NOAA TM ERL APCL-16

NOAA Technical Memorandum ERL APCL-16

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Environmental Research Laboratories

Cloud Physics Program in Support of GATE

H.K. WEICKMANN, Coordinator

Atmospheric
Physics and
Chemistry
Laboratory
BOULDER,
COLORADO
December 1973

RONMENTAL RESEARCH LABORATORIES

HERIC PHYSICS AND CHEMISTRY LABORATORY

IMPORTANT NOTICE

Technical Memoranda are used to insure prompt dissemination of special studies which, though of interest to the scientific community, may not be ready for formal publication. Since these papers may later be published in a modified form to include more recent information or research results, abstracting, citing, or reproducing this paper in the open literature is not encouraged. Contact the author for additional information on the subject matter discussed in this Memorandum.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories

NOAA Technical Memorandum ERL APCL-16

CLOUD PHYSICS PROGRAM IN SUPPORT OF GATE

H. K. Weickmann, Coordinator

Atmospheric Physics and Chemistry Laboratory
Boulder, Colorado
December 1973

TABLE OF CONTENTS

CLOUD PHYSICS PROGRAM IN SUPPORT OF GATE

(H. K. Weickmann Coordinator)

1. INTRODUCTION

As the program for GATE emerges from the general uncertainty into subprograms, flight plans and scale interrelationships, the need for a cloud physics program which reaches down to the D scale becomes increasingly apparent. Subsequently, a review is given of the cloud physics program as it stands today composed from bits and pieces; also a proposed supplementary program is discussed which the reader will find to be well justified. It is to be carried out within the convective subprogram and as far as possible on the flight program which is currently planned.

GATE Report #1 states under the heading "Other Sub-programmes": "...as soon as the number and type of platforms to be contributed by the participating nations are known, these programmes must be formulated without delay. For example, the *cloud physics* programme could contribute to the Central Programme by a cloud census (for the parameterization of convection) and by the measurement of liquid water content in clouds and precipitation as a function of height and time (for the energy cycle of B- and C-scale phenomena). However, the complete cloud physics programme will be more complex and remains to be determined."

It also postulates: "All the bulk properties of cumulus ensembles ...must be verified by direct sampling from research aircraft, especially on the C- and D-scales."

Report #1 suggests that these data are obtained from averaged profiles of wind, temperature and moisture, and averaged precipitation at different heights where "averaging covers areas comparable in size to a considerable part of the B-scale area and times of the order of hours or even a day."

Since averages are being made up from a number of individual measurements and individual times steps, the need for sampling on the D-scale in order to obtain meaningful averages on the C- and B-scales is obvious.

2. JUSTIFICATION FOR SPECIAL CLOUD PHYSICS STUDIES

One of the major energy sources which drive the tropical weather machine is the latent heat of condensation. Since this energy source is being processed during the life history of the clouds, measurements of the clouds water budget are necessary. There are essentially three parameters which should be known and which are within the state of the art of present day measuring technology:

1. The rate of condensation of a cloud or cloud system, i.e., the influx of water, which gives the amount of latent heat taken up;
2. The rain-out of water which determines how much latent heat is being realized by the cloud system and;
3. The amount of water remaining in the rest of the cloud.

From these considerations it follows immediately that a number of typical cloud physics parameters need to be measured in order to produce valid estimates of how nature processes this energy source: Some of these parameters are: Influx of water at cloud base, water content inside cloud, temperature inside and outside of cloud, rain-out, entrainment and detrainment, water remaining in rest of cloud, etc.

Special Cloud Physics Studies are required in support of various GATE sub-programms--these studies are being combined and subsequently written up as a Cloud Physics Subprogram.

2.1 Cloud Physics Studies as GATE Support

2.1.1 Radar-rainfall measurements

Rainfall measurements within the B-scale ship array are to be made using radar information. This requires a well calibrated radar, the measurement of reflectivity (Z-value) and a known raindrop size distribution which is measured either on shipboard or from aircraft (measured at different heights). The measurement of drop-size distributions are by no means simple due to high natural variability in space and time. The primary limitation is the sampling volume of the instrumentation. To compensate for possible error, one needs to calculate ensemble averages from a sample size large enough for statistical significance. Furthermore, the shower core area, not just the periphery, must be sampled if meaningful comparison to radar data is attempted. Surface (shipboard) measurement techniques include distrometer and drop camera systems. It is important for accurate and representative sampling that the horizontal component of velocity be minimized. Since the GATE ships will not be moving and since the array is essentially established in the doldrums, it is likely that the necessary low wind conditions will be frequently achieved. As with raingage data, it can be expected that shipboard drop-size measurement error will increase rapidly with increasing windspeed.

The measurement of drop spectra from an aircraft platform has been routinely accomplished in the U.S.A. by a foil impactor with a sampling area of 12 to 15 cm^2 (sampling volume of about 30 ℓ/sec in an aircraft moving forward at 100 m/sec). Although foil data cannot be analyzed in real-time, optical scanning techniques have made it possible to provide drop spectra results rapidly and in great quantity. Recently, arrays of optical fibers have been used in aircraft (e.g., Knollenberg probe) to provide a real-time analysis of drop spectral data. Foil impactors are to be installed on the NOAA DC-6, the NOAA C-130, and possibly on the NCAR Electra. The Knollenberg probe may also be available on the NCAR Electra.

With the realization that an *accurate* determination of the actual Z-R relationship must await data analysis, it may still be possible to make an approximate conversion of radar reflectivity to rainfall for GATE operational purposes by applying data previously collected and analyzed elsewhere. It may be possible to use the Z-R relationship which has been derived from rain drop spectra measured by the Illinois State Water Survey for Majuro, Marshall Island, Pacific Ocean, 8°N, 172°E. For a 3 cm weather radar, the Z-R relationship derived by Stout and Mueller (1968) is as follows:

$$Z = AR^b \qquad A = 221 \qquad b = 1.32.$$

It shall be remembered that the useful range for the radar measurements of rain fall below cloud base is probably limited to about 40 miles. For 5 cm radar as suggested for use in GATE, the corresponding Z-R relationship must be determined from the original Majuro rain drop spectra which are most probably still available in the Illinois State Water Survey files.

The validity of this approach will be evaluated when the GATE foil data are analyzed, and the GATE Z-R relationship is determined.

2.1.2 *Radiation effects*

The effect of radiation fluxes from clouds upon the environmental atmosphere is little explored and is, of course, one of the purposes of the GATE radiation subprogram. Specific properties of this program in relation to clouds are as follows:

2.1.2.1. The DC-6 aircraft will be equipped with a vertically downward looking radiometer in order to measure sea-surface temperature and hot spots within the sea surface. These hot spots may be related to the formation of clouds and cloud clusters even though it is suggested from the research of Bunker et al. (1949) that clouds over the tropical ocean do not seem to have any roots which originate at the surface.

