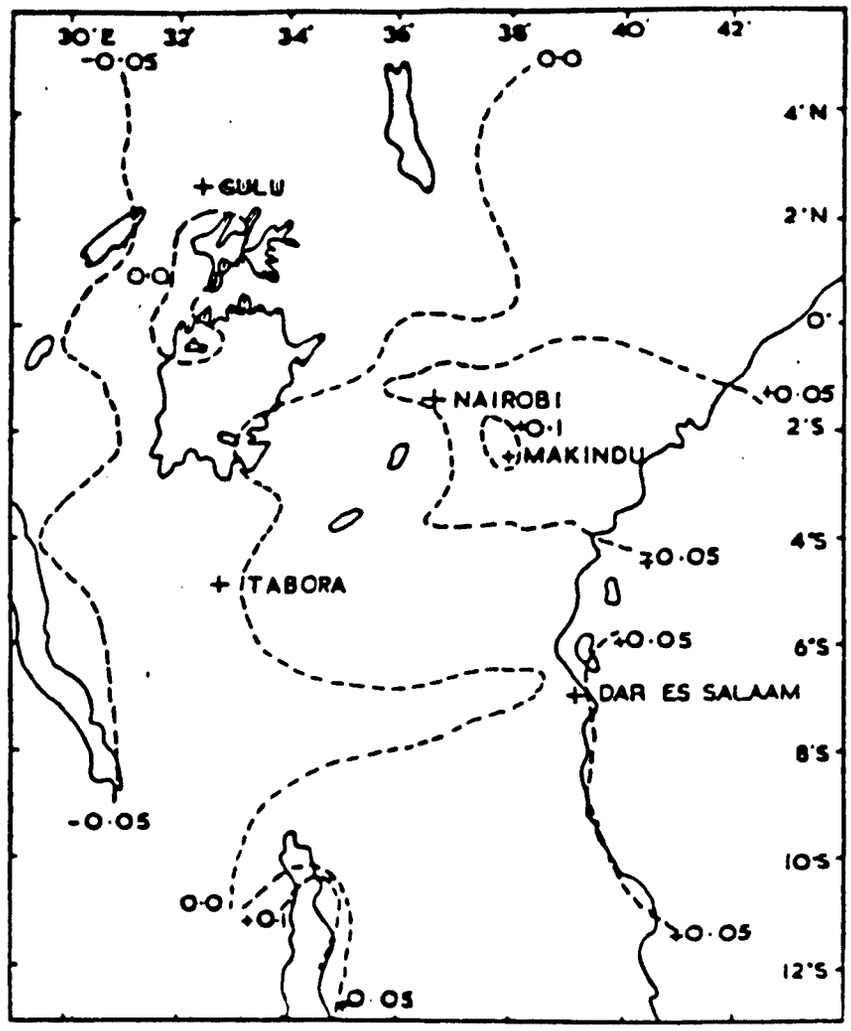


Figure 5. Anomalous Areas in East Africa

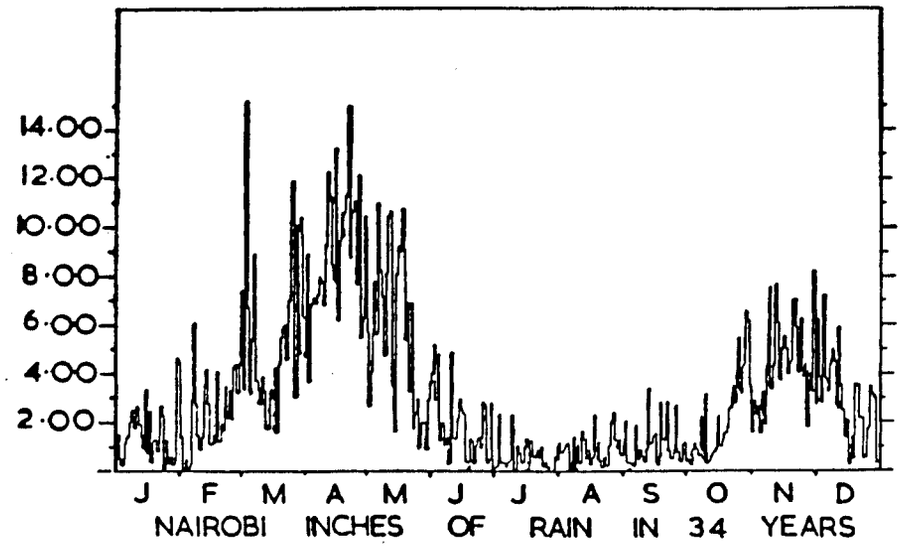


Figure 6. Distribution of Daily Amounts of Rain for Nairobi, Kenya

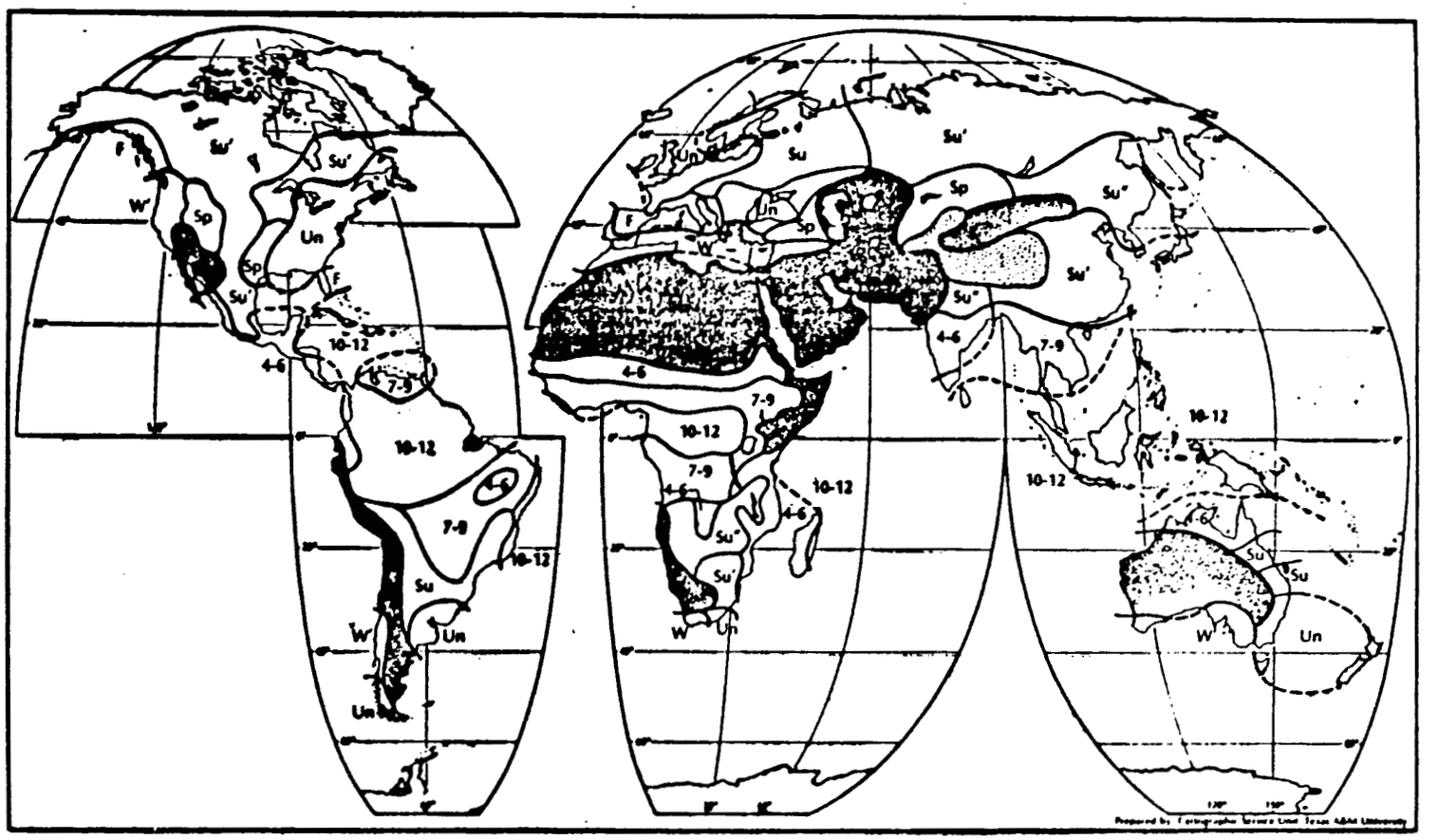
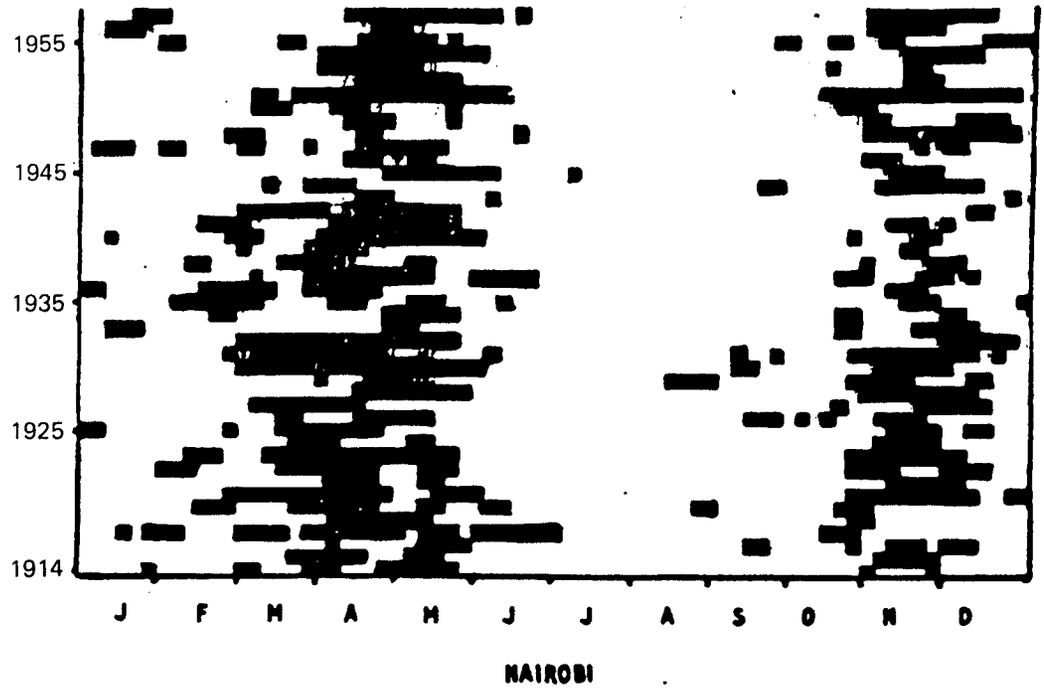


Figure 7. Regimes of Annual Precipitation



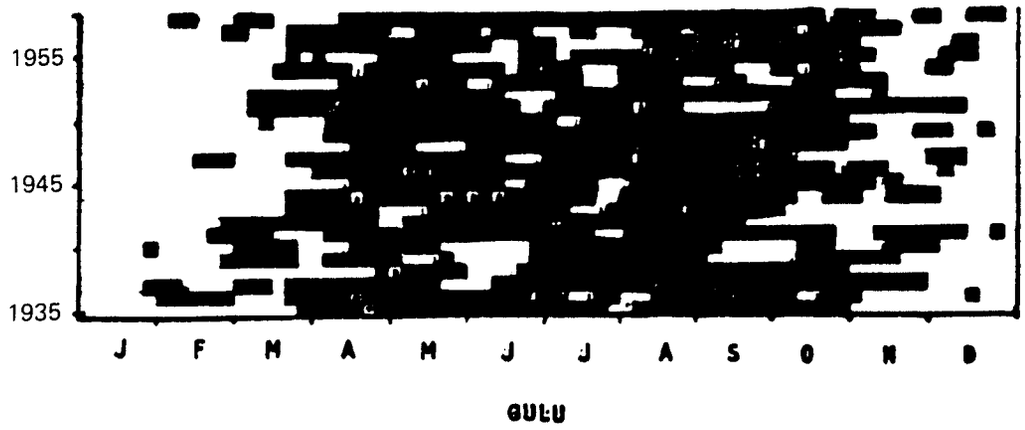


Figure 8. Rainy Pentads for Nairobi, Kenya and Gulu, Uganda

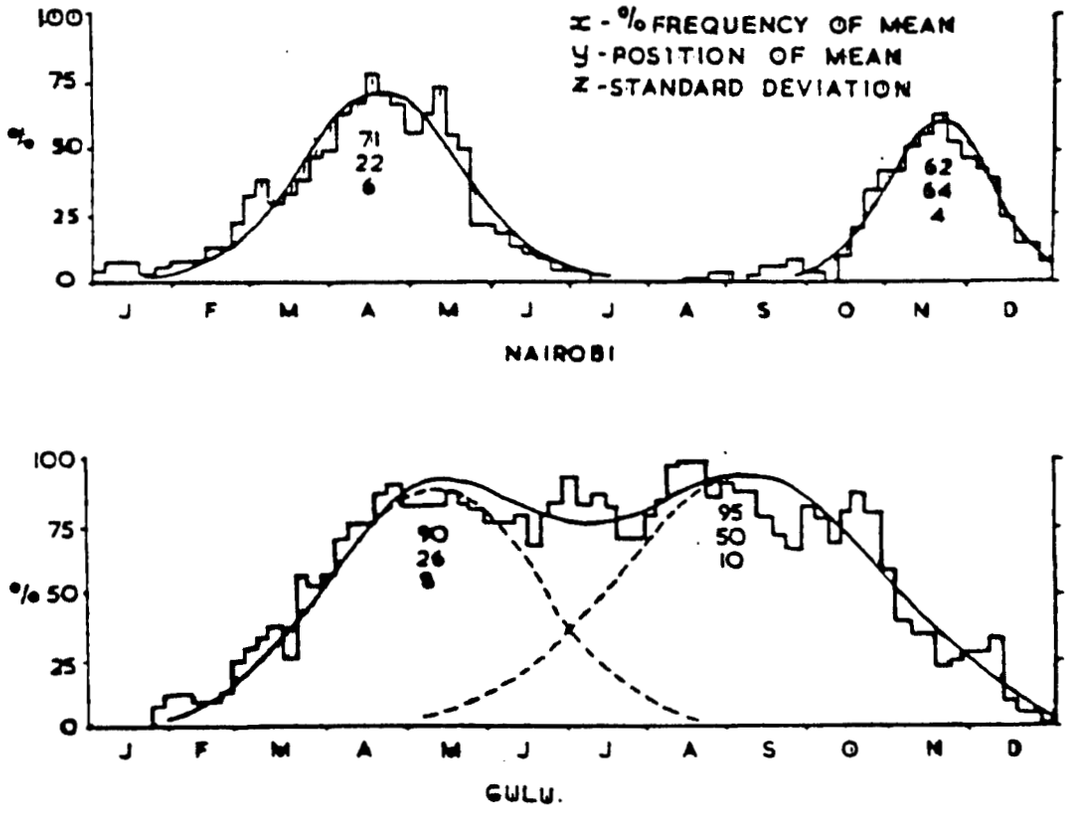


Figure 9. Distribution Types for Nairobi and Gulu

It has been reported that with a gauge density of less than one per 1000 km2 (about 40 in a 2.5° latitude x 2.5° longitude box), a combination of gauge measurements and radar estimates reduces the errors to about 10 to 30 per cent, compared with the use of either system alone. For higher accuracy (10-20 per cent), the advantage of radar is diminished as the number of gauges is sufficient to obtain the desired accuracy.

A WMO publication cites work by Jenne and Joseph at NCAR, in which they examined the error statistics for precipitation in a 220 x 256 km^2 box (2.3° latitude x 2.3° longitude) in south-central Texas. The 'true' rainfall was calculated from 67 stations. I assume that this was a straight arithmetic mean but, as the map in Figure 11 shows, this method introduces a bias and is not necessarily the best estimate of the 'true' rainfall for the area.

5. STATISTICAL ASPECT

Because our focus is mainly on monthly amounts, it is well to consider the frequency distributions of these so as to assess the inherent variability. Generally, three distributions are suggested as giving a good fit to monthly totals at a single station. These are the Gamma, shown in Figures 12 and 13 (or, as it is often called, the incomplete Gamma), the normal, and the square root normal (i.e., the square root of the individual monthly totals conform to a normal or Gaussian distribution). It is clear that the distributions are skewed so that the probability estimates are not symmetric with respect to the mean. This will lead to a biased interpretation of error terms.

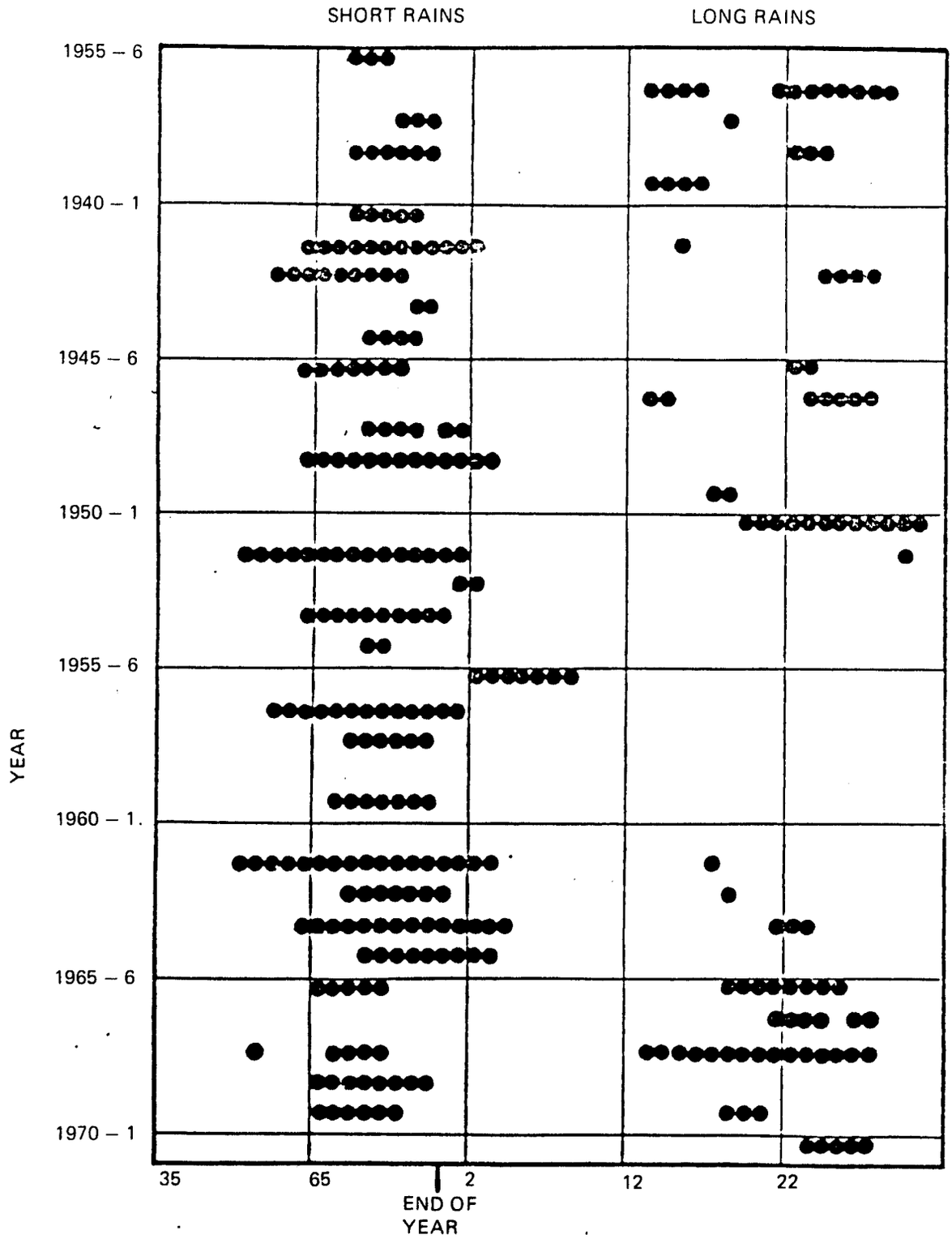


Figure 10. Short and Long Rainfall Patterns for Kenya

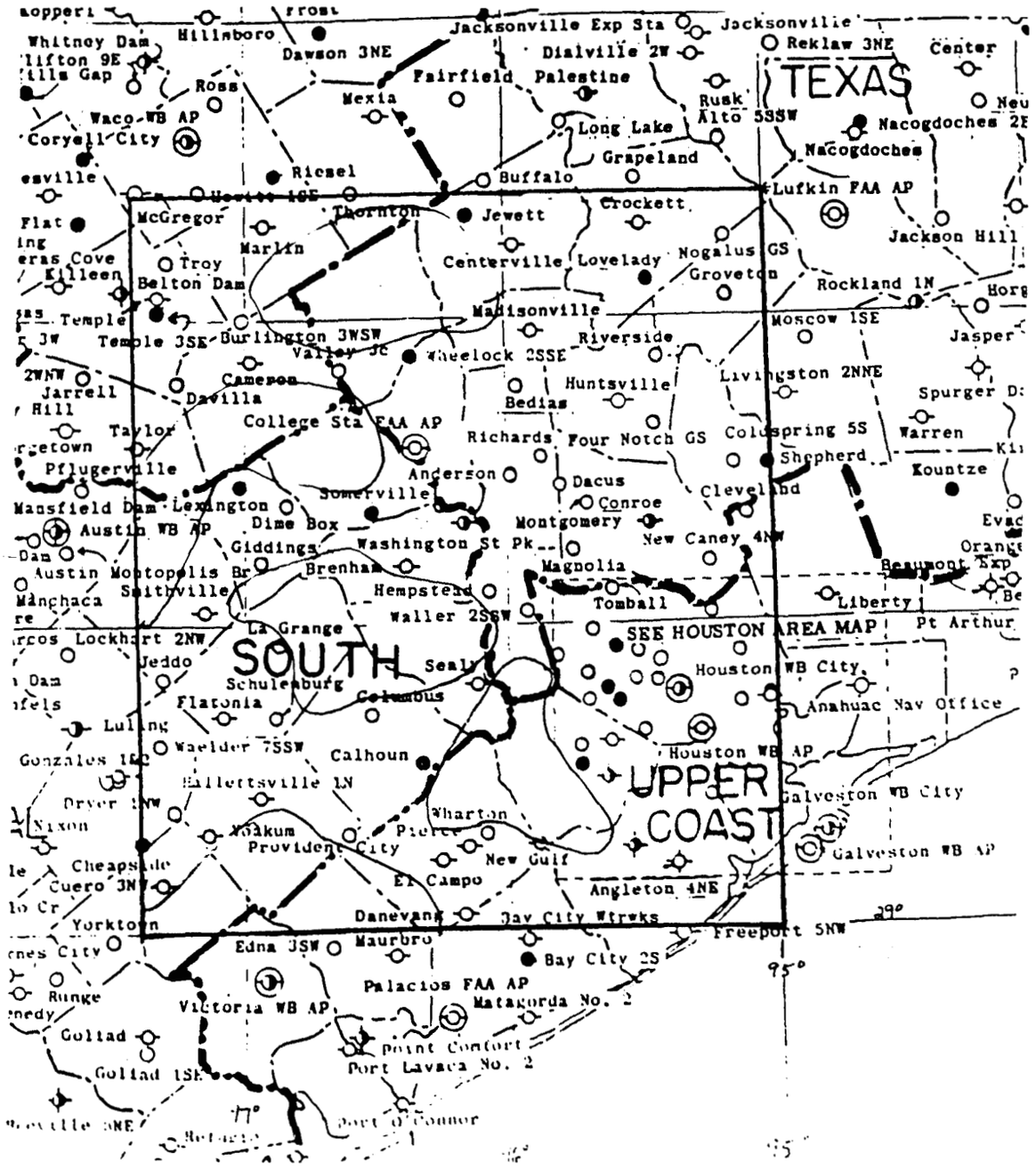

TEXAS
SOUTH
UPPER
COAST
SEE HOUSTON AREA MAP
Jacksonville Exp Sta
Jacksonville
Reklaw 3NE
Center
Hillsboro
Dawson 3NE
Dialville 2W
Fairfield
Palestine
Ross
Mexia
Rusk
Alto 5SSW
Nacogdoches
Waco WB AP
Coryell City
Long Lake
Grapeland
Riesel
Buffalo
Lufkin FAA AP
McGregor
Thornton
Jewett
Crockett
Jackson Hill
Marlin
Troy
Belton Dam
Centerville
Lovelady
Nogalus GS
Groveton
Rockland 1N
Killeen
Temple
Madisonville
Moscow 1SE
Jasper
Temple 3SE
Burlington 3WSW
Valley Jc
Wheelock 2SSE
Riverside
Cameron
Huntsville
Livingston 2NNE
Jarrell
Davilla
Bedias
Spurger
College Sta FAA AP
Taylor
Richards
Four Notch GS
Coldspring 5S
Warren
Pflugerville
Anderson
Shepherd
Kountze
Dacus
Cleveland
Mansfield Dam
Lexington
Somerville
Conroe
Austin WB AP
Dime Box
Montgomery
Giddings
Washington St Pk
New Caney 4NW
Brenham
Magnolia
Beaumont Exp
Austin Montopolis Br
Smithville
Hempstead
Tomball
Liberty
Manchaca
Waller 2SSW
La Grange
Lockhart 2NW
Pt Arthur
Jeddo
Seal
Houston WB City
Schulenburg
Columbus
Flatonia
Anahuac Nav Office
Luling
Waelder 7SSW
Calhoun
Houston WB AP
Gonzales
Halletsville 1N
Galveston WB City
Dryer 1NW
Wharton
Nixon
Yoakum
Pierce
Provident City
New Gulf
Galveston WB AP
Cheapside
Cuero 3N
El Campo
Angleton 4NE
Yorktown
Danevang
Bay City Wtrwks
Freeport 5NW
Edna 3SW
Maurbro
Bay City 2S
Palacios FAA AP
Runge
Victoria WB AP
Matagorda No. 2
Goliad
Point Comfort
Port Lavaca No. 2
Goliad 1SE
Port O'Connor
Refugio
95°
97°

Figure 11.

