As this article is being written the first ships are leaving their ports for the Atlantic. Therefore, pending unforeseen events, the international plans for GATE are by necessity final. In this report the scientific plans and the experiment design are briefly described. The operational and data management plans may be described at a later time.

Details of all international plans are contained in the GATE Report Series of the WMO-ICSU GARP publications. The following GATE Reports have been published by the International Scientific and Management Group for GATE (ISMG):

**GATE REPORTS**

No. 1 Experiment Design Proposal, 1972 (Kuettner *et al.*)
No. 2 Pre-GATE Tests and Studies, 1974 (Petrosians *et al.*)
No. 3 The Central Programme, 1974 (Houghton)
No. 4 The Radiation Subprogramme, 1973 (Kraus)
No. 5 The Boundary-Layer Subprogramme, 1973 (Hoeber)
No. 6 The Synoptic-Scale Subprogramme, 1974 (Houghton and Parker)
No. 7 The Convection Subprogramme, 1974 (Rodenhuis and Betts)
No. 8 The Oceanographic Subprogramme, 1974 (Philander *et al.*)
No. 9 International Operations Plan, 1974 (Long *et al.*)
No. 10 Ship Operations, 1974 (Tarbeev and Petersen)
No. 11 Aircraft Plan, 1974 (Aanensen and Zipser)
No. 12 Telecommunications, 1974 (Weiss *et al.*)
No. 13 Data Management Plan, 1974 (de la Moriniere)

After the conclusion of the GATE field phase a comprehensive report will be given on the field operations and related events.

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1 Copies may be obtained from the Secretariat of WMO at Geneva.

### Contents

- General description and central program of GATE, J. P. Kuettner .......... 712
- The synoptic-scale subprogram, D. E. Parker ......................... 720
- The convection subprogram, D. R. Rodenhuis ............................ 724
- The boundary-layer subprogram for GATE, H. Hoeber .................... 731
- The radiation subprogram of GATE, H. Kraus ............................. 734
- The oceanographic subprogram of GATE, S. G. H. Philander .............. 738
1. Introduction

The GARP Atlantic Tropical Experiment (GATE)—long planned by the international scientific community—will begin on 15 June 1974 and last about 100 days. The experimental area centered over the tropical Atlantic is shown in Fig. 1. There will be three observing periods of three weeks each (Table 1).

The final plans for GATE follow closely the original "Experiment Design Proposal" (Kuettner, Rider, Sitnikov, 1972) approved by the Joint Organizing Committee for GARP (JOC) and the Tropical Experiment Board (TEB). In this connection, it may be recalled that plans for an international Tropical Experiment (originally to have been located in the Pacific) go back to 1966 when the second meeting of the ICSU/IUGG Committee of Atmospheric Sciences was held at Geneva.

From the very beginning it has been clear that the resources required for this project exceed those available to any single nation. For a while there has been some doubt whether or not the "critical mass" for a meaningful experiment would be reached. However, the response of the participating nations inside and outside the GATE area (about 70 countries, Table 2) has been such that the necessary platforms and land stations are now assured. Approximately 40 ships and 13 aircraft will be available (Tables 3 and 4). Of the latter, 11 will have the required long range of 4,000 km or more.

The upper-air sounding network over the GATE land area will be nearly tripled during GATE over that available in 1973. This has been accomplished by acceleration and augmentation of the World Weather Watch through an extraordinary effort of the countries concerned, in cooperation with WMO and the nations supporting the Voluntary Assistance Program (VAP). The Global Telecommunication System (GTS) is likewise being up-graded in the GATE area, however not all upper-air soundings can be expected to be available in real-time.

2. The scientific program of GATE

(Central Program and Subprograms)

The design of a complex field experiment such as GATE is essentially the process of condensing its general scientific aims into specific objectives and to translate them into a detailed observing program.

In order to utilize the available scientific resources efficiently it is important to focus the effort on the specific objectives and to keep priorities fixed. The danger in planning this type of experiment is to try to solve too many problems at once. As more and more platforms become available there is a natural tendency to ex-

---

### Table 1. GATE operations schedule.

<table>
<thead>
<tr>
<th>Consecutive days</th>
<th>Dates (1974)</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–9</td>
<td>17 June to 25 June</td>
<td>In port, stand-down, en route, intercomparisons (Observation Phase I) (21 days)</td>
</tr>
<tr>
<td>10–30</td>
<td>26 June to 16 July</td>
<td>In port, stand-down, en route, intercomparisons (Observation Phase II) (21 days)</td>
</tr>
<tr>
<td>31–41</td>
<td>17 July to 27 July</td>
<td>In port, stand-down, en route, intercomparisons (Observation Phase III) (21 days)</td>
</tr>
<tr>
<td>42–52</td>
<td>28 July to 17 August</td>
<td>In port, stand-down, en route, intercomparisons (Observation Phase III) (21 days)</td>
</tr>
<tr>
<td>63–74</td>
<td>18 August to 29 August</td>
<td>In port, stand-down, en route, intercomparisons (Observation Phase III) (21 days)</td>
</tr>
<tr>
<td>75–95</td>
<td>30 August to 19 September</td>
<td>In port, stand-down, en route, intercomparisons (Observation Phase III) (21 days)</td>
</tr>
<tr>
<td>96–99</td>
<td>20 September to 23 September</td>
<td>In port, stand-down, en route, intercomparisons (Observation Phase III) (21 days)</td>
</tr>
</tbody>
</table>

