FINAL REPORT ON PHASE I OF DEVELOPMENT OF SATELLITE IMAGE PROCESSING TECHNIQUES FOR THE FIRST GARP GLOBAL EXPERIMENT

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I. Introduction

The objective of the effort discussed in this report will be to develop systems using GOES VISSR data to:

1) Estimate convective rainfall and latent heating using data from satellite images
2) Measure cloud parameters objectively.

The effort has three projected phases. The first phase is a feasibility study. The second will be a technique development program, and the final phase will be demonstration and transfer of the techniques to appropriate users. This report will discuss the progress made on the first phase.

The efforts during this phase have been to determine:

1) Who are the potential users of cloud measurement and rainfall data and what are their requirements.
2) What is currently available to meet these requirements.
3) How adequate are the currently available techniques.
4) What developments would be required to meet the potential user requirements.

The discussion of these efforts will be separated into two sections, one on cloud census and the other on rainfall estimation.

II. Cloud Census

The following classes of potential users have been contacted.

1. General circulation modeling (GCM) and climate modeling groups
2. Tropical and GATE research groups
3. Pilot and aviation groups
4. Forecast groups

5. Cloud wind measurement groups

6. Mesoscale forecast research

The requirements of the different groups are quite different as are the currently available products. The different groups will be discussed separately as to requirements, currently available cloud products, adequacy of the currently available products for their needs, and developments which would be required to fully meet the needs of the group.

A. GCM and climate modeling groups

For time scales of greater than 2-4 days, radiation becomes one of the main forcing functions of the atmosphere's circulation. Of the many factors which influence the radiation budget of an area, the factor which is the largest and most variable is cloudiness. Clouds can be considered to be "the shutters of earth." Data from meteorological satellites show clouds to be organized by the large scale flow. Hence there is a strong internal feedback mechanism between radiation, the circulation of the atmosphere, and clouds. If the circulation of the atmosphere is to be modeled for periods longer than 2-4 days, the linkages between large-scale atmospheric variables, cloudiness, and radiation must be firmly established. Of these linkages, the relationship between cloudiness and atmospheric variables is the weakest.

1. Requirements

The requirements for cloud information vary with the different types of climate models. The simplest climate models are the vertically and zonally averaged atmospheric models which address the mean radiative equilibrium heat balance of the earth such as those of Budyko (1969), Sellers (1973), and Bryson and Dittberner (1976). In these models the cloudiness is set at a mean effective fractional cloud cover and maintained as a constant with the assumption being that cloud cover variations are negligible on the hemispheric scale over the past century. All these simple models are looking for external changes which affect the atmospheric climate. However, even in these simple climate models, sensitivity analysis shows cloudiness to be a major factor. In the Bryson and Dittberner model (1976) the effective fractional cloud cover was assigned to be .40. Sensitivity analysis showed a 1% variation in that value caused a .5°K change in the Northern Hemispheric mean surface temperature. The observed change over the period 1880-1945 was .6°K.

Even in the more complex climate models, the treatment of cloudiness is still rather crude. In the Geophysical Fluid Dynamic Laboratory (GFDL) general circulation model (GCM) the clouds for radiational purposes are specified from annual mean observed distributions of clouds which varies with latitude and height, but not longitude or time (Manabe et al., 1974). In the NCAR model (Kasahara and Washington, 1971) and the GISS model (Somerville et al., 1974) the clouds are determined by dynamical processes. While the monthly mean cloudiness does resemble the observed mean cloudiness, the instantaneous cloud fields have little relationship to observed clouds.

Studies of the sensitivity of the global climate to changes in cloudiness have shown the climate to be very sensitive to cloud variations. Schneider (1972) has shown that an increase in the cloud amount will decrease the global average surface temperature,while an increase in the effective cloud top height will increase the surface temperature. An increase of the effective cloud height from the present 5.5 km to 6.1 km could raise the surface temperature by 2°K. An increase in fractional cloud cover per se from 50% to 58% should decrease the surface temperature by 2°K.

Observed cloudiness is required by all climate models either as an input parameter for the simpler models or as a verification tool by the more complex models. The need to obtain cloud observations has been reflected in the GARP requirements (GARP Special Report No. 14). Because of the sensitivity of the climate to cloudiness, the GARP program has specified the desired measurement of cloudiness with the following specifications:

space resolution	100 km
time resolution	1 day
period of measurement	FGGE
desired accuracy	1 km vertical 1° cloud top temperature 5% amount
observing technique	subjective analysis of RAOB and satellite imagery

This data would be used in several ways. The simpler models require an "effective" fractional cloud cover of opaque clouds. Present estimates range from 40% (Bryson and Dittberner, 1976) to 50% (Budyko, 1969). Existing GCM models which input climatical clouds for radiation calculation such as the GFDL model require average cloud distributions as a function of position and height. Other GCM models such as the NCAR, UCLA, and GISS models require observations to verify the existing cloud parameterization routines. The development of the next generation of cloud parameterization techniques will also require detailed cloud data.

2. Existing Observations

There are two types of cloudiness observations. One is average cloud cover over a period and the other is detailed cloud measurements. The average cloud cover is useful for inputs to simpler models and for qualitative verification of more complex models. The detailed cloud measurements are required for cloud parameterization studies. The cloud climatology studies available and their sufficiency will be discussed first, followed by existing systems of detailed cloud measurements.

a: Cloud Climatologies

The first, and in many cases still the standard cloud climatology, was Telegadas and London (1954). This study was done before the age of the satellite and is limited to mainly land based observations. However it contains information on average cloud types and the heights of these cloud types as a function of latitude in addition to observations of total cloud cover. Satellite data from the early TIROS, ESSA, and NOAA satellites have been used by Miller and Feddes (1971), Sadler and Harris (1970), Schutz and Gates (1971), Van Loon (1972), Clapp (1964), and others to produce climatologies of total cloud cover based on analysis of fractional cloud cover of grids on visual satellite images. These satellite climatologies contained no information on the vertical distribution of clouds or information on cloud types. These fractional cloud cover climatologies are presently being used by modelers as a qualitative verification because they are the only data available.