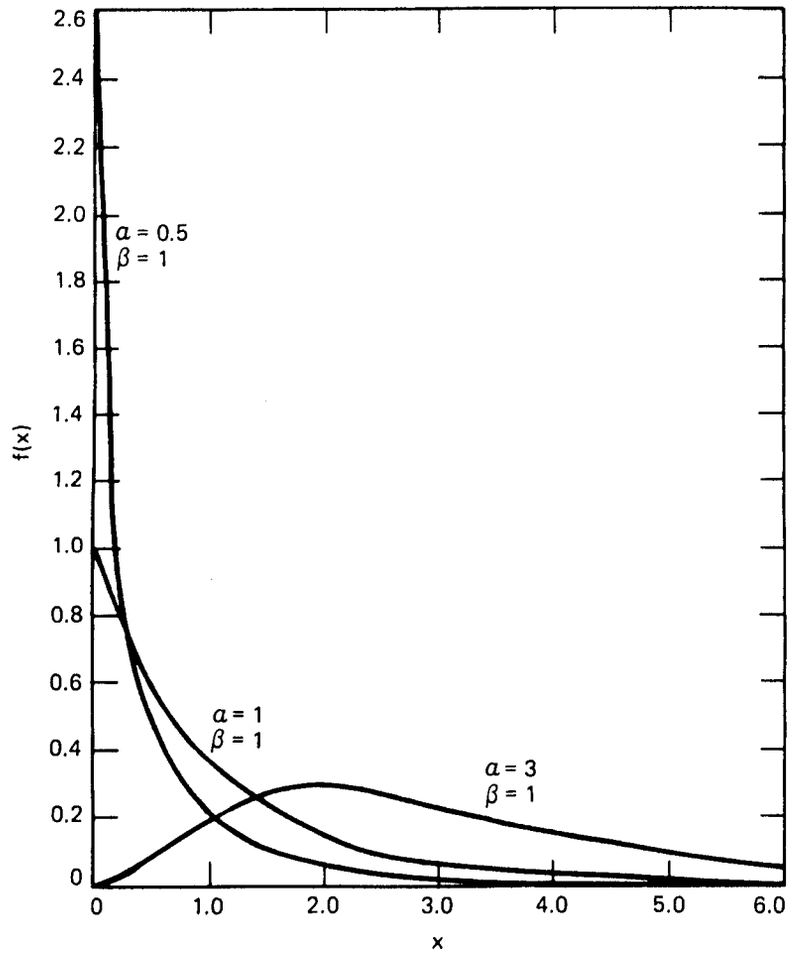


Figure 12a. Gamma Distributions with β = 1 and Various Values of α

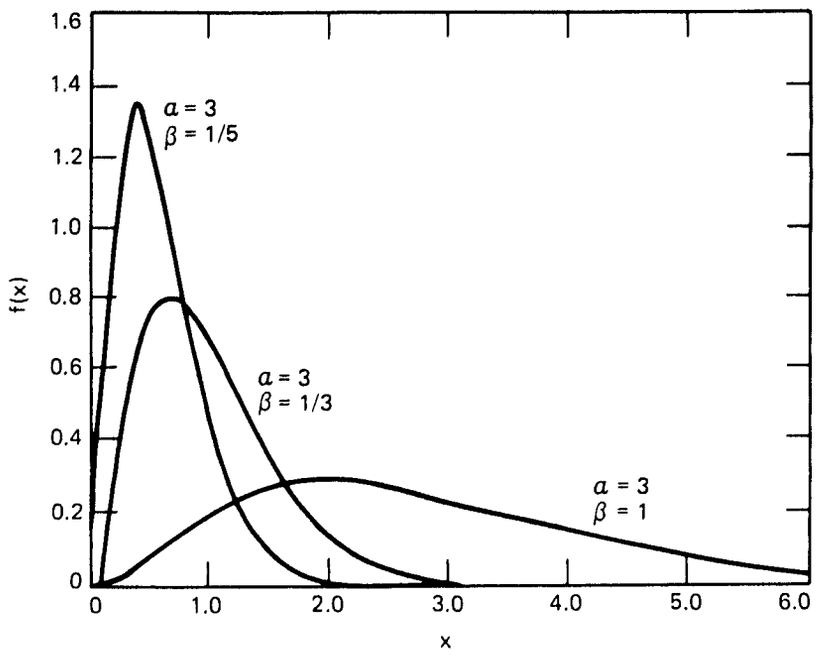


Figure 12b. Gamma Distributions with α = 3 and Various Values of β

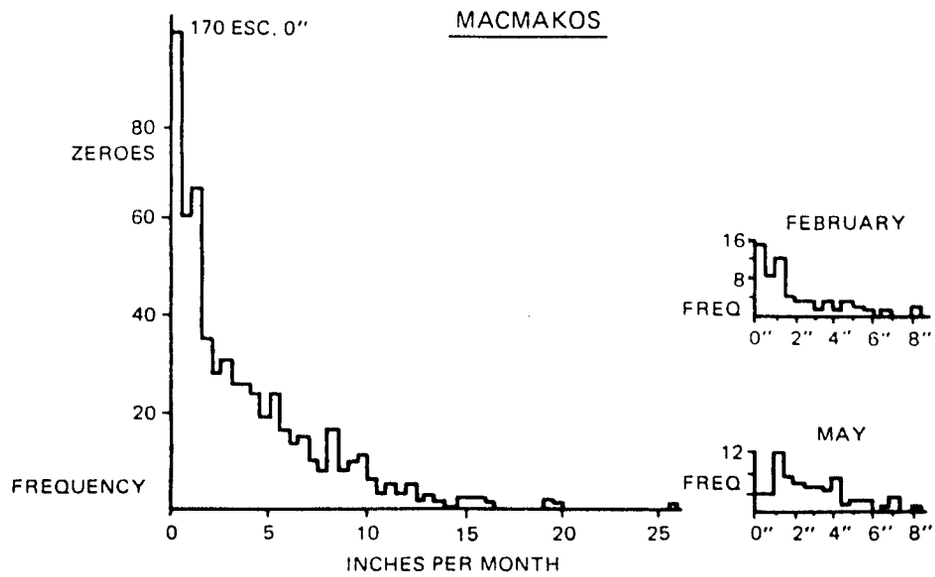


Figure 13

We have already learned some of the problems inherent in the measurement of precipitation. Unfortunately, the trouble does not stop there. Even if the measurements were completely accurate, there is still the difficult step of obtaining, from these the truth concerning the areal distribution of amounts.

Let us illustrate the problem with a simple example. Initial (T.O.) features cause the measurements to exhibit "natural" variations following a linear (not constant) distribution--an approximation to some Gamma distributions (See Figure 14).

We allow the measurements to be as shown in scenario I (Figure 15a), with stations at the centers of the nine equal-area boxes. Thus, the mean value is 0.55. If now, 4 stations are selected from the 9 available, there are 126 variations possible. If simple arithmetic averaging is used, then the range of values of the mean is 0. to 1.25. The extremes using 4 stations and an area-weighting are 0. to 1.11. Under simple arithmetic averaging, certain statistical estimates, such as standard errors, can be applied assuming observations are independent, which for some rain-causing systems they are not. With area weighting, a Monte Carlo technique would be necessary.

Problems do not cease here. Consider scenario II (Figure 15b), where the same nine measurements are distributed differently. Now the extremes from an arithmetic average are 0 to 1.25, with a selection of four stations, but for an area weighting are 0. to 1.5 and the standard error of the mean will be greater.

6. RAIN-CAUSING SYSTEMS

Although our aim is to estimate rainfall amounts, attention must be paid to the nature of the rain-causing systems because their characteristics will have great bearing on the overall coverage and intensity patterns in the areas receiving rain. A suggested classification of such systems is:

AREAL RAINFALL = f (SATELLITE I-R DATA)

f - WHY LINEAR ?

REGRESSION COEFFICIENTS

- HAVE STANDARD ERRORS
- MAY CHANGE WITH THE RAIN - CAUSING SYSTEM

COEFFICIENT OF DETERMINATION (R^2)

- NOT NECESSARILY A MEASURE OF PREDICTABILITY

Figure 14

0	0	0
0	0	1
1	1	2

0	2	0
0	0	0
1	1	1

Figure 15

(i) Extratropical Cyclonic (Frontal)

(ii) Tropical Cyclonic

(iii) Meso-scale Convective (Storm Cluster or Complex)

(iv) Squall Line (Temperate and Tropical)

(v) Sea-Breeze

(vi) Tropical Convergence

(vii) Orographic

With this classification in mind the following geographical areas are put forward as candidates for special ground truth networks:

(i) Central Great Plains (USA)

(ii) Gulf of Mexico Coast of Florida; Australia

(iii) Nigeria

(iv) Florida/Yucatan

(v) Eastern Kenya; India; Brazil

(vi) Kenya Highlands; Appalachia (USA)

In each case, it is most desirable to use proxy data such as from radar and/or river flows wherever these are deemed relevant.

7. TAMU PRECIPITATION DATA BANK

There is a great store of precipitation information on monthly totals. For some regions the network of stations is very dense. During the past 20-25 years, we have collected at the Meteorology Department at Texas A&M University a vast amount of such data, mainly with emphasis on the tropics. Tables 1-5 show the number of stations according to the years of record we hold. Although a University grant has enabled us to prepare a digitized inventory, unfortunately, due to lack of funds, many of the data have not been digitized and remain in paper copy.

To give some idea of the density pattern of stations, I will show two examples, one from Central America (Honduras), Figure 16, and the other from South America (Ecuador), Figure 17. We have similar densities from many parts of the world and from these the error statistics related to ground truth can be calculated. This will enable the limitations of the point estimate method to be derived and related to the different rainfall systems - an essential step in the satellite estimation of precipitation.

8. THE FUTURE

For a couple of hundred years, climatological data have been accumulated from specific points. They are measurements that, most unfortunately, are polluted by instrument and observer errors, site changes, instrument changes, local urbanization, and many other variables. It is time to make the change to the taking of areal measurements, admittedly less accurate in their initial stages, which are capable of giving the global picture we need so badly. We have a great opportunity here to tackle this challenging problem.

Table 1. SUMMARY
YEARS OF DATA

	10-19	20-29	30-49	50-69	70-99	100---	Totals
C. AMERICA	641	317	176	74	9	2	1219
CARIBBEAN	242	130	93	53	11	1	530
S. AMERICA	853	430	332	239	11	1	1866
S.E. ASIA	113	188	194	179	72	2	749
TOTALS	1849	1065	795	545	104	6	4364

NOTE:
1. There are stations not included here, especially from Africa.
2. Data collected in 1985 from the Caribbean have not yet been inventoried.
3. Almost no data since 1970 (except in S.E. Asia - 1975) have been inventoried.

Table 2. CENTRAL AMERICA
YEARS OF DATA

	10-19	20-29	30-49	50-69	70-99	100---	Totals
BELIZE	27	15	4	4	1	--	51
COSTA RICA	113	54	12	1	--	1	181
EL SALVADOR	55	30	22	6	--	--	113
HONDURAS	148	52	19	7	1	--	227
GUATEMALA	180	103	63	40	1	--	387
NICARAGUA	44	24	16	--	3	--	87
PANAMA	74	39	40	16	3	1	173
TOTALS	641	317	176	74	9	2	1219

Table 3. CARIBBEAN
YEARS OF DATA

	10-19	20-29	30-49	50-69	70-99	100---	Totals
BAHAMAS	8	6	11	3	--	1	29
BARBADOS	85	1	--	--	--	--(only thru 1899)	86
GRENADA	7	5	1	2	--	--	15
LEEWARD IS.	1	--	4	--	--	--	5
ST. VINCENT	--	--	1	--	--	--	1
ST LUCIA	15	19	14	--	--	--	48
GUADELUPE	18	--	1	--	--	--	19
MARTINIQUE	19	--	--	--	--	--	19
NET ANTILLES	23	--	--	--	--	--Curacao	23
	8	--	--	--	--	--Aruba	8
	8	1	--	--	--	--Others	9
JAMAICA	50	98	61	48	11	--	268
TOTALS	242	130	93	53	11	1	530

Table 4. SOUTH AMERICA
YEARS OF DATA

	10-19	20-29	30-49	50-69	70-99	100---	Totals
BOLIVIA	64	15	2				81
BRAZIL	24	90	178	182			474
COLOMBIA	198	58	21	2	1		280
ECUADOR	180	18	12	1			211
FRENCH GUYANA	22			1			23
GUYANA	54	35	49	24	5		167
PARAGUAY	8						8
PERU	40	30	3				73
SURINAME	57	5	9	24	3	1	99
TRINIDAD	45	45	14	2	2		108
VENEZUELA	161	134	44	3			342
TOTALS	853	430	332	239	11	1	1866

Table 5. SOUTHEAST ASIA
YEARS OF DATA

	10-19	20-29	30-49	50-69	70-99	100---	Totals
BURMA				1	4		5
CAMBODIA	13	8	9	1			31
INDONESIA	0	42	106	97	44	1	290
LAOS	17	5	3				25
MALAYSIA		83	31	10	22		146
PHILIPPINES	13	14	13	30			70
SINGAPORE		5	1		2	1	9
S. VIETNAM	47	11	20	5			83
THAILAND	23	20	11	35	1		90
TOTALS	113	188	194	179	73	2	749

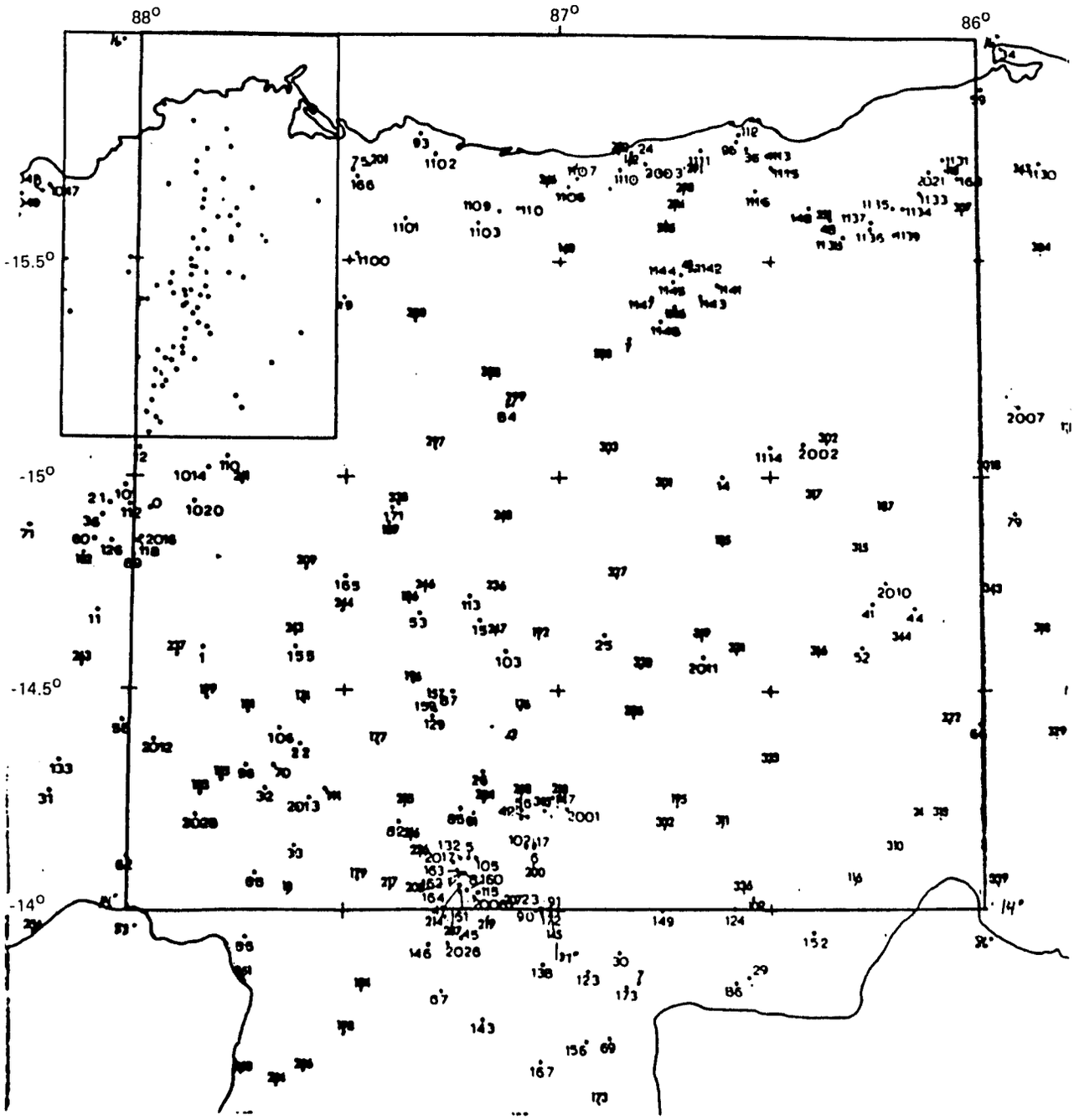


Figure 16. Honduras

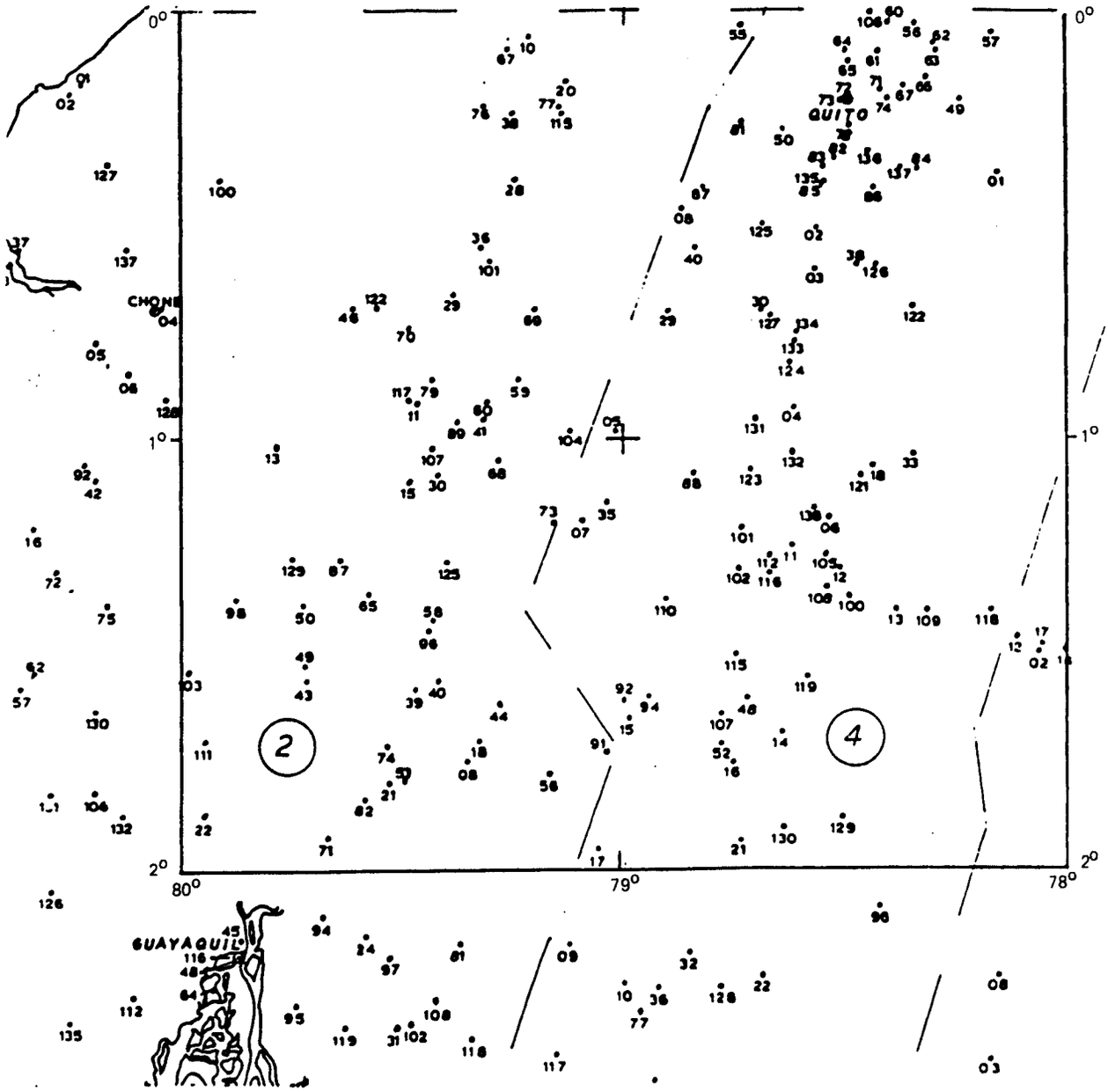


Figure 17. Ecuador

PRECIPITATION MEASUREMENTS: AGRICULTURAL CONCERNS

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Accurate and reliable measurements of precipitation provide an essential input to operational decisions by farm operators responding to local conditions in such activities as planting and harvesting crops, applying pesticides and herbicides, scheduling irrigation and protective soil conservation measures. At the national level, timely information about precipitation facilitates the issuance of analyses and advisories for decisionmakers in business and marketing as well as farm policies and programs.

Precipitation measurements for operational and research use in agriculture and forestry have been collected for decades at ground stations. On the plus side, where the observations in rural areas are associated with the national network of cooperator stations, the measurements are in accordance with established standards and provide a continuous record. Such measurements have been extremely useful in creating models which simulate the impact of weather on crop development and relate the crop yields to growing season weather conditions.