Note: There will be so-called "intensive periods" during Observation Phases 1, II and III in which the rate of data collection is increased.

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### Table 2. States and territories participating in GATE

<table>
<thead>
<tr>
<th>Members of Tropical Experiment Council</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Algeria</td>
</tr>
<tr>
<td>2. Barbados</td>
</tr>
<tr>
<td>4. Brazil*</td>
</tr>
<tr>
<td>5. Burundi</td>
</tr>
<tr>
<td>6. Cameroon, United Republic of</td>
</tr>
<tr>
<td>7. Canada*</td>
</tr>
<tr>
<td>8. Central African Republic</td>
</tr>
<tr>
<td>9. Chad</td>
</tr>
<tr>
<td>10. Colombia</td>
</tr>
<tr>
<td>11. Congo</td>
</tr>
<tr>
<td>13. Cuba</td>
</tr>
<tr>
<td>14. Dahomey</td>
</tr>
<tr>
<td>15. Democratic Yemen</td>
</tr>
<tr>
<td>17. Ecuador</td>
</tr>
<tr>
<td>18. Egypt, Arab Republic of</td>
</tr>
<tr>
<td>19. El Salvador</td>
</tr>
<tr>
<td>20. Equatorial Guinea</td>
</tr>
<tr>
<td>21. Ethiopia</td>
</tr>
<tr>
<td>22. Finland*</td>
</tr>
<tr>
<td>23. France*</td>
</tr>
<tr>
<td>24. French Polynesia**</td>
</tr>
<tr>
<td>25. Gabon</td>
</tr>
<tr>
<td>27. Germany, Democratic Republic*</td>
</tr>
<tr>
<td>29. Ghana</td>
</tr>
<tr>
<td>30. Guatemala</td>
</tr>
<tr>
<td>32. Guyana</td>
</tr>
<tr>
<td>33. Haiti</td>
</tr>
<tr>
<td>34. Honduras</td>
</tr>
<tr>
<td>35. Indonesia**</td>
</tr>
<tr>
<td>36. Ivory Coast</td>
</tr>
</tbody>
</table>

* Members of Tropical Experiment Board.
** Special equatorial observations outside GATE area.
Fig. 1. Ship and land observing network during GATE. Note: the ship distribution changes slightly from phase to phase.
For the 17 ships of the East Atlantic Arm refer to Fig. 6.
### Table 3.
GATE ship participation.

<table>
<thead>
<tr>
<th>Country</th>
<th>Name</th>
<th>Full time (F)</th>
<th>Part time (P)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Brazil</td>
<td>Sirius</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Brazil</td>
<td>Alv. Saldaña</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Canada</td>
<td>Quadra</td>
<td>F</td>
<td></td>
<td>5.7-cm radar</td>
</tr>
<tr>
<td>4. France</td>
<td>Mar. du France</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. France</td>
<td>Bidassoa</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. France</td>
<td>Capricorne</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. France</td>
<td>Charcot</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. F.R.G.</td>
<td>Meteor</td>
<td>F</td>
<td></td>
<td>3.2-cm radar</td>
</tr>
<tr>
<td>9. F.R.G.</td>
<td>Planet</td>
<td>P</td>
<td></td>
<td>3.2-cm radar</td>
</tr>
<tr>
<td>10. F.R.G.</td>
<td>Anton Dohrn</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. G.D.R.</td>
<td>Alex. Von Humboldi</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12. Mexico</td>
<td>Marianao Mutilanos</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13. Netherlands</td>
<td>Ovsersagd</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14. U.K.</td>
<td>Charterer</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15. U.K.</td>
<td>Endurer</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16. U.K.</td>
<td>Heda</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17. U.K.</td>
<td>Discovery</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18. U.S.A.</td>
<td>Oceanographer</td>
<td>F</td>
<td></td>
<td>5.7-cm radar</td>
</tr>
<tr>
<td>19. U.S.A.</td>
<td>Researcher</td>
<td>F</td>
<td></td>
<td>5.7-cm radar</td>
</tr>
<tr>
<td>20. U.S.A.</td>
<td>Gilizt</td>
<td>F</td>
<td></td>
<td>5.7-cm radar</td>
</tr>
<tr>
<td>21. U.S.A.</td>
<td>Gyre</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22. U.S.A.</td>
<td>Dallas</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23. U.S.A.</td>
<td>Vanguard**</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24. U.S.A.</td>
<td>Col. Iselin</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25. U.S.A.</td>
<td>Atlantis II</td>
<td>P</td>
<td></td>
<td>3.2-cm radar</td>
</tr>
<tr>
<td>26. U.S.A.</td>
<td>Trident</td>
<td>P</td>
<td></td>
<td>3.2-cm radar</td>
</tr>
<tr>
<td>27. U.S.S.R.</td>
<td>Prof. Vise</td>
<td>F</td>
<td></td>
<td>3.2-cm radar</td>
</tr>
<tr>
<td>28. U.S.S.R.</td>
<td>Prof. Zibov</td>
<td>F</td>
<td></td>
<td>3.2-cm radar</td>
</tr>
<tr>
<td>31. U.S.S.R.</td>
<td>Passat</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32. U.S.S.R.</td>
<td>Ernst Kronkel</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33. U.S.S.R.</td>
<td>Osum</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34. U.S.S.R.</td>
<td>Voluta</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35. U.S.S.R.</td>
<td>Priboy</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36. U.S.S.R.</td>
<td>Porya</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37. U.S.S.R.</td>
<td>Musson</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38. U.S.S.R.</td>
<td>M. Lomonovov</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>39. U.S.S.R.</td>
<td>Stamen Desimov</td>
<td>F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40. U.S.S.R.</td>
<td>Akad. Vernadsky**</td>
<td>P</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Primary use for oceanography.
** Ships conditionally available.