However the present cloud climatologies do not provide enough information. As stated by Arakawa (1975):

> "Obviously any cloud modelling must be verified and tuned. It is therefore necessary to establish a global climatology of the geographical and seasonal distribution of the clouds, in which the high, middle, and low clouds are treated separately, and if possible, by cloud type. The climatology of total cloudiness, which is all that is presently available, is of very little help in modeling clouds and cloud processes."

b. Current Cloud Measurement Programs

One of the currently operational cloud measurement systems which potentially could be used for cloud parameterization is the Air Force three dimensional Nephanalysis (3DNEPH) model (Coburn, 1971). This system produces an objective three-dimensional cloud field analysis with a horizontal grid spacing of approximately 25 nautical miles and 15 vertical layers with the highest vertical resolution at the earth's surface. The 3DNEPH uses as its inputs all the available data which could be related to cloud fields: surface observations, radiosonde soundings, aircraft reports, and meteorological satellites. The 3DNEPH has a modular data processing design based on decision tree type logic. It handles a very large volume of input data and generates global analyses of cloud type, weather, maximum tops, minimum bases, total cloud cover and percent cloud amounts at 15 levels. This data is used for Air Force requirements which will be described later in this report in the section on aviation requirements. The 3DNEPH is produced every three hours. The area of coverage is determined by military priorities and availability of computer resources, but is generally limited to the northern hemisphere. The 3DNEPH has been archived since 1 March 1974 at Asheville. Approximately 120 tapes of 3DNEPH data are produced each month.

While the 3DNEPH potentially could be used for cloud parameterization research, in actuality it has received very little use outside the Air Force. There have been only three serious inquiries at Asheville on the 3DNEPH which have obtained sample tapes. These inquiries were from GFDL, NCAR, and NASA's climate program. None of them however have made any extensive orders of data.

There are several problems with the 3DNEPH which limit its usefulness for cloud parameterization studies. One, the data sources are not specified on the resultant data tapes. All available data are used in the 3DNEPH including radiosonde data which has inferred cloud cover by a temperature-humidity-cloud parameterization technique. Cloud parameterization studies which try to relate relative humidity data to clouds require an independent measure of clouds. Because the sources of the cloud information are not recorded, the 3DNEPH analysis could be contaminated with radiosonde data in the regions where they are available making independent comparisons of clouds and relative humidity impossible. Another problem is the lack of published verification of the 3DNEPH. It is difficult for an outside scientist to verify the 3DNEPH since it uses all sources of currently available cloud data. The verification is very important because much of the basis of the 3DNEPH satellite processing is empirical relations. The techniques for deriving fractional cloud cover, cloud height, and cloud thickness from the satellite data potentially could not be accurate enough for scientific purposes and would require extensive verification. The cloud amount is determined with a clear/overcast assumption for each picture sample. Shenk and Salomonson (1972) have shown that this type of procedure can lead to serious errors if the cloud area is less than 100 times the field of view of the sensor. Hence the 3DNEPH potential could have cloud amount errors in regions of broken and small clouds. The cloud height determination is made using a black body assumption which would cause erroneous measurements of cirrus heights because of emissivity problems. Cloud thickness is determined by the variance of the IR data around the level of the cloud height. This method requires a broken cloud field to work at all and completely ignores the variations in cloud temperature due to emissivity variations and small clouds filling only part of the field of view of the infrared sensor.

The other currently available cloud measurement product which might be used for cloud parameterization studies is the retrievals of the atmospheric sounders. In the sounding retrieval processing, cloud height and cloud amount are byproducts (Smith and Woolf, 1976). The assumption has been made that the clouds are at the same height in the processing area. This area is approximately 120 x 280 km. The sounding retrievals for the Data Systems Test (DST) periods are available using these techniques. NCAR is presently starting the evaluation of the usefulness of this cloud amount and cloud height information for cloud parameterization studies.

B. Tropical and GATE Research Groups

The GATE researchers are concentrating on the interactions between cumulus convection and the synoptic scale flow field. These research programs are tied closely to the needs of the general circulation models for better cumulus cloud parameterization techniques. For these studies detailed analyses of convective activity are required. All measurements of the vertical transports of heat, moisture, and momentum that are being made from GATE data must be related to the cumulus convective activity since convection can cause large changes in these transports.

The GATE workshop (Charlottesville meeting, January, 1977) has specified a strong need for a uniform description of the state of the convection. At the present time the convective state is being described independently by individual researchers. The data sources used for describing the state of the convection are satellite images, radar, photographic pictures from ships, and radiosonde profiles. Radar, radiosonde, and ship sky cover pictures are limited in the area that they can cover. The satellite coverage is not limited and can be extremely valuable for studying the relationship between convection and synoptic scale motions. Most GATE researchers do not have access to digital satellite data and therefore can not make quantitative measurements. Hence a cloud measurement analysis for the GATE periods of interest would greatly help the GATE research programs.

For GATE studies analyses of the state of convection in the entire GATE area are needed. The important parameters are the stage of the convection (growth or decay), the depth of penetration, and the amount of area covered by convective cells. In most cases these quantities can be measured from the satellite data. Some problems will exist in areas of deep convection because of cirrus anvils covering the lower cloud fields. Similarly, inactive cloud layers will have to be distinguished from convectively active cells. It is desirable that these statistics be made for grid scales no larger than 30 km. Such resolution will provide information on a scale small enough to be useful to boundary layer and point location studies. This grid resolution is comparable to that provided by other observing systems. These detailed analyses need not be made for a long time period. Most research is being concentrated on phase 3 data with a few other studies being made on the latter part of phase 2. This period consists of only 35 to 40 days in total.

If the effects of convection can be understood in relation to the satellite measurements, then the satellite data can be used to determine the total area affected by convection and thus the total effect of the convection on the large-scale motion field. Empirical descriptors of this type of relationship have already been made with satellite and rainfall data. Using the detailed studies of GATE it may be possible to correlate satellite cloud measurements with latent heat release. The manner in which latent heat is released in the atmosphere, and the amount of vertical mixing, also may be correlated with the satellite measurements. Such relationships between satellite measurements and atmospheric processes could be used for studying large areas over long time periods to collect the large data sets needed for developing parameterzation schemes for global numerical models.

C. Pilot and Aviation Groups

Clouds influence flight operations. The groups which are most affected by clouds are small aircraft pilots, military operations, and overseas commercial flights.

1. Small aircraft flight forecasts

Many small aircraft pilots are restricted to flight patterns where visibility is not obscured by clouds. These visual flight rules (VFR) severely impact the majority of private pilots without instrument ratings. (The VFR pilots are required to fly below clouds unless the cloud field is scattered so that ascent and descent can be made between clouds.) Flight forecasts including cloud cover information are prepared by NOAA and distributed by the FAA.

The information for the cloud description in the flight forecast briefing comes from two main sources, the surface weather depiction facsimile chart and the experimental satellite cloud analysis chart. The surface weather depiction chart is based on surface observations of clouds report. The experimental satellite cloud analysis is produced by NESS from the hard copy satellite image. A NESS analyst outlines the major cloud features, annotates them as to cloud type, cover, growth patterns and measures the height using the infrared temperature from the MMIPS (Cooley, 1976). The experimental satellite cloud analysis chart is currently made once per day. This analysis is useful for cloud top flight requirements and compliments the surface weather depiction which views the clouds from the bottom. Flight Service forecasters are finding the satellite analysis product useful (Bittner, 1977, private communication).

2. Military Operations

The military requires cloud information for several types of missions.

Cloud information is required for the programming of reconnaissance satellites. Missile target selection decisions require cloud information. Flight operations which require visibility such as mid-air refueling also require cloud information. Cloud data are by the military in flight path fuel optimization to infer winds over data sparse regions.

To meet these needs, the Air Force has developed the 3DNEPH described previously, and a cloud forecast model which uses the 3DNEPH as input data. The 3DNEPH uses all available cloud data for inputs and is continually being expanded as new data sources become available. The area of coverage is limited to those areas with military reconnaissance, target selection, or flight requirements which are generally in the northern hemisphere.

D. Forecast Groups

An objective cloud analysis was produced by NOAA, NESS on an experimental basis (DeCotiis and Conlan, 1971) from NOAA-1 polar orbiter data. There was not much demand for this type of analysis in the NMC operations so the cloud analysis never became an operational product. The techniques were transferred to the Air Force and became part of the 3DNEPH.

With the advent of improved satellite capabilities, interest within NOAA for cloud analysis has revived. The experimental cloud analysis for aviation briefings is one example. Another is the subjective moisture analysis of the eastern N. Pacific (170°E - West Coast) and the Gulf of Mexico. This moisture analysis is done with VTPR channel 7 water vapor sensor and the satellite imagery. From the cloud patterns, ten different moisture profiles are inferred. This information is operationally entered into the LFM as bogus ship reports.

Another product which requires cloud information is fog dissipation forecasting. One of the key parameters of fog dissipation forecasting is the depth of the fog layer. Also the knowledge of the presence of clouds above the fog layer is required to compute the amount of solar radiation available to burn off the fog. NMC is presently using the experimental satellite cloud analysis for this fog forecasting, though it is not aimed specifically toward fog forecasting.

Still another forecast problem which requires cloud information is convection forecasting. For most mid-latitude precipitation to occur, the tops must be below freezing to provide the ice nuclei to start the precipitation process. Vincent Oliver of NESS has been experimenting with radical enhancement techniques which outline critical temperature areas on SMS/GOES infrared images. This technique also has been applied to severe convection to outline very deep cells. This technique has been developed to be applied to the image sectors going to the forecast offices. NESS is also investigating the development of a cloud top height analysis which would be comparable to radar top information.

The forecast problems which require cloud data boil down to requiring quantitative information on cloud height, cloud thickness, cloud type, or cloud temperature. This information is available in the experimental satellite cloud analysis which is transmitted to forecast offices on the facsimile circuit. Like all facsimile products the forecaster does not get the analysis until several hours after the observation time. The experimental satellite cloud analysis and the surface weather depiction appear to satisfy those operational requirements which are met via the facsimile circuit. However, there is a need for quantitative cloud measurements with a short lead time. Fog forecasting and severe storm forecasting are examples of this need. The forecaster needs to view a sequence of satellite images, select the interesting areas, ask for quantitative measurements of cloud parameters, and receive immediate answers. This capability is currently available on the McIDAS at Wisconsin and potentially on the MMIPS at NESS. When the AFOS becomes operational, the data base required for this type of cloud analysis will be available at the forecast offices along with the sections of the satellite images. Some additional hardware and software development is required, however, to provide the forecaster with real time quantitative cloud information.

E. Mesoscale Forecasting Research

Mesoscale forecasting research is centered in two main areas. One is to develop quanlitative tools to aid the forecaster making a short-range forecast. The other is to develop quantitative tools to make measurements which can be used to initialize mesoscale models. Satellite data impact mesoscale research because the space-time resolution of the satellites observations is closer to that required to describe the weather phenomena that are most other types of weather data. Research on development of qualitative, quasi-quantitative techniques have shown that data from images of cloud fields can be used to locate the areas of initial convergence which trigger severe storms (Purdom, 1976), fine tune the local mesoscale forecast (Scotfield, 1976), and measure the severity of the instability by measuring the growth rate of the anvil (Sikdar et al., 1970). However these techniques have not made their full impact on the operation forecasts because of the present problems of transmission, display, and inability to make simple measurements from the satellite images at the forecast offices. As these problems are overcome, the impact of geostationary satellite data on qualitative mesoscale forecasts should increase in the near future.

Research on quantitative measurements of satellite images for mesoscale model initialization is progressing, but at a slower rate than the qualitative research, Houghton and Wilson (1976) have demonstrated the ability to measure mesoscale wind fields, measure convergence and infer realistic vertical motion fields. Kreitzberg (1976) has developed a mesoscale model which uses cloud images to aid in the model initialization and has stated that an operational mesoscale forecast system using satellite inputs could become operational within 5 years. Development of geostationary sounders will influence the development of the ultimate operational mesoscale forecast system.

One initialization mesoscale model parameter which could be measured directly from the cloud fields is the vertical motion field. The growth and decay of clouds is caused by vertical motions. By measuring the changes in the cloud field and using a knowledge of the wind field advecting the clouds (which also could be measured from the cloud field), a vertical motion field could be determined. However, research on this type of cloud analysis has not yet been started.

F. Cloud Wind Measurements

Aside from techniques to measure cloud displacements for wind purposes, cloud analysis techniques are required to measure the height and thickness of the cloud being tracked. The nature of cloud tracking requires that the height and thickness be measured for each cloud tracer. The thickness is required in addition to the height because studies such as Hasler et al. (1976) have shown that some clouds, such as cumulus, move with the speed of the wind at their base.

Measurements of cloud heights from cloud top temperature is made difficult by varying cloud emissivity. During night time hours, only the infrared images are available. Because many of the cirrus tracers are near cloud edges or cloud fragments, the cloud emissivity becomes a crucial factor in the height measurement. If there were two infrared channels, the emissivity could be computed using the techniques developed for sounder retrievals (Smith and Woolf, 1976), but on the current generation of geostationary satellites only one channel is available. Hence the only technique which is presently available for determining the temperature of a thin cloud element is to make a subjective judgment of what constitutes a cloud field ensemble where all the clouds are approximately at the same level, measure a temperature near the coldest center of the ensemble where the emissivity should be closest to unity, and assign that temperature/height to all the clouds tracked in that ensemble. This method was developed by Les Hubert of NESS and has been used in a similar manner at the University of Wisconsin for infrared-only tracking.