Ground observation points, many of which were established in relatively recent times, have provided local and regional precipitation data for limited research and operational uses. In specific research projects, the area covered by the measurements is usually small and, frequently, the measurements are taken only for the period of time required in the research. In supporting operations at the regional level, some networks collect data only for critical decision periods. For example, the remote automated weather stations operated by the Forest Service and the Bureau of Land Management for assessment of forest fire conditions do not acquire data during seasons of low fire danger. Furthermore, when the data are collected, transmission is limited to daily observations rather than hourly or 3-hourly reports.

Precipitation measurements by local authorities often complement measurements made by Federal agencies. However, these data are usually local in coverage (e.g., a small watershed), directed to a specific purpose, and do not provide a continuous record. Calibration of satellite systems will be hampered by data gaps, lack of coverage in rural areas, and data inconsistencies depending on the type of observational system suited to specific needs.

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ADVANCES IN RAIN GAUGE TECHNOLOGY: AN OPTICAL RAIN/SNOW GAUGE

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Abstract

Precise measurements of rainfall are nowhere near as simple as one might imagine. The time resolution of conventional mechanical gauges is poor at even moderate rainrates. The accuracy in measuring high, instantaneous, rainrates is also severely limited. Recent work indicates that detected rain and snow induced optical scintillation can be used as the basis for measuring instanteous rainfall rates and snow intensities. A major advantage of the optical gauge over its mechanical counterparts is its ability to accurately measure true, instantaneous rain and snow intensities over a dynamic range of more than four decades (from less than 0.1 mm/h to over 1000 mm/h). The instrument is so sensitive that its use for reliable precipitation state identification (yes/no) has been successfully demonstrated. At the other extreme, it can accurately measure extremely high rainfall rates, at which other gauges fail.

An optical rain/snow gauge has been designed and field tested. The entire instrument is mounted on a single pedestal, assuring ease of handling and eliminating the need for field alignment of the optics. An Infrared Emitting Diode (IRED) is used as the light source. The IRED is modulated to enable the receiver to reject background noise. The IRED is very reliable for field operation. It is also invisible to the naked eye and there are no radiation hazards to the eye.

1. INTRODUCTION

Accurate rain measurement is important for meteorological, hydrological, remote sensing and communications studies. Recent work indicates that raindroplet-induced optical scintillations can be used to measure rain parameters (1-14). The technique measures the path-averaged rain parameters along a line-of-sight optical path. This technique is simple to implement as a real time instrument without extensive data reduction.

When a visible or infrared light beam passes through an irregular medium, the irregularities in the medium produce changes in the wave front. This phenomenon has long been known as scintillation. The twinkling of stars is a familiar example. Different weather conditions produce different signatures of the detected scintillations. The rain and snow induced scintillations can be used to measure rain and snow parameters (4).

For a coherent wave incident on a raindrop, the scattered light can be considered as a spherical wave emitted from the center of the raindrop in the far-field region. The interference at the receiving plane, caused by the incident wave and the scattered spherical wave, gives the fine fringes shown in Figure 1. The envelope of the interference pattern is the well-known Airy diffraction pattern of a sphere. Rain parameters can be measured by observing the movement of these interference patterns (7-13).

Earlier versions of optical rain/snow intensity measurement, using scintillation techniques, were designed according to the "far-field approximation" (4,7-11). As a result, the long baseline needed for an optical rain/snow gauges was impractical for large-scale field deployment. Recently, Wang et al. (12,13) showed that by advancing the scintillation theory to the near-field region, accurate measurement of the rain/snow parameter is possible. A system has been designed, fabricated and field tested using a short path length (less than one meter) to measure rain and snow parameters. Also, in the near-field region, a partially coherent source like an infrared light emitter (IRED) may be used. An IRED is more reliable than a laser source and has no safety hazards.

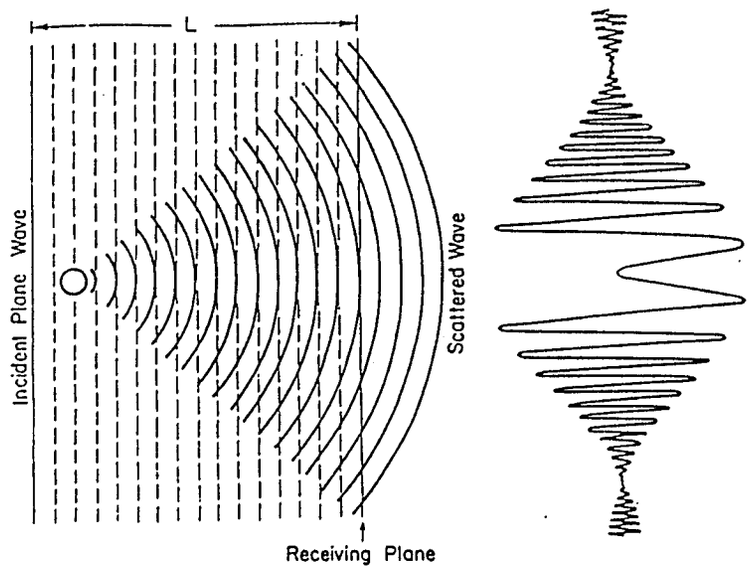

Figure 1. The Interference Pattern Produced by a Spherical Raindrop. The Fine Fringes are Caused by Phase Interference of the Incident Plane Wave and Scattered Spherical Wave.

2. IMPLEMENTATION

An overall system block diagram of an optical rain/snow gauge is shown in Figure 2. The system consists of:

(i) an IRED modulator,

(ii) a transmitter optical assembly,

(iii) a receiver optical assembly,

(iv) a PIN photodetector with preamplifier,

(v) an AGC normalizer, and

(vi) a signal processing unit.

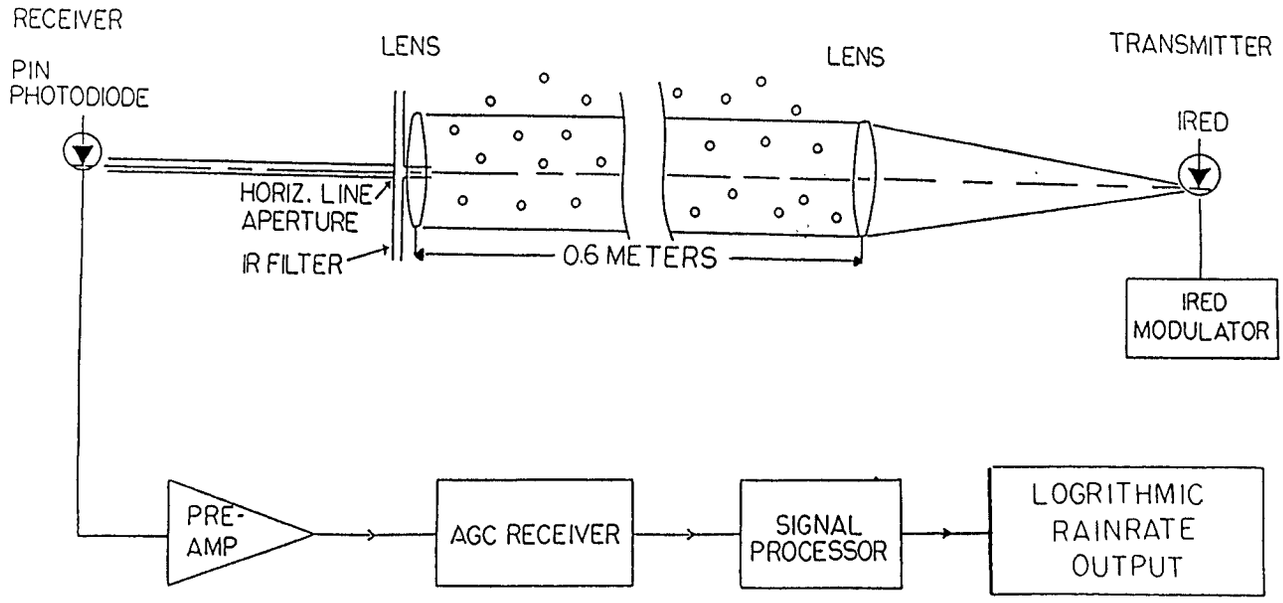

Figure 2. Functional Block Diagram of an Optical Rain/Snow Gauge

The infrared light emitted from the IRED is collected by the transmitter optics to form a partially coherent beam. The light beam is pointed to the receiver optics. Particles falling through the beam modulate the beam to cause optical scintillation of the received signal. The receiver uses a horizontal line aperture to be sensitive only to the vertical motion of the precipitants. The infrared light is detected by a PIN photodiode followed by a preamplifer and an automatic-gain-controlled (AGC) receiver. The AGC acts as a normalizer to overcome the problems associated with received power fluctuations caused by temperature change, component aging, dust on the lens and weather obscurations (fog/haze). The output of the AGC amplifier passes through a buffer amplifier, a bandpass filter, an RMS-to-DC converter and an itegrator (10-second time constant). The logarithmic output of the RMS-to-DC converter is used to cover more than four decades of the overall dynamic range of the system.

Special attention has been paid to the ease of field installation and maintenance, lightning protection and weather proofing, electromagnetic interference, freedom from optical obscuration caused by dew and frost, and insect and bird nesting. It has been demonstrated that the Optical Rain/Snow Gauge can provide uninterrupted continuous service under severe weather conditions.

3. FIELD TEST

The optical rain/snow gauge has been under field evaluation by the Test and Evaluation Division of the National Weather Service at Sterling, Virginia (Dulles Airport) since September 1985. Figure 3 shows a photograph of the unit installed at Dulles Airport. A comparison of the rainrates measured by an optical raingauge and a nearby tipping-bucket raingauge (calibrated by Test and Evaluation Division of NWS) during hurricane Gloria on 26-27 September, 1985 is shown in Figure 4. The comparison of a much heavier rain event on 15 October 1985 is shown in Figure 5. The tipping- bucket raingauge failed to detect the light rainfalls at the beginning and the end of

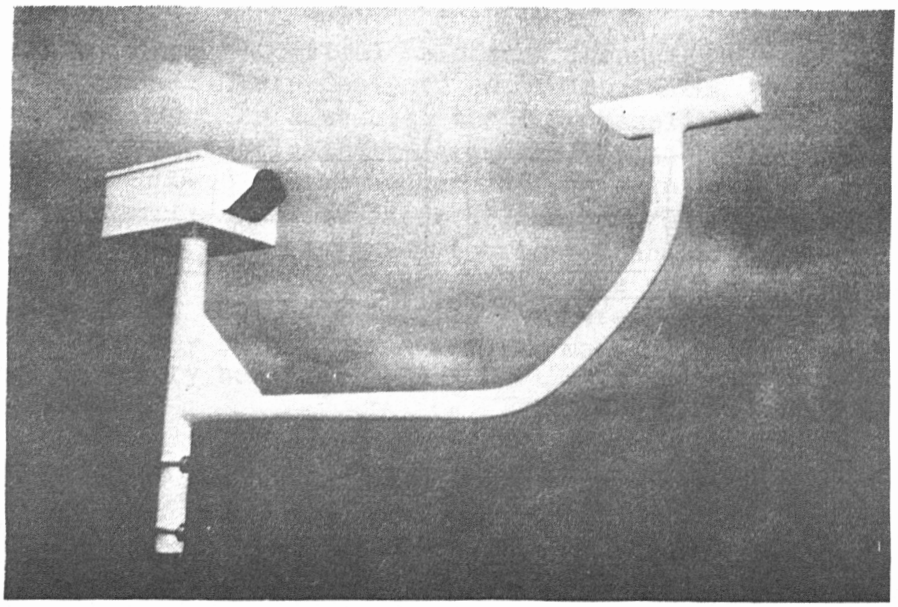

Figure 3. Optical Raingauge Installed at Dulles Airport, Virginia

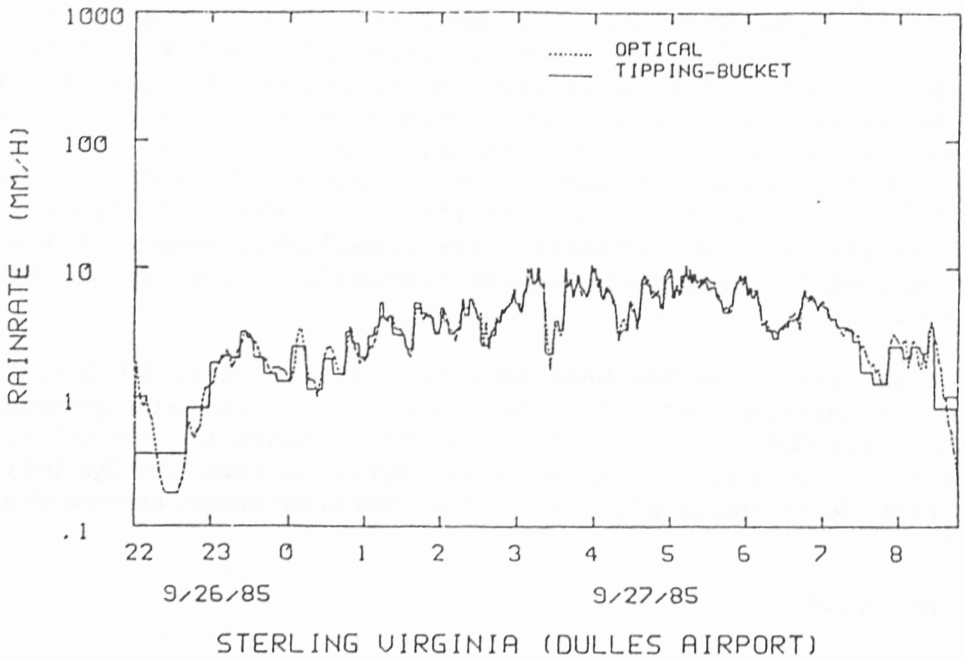

Figure 4. A Comparison of the Rainrates Measured by the Optical Raingauge (Dashed Line) and the Tipping-Bucket Raingauge (Solid Line) During Hurricane Gloria on 26-27 September 1985.

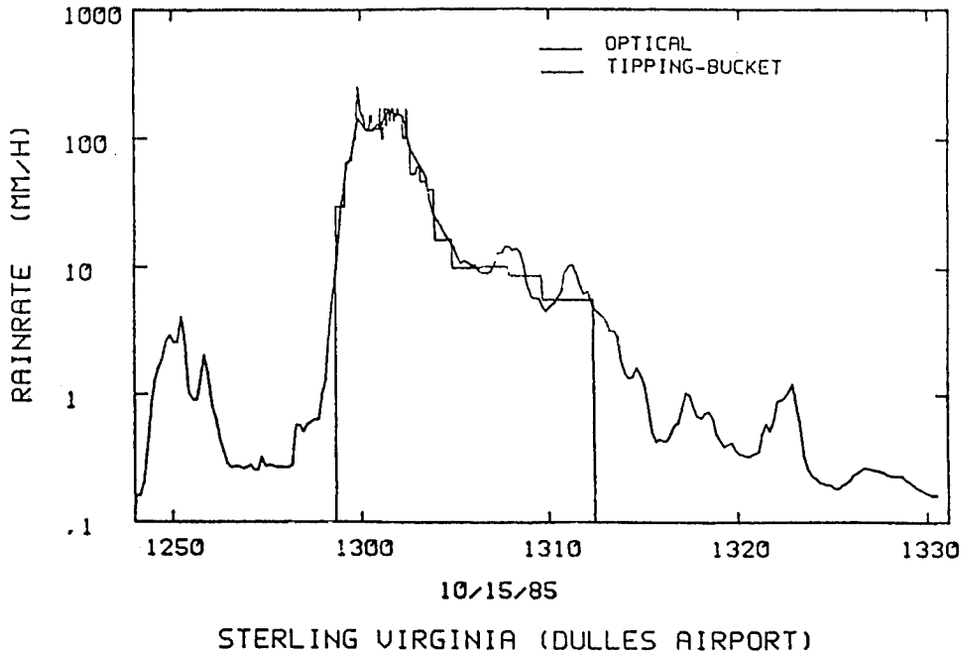

Figure 5. A Comparison of the Rainrates Measured by the Optical Raingauge (Dashed Line) and the Tipping-Bucket Raingauge (Solid Line) of a Heavy Shower Event on 15 October 1985.

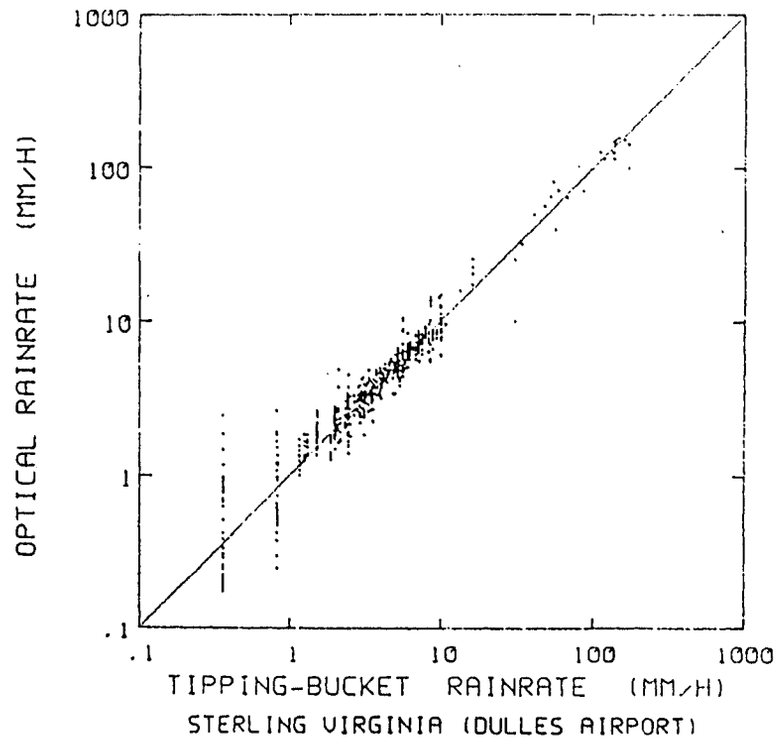

Figure 6. The Scatter Diagram of the Rainrate Measured by the Optical Raingauge and the Tipping-Bucket Raingauge.

the event. Small disagreements in heavy rainrates was probably caused by the inaccurate measurements of the tipping-bucket raingauge in the range. A scatter diagram of the two measured rainrates is shown in Figure 6. The general agreements of the two measured rainrates are very good for moderate rainrates. For light rainrates, the results show some discrepancies because of the limitations of the time resolution of the tipping-bucket raingauge. The gauge is also able to measure snow intensity. A sample measurement of a snow event on 5 December 1985 is shown in Figure 7.

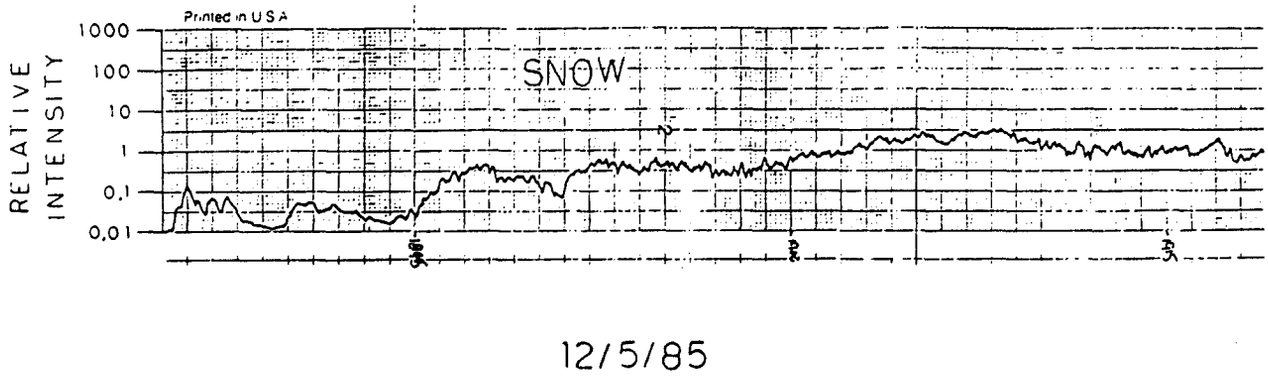

Figure 7. Measured Relative Snow Intensity of an Optical Rain/Snow Gauge at Dulles Airport, Virginia

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HYDROLOGY-RELATED OBSERVATIONS AND THEIR APPLICATION TO VALIDATION OF SATELLITE-DERIVED RAINFALL ESTIMATES

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The water balance of a land surface area may be written so that the precipitation is apportioned into evaporation, runoff or changes in storage. This paper summarizes how we may make estimates of these quantities to validate monthly precipitation estimates from remotely-sensed data for a 2.5° latitude x 2.5° longitude area.

Conventional precipitation data, measured using raingauges, may be used with a suitable interpolation technique. However, a large number of conventional gauges may be required. Figure 1, after O'Connell et al (1977), shows the spacing of rain gauges if laid out on a square grid that are required to produce rainfall estimates with an interpolation error of a fraction of a standard deviation for two areas in Great Britain. An error of 5 per cent of the standard deviation needs a grid spacing of 50 km, with all gauges being Class 1 stations. Given the frontal nature of most British rainfall and the unrealibility of many observing sites, this is probably an upper limit on spacing.

Runoff from a catchment is measured at many sites and, in its nature, is an integrated measure. However, the distribution of such data is in no sense geographically uniform. Figure 2, after Willmott et al. (1985), shows the sites used in a study of the global water balance. It may be seen that there are comparatively few sites in tropical areas and a preponderance in economically wealthy nations. There are further reasons that it is difficult to use runoff data for rainfall verification. The interception loss and evaporation loss vary considerably regionally. The runoff tends to come preferentially from those areas near the streams and the catchment storage varies considerably, both near the surface and as groundwater. It is thus necessary to have estimates of these quantities to use the runoff data.

Groundwater storage changes are monitored using well levels. Near surface soil moisture is only measured conventionally in small experimental basins because of its spatial variability and the difficulty of the measurements. However, it is possible to use remotely-sensed passive microwave data to make estimates of near-surface soil moisture. Time series of these data may be used to estimate changes in storage in a soil profile. Camillo and Schmugge (1984) correlated rainfall with remotely-sensed microwave data and showed that some soil physical information was needed in order to estimate rainfall totals. Figure 3 shows the relationship between rainfall, soil moisture and microwave emission for a ten day period simulation. Similarly, snow data may be monitored using remote-sensed data. Figure 4 shows some of the data used to verify the theoretical relationship between microwave emission and snow depth (after Foster et al., 1984). The change in snow depth may be used to infer precipitation.

Evaporation from the surface is a confusing term in trying to verify precipitation. It is clearly linked to how much water is available, and is also needed in order to use runoff data or other data to verify precipitation

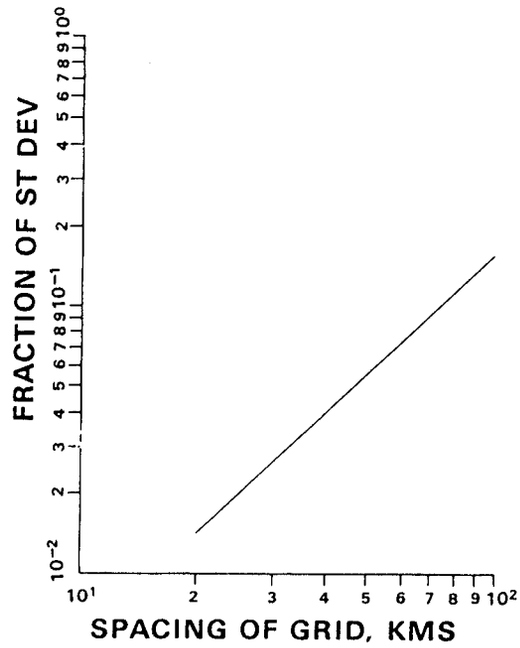

Figure 1. Error of Estimate of Average Monthly Rainfall Interpolated Over a 40000 km^2 Area Using a Square Raingauge Grid for Rainfall in East Anglia, United Kingdom (After O'Connell et al., 1977)

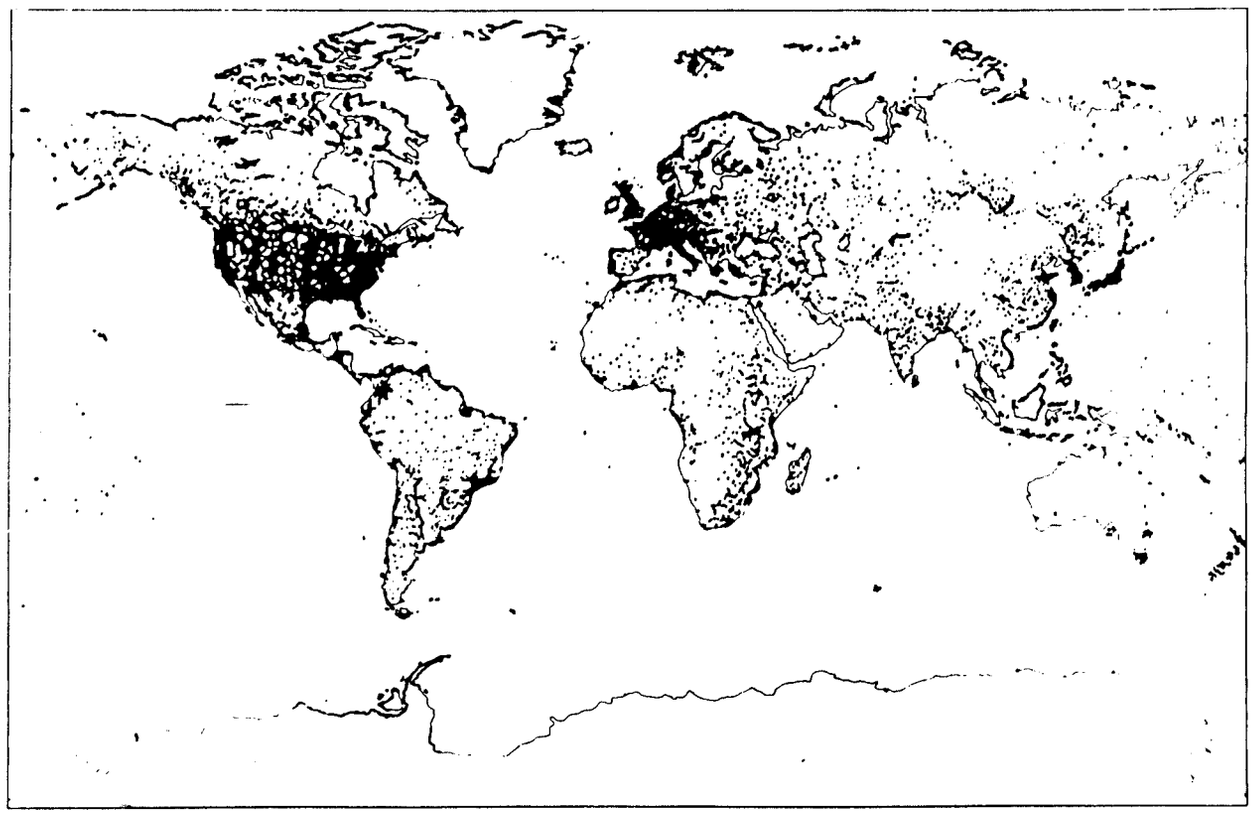

Figure 2. Stations at Which Monthly Surface Water Balances Were Computed in an Empirical Study of the Global Water Balance (After Willmott et al., 1985)

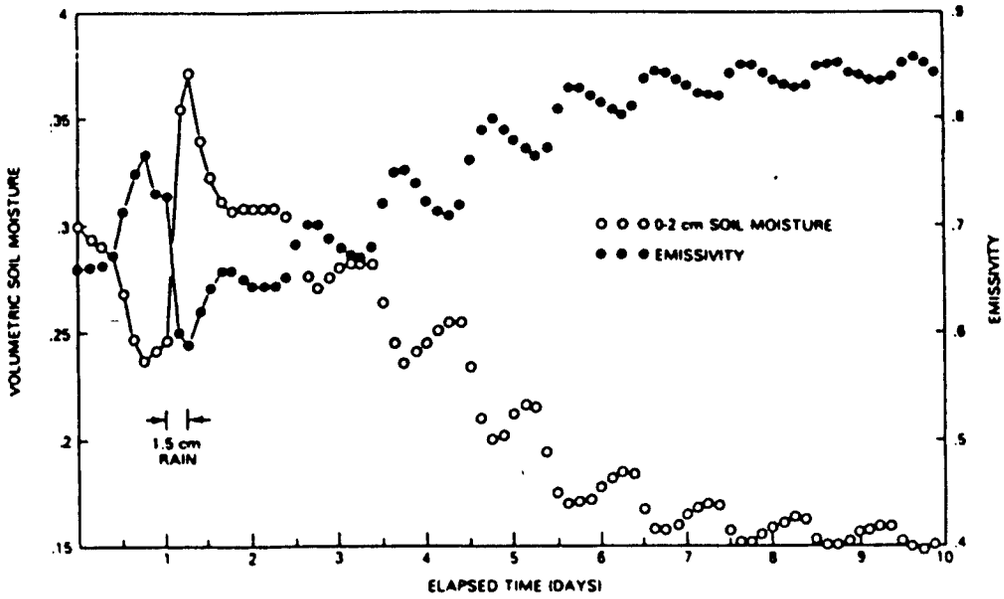

Figure 3. Soil Moisture and L-Band Emissivity for a Ten-Day Simulation After a 1.5 cm Rainstorm on a Clay Soil with a Pre-Rain Soil Moisture of 0.30. Meteorological Data were from Phoenix, Arizona (After Camillo and Schmugge, 1984)

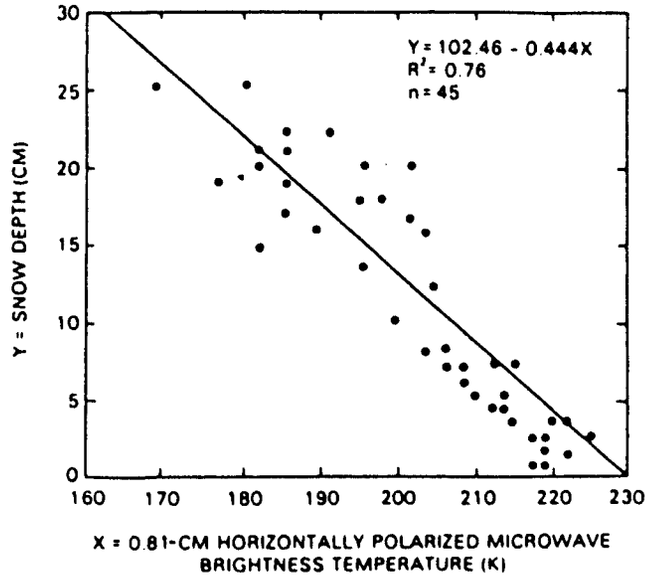

Figure 4. Nimbus-7 37 GHz Horizontally-Polarized Micro-Wave Brightness Temperatures Compared to Snow Depth Measurements Over Central Russia. A Least-Squares Linear Regression Line is Also Plotted (After Foster et al., 1984)

data by solving the water balance. Very few conventional measurements are available. Interception losses in particular are rarely estimated but can be a high proportion of the precipitation. Areal evaporation estimates may be made using energy balance models, and there are some strong possibilities that soon remotely-sensed data may be useful for areal evaporation estimation. These approaches have only been verified for point data. For instance, Figure 5 (after Choudhury, 1986) shows a comparison between measured and estimated evaporation for a wheat canopy where the estimated evaporation is produced with the aid of remotely-sensed data.

Potentially, then, we can solve the water balance of an area leaving the precipitation as a residual which may be used to verify the areal precipitation data, together with the conventional precipitation information. Remotely-sensed data should assist the areal estimation of some of these quantities considerably, but not all the procedures are yet routine.

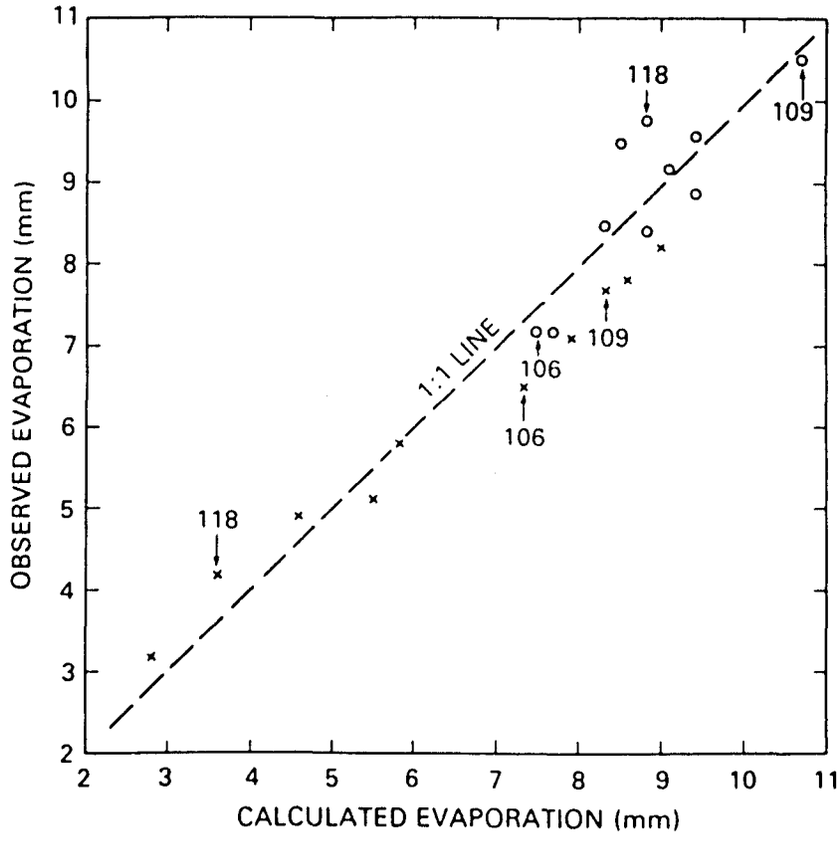

Figure 5. Comparison of Calculated Daily Total Evaporation with Stability Corrected Aerodynamic Resistance with Lysimeter Observations of Evaporation Over Wheat in Phoenix, Arizona (After Choudhury et al., 1986)

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RADAR REFLECTIVITY AND RELATED MEASUREMENTS OF RAINFALL

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We first review the basic relationships between radar reflectivity and other remote measurables (e.g., optical and microwave extinction) to rainfall rate and the parameters of an exponential drop-size distribution (DSD). The latter contains two parameters, N(o) and D(o), although Marshall and Palmer assumed that N(o) was constant and D(o), the median volume diameter, is uniquely related to rain rate, R. Under such an assumption, all integral parameters of the DSD are also unique functions of R, thus explaining the long-sought-for mythical relation between the reflectivity factor, Z, and R. (All of this also assumes integration over a sufficiently large drop-size range, an assumption which is also often not valid).

Over the years there have been hundreds of Z - R relations reported and in some climatic regions and in steady stratiform rain, one may use one of these relations with some degree of confidence, particularly when using large time/space averages. We shall show, however, that this practice can lead to large errors in total storm rainfall even over periods as long as ten hours and areas of 10^3 - 10^4 km^2.

A partial solution to this problem has been to calibrate the radar against one or more raingauges but this, too, leaves large residual errors, especially in storms characterized by sharp gradients in their isohyetal patterns (i.e., most convective storms). Other problems such as contamination by the bright band, unfilled beams, orographic effects, etc. also cause potentially serious errors. Nevertheless, the U.K. has installed a network of automated radars which are combined with satellite data for the purpose of short-range forecasting of precipitation. As yet, I have not heard of any results of the use of this system for climatological purposes, although this may well be reported by Browning at this meeting.

The above difficulties have led to the search for other remotely measurable parameters which would then allow us to account for the variability of N(o) and D(o) in the exponential DSD from predetermined relations. These include,

(i) Dual wavelength measurements of attenuation,,

(ii) Microwave or optical attenuation over fixed paths to either a receiver or a reflector,

(iii) Passive radiometric measurements, and

(iv) Differential polarization.

Each of these will be touched upon and their strengths and weaknesses noted.

Differential polarization, as conceived by Seliga and Bringi, is a particularly attractive method in which the radar transmits alternately at horizontal and vertical polarizations, the difference between the echoes being

related to the ellipticity and thus to some representative size such as D(o). The ratio of the echoes, known as ZDR, is thus a proxy for D(o). With the reflectivity Z itself, this allows determination of the rain rate without any prior Z - R relation. On the other hand, it assumes a fixed relation between drop ellipticity and its equivalent spherical diameter. It also requires improved "polarization-pure" antennas and very precise measurements of ZDR, because ZDR is an insensitive function of D(o). Also, in order to minimize the contaminating effects of the rain medium on the ZDR, one must operate near 10 cm. This in turn implies the use of large dishes and narrow beams so that the radar may view rain entirely below the melting level without contamination by either snow or the bright band. The latter has a very large ZDR and shows dramatically on the display.

At this writing, insufficient results have been forthcoming to state the accuracies which have been achieved in extensive observations. However, this author holds the view that such radars must be used, in combination with supporting measurements, as primary standards at a few locations around the globe.

For local measurements, small, economical, vertically-pointing Doppler radars also hold the promise of replacing conventional raingauges, mainly because they sample much larger volumes and do not suffer the catchment problems in high winds. Here, the mean Doppler fall velocity is used as a proxy for D(o) and combined with Z. Alternatively, the Doppler spectrum may be inverted to obtain the DSD and then integrated to give R. The method needs extensive trials.

Over the oceans, I propose the use of airborne methods for calibration and validation purposes. In situ measurements with optical probes are vital. Also, there is a means of using an airborne Doppler radar, such as that on the NOAA P-3, to measure both reflectivity and mean Doppler fall speed by exploiting both the direct echoes from the precipitation and their mirror image echoes reflected from the ocean. This method is limited to some yet unknown range of surface wind speeds and wave heights and can operate out to a distance of about twice the aircraft height on either side of the aircraft. Although one could not use this approach for extended period validations, it would be useful for extended area calibrations over regions which are out of range of high performance island or shipboard radars. Other airborne methods such as the Stepped Frequency Microwave Radiometer of Swift et al also deserve comprehensive trials.

RAIN GAUGES ON SHIPS OF OPPORTUNITY

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1. INTRODUCTION

Data on precipitation at sea are at present both sparse and uncertain, largely because of the difficulties of making direct measurements. On land, raingauges are placed at or near ground level in clear, exposed areas and give reasonably representative results even in relatively high winds. Over the ocean, the wind speed is on average higher and tends to be increased by the speed of the ship. The siting problem is severe, since sufficiently large flat areas are usually not available. Wind speed at the gauge tends to be high, since an elevated location is needed to avoid spray. Rolling and pitching of the ship, together with any mean list angle, complicate the collection.

Field experiments were undertaken by the Institute of Ocean Sciences in cooperation with the Atmospheric Environment Service of Canada, to assess the problems of mounting gauges on modern, fast cargo vessels of opportunity. These offer advantages associated with larger, more stable ships, and could provide a wide data net, at least along major shipping lanes.

2. PREVIOUS EXPERIENCE

WMO (1962) and Olbruck (c.1979) have indicated where problems lie and describe many attempts to evaluate error sources. Most of the data discussed were collected by nearly stationary ships at weather stations, or during scientific cruises such as GATE. Results show that reasonably consistent data can be gathered from stationary vessels. Data collected at ocean weather stations are therefore a valuable source of time series information, but such data were collected at only a few stations.

The WMO report concluded, on the basis of weather ship observations, that the preferred gauge location is high on the foremast, away from disturbed airflow round the ship. Collection at such a location seemed to give about twice the amount collected at a more sheltered location on deck. Olbruck, however, reported results from GATE in which deck mounted gauges collected slightly more rain than one on a mast. Pitching and rolling does not appear to be a severe problem, particularly for larger vessels.

Both reports concluded that more tests are needed and that different types of experimental installations should be tried on research vessels and ships of opportunity.

3. IOS/ASAP EXPERIMENTS

Preliminary tests of the consistency of raingauge measurements, made at different locations on a large modern ship of opportunity, were conducted in conjunction with the Automated Shipboard Aerological Program (ASAP) package on the Japanese car transporter, M.V. Friendship, in the North Pacific, during the 1983/4 and 1984/5 winters (WCP, 1986).

In 1983/4, nine gauges were located round the upper deck of this vessel, and rain samples were collected by the ASAP technician during nine rain events. The resulting readings were strongly position dependent, varying with the relative wind speed and direction. Since the ship travelled at 17 Kt, many of the wind speeds are over 20 Kt, and only drop below 10 Kt under tail-wind conditions. Only under these tail-wind conditions did the consistency between the readings approach ±10 per cent. Otherwise, variations of 5 to 1 are common, with 2 to 1 differences even between closely spaced gauges. Such variations are expected from past experience and from modelling efforts. These show the strong effect of air flow near the gauge, due both to the shape of the gauge itself, and to the air flow over the ship. The latter effect was undoubtedly important in the 1983/4 measurements, because the gauges were sited around the edge of the deck for simplicity and ease of access.

In 1984/5, a second set of data was collected using gauges sited at wide intervals down the centre-line of the ship on the flat upper deck forward of the ASAP trailer. The results suggested that reasonably consistent data (to within ±20 per cent) can be collected for sites on the centre line of the ship's open and exposed upper deck.

For 1985/6, the ASAP container was removed from the Friendship, and another nearly identical unit was loaded on the M.V. Skeena, a similar modern roll-on/roll-off car and general cargo ship, also operating across the Pacific. The speed of this ship is less (10 to 13 knots), reducing the average relative wind somewhat. A small array of collectors was installed on the flat upper deck at a point about 15 m forward of the ASAP container and 15 m aft of the 2.5 m high bridge. The array is supported on a frame 2.5 m square and 0.7 m high and consists of about eight gauges of different designs and tilts.

Folland (1985) has studied raingauge exposure effects and summarized measurements and flow modelling results made for the U.K. Meteorological Office. These show that horizontal airflow around a standard cylindrical raingauge will be distorted by the gauge itself so as to give a loss of about 50 per cent in 10 m/s winds for a rain rate of 1 mm/hour. With a conical or wine-glass shaped gauge, designed to reduce air-flow distortion, the loss drops to about 5 per cent. Our standard gauges are intermediate between the cylindrical and the conical forms, having a conical collector 19 cm in diameter in a hemispherical holder, with a 10 cm diameter collector directly beneath.

Folland's recommended shape combines a large collecting aperture, a wide collecting angle to minimize airflow distortion and a vertical rim to reduce "out-splash". In two sets of cruises (August to November 1985 and January to March 1986), the frame was used to test two designs: the original 19 cm collector, and a 24 cm collector that approximates more closely the conical form recommended by Folland. The effect of tilting the 19 cm gauges in each of four directions (fore, aft, port and starboard) by 10° was also tested.

In a total of 15 rain events, the observed variations were relatively small (±10 per cent) and the larger, more conical gauges did not appear to collect significantly different volumes.

In the most recent configuration, two wineglass collectors (one 25 cm and one 44 cm in diameter) specifically to Folland's design and a dual horizontal/vertical gauge have been added. The latter was used on the

Canadian weatherships at station PAPA in the Pacific and collects separate samples from a standard conical collector 25 cm in diameter and from the vertical cylindrical surface immediately below this. The latter will collect rain with a horizontal component of velocity from any direction. The two collecting areas are about equal. In use on station PAPA, the volumes of the two samples were added together.

Data from these gauges are currently (winter of 1986/7) being collected. Scatter in the results again appears low.

4. DISCUSSION AND FUTURE PLANS

On the basis of measurements so far, shipboard data collection appears feasible with an accuracy that ought to be acceptable for satellite validation. Some readings, under high relative wind conditions, may need to be ignored.

Tests with the latest set of collectors are continuing on the Skeena. A lower vessel, such as a fully loaded oil tanker might cause smaller air flow effects, but would lead to a higher likelihood of spray contamination of samples. Also, for logistic reasons, it is easier to continue working from the ASAP ship. On the basis of these experiments, we plan to mount one or more gauges more permanently, and to record rain collection continuously.

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SOME SELECTED RESULTS FROM DENSE RAINGAUGE NETWORKS

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1. INTRODUCTION

Some rainfall characteristics using data from dense recording raingauge networks will be reviewed. Data from such networks have qualified temporal and spatial rainfall distributions, and have supplied specialized information about local and orographic effects. The natural variability, temporally and spatially, for annual, seasonal, monthly and individual events will be treated. Especially important are the spatial variations of precipitation as a function of synoptic type, precipitation type, amount, and duration. Much of this review will concentrate on results from dense raingauge networks in Illinois, but some data from other climatic regions will also be treated.

A major portion of the data analysis of the dense raingauge networks in Illinois has defined the natural variability of annual, seasonal and individual rain events. Early in the analysis of network data in the 1950's, the Water Survey coined the term "storm" to describe a discrete period of rainfall within a fixed network area. Huff (1966), in a study of rainfall on a dense raingauge network of 1000 km^2, developed an objective definition of storm as any rain period separated by more than six hours without rain on the network. This definition of storm allowed discrete rain periods to be identified with specific weather systems. The operation of larger networks, with areas greater than 5000 km^2 necessitated an altered storm definition (Vogel and Huff, 1978) consisting of time-space delineations for individual rain events. For these larger networks, a storm was considered to be a rain period identified with a specific synoptic weather event and separated from other rain areas by 32 km and more than one hour between rain events at any gauge.

2. RAINFALL VARIABILITY

An important measure of rainstorm climatology is the natural variability of rainfall with duration. Table 1 from Huff (1969) shows how the climatological distribution of storm mean precipitation is related to storm duration based on an assessment of 12 years of data from a 1000 km^2 network in east-central Illinois. For example, reading horizontally in the upper portion of the table it is seen that for durations of three hours or less on the network, 28 per cent of the total precipitation, on the average, will result from a network mean exceeding 12.7 mm. This table also shows that 61 per cent of all precipitation is associated with storms that exceeded 12.7 mm and had a duration of 12 hours or less. Indeed, 95 per cent of the total precipitation is associated with storms that exceed 12.7 mm. Reading vertically in the upper portion of the table, an estimate of the distribution of storm mean rainfall in each duration category is obtained. Thus, for storms with durations of three hours or less, 80 per cent of the rainfall, on the average, results from a network means exceeding 2.5 mm compared with 7 per cent in storms exceeding 25.4 mm. The lower part of Table 1 shows the effect of storm duration and the relation between storm mean rainfall and the frequency distribution of storm occurrences. For example, it shows that for a

Table 1. Average 12-yr Distribution of Network Storm Precipitation Grouped by Storm Duration

Network Mean Storm Precipitation (mm) Exceeded	Cumulative Per Cent of Total Precipitation for Given Duration (hrs)					Cumulative Per Cent All Storms Combined
	≤3	3.1-6.0	6.1-12.0	12.1-24.0	24.1-48.0	
25.4	7	22	29	54	80	41
12.7	28	52	61	85	95	70
6.3	52	79	87	96	99	86
2.5	80	93	96	>99	99	95
	Cumulative Per Cent of Total Occurrences for Given Duration (hrs)					
25.4	<1	4	8	26	53	7
12.7	2	15	26	56	78	19
6.3	9	34	52	80	89	33
2.5	26	60	80	95	96	50

duration of three hours or less, only 26 per cent of the storms, on the average, have an areal mean rainfall greater than 2.5 mm. The three-hour storms in excess of 2.5 mm, which account for only 26 per cent of all the storms, accounts for 80 per cent of the total precipitation. The last column in the table indicates that 7 per cent of the storms accounted for 41 per cent of all precipitation and that only 50 per cent of all storms account for 95 per cent of all rainfall.