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### Table 4. GATE aircraft participation.

<table>
<thead>
<tr>
<th>Country</th>
<th>Type</th>
<th>Prop</th>
<th>Turbo Prop</th>
<th>Jet</th>
<th>Special Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Brazil</td>
<td>C-130E</td>
<td>x</td>
<td></td>
<td></td>
<td>Dropsonde</td>
</tr>
<tr>
<td>2. France</td>
<td>DC-7</td>
<td>x</td>
<td></td>
<td></td>
<td>Inert. platform</td>
</tr>
<tr>
<td>3. U.K.</td>
<td>C-130</td>
<td>x</td>
<td>Inert. platform</td>
<td></td>
<td>Dropsonde</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Inert. platform</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. U.S.A.</td>
<td>CV-990</td>
<td>x</td>
<td>Inert. platform</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. U.S.A.</td>
<td>WC-130B</td>
<td>x</td>
<td>Inert. platform</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. U.S.A.</td>
<td>Electro</td>
<td>x</td>
<td>Inert. platform</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. U.S.A.</td>
<td>RP-3A</td>
<td>x</td>
<td>Inert. platform</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. U.S.A.</td>
<td>DC-6</td>
<td></td>
<td>Inert. platform</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. U.S.A.</td>
<td>KC-135A</td>
<td>x</td>
<td>Inert. platform</td>
<td></td>
<td>Wind dropsondes</td>
</tr>
<tr>
<td>10. U.S.S.R.</td>
<td>IL-18</td>
<td></td>
<td>Inert. platform</td>
<td></td>
<td>Radiations</td>
</tr>
<tr>
<td>11. U.S.S.R.</td>
<td>IL-18</td>
<td></td>
<td>Inert. platform</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Primary use for Radiation Subprogram.

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Fig. 2. Scientific organization of the Central Program and the Subprograms.

The magnitude of the scientific program made it necessary to break it down into subprograms. For practical reasons the entities are selected according to major disciplines involved in the GATE observing program. Their contribution to the Central Program will become clear in the following sections. They are: The Synoptic-Scale Subprogram; The Convection Subprogram; The Boundary-Layer Subprogram; The Radiation Subprogram; The Oceanographic Subprogram. These and the Central Program are available as GATE Reports Nos. 8–8 (1973/4).

Figure 2 illustrates their organization and indicates that each subprogram is not only “horizontally” divided into the three aforementioned priority classes (rings) but also “vertically” into four main sections (layers) dealing with the scientific objectives, the experiment design, the data management, and the research participation. The possibility that these subprograms may diverge as a re-

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sult of their own vitality is generally averted by the existence of the Central Program which holds the subprograms together and ensures that the significant interrelationships are not neglected. It is felt that, due to this and the close cooperation among the subprogram scientists in the International Scientific and Management Group (ISMG), the cake depicted in Fig. 2 will be as cohesive and tasty as it looks.

The difficult task of defining the Central Program in detail was undertaken by D. D. Houghton during the year he spent with the ISMG. The brief description in this article follows generally his approach (Houghton, 1974).

3. The Central Program
(Scientific Objectives and Experiment Design)

In the most general terms the aim of GATE is to explore the mechanism by which the solar heat stored in the tropical oceans drives the global circulation of the atmosphere and to incorporate this mechanism into numerical models.