When visible data are available, this can provide information on cloud thickness which can be used to infer the infrared emissivity. The cloud height system developed at Wisconsin by Mosher (1974) uses the visible data to help correct the infrared data for non-unity emissivity problems. An evaluation of this technique was undertaken. The data set of Joanne Simpson of aircraft 3-D measurements of clouds in the GATE area was used for ground truth. The results of this evaluation are:

1. The cloud height system readily can identify the clouds which are blackbody and make corresponding height measurements. The heights of the deep convecting cells agreed to within the error limits of the 3-D measurements. The 3-D measurements of the lower cumulus were of the height of the highest towers while the satellite measurements were of the average height of the cloud. Because of the differences in the thing measured, the height measurements of low cumuli made from satellite data were

lower than 3-D measurements. The thickness plot of the satellite data showed a strong resemblance to the major features of the aircraft photographs. The thickness of the small cumuli was underestimated by about 20% as the theory of finite cloud scattering would suggest (McKee and Cox, 1974).

2. If the assumptions of the cloud model used in the scattering calculations (single layer, horizontally homogeneous) were fulfilled, the emissivity correction worked and raised the cirrus cloud height to within the measurement error of the 3-D measurements.
3. If there were multiple layer cloud fields with the upper layer being a broken thin layer such as altocumulus or cirrus over lower thicker clouds such as cumulus, then the cloud height system gave erratic results in the measurement of both cloud layers.
4. The original cloud height system has emissivities calculated assuming ice spheres. To obtain more accurate emissivities, the visible calibration was modified slightly using empirical data. Using the emissivity calculations of Liou (1974) with ice cylinders rather than spheres has resulted in much more realistic emissivity measurements without any empirical modifications of the visible calibration.
5. The verification data base using the one GATE data set was not considered an adequate statistical verification. A data base of aircraft reports of cloud tops and cloud bases and airport observations of cloud bases appears to be the most extensive data base possible for a large variety of cloud situations.

Programming of a system which will extract this information from a high speed data line, file it, display the conventional reports on top of the satellite image, and file comparisons with satellite measurements has almost been completed.

G. Summary and Recommendations

1. Climate Modeling Community

The needs of the various user groups is quite varied. The climate modeling community has the most pressing needs and also the most stringent accuracy requirements. These modeling requirements are reflected in stated GARP requirements. The modeling community requires detailed cloud measurements to assist in development of more refined cloud parameterization techniques. In addition, cloud climatologies are required to verify the performance of models. Presently available cloud measurement products are not sufficiently accurate to meet the parameterization needs. The presently available climatologies of total cloud cover without height discrimination are not sufficient to meet the verification of the modeling community.

The detailed cloud measurement effort should be carried out in a coordinated manner with an effort on cloud parameterization. The cloud measurements will generate a large volume of data. Only those data which actually are required by the modeling group should be processed. The cloud climatology could be produced by averaging a long period of detailed measurements, but this is a very costly approach. A more cost effective approach would be a simple system which segregates the image data into levels and cloud types and performs running averages. At the end of an average period (1 month or 1 year) the detailed measurements would be obtained from the averaged data.

2. GATE Research Community

The detailed cloud measurement requirements of the GATE community are very similar to the requirements of the cloud parameterization effort. The area coverage requirement is modest and the time period requirement is for only a few weeks of data. Hence, if the cloud parameterization groups could use the GATE area to perform some detailed cloud measurements, the spin off of the effort would provide the GATE research community with a very useful data set for convective adjustment research.

3. Aviation Community

The needs of the aviation community for cloud information have been recognized and both the Air Force and NOAA have acted upon these needs. The Air Force produces the 3-Dimensional Nephananlysis (3DNEPH) every three hours to meet their cloud information needs. NOAA produces weather depiction fax charts based on surface observations of clouds and has initiated an experimental satellite cloud analysis fax chart. The initial reaction to the NOAA/NESS satellite cloud analysis has been favorable.

The Air Force has maintained a continuing developmental attitude toward the 3DNEPH, so any technique developments in cloud measurements could ultimately be incorporated into the 3DNEPH. The NOAA/NESS satellite cloud analysis is a useful and cost effective approach for the present needs of NESS and NWS. It should be expanded to include more periods during the day.

4. Forecast Community

The most pressing forecast needs for cloud information is for short time mesoscale forecasts of fog and convective storms. The analysis techniques of determining cloud heights, thickness, growth rates, etc. are presently at hand. However, a new generation of hardware is necessary to provide the forecast offices with real time access to the quantitative satellite data.

5. Mesoscale Forecast Research

Real time access to satellite images and the ability to make simple measurements from these images is required for qualitative forecasting. Quantitative forecasting, however, requires input data for models. Techniques to determine the mesoscale distribution of water need to be developed. Extension of current efforts at producing bogus moisture sounding data from cloud images and moisture sensors needs to be done, probably by using VAS data. Techniques to measure the mesoscale wind fields need further development. Tracking clouds can produce horizontal wind fields. Measurements of the growth and dissipation of clouds could provide vertical wind measurements, but the techniques have not yet been developed.

6. Cloud Tracked Wind Groups

The weakest part of present cloud tracking technology is the height determination. When only infrared data is available, subjective judgment is required to assign heights to individual clouds in a field because of emissivity ambiguities. The most reasonable solution to this problem would be to include a second window channel infrared sensor with a different frequency response on the geostationary satellite, and use the techniques developed by the sounding groups to get cloud altitude.

Techniques to obtain cloud heights and cloud thickness using existing visible and infrared sensors show promise and efforts should be made to continue their development and verification. The measurement of cloud thickness using visible images appears promising and could aid in the problem of height assignment for clouds which move with the wind at their base.

III. Precipitation Estimation

The following classes of potential users of precipitation data have been contacted:

1. GCM and climate modeling groups.
2. Agricultural crop prediction groups.
3. River water management and flood forecasting.

Each of these general areas requires routine precipitation measurements on a global basis or in remote areas that are not sampled adequately with rain gauges. A satellite rain estimation system could benefit both researchers and operational forecasters in each of the three groups. In this section the needs of each group will be discussed. The presently available methods of rainfall estimation that could be used for a global precipitation monitoring system will then be discussed.

A. User Requirements

1) Numerical Modelers

Rainfall is an important result of convective cloud circulations since it represents the amount of latent heat released to the atmosphere. The vertical circulations in the clouds cause the latent heating, and also redistribute mass, energy, and momentum between vertical layers. Thus, the measurement of rainfall represents two quantities that are important to the modelers: 1) the amount of heating that has occurred, and 2) the intensity of the vertical mass exchanges. The latent heating is a directly quantifiable measurement, while the vertical mass circulations must be inferred from rainfall measurements.

There have been many models developed to describe cloud circulation. The most notable are Arakawa and Schubert (1974) and Kreitzberg (1976). These models all attempt to describe the vertical mass circulations inside and outside the clouds. The heating/cooling and moistening/drying are calculated from budget equations using the mass circulations. These models are used as sub-grid parameterizations in the CGM's to account for convective circulations.

The vertical mass circulations of convective cloud systems are difficult to measure. Programs such as GATE have been required to obtain these measurements. However, it is not possible to make GATE type measurements on a global scale. Therefore, other data sources are needed to verify model operation. Satellite rainfall estimates can provide this type of information.

The rainfall estimates would be used along with the cloud census data for model parameterization studies. Thus, the same basic format as stated in the cloud census section of this report is needed. A climatology of rainfall over both land and ocean is needed for general verification. In addition, detailed measurements of precipitation with high space and time resolution are required for regional studies associated with model development. The present observing networks cannot satisfy these needs. Raingauge networks are very sparse in many areas. Tropical areas and oceanic areas have little or no coverage. Climatologies based on these data are very poor because of the sampling problems. A satellite based observing system is definitely required.

2) The agricultural community

The need for grain crop forecasting has increased strongly in recent years. Currently crop forecasts are made by the Center for Climatic and Environmental Assessment (Division of NOAA, Columbia, MO), and several private consulting firms. These groups are all involved in forecasts of world crop yields for prediction of the international grain market. Both government and private corporations are using this information for trading purposes and government policy decisions.

Rainfall is an essential input to all models or forecast schemes. Data are needed in the underdeveloped countries of South America, Africa, and Asia because of the lack of good meteorological networks in most of those countries. In addition, data are needed from the Soviet Union and China. Satellite measurements have been made experimentally in those areas (Follansbee, 1976) with reasonably successful results. In addition, satellite data are being used over North America to account for deficiencies of the present raingauge networks (E. Merrit, Earthsat Corp., 1976). Raingauge networks often are considered inadequate for sampling of isolated convective storms. A remote system from satellites could be very useful in providing good spacial measurements to augment raingauge networks. The problem of rain gauge sampling will be discussed more extensively in the next section.

In crop prediction, the rainfall measurements are used to derive available soil moisture for plant use. Soil moisture is usually calculated from hydrological budgets using rainfall, evaporation, and stream runoff. Crop models are run continuously during the year, even in the non-growing seasons, so that soil moisture levels are known adequately. Both winter and summer precipitation measurements are needed. Satellite measurements of radiation could be used to advantage because of the effect of radiation on evaporation.

Even without using crop growing models, some forecast information has been derived from satellites by looking for the existence of precipitation at selected critical times in the growing season. For example, the grain crop on the Indian sub-continent critically depends on the arrival of the monsoon rains. This feature can be easily identified on satellite pictures.

The sampling time and space scales required for crop forecasting are slightly different from those required by the numerical modelers. High spatial resolution is desired while high time resolution is not. A spatial resolution of 50 x 50 miles is needed over the United States because this is the common grid resolution used in crop prediction models (Earthsat Corp. Report, 1976). Total rainfall volumes for each day will satisfy their requirements.

3) The Hydrological Community

Hydrologists require information on a short time scale for flash flood prediction, and a longer time scale for water resource management. These two requirements are quite different.

Flood forecasts require rapid dissemination of rainfall data (1-2 hours), mostly for small river basins. The accuracy of the measurements is not as important as the simple identification of heavy rainfall rates in the river basin. Raingauge networks are often not installed in sufficient density to locate storms. The use of radar for quantitative precipitation measurements is just beginning. The radar data has to be digitized and calibrated. Use of radar precipitation data will undoubtedly increase as NOAA converts its radar stations to digital formats for AFOS.

Flash floods occur when a large volume of rain falls on a limited area. The system causing the flooding can be either a single thunderstorm complex such as the Big Thompson and Rapid City floods or a large storm system such as Hurricane Agnes. Frequently the intense thunderstorm flooding occurs in mountainous regions. This limits the ability of radar to observe the rain producing regions of the storm, making precipitation measurements for flood forecasting difficult. The monitoring of large storm systems such as hurricanes requires the use of several radar installations at different locations. In the regions of overlap the curvature of the earth prevents radar observations of the lower portions of the clouds. During Hurricane Agnes in central Pennsylvania a significant amount of rainfall was produced in the lower portions of the cloud, and was missed by the radar (National Advisory Committee on the Agnes Floods, 1972). Hurricanes also present radar range limitation problems when the storm is first approaching landfall. Because of these limitiations of radar precipitation measurements, the National Hurricane Center is developing satellite techniques for measuring rainfall and predicting the storm's flood potential.

The other hydrological interest is in the area of water management. These groups require longer time period measurements and accuracies of the measurements become more important. Rainfall measurements are used for hydrological budget studies for water resource planning and for river flood prediction. The river flood potential in river basins depends on the ability of the basin to absorb water. Knowledge of previous precipitation and soil water content is extremely important in river flood prediction.

A large effort has been made by NOAA to measure the winter snow accumulations in watersheds. The satellite pictorial techniques are most successful in mountainous regions where the altitude of snow cover or area of snow cover depict the available water. In areas of lesser orographic relief, these measurements become more difficult because snow depth cannot be sampled from pictorial data. Winter precipitation measurements can provide information for the prediction of the available river water at spring runoff.

B. Presently Available Techniques for Precipitation Measurement

1) Rainfall Estimation Using Satellite Images

Satellite rainfall measurements have been made by several institutions.

The geostationary satellite data have been used by the University of Wisconsin, the National Hurricane and Experimental Meteorology Laboratory (NHEML) of NOAA, Colorado State University, NOAA/NESS and NASA/Goddard. Polar orbiting satellite imagery data have been used by NOAA/NESS, the University of Bristol (England), and the University of Hawaii. The techniques are comprised of two general types: 1) those using the expansion of the cirrus anvil, and 2) those using cloud area correlations.

The needs for rainfall data and the availability of the particular type of satellite data have, in the past, dictated the method used by each institution. These methods will be summarized below. A discussion on how each method could be expanded to a globally operational system to satisfy the general needs previously stated will be given with the method descriptions. The utility of ground based measurement systems will be discussed.

a) Cirrus anvil expansion method (Geostationary Satellites)

Data from geostationary satellites have made it possible to monitor the cirrus anvil growth over deep convective clouds (Sikdar and Suomi, 1971). Correlations of rain volumes from convective clouds with the anvil growth rate have been made at Wisconsin (Sikdar, 1972), NHEML (Griffith and Woodley, 1976), and at Colorado State (Negri, _et_ _al_., 1976).

The most extensive research on the relationship between anvil growth and precipitation has been made jointly by Wisconsin and NHEML. This research has been primarily on convective clouds over south Florida and over the tropical Atlantic Ocean (GATE area). An empirical relationship between the rain volume from the storm and the cirrus anvil growth has been developed (see Figure 1). This relationship incorporates the stage in the cloud's lifecycle as well as the anvil growth rate.

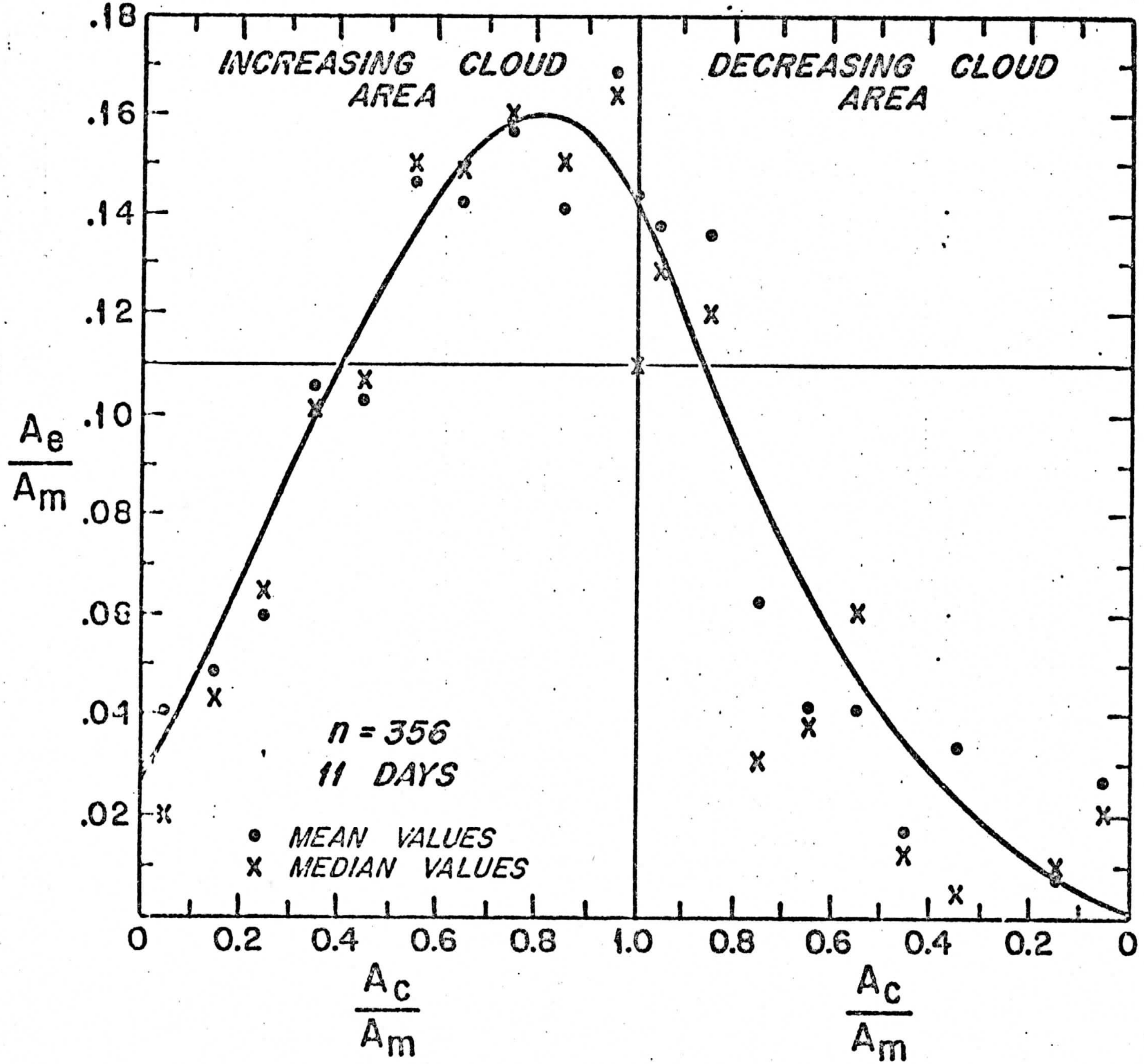

Figure 1: Cloud area on satellite pictures (A_c), maximum cloud area (A_m), and radar echo area (A_e) for tropical convective clouds. The rain volume is directly related to the echo area. From Griffiths et al., 1977.

A similar method also is used by NOAA/NESS for precipitation measurements over the United States and other land areas (R. Scofield, NESS). This method is intended for use by field forecasters who do not have digital data. Hard copy pictures are used, and rainfall rates determined by visual inspection of the pictures. This system employs in a subjective manner the same basic concepts as used by Wisconsin and NHEML.

The anvil expansion technique is based on identifying convectively active clouds. Clouds with tops colder than a threshhold temperature of -20°C for NHEML or -32°C for NESS, and that exhibit rapidly expanding anvils, are identified as rain clouds. The NESS technique separates areas of convectively inactive anvil from the active convective cores for deriving the horizontal details of the precipitation under the anvil. This technique can be applied to very small areas.

Comparisons with ground based measurements have shown that the satellite measurements can be accurate to a factor of 1.5 of the ground truth (Griffith et al., 1976, D. Martin personal communication). (Accuracies are usually expressed as the ratio of satellite over ground truth or vice versa, depending on which value is larger.) Researchers suspect that some inaccuracy occurs because low level rain clouds are not included. In the tropics substantial amounts of rainfall can come from clouds that do not reach the freezing level. The effect of these clouds is being studied currently.

Mid-latitude verifications of the Wisconsin-NHEML system have not been made yet. It is suspected that this relationship is accurate only for tropical convection. The extension of the Wisconsin-NHEML system to other geographic areas will require testing of the nomogram of Figure 1 and possibly new curves for geographic differences.

NHEML has developed an automated objective analysis scheme for applying the expanding anvil technique. This is the only existing automated satellite rainfall measurement system. It has been applied with reasonable success to a variety of situations, hurricanes, Florida cumulus clouds, and GATE area convective systems. Their best success has been with Florida cumulus clouds where the clouds appear as separate well defined objects on the satellite pictures. Reasonable results have been obtained with hurricane measurements, though the ground data used for comparisons are sparse and seldom considered reliable.

To apply the automated technique to GATE data the resolution of the satellite pictures has to be reduced to make computing over the larger area feasible. The data are reduced to statistics on a resolution size of approximately 40 x 40 km ($1/3^o$ squares). This implies that cloud clusters are being tracked by the program and not individual Cb's. It is not clear at this time what the impact of this scale change will be on the measurements. Verification of the measurements with ground truth data currently is being attempted, and a final assessment is not available.

It is concluded, from the research done at Wisconsin and NHEML, that it would be possible to obtain rainfall measurements at a time resolution of 1 hour. These measurements can satisfy FGGE and numerical modeling requirements. For global measurements, however, the technique will have to be expanded to higher latitudes. Only a small amount of work has been done on mid-latitude cyclone situations by NESS, Stanford Research Institute (Davis and Wiegman, 1973), and Colorado (Negri et al., 1976). These studies have indicated that the large cirrus canopies which occur over these weather systems make the identification of convective cells more difficult. Skilled operators on a man-computer system could be used for quality control and segregation of convective from non-convective clouds. There do not appear to be any major obstacles to extending rainfall techniques to higher latitudes.

An operational system developed for FGGE would satisfy agricultural requirements at the same time. Higher horizontal resolutions would be required over the United States. However, the largest need for data is in the undeveloped countries of South America and Asia. These needs could be satisfied, provided that geostationary satellite data are taken continuously and disseminated directly to a rainfall measurement system. Large delays in time will reduce the usefulness of the measurements. The present GOES satellites can cover both North and South America. Future plans call for coverage of the Asian areas by satellites operated by other nations. If a rapid and reliable data exchange is not made between countries, the agricultural utility of the measurements will be limited.

The geostationary satellite data can be of benefit in making flash flood predictions. These measurements are needed for identification of large raining convective systems in watersheds of high flood potential. A man-computer system could be used for the cloud identification. Once a severe convective storm is identified, rainfall calculations could be made from anvil expansion relationships. River runoff and flood potential could be predicted from simplified watershed models. Griffith and Woodley (1977) have applied their rainfall system to the Big Thompson flood of 1976 and have shown that the reasonable rainfall measurements could be made in a real-time format. A system of this type could be used to cover many river basins from one central forecast area.

b) Cloud coverage correlations (Polar Satellites)

Rainfall has been related to the amount of time an area is covered by precipitating clouds. This has been done by three groups: NOAA/NESS (Follansbee, 1976), the University of Hawaii (Kilovsky and Romage, 1976), and Barrett (1975), using polar orbiting satellites. In addition, Gruber (1973), Merrit (1976), and Craig (1975) have applied similar techniques to geostationary data. In all of these methods convective clouds are delineated subjectively by operators at 6 or 12 hour intervals. Geometric shapes were fitted to the cloud systems and moved with time to determine the amount of time an area was covered by the convective systems (Follansbee, 1976; and Kilovsk and Ramage, 1976). Linear correlations between cloud cover and rainfall were made (see Figure 2). These relationships are stated as being accurate within a factor of 2 for monthly averages.

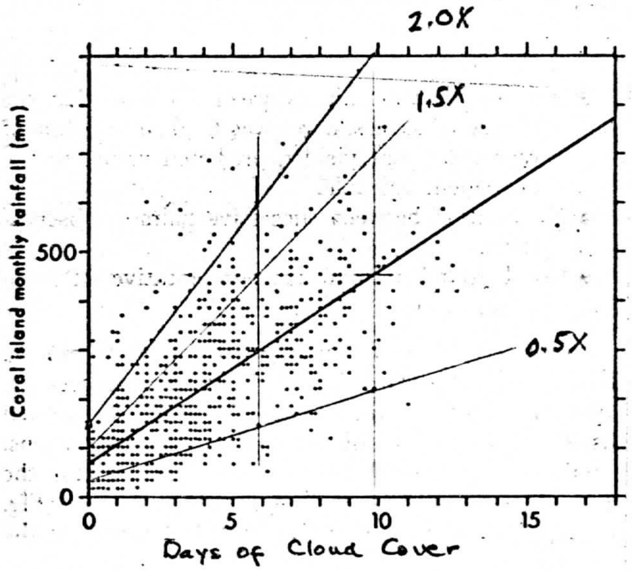

Figure 2: Rainfall-Cloud cover correlation given by Kilonsky and Ramage (1976) for the Tropical Pacific Ocean.

Follansbee (1976) has modified the technique to incorporate the climatic monthly precipitation for the study area. He has calculated the 12 hour precipitation (P_{12}) by: $P_{12} = 0.0075\ DP_n$

where (P_n) is the monthly normal, and (D) the duration of precipitating cloud cover. This refinement essentially is a measure of climatic anomalies.

Gruber (1973) has modified the simple duration of precipitating cloud cover correlation with rainfall to include the amount of precipitate moisture available for rainfall.

It is apparent that cloud cover correlations are more applicable to weekly or monthly precipitation than to daily precipitation. The value of a simple method of this type is that it can be applied to polar orbiting satellites and would be easy to automate. The accuracy and time resolution that can be obtained from this method are definitely not as good as can be obtained with the anvil expansion technique. However, the advantage of the polar system is the uniform global coverage that it can provide at a low cost. The system does not depend on obtaining data from foreign countries as the geostationary data will for a large portion of the globe.

The polar satellite data can be used only for global rainfall climatologies and for agricultural studies in other countries. None of the other needs could be satisfied with this system.

To develop an operational system of this type there are three areas that require study: 1) diurnal variability and the effects of sampling over long time intervals (3, 6, or 12 hours), 2) geographic and regional variance in the cloud cover-rainfall relationships, and 3) objective methods to distinguish precipitating from non-precipitating clouds. Areas one and three can be studied using the high time resolution data from ground based measurements and geostationary satellite data. The geographic anomalies require use of polar orbit data in many areas. Corrections for geographic variations could be applied to the measurements after they are made. For development of an operational system the criteria for recognizing precipitating clouds needs to be established first.

2) Rainfall Estimation Using Satellite Microwave Sensors

Rainfall measurements have been made from microwave data taken from the Nimbus satellites (Rao, Abbott, and Theon, 1976; and Adler and Rogers, 1976). These measurements have been confined to areas over oceans because of the variable emissivities of land surfaces. As a result of the geographic confinement of these measurements there are few data available for ground truth comparisons. Accuracies for these measurements are estimated as being in the vicinity of a factor of 2.

Microwave data could be useful for developing rainfall climatologies. This system essentially identifies the location of raining cloud systems. These measurements are similar to the other polar imaging systems discussed in the last section because they both are flown on polar orbiting satellites. However, the microwave sensors provide more detail to these measurements because rainfall rates are determined directly. Interpolation of the rainfall rates between satellite orbits is not always accurate because of the short lifecycles of the convective clouds and diurnal changes in convective activity. Averaging of measurements over time should improve the quality of the rain volumes derived. This was done by Rao, et al. (1976). Microwave data appear to be more applicable to climatological studies than for daily measurements.

The lack of measurements over land eliminates the use of these data for agricultural and hydrological purposes. Savage (1976) has discussed the possibility of making land measurements, but plans for such a system have not been made yet.

The main value of these measurements would be for latent heat release studies. There data could be used for rainfall climatologies for numerical modeling studies. Trial measurements of the latent heat release in one hurricane have been made by Adler and Rogers (1976). This study has shown that the microwave data have some utility for hurricane studies. They also could be utilized to forecast flood potential of hurricanes. This type of forecast is being considered by NHEML (Griffith and Woodley, 1977).

3) Ground Based Measurements

Studies by Woodley et al. (1974) and Huff (1971) have shown that extremely high density raingauge networks are needed for sampling convective storms. For an accuracy of a factor of 2 on a daily basis, a raingauge density of 12 mi^2/gauge would be needed (see Figure 3). Such a density is not economically feasible to maintain except over small areas for experimental purposes. The present weather network has gauges spaced over 50 miles apart. Thus, convective rains are poorly sampled with the present network. More accurate rain volume measurements can be obtained only by time averaging of the gauge data for monthly or seasonal periods.

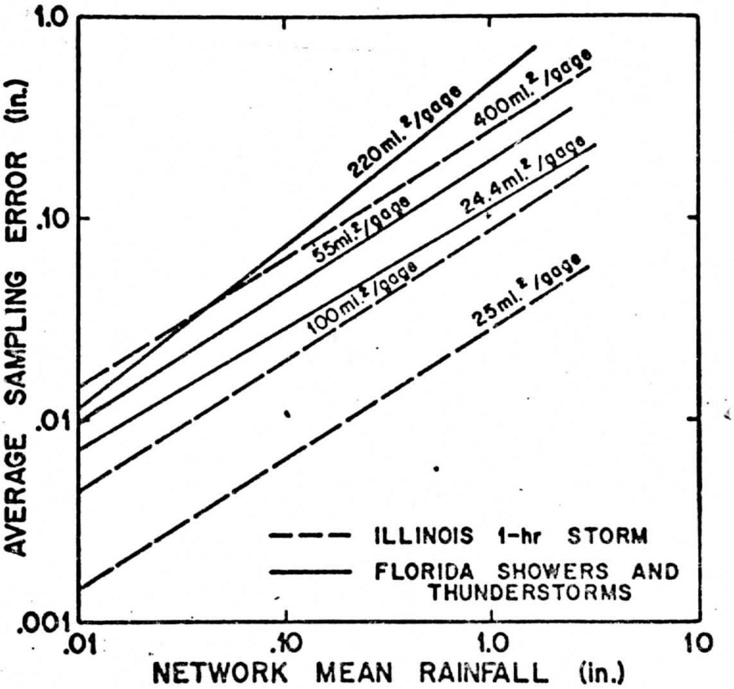

Figure 3: Average sampling error versus network mean rainfall.

Radar measurements have been made in a few selected areas for more accurate measurements (National Severe Storms Lab., OK; McGill University, Canada; and NHEML, Miami). However, these measurements are not easily obtained. Calibrations of the system with raingauge data have to be made on a daily basis for reliable measurements. Changes in atmospheric refractivity, non-uniform beam filling by the precipitation, and anomalous propagation of echoes cause uncertainties in the measurements. Digitized radar data is required for computer processing of precipitation measurements. Woodley *et al*. (1974) have shown that the calibrated radar system is by far the most accurate rainfall system if calibrations are done properly.

A system of calibrated radars could be used to meet rainfall requirements in most agricultural areas. Such a system could be made by upgrading the present weather radar facilities to provide digital output, establishing calibration procedures, and providing minicomputers to process the radar data.

Radar measurements are difficult to make in mountainous areas (Peck, 1975). The rough terrain prevents sampling of many clouds. In many areas where flash floods occur the use of radar is limited.

It is obvious that radar cannot satisfy FGGE requirements because of the need for oceanic measurements. In addition, agricultural requirements outside of the United States will not be satisfied because of the lack of radar systems in foreign countries. The radar system is only useful for selected areas of the United States.

C. Summary and Recommendations for Rainfall Measurements

There are three main groups of users of precipitation data:

1) General circulation modeling groups
2) Agricultural crop prediction groups
3) Flood forecasters and water management groups.

The general circulation modeling groups are concerned mainly with latent heat release. Their requirements are reflected in the GARP data requirements of precipitation. The agricultural crop predictions require global land data but with high spatial resolution. The flood forecasters require high time resolution over limited land regions. Systems which can provide precipitation data include raingauge networks, radar, satellite microwave sensors, and satellite visual and infrared images. All the systems are only accurate to within a factor of 2. Each of the systems has special strengths, but each also has some weakness. Hence, no one system is ideal for meeting all the user requirements. The general circulation modeling requirements could be satisfied with a special data set, such as FGGE, but the other users require an ongoing operational system. The ultimate operational system will probably be a composite of several systems.

The best system for FGGE would be a composite of polar orbiter microwave measurements over ocean areas and once per day images inferring rainfall over land and ocean areas. The image processing should be done over ocean areas to relate the two systems and to aid in the identification and measurement of deep convective regions which present problems for the microwave sensors. Both systems should be benchmarked against geostationary measurements of precipitation, using the expanding anvil techniques and raingauges where available.

In the composite data set, the source of information for each precipitation measurement needs to be kept with the data. Since each system has limitations and potential biases, the user of the data should be made aware of any limitations and be able to sort out measurements which could cause problems.

The best system for agricultural crop prediction is the polar orbiting image technique with benchmarks provided by geostationary expanding anvil data and raingauge data. The best system for flash flood forecasters is digitized radar supplemented with geostationary data in mountainous regions and for hurricanes. The best system for hydrological and water management groups with high accuracy requirements is a raingauge-digital radar cooperative approach. The raingauges would be used to calibrate the radar, and the radar would be used to extend the coverage of the raingauges. Satellite image data can be used to extend the coverage into mountainous regions with poor radar coverage.

All the systems for precipitation measurement require further development. The radar system requires the conversion of the present radar network to digital outputs. This is gradually being done by NWS as part of the AFOS implementation plan. The calibration procedures need to be developed, as do the data processing techniques. The system for determining precipitation from polar orbiter images requires further technique development efforts to distinguish objectively between precipitating and non-precipitating clouds, to develop transfer equations for different geographic regions, to include diurnal effects, and to establish ongoing verification procedures. The system for determining precipitation from geostationary images requires development efforts to extend the technique to mid latitudes, to identify precipitation from stratus clouds, and to measure precipitation from small clouds in the tropics. The microwave systems require verification over the oceans and sensor development to include multi-channel response with polarized sensors for measurements over land.

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