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GATE: Report on the Field Phase

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International Scientific and Management Group for GATE

Preface

The following report, describing the field phase of the GARP Atlantic Tropical Experiment, will, in general, not repeat details of the scientific plans for GATE. These are well known and were summarized in an earlier article in the BULLETIN (**55**, 711–744) referred to from here on as "Article I." Furthermore, the scientific and operational plans for GATE were comprehensively documented in GATE Reports Nos. 3 to 13 (1973/4) of the WMO-ICSU GARP Series. However, significant changes to those plans will be related here.

Regarding the field phase itself, the International Scientific and Management Group for GATE (ISMG) has described the events of the field phase in the following "Reports on the Field Phase of GATE":

GATE Report[3] No. 15: "Operations" (ISMG, 1975)
" " " 16: "Scientific Programme" (Kuettner and Long, 1975)
" " " 17: "Meteorological Atlas" (ISMG, 1975)
" " " 18: "Aircraft Mission Summary" (Aanensen, 1975)
" " " 19: "Summary of Data Collected" (de la Moriniere, 1975)

"Preliminary Scientific Results" of GATE are contained in 2 volumes of GATE Report No. 14 (ISMG, 1975). For more details than those given in this article, reference is made to these reports.

To refresh the memory of the reader we mention only four facts which frequently recur in this report:

1) The GATE field phase was divided into three phases of about three weeks each.
2) The GATE scientific program was divided into five subprograms held together by the "Central Program."
3) Four scales were defined for GATE, namely:

   the A-scale (10^3 to 10^4 km) = Synoptic scale
   the B-scale (10^2 to 10^3 km) = Cloud cluster scale
   the C-scale (10 to 10^2 km) = Mesoscale
   the D-scale (1 to 10 km) = Cumulus scale

4) The main base for GATE was Dakar, Senegal.

The area of the East Atlantic in which ships were concentrated in two hexagons (see Fig. 3) was simply called the "B-Scale area." The ships in the outer hexagon were called the "A/B-Scale ships," those of the inner hexagon the "B-Scale ships." The small triangle of ships within the inner hexagon during Phase III (Figs. 3 and 14) was called the "C-Scale area" and the "C-Scale ships." This terminology will be used in the following sections.

1. The experience of GATE

When the hundred days of GATE were over it was a tired but happy crowd that headed for home ports scattered from Vladivostok to Rio de Janeiro: happy, because they carried with them a wealth of scientific data and many new bonds of friendship; tired, because it seemed that the exhausting effort could not have lasted a day longer.

The success of a scientific experiment cannot and should not be stated before the scientific results are

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[1] Now at the World Meteorological Organization, Geneva, Switzerland.
[2] Now at the Meteorological Office, Bracknell, U.K.
[3] These GATE Reports can be obtained from the WMO Secretariat, Geneva.

in. Nevertheless, the question is now being raised whether this first large test of the GARP concept casts any light or shadow on future global research projects such as FGGE and its various subprograms. Actually there is one way to answer this question before the scientific outcome is fully known: If the observing program was tailored tightly to the scientific objectives it is reasonable to expect that they will be attained if the observing program was fulfilled. This, however, can already be judged to a fairly acceptable degree.

The fulfillment of an observing program depends on factors of a scientific, technological and human nature. Surprisingly, in projects as large and complex as GATE, human problems usually over-ride the others. If they can be solved, the technological and scientific difficulties may also be overcome, but not vice versa. In GATE, the anticipated human problems either did not arise or they solved themselves by the extraordinary goodwill and competence of the international participants. No efforts were necessary to tear down walls; there were none. As a consequence the collaboration in this international effort was probably smoother than in most national projects.

If there were problems in GATE they were primarily of a technological nature and, as the field phase progressed, many could be corrected or at least improved. Examples for such technical difficulties were the premature departure or non-arrival of certain ships; the failure of some upper-air land stations and telecommunication links of the World Weather Watch (WWW); operational problems with certain types of shipborne wind-finding systems, etc.

It is common experience that no field project achieves 100% of its goal. Given the vagaries of the laboratory we must work in—the earth's atmosphere—an 80% success is about all one can hope for in the atmospheric sciences.

The five subprograms of GATE were not equally successful ranging from an estimated 70% for the synoptic-scale subprogram to a near 100% for the radiation program as far as the observing program is concerned. What really matters, however, is how those parts of the subprograms fared which jointly constitute the Central Program of GATE based on the primary scientific objectives. It is our best judgment that the observing program supporting this Central Program was fulfilled to at least 80%.

2. Scientific strategy and the evolution of the observing program

The scientific strategy applied during the GATE field phase was one of balancing operational constraints and scientific demands. The detrimental consequences of operational changes often outweigh their scientific benefits. On the other side, a research project cannot be conducted rigidly if its subject of exploration is as highly variable as the tropical atmosphere. Therefore the observational program of GATE had been divided into a flexible and a fixed part.

For the flexible part of the observing program the attempt was made to anticipate, in the planning stage, as many options as possible, to prepare them in detail and to set up an effective decision-making process. The Scientific Aircraft Plan (GATE Report No. 11, Aanensen and Zipser, 1974) and the Mission Selection Team activities (GATE Report No. 9, Long *et al.*, 1974), which were tested in advance during the Boulder Workshop (March 1974), served that purpose. In this way the operations could be adapted to the scientific opportunities offered by the atmosphere almost at a moment's notice.

For the fixed part of the observing program, primarily

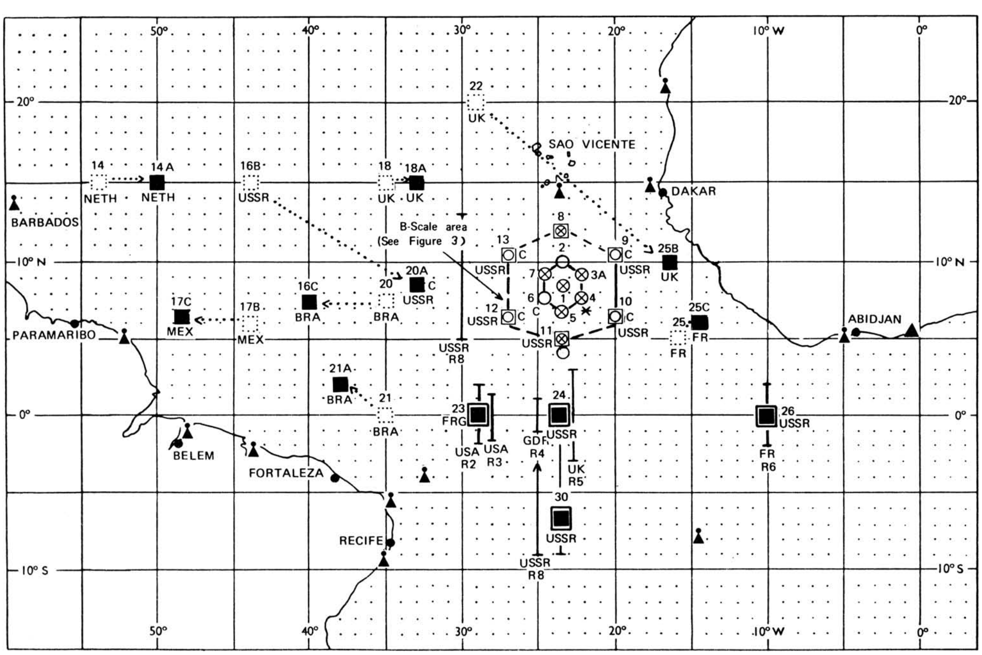

FIG. 1. Phase II ship distribution (28 July–16 August 1974).
Note: For definition of symbols, see Fig. 3.

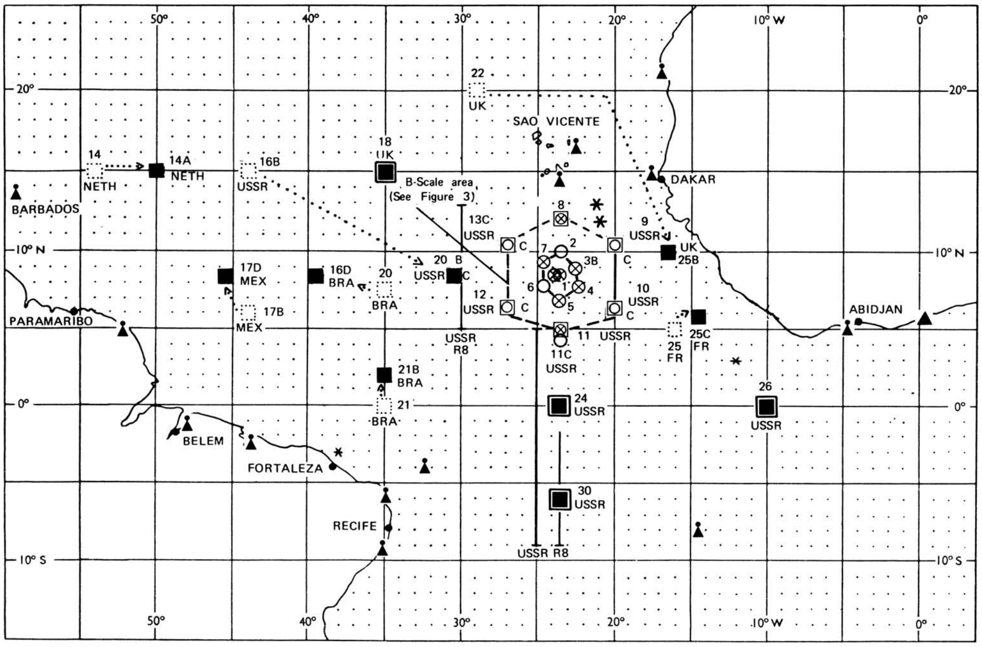

FIG. 2. Phase III ship distribution (30 August–19 September 1974).
Note: For definition of symbols, see Fig. 3.

the ship and land based stations, the principle was followed to minimize changes unless one of two considerations entered the picture: The achievement of the primary objectives of the GATE Central Program was in jeopardy (see Table 4); the safety of any of the participants was endangered. The latter always had priority.

The three phases of GATE, separated by about 10 days "inter-phase" time, gave an opportunity to effect major changes before a new phase began. Real-time data transmission enabled the Special Analysis Group [4] at Dakar to evaluate the performance of ship and land observing systems in time to adjust ship schedules and positions for the following field phase. Major decisions of this type were taken jointly—and often unanimously—by the international "Mission Selection Team" (see Section 3), the National Coordinators, and the GATE Director, with the advice of the Experiment Review Board.

[4] Headed by Dr. D. Rodenhuis.