The Central Program states the primary objectives as follows:

1) To estimate the effects of smaller-scale tropical weather systems on the large-scale circulations;
2) To advance the development of numerical modeling and prediction methods.

It can immediately be seen that the first objective comprises studies of "scale interaction" and "parameterization." These have to be based on an adequate description of the tropical phenomena existing on various scales ("scale phenomena") and of the basic state in which they are embedded.

It is also obvious that the second general objective can be achieved by providing a good tropical data set and by an advance in the aforementioned parameterization techniques.

Figure 3 illustrates this scheme. The heavy arrows indicate the order in which the scientific work may logically proceed and contribute to the GARP objectives.

a. Scales and related tropical phenomena

Four scales are conveniently used in GATE. They are listed in Table 5.

The largest scale, the A-scale (10⁶ to 10⁸ km), incorporates the synoptic and planetary scales. According to what is known at this time it covers the following tropical features: 1) the westward moving waves of short wavelength (1500-4000 km) in the lower troposphere —called here for simplicity "easterly waves"; 2) the likewise westward but faster moving waves of large wave-

* Essentially identical with Riehl's (1954) "Waves in the Easterlies," but not necessarily having all the characteristics described by him.

<table>
<thead>
<tr>
<th>Scale</th>
<th>From (km)</th>
<th>To (km)</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10⁶</td>
<td>10⁸</td>
<td>Wave scale</td>
</tr>
<tr>
<td>B</td>
<td>10⁶</td>
<td>10⁴</td>
<td>Cloud-cluster scale</td>
</tr>
<tr>
<td>C</td>
<td>10</td>
<td>10⁴</td>
<td>Mesoscale</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>10⁴</td>
<td>Cumulus scale</td>
</tr>
</tbody>
</table>

Fig. 3. The objectives and components of the GATE Central Program.
length (5000–10,000 km) in the upper troposphere often interpreted as Rossby-gravity waves—called here “Yanai-Maruyama waves” (Yanai and Maruyama, 1966); and 3) the very long eastward-moving waves in the stratosphere discovered by Wallace and Kousky (1968) generally interpreted as Kelvin waves. These waves have long lifetime, sometimes several weeks, as they travel considerable distances around the world. The A-scale is therefore called the “wave scale.”

The next smaller scale, the B-scale (10⁶–10⁷ km) although generally not of great significance at higher latitudes, is the important scale on which tropical “cloud clusters” develop. Discovered by satellite, they form the link between the short-lived smaller scale convective elements and the long-lived tropical waves as well as the Intertropical Convergence Zone (ITCZ). The description of their structure and life cycle and the study of their role in the energetics of the tropical atmosphere are one of the main objectives of GATE which has therefore sometimes been called a “cloud cluster experiment.”

The ITCZ, often only 100 to 200 km wide, but thousands of kilometers long, has characteristics of both the A- and the B-scale. As a statistical location of maximum convective activity in the tropics it may be considered a phenomenon of the general circulation.

On the next smaller scale, the C-scale (10⁶–10⁷ km), we find those structures of organized convection (bands, rings, etc.) that form the subsystems of the cloud clusters. This scale corresponds to the well known “mesoscale.”

The smallest horizontal scale to be studied in GATE, the D-scale (1 to 10 km), contains the individual convective elements themselves, and is therefore called the “cumulus scale.”

Figure 4 depicts the scale phenomena described here.

b. “Description” of scale phenomena

The first objective of the Central Program is the description of the forementioned scale phenomena.

The tropical phenomena of the largest scale, the wave (A)-scale, determine the size of the experimental area (150 by 30⁰) and the spacing of the A-scale land and ocean stations (5 to 10° where possible). The area extends from the westernmost part of the Indian Ocean across tropical Africa, the Atlantic, South and Central America to the easternmost part of the Pacific Ocean and encompasses about 40% of the earth’s tropical belt between 20⁰N and 10⁰S (Fig. 1). The upper-air sounding network over the land areas will have a density approaching that now in use over the land areas of the Northern Hemisphere in the temperate latitudes. Over the tropical Atlantic spatial continuity of this network will be preserved by a system of fixed ocean stations of comparable density. These ships are equipped to conduct a minimum of four daily ascents to measure wind, temperature, and humidity to at least 70 mb.

Unfortunately the navigation-aid wind-sounding system (Beukers) installed on the majority of the fixed ships has limitations—caused by the location of the Omega and VLF transmitters—which do not allow the ocean area to be covered south of the equator with as many ocean stations as one would like to see. Some ships equipped with stabilized windfinding radar will, however, be deployed in this region.

Detailed observational requirements on the A-scale are dealt with in the section on the Synoptic-Scale Subprogram below.