Figure 1 (Huff, 1969) provides quantitative estimates of the average distribution characteristics of network rainfall as a function of storm duration. This figure illustrates well the tendency for a large percentage of the precipitation to fall in a small percentage of the total storm occurrences, no matter what the duration. For example, the curves indicate that 50 per cent of the total precipitation occurring in storms of less than three hours is recorded in 9 per cent of the storms that occur in an average year. Garstang (1972) notes that in the Tropics, 10 per cent of the time during which precipitation falls produces 50 per cent or more of the total precipitation. Thus, even though there are many storms associated with precipitation, a small number of these storms in most climates are responsible for most of the precipitation.

Equally important is the distribution of total precipitation by warm and cold seasons in mid-latitudes. Warm season (May to September) rainfall is characterized synoptically by scattered showers, semi-organized to organized

mesoscale systems, and a few large-scale cyclonic storms (Vogel and Huff, 1978). Cold season (October-April) precipitation is dominated by organized large-scale cyclonic systems and well-organized mesoscale systems, such as squall lines (Huff and Schickendanz, 1970). The warm season rainfall in Illinois is typical of tropical convective rain. However, the tropical regions might be characterized by more frequent, shorter duration showers.

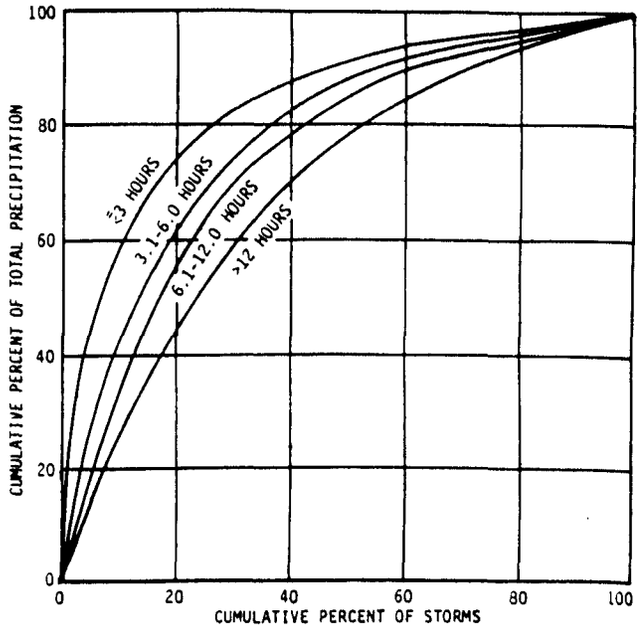


Figure 1. Relation Between Distribution of Total Precipitation and Storm Occurrences in the Central Illinois Network.

Table 2 presents the per cent of total precipitation and per cent of total storm occurrences for the warm and cold seasons for various storm durations (Huff, 1971). During both seasons, storm durations of three hours or less were most frequent. However, over 20 per cent of all precipitation falls from these storms during the warm season and less than 10 per cent of the precipitation occurs within these storms during the cold season. In the warm season, 63 per cent of the precipitation occurs with storms of less than 12 hours duration, whereas 59 per cent of the precipitation during the cold season occurs with storms with durations greater than 12 hours. This reflects the difference in the synoptic weather regimes from warm to cold seasons. The warm season rains are mainly convective and often occur within a tropical air mass. During the cold season, precipitation occurs in cyclonic storms near or in the boundaries of cold air masses. Thus, there are major differences between the durations of warm and cold season precipitation.

Precipitation type helps to define the spatial and temporal characteristics of precipitation. Thunderstorms dominate summertime warm season precipitation, frequently being the major producer of rainfall, intermingled with light rain showers. During a 12-year period (1955-1966) over a 1000 km^2 network in east-central Illinois, Huff and Schickedanz (1970) found that the combination of thunderstorms and rainshowers accounted

Table 2. Average Distribution of Precipitation on a 1000 km^2 Raingauge Network in East-Central Illinois Grouped by Storm Duration

Storm Duration	Per Cent of Total Precipitation		Per Cent of Storms	
	May-Sep	Oct-Apr	May-Sep	Oct-Apr
≤3	22	9	57	35
3.1-6.0	21	11	20	19
6.1-12.0	20	21	12	22
12.1-24.0	23	40	8	19
24.1-48.0	13	16	3	5
>48	1	3	0+	0+

for 88 per cent of the May-September rainfall and were associated with 87 per cent of the storm occurrences. From October to April the thunderstorm-rainshower combination was observed with 40 per cent of the storm occurrences, but 55 per cent of the total precipitation. Stable-type rains accounted for about 30 per cent of all precipitation and storm occurrences in the cold season. Snow and rain mixed with snow were associated with 30 per cent of the cold-season storms, but only 14 per cent of the total seasonal precipitation.

3. PRECIPITATION GRADIENTS

The variation of point rainfall with distance is another method of evaluating spatial variability of precipitation. Results from studies in Illinois (Huff, 1967), Florida (Woodley et al., 1975), and southwest USA (Osborn et al., 1980), are presented (Table 3). The Illinois analysis had a total of 186 storms, during the period 1950-1954, from two networks over flat agricultural lands. One network consisted of 25 gauges over 260 km^2 and the other had 50 gauges over 260 km^2. All analyses were confined to convective rainfall occurring from spring to fall with durations of 24 hours or less. Synoptically, the precipitation ranged from air mass showers to organized mesoscale systems to some large-scale precipitation events.

The Florida data consisted of measurements from 127 storms collected during the summers of 1971 and 1973 as part of the Florida Area Cumulus Experiment. This raingauge network had 186 separate gauge locations spread over 570 km^2 of flat agricultural land. The dominant rain type during the period was air mass showers, forced at times by converging sea breezes. The Southwest USA data were derived from the 150 km^2 Walnut Gulch Experimental Watershed in southeastern Arizona with 95 gauges and the 174 km^2 Alamogordo Creek Experimental Watershed in eastern New Mexico with 65 gauges. The precipitation gradients for the last two networks represent individual airmass thunderstorms (Osborn et al., 1980).

Table 3 presents the per cent changes in rainfall with distance, normalized by dividing from a central gauge. The Illinois data were stratified by areal average rainfall and showed that the relative variability decreased

Table 3. Precipitation Gradients for Illinois, Florida and Southwest USA Expressed as Per Cent Change

Distance (km)	Illinois Average 2.5 mm	Illinois Average 6.3 mm	Illinois Average 25 mm	Illinois Extreme 25 mm	Florida Average	Arizona Storm	New Mexico Storm
1	57	83	90	76	73	80	95
2	37	71	86	66	59	69	90
3	24	63	83	57	48	60	85
4	14	57	80	53	40	50	80
5	0	52	79	49	33	45	76
6	0	48	78	45	28	42	71
7	0	45	77	43	24	35	67
8	0	43	76	40	21	25	63
9	0	42	75	38	19	17	60
10	0	41	74	36	17	11	57

with increased rainfall volume. This is reflected by the changes in the rainfall gradient for those storms which had network average rainfall of 2.5, 6.3, and 25 mm, which are average curves. Huff (1967) also calculated extreme precipitation gradients expected to occur less than 5 per cent of the time. Such a gradient for a 25 mm storm is given in Table 3. The extreme gradient decreased much more rapidly than the average curve. For example, at 10 km for an average gradient, the precipitation would be expected to be 74 per cent of the central gauge, whereas in an extreme gradient situation the precipitation at 10 km is 36 per cent of the central gauge. The extreme gradients are about 2.5 times the average values.

The Florida data were analyzed for N-S and E-W profiles of precipitation change with distance. These profiles were averaged for Table 3, since the results suggested symmetry in all directions and the differences were minor. The variation of precipitation with distance changes rapidly and by 10 km only 17 per cent of the point maximum precipitation is expected on the average. Thus, the average Florida precipitation gradient is more extreme than the average Illinois curves and more comparable to the extreme Illinois curves. However, at 10 km they fall off more rapidly than the extreme Illinois curve. This reflects the predominant air mass shower activity in Florida.

The Arizona and New Mexico data represent precipitation gradients for extreme airmass thunderstorms derived from area-depth curves (Osborn et al., 1980). As a result, the values represent smoothed gradients for these extreme

events. The gradient for storms over Walnut Gulch, Arizona, resembles the extreme 25 mm gradient for Illinois for the first six kilometers, but then the gradient changes sharply and resembles the average Florida curve. The precipitation gradient over Alamogordo Creek, New Mexico, is relatively smooth and falls between the 6.3 and 25 mm Illinois gradients. Thus, for individual storms, extremely sharp changes in precipitation gradient can be anticipated.

Average monthly and seasonal precipitation gradients have been calculated for Illinois by Huff (1971). The per cent change of precipitation with distance depended upon the average precipitation for the area, with the sharper gradients occurring with lighter rainfalls. Extreme per cent differences of as much as 65 per cent over 16 km for monthly values and 15 to 20 per cent over 16 km for seasonal values can be expected. On the average, in Illinois, monthly differences of 20 to 25 per cent can be expected in the warm season (May to September) and 10 to 15 per cent differences are found in the cold season (October to April). Woodley et al., (1975), for three months of data in Florida, measured an extreme gradient of 355 mm in 6 km. Thus, individual months or seasons, especially in those regions characterized by convective rainfall, can expect extreme changes in precipitation amounts over relatively short distances for individual storms, months or seasons.

4. CORRELATION ANALYSIS

4.1 Annual

Annual correlation patterns were obtained for Illinois using 36 long-term stations (Huff, 1979). The results showed that the correlation between raingauges decreases faster in some directions than in others. These directional differences were primarily due to prevailing storm movements, but the correlations can also be affected by topography and other factors. These results indicated that the optimum raingauge spacing for the measurement of annual precipitation in Illinois require a greater density of raingauges in the north-south direction than in the west-east direction to maintain an equivalent degree of measurement accuracy in all directions.

Table 4 shows median correlation coefficients in each of eight directions for all stations combined over distances of 40 to 240 km. The largest correlation coefficients at all four distances occurred with NE, E, SW, and W directions, which is in agreement with expectancies from the standpoint of prevailing storm movement. However, differences between directions are not exceptionally large. For example, the highest correlation at 80 km was 0.76 and the lowest was 0.68. These account for 58 per cent and 46 per cent, respectively, of the variance between point precipitation measurements separated by this distance. For all directions combined, the coefficients of 0.90, 0.72, 0.58 and 0.45, at distances of 40, 80, 160 and 240 km, account for 81 per cent, 52 per cent, 46 per cent and 20 per cent of the variance. Thus, the correlation decay with distance and representativeness of point precipitation measurements decreased quite rapidly.

Table 4. Correlation Decay of Annual Precipitation with Distance and Direction of Illinois

Direction	Median coefficient at given distance (km)			
	40	80	160	240
NE	0.93	0.76	0.63	0.52
E	0.92	0.75	0.60	0.55
SE	0.89	0.71	0.57	0.38
S	0.88	0.69	0.53	0.38
SW	0.90	0.73	0.62	0.53
W	0.90	0.73	0.60	0.50
NW	0.85	0.68	0.51	0.33
N	0.89	0.72	0.55	0.38
All directions combined	0.90	0.72	0.58	0.45

4.2 Monthly And Seasonal

Huff (1979) used data from two dense networks in east-central and southern Illinois to investigate monthly and seasonal correlation patterns. Analyses were restricted to the May-September or warm period. Convective precipitation dominates in this period and the spatial variability of rainfall was obtained (Huff, 1966). Correlation coefficients were calculated for distances of 3.2 to 32 km. Results of the monthly and seasonal analyses combining data from both networks are summarized in Table 5. Only small differences occurred between monthly and seasonal correlation relations so that a total storm sampling network would satisfy sampling for either period.

Table 5. Average Monthly and Seasonal Correlations for May-September in Illinois

Period	Average Correlation Coefficient at Given Distances (km)							
	3.2	6.4	9.6	12.8	16.0	19.2	24.0	32.0
Monthly	0.95	0.91	0.89	0.86	0.84	0.83	0.81	0.78
Seasonal	0.95	0.91	0.89	0.87	0.86	0.85	0.84	0.81

4.3 Storm

Huff (1979) analyzed the spatial correlation relationships in storms, using data from two Illinois dense raingauge networks to provide a range of measurements that included 1-minute and 10-minutes average rainfall rates and total storm rainfall. The two networks were 260 and 1000 km^2, respectively. Analyses were made of the effects synoptic weather type, storm intensity and duration have upon the spatial distribution of storm precipitation and are summarized in Table 6.

Table 6. Variation of Correlation Coefficient with Distance about Central Gauge in Illinois during May-September Storms

		Average Correlation Coefficient for Given Distance (km)					
Group	N	1.6	3.2	6.4	9.6	12.6	16.0
Fronts	195	0.98	0.96	0.94	0.91	0.88	0.86
Low centers	28	1.00-	0.99+	0.99	0.98	0.97	0.96
Air mass storms	73	0.97	0.94	0.87	0.79	0.76	0.74
≤3 hour	184	0.96	0.91	0.82	0.75	0.70	0.65
3.1-6.0 hour	61	0.97	0.95	0.90	0.86	0.81	0.76
6.1-12.0 hour	29	0.98	0.96	0.93	0.91	0.89	0.87
12.1-24.0 hour	19	0.97	0.95	0.82	0.72	0.69	0.66
0.01-0.10 inch	111	0.96	0.93	0.90	0.88	0.87	0.82
0.11-0.25 inch	53	0.64	0.22	0.05	-0.02	-0.06	-0.10
0.26-0.50 inch	33	0.86	0.69	0.32	0.11	0.06	0.03
0.51-1.00 inch	36	0.84	0.68	0.38	0.22	0.12	0.06
>1.00 inch	19	0.96	0.93	0.88	0.82	0.77	0.71
1-min rainrate (Goose Creek)	3142	0.77	0.60	0.40	0.31		
10-min rainrate	2892	0.76	0.61	0.44	0.38		

The data were separated into three basic synoptic storm types through use of published synoptic weather maps of the National Weather Service. Types included frontal storms, low center passages and air mass storms. Analyses

did not show substantial differences in the patterns associated with the various frontal types and squall lines, so all were combined in the frontal storm group (Huff and Shipp, 1969). Low center storms show little variations with distance. Frontal storms decrease somewhat with distance and the correlation in air mass storms decreases sharply to 0.74 at 16 km. The correlation patterns for the synoptic conditions (not shown) indicate striking differences between air mass storms and low centers. With low centers, the correlation coefficient exceeds 0.90 over the entire 1000 km^2 network, whereas in air mass storms, it decreases to less than 0.60 in some directions, only 16 km from the central gauge.

The storm duration relations in Table 6 are interesting. The correlation decays with increasing duration for storms lasting up to 12 hours, then the trend reverses. A similar behavior was observed in the October-April storms and on other networks. The reversal appears to be real rather than a sampling vagary present in this particular sample of storms. A possible explanation is that the long duration storms are usually associated with extensive synoptic storm systems, and storm movements across the network are more likely to shift during these lengthy storm periods as the weather system approaches and passes.

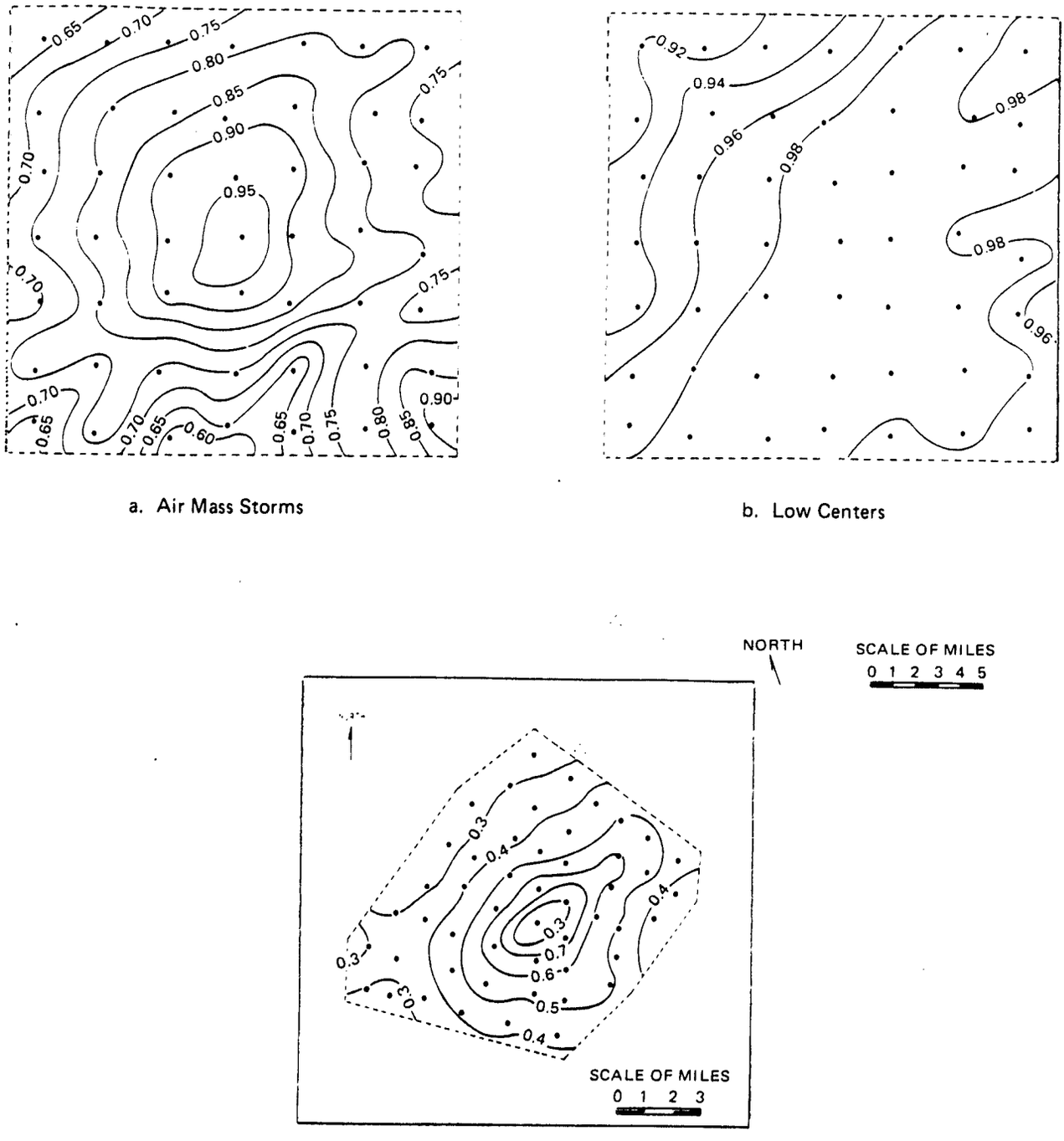
The mean rainfall groupings in Table 6 indicate that mean precipitation amounts within a sampling area have little effect upon point-to-point correlations. The trend of correlation is very erratic with increasing mean rainfall and is relatively low in three of the five data groups. Erratic trends and relatively low correlation coefficients were also found during the October-April period.

At the bottom of Table 6, relations are shown for 1-minute and 10-minutes rainfall rates for comparison with grouped storm relations. The 1- and 10-minute correlations show rapid decay with distance indicating the great variability in rainfall rates within storms.

Correlation patterns of air-mass storms and low centers are illustrated in Figure 2 for the warm season. The differences in correlation are striking. The low centers show only minor variations over the network, whereas the correlation pattern of the air mass storms decreases to less than 0.60 at the southern edge of network, only 16 km from the central gauge. The correlation pattern of 1-minute rainfall rates about the central gauge consists mostly of thunderstorms or rainshowers during the warm season. This correlation pattern shows that for a nearly instantaneous convective pattern, the correlation falls sharply to less than 0.3, to the west and south, and less than 0.4 in all other directions. The higher correlation from the southwest to the northeast represent the preferred direction of movement.

4.4 Gauge Spacing

For accurate determination of individual storm rainfall in Illinois, Huff (1970 and 1979) has shown, using correlation analysis for the warm season, that a gauge spacing of one gauge in every three kilometers is needed to explain 90 per cent of the storm variance, on the average. Similarly, in the cold season (October-April) a space of one gauge every ten kilometers is needed to explain 90 per cent of the storm variance, on the average. If one wishes to measure air mass storms with a similar accuracy, a gauge spacing of 1.6 km is required. If widely uniform precipitation is to be measured, a spacing of 13-15 km would be adequate to achieve an explained variance of 90 per cent in Illinois.



a. Air Mass Storms

b. Low Centers

c. 1-minute Rates

Figure 2. Average Correlation Patterns

5. SYNOPTICS

Generally, summer or warm season storms provide the most rainfall variability in mid-latitudes (Huff and Schickedanz, 1970), because of the convective nature of many of the rain events. A study of the general weather types and some of the pertinent summertime precipitation characteristics was done for METROMEX (Vogel, 1977, Vogel and Huff, 1978) using available synoptic and mesoscale data for each of the 33 rain events or storms, which occurred

during the five summer periods from 1971-1975. Each storm was classified into general weather types which best defined the rain-producing mechanism of each storm. The eight storm types are given in Table 7. A complete definition of each storm type is given in Vogel (1977). The METROMEX raingauge network consisted of 222 gauges distributed evenly over 5100 km^2 surrounding the city of St. Louis. The network was circular, had a radius of 40 km, and an average raingauge spacing of 5 km.

The storm type with the greatest frequency of occurrence was air mass storms which made up 27 per cent of all storms. Air mass storms, with no apparent large-scale or mesoscale support, were usually widely scattered to scattered and weak. However, these storms, even though they were observed most frequently, accounted for only 2 per cent of the total precipitation. The average network mean rainfall for air mass storms was 0.2 mm and the average rainfall recorded in only those gauges with rain was 2.8 mm. These storms covered about 7 per cent or 360 km^2. The individual convective entities covered an area between 20 - 70 km^2. At specific points, these storms can provide some locally heavy rains, in excess of 12 mm, but they make up only a small percentage of the storm rainfall over the region for individual events or for a summer. In southwestern USA, which is a semi-arid to arid area, extreme spatial variability has been observed over small areas (Osborn et al. 1980). Such air mass rains typically make up a large part of the annual rainfall.

Table 7. Summary of Precipitation Results from Synoptic Analysis of 1971-1975 METROMEX Summers

Weather Type	Per Cent Frequency of Weather Types	Per cent of Total Precipitation	Storm Point Average Precipitation (mm)		Per Cent of Storm Area With Precipitation
		All Gauges	All Gauges	Gauges with Precipitation	Precipitation
Squall line	15	51	11.9	15.7	76
Squall zone	25	25	3.4	6.4	52
Cold front	14	12	3.1	9.4	33
Stationary front	6	7	3.9	10.9	38
Warm front	4	2	1.6	4.1	36
Pre & Post frontal	8	1.5	0.7	3.3	20
Air mass	27	1.5	0.2	2.8	7
Low	1	+	1.3	5.1	25

The next most frequent storm type was squall zones which consisted of semi-organized to organized clusters or groups of showers and/or thunderstorms with motion continuity in time and space. Squall zone storms comprised 25 per cent of the storms and 25 per cent of the total summer rainfall. On the average, they covered slightly more than half of the network, had a network areal average rainfall of 3.4 mm, and those gauges with rain in the network averaged 6.4 mm. Squall line storms were the next most frequent storm type over METROMEX. The squall lines were usually intense, well organized lines of convection accompanied by strong, upper-air impulses. Even though these storms only made up 15 per cent of the storms, 51 per cent of all the rainfall was recorded during these storms. The average network rainfall in squall lines was 11.9 mm. For only those gauges with rain, the average gauge amount was 15.7 mm and 76 per cent of the network had rainfall amounts of 0.25 mm or more. Squall line and squall zone storms were the only two storm types which, on the average, covered more than half of the network.

Cold fronts occurred almost as frequently as squall lines (14 per cent). The rains associated with these fronts were often well organized, but occasionally they moved across the network with only widely scattered convective elements and light rain amounts. Cold front storms accounted for 12 per cent of the total rainfall, and had network average rains of 3.1 mm. In only those gauges with rain, the average point rainfall was 9.4 mm and the average areal coverage was 33 per cent. Overall, squall lines, squall zones and cold front storms were often well organized, covered large portions of the network and consisted of convective elements with locally intense rain rates, with large spatial and temporal variations in time and space within the storm and for the whole storm.

In addition, squall line, squall zone and cold front storms accounted for 54 per cent of all storms which traversed the network, but 88 per cent of the total summer rainfall. For reasonable measurements of climatic precipitation amounts in the Midwest or in other regions with a similar warm season climate, it is necessary to be able to measure the rainfall within these storms. Other climatic areas receive a significant portion of monthly, seasonal or annual rainfall from air mass storms and, to adequately measure rainfall in these regions, it is necessary to be able to delineate rainfall amounts from these storms. Thus, to represent precipitation amounts from convective storms, it is necessary to resolve rainfall amounts from widely scattered air mass storms to well-developed showers and thunderstorms organized into mesoscale and large-scale atmospheric disturbances.

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MULTIPLE SENSOR RAINFALL ESTIMATION

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A combination of radar and raingauge networks seems to be a very attractive alternative for validation of satellite-derived precipitation measurements. The two sensors complement each other, providing good estimates of areal extent of rainfall fields and high accuracy of point measurements. However, several difficult problems must be resolved before rainfall estimates possessing both characteristics can be obtained. These problems can be divided into a few main categories: sampling characteristics, measurement error characteristics and quality control of rainfall data. A rainfall estimation scheme that would combine the data from both sensors must account for different sampling characteristics of the sensors, consider measurement error characteristics inherent to the sensors and ensure that bad data (or outliers, in a wide sense) do not contaminate the results.

Differences in sampling characteristics are well recognized but are often dealt with on a somewhat empirical level. Although it is not fully understood what the effect of these practical approaches is, their influence diminishes with the increase of temporal and spatial scales. More difficult situations exist in the areas of measurement errors, particularly concerning radar-rainfall estimates. Many error sources are recognized and some qualitative knowledge of their influence on radar-rainfall estimates exists, but the quantitative knowledge of statistical error structure is still lacking. The problem of quality control of rainfall data is of more concern to operational environments rather than to post-analysis type studies. However, lack of quality control steps can, in any environment, lead to seriously distorted results. The most prominent problem in this area is automatic detection and elimination of anomalous propagation echoes. Also, spurious echoes resulting from targets other than rainfall or malfunction of data transmission links should be examined.

The Hydrologic Research Laboratory of the National Weather Service (NWS) is developing a multi-sensor precipitation processing system that addresses all the problems mentioned above. The system uses operational digitized radar-rainfall hourly data from RADAP II systems and daily raingauge data from the NWS River Forecast System data base. In the quality control steps, GOES satellite infrared images and surface synoptic meteorological data are used.

The estimation component of the system works under the assumption that rainfall fields are homogeneous random fields. This assumption leads to stochastic interpolation as the way of estimating rainfall. The weights in the stochastic interpolation step are determined from the spatial covariance structure for both radar-rainfall and raingauge-rainfall fields. Differences in spatial sampling characteristics (raingauge data represent a point process while radar data represent an areally-averaged process) can be taken into account by integrating appropriate covariance functions.

Measurement error is accounted for by using the correlation function of the measured and true values. The form of this correlation function is assumed to be known and has been studied via a numerical simulation experiment. Since only daily raingauge data are available, the merging of the two data sets must be done on a daily scale, which means that hourly radar data have to be accumulated into daily estimates. Rainfall estimation is carried out with spatial resolution of about 4.5 x 4.5 km^2.

Produced rainfall analysis is designed to be used as an input to hydrologic models, but can be of value to many other users. Currently, the analysis is routinely performed for radars located in the Arkansas River Basin, Oklahoma City, Oklahoma and Monett, Missouri. In the near future, it will be extended to provide full coverage of the basin by analyzing data from four more radars equipped with RADAP II processors.

The pertinence of the above-described project to the problem of validation of satellite-derived precipitation measurements is obvious. The high resolution analysis can be conveniently averaged to produce monthly estimates over one or more 2.5° latitude x 2.5° longitude areas. The described methodology which attempts to account for the most important problems in multiple sensor rainfall estimation can be used as is or with slight modifications. Inclusion of radar data into the verification process ensures accurate estimates of areal extent of rainfall fields. The analysis is already performed on a routine basis, it would take only a little extra effort to derive products required by the validation project and archive them in any desirable way. High accuracy of the products would be guaranteed by the fact that hydrologic requirements for automated real-time precipitation processing system, using multiple sensors, are much more stringent than those for the climatological validation project. Finally, the project takes place in a very meteorologically interesting region of the USA.

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SOME PROBLEMS AND PROSPECTS IN SAMPLING PRECIPITATION

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The problem of quantitative estimation of surface precipitation is a very old one with some of the earliest attempts occurring in approximately 400 B.C. in India, where bowls of about 46 cm in diameter were used to collect rain to determine the best crop for planting. It also is a difficult problem no matter what measurement techniques are employed (e.g., gauges only give evidence for the exact gauge sites, radars typically overestimate light rain and underestimate heavy rain, etc.; Flueck, 1981). One only needs to experience the rather steep gradients of precipitation in time and space on virtually all scales to become aware of some of the difficulties in quantitatively estimating surface precipitation. Although the focus in this presentation will be problems and prospects in sampling precipitation, a few comments also will be presented on other dimensions of the problem.

1. VARIABILITY AND COMPLEXITY

Precipitation, typically, is highly variable in time and space. For a given location or site, we often attempt to model precipitation amounts for a unit of time by long tailed distributions such as the lognormal, gamma, weibull, and others (Figure 1). Although the gamma appears to have received considerable support for this task (e.g., NRC, 1973), there still is need to rigorously compare different fitted distributions over different geographical locations.

Daily or hourly precipitation amounts typically require a mixed distribution with a point distribution for zero amounts and a continuous distribution for non-zero amounts. When the time periods for aggregation are longer (i.e., weeks or months), a single continuous distribution often is appropriate.

The initial attempts at spatially modeling precipitation were through bivariate distributions such as the bivariate gamma (e.g., NRC, 1973, Mielke and Flueck, 1975). More recently, the random field approach has begun to receive attention in this problem (e.g., Bell, 1986). Considerable work still is needed to verify how well the random field, or any other models, emulate real precipitation fields in space and time.

As we are learning more about precipitation and its possible processes, we have realized they are much more complex than originally anticipated. Figure 2 (Braham and Squires, 1974) well illustrates this situation. Clearly there is a need for further cloud physics work to assess what claims or conceptual models of precipitation are supported by field evidence.

2. SAMPLING AND ESTIMATION PRACTICES

When considering how the National Weather Service, cloud seeding experiments, ships-at-sea, and others collect precipitation data, it is obvious that convenience samples, grab samples, or sub-populations are the

Problems in Sampling and Estimating Precipitation

(1) Precipitation is highly variable in space and time.

a. The amount is skewed for a given location, and has been described by Gamma, Lognormal, Weibull, Kappa 1, 2, and other distributions.

b. The daily or hourly amounts require a mixed distribution.

c. For spatial variability, mixed bivariate distributions are needed and, more recently, the random field approach has been tried.

(2) The precipitation process is complex (e.g., warm and cold, accretion or aggregation, ice crystals or cloud droplets) and there is little confirmed theory.

a. As an example, if ICC = 100/ℓ; LW = 0.5g/m^3; T = +5°C at CB, then precipitation??

b. What other information is needed to resolve the question of precipitation when and where?

(3) Theory on sampling and estimation of precipitation and precipitation fields is meager. Validation presently is non-existent.

a. Convenience of "grab" samples are the norm.

b. Time period totals or averages are the typical summary "statistics."

(4) Little attention is given to "non-sampling" errors.

a. Field calibration.

b. Instrument resolution (bench and field).

c. Quality control (QC) of data.

d. Location of measurement system or sampling points.

(5) Thus, quantitative estimation of precipitation is a <u>research topic</u>! Not an engineering problem.

Figure 1. Some Problems in Sampling and Estimating Precipitation

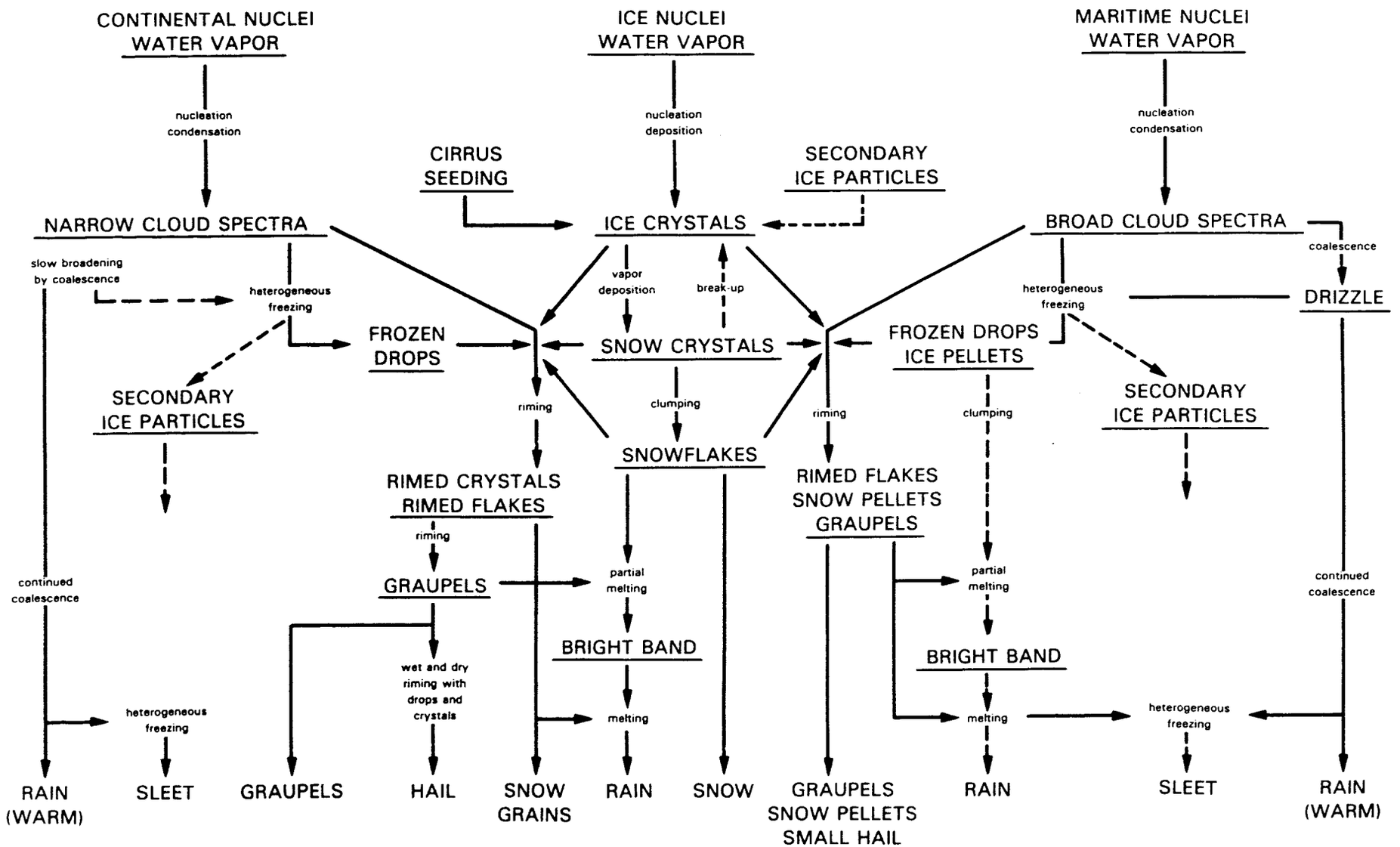


Figure 2. Flow Diagram Depicting the Various Physical Processes Contributing to Precipitation Formation [From Braham and Squires (1974)]

utilized sampling techniques. Few groups, if any, actually attempt to randomly sample or select precipitation in space or time. We all should be aware of the problems with non-random sampling such as the permanently sheltered raingauge. Even the mathematical idea of a regular sample point grid is rarely attempted. The results of these sampling decisions should leave even the most casual observer somewhat uneasy.

With regard to estimation, the typical statistics currently employed for precipitation estimation are time period totals (amounts) or averages. Rarely does even a simple measure of uncertainty (e.g., standard deviation) accompany these values. The important recent advances in resistant estimation theory (e.g., Mosteller and Tukey, 1977) appear to be entirely ignored.

Thus the present techniques for estimating precipitation seem to be based on population concepts. Much of the precipitation data appear to be viewed as if they are entirely free of error. At a minimum, some objective, meaningful and statistically sound quality control and editing rules are needed. Furthermore, important practices such as laboratory and field calibration and resolution tests, theory-guided selection of sampling points, adequate monitoring and service procedures, etc. typically are not utilized.

The end result of all of the above problems and concerns is simply that the scientific estimation of precipitation in time and/or space still is an important research question. It is not simply an engineering problem. This does not imply that we should not operationally measure precipitation, but it does suggest that we should be careful in accepting and interpreting most precipitation values and results. This also suggests that there is no such thing as established "ground truth" in any precipitation problem (at best there is a useful "reference set").

3. THE PRESENTATION

The workshop presentation will focus on the precipitation "coverage" and sampling problems (Table 1) and the advantages and disadvantages of the three major competing measurement systems (i.e., satellite, radar and gauges), Table 2. The potential impacts of each of these systems on variance and bias of precipitation estimation will be discussed. Some possible sampling point geometries will be offered and evaluated (Figures 3 and 4).

4. CONCLUDING COMMENTS

A number of suggestions will be presented in the desire to resolve some of the problems inherent in precipitation estimation in time and space (Figure 5). The author continues to believe that the idea of a Great (or Global) Precipitation Estimation Experiment (Flueck, 1981) still should be given serious consideration. Perhaps, the current Global Precipitation Climatology Project could be the vehicle for such a comparative learning exercise. If so, we would have the opportunity to both begin global estimation of precipitation fields and to scientifically improve our techniques and estimators.

Table 1. The Complete Coverage Problem for a 200 x 200 km^2 (40,000 km^2) Area

System	Instrument Characteristic	Unit Coverage	Number of Units
(1) Satellite	VIS/IR: 8 km resolution	40,000 km^2	1
(2) Radar	1° Beam Width and 50 km radius	10,000 km^2	4
(3) Gauges	12 in. (30.5 mm) catch	10^{-8} km^2	4×10^{12}
		a. 1 in 5 km	1600
		b. 1 in 10 km	400
		c. 1 in 20 km	100

Table 2. Sampling Considerations and Systems Effects

A. Minimize some criteria

1. Mean Square Error (MSE),
2. Median Absolute Error (MAE).

Remember,

$$MSE(\theta) = VAR(\theta) + BIAS(\theta)^2$$

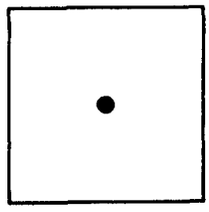
	Variance	Bias
B. Hypothetical gauge network (e.g., 8" recording gauges)		
1. Catch Size	✓	✓ (Snow)
2. Geometry	✓	✓ (Snow)
3. Density	✓	
4. Location		✓
5. Detection Threshold		✓
6. Time Resolution	✓	
7. Wind		✓
8. Service		
C. Hypothetical Radar (e.g., BW = 1°, Res. = 50 km)		
1. Beam Filling	✓	
2. Scan Angles	✓	✓
3. Attenuation		✓
4. Location		✓
5. Detection Threshold		✓ (Ice, H_2O)
6. Wind	✓	✓
7. Z-R Relation	✓	✓
D. Hypothetical Satellite (e.g., VIS/IR)		
1. Pixel Filling	✓	✓ (Edge of Precip)
2. Time Resolution (e.g., 1 to 8 day)	✓	✓ (If cycle $\leq$ 8 days)
3. Space Resolution (e.g., 8 km^2)		✓
4. Location (e.g., sun angle, nights)		✓
5. Blockage (e.g., cirrus)		✓
6. Wind	✓	✓
7. Temperature Delay on IR		✓

E. Others

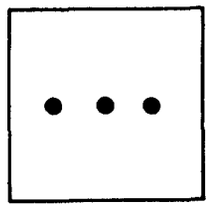
(Aircraft, microwave, acoustic, etc.)

Result: There is no "ground truth"!! Each system has its comparative advantages and disadvantages.

1. A POINT



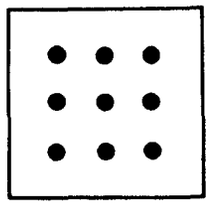
2. ONE LINE



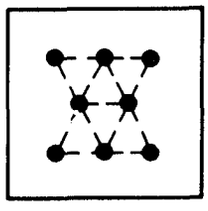
a. "ALLEYS" BETWEEN GAGES

b. "JUMPS" OVER GAGES

3. UNIFORMLY SPACED LINES



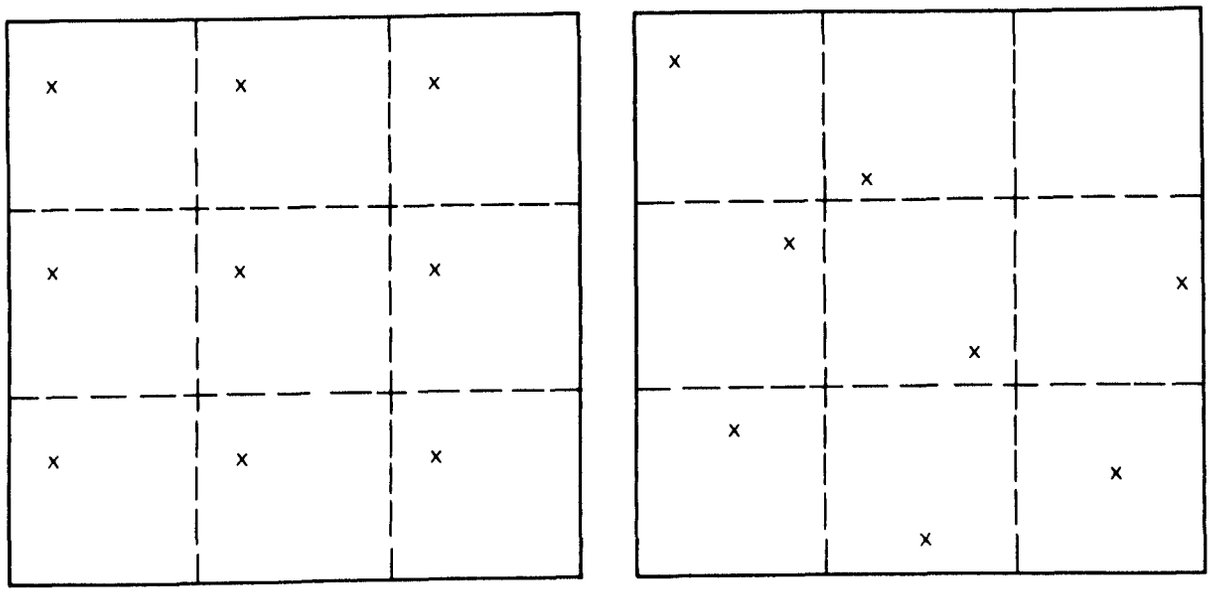
4. TESSELATION OF THE AREA WITH TRIANGLES



a. EQUILATERAL TRIANGLES

b. DENSITY OF GAGES

Figure 3. Some Sampling Geometries



(a) ALIGNED OR "SQUARE GRID"

(b) UNALIGNED

Figure 4. Two Types of Area Systematic Sampling Techniques (Cochran, 1977)

Solutions of the Precipitation Sampling and Estimation Problems

(1) We must realize that progress, for a number of reasons, has not always been rapid in this topic.

a. 400 B.C., India used 46" dishes for estimating.

b. 1677, R. Townley, U.K. used a weighing bucket.

c. 1800's produced recording raingauge.

(2) Plan for future "Big Studies" with both theory and application components.

a. Plan as if you were the emperor.

b. Plan for compromises.

(3) Ride on "projects of opportunity"

a. Piggyback

b. Joint research

(4) Continue numerous "small steps".

a. Estimate and approximate
(brute force and AI).

b. Automate
(computerize).

c. Paginate
(combine surface precipitation systems).

d. Simulate
(computerized models of precipitation response surface).

e. Compare and rate
(intercompare, compare to reference set, and rank or rate!).

f. Hibernate
(put some problems on "hold").

g. $GPCP_{86}$=$GPEE_{81}$

Lastly, we must realize that precipitation estimation still is a research problem and, hence, we all need to promote sustained research on conceptual models, measurement systems, sampling techniques and estimation of precipitation.

Figure 5. Toward Solutions of the Precipitation Sampling and Estimation Problems

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A STATISTICAL MODEL OF RAINFALL FOR REMOTE-SENSING STUDIES

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The high variability of rainfall, in space and time, makes it one of the most difficult of physical quantities to measure for hydrological and climatological purposes. We describe a stochastic model capable of generating two-dimensional rain fields with spatial and temporal correlations resembling those of tropical rainfall observed with radar during GATE (Global Atmospheric Research Program Atlantic Tropical Experiment). The purpose of the model is two-fold. It is intended to help evaluate sampling problems for satellite derived rainfall when the observations are intermittent, as occurs with satellites not in geostationary orbit, and it can help in the investigation of the beam-filling problem, which occurs when the spatial inhomogeneities of rainfall cannot be resolved by the satellite instrument and the relationship to rain rate of the radiation emitted by the rain is a nonlinear one.

The model generates rain fields with these characteristics:

(i) The statistics are homogeneous and isotropic in space.

(ii) Rain occurs over a fraction of the area, a fraction that varies with time but whose average is determined by the average observed in the data.

(iii) Rain rate is log-normally distributed.

(iv) Spatial correlation of the rainfall can be arbitrarily prescribed.

(v) Time stepping is carried out so that large-scale features persist longer than small-scale features.

The rain model starts by generating a spatially correlated gaussian random field using a Fourier expansion with random coefficients. It evolves in time using a Markov process. The portions of the field that fall below a threshold are assigned zero rain rate. The portions of the field above the threshold are rescaled so that rain rates statistically have a log-normal probability distribution. The parameters of the model were determined from a statistical analysis of a GATE Phase I radar data set covering 28 June - 16 July 1974, created by Hudlow and Patterson (1979). The distribution of rain rates was fit to a log-normal distribution. Rain, on the average, covers eight per cent of the field. Spatial correlations and time-lagged auto-correlations of area-averaged rainfall (Laughlin, 1981) were used to specify the statistics of the random gaussian field. A more detailed description of the model may be found in Bell (1987). FORTRAN code written for a Control Data Corporation CYBER 205 generates 512 x 512 km^2 rain fields at 4 km resolution in 0.2 CPU sec/time-step. A sample snapshot produced by the model with more than average rainfall is shown in Figure 1.

The model has been used to evaluate the ability of a proposed Tropical Rainfall Measuring Mission satellite to obtain a rainfall climatology in the

tropics from a non-sun-synchronous orbit inclined 30° with respect to the equatorial plane. It will also be used to help estimate the effect of unresolved spatial variability of rainfall on the development of algorithms to infer rain rate from measured microwave brightness temperature.

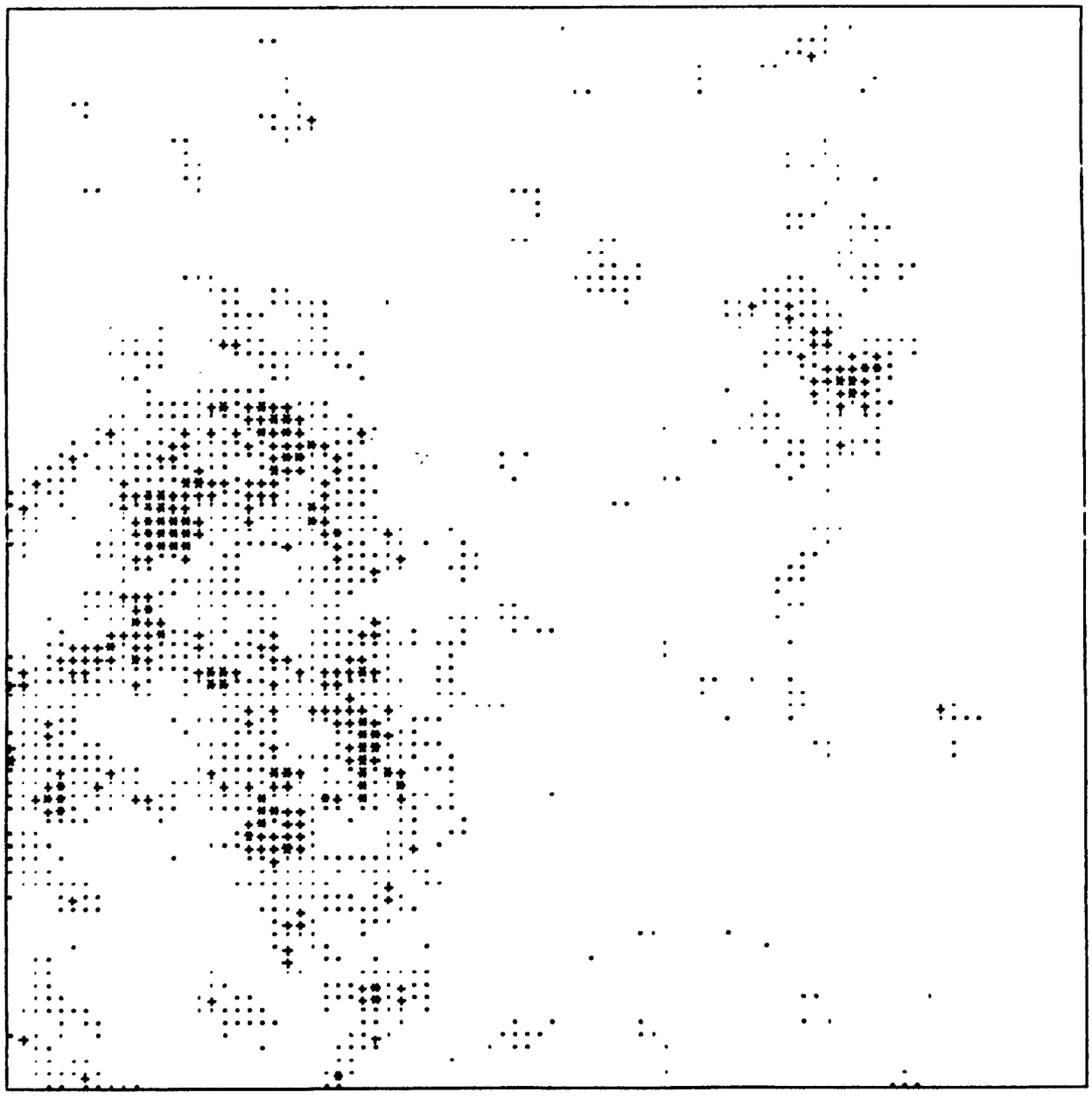

Figure 1. Model Rain field, 340 x 340 km^2 Portion from a 1024 x 1024 km^2 Simulation. Dots Include Rain Rate $r < R_1 = 10$ mm/hr, Pluses Indicate $R_1 < r < R_2 = 22$ mm/hr, and Asterisks Indicate $r > R_2$. The Divisions R_1 and R_2 are Chosen such that during Half of the Time, Mean Rain is Due to Rain Rates Less Than R_1 and One Quarter is Due to Rain Rates Greater Than R_2. Rain Occurs Over 20 per cent of the Area Displayed.

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STATISTICAL VARIATIONS OF PRECIPITATION ON SPATIAL SCALES SMALLER THAN 256 KM

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The successful remote sensing of rain accumulation on the ground from a satellite over spatial regions in excess of 200 km on a side will require adequate models for the variations of precipitation on smaller spatial scales. The footprint of a microwave radiometer on the Earth's surface spans spatial scales of the order of 10 km or larger. Significant variations in rainfall intensity and rain height will occur within the radiometer beam making rain rate estimation impossible without an adequate model for the spatial variation of rain rate. On the larger scale, low orbiting satellites will sample rain rate over a location infrequently, perhaps only twice a day. Significant temporal variations in rain rate integrated over areas as large as 200 km on a side may occur between samples, again making interpretation difficult without an adequate model. This presentation summarizes recent research on the spatial and temporal variations of rain on the scales of importance to this remote sensing problem.

Weather radar observations from several climate regions were analyzed to obtain the spatial spectrum of rain rate variations. The logarithm of rain rate was employed in this analysis because the probability distribution for rain rate at a point is approximately log-normal when integrated over time intervals of five or more minutes. The rain rate estimates were vertically integrated over a 2 km thick layer and interpolated onto a horizontal cartesian grid with a 1 km spacing between samples. A log-rain rate map was produced for each volume scan of the radar. A two-dimensional fast Fourier transform (FFT) was generated for each map. An average of the spatial power spectra from the FFTs was calculated to provide a statistically stable estimate of the spectrum of the variations in log-rain rate. The averaging interval was varied to provide estimates for reasonably similar conditions.

Spectra were generated for radar observations from Boston, Memphis, Denver and Bintulu, Malaysia. The results were the same for each location. The spectra all had the same shape when calculated for a wide enough area. For smaller subareas, the shape of the spectrum depended on the state of development of the precipitation process. When the spectra from the subareas were averaged over the wider area for analysis, the resultant spectrum tended to the universal shape. These results are typical of those expected for an intermittent turbulent process. A significant departure is the near constancy in time of the variance conditioned on the occurence of rain when calculated for the larger area. With a sufficient water flux, the rain-conditioned variance calculated for areas in excess of 200 km on a side approximated the climatological value for a single point. This approach to a constant value is illustrated in Table 1 for data from the Denver area.

Figure 1 displays one-dimensional spectra calculated for observations with different variance values averaged over 16 subareas within a 256 x 256 km^2 region and over a six-hour period. The measurements were made near Bintulu in the tropics. At the higher variance levels, the shapes of the averaged spectra are identical. They approximate predictions from

two-dimensional turbulence theory, the dot-dashed lines. Similar results were obtained for each radar location. The spectra display the power-law segments characteristic of turbulence and the larger variances at large spatial scales (small wavenumbers) typical of a non-stationary process. Care must be exercised in the development of the spatial correlation functions needed for the analysis of beam-filling and spatial sampling problems because of the lack of stationarity. Although the variance conditioned on the occurrence of rain tended to a constant value, the variance calculated by integrating the power spectrum varied with the size of the analysis area leading to the observed non-stationarity of the precipitation process. The latter result was obtained because the spectra were calculated for the entire analysis area including subregions without rain while the conditioned variance values were only for locations with rain.

Table 1. Standard Deviation Ln (Rain Rate)

JULY 9_CP2
Rain rate threshold = 0.30
VOLUME SCAN = 2, TIME = 1524

1) 128 x 128 km^2 analysis subareas

1.2	1.2
1.2	1.0

2) 64 x 64 km^2 analysis subareas

0.0	0.6	1.3	1.2
0.3	1.5	1.2	0.3
0.3	1.3	0.9	0.8
0.0	1.3	1.2	0.8

3) 32 x 32 km^2 analysis subareas

0.0	0.0	0.0	0.1	0.1	0.5	0.9	1.9
0.0	0.0	0.0	0.0	0.3	1.6	1.0	0.0
0.3	0.2	2.0	0.3	0.5	1.1	0.3	0.0
0.0	0.3	1.4	0.3	0.7	1.2	0.3	0.1
0.1	0.2	1.4	0.2	0.0	1.0	0.2	0.2
0.0	0.3	1.4	0.4	0.0	0.7	1.0	0.4
0.0	0.0	1.7	1.2	0.4	1.2	0.9	0.3
0.0	0.0	0.1	1.2	0.9	0.0	0.8	0.9

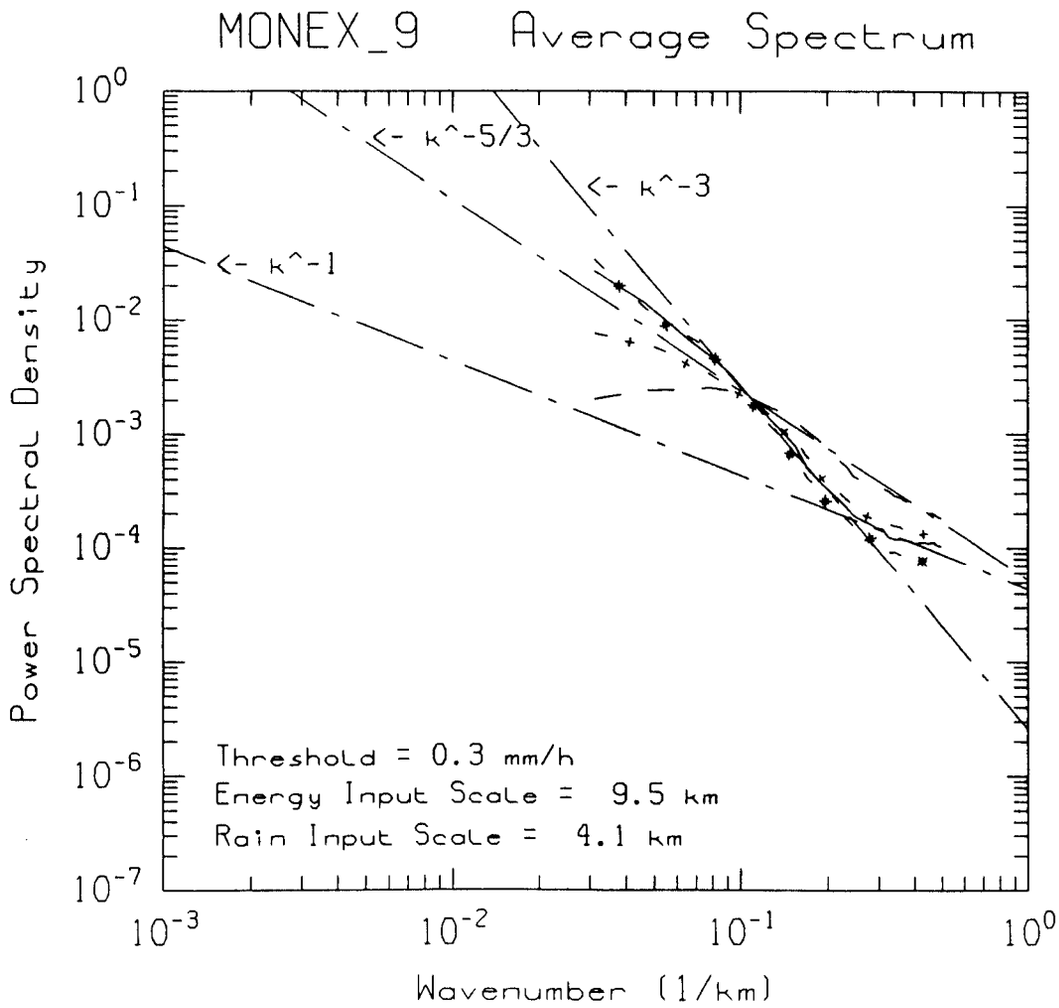

Figure 1. One-Dimensional Spectra

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PRECIPITATION STATISTICS USING MODEL OUTPUT

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A considerable wealth of knowledge about the structure and dynamic organization of tropical mesoscale convective systems has been obtained by analyzing the data set collected during the Global Atmospheric Research Program Atlantic Tropical Experiment (GATE) (reviewed by Houze and Betts, 1981). A mature mesoscale convective system can generally be regarded as being composed of two distinctive regions: a leading line of convective cells (called convective region) and a trailing stratiform (or anvil) cloud portion (called stratiform region). Precipitation within and beneath the stratiform region exhibits a characteristic signature when observed by radar. Its near horizontal uniformity over a widespread area and its long duration contrast sharply with the strong horizontal gradients and the erect orientation of the shorter-lived echo patterns that typify the convective region (House, 1977; Learly and Houze, 1979). Frequently, a thin horizontal layer of high reflectivity called the "bright band" is observed just below the 0°C isotherm when the radar scans a vertical cross section through stratiform-type precipitation (see Figure 1). In precipitation statistics obtained from studies of individual GATE mesoscale convective systems (Houze, 1977; Zipser et al., 1981; Gamache and Houze, 1983; Houze and Rappaport, 1984; Leary, 1984), widespread stratiform rain accounted for about 30-50 per cent of the total rainfall from the mesoscale system. The anvil component of rainfall was shown to increase as a system ages (Figure 2). Moreover, the vertical profile of latent heat release is drastically different in the anvil areas than in convective portions of the system (Johnson, 1984). All of these results indicate the important contribution of stratiform precipitation.

In this paper, we will present precipitation statistics from simulations using a numerical cloud model. The evolution of the total convective and stratiform portions of rainfall associated with a tropical convective system will also be estimated using model output. This paper is divided into three sections. The first briefly describes the model. The comparison of model output with observations estimated from radar-based techniques is discussed in the second section. The last discusses the application of model output to study the convective system and its connection to the workshop.

1. THE MODEL

The multi-dimensional, time-dependent, dynamic and microphysical cloud model is essentially described in Soong and Ogura (1980), Soong and Tao (1984) and Tao and Soong (1986). The model is non-hydrostatic and anelastic. Model variables include horizontal and vertical velocities, potential temperature and mixing ratio of water vapor. In addition to the Kessler-type of two-category, liquid-water (cloud water and rain), parameterized microphysics, a sophisticated three-category, ice-phase (cloud ice, snow and graupel) scheme is included (Lin et al., 1983; Lord et al., 1984). Particles comprising cloud water and cloud ice fields are each assumed to be monodisperse. Rain, snow and graupel particles are distributed in size according to an inverse exponential distribution (Marshall and Palmer, 1948). Cloud water and cloud

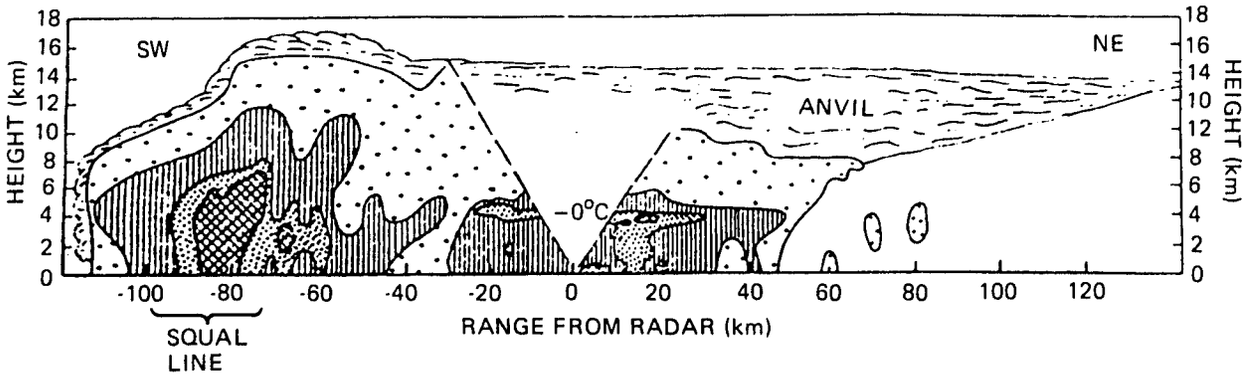


Figure 1. Vertical Cross Section through Entire Squall Line System, Along Azimuths 223 (SW) and 43 (NE) from Oceanographer Radar at 1545 UT, 4 September 1974. Inside Contours are for 38, 33, 23, and Minimum Detectable Echo (dBz). Outside Scalloped Contour Outlines Cloud Boundary Estimated from Infrared Satellite Imagery. From Houze (1977).

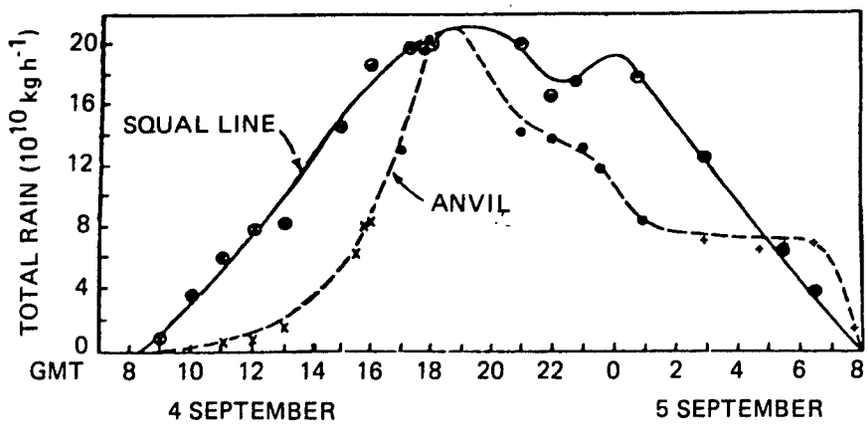


Figure -2. Total Rain Integrated Over Areas Covered by Squall Line and Anvil Portions of a Squall Line System. From Houze (1977).

ice are assumed to advect with the airflow, having no appreciable terminal velocities of their own. Rain, snow and graupel, while moving with the horizontal wind, also fall relative to the updraft with their respective terminal velocities. More than 27 different microphysical processes are included in association with the growth and transfer rates among the hydrometeors.

During GATE, six mesoscale convective systems (28 June, 9-10 August, and 4, 11, 12 and 16 September) were identified as squall-type convective lines. These systems distinguished themselves from other tropical cloud systems by their explosive growth, their distinct and generally convex-shaped leading

edge and their rapid propagation. The environmental conditions composited from three squall-type systems (28 June, 12 September and 16 September) have been analyzed by Barnes and Sieckman (1984). Their results showed that the vertical shear of the horizontal wind is normal to the leading edge of convection in the squall-type convective lines. This makes it possible to define a coordinate system relative to the squall line orientation. In our numerical simulations, the x-coodinate of the squall-relative system is chosen to be perpendicular to the convective line, directed against the direction of the vertical shear of the horizontal wind. The y-axis is chosen to lie parallel to the squall line. Temperature, mixing ratio and wind profiles from composited squall-type systems will be used as initial conditions for the model.

2. COMPARISON BETWEEN MODEL RESULTS AND OBSERVATIONS

The two-dimensionality of the model may impose restrictions in its ability to simulate certain features of convective systems. For example, the directional shear at low levels was shown to be critically important in determining the structure and evolution of mesoscale convective systems (Barnes and Sieckman, 1984). Ideally, a three-dimensional model with a large horizontal domain should be used. However, due to the limitation of current computing capacity, a three-dimensional version of the model will only cover a horizontal domain about 96 x 96 km^2. The horizontal extent of the observed stratiform region is a few hundred kilometers. Therefore, a two-dimensional version of the model with a 512 km horizontal domain will be used to incorporate a complete anvil region. The precipitation statistics obtained from the two-dimensional simulation will be used mainly for comparison with observations. The three-dimensional model results will be viewed as a supplemental tool. By comparing the two- and three-dimensional simulation results, the credibility or deficiency of the two-dimensional simulations can be estimated.

Figure 3 shows the time-sequence of estimated surface rainfall rate over the 512 km horizontal domain (two-dimensional simulation). Two cloud systems have developed inside the model domain. The life cycle of each exceeds nine hours and the areal coverage is more than 150 km in horizontal extent. The heavy precipitation area (greater than 20 mm h^{-1}) is always located along the leading edge of each system. The trailing part of the system is characterized by light precipitation (less than 10 mm h^{-1}). The vertical cross section of model-predicted radar reflectivity associated with one of the systems is shown in Figure 4. Many observed features (compare with Figure 1) have been reproduced by the model simulation. In particular, a distinctive bright band near the freezing level is simulated in the trailing part of the squall system.

The modeled precipitation has been grouped into 13 different rainfall rate categories. The first 12 categories are separated by 5 mm h^{-1} increments beginning with 0-5 and ending with 55-60 mm h^{-1}. The last category is for rainfall rates greater than 60 mm h^{-1}. The per cent contributed by the different categories to the total amount of rain is shown as a dashed bar in the histogram in Figure 5(a). The rainfall accumulated from the lowest category to a respective category is represented by a blank-bar. The corresponding total precipitating area covered by each category is shown in Figure 5(b). Note that the light rain (<10 mm h^{-1}) only accounts for about 26.5 per cent of total rain, but it covers 90 per cent of the total rain area. On the other hand, heavy precipitation (>30 mm h^{-1}) accounts for

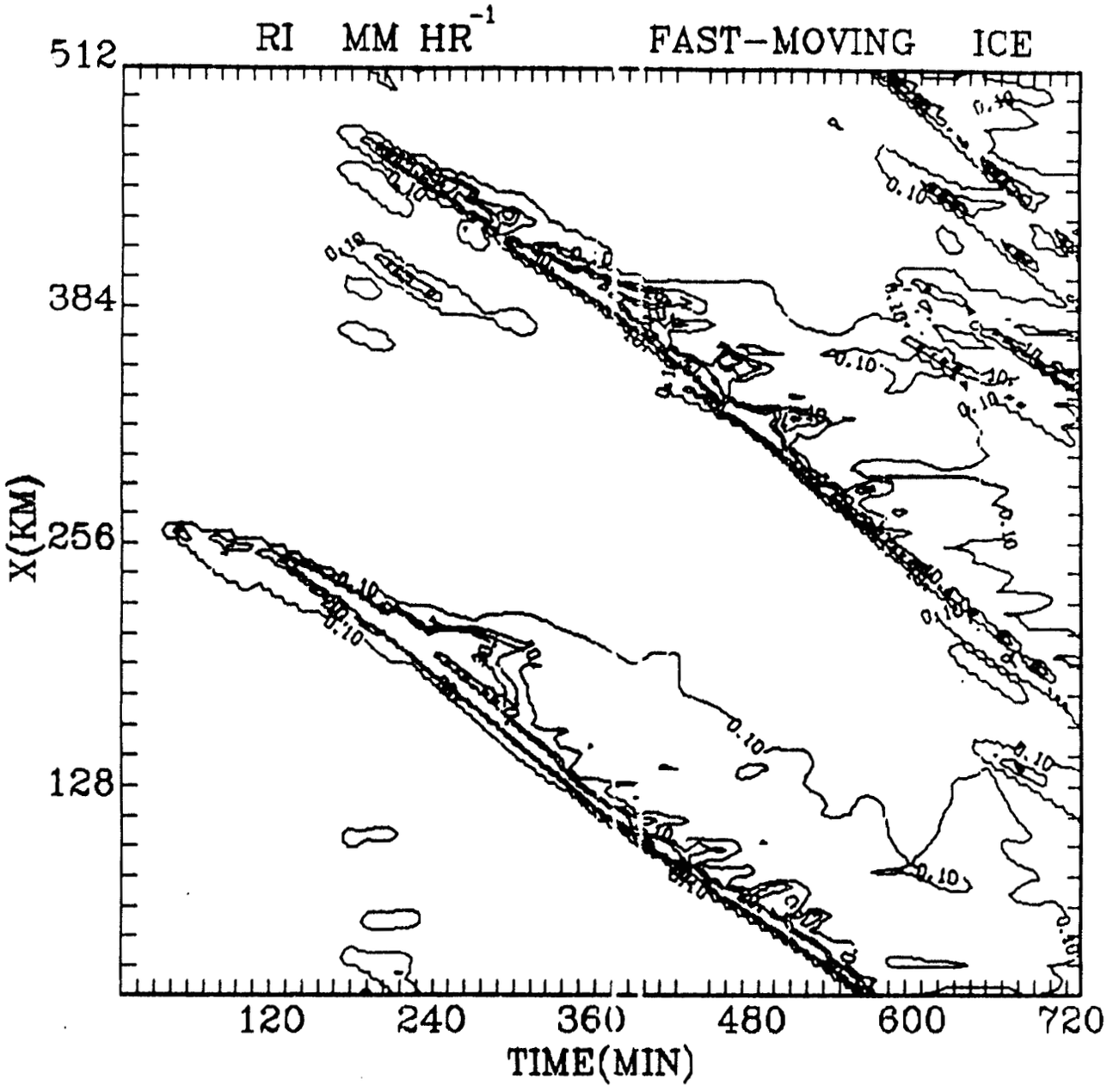


Figure 3. Time Sequence of Estimated Surface Rainfall Rate Over the Horizontal Domain (Two-Dimensional Simulation). The Contour Interval is 10 mm h^{-1} Starting at 0.1 mm h^{-1}.

a large portion of the total rain, but it covers very little rain area. These model results are generally in good agreement with GATE observations (Chiu et al., 1986). In order to partition the convective and stratiform precipitation, an algorithm developed by Churchill and Houze (1984) was used. Total rain integrated over areas covered by convective and stratiform regions is shown in Figure 6. It is found that the rain which falls from the stratiform region accounts for about 35 per cent of the total rain. The general rainfall distribution in Figure 2 has been replicated by model simulation. During the first few hours of the disturbance, little anvil rain fell. As the anvil developed and expanded, the amount of rain falling from it became equal to that generated in the convective region.

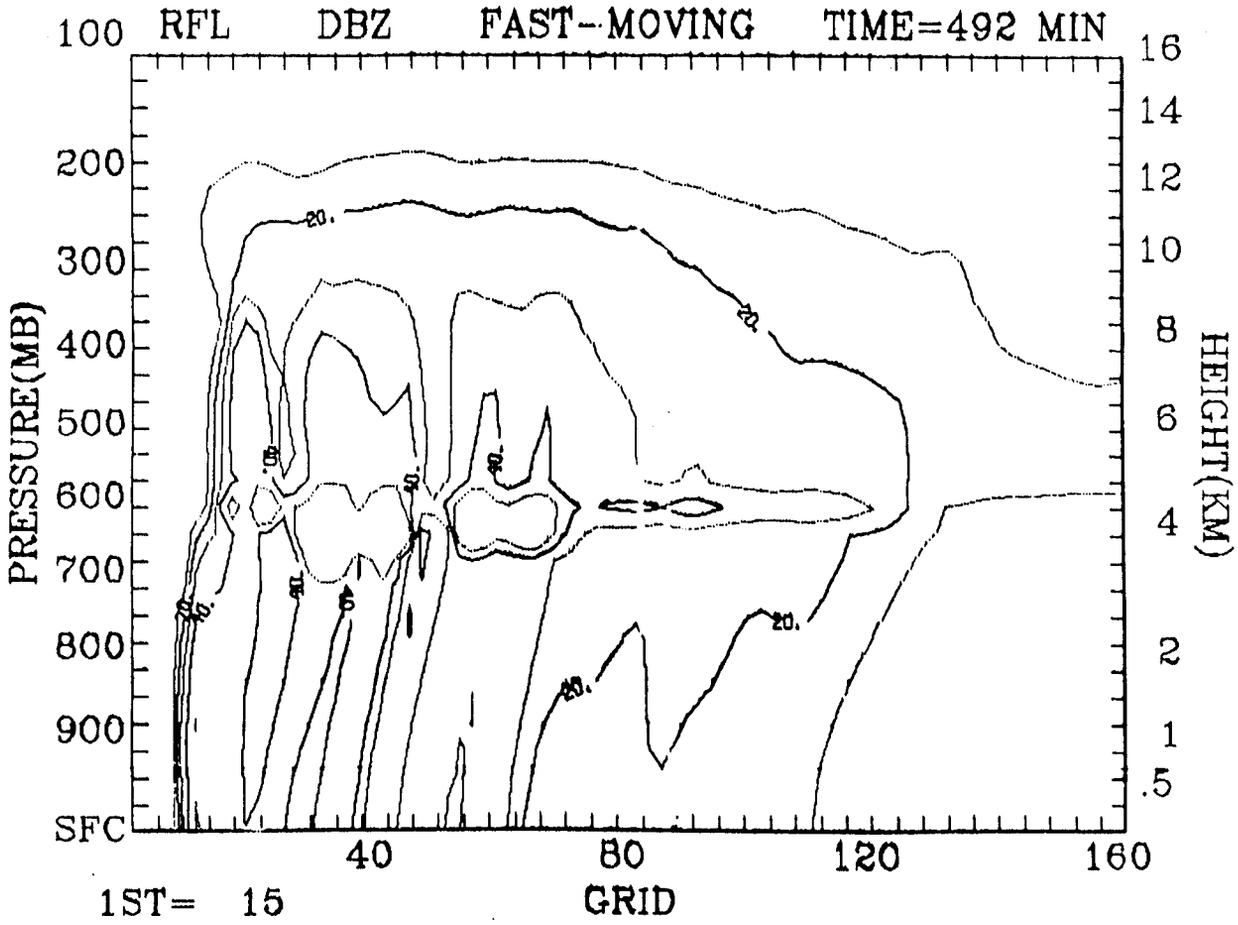
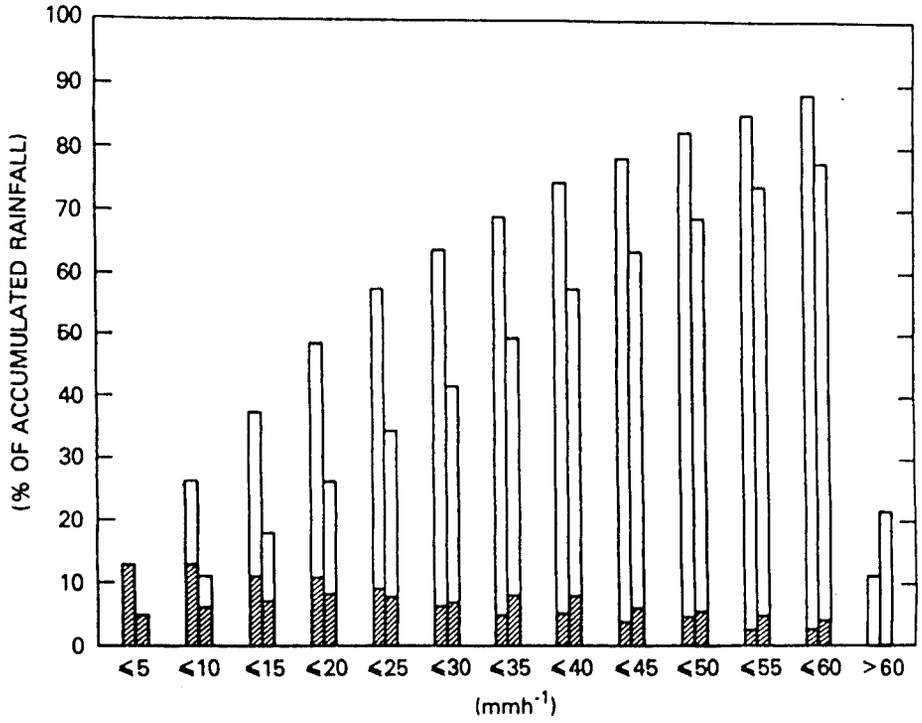


Figure 4. The Vertical Cross Section of Model-Predicted Radar Reflectivity Simulated From Two-Dimensional Model

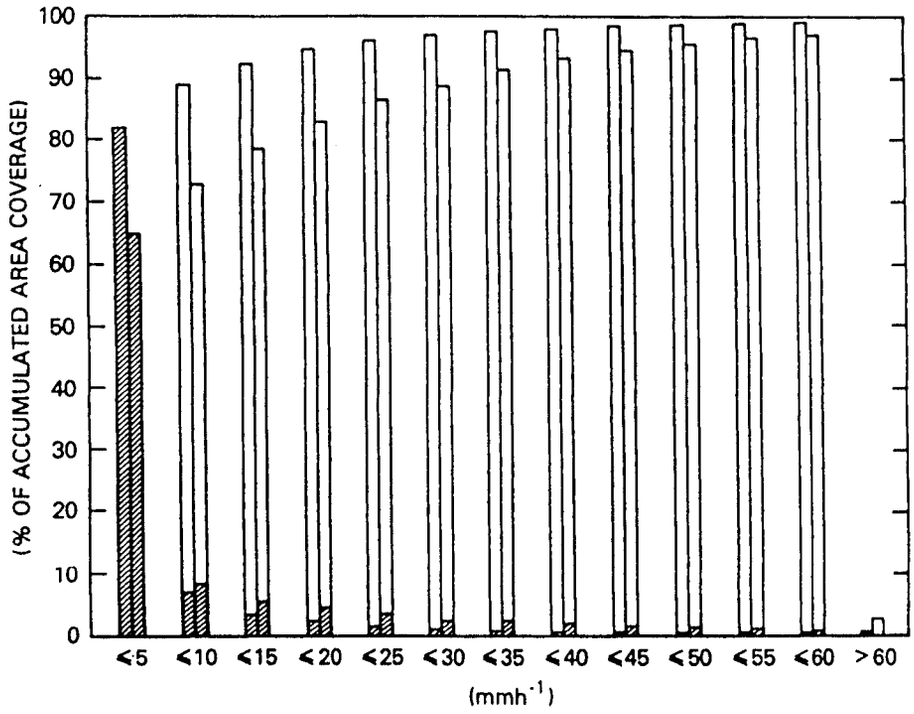
Figure 7 shows the surface rainfall rate simulated from the three-dimensional version of the model. A convective line formed along the direction perpendicular to the low level environmental wind shear. This is the same orientation as observed. An arc-shaped leading edge is also evident in this picture. The average propagation speed simulated by both models is about 8-9 m s^{-1}. It is slower than the reported composited speed of 11 m s^{-1} (Barnes and Sieckman, 1984). More comparison studies will be needed. Specifically, three-dimensional simulations will be needed to determine whether the environmental mid-level air flows around convective cores and then enters the updraft and downdraft circulation.

3. APPLICATION OF MODEL OUTPUT AND ITS RELATIONSHIP TO THE WORKSHOP

The cloud model is presently being coupled to a one-dimensional microwave radiative transfer model (Wilheit et al., 1977, Szejwach et al, 1986) to determine the relationship between rain rate and microwave brightness temperature (T_B). The cloud model will produce a vertical distribution of microphysical parameters (e.g., Figure 8) required as input for the radiative transfer model. Then, it will be determined at selected individual locations what T_B's would be given by the vertical hydrometeor distribution and the radiation model relationship between T_B and rain rate will be compared with



(a)



(b)

Figure 5. The Per Cent Contributed By Different Categories of Rainfall Intensity to the Total Amount of (a) Rain and (b) Precipitating Area

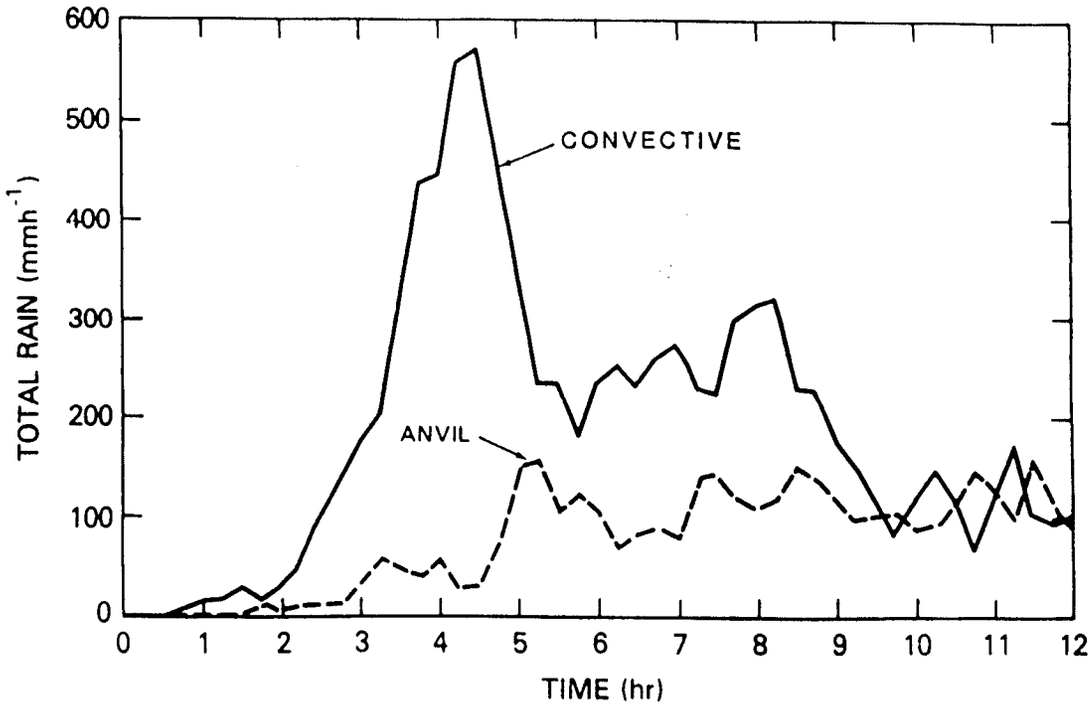


Figure 6. Same as Figure 2 Except Simulated By A Two-Dimensional Model.

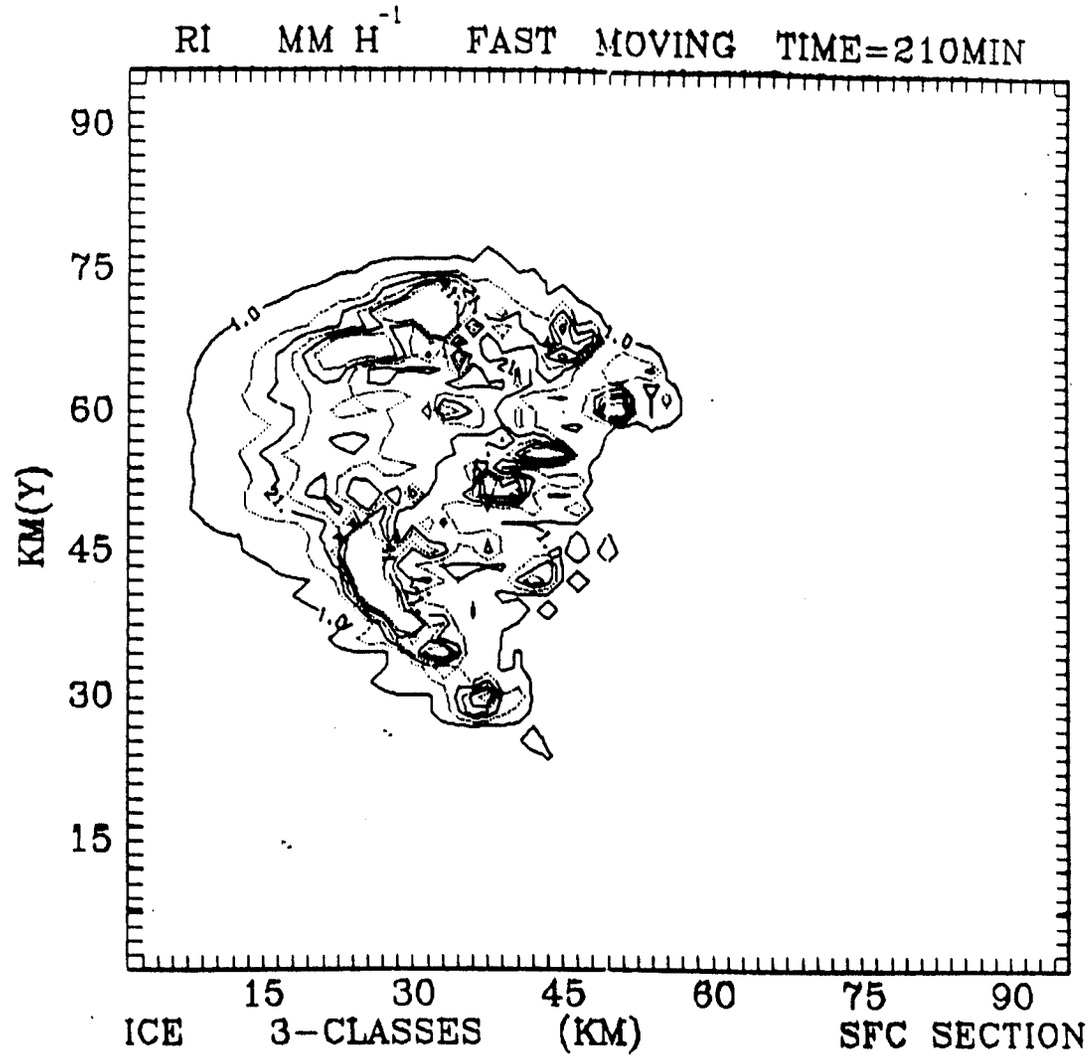


Figure 7. Estimated Surface Rainfall Rate Over the Horizontal Domain at 210 min Simulated From Three-Dimensional Model. The Contour Intervals are 10 mm h^{-1} Starting at 1 mm h^{-1}.

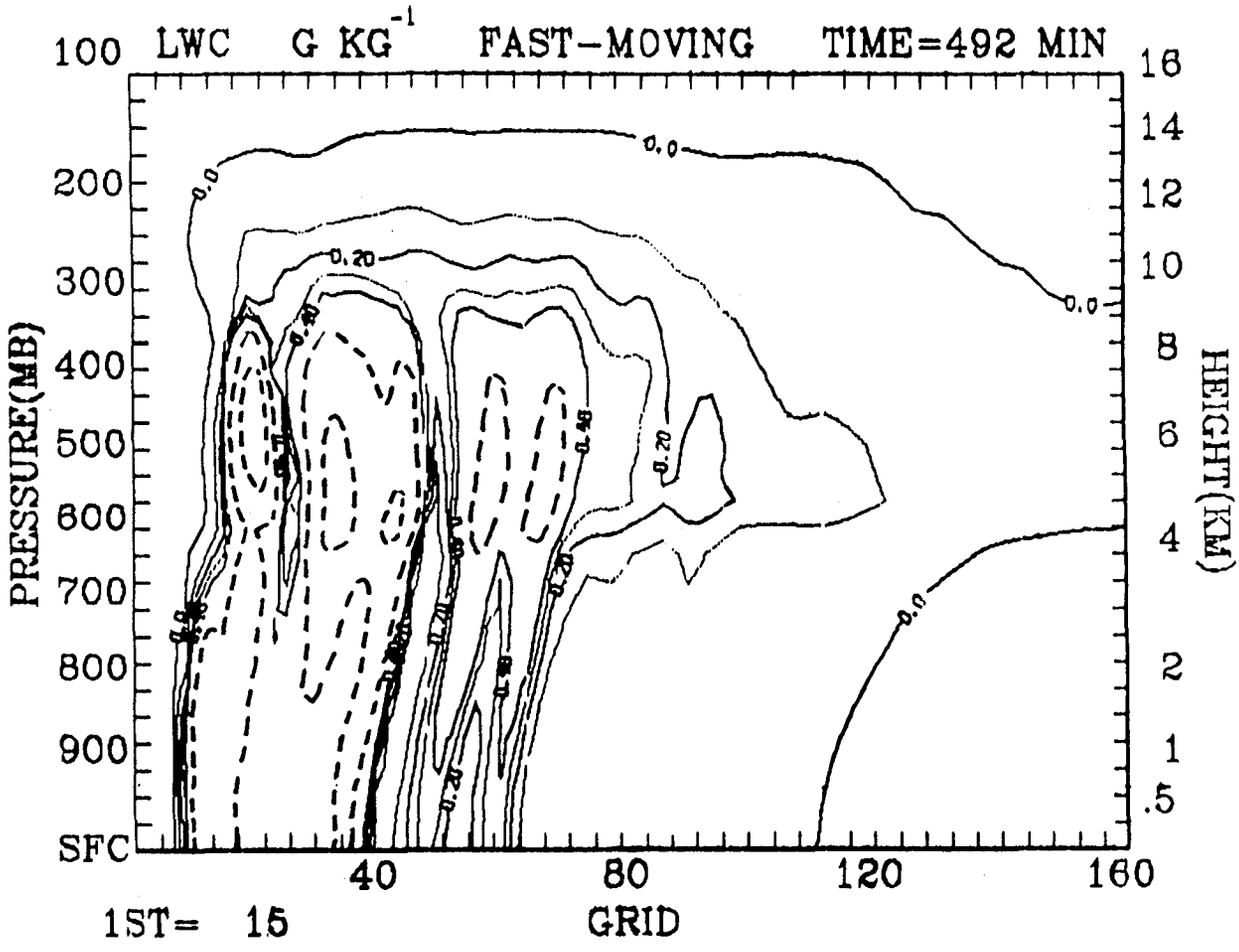


Figure 8. Same as Figure 4 Except for Total Precipitating Water and Ice. The Dashed-Line Contour Interval is 1.5 g kg^{-1} Starting at 1.5 g kg^{-1}. The Solid-Line Contour Interval is 0.1 g kg^{-1} Starting at 0.001 g kg^{-1}.

actual rain rate reaching the surface below the modeled cloud position. The next step will be to use the whole model domain (e.g. Figure 7), under varying degrees of cloudiness and rainfall, and to deduce the distribution of T_B and its area average for each microwave frequency, comparing the radiative-model deduced mean area rain rate with area-averaged rain rate actually prevailing in the cloud population model. Finally, the statistical vertical distribution of hydrometeors corresponding to different categories of rainfall rate (Figure 5) will be used to deduce T_B. The model will also be applied to a variety of geographical locations, especially those of different climatic rainfall conditions. This type of study is needed to refine estimations of rainfall from radiances and radar signals measured from space.

The stratiform region which evolves in mesoscale convective systems has many impacts on the global general circulation as well as climatological change. The vertical distribution of heating and moistening profiles by clouds will be significantly affected by its appearance. Another impact is a pronounced lag of a few hours (Figures 2 and 5) in the development of

stratiform precipitation in the early stages of the life cycle, indicating the importance of the storage of condensate in the anvil cloud to the water budget of mesocale convective systems. Probably the most important impact of the stratiform region is on the global radiative budget because of its large areal coverage. The cloud model has been applied with a limited domain size to study the heating and moisture profiles in a tropical (Tao and Soong, 1986) and an extratropical mesoscale convective system (Ogura and Jiang, 1986). The model with a large horizontal domain, which also treats the microphysical processes fairly realistically (although by no means perfectly), could be used and it would help us to understand precipitation processes associated with convective and stratiform regions.

Cloud model results provide complete, dynamically consistent data sets within the limitation of the specific model employed. These data sets will help enormously in interpreting observed data by providing new insight into the dynamics and energetics of complex convective systems. The cloud model should be included as an integral component of the proposed ground truth study. Ideally, a three-dimensional model domain should be used. Since doubling the number of grid points in a three-dimensional domain implies a 16-fold increase in computer time, this demand may exceed available computing power. Both two-and three-dimensional simulations need to be run in combination with any proposed ground truth study.

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LIST OF REPORTS

WCRP-1 VALIDATION OF SATELLITE PRECIPITATION MEASUREMENTS FOR THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT (Report of an International Workshop, Washington, D.C., 17-21 November 1986) (WMO/TD-No. 203)