2.1.2.2. The radiation flux from the top of the cloud must be measured specifically as an important diabatic heat loss parameter in the cloud's life history. It has been found by Dr. P. Kuhn that the cooling rate on top of a thunderstorm anvil near the tropopause can be as large as 4 degrees per hour. Such cooling rates may affect the cloud life history in two directions: 1) it may initiate the formation of downdrafts in the cloud tops or, 2) it may for convective clouds which have penetrated the tropopause and have spread out horizontally cool the spreading anvil and set the stage for the next tower to penetrate still higher above the tropopause.

2.1.2.3. The IR radiometer is also a very powerful tool if used as a remote sensing thermometer during flight penetrations of cloud systems.

It measures a surface temperature of the cloud droplets without making contact with these and therefore without errors due to release of heat from fusion in supercooled clouds or evaporative cooling in warm clouds. It is consequently an instrument which can be used to measure the cloud buoyancy.

2.1.2.4. It is known from the German Atlantic Exploration with the ship *Meteor* in 1925-27 that *Pibals*, which had been launched near the equator between 10°N and 10°S, developed little Cirrus clouds after balloon burst. These Cirrus clouds occurred preferably at levels of 18-19 km and it is likely that their existence indicates the location of the ascending branch of the Hadley Cell. It is therefore desirable to make in situ humidity measurements from the CV 990 platform using the Kuhn IR radiometer which is scheduled to be installed on this aircraft. Dr. Kuhn's method permits the determination of relative humidity by radiometric methods with an accuracy of 10-15%. Such an accuracy cannot be reached with conventional humidity instruments for the temperature range in question. In this connection it should also be mentioned that the CV 990 platform will permit obtaining by radiometric methods the atmospheric temperature profile below flight level as well as the humidity profile. The feasibility of these methods for incorporation into the GATE cloud physics effort is being studied presently.

2.1.3 Parameterization

The parameterization of cloud convection has been discussed by Yanai et al. (1972) and others. Yanai's scheme proposes that all convective clouds are similar in that they entrain air at the base and detrain air at the top (aside from the part which is detrained by precipitation downdrafts in clouds that do precipitate). This scheme does not necessarily apply to all clouds as observations indicate that clouds collapse in themselves, or just cease to exist, instead of detraining at the top. It is therefore necessary to conduct measurements which permit an assessment of the cloud life history. Such measurements are being discussed below. The parameterization problem is thoroughly discussed in GATE Report #1 as well as in the Convective Sub-programme for GATE and needs not to be discussed in greater detail here.

2.1.4 *Significance of undisturbed conditions as water source for temperate climates*

Riehl and Malkus were the first to call attention to the important role that the normal trade wind cumuli play for the atmospheric water supply of the temperate climates. They are the engines which transport liquid water above the trade wind inversion, where it is being injected into the large scale meridional circulation and transported north as a source of water vapor for the troposphere at higher latitudes. It is desirable to study this interesting theory within the GATE convective subprogram, and it is believed that this can be done with a minimum of modification of existing aircraft operational plans. The cloud physics program which would serve the parameterization problem as well as the tropical water vapor export is being discussed below in more detail.

2.1.5 *Water and flux budget of individual, isolated Cb-complexes*

The transport of water and sensible heat in isolated Cumulo-nimbus complexes may be of similar importance as the transport of these parameters by the numerous trade wind clouds which would appear under undisturbed conditions over the same area as the isolated thunderstorm complex. While the cloud cluster systems have already received much attention in the GATE programs, it appears that the forces that drive the isolated thunderstorm complexes have received insufficient attention. The life histories, water budgets of the cloud and its environment are parameters which should be known for at least a few typical clouds in order to present the background for the parameterization schemes as mentioned above.

3. REVIEW OF PRESENTLY PROPOSED U.S. CLOUD PHYSICS STUDIES

The following projects have been proposed and are partially funded:

3.1 Stereoscopic Cloud Census (proposed by the Atmospheric Physics and Chemistry Laboratory, NOAA)

In the observation of deep convective systems over the tropical Atlantic Ocean, one of the important areas of investigation should be the spatial distribution of condensed water. It is to this end that a stereoscopic cloud census is proposed.

The purpose of such a cloud census would be to provide a cloud and/or cloud system profile at 2 km height intervals within an approximately 100 km square. That is, for a given altitude to determine the intersection of the x-y plane with the cloud columns.

The proposed method of data acquisition is airborne stereo photogrammetry with photographs taken at intervals along a straight line flight path. Two pictures of the same object taken at a known distance apart yield a three-dimensional scale model of the object when viewed stereoscopically. A side-looking camera mounted on an aircraft and taking pictures at a pre-set rate will yield stereo pairs suitable for stereoscopic interpretation, provided the position and altitude of the aircraft at the times of exposure is known. Straight line flight paths are required and most easily satisfy the need for accurate position data between photographs. In a box type flight pattern (as large as a 100 km square), one side of the box will yield a hemispheric delineation of the cloud and/or cloud system, i.e., it will give the cloud profile facing the aircraft, while pictures from two adjacent sides will yield about 80 percent delineation. Two adjacent sides could be flown in approximately 20 minutes, which is about maximum time that cloud positions can be expected to remain unchanged for census purposes. With 80 percent delineation, the remainder can be inferred.

3.1.1 The advantages of stereo photogrammetry are:

1. Simplicity of physical concept and ease of analysis.
2. Observations are nearly of synoptic scale by utilizing a wide field of view and aircraft of moderate to fast speeds.
3. Accurate and reliable observations, and
4. Photographs are a permanent, graphic record for archives and supplemental studies.

Data reduction and analysis can easily be accomplished by the use of a stereoplotter. Using a stereo pair of photographs, the stereoplotter provides graphical contour plotting of the x-y plane intersection with the clouds for a fixed z. Compiling such profiles for each leg will give a full 2 dimensional profile for a given altitude within the box.

3.1.2 The required instruments and materials to accomplish this investigation are:

1. Two 70 mm cameras with internal time marking, 3 inch focal length lens, automatic exposure setting, and four 100-foot film holders.
2. Film--black and white, moderate speed, high resolution, stable base.
3. Stereoplotter and accessories (ER-55 Balplex Plotter available from Geological Survey, Department of the Interior, as excess).

3.1.3 Additional requirements are:

1. Record of aircraft altitude vs time.
2. High quality film processing.
3. Optical viewing port (provided by NASA).
4. Camera mount tilt down capability up to 20 degrees.

3.2 Cumulus Ensemble Averages of Cloud Physics Parameters in GATE (proposed by the National Hurricane Research Laboratory, NOAA)

Yanai et al., 1972, and others, have developed methods of parameterizing convection in numerical models of larger scale circulations. These models and parameterizations inherently involve cloud physics parameters and the program proposed has as its central purpose obtaining aircraft cloud physics measurements to provide direct comparisons to the cloud physics aspects of these models of convection. Specifically, it is proposed to provide ensemble averages of the water content characteristics of convective clouds within the GATE B array as a function of cloud size.

It is proposed to sample clouds of several scales and at several elevations within the B array over the three month course of the project. Long flight tracks are to be flown through the B array with minor deviations so that the centers of clouds near the flight track are penetrated.

After completion of the field phase of the project, the following basic analyzed data sets are provided:

3.2.1 *Liquid water content*

A large sample of the liquid water content of convective clouds as a function of cloud size and altitude. Data in 6-10 scale size classes and from 3-5 levels are evisioned.

3.2.2 *Detrainment*

We propose to quantify the detrainment and hence the moistening and warming of the larger scale environment by convection as a function of: 1) cloud size, 2) elevation, and 3) time in the diurnal convective cycle. This is accomplished by measuring the mixing ratio field in the vicinity of convective clouds as a function of: (a) cloud size, (b) elevation, and (c) time of day. It is also proposed to calculate the equivalent potential temperature field in the immediate convective cloud environment.

3.2.3 *Entrainment*

We propose to quantify the entrainment of environmental air as a function of cloud size and elevation and compare these values with the entrainment values calculated by the theoretical entrainment formulae. This will be accomplished by comparing the small droplet liquid water content with the theoretical adiabatic values.

3.2.4 *Vertical velocity fields in the vicinity of convective clouds*

We will compute the vertical velocity profiles across the cloud and in the cloud as a function of cloud size and elevation; and correlate the vertical velocity values with the liquid water content values.

3.2.5 Parameterization of convective cloud rainout rate

We will use foil impactor data in conjunction with selected radar reflectivity measurements to refine the Z-R relationship over the B-scale network at cloud base level.

3.2.6 Computation of ensemble averages of cloud physics parameters

We will combine the satellite and other photo data and the cloud physics data above to define ensemble averages of LWC, rainout rate, detrainment, and entrainment over the B scale network on 5-10 selected days.

3.3 The Experimental Meteorology Laboratory GATE Program

The EML GATE cloud cluster documentation program is three-pronged. The prongs consist of a) Satellite measurement of precipitation together with cloud heights and patterns; b) Measurement of precipitation amounts and patterning from shipboard, using radar, raindrop disdrometers and raingages, and c) Quantitative airborne photography and cloud mapping.

These three efforts will combine to obtain a three-dimensional, time dependent picture of clouds, cloud interactions and organization and their rainfall. This cloud effort forms an indispensable part of the whole GATE objective. The heart of the program would be irreparably damaged if any one of these groups were to be eliminated or were to fail. In particular, satellite cloud and precipitation studies must have comparative studies by radar and ground-truth in gages and determined drop size distributions. A Z-R relation for the GATE situation must be determined. The whole cloud cluster and rainfall study must be tied together by cloud maps constructed from precisely taken airborne cameras.

3.4 Aerosol and Nuclei Program (proposed by Atmospheric Physics and Chemistry Laboratory, NOAA)

3.4.1 Purpose

The purpose of this program is to study the aerosols over the B-scale area that furnish the condensation and freezing nuclei for the clouds in that region. Two places of origin exist for this aerosol: a) the vast stretches of the South Atlantic Ocean from which southerly winds carry maritime aerosol northward and determine CCN and IN concentrations for the cloud systems, and b) the African mainland and the Sahara Desert from where continental aerosol may reach the experimental area and determine cloud drop spectra and precipitation mechanisms. This program will also support three GATE subprograms: the convection, boundary layer, and radiation subprograms. In detail the relationship is as follows:

Convection subprogram. This subprogram deals with structure and life history of cloud clusters. The microphysics and type of precipitation mechanisms of the clouds depend on the concentration of the cloud condensation nuclei and of the freezing nuclei. Both parameters are measured within the activities of this proposal.

Boundary layer subprogram. Much of the aerosol content of the atmosphere over the tropical ocean is generated in that layer, measurements of aerosol concentrations and properties on shipboard and aircraft is therefore immediately related to the characteristics of that layer.

Radiation subprogram. Aerosol particles affect radiation fluxes in the short wave sun and sky radiation through scattering and absorption (albedo) and therefore affect immediately the incoming radiation energy. It also contributes to the IR fluxes of the terrestrial radiation and is therefore of immediate significance to the atmospheric radiation budget.

3.4.2 Approach.

3.4.2.1. Airborne measurements will be performed on the concentration of airborne particulates of the following kinds in the atmosphere:

a) Aitken nuclei with
   (1) E-1 counter, automatic operation and recording,
   (2) Gardner counter available for standby, hand operation.

b) Cloud droplet condensation nuclei with
   (1) Mee cloud condensation nuclei counter, automatic operation and recording (not part of APCL instrumentation).
   (2) NOAA-APCL CCN counter. Manual operation, photographic recording, manual counting.

c) Ice nuclei with
   (1) NCAR acoustic ice nucleus counter, automatic operation and recording.
   (2) Membrane filter collection of ice nuclei for later analysis of ice nucleus concentration at Boulder, Colorado, in a sub-freezing thermal diffusion chamber.

d) Light scattering coefficients with MRI nephelometer, automatic operation and recording.

The NOAA-RFF DC-6 has been flown on several APCL projects using the NCAR acoustic ice nucleus counter, the Gardner counter and the NOAA-APCL CCN counter. On other APCL projects the NOAA-RFF C-130 has carried the NCAR acoustic ice nucleus counter, the E-1 Aitken nuclei counter, the NOAA-APCL CCN counter and the MRI nephelometer. For either of the above configurations APCL has two 28 VOC to 110 VAC converters that have approximately a 1000 VA capacity as power source for airborne equipment. Of the abovementioned equipment APCL has available all except the Mee CCN counter. The latter instrument would bring APCL the capability of having a completely automated airborne atmospheric particulate concentration measurement system.

3.4.2.2. Surface measurements:

a) Temporal and spatial variations of the proportions in the oceanic aerosol of the following type of aerosols:

(1) Aitken nuclei (with E-1 counter)
(2) CCN (with MRI CCN counter)
(3) Sea salt particles (with flame scintillation counter)
(4) SO_4 particles (with flame scintillation counter)
(5) Ice forming nuclei (with acoustic IN counter).

b) Spatial (and temporal) variation of the hygroscopicity of sea salt particles (with nephelometer and attached humidifier).

c) Organic matter in the ocean water and their sea-to-air transfer. This will be done by collecting samples for immediate extraction on board the ship and subsequent gas chromatographic and mass spectrometric analysis in the lab.

d) Temporal and spatial variations of "sea-smog" formation. This experiment will consist of simultaneous Aitken, CCN and light scatter measurements of the aerosol formed when air from the oceanic boundary layer is exposed to different levels of radiation.

3.5 GATE Convair 990 Radiation Program

The widespread use of the NASA CV-990 together with much experience by APCL in high altitude aircraft radiation measurements as reported in numerous publications confirms its ready availability to such measurements for GATE (David, 1971; Kuhn and Weickmann, 1969; Kuhn, 1971; Gebbie, Kuhn and Bohlander, 1970; Kuhn, 1971).

3.5.1 Planned program

The CV-990 has carried a wide variety of infrared radiometric detectors, scanning from zenith to nadir over the spectral range from 5.0 μm to 30.0 μm involving such sophisticated detectors as the satellite MRIR (medium Resolution Infrared Radiometer), L band microwave radiometers, fixed field special purpose water vapor radiometers and 10.0 to 12.0 μm infrared line scanners. Solar radiation detectors of many types are also standard flight instruments.

Applications of these instruments have involved a wide span of research, such as,

a) Low level cloud emissivities. B and D scale GATE.
b) Low level cloud radiation budget. B and D scale.
c) Cirrus and contrail transmissivities in conjunction with simultaneous LIDAR observations. A and C scale.
d) High level radiation budget. A and C scale.
e) Free air temperature radiometry (15.0 μm CO_2 band). All scales.
f) Total water vapor mass (18.0 - 30.0 μm). B and D scale.
g) Interface temperature measurements. All scales.
h) Infrared thermal mapping. All scales.
i) Satellite instrumentation calibration and ground truth. All scales.

3.5.2 Purpose of planned program:

The purpose of the proposed radiation research which will certainly be only one portion of the coordinated CV-990 research effort is five-fold:

1) To determine the B and D scale hemispheric radiation budget profile (total, IR and solar) from the sea

surface to 14.0 km over a controlled area in virtually real time as direct support of GATE sea-air interface and columnar power budget studies.

2) To analyze the hemispheric, specular and selected spectral radiation budget of the various GATE scale cloud and aerosol condition solar and IR transmissivities. This would be in direct coordination with simultaneous on-board LIDAR observations and would involve a flight track over the African desert to assess the Harmattan haze radiative cooling profile effects at origin and then downstream in the Atlantic.
3) To provide high, medium and low altitude thermal (IR) imagery cloud and ocean surface mapping.
4) To determine spectrally selected IR and solar radiation budget profiles from the sea surface to high altitudes.
5) To provide accurate radiometric, real time, cloud and free air temperature profiles at all altitudes over all GATE scales.

3.5.3 Additional measurements

Practically all instruments under "purpose" are in support of a cloud physics program. Additional measurements are being considered as follows:

a) A survey of cloud base temperatures using a vertically pointing IR radiometer has been suggested for installation in the NOAA DC-6. This radiometer will also be a "yes-no" device for the determination of a cloud overhead.
b) The feasibility of a temperature profiler using lines of the 15 μ CO_2 band to give the atmospheric lapse rate from the CV-990 platform is presently being considered. An analogous humidity profiler is also under consideration.
c) A measurement of ice supersaturation in the upper troposphere using Dr. Kuhn's IR radiation transfer method is feasible.

4. PROPOSED COORDINATED CLOUD PHYSICS MEASUREMENT PROGRAM

The purpose of this document is to outline a cloud physics program within the primary flight missions planned. Minor deviations in already planned flight tracks will in many cases adequately serve the cloud physics data-gathering effort proposed.

It is our understanding that Table 1 reflects the present allocation of approximately 44 planned flight missions.

Table 1.

		No of Missions
I	Cloud Cluster Missions	
	1. Cluster or C Scale - emphasis on fields of meteorological parameters and budgets.	8
	2. Cluster or C Scale - emphasis on time continuity.	3
	3. Mesoscale or D Scale - emphasis on maximum sampling of individual clouds.	5
	4. Mesoscale or D Scale - emphasis on mesoscale systems smaller than a cluster, possibly a developing cluster.	5
II	ITC Crossing Missions	5
III	Boundary Layer and Radiation Missions	8
IV	Miscellaneous Missions	8-10
	Total	44

4.1 Undisturbed Condition

Measurements taken during suppressed conditions during the GATE are of great importance to GATE's central objective. Observations of cloud-subcloud layer interaction will complete the measured spectrum of convective conditions. The measurements of cloud physics parameters, particularly the liquid-water fluxes and the detrainment of water by dead or dying clouds, is of significance during these conditions. These measurements would be most useful if made in conjunction with the planned boundary layer flux and radiation measurement programs planned for these undisturbed, or suppressed, conditions.

4.1.1 Objective

The objective is to measure the vertical fluxes of liquid water by convective clouds during undisturbed conditions and the moistening of the cloud environment by this smaller scale convection. These effects can then be compared with the effect of the larger more organized convective scales.

Since the trade wind clouds of the undisturbed conditions form during day and night, the diurnal variation of these clouds in depth and numbers must be ascertained. As their development is closely related to the level of the trade wind inversion, diurnal changes of the level of this inversion must be studied. Pertinent data are probably received through the radiosonde program if it is executed on a 24 hr schedule. The day and night presence of these clouds supports the notion that they do not originate through convection from the water surface but perhaps through destabilization from radiation processes.

Ideally, the pattern, discussed below, would be flown in conjunction with boundary layer and radiation flights. The tactic would be to have a high level aircraft making a continuous cloud census of the volume being considered and vectoring the other aircraft into the same area.

4.1.2 Experimental Design

The flight pattern should be designed to concentrate nearly all available aircraft in the same volume for the same time period to give the most complete 4-dimensional structure of the region of interest.

The use of the cloud physics measurement program would then be as follows: The CV-990 will identify to the other aircraft the area selected for the flight program by giving the corner coordinates of the rectangular area. The other aircraft will then roam freely within the area at their prescribed altitudes to obtain a statistical sample of cloud and environmental parameters. The boundary layer aircraft will measure fluxes and turbulence in that layer, making sure that frequent under cloud traverses are included. The "Electra" will make cloud penetrations at about 1000 feet above base level for the measurement of drop spectra and fluxes making sure that as many cloud penetrations as possible are executed. Preferred directions during cloud penetrations are from the upwind or downwind sides. The C-130 aircraft will make cloud penetrations near the cloud tops for a measurement of cloud liquid water content, and in-cloud temperature. Preferred directions for penetrations are the same as for the lower aircraft. After having made a sufficient number of penetrations it will fly above the cloud tops and measure the radiative fluxes from the cloud tops. The top aircraft (CV-990) will compile data for a cloud census and will also measure radiation parameters, as well as the total albedo over the area. It is believed that the cloud physics aircraft of the USSR may participate in this research together with a Soviet weather radar ship. The Soviet aircraft is equipped to measure rain drop spectra and would then be another important link for the determination of the Z-R relationship.

The selection of the undisturbed day, and the volume of interest should receive very careful consideration. Under these conditions at least a quasi steady state condition often exists, and this is a necessary criterion. Hopefully, these missions will be carefully selected to meet the requirements of the boundary layer flights, and the cloud physics aspects proposed can be accomplished in this context.

The flight levels are as follows:

Electra and/or USSR aircraft - Cloud level, about 1000 feet above base, maximum penetrations of clouds for drop spectra and in-cloud fluxes.

C-130 - Near cloud tops cloud penetrations. Measurement of liquid water content, in-cloud and environmental temperature (CO_2 radiometer), radiation flux above cloud tops.

CV 990 - High level. Cloud census and radiation missions.

DC-6 - Subcloud gust probe aircraft levels and tracks as specified in boundary layer flight plans. Nuclei measurements on DC-6, precipitation measurements.

4.2 Cluster Missions - Disturbed Conditions

The central GATE objectives are geared to the active cloud cluster, and from Table 1 follows that one-half of the flight missions are dedicated to cluster missions. The operation of this proposed cloud physics program will be within the framework of the convection subprogram, although data from other subprograms are required. The general objective of the aircraft program on the C/D scale is to describe the physical properties, statistics, and types of organization of cumulus clouds and cumulus ensembles on horizontal scales up to about 200 km, since these are the scales which must be parameterized in numerical models. It is to the end of providing the observational data necessary to provide the descriptions of the cloud physics parameters of the convective clouds making up the cluster, and to provide the data necessary for improving and further developing the parameterizations of the microphysics of these clouds, that the proposed cloud physics measurement program is addressed.

4.2.1 *Objectives*

To obtain a statistical description of the fields of liquid-water and water vapor in clouds and in their immediate environment, including the amount of rain-out.

With respect to a study of the diurnal variation of these clouds, it is desirable to have some flight data during night conditions. We believe that pertinent data can be obtained from radiation measurements with the C-130 aircraft alone during special night missions. These flights would conduct vertical profiles from the ocean surface through the tradewind inversion to above the 500 mb level as well as measure the radiation transfer from the cloud tops. Cloud penetrations would also be made for a measurement of the buoyancy.

To obtain a sample of directly measured vertical transports of liquid-water as a function of cloud scale, elevation and stage of development to compare with the transports derived from budgets.

To quantitize the cloud-environment exchange through measurements and estimates of entrainment and detrainment, as well as temperatures inside and outside of clouds.

To make studies of convection cloud microphysics as necessary to improve the parameterization of cloud microphysics for cumulus and cumulus ensemble models.

4.2.2 *Experimental Design*

The proposed aircraft flight plans for the cluster mission are adequate as long as:

1. Minor deviations in flight track are made to penetrate the centroids of individual clouds and identifiable cloud systems within 10 km on either side of the flight track. This is particularly important on the crossed legs of the proposed butterfly pattern.
2. The patterns are oriented with respect to wind direction so that adequate sampling of the individual cloud and cluster environments is accomplished both upwind and downwind.
3. An adequate range of altitudes and cloud sizes are covered by aircraft with adequate cloud physics instrumentation.

Two example flight patterns for cluster missions from a draft of the GATE aircraft plan are presented in figures 1 and 2. In accordance with the above requirements we would suggest orienting a diagonal across the box pattern of figure 1 along the flow vector through a significant depth of the cloud. Alternately the pattern could be oriented along the cloud environment wind vector at the flight level if there were not a requirement to have patterns at all levels oriented the same. This would provide maximum sampling upwind and downwind of the box. (Fig. 1a).

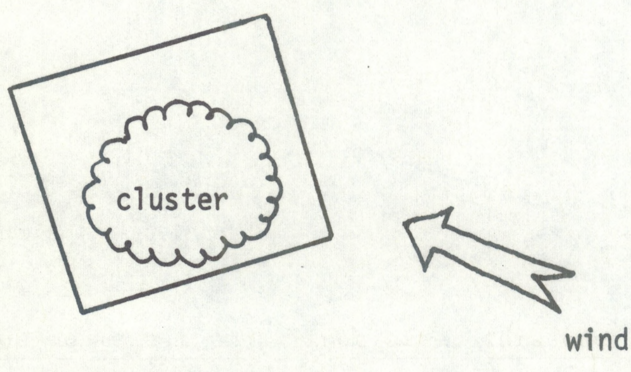
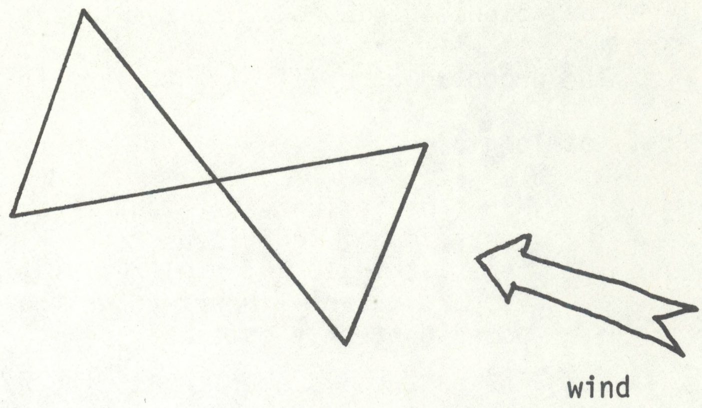


Figure 1a.

Figure 2a.

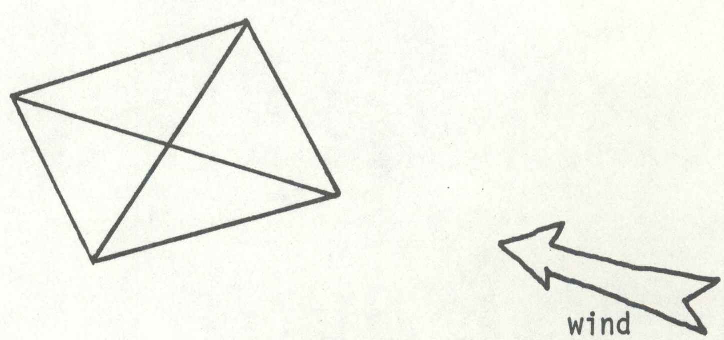


Also, we would suggest more sampling at intermediate levels with the NOAA C-130 in the range of 18,000 to 23,000 feet or about the -5 to -15C levels. Some important cloud microphysical processes occur here.

The butterfly pattern of figure 2 should be oriented to maximize sampling upwind and downwind of the identifiable cluster system. (Fig. 2a).

Also, it would be desirable to penetrate individual clouds along the flow vector, so if the boxed-butterfly were used it would be desirable to have at least one long penetrating leg along the flow vector. (Fig. 2b).

Figure 2b.



Pattern: Box, side 55 n.m.
Initial point: 9°N, 22°W (404 n.m. from Dakar).
Time at initial point 0930 GMT.
Displacement of pattern: 290°T at 15 knots.

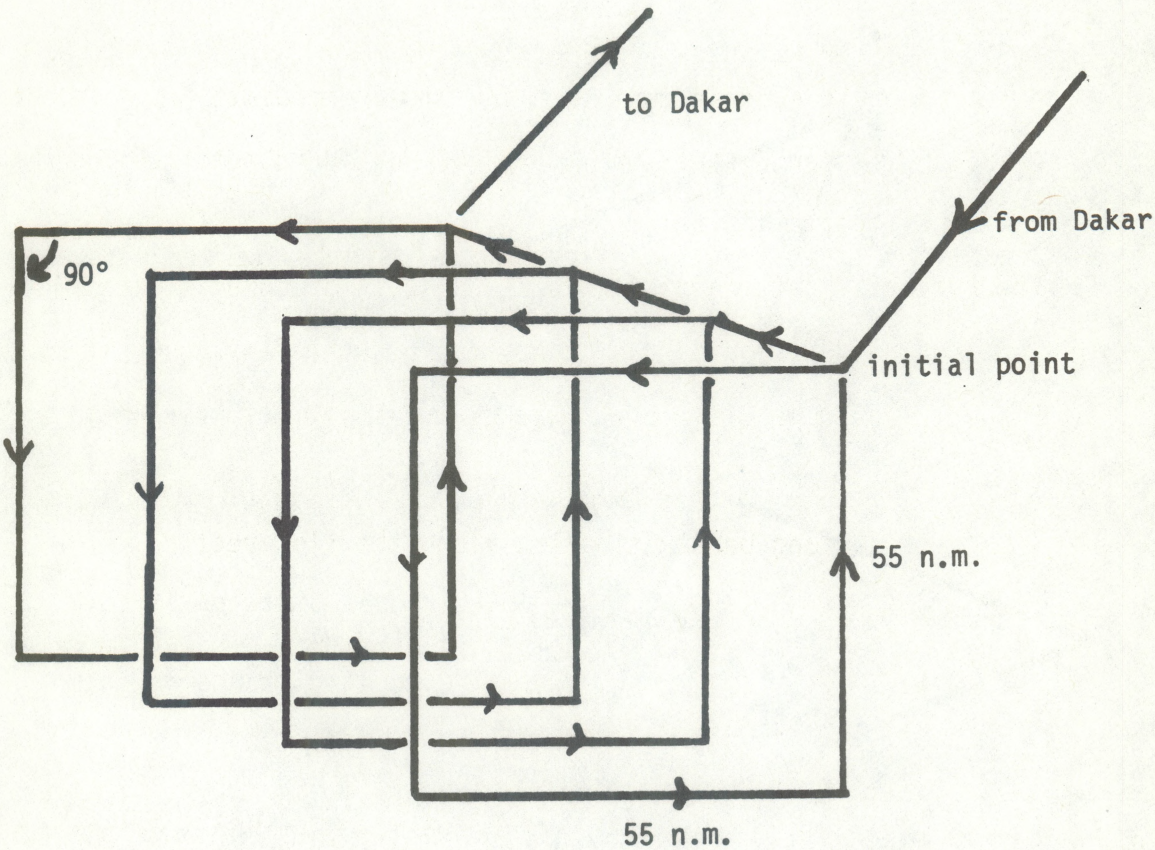


Figure 1.

Pattern: Butterfly, side 72.5 n.m. (150 km).
Initial point: 8°N, 23°W (528 n.m. from Dakar).
Time at initial point 0930 GMT.
Radar pattern diffuse, therefore no allowance for drift.

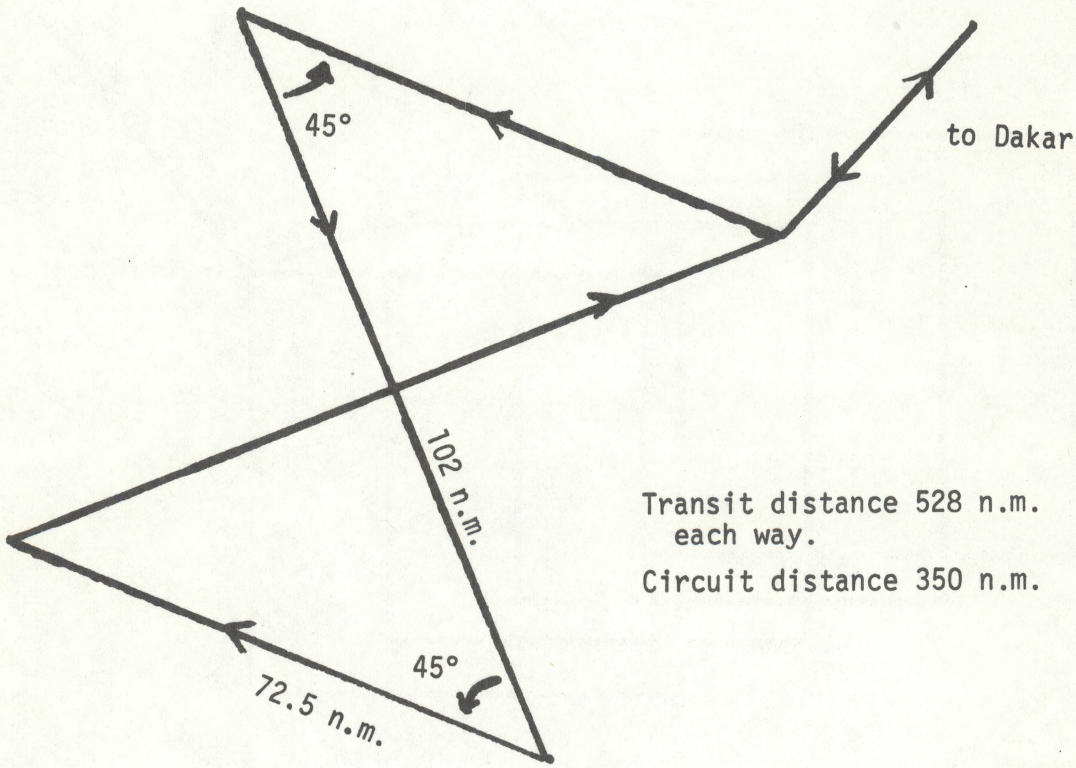


Figure 2.

The only other requirement for cluster flight cloud physics in addition to those above, is that the NOAA DC-6 and/or the NCAR Electra penetrate a large enough sample of rain shafts of various intensities to obtain foil drop spectra to properly evaluate the Z-R relationship for the GATE area.

This covers the C scale cluster flights. In addition, five D scale flights are planned with the emphasis being maximum sampling of individual clouds (table 1). For these flights we propose that the penetrations be made along the flow vector at the sampling level, so that the immediate upwind and downwind environment of each cloud is sampled. Other considerations are to insure that an adequate range of cloud sizes, stages of development and elevations are sampled. It is a requirement that a trained observer note the visual size and stage of development of each cloud sampled.

Five D scale flights are also planned on organized mesoscale systems smaller than a cluster. The recommendations made for the cluster flight patterns apply here, as only the size of the pattern is reduced.

4.3 Isolated Cloud Studies

The measurements of cloud microphysics on the cluster flights aimed at improving the parameterizations of cloud microphysics in cumulus models, and treated statistically, will be more useful if we have comparable measurements for a simpler case. Similarly, the estimates of entrainment and detrainment will be more productive if we have high resolution measurements on the entire life cycle of a simpler case for comparison.

The fluxes of water substance inferred from budget measurements will have to be verified with direct sampling measurements. Since the life cycle of tropical convective clouds is often very short, this comparison will require careful analysis of the stage of development of a cloud system associated with the flux calculations. A fairly simple, intensively sampled isolated, or single cloud system, is an absolute requirement to enable proper analysis of the measurements taken in the more complex cluster, or mesoscale system situations.

4.3.1 Objective

The objective of the proposed single cloud study is to obtain detailed time and space resolution measurements of cloud physics parameters of a fairly simple isolated cloud system within the B scale GATE data array. This simple case then can be compared to the results of the more complex situations.

4.3.2 Experimental Plan

The measurements proposed here will consume a total of about 2 to 3 hours on station, and should be treated as a special case under the miscellaneous category of the aircraft plan. In reality the flight plan should be treated as a target of opportunity situation, and may be best invoked as a contingency plan on days when a cloud cluster situation deteriorates, or does not develop as forecast, after aircraft have been committed. (It is known that in the tropics a nocturnal rain maximum exists, and it appears to be well within the GATE purpose to study this phenomenon. Such studies should be carried out in the cloud physics program. Hopefully ground and satellite observations, radar and Rawin wind data will shed light on this subject. An alternate approach would be to conduct aircraft night missions within the program described here. In view, however, of the very difficult logistics for such flight plans with respect toward predicting such an event and executing the research plan, we categorize such a study as "desirable" and not as a requirement.)

The essential elements of the flight plan are listed below. The key to the success of the program is proper cloud selection, and it will take about 6 attempts to get the required 2-3 cases. The basic pattern consists of a below cloud base aircraft making divergence boxes around the system (box should not be larger than 50 km at a side), an anvil level jet making divergence boxes and photo documentation, and two or more middle level cloud physics aircraft making very rapid penetrations of the cloud and its immediate upwind and downwind environment. The individual aircraft missions are as follows:

NOAA DC-6 - below cloud base - divergence box, gust probe fluxes, drop size measurements in rain shafts.

NCAR Electra - 1000 ft above base in cloud below trade inversion - rapid penetrations along flow or shear vector, cloud and raindrop size measurements, flux measurements.

NOAA C-130 - -15C level - rapid penetrations along flow or shear vector, liquid water content data, in cloud temperature (IR method), ice crystal content.

CV-990 - anvil level - divergence boxes and photo documentation. Radiation flux of cloud tops.

Dropsonde Aircraft - Omega dropsondes for cloud environment.

4.3.3 *General Remarks*

In view of what has been said in the Introduction, the purpose of this project is a very important one: It shall present a well coordinated effort to assess the energy budget of isolated Cumulo-nimbus clouds of the type that are the basic building blocks of cloud clusters. This requires above all a determination of the latent heat of condensation throughout the cloud's life history as it manifests itself in the rate of condensation, the water storage in the cloud, the amount of water which is discharged by rain and finally the amount left in the restcloud which will eventually evaporate and form a cold source. Diabatic processes in clouds e.g., radiation transfer are also being considered.

The following plan of operation is proposed: The top aircraft, i.e., the CV-990 will select the experimental area and will determine a rendezvous location. Conditions for selection of a certain cloud: it is to be located well within the useful radar range of a weather radar ship, making sure that it will not move out of radar range while it produces rain. The following individual measurements are proposed by participating aircraft:

1000 feet level

DC-6 subcloud layer measurements:
- Nuclei (CCN, IN and Aitken)
- Rainfall using foil impactor
- Water vapor fluxes, divergence boxes
- Sea surface temperature (IR looking down)
- Cloud base temperature (IR looking up).

2000 feet or just below cloud base

Soviet Cloud Physics aircraft measurements of raindrop spectra.

below 0°C, about 700 mb level

Electra: penetrate from upshear to downshear, then fly butterfly pattern. Measure fluxes inside and outside of cloud, cloud and rain droplet spectra, and winds with inertial navigation system (INS), and others.

about 500 mb

C-130 fly similar pattern as Electra, measure liquid water content, inside and outside temperatures using IR radiometer, provide winds (INS) and others.

Level of anvil

CV-990 measure detrainment on cloud tops by flying a box pattern at anvil level but remaining inside anvil boundaries, measure winds and water vapor in situ. Also provide project guidance and - where feasible - cloud census information.

Additional requirement:

It is most desirable that the radar ship is equipped with a Joss raindrop spectrometer and a raingage.

5.1 Cloud Physics Instrumentation

Tables 2 and 3 list the instruments which are available for the cloud physics measurements, as well as principle of operation, range, accuracy, sampling volume, sensitivity, etc. Table 4 indicates which instrument is installed into which aircraft.