As far as the cloud cluster (B)-scale is concerned it would obviously be prohibitive to cover the whole tropical Atlantic with a subsynoptic ship network. Instead, an area in the East Atlantic where convective cloud clusters frequently occur has been selected for a more concentrated ship array (Figs. 5, 6). Most of these ships are highly instrumented, carry meteorological radar and will make more frequent observations when required.

On the only (C)-scale the structure of the different types of convective organizations, their life cycles, and the vertical and horizontal fluxes of mass, heat, moisture,
and momentum must be described. The main tool for this program will be the fleet of highly instrumented long-range aircraft (Table 4). These aircraft will operate primarily over the B-scale area. Their flight tracks often flown in a vertical stack are described in the Aircraft Operations Plan (GATE Report No. 11, 1974). An example is given in Fig. 7. In Phase 3 of the project a special "C-scale network" of five ships with spacings of the order of 50 to 100 km will be inserted into the central B-scale area (Fig. 6). A small scale buoy array lies inside the C-scale area.

Regarding the cumulus (D)-scale, some convective towers will be sampled by individual aircraft with regard to vertical motions, liquid water content, and other cloud physics parameters. A cloud census will be conducted supported by satellite images and observations from the French "ESSOR" balloon tethered at 20 km height. The description of the life cycles of individual cumuli is not part of the Central Program.

The system of telescoping scales in the ship network resembles a "nested grid." This system will fulfill the observational requirements only in combination with the aforementioned aircraft flights and satellite observations. In this connection it should be pointed out that the geostationary satellite SMS-A will be placed over the equatorial Atlantic and will continuously observe the GATE area in the visible and infrared spectrum with resolutions of 0.5 and 5 n mi, respectively. Imaging and vertical sounding information is also expected from several U.S.A. and U.S.S.R. satellites in polar orbit (NOAA-2 and 3, Meteor, Nimbus-5, possibly DMSP). Some of these data will be used on real-time for operational planning and the necessary ground facilities are being installed at the GATE Operational Control Center (GOCC) in Dakar, Senegal.

c. Scale interaction

Interaction of the different scale phenomena, both among themselves and with the basic state, refers to their spatial and phase relationships and to mass, momentum, moisture, and energy transports, conversions, and budgets. These may give considerable physical insight and reveal the dynamics of a system.

Scale interactions may also be understood in terms of control and feedback. Although, for example, no convincing physical model of the cloud cluster is at present at hand, it is known that cloud clusters are frequently (but not always) associated with tropical waves which in turn are thought to be driven by the release of latent heat of condensation. It is expected that case studies from GATE will shed some light on the possibility that tropical waves and cloud clusters interact by an A → B-scale control with B → A-scale feedback.

A similar situation exists in the ITCZ where convective activity appears to interact with the ocean surface, the atmospheric boundary layer and the tropical waves. Corresponding theories based on ocean-atmosphere coupling, the CIK hypothesis and the so-called "critical latitude" concept may be tested in GATE.

Atmospheric forcing by small- and large-scale circulations may be considered as an atmospheric control of

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3 Because of an expected late launch of the SMS-A satellite, these data may not be available in the beginning of the field project. However, ATS-3 data should be available.
the ocean mixed layer. The resulting surface fields of the ocean then provide the feedback to the atmosphere. This problem will be studied in GATE (see the section on the Oceangraphic Subprogram).

In all interaction studies and particularly in the evaluation of heat and moisture budgets of convective systems, the radiative flux divergence, the boundary layer, and the ocean mixed layer processes play an important role involving all subprograms of GATE.

It is especially in the scale interaction studies that accurate wind measurements at height are needed. The wind is the most important parameter to be measured in GATE. The vertical mass flux on all scales except the D-scale must be calculated from vertical integrals of weak divergence fields. The B-scale ship array provides numerous triangles and polygons of various sizes for this purpose. Vertical stacks of aircraft flying so-called butterfly pattern (Fig. 7) will yield detailed divergence fields down to the D-scale. Satellite data on cloud displacements should provide wind and divergence fields over most of the Atlantic for at least two levels. It is expected that this combination of different observing systems will provide satisfactory data. In addition, 90-min ship soundings in the B-scale area are planned during and near aircraft group flights for sufficient statistical sampling.

d. Parameterization

The problem of parameterizing the small-scale convective processes of the tropics in terms of the observable large-scale quantities is, of course, intimately connected with the scale interaction. Unless there is some degree of control of the smaller scales by the large-scale fields, successful parameterization cannot be achieved. While there is indication that such control exists, GATE must provide the supporting data.

It has been known since Riehl and Malkus’ (1958) basic work that the heat balance of the tropical atmosphere is maintained by penetrative cumulus towers carrying the released heat almost undiluted into the upper troposphere. This seems to occur on scales and over areas too small to be detected by synoptic-scale observing networks or to be resolved explicitly by even the finest grid mesh used in large-scale models. In other words, the basic elements of the heat engine for the general circulation of the atmosphere slip through the mesh.

Many parameterization schemes have been developed in recent years for moist convection. (See the section on the Convection Subprogram, p. 724). They should now be tested in GATE. Such tests will include the determination of cloud mass flux, diabatic heating rates, vertical profiles of radiative heating, sensible and latent heat fluxes from the ocean surface, the precipitation and a census of cumulus clouds, especially of deep towers (Yanai, 1971). The inferred bulk properties will be validated through direct sampling by research aircraft on the D-scale. Such sampling will include vertical motions and liquid water content. The quantitative determination of precipitation in the inner B-scale area with calibrated radar will be marginal in GATE as only four of the nine radar ships have the specified 5.7-cm radar, but representative estimates may be expected in combination with other observing systems including satellites.

The parameterization of moist convection cannot be separated from that of radiation. The difficult problem of parameterizing the radiative flux divergence under conditions of changing convective cloudiness is one of the central objectives of the Radiation Subprogram (see the section on this subject). It is also shown there that the radiation terms are surprisingly important in the heat budgets of convective systems being of a magnitude comparable to that of the eddy heat fluxes. Radiation equipped aircraft and shipborne radiometers sondes are among the main tools for the determination of these terms.

Also closely connected with the parameterization of convection is that of the atmospheric (and oceanic) boundary layer. The turbulent fluxes of momentum and energy and the mass and moisture convergence in the planetary boundary layer are highly related to moist convection. Schemes of parameterization based on the large-scale variables must be tested in GATE not only indirectly through B- and C-scale budget measurements but directly from ship and aircraft working on the turbulent scale in the subcloud layer. The planned tethered balloon systems, structure sondes, and airborne gust
probes will provide these data. (See the section on the Boundary-Layer Subprogram, p. 731, and Fig. 15). The oceanic boundary layer will be probed by salinity-temperature-depth (STD) soundings, sea surface temperature surveys, and current-meters. (See the section on the Oceanographic Subprogram, p. 738).

c. Tropical data sets for numerical models

Continuous sets of A-scale data (surface and upper-air) at 12-hr intervals for periods of about 20 days will become available from the entire experiment area. For global models, the data voids around the GATE area and between the observing periods will limit the usefulness of these data sets. Some models, such as those of the Washington NMC and Bracknell, may use the data in real-time. The numerical data sets are developed from the observed data sets by specific operations with a given numerical model. This is necessary to provide compatibility. The data sets will be utilized for initialization and verification of models.

For limited areas and nested models of the tropical atmosphere B-scale area data at frequent intervals and 6-hourly data from certain West African stations (surface and upper air) will serve to develop data sets, for example for a 2° mesh with 20 levels. For these models GATE should provide data of unprecedented quantity and quality.

4. Data management

A follow-up article will describe the GATE Data Management Plan in detail. Here it should only be mentioned that all data will be made available in agreed formats suitable for scientific analysis to all nations and scientists. National Processing Centers (NPCs) in all countries collecting data will be responsible for processing their own data. International processing and validation of these data will be done in five international Subprogram Data Centers (SDCs). These are: a) Synoptic Subprogram Data Center (SSDC), Bracknell, U.K.; b) Convexion Subprogram Data Center (CSSC), Washington, U.S.A.; c) Boundary-Layer Subprogram Data Center (BSDC), Hamburg, F.R.G.; d) Radiation Subprogram Data Center (RSDC), Leningrad, U.S.S.R.; e) Oceanographic Subprogram Data Center (OSDC), Brest, France.

These Centers will deposit their validated products in agreed formats at the World Data Centers (WDCs) A and B (Asheville, U.S.A., and Moscow) for archiving and distribution to the users.

The data flow will start immediately after the GATE field phase and is expected to be completed in early 1977. As soon as the first internationally validated data are produced they will be available to users through the WDCs. This is expected to happen six months after the end of Phase III.

Acknowledgments. In developing the GATE Central Program and its subprograms the International Scientific and Management Group had close and harmonious cooperation with JOC, the International Subprogram Advisory Groups, the national project offices and numerous consultants. Without their help the comprehensive program would never have been accomplished. We are grateful to the Secretary-General of WMO, Dr. Davies, and the Chairman of the TEB, Dr. Mason, for their generous support in our work. Special thanks are due to Prof. Döös of the Joint Planning Staff (JPS) and to the JOC GATE Panel, its Chairman Prof. Suomi and its members, Mr. Sawyer, Prof. Yanai, Dr. Miyakoda and Dr. Sitnikov.

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The Synoptic-Scale Subprogram

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1. Introduction

The Synoptic-Scale Subprogram encompasses a broad range of scientific problems and serves in a supporting role for most of the special studies of GATE. It is unique among the five subprograms in its emphasis on data from a wide area of the tropics consisting of both land and ocean, and therefore is closely related to the coming First GARP Global Experiment (FGGE). However it can only fully be understood within the context of the GATE Central Program and the other four GATE subprograms. The Central Program and the relationships between it and the subprograms are described in the section "General Description and Central Program" above in the present paper; therefore this section on the Synoptic-Scale Subprogram must be read in the light of what is stated in that section.

Greater detail can be found in GATE Report No. 6, "The Synoptic-Scale Subprogram for GATE" (Houghton and Parker, 1974).

2. Scientific objectives

a. Scientific objectives within the Central Program

The scientific objectives of the Synoptic-Scale Subprogram falling within the scope of the Central Program are as follows:

"Description of the synoptic-scale disturbances in the tropical troposphere and lower stratosphere from West Africa to the western Atlantic Ocean."

"Description" is a necessary prelude to the study of "interactions" involving the disturbances. The interactions can of course be with smaller-scale phenomena such as B-scale features including cloud clusters, or with larger-scale phenomena which comprise the basic state. For discussion of scale interactions in general see GATE Report No. 1, "Experiment Design Proposal for GATE" (Kuettnner, Rider, Shimok, 1972) and see also the section "General Description and Central Program" above in the present paper. The lower stratosphere has been included because Murakami (1975) and Holton (1978) have in numerical modeling studies shown the induction of equatorial lower-stratospheric waves by tropospheric heat sources. Description for West Africa and the Atlantic Ocean is specified because such description will best facilitate the synoptic-subsynoptic interaction studies which can only be carried out in detail for the GATE B-scale area (5-15N, 20-27W) and environs.

"Description of the averaged state of the GATE area troposphere particularly in terms of the jet streams, meridional circulations, and the Intertropical Convergence Zone, and clarification of the nature of the interactions between the basic-state flow and the synoptic-scale disturbances."

The behavior of the synoptic-scale disturbances and their interactions with subsynoptic features can be fully understood only when proper account is taken of the pervasive influence of the planetary-scale tropical background state. To provide sufficient information on this background state the troposphere over the whole GATE area needs to be monitored.

"Description of the synoptic-scale environment of cloud clusters passing through the B-scale area in sufficient detail to allow investigation of the interactions between the clusters and the large-scale motions."

This scientific objective is a culmination of the two previous objectives: note that "synoptic-scale environment" includes not only disturbances as such but also the background atmospheric state.

"Development of complete and internally consistent data sets for tropical numerical models."

Other than the fundamental aim of directly understanding the functioning of the atmosphere itself, the reason for placing such emphasis in GATE on synoptic-subsynoptic interactions is to facilitate the expression of sub-grid-scale features in large-scale numerical models implicitly in terms of grid-scale features, i.e., parameterization. New or improved parameterization schemes in the models will, it is hoped, provide an indirect avenue to increased understanding of the atmosphere, as well as to improving operational forecasting skills. This fourth scientific objective of the Synoptic-Scale Subprogram is therefore of great importance.

The contribution of the Synoptic-Scale Subprogram to the models will of course be in terms of synoptic-scale data, which should be spatially and temporally as complete and consistent as possible; other subprograms will supply additional data of the appropriate types. The synoptic-scale data should cover the whole GATE area so that the models can take into account planetary-scale as well as synoptic-scale features, and so that sufficient data will be available to cover all the coarse-resolution outer areas of nested-grid models whose fine-resolution inner areas will generally coincide with the GATE B-scale area. Data sets for the GATE A-scale area should be suitable for use as initial data for predictions, insertion data for four-dimensional or continual data assimilation models (see Miyakoda and Talagrand, 1971), and verification data for diagnostics. Some of the models served will be of limited area: such models can provide useful insights (Krishnamurthi and Kanamitsu, 1975). Other models will of course be global.

Care needs to be taken concerning the internal consistency of the data sets for numerical modeling. For example, large-scale, long-period models could be adversely affected if there is a serious lack of equatorial upper-air wind data south of the B-scale area.

There is expected to be a large number of Synoptic-
Scale Subprogram participants involved in modeling. Over a dozen models will be used. See Section 7 of GATE Report No. 6 (Houghton and Parker, 1974).

b. Other scientific objectives

The scientific objectives listed below are outside the scope of the GATE central program, but their achievement will nevertheless provide a useful supporting role for GATE and will help in further understanding the atmosphere as a whole.

Investigation of planetary-scale waves in the lower stratosphere throughout the equatorial zone.

Investigation of lower stratospheric features in the central parts of the GATE area has a place in the Central Program objectives (see above). It is clear from the argument given above that an increase of understanding of the atmosphere could result from a study of equatorial stratospheric waves in general. The more notable of these waves are of a planetary scale (Yanai et al., 1968; Wallace and Kourosky, 1968).