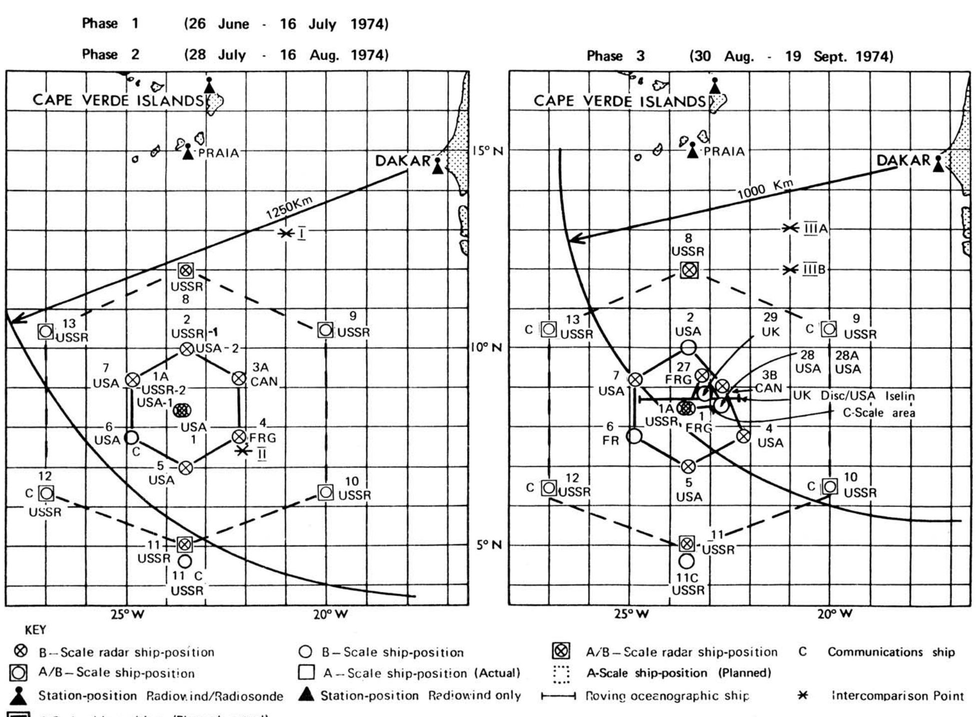

FIG. 3. Ship distribution in B-Scale area, including C-Scale triangle in Phase III
(30 August–19 September 1974).

The learning curve in GATE was steep—and the overall performance of Phase III vastly exceeded that of Phase I.

a. Ship Program

During the first phase it became apparent that the upper wind soundings from ships and land stations showed gaps both up and down-stream of the East Atlantic ship array (B-scale area). Some crucial stations on the African west coast were not operating and several shipborne windfinding systems using radio navigation aids showed erratic results, at least in the form of real-time data collection in Dakar. In addition, several ship stations were not occupied due to mechanical difficulties.

To assure that the key problem of GATE, namely the interaction of the cloud cluster and smaller-scale convective systems with the large-scale, would be solved, the decision was made to place ships with reliably working windfinding systems (radar) closer to the B-scale area and to fill the gap near the African coast by additional ship positions (Fig. 1). The resulting dilution of the observing network in the Western and Northern Atlantic was carefully considered and accepted as the lesser evil.

Already during Phase II most systems improved perceptibly—many by gaining operational experience—and it was possible to partly readjust the ship distribution for Phase III (Fig. 2). Details of the B-Scale array, including the C-scale triangle, are shown in Fig. 3 and Fig. 14. Several ship positions had double occupancy in order to combine and back up related measuring systems.

A total of 39 ships participated in GATE. Table 1 shows the final list containing several changes over the original plans.

TABLE 1. GATE ship participation.

Country	Name	Full time (F) Part time (P)	Remarks
1. Brazil	*Sirius*	F	
2. Brazil	*Alm. Saldanha*	F	
3. Canada	*Quadra*	F	5.7 cm radar
4. France	*La Perle*	P	
5. France	*Bidassoa*	P	
6. France	*Capricorne*	P	
7. France	*Charcot*	P	
8. F.R.G.	*Meteor*	F	3.2 cm radar
9. F.R.G.	*Planet*	P	3.2 cm radar
10. F.R.G.	*Anton Dohrn*	P	
11. G.D.R.	*Alex. Von Humboldt*	P	Oceanography*
12. Mexico	*Mariano Matamoros*	F	
13. Netherlands	*Onversaagd*	F	
14. U.K.	*Charterer*	F	
15. U.K.	*Endurer*	F	
16. U.K.	*Hecla*	P	
17. U.K.	*Discovery*	P	Oceanography*
18. U.S.A.	*Oceanographer*	F	5.7 cm radar
19. U.S.A.	*Researcher*	F	5.7 cm radar
20. U.S.A.	*Gilliss*	F	5.7 cm radar
21. U.S.A.	*H.J.W. Fay*	P	
22. U.S.A.	*Dallas*	F	
23. U.S.A.	*Vanguard*	P	
24. U.S.A.	*Col. Iselin*	P	Oceanography*
25. U.S.A.	*Atlantis II*	P	Oceanography*
26. U.S.A.	*Trident*	P	Oceanography*
27. U.S.S.R.	*Prof. Vize*	F	3.2 cm radar
28. U.S.S.R.	*Prof. Zubov*	F	3.2 cm radar
29. U.S.S.R.	*Akad. Korolov*	F	3.2 cm radar
30. U.S.S.R.	*Akad. Kurchatov*	F	
31. U.S.S.R.	*Passat*	F	
32. U.S.S.R.	*Ernst Krenkel*	F	
33. U.S.S.R.	*Okean*	F	
34. U.S.S.R.	*Volna*	F	
35. U.S.S.R.	*Priboy*	F	
36. U.S.S.R.	*Poryv*	F	
37. U.S.S.R.	*Musson*	F	Communication
38. U.S.S.R.	*M. Lomonosov*	F	Oceanography*
39. U.S.S.R.	*Semen Dezhnev*	F	Oceanography*

* Primary use for oceanography.

b. Aircraft Program

While in the beginning the flight program adhered strictly to the aircraft plan, it was possible later to combine certain missions or to modify patterns for a given mission. It also became necessary to create some new flight missions best suited to a given situation. A number of reconnaissance missions were developed as soon as the feasibility of the Omega wind dropsonde was established and these missions were also used to fill gaps in the A-scale ship array. Once a dedicated aircraft for the Oceanographic Subprogram became available, special flight missions for sea-surface temperature and wave measurements were developed.

Certain atmospheric phenomena were so elusive that they could only be scheduled as alternate or "add-on" flight missions, according to the latest information available during flight. An example was the so-called "cloud ring mission," the formation of convective rings on the mesoscale not being sufficiently predictable.

Some flight mission types had to be abandoned. For example, it was hoped originally to follow the life of a cloud cluster by consecutive group flights with take-offs staggered in time. However, the unexpectedly rapid development of cloud clusters presented an insurmountable problem in scheduling successive group flights at the proper time in view of the operational constraints on crew rest and "down time" of the aircraft.

Finally, it may be mentioned that the Mission Selection Team first followed the principle to schedule all aircraft that were flight-ready for next day's mission. After several opportunities were lost a system was developed that made it possible to always have two aircraft equipped with gust-probe and two aircraft equipped with inertial systems available. In this way substantial multi-aircraft missions could be scheduled practically every day during Phase III.

Throughout the field operations careful attention was given to preserving the balance between the Central Program and the individual Subprograms. Prior to the GATE field phase it had been agreed upon by the Joint Organizing Committee for GARP (JOC), the Tropical Experiment Board (TEB), and the ISMG what approximate proportions should be maintained among the flights devoted to the various scientific programs. By

TABLE 2. Distribution of flight missions planned and flown according to scientific objectives.

Type of mission	General goal (JOC, TEB, ISMG) %	GATE aircraft plan %	Actually flown %
Basic GATE missions plus convection flights (Central Program)	60	62	57
Special boundary-layer missions	20	18	18
Special radiation missions	15	18	21
Special oceanographic missions	5	2	4

continually keeping track of the number of sorties devoted to these programs and by estimating their success it was possible to adjust the flight program during the three field phases so as to stay within a few percent of the original goal (see Table 2).

Only through the good will and the unselfish cooperation of the participants who put the common scientific goal above national aims was it possible to implement this scientific strategy.

The importance of the ship radar and satellite information for flight planning should again be mentioned here.

A total of 13 aircraft participated in GATE, as listed in Table 3.

c. Satellite Program

There was some apprehension in early 1974 that the geostationary meteorological satellite SMS-1 would not be launched in time for GATE. The U.S.A. therefore decided to send NASA's Direct Readout Ground Station (DRGS) to Dakar which provided high resolution images of the polar orbiting NOAA-2 and 3 satellites using a laser recorder. However, the SMS-1 became operational on the first day of GATE and after some successful parallel operation of the two ground stations the DRGS was withdrawn. SMS-1 was stationed at 45°W, 15° farther west than originally planned with some loss of coverage over Central Africa.

Throughout GATE the work of the Satellite Field Service Station (SFSS) at the Control Center in Dakar was virtually flawless and its products became the backbone of flight mission planning and a very important input to the forecasts for the B-scale area. High resolution images in the visible and infrared spectrum were available every 30 minutes when needed, but 3-hourly intervals were often sufficient. These and the radar-radio facsimile pictures from the ships *Quadra* and *Oceanographer* available at Dakar in real-time revealed enough of the external and internal structure of cloud clusters to enable ongoing flight missions to be optimized (see Section 5 *b* below). Daily "satellite loops" produced in near-real-time made the motions of the convective systems visible to returning flight crews and became a valuable prognostic and analytical tool. Cloud displacement winds and sea surface temperature analyses from satellite data were also transmitted from Washington to Dakar.

The only serious loss was Nimbus F which could not be launched in time for GATE. This affected some aspects of the radiation subprogram (see Section 5 *d* below) and eliminatel several drifting-balloon programs.

In the meantime it has become apparent that satellite-derived winds at two, possibly three cloud levels give consistent and dense wind fields in the GATE area based on over 1000 wind values per day. They supplement the ship and land based wind data which provide the needed vertical resolution, by adding horizontal resolution where it is missing. If some of the gaps in the A-scale can be filled in this way the synoptic scale subprogram will be the main beneficiary (see Section 5 *a* below).

d. Land stations

The status of upper-air land stations during GATE is shown in Fig. 4. Regrettably, a number of planned World Weather Watch stations did not operate, although their priorities had been established more than 3 years before GATE.

Due to telecommunication problems, real-time data acquisition (for example at Bracknell, U.K., within 9 h of data time) was on average only 36% of that planned, being lowest for central and eastern Africa and highest

TABLE 3. GATE aircraft participation.

Country	Type	Range*	Available**	Prop	Turbo prop	Jet	Remarks
1. France	DC-7	L	F	x			Inert. platform
2. U.K.	Hercules	L	F		x		Gust probe, inert. platform
3. U.S.A.	CV-990	L	F			x	Inert. platform
4. U.S.A.	C-130	L	F		x		Inert. platform
5. U.S.A.	Electra	L	F		x		Gust probe, inert. platform
6. U.S.A.	DC-6	L	F	x			Gust probe, inert. platform
7. U.S.A.	KC-135	L	P			x	Wind dropsonde
8. U.S.A.	WC-135	L	P			x	Wind dropsonde
9. U.S.A.	Lockheed P-3a	L	P		x		Oceanography
10. U.S.A.	Sabreliner	M	P			x	Inert. platform, gust probe
11. U.S.A.	Queenair	S	P	x			Gust probe
12. U.S.S.R.	IL-18-M	L	F		x		Radiation
13. U.S.S.R.	IL-18-C	L	F		x		

* L = Long range. M = Medium. S = Short range.
** F = Full time. P = Part time.

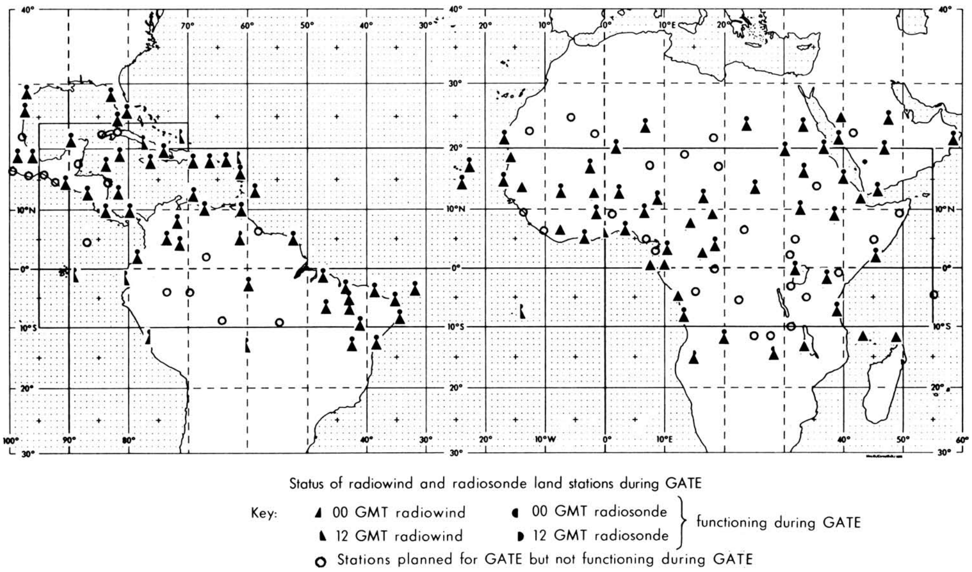

FIG. 4. Status of radiowind and radiosonde land stations during GATE.

for the Caribbean and Brazil. This, however, had been anticipated and a mail collection of teleprinter paper tapes was pre-arranged resulting in a very worthwhile increase to about 50%, still a lower than desirable figure.

As mentioned before, most serious was the gap created by the west African coastal stations east and southwest of the B-array making rearrangements in the ship distribution necessary. Also in western South America, south of the equator, and in parts of central and eastern Africa, a number of stations did not function.

While there was a more than 100% improvement over prior years, the overall performance of the World Weather Watch in the GATE area was less than expected and needs to be vastly enhanced for future GARP projects such as FGGE.

e. Commercial Ship and Aircraft Program

Prior to the GATE field phase special preparations had been made to obtain a maximum amount of commercial ship and aircraft data. It now appears that more than 20 000 reports were received in each of the two categories and that many airline pilots crossing the east Atlantic GATE area made detailed reports and sketches of their observations. The ship data were collected in Hamburg and the aircraft data by several research groups in the U.S.A. As far as wind fields are concerned, it is already clear that the commercial operations are a data source of surprising importance.

3. Operational control

For the operational control an organizational structure was created in which the national and international functions were closely intertwined (Fig. 5). The responsibility for the international direction was vested in the International Scientific and Management Group (ISMG) which operated under the auspices of WMO, with the support of many nations. The responsibility for the operations of the national contingents was carried by

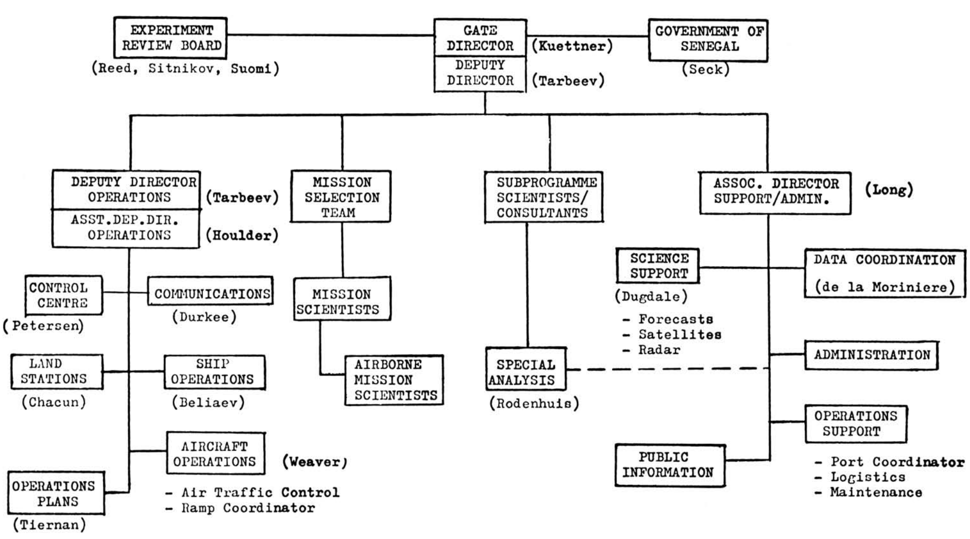

FIG. 5. International organization of the Operations Center in Dakar.

the National Coordinators[5] supported in some cases by Chief Scientists. The GATE Operations Control Center (GOCC) was housed in a special building constructed by the participating nations and the host country, Senegal, on the airport of Dakar, the main base of GATE, (Fig. 6).

As mentioned earlier the key to the scientific control was an international group, the Mission Selection Team (MST), chaired by the GATE Director, which made its decisions daily, with about 12 h lead-time, on the basis of the latest information presented by the forecasting team, the ship and aircraft operations directors, the subprogram scientists, and the scientific analysis team. The advice of the Experiment Review Board, representing JOC through Prof. R. Reed, soon turned into a valuable active cooperation with the MST.

The implementation of these decisions was placed in the hands of the Operations Director while the detailed planning was the task of a Mission Scientist (MS) selected for each mission by the MST. On-the-spot decisions, often required during a flight mission, were the responsibility of an Airborne Mission Scientist riding on the lead aircraft after radio coordination with radarships, the Air Traffic Control, and the MS at Dakar. Several of the flying scientists acquired an admirable skill in this type of short-time decision-making.

With more than 4000 participants on the various floating and flying platforms, the operational control depended entirely on reliable functioning of the GATE Telecommunication System (Fig. 7) which also served

FIG. 6. The GATE Operations Control Center (GOCC) on the Airport of Dakar, Senegal.

the real-time data collection. It consisted of a special HF-radio-ship-communication system, the Global Telecommunication System (GTS) of the WWW, a number of satellite links and an international communication center in the GOCC building. The notorious radio transmission difficulties over long east-west distances in this area were overcome by dividing the ships into six groups and assigning one ship in each group as a "collection ship"; furthermore, a selected frequency schedule was used following a special study by the Institute of Telecommunications in Boulder, Colorado. This resulted in a path reliability of 90 to 95%.

Data from the platforms collected in Dakar were entered into the GTS for use in real-time by the Regional and World Meteorological Centers as well as for some near-real-time numerical experimentation by certain research groups in the U.K., U.S.A., and U.S.S.R.

[5] Those present in Dakar were: J. Alt for France; H. Kraus for F.R.G.; G. James for U.K.; W. Barney, D. Sargeant, J. Rasmussen for U.S.A.; A. Borovikov for U.S.S.R. (M. Petrossiants for overall U.S.S.R. coordination).

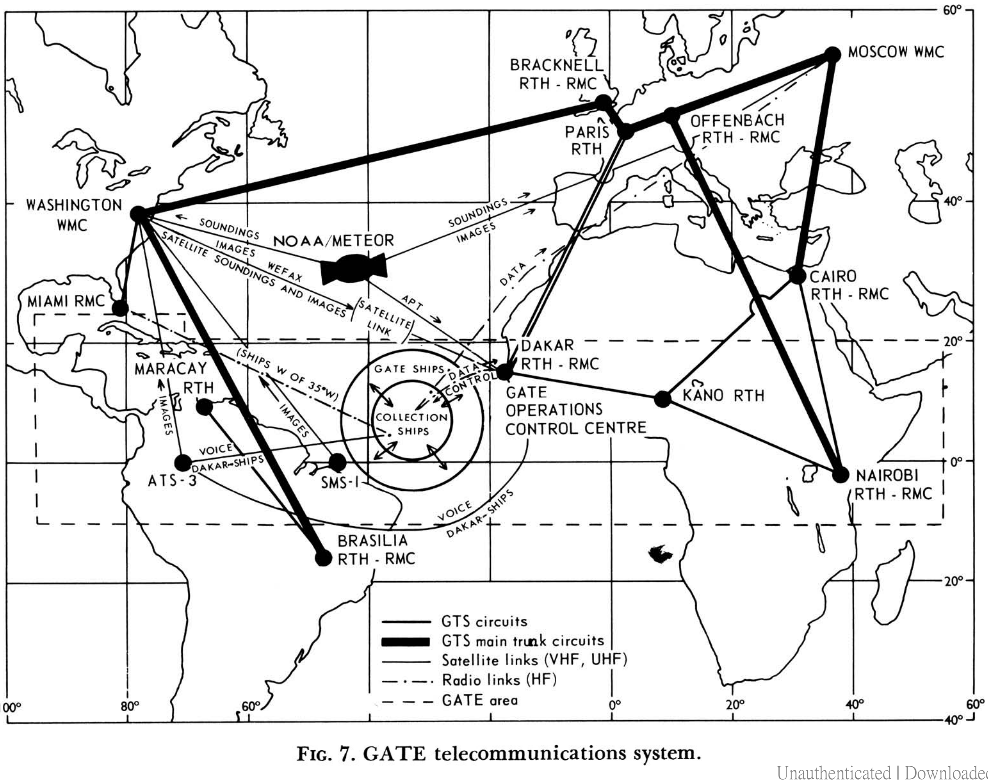

FIG. 7. GATE telecommunications system.

With a fleet of ships as large as that deployed in GATE, medical problems became a serious consideration. It was necessary during the field phase to devise a Medical Plan by which medical expertise and facilities could be provided from one ship to another. Nevertheless, it was unavoidable that there were always some ships off station bringing medical cases to shore; and unfortunately, two lives could not be saved under the given circumstances.

Flight and ship safety was another operational concern. During intercomparison flights aircraft were flying in close proximity to each other and near ship-born tethered balloons. Also airliners were crossing the experiment area over the Atlantic and commercial ships the ship arrays. (At one time a rudderless super tanker drifted into the C-scale buoy array). Finally, the ship-intercomparisons required very close operations of as many as 15 ships and their respective buoys. With an extraordinary effort—and some initial difficulties—all these problems were overcome by the devoted controllers and crews, in spite of the language difficulties, and GATE ended without a single serious accident.

4. Weather trends

During the planning of GATE a prolonged debate had preceded the final positioning of the B-scale ship array in the east Atlantic. The years before GATE had been meteorologically abnormal. The viewpoint prevailed, however, that the ship distribution should be based on what could be considered as "normal" behavior of the tropical atmosphere. The center of the double hexagon (see Fig. 3) was fixed at a longitude as far from the African coast as the aircraft range allowed (23.5°W) and at a latitude (8.5°N) which would ensure that the Inter-Tropical Convergence Zone (ITCZ) would bring a maximum of tropical cloud clusters through the ship array. (Note that it was not 8° and not 9° but 8-1/2°, i.e., about 50 km variation was considered in view of the sensitivity of the ITCZ position).

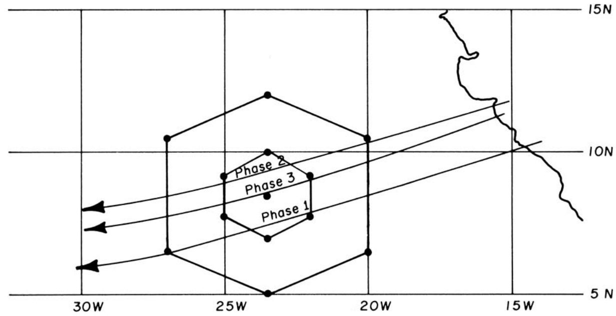

FIG. 8. Mean path of convective systems through B-Scale area during the three phases of GATE. (After Burpee and Dugdale, 1975.)

Figure 8 shows that this selection was fortunate indeed, as the mean cloud cluster tracks intersected the inner array precisely as anticipated. Almost all of the convective systems during each phase moved along paths within 5° of the mean path for that phase; however, the tracks followed by each separate convective system showed considerable deviation from these average paths.

As expected, and as described by Burpee and Dugdale (1975) in more detail, the most prominent synoptic scale features affecting the lower troposphere of western Africa and the eastern Atlantic were the easterly waves. Between late June and mid-September 1974, 24 waves crossed the east Atlantic experiment area with an average wavelength of 2500 km, period of 3.5 days and phase speed of 6 m/s.

These waves modulated the convective activity in the ITCZ region near the GATE ships such that maximum intensity and northward displacement of the cloud clusters occurred just before or at the time of trough passage at 700 mb and minimum convective activity one day after the trough passed. Figure 9 based on infrared satellite information gives a record of the occurrence of deep convection over the axis of the B-scale array (23.5°W). The influence of the easterly waves on the ITCZ is clearly visible. It was found that this influ-

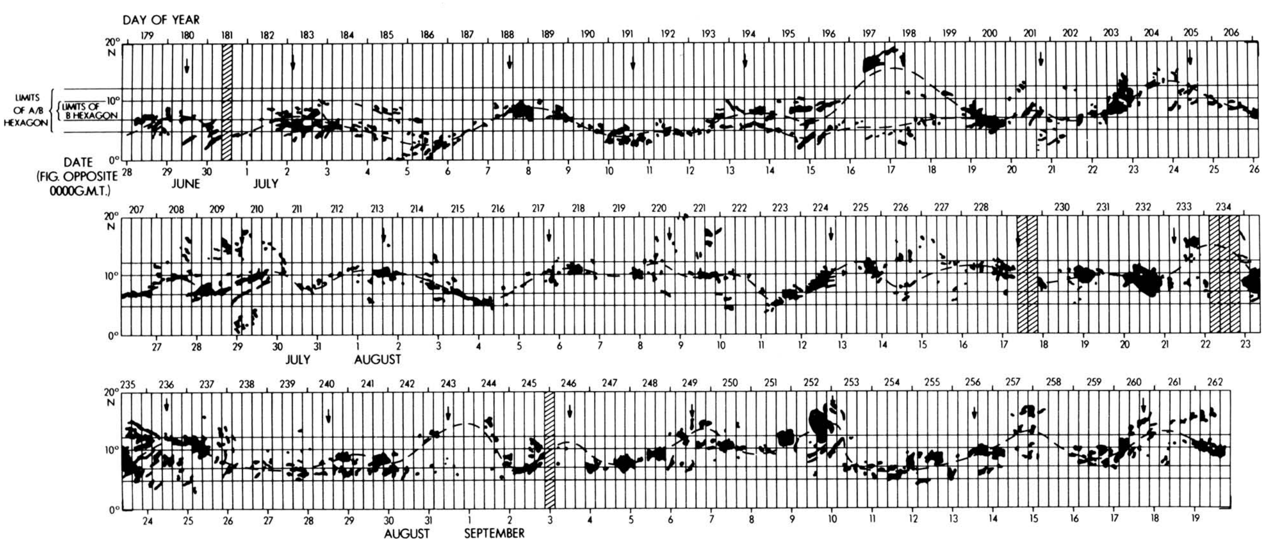

FIG. 9. Time section of deep convection over B-scale area at 23.5°W, based on infrared satellite images. Arrows indicate passage of 700 mb troughs of easterly waves. (After Burpee and Dugdale, 1975.)

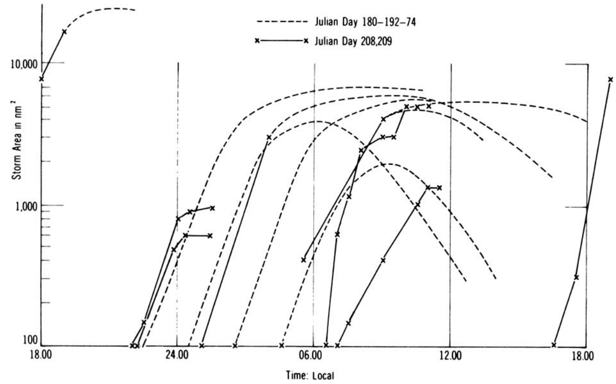

FIG. 10. Explosive growth of cloud clusters in GATE experiment area. The storm area is derived from infrared satellite images of cold cloud tops. (After Weickmann, 1975.)

ence could still be detected in the wind field at the equator and even south of it.

Severe aerosol outbreaks consisting mostly of Saharan dust took place several times during GATE. These dust outbreaks were generally confined to 10–25°N and were associated with the easterly waves. On occasion the dust reached as far west as 80°W. Their effects on the convective activity and the radiation budget are presently under study.

Most impressive—and upsetting to the flight mission planning—was the explosive development of the cloud clusters in and near the B-scale array, their typical areal growth rates at the cirrus level being of the order of 10^4 km^2/h (Weickmann, 1975) (see Fig. 10), and their life times usually under 24 h (Martin, 1975) (see Fig. 11). Their internal structure, often connected with intense C-scale convective bands, should become clear from the shipborne radar and multi-aircraft measurements.

While it was impossible to forecast the formation of an individual cloud cluster, the intensity of the convective activity over the B-area was surprisingly well predicted by the capable international forecasts team,[6] based on techniques developed during the field phase. During Phase I the intensity of convective activity in the B-area was related to the latitudinal position of the ITCZ and the positions of the troughs and ridges of the easterly waves. Twenty-four hour forecasts of convective activity thus required prediction of the latitude of maximum cloudiness associated with the ITCZ and the positions of the easterly waves. These forecasts were possible with the aid of the SMS-1 satellite pictures and the synoptic charts prepared in Dakar.

Six tropical cyclones formed in the North Atlantic during the experiment period. Four of these, two tropical storms (Alma and Elaine) and two hurricanes (Carmen and Fifi), formed in the GATE area and could be traced eastward to an origin in the eastern Atlantic or the African continent. Hurricane Fifi devastated Honduras.

In summary it can be said that not only the participating 70 nations, but nature itself must be given credit for its fine cooperation with GATE.

[6] Headed by Dr. R. Burpee.

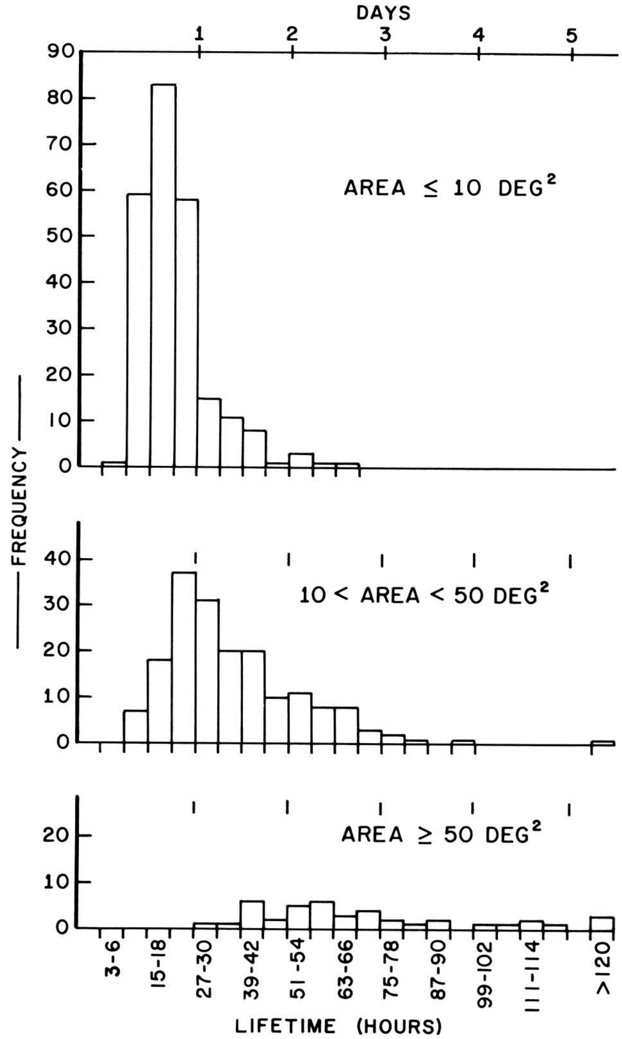

FIG. 11. Lifetime of cloud clusters as function of size. (After Martin, 1975.)

5. The scientific subprograms

As has been described in Article I, the total scientific program of GATE has been divided into five subprograms (synoptic, convection, boundary-layer, radiation, and oceanographic subprograms). The Central Program defining the high-priority scientific objectives, contains only a portion of each subprogram (see Fig. 2 of Article I), but it is this portion that will be addressed here. From our earlier discussion of the performance of the observing program it is clear that its shortcomings affect the various subprograms in different degrees. Since most of these shortcomings occurred in the A-scale observing network, the synoptic subprogram was more affected by them than others. We will first assess the subprogram individually and then, in Section 6, draw some preliminary conclusions as to the probable achievement of the primary scientific aims of the GATE, i.e., the Central Program. The specific scientific objectives of each subprogram have been described in Article I. Table 4 summarizes the objectives of the Central Program.

TABLE 4. GATE—Primary scientific objectives.

Description	Interaction	Parameterization	Tropical data set
Scale Phenomena: Tropical waves (A) Cloud clusters (B) I.T.C.Z. (A/B) Meso-systems (C) Cu-convection (D)	A: Synoptic scale B: Cloud cluster scale C: Mesoscale D: Cumulus scale Atm. boundary-layer Ocean. mixed layer	Moist convection Planetary boundary layer Radiation	Global models Limited area models

a. Synoptic-Scale Subprogram

The main events adversely affecting the Synoptic-Scale Subprogram in the field phase were the absence of two western Atlantic A-scale ships in Phase I; the marginal performance (in real-time) of the Omega and VLF wind soundings from certain A-scale ships; and the failure to receive certain upper-air sounding data from land stations in parts of Africa and South America. It is hoped that re-processing of GATE ship upper-air Omega and VLF data will improve the situation considerably. The upper-wind sounding coverage by the six A/B ships (which had radar windfinding) was excellent.

The Synoptic-Scale Subprogram benefitted immensely from coverage by SMS-1 geostationary satellite images and winds everywhere west of 15°E. Winds may yet be derived for three levels. The Omega windfinding dropsonde aircraft also proved to be of great value over the central and eastern Atlantic. A considerable amount of data from commercial ships and aircraft is expected to supplement the Synoptic-Scale Subprogram Final Data Set.

It is considered that satisfactory description of tropospheric and lower-stratospheric synoptic-scale disturbances from west Africa to the western Atlantic Ocean (first major objective) can be achieved except perhaps for the western Atlantic in Phase I.

Calculations of the mean atmospheric structure and dynamics on the A-scale, i.e., the basic state, should give reliable results except over western South America south of the equator, the Atlantic south of the equator, over some central parts of Africa, and east of 45°E, where reliability will be marginal. Similar considerations apply to A-scale interactions with the basic state.

Description of the synoptic-scale environment of B-scale cloud clusters in sufficient detail to allow A-B-scale interaction studies should be possible by virtue of the excellent coverage of A/B and B-scale ships. There may, however, be difficulties for Phase I because of data sparsity immediately east and southeast of the B-scale area and for Phases I and II in the west Atlantic.

Development of complete and internally consistent data sets for tropical numerical models, the fourth and final major objective (see Table 4), is not likely to be fully achieved because of the data gaps mentioned. However the SMS-1 winds will fill many of these gaps and, if all data are used, large-scale tropical modeling studies should profit, especially forecast-analysis models with good space and time interpolation schemes.

b. Convection Subprogram

Most observations planned to support the Convection Subprogram were accomplished. As mentioned earlier, the Omega and VLF windfinding systems on some of the B-scale and A-scale ships, which were new systems developed for GATE, did not work as well as the well-proven radar windfinding systems. Improvement in data quality is, however, expected from post-processing.

On the other hand, the data base for the study of A-B-scale interactions will be adequate because the

TABLE 5. Convection Subprogram: Aircraft mission summary.

Mission type	Objective	Planned maximum (minimum)		Flown	
		Missions	Sorties	Missions	Sorties
1A/1C1/3	Cluster budget study (Butterfly or box pattern)	13	71	13	65
1C2	Structure of convective bands (Line pattern)	4	12	6	30
1D	Sub-cluster mesoscale convection (Area pattern)	5	25	4	20
1B	Cluster life cycle	3	24	—	—
	(subtotal 1A–1B)	25 (23)	132 (115)	23	115
2	Boundary-layer ITCZ (to equator)	5 (5)	25 (22)	3	16
2B	ITCZ (Line or box pattern)	—	—	3	16
	(subtotal 2–2B)			6	32
Total (Basic GATE missions)		30 (28)	157 (137)	29	147
4	Vortex off Dakar	3 (2)	15 (10)	1	4
8	Cloud physics/rings	6 (3)	18 (6)	11	16
9C	Cluster life cycle (dropsonde)	8	8	1	1
	(subtotal 4–9C)	17 (13)	41 (24)	13	(21)
Total		47 (41)	198 (161)	42	168

Note: The maxima are based on 290 total sorties by long-range aircraft; the minima are based on 210 sorties (see GATE Report No. 11, Aanensen and Zipser, 1974). The actual number of sorties flown was 288.

A/B ships' radar wind soundings performed very well and the better A-ships were moved after Phase I to strategic positions nearer the B array (Figs. 1 and 2).

As regards the C-Scale, the weather radars on most B and C ships gave reliable coverage with few data gaps. These radars revealed the distinct mesoscale structure of precipitating cloud clusters, often in the form of bands oriented E-W or NE-SW. Also the aircraft program was remarkably successful (Table 5) despite the fact that the transience of B-scale area cloud clusters made aircraft mission planning and execution difficult. Many GATE aircraft missions successfully concentrated on the mesoscale sub-system of the cloud clusters which had appeared on the radar. Figures 12 and 13 give an example: A group of 6 long-range aircraft participated in this successful "basic GATE mission," in addition to other aircraft flying simultaneously a radiation, a squall-line, and an oceanographic mission over the eastern Atlantic and western Africa, typical of the daily flight activities in the third phase.

The special capabilities of the 5.7 cm radars on the Canadian ship *Quadra* and the U.S. ships *Oceanographer, Researcher,* and *Gillis* will be particularly valuable for the scientific analysis.

Thus it appears that the combined observing system of ships, satellites, radars, and aircraft has given a good data base for description of the B and C-scale phenomena and the study of B-C-scale interactions.

Although fewer 1/2-hourly soundings were obtained during Phase III than had been planned, sufficient detail appears to have been obtained from the radars and aircraft to enable studies of interactions between the D-scale and the larger scales. The boundary-layer pilot balloons and thermodynamic structure sondes in the C-scale area in Phase III will also have provided useful data for these aspects.

An overall assessment may be premature at this stage, but it seems that enough of the observational objectives were met to provide the data needed for the studies of convection and convective interactions over the eastern tropical Atlantic, which are themselves an essential step toward the improved parameterization of tropical convection. Considering the complexity of the experiment and its objectives, a preliminary assessment is that it was a remarkable success.

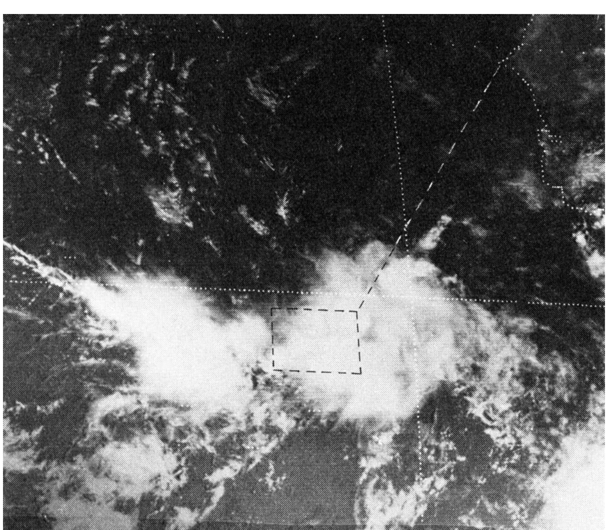

FIG. 12. Double cloud cluster over B-scale area on 5 September 1974 at 12:00Z. Explored by aircraft, ship radar and soundings. The aircraft track is marked.

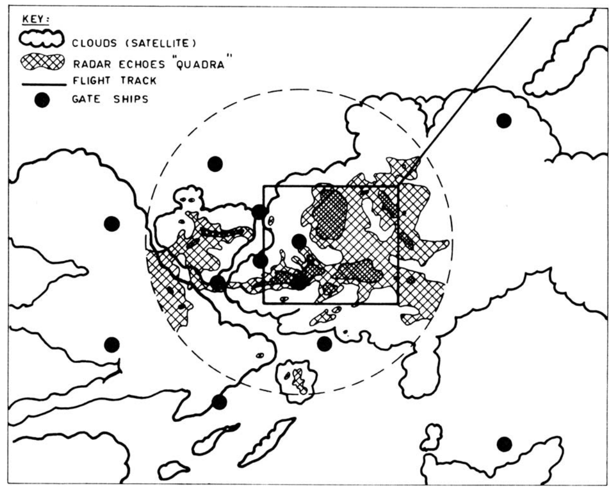

FIG. 13. Radar echoes in cloud cluster of 5 September 1974 at 12:00Z (Fig. 12) transmitted by the Canadian ship *Quadra* and received in real-time to determine the flight pattern of multi-aircraft mission. The main low-level inflow and high-level outflow area of the system were successfully "boxed-in."

c. Boundary-layer Subprogram

In the surface layer, the measurements of fluxes and profiles will enable determination of the flux-profile relationship and, thus, of the transfer coefficients for momentum, heat, and moisture under different conditions. In general, the validity of the bulk aerodynamic method for flux determination under a variety of atmospheric conditions can be tested with sufficient material. Most of these results can be extrapolated to other parts of the GATE area and used in budget computations.

The spectra computed from high and medium resolution fluctuation measurements on buoys and booms will cover a frequency range between 10 and about 3×10^{-6} Hz. We should therefore be able to define in a more objective way the scales of the atmosphere structure as a function of the convective conditions (showers, squallines, clusters, etc). The prevailing frequencies of the surface flow can thus be related to external parameters.

Surface pressure measurements will probably run into difficulties. From a quick look at the intercomparison data it appears that the absolute accuracy may not be acceptable. For the determination of pressure gradients and their rate of change with time, aircraft measurements by radio altimeter (in connection with pressure altimeter) will be of value but will be confined mainly to the B-scale area. This will be of importance to testing certain aspects of the CISK theory (e.g., Bates, 1973; Charney and Eliassen, 1964). The solution of the equatorial boundary-layer parameterization problem is in doubt because of the limited latitudinal range of the data.

Investigations of the upper layers of the boundary-layer (BL) will benefit from the large amount of information on the dynamic and thermodynamic structure gathered by tethered balloons, structure sondes, pibals, and aircraft.

It should be remarked that after early difficulties, as a result of which tethered balloons were lowered during aircraft missions, the coordination between low-flying aircraft and tethered balloons improved and by Phase III was virtually perfect so that the Phase III tethered-balloon data set, although somewhat biased towards undisturbed weather, is very substantial, and continues through periods of aircraft missions.

Vertical profiles of the fluxes of momentum, sensible heat, and water vapor have been measured on many occasions by aircraft gust probes and—in the third phase—by the special tethersonde of *Hecla*. The surrounding fields and profiles of mean quantities are available from ships and aircraft and can be related to the fluxes.

Divergence and vorticity can be computed on a variety of scales using tethersondes, pibal wind profiles, and aircraft data. Although the C-area Phase III pibals were only able to be launched every hour rather than every 30 min, the budgets of mass and energy can be derived and the concept of scale interaction through energy transfers from one scale to another be tested.

In summary, the Boundary-Layer Subprogram will meet the Central Program requirements. Despite certain data losses, models of the undisturbed boundary layer can be tested and improved models applicable to cloud cluster conditions can be developed. Input quantities to the other subprograms, e.g., mass and energy fluxes at cloud base, boundary layer convergence, etc., can be provided. In general a considerable step forward will have been taken in the parameterization of the BL and in the understanding of the physical processes of the BL in the presence of deep tropical convection.

d. Radiation Subprogram

The Radiation Subprogram was planned to rely on data from aircraft, ships, satellite, radiometersondes, and land stations.

Table 6 summarizes the aircraft missions devoted to the Radiation Subprogram. Additional radiation data were collected on other flight missions with different primary objectives. It may be seen that almost all the plans for radiation aircraft missions were accomplished or exceeded. This, together with the aircraft intercomparison flights, leads to the conclusion that the aircraft part of the Radiation Subprogram will give an excellent data set.

From the apparent high quality of the intercomparison data for the A/B and B ships one may expect the ship data set for this area to be adequate. The quantity is also known to be adequate. However the incompleteness during all phases of the A-scale ship array and uncertainty about the instrumentation of some of the vessels means that the hoped for data set on the whole A-scale will probably not be fully achieved. However this does not affect any of the fundamental objectives of the Radiation Subprogram.

Current indications are that the programs of all satellites except the Nimbus-F were met. The excellence of the SMS-1 satellite picture cover will permit the coordination of cloud field and radiation profile data throughout the experiment. It is planned to use post-GATE data of Nimbus-F to derive relationships with satellites operating during GATE, especially SMS-1, and to apply these relationships to GATE satellite data in order to improve the upper boundary values for radiation budget computations.

No firm assessment of the radiometersonde program can be made until the data are available. Encouragement may be taken from the general adherence to

TABLE 6. Radiation Subprogram: Aircraft mission summary.

Mission type	Objective	Planned maximum (minimum) based on 290 (210) total sorties by long-range meteorological research aircraft.		Flown	
		Missions	Sorties	Missions	Sorties
7A2	Horizontal "Snake" pattern with selected cloud fields	10 (7A2 and 7A3)	35 (7A2 and 7A3)	7 (7A2 and 7A3)	18 (7A2 and 7A3)
7A3	Line integral pattern with selected cloud fields				
7B1	Vertical "Serpentine", steady state weather mission	7 plus several part missions	7 plus several part missions	45 (7B1 and 7B2)	47.5 (7B1 and 7B2)
7B2	Constant inclination, dust mission	Several part missions	Several part missions		
7B1A	Vertical "Serpentine," dust mission	2	2	3	6
701	Intercomparison with satellite	2	2	1	1
702	Intercomparison with ships	Several part missions	Several part missions	3.5	5
703	Intercomparison with radiometersondes	2	2	1	1
Total		23 (14) + several partial missions	48 (27) + several partial missions	60.5	78.5

launch schedules and the achievement of some intercomparisons. Also nothing can be said yet about the radiation data that are expected from about 100 land stations in the GATE area. Regarding the radiative properties of aerosols, an excellent data set should become available from the Sahara dust studies made by aircraft, ships, land stations (Cape Verde), and satellites.

Despite the drawbacks with regard to the lack of Nimbus-F data and the sparsity of the A-scale ship network, the overall success of the radiation observing systems in GATE appears to have been better than most scientists expected. Indications are that all major Radiation Subprogram objectives regarding the acquisition of data have been met. In other words, the vertical profiles of radiative fluxes and heating rates under varying cloud and aerosol conditions will be sufficiently known to enable parameterization, and so will the net radiation and its components at the ocean surface in the B-scale area, in accordance with the scientific objectives of the subprogram.

e. Oceanographic Subprogram

The Oceanographic Subprogram was for convenience divided into two main parts: the study of the large-scale oceanic circulation, and the study of upper-layer processes. The former was subdivided into the description of the tropical current system and the equatorial experiment of Phase II, whereas the latter was split into the Phase III studies of upper-layer processes in the C-scale area, and mixed layer budget studies in the B-scale area. For details see Chapter 9 of GATE Report No. 16 (Philander, 1975).

The description of the tropical current system was somewhat affected by the absence of some A-scale ships in the western Atlantic, but these data losses were more than offset by the repeated sections of the *S. Dezhnev* and by additional soundings along the tracks of several other vessels.

On or near the equator all measurements went essentially according to plan, except that some current-measuring plans for moving ships had to be revised because of buoy problems. Most of the planned time-series of data from instrumented current buoys were obtained. The overall equatorial data set is unprecedented. The equatorial undercurrent as well as the surface currents above it were observed to meander about the equator. A wavelength of about 2600 km and a (westward) phase speed of 1.9 m/s are suggested by the data (Düing *et al.,* 1975). The sea surface temperature field is strongly modified by upwelling of the undercurrent.

The platforms used to measure upper layer processes in the C-scale area included aircraft, stationary and roving ships, and buoys moored to the ocean floor or tethered to ships. The distribution of ships and some of the oceanographic buoys are shown in Fig. 14. The surface wave program suffered slightly from the loss of some buoys but gained from airborne wave measurements.

Water masses drifting through the C-scale area were followed by roving ships using the "batfish" sounding system while aircraft mapped the corresponding sea-surface temperature fields. The simultaneous oceanographic and meteorological measurements should be adequate for a detailed study of mixed layer development. Some early results on the C (and B)-scale upper layer processes are included in GATE Report No. 14 (ISMG, 1975).

The interaction of the tropical ocean and atmosphere

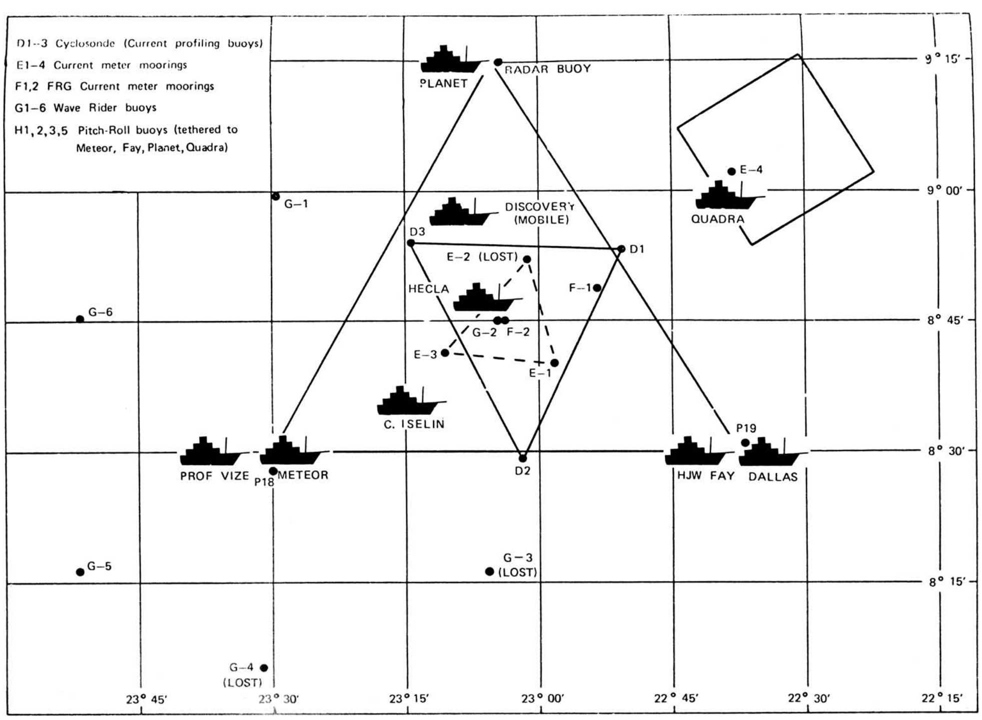

FIG. 14. C-scale ship and oceanographic buoy array during Phase III (30 August–19 September 1974).

—including dynamic atmospheric forcing and thermal oceanic forcing—will, for the first time, have a broad data base. In summary, it can be stated that the main objectives of the Oceanographic Subprogram will almost certainly be met.

6. The Central Program

The previous discussion leads to certain conclusions regarding the achievement of the primary objectives of GATE as defined in the Central Program (see Table 4 and GATE Report No. 3, Houghton, 1974). The achievement of the aims of the Central Program will accordingly be discussed here under the four main headings: "Description," "Interaction," "Parameterization" and "Tropical Data Set." For greater detail the reader is referred to GATE Report No. 16 (Kuettner and Long, 1975), Section 4.

a. Description of scale phenomena

It is considered that the GATE data are sufficient for describing synoptic-scale tropical waves and disturbances as planned, although there may be difficulties in the western Atlantic for Phase I.

Description of the A-scale basic state should be possible with sufficient accuracy except perhaps over western South America south of the equator, the Atlantic south of the equator, some central parts of Africa, and east of 45°E. Description of A-scale features of the ITCZ will be possible in the eastern Atlantic, as intended by the design of GATE. Description of B-scale facets of the ITCZ and of B-scale cloud clusters should be possible in considerable detail.

Except for the 1-1/2-hourly sounding data from B and A/B ships, the data acquired by ships, aircraft, radar, and satellite generally exceed expectations, so that descriptive studies of C- and D-scale moist convection will certainly be successful. The "description" of these scale phenomena comprises the characteristics of the planetary boundary layer under disturbed and undisturbed conditions, the radiation flux profiles under varying degrees of cloudiness, and the sea surface temperature and the density and current fields of the oceanic mixed layer.

We conclude that the GATE data are largely sufficient for the descriptive studies required by the GATE objectives.

b. Interaction of scale phenomena

The study of the interactions of the A- and B-scales is a key objective of GATE.

There appears to be no problem with A $\rightarrow$ B-scale interactions because their study only requires good data on the B-scale features and on the superimposed A-scale fields (which we have), while the contributions of the total GATE (A-scale) area are less vital. Studying the B $\rightarrow$ A-scale interaction will require monitoring the A-scale not only at the region of maximum B-scale input but also over a significant portion (in space and time) of the A-scale, i.e., at least for one or two synoptic-scale wavelengths. The data gaps over the western Atlantic in the first part of the field phase may therefore affect the B $\rightarrow$ A-scale interaction more than vice versa. However, for the latter part of GATE a complete study of the A $\leftrightarrows$ B scale interactions, i.e., control and feedback, should be possible.

This conclusion was reached by considering the budget equations for A-scale eddy kinetic energy, eddy available potential energy, and moisture averaged over the depth of the troposphere. It remains to be seen how comprehensively this can be done. The rearrangement of ships in Phases II and III served to improve the situation. Research into interactions between A-scale and the basic state should produce useful results but there will be data deficiencies in the areas mentioned above.

Study of interactions involving the ITCZ should be possible to the degree intended in the GATE plans, and we should learn more about the mechanisms involved in the formation of the ITCZ. For these latter studies careful use of surface pressure data may be needed. While reliable absolute values may not be obtainable, relative values (gradients) should be available, especially with the aid of pressure and radio altimeter data on board low-level GATE aircraft.

Finally, there is little doubt that a wealth of data will support studies of interactions between clusters (B-scale) and mesoscale convective features (C-scale), and between these C-scale features and cumulus-scale (D-scale) processes.

c. Parameterization

The aim to further the successful development of schemes for parameterization of moist convection in the tropics will almost certainly be fulfilled with the GATE data. In the light of the success of the Radiation Subprogram, the same is considered to hold for parameterization of radiation. There is also guarded optimism that the parameterization of the tropical boundary-layer under disturbed *and* undisturbed conditions polewards of about 5° latitude will be achieved or at least considerably advanced.

d. Tropical data set for numerical models

Although the total data set of GATE will exceed anything available from the tropics in the past, the lack of upper-air soundings over certain parts of the GATE land areas and the shortcomings in wind soundings over the western Atlantic will affect the value of the GATE data set to global models. Satellite cloud motion data west of 15°E could prove invaluable in filling some of these data gaps especially if they cover three levels, as can now be expected. GATE data should be especially useful to those global models applying four-dimensional assimilation schemes which make adequate use of data from previous times for data-sparse areas.

The above remarks on global models also apply to limited area and nested models, but the latter will have an extra benefit, in that the unprecedented data set from the eastern Atlantic ship array should provide a sound basis for parameterization studies, especially with nested fine mesh grids.

7. Data management

As originally planned (de La Moriniere, 1974), the data will flow from the National Processing Centers

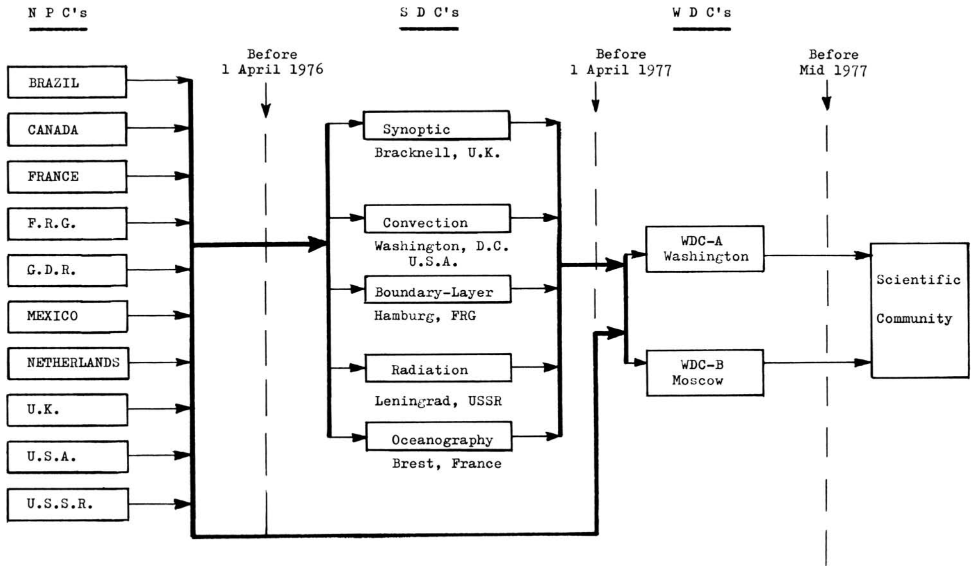

FIG. 15. Data flow of GATE Data Centers. NPC = National Processing Centers, SDC = (International) Subprogram Data Centers, WDC = World Data Centers.

(NPCs) in ten countries to the five international Subprogram Data Centers (SDCs) and the two World Data Centers (Fig. 15).

The NPCs are now involved in the processing and validation of their national data and are striving for delivery of all nationally validated data sets to the SDCs in agreed GATE format on magnetic tape by 31 March 1976. Most of the SDCs are prepared to accept the first NPC data and are developing the necessary software for quality control and international validation. The GATE Archives already contain some important preliminary data sets available to the scientific users and are continually increasing.

a. Data now available

Among the GATE data sets now available in the GATE Archives at World Data Centers (WDCs) A or B are the following:

a) preliminary data set (satellite, aircraft, ship data, etc.) from GOCC Dakar (microfilm);
b) special analysis products (A, B-scale analyses, cloud clusters analyses, etc.) from GOCC Dakar (35 mm microfilm);
c) quick-look synoptic data set from SSDC Bracknell (magnetic tape);
d) teleprinter paper-tape synoptic data set (surface, upper-air) from SSDC Bracknell (magnetic tape);
e) SMS-1 visible and IR satellite images (35 mm microfilm);
f) meteor (U.S.S.R.) satellite images (500 photos);
g) SMS-1 satellite "movie-loops" from GOCC Dakar (125 on microfilm);
h) radar photographs from *Oceanographer* (microfilm);
i) some ships and aircraft intercomparison data.

b. Availability of further data

The quality of data sets based on a great number of independent platforms and measuring systems depends entirely on good intercomparison tests. Ship intercomparisons took place nine times in different parts of the Atlantic before, during and after the field phase and involved up to 15 ships at a time. Aircraft intercomparisons among two to three planes flying in formation were made 14 times, in addition to 17 "fly-bys" at an instrumented and calibrated tower. It is these data that are needed first by the SDCs. Therefore, the first data products due to arrive from the NPCs were the intercomparison data. While some nations have delivered their data on time there is concern that others indicate schedule slippages of several months which may ultimately affect the date at which the final GATE data sets will become available. Action is being taken to find a solution to this problem.

Regarding the field phase data, it is planned that NPCs will make nationally validated data available to SDCs and WDCs according to the following schedule:

1) Phase II and Phase III data for "high priority days" before 31 October 1975.
2) Remaining national data before 31 March 1976.

It is anticipated (and hoped) that the internationally validated data sets from the SDCs will begin to become available in late 1976 with all planned products completed by 31 March 1977.

Two independent mechanisms will advertise GATE data as they become available. The first will be the published quarterly status reports on data management of the GARP Activities Office in WMO, Geneva. The second will be the GATE data catalogs prepared by the WDCs in Washington and Moscow.

8. Scientific analysis phase and future international plans

A very large number of papers giving preliminary scientific results of GATE has already been published [7] or presented at national or international scientific meet-

[7] See for example GATE Report No. 14 (ISMG, 1975), 2 volumes.

ings. We resist the temptation here to give typical samples of these results as the selection would have to be arbitrary and the data base is still largely unvalidated. An international GATE bibliography list will shortly be produced and will be updated periodically. It can be expected that many specialized papers, based on the investigator's own experiments, will be published in the near future, while the more comprehensive studies will have to await the internationally validated data sets.

The International Scientific and Management Group (ISMG), consisting of scientific, operational, and data experts from many countries was disbanded in April 1975 after 3 years of intensive work at Bracknell, U.K., Geneva, Switzerland, and Dakar, Senegal. Throughout this time its collaboration with the national project leaders (or GATE "Focal Points") in the participating countries has been close and harmonious. Many lessons [8] were learned which will be of value to future projects of this kind.

The responsibility for the data management and research phase has now been transferred to the GARP Activities Office (GAO) of WMO at Geneva. The GAO will monitor the data flow among the 17 data centers involved and will publish the progress of data processing in the forementioned quarterly status reports. It will act as international coordination point for all data problems and assist the International Subprogram Data Centers (SDCs) as needed.

On the research side the GAO will continue the existing close cooperation with the national focal points, the international scientific community, and the data centers, and will help to solve their problems. It will monitor the progress of scientific analysis with a view towards the achievement of the primary objectives of GATE. GAO will publish bibliography lists, plan scientific seminars, workshops, and symposia; and report the latest developments in the *GARP Newsletter*.

The scientific analysis phase will be closely followed by JOC through its Panel on the Tropical Subprogram. Furthermore, the Tropical Experiment Board (TEB), representing the governments of the participating nations, will continue its function for the time being to ensure that the necessary resources are available to bring the data management and research phase of GATE to a successful conclusion. Eventually a comprehensive report on the results of GATE will be compiled.

9. Conclusion

To many, the field phase of GATE was a surprising experience. Although carefully prepared and planned, there had been no possibility for a prior full-scale test, and there was no certainty that a field project of this magnitude and complexity could succeed.

The extraordinary effort by the participants and the prevailing atmosphere of good will gave the joint research work the chance to succeed. In our best judgment it did and we estimate that at least 80% of the scientific objectives of GATE will be achieved, if the data processing and scientific analysis phases proceed with the same vigor and thoroughness as the field phase. It can therefore be expected that the tropical phenomena of all scales will be described in great detail, especially the tropical cloud clusters; that the interaction among the scale phenomena will be sufficiently understood to arrive at more realistic schemes for parameterizing moist convection on subsynoptic scales, as well as boundary-layer and radiation processes in the tropics; and finally that the unprecedented amount of data from the equatorial belt—in spite of its limitations—will lead to a marked advance in tropical modeling. The preliminary scientific output of GATE is already impressive.

This alone, however, does not justify our guarded optimism with respect to future GARP projects, their aims and technology not being directly comparable with GATE. What makes us hopeful is the experience that, in a carefully designed experiment, scientific teams from many countries, bringing along a multitude of technical systems, speaking many different languages, having different scientific or political outlooks and varying national priorities, can—if they set their minds to it—successfully execute a highly complex observing program.

[8] Some are listed in Chapter 6 of GATE Report No. 15 (Tarbeev *et al.*, 1975) and Chapter 13 of GATE Report No. 16 (Kuettner and Long, 1975).

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The GATE Aircraft Program: A Personal View

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1. General comments

The outstanding feature of the GATE Experiment, in my opinion, was its success. The success exceeded my own and most scientists' anticipations.

The field phase of GATE, I believe, more than achieved its goals, and went beyond expectations in the performance of data systems, the cooperation and dedication of the diverse people, groups, and nations involved, and in the operation itself. More multi-aircraft missions were obtained, with apparently good data, than could reasonably have been anticipated. Furthermore, missions were well distributed among the pre-determined programs and objectives.

2. Hypothesized reasons for success

The reasons for the success of the GATE field phase were, I believe, as follows:

A. People—Enormous devotion and hard work of nearly everyone involved. High level of competence. Relative absence of visitors, operators, arm wavers, and boondogglers. Young and old complemented and stimulated each other. Famous scientists and graduate students together sweated 18–20 hour mosquito-infested days, broiled and froze on aircraft, wielded screwdrivers, tephigrams, calculators, typewriters, xeroxes, and performed good old manual labor, which no one fancied himself or herself too good to do, since it had to be done.

B. Advance planning and rehearsals. These paid off in providing clear-cut goals, priorities, plans for flight patterns and communications and, most of all, pre-acquaintance and teamwork among key participants.

C. Considerable on-site analysis and evaluation of data on all scales. Among the outstanding examples were: analysis relating convection code to dynamic variables; studies of African squall lines; documentation of diurnal convection cycles in the B-array; work on aircraft data and dropwindsonde data in the reconnaissance of several evolving and non-evolving Dakar disturbances.

D. Just plain good luck. Never in 30 years have I seen so many untried systems work on their first major field program. Noteworthy were the NOAA AWRS system and the NCAR dropwindsonde, which I believe may revolutionize some important aspects of meteorology if adequately exploited. In Phase 1, difficulties were experienced with the shipboard Beukers omegasonde windfinding equipment. By the end of Phase 3, however, a few intercomparisons suggested that at least some of these systems may have produced some reliable or at least correctable data.

3. Ship-aircraft relationships

By the time of Phase 3, I believe that ship-to-aircraft communications and cooperation had had the major bugs removed and were working very well. The ship reports were vital in both the pre-flight and in-flight aircraft mission planning. Furthermore, I believe the ships worked with better efficiency and morale when informed of what the aircraft were doing. The horrendous air traffic problems posed by the ship balloons were handled well, with compromises on both sides, with minimal requests to keep ship balloons down because of aircraft tracks. The reports of the vessel *Dallas* to the aircraft team at the beginning of and during missions concerning the boundary layer structure were particularly valuable to the Airborne Mission Scientists in setting flight altitudes.

4. Cooperation among scientists

I was amazed and delighted at the spirit of cooperation and exchange between groups and individuals of all organizations and nations. The less fortunate aspects of competitive spirit and abrasive interactions were minimal. Although sheer exhaustion and illness led to occasional temper flare-ups (including my own), the cause of these was generally recognized with toleration. Good feelings were soon restored, so that overall stimulating and friendly exchanges prevailed between scientists at nearly all times.

5. SMS-GOES satellite imagery—its value and limitations

The GOES satellite imagery was beautiful. The IR and visible pictures were essential to and superbly used in the weather forecasts, overall mission selection, and general planning. The satellite imagery was at its best in following ITCZ developments, in tracking Dakar waves and vortices, and also in following African squall lines.

Even the one-half mile resolution, however, failed to identify most active oceanic mesoscale cloud lines in their growing phases. Many convective systems were not recognized until the dying stages, when cirrus anvils predominated. Enhanced products (e.g., by densitometer) would have greatly helped in the field and will greatly aid in the analysis—if they are not so costly as to be unavailable to those of us working on the data.

One of the major lessons learned in GATE was the limitation of even the best current satellites to identify the early stages of active convection, particularly when short-lived and not organized into persistent systems larger than mesoscale. When many systems became recognizable as so-called "cloud clusters" on the GOES imagery, they in reality consisted only of orphan anvils and dead remnants of earlier convection.

A fact which I suspected before GATE and have now properly documented is that the term "cloud cluster" is unfortunate and should be abandoned. The reason is that it not only says nothing meaningful about the convection, but in fact often gives misleading information regarding the dynamics, physics, organization, and large-scale impact of the convective processes. Only once on my 13 missions in Phase 3 did I see anything resembling a proper "cloud cluster" and then I doubt that this real "cloud cluster" of clouds would have been detected on the satellite prior to its dying stages, if then.

Virtually all convection that I and the other Airborne Mission Scientists investigated and/or saw were *cloud lines*. The isolated penetrative cumulus or cumulonimbus was almost but not quite as rare as the bona-fide "cloud cluster." The point that the term "cloud cluster" is not meaningful, at least in the GATE area, has been made by several other GATE scientists.

Another vitally important limitation in satellite deductions, which can be turned around with further research into important revelations regarding the tropical atmosphere, was the frequent lack of relationship between spirals or rings of penetrative towers and corresponding closed circulations in the wind field. On numerous occasions, satellite stills and/or loops showed cloud features suggesting a closed circulation, which either did not exist in the wind field, or existed at a remote distance from the cloud "center" in a place where it never could have been located by any type of cloud imagery, from satellite, through radar, visual photography or eyeball. This observation does *not* imply a lack of relationship between wind convergence and penetrative convection, which should be a primary subject of study with the GATE data.

6. Radar in relation to mission planning and analysis

The performance of the ships' radars was unexpectedly fine. The reports from those ships which were regularly made available at GOCC (in Phase 3 primarily from the *Quadra* and the *Oceanographer*) were vital aids in mission planning, from 0400 hours when the scientists arrived at GOCC to the final establishment in the air of pattern coordinates, usually at about 1200 hours. The airborne radar on the NOAA C-130 was invaluable in the final decision process on days when missions involving convection were flown.

When acting as Airborne Mission Scientist, I personally used radar (mainly *Quadra* and NOAA C-130) and eyeballs entirely to set my patterns. On each of the occasions that we had a good lively convective day, my Mission Scientist radioed from GOCC that his satellite imagery told him that we were boxing around nothing (!), while I was seeing a beautiful line of building cb's from my aircraft. In each case, when the *Quadra* radar facsimile became available to him, he reported back that we were indeed flying in exactly the right place!

7. Scientific highlights and puzzles

The GATE data will surely provide a gold mine for the study of an atypical tropical region, which has received very little previous investigation. Ingenious investigations with these data may shed light on processes in other parts of the tropics, in part by revealing and explaining differences, as in a nature-performed experiment. However, great caution must be used in extrapolating GATE results to any other part of the tropics.

My pre-GATE contention that the GATE area is almost a "freak" region of the tropics is stronger than ever as a result of my participation. The GATE region differs from the central and western Atlantic and Pacific tropics in the following main ways:

A. Intense latitudinal gradients in both ocean and atmosphere, with a strong oceanic temperature decrease poleward and a very large increase in atmospheric static stability, particularly from about 850–400 mb.

B. The abrupt transition from continental Africa to ocean, resulting in systems in transition, many dying out and others rapidly changing their structure and dynamics.

C. The impact of African disturbances (on the synoptic scale: Dakar waves and vortices. On the mesoscale: squall lines) and *African dust,* which will prove to be a much greater factor than most everyone expected.

D. The abrupt vertical transition between lower monsoon and overlying drier continental air.

E. Much greater static stability than "mean tropical" in mid-troposphere.

F. Predominance of layer-type clouds, irregular cumulus bases, "incoherent" cumuli with poor bottoms, which die from the bottom upward.

G. Unexpectedly strong ocean currents and associated sea temperature gradients.

8. Probable impact of the GATE area meteorological oddities upon analysis objectives

Firstly, I suspect that the CISK concept will be found inapplicable in the GATE area, particularly with regard to "Dakar waves" after they leave the continent. Our dropwindsonde results suggest that the inflow and "action" in these disturbances were in the mid-troposphere and that the lower layers (often mistakenly called the "boundary layer") were apparently inert. The CISK concept may prove more viable in the ITCZ region of the B-array. Findings from this array, however, will not tell us much about disturbances and their development, but only about the extreme eastern tail of the ITCZ—possibly applicable to the corresponding zone in the Eastern Pacific. I am not at all confident that this circulation feature plays any key role in global dynamics, although I shall be happy to be proved wrong on this point.

I would also be highly suspicious of generalizing to the global tropics any parameterization schemes which may be developed and tested in the GATE area. I suspect that there may be as many as 4–5 types of tropical regions which must be differently treated: e.g., Atlantic (eastern and western); Pacific (eastern and western); and continents. Convection operates differently and so do disturbances between these regions, and hence it is hard to imagine that any one simple parameterization scheme will catch the essential energy transactions and large-scale impacts of all of them, although it may eventually be possible to isolate those features that cause the differences and feed these into models via a hierarchy of parameterization schemes.

Finally, I believe that cumulus modelers may be in for rough going in their attempts to simulate the GATE cumuli. The cumuli in the GATE area were more transient than those in Florida or the Caribbean, had poor, uneven and variable bottoms, and frequently cumulus bases existed at four or more levels. "Hot towers" originating at the altocumulus level were not uncommon! It would appear that "entity" models may be useless as may be any isolated cloud model, of the one, two or three dimensional variety. At the present time I believe that the most promising model avenues for the GATE cumuli be in either 1) the field of motion multicloud model of the type developed by Hill (1974), or 2) adaptations of Pielke-type (1974) mesoscale models introducing phase changes and key cloud processes, perhaps highly parameterized.

9. Support and management

A. Forecasts: The forecasts for convection in the B-array made in Phase 3 were the best job of tropical forecasting (omitting severe disturbances) that I have ever had the pleasure to observe. I still cannot decide whether remarkable new skills and tools were responsible, whether the GATE area may be not quite as difficult to forecast as the Caribbean and/or Florida, or what role luck may have played, if any. In any case, the forecasts were both terrific and well communicated.

B. GOCC Operations and Traffic Control: A good job was done. Many scientists felt from time-to-time that the rulebook was too rigidly applied. My view is that with so many aircraft not used to working together and in the midst of ship balloons, as much flexibility was usually allowed as common sense dictated.

C. Aircraft Crews and Maintenance: Excellent.

D. Management: Excellent. A difficult job well handled. Somehow I did not get the impression as I have in smaller examples of "big science" that politics was dominating nor that there were too many cooks in the kitchen. If all "big science" went like the field phase of GATE, most of us would find our reservations about it greatly allayed. The final test will lie in the follow-up and availability of GATE data, discussed in Section 10.

E. Services: Supporting services were sometimes less than adequate. Demands for transportation, clerical support, and technical assistance often overtaxed the available resources. I believe that planning for future field programs should place greater weight on these essential support functions.

10. Conclusion, outlook and major concern

On the whole, the plusses in GATE exceeded the minuses by an order of magnitude. Virtually everything was done either well, or the best it could be under the circumstances. Dozens of groups dedicated themselves unselfishlessly to the achievement of the GATE goals. These goals were, in fact, more than achieved in the field phase.

Whether or not the GATE program really achieves its goals and contributes its potential to meteorology now depends upon the data analysis, which will require large funding, cooperation and dedication, over at least the next five years.

Unfortunately, my experience has been that where most field experiments fail is in their follow-up, namely analysis and publication. The fault in the past has lain with both management, who finds other pressures on funds, and scientists, who find more glamour in running out to the field again, than in gluing their bottoms to a desk chair to carry through the painful and laborious scrutiny, corrections, analysis, reanalysis of data.

In GATE I have still another concern. How are younger, less known, less well-funded meteorologists going to obtain access to the data? Satellite and radar imagery is costly to copy, as are cloud pictures.

How is distribution going to be provided? How is a balance going to be maintained between giving some data rights to those whose ingenuity, dedication, and suffering obtained particular parts of the data and accessibility to the general meteorological public who paid for them in many ways? How is the problem of premature publication of half-baked papers generalizing from fragments of the data to be avoided?

In my opinion, the last question is less important than the first—the main task is for management to fund the data distribution and analysis and for participants and non-participants alike to get to work on them. I do not believe that anyone or any group should "own" any data and that any GATE data must be supplied to anyone on request, requiring at most the cost of duplication. Clearly an honor system must be tried to deal with the possibility of some persons running into print with someone else's data. Alternatively, a review board may have to be established for all publications based on GATE data.

A special effort should be made to disseminate the GATE data throughout the university community and not to confine most of the analysis to government laboratories or to a few well-funded university groups. My experience has been that proper field program analysis requires 5–10 times the financial expenditures as the actual operation and 25–50 times the time expended. The expenditure in money cannot be reduced much, but can be minimized, and the benefits for the future maximized as more students become involved per senior employee. The actual time duration of the analysis can be greatly reduced by wide dissemination of data so that very many people will be motivated to work on them.

Finally, I believe the GATE data, if followed up and analyzed properly, should advance tropical meteorology by a quantum jump, despite the "oddity" of the region studied. If tropical meteorology is advanced by a quantum jump, global meteorology should move forward by a significant amount.

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