6. ACKNOWLEDGMENTS

Subject study is the outgrowth of a small workshop with the following participants: P. Allee, B. Bean, A. Betts, J. Cunning, P. Kuhn, B. Patten (for J. McFadden), B. Phillips, A. Miller, S. Whitaker, P. Willis, and E. Zipser. The cooperation and advise of these scientists is much appreciated. The interest of Dr. J. Rasmussen, NOAA GATE Office in this endeavor is thankfully acknowledged.

Table 2.

Type	Objective of Measurement	Type of Instrument	Principle of Operation	Range	Accuracy
(1) Total Water Content Probe	Total water in cloud and in the cloud environment.	Lyman Alpha	Absorption of Lyman Alpha radiation by water vapor.	0-15 g/m³	±10% Total Water
(2) NHRL Total Liquid Water Probe	Total liquid water content of clouds.	Hot Wire	Constant temperature device below boiling point of water.	0-7 g/m³	±20% *
(3) Johnson Williams	Cloud droplet water content.	Hot Wire	Constant current complete water vaporization device.	0-3 g/m³ at 200 knots	±20% over small droplet size range of spectrum.
(4) Airborne Hydrometer Sampler	Drop size distributions.	Foil Impactor	Impaction impressions on soft foil.	drops >250μm diameter	±10% of large drop liquid water content.
(5) Continuous Particle Replicator	Droplet distributions and crystal habits.	Formvar Replication	Particle impression on plastic resin.	Qualitative Indications	------------------
(6) MEE Ice Particle Counter	Ice particle concentrations.	Optical	Cross polarization discrimination of pulses produced by ice, count particles above a size threshold.	count particles above 150μm diameter	±20% some ambiguity from large drops (>4 mm diam.)
(7) Infrared Hygrometer	Humidity measurement.	Spectrometric	IR absorption by water vapor.	see RFF Document	see RFF Document
(8) C.S.I Dew Point	Humidity.	Dew/frost point	"	"	"
(9) Rosemount Temp. Probe	Total temperature.	Platinum Resistor	Heated air due to deicing bled off.	"	"
(10) #1	Total liquid water.	Hot Wire	Constant voltage resistance changed by evaporation.	0-15 g/m³	±20% of total water content.
#2	Volume medium drop dia.	Wire Array	Cooling proportional to liquid water.		±45%.
(11) Interface Temp. PRT-5	Ground surface temperatures.	IR Radiometer 9.5-11.5μ	Bolometer type receiver.	-40 to +40C	Relative ±.15C. absolute ±.4C.
(12) Air/Cloud Temp. radiometer FW 14-330	Air temperature in cloud temperatures.	IR Radiometer 15μ CO_2 band	Bolometer type receiver.	-40 to +40C	relative ±.3C. absolute ±.5C.
(13) Water Vapor Radiometer	in situ water vapor.	IR Radiometer 17 to 38μ	Bolometer type receiver.	humidities above 15K feet.	15 to 20% relative humidity.
(14) Knollenberg Cloud drop spectrometer	Cloud droplet spectrum	Optical array cloud droplet spectrometer	Laser beam absorption 14 channels	20-280μ	
Raindrop Spectrometer	Raindrop spectra.	"	"	300-4500μ.	
(15) Aitken Counter (E-1)	Total particulate concentration (Aitken Nuclei).	Particle Counter	Light beam extinction through cloud formed in water saturated adiabatic expansion chamber.	50 - 1 x 10^7/mℓ	±30%
(16) CCN Counter	Cloud droplet condensation nuclei (CCN) concentration.	CCN Counter	Water saturated thermal diffusion chamber forms droplets on CCN.	50 - 1 x 10^4/mℓ	±10%
(17) IN Counter (NCAR)	Ice nuclei concentration.	NCAR Ice Nuclei Counter	Supercooled cloud chamber, acoustic counter.	.01 - 1 x 10^3/ℓ	
(18) Membrane Filter	Ice nuclei concentration.	Sub Freezing Thermal Diffusion Chamber	Ice nuclei activation at saturated water vapor pressure.	.1 - 1 x 10^3/ℓ	

*Prototype Instrument - Calibration Incomplete.

Table 3.

Instrument	Sensitivity	Sampling Volume	Accuracy
(1) Lyman Alpha	Individual large drops provide detectable signal.	7.5 ℓ/sec	±10% total water less on liquid particularly at low altitudes.
(2) NHRL (Merceret-Schricker)	Higher than Lyman Alpha, detects individual large drops.	250 ℓ/sec	±20% preliminary value — calibration incomplete.
(3) Johnson Williams	0.05 g/m³	1.5 ℓ/sec	±20% for small droplets only much less if used as total LWC.
(4) Foil Replicator	Individual impression above 250μm dia.		±10% in sizes above instrument threshold.
C-130		19.2 ℓ/frame	
DC-6		29.0 ℓ/frame	
(5) Formvar	Individual droplet replications.	3.175 ℓ/sec	Qualitative particle impressions.
(6) MEE Ice Particle Counter	Individual ice particles above 150μm dia.	10.0 ℓ/sec	±20% gross number of ice particles above a threshold. Some ambiguity by liquid drops 71 mm dia.
(10) Levine Instrument Water Content	.1g/m³	200 ℓ/sec	±20%.
Volume Medium Drop dia.		400 ℓ/sec	±45%.
(15) Aitken Counter (E-1)	Depends on accuracy of calibration.	30-70 mℓ/sec	±30%.
(16) CCN Counter	Individual droplets	~.02 mℓ	±10%.
(17) IN Counter (NCAR)	10% of total nuclei conc. at -20C.	10 ℓ/min	Natural ice nuclei ±20%.
(18) Membrane Filter	Individual nuclei.	~300 ℓ	Internally consistent results only with standardized procedure equipment and materials.

Table 4.

DC-6 NOAA	1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 15, 16, 17, 18 plus basic data from aircraft system.
C-130 NOAA	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 plus Airborne Weather Reconnaissance System (AWRS).
Electra NCAR	9, 11, 14 plus basic data from aircraft system.
CV-990 NASA	11, 12, 13

7. REFERENCES

Bunker, A. F., B. Haurwitz, J. S. Malkus, and H. Stommel (1949): Vertical distribution of temperature and humidity over the Carribean Sea, *Pap. Phys. Ocean. Meteor.*, MIT and Woods Hole Oceano. Inst., 11(1):82 pp.

GATE Report #1 (1972): Experimental design proposal for the GARP Atlantic Tropical Experiment. WMO Publication, 188 pp.

Stout, G. E., and E. A. Mueller (1968): Survey of the relationship between rainfall rate and radar reflectivity in the measurement of precipitation. *J. Appl. Meteor.*, 7:465-474.

Yanai, M., S. Ebensen, and J. Chu (1972): Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets, Dept. of Meteor., Univ. of Calif., Los Angeles, 66 p.