Investigation of the causes and origins of the West African easterly waves.

Fulfilment of this objective will aid fulfilment of the first three Central Program objectives of the subprogram mentioned above.

Clarification of the role of the tropics in the general circulation of the atmosphere.

The tropics should not be considered in isolation from higher latitudes. Direct tropical-extratropical interactions are important (Mak, 1969; Nitta, 1970; and Morell, 1973).

Provision of data for intercomparison between satellite and conventional observations.

Many areas of the tropics are endowed with only very sparse networks of surface-based data. Oceanic areas are particularly severe examples of this. However, satellite data can cover the whole globe, and therefore an ability to infer atmospheric flow and thermodynamic conditions in a precise manner from satellite data alone would be of immense value.

Contribution to other experimental programs of GARP concerned with global observation and data collection, particularly those relating to FGGE.

The FGGE data systems test (DST) was particularly in mind when this objective was formulated.

3. Observations

The data proposed in support of the Synoptic-Scale Subprogram will come principally from GATE ships, WWW land stations, and satellites. There will also be valuable data from commercial ships, commercial aircraft, and GATE aircraft.

Figure 8 shows the proposed network of 00 and 12 GMT land and (observing phase II) GATE ship radio-wind and radiosonde observations. The GATE observ-

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Some GATE ships will use very low frequency navigation signal windfinding and others radar windfinding. Some land stations will use radar and others radiotheodolites for windfinding.
ing period will be 15 June through 23 September 1974. Almost all regular GATE ship data will be limited to the three 21-day observing phases, although some upper-air observations are planned by some GATE ships en route to and from ports, and there will be surface observations from all moving GATE ships. The GATE ships, three land stations in West Africa west of 10W, and one land station in the Cape Verde Islands are expected to have 06 and 18 GMT radiowind and radiosonde observations during the three 21-day observing phases. Selected equatorial land stations around the globe will have radiowind and radiosonde ascents to 10 mb daily throughout GATE in order to investigate planetary scale waves in the lower stratosphere throughout the equatorial zone (see section 2b above). Ascents from GATE equatorial ships are planned to reach 10 mb for the same reason.

Land station pilot balloon data will be vital as backup data and as compensation for the marginal adequacy of the spatial resolution of the planned radiowind and radiosonde data. See Fig. 9.

Land station standard surface reports, rainfall total reports, graphical rainfall records, and special phenomena reports will all serve the needs of the Synoptic-Scale Subprogram. The graphical rainfall records will be useful in studies of estimation of rainfall from satellite images, and the special phenomena reports will aid in tracking squall lines and similar perturbations. The GATE ships and commercial ships will provide 6-hourly (hourly in the case of stationary GATE ships) standard surface data including sea-surface temperature. The GATE ships will also provide 6-hourly rainfall totals and some GATE ships will provide graphical rainfall records.

Five types of satellite are expected to provide the bulk of the needed satellite data. The synchronous meteorological satellite (SMS) should provide 1-km nadir resolution visible images (daytime only) and 10-km nadir resolution infrared images (day and night) at least every hour. The SMS data will cover the area from 20E to 110W. See Fig. 10 (in the Convection Subprogram section, p. 725) for details. From sequences of these images winds can be derived, although only for one or two levels. However, these winds can often have much better than the 500-km horizontal resolution which is the basic synoptic requirement. Image data from the remaining satellites, NOAA, DMSP, NIMBUS, and METEOR, which are all polar-orbiting, will provide coverage of the GATE area with approximately 6-hr time resolution when the data from all four are combined. Spatial nadir resolution will be 2/3 to 4 km in the visible and 2/3 to 15 km in the infrared. NOAA, DMSP, and NIMBUS will also provide valuable sounding data giving often better than 300-km horizontal resolution. These NOAA, DMSP, and NIMBUS soundings will separately give 12-hr time resolution, and the orbit times at a given location will be up to 4 hours different. METEOR will provide special radiation budget data. Infrared image data and sounding data from satellites in general can be used to derive sea-surface temperatures when the cloud conditions permit. For greater details see the GATE Satellite Operations Plan (Parker and Kanehigé, 1974).

A special effort will be made to collect standard meteorological reports from commercial aircraft. Plans are also under way to obtain automatically recorded data from some of these platforms. Commercial aircraft data coverage will be mainly at the 200-mb to 300-mb levels. Data for most parts of the GATE area will be available.

There should be thermodynamic and wind data from dropsondes launched from GATE aircraft over the Atlantic and some flight-level data from GATE aircraft particularly over the Atlantic.

Special measurements are planned to be made by GATE ships to compare their surface and upper-air observing systems: these special measurements will be treated in the follow-up article on the GATE international operations plans. Statistical techniques on the regular GATE ship observations can also, of course, be used for intercomparison. The unproven nature of the Omega windfinding system in the southeastern tropical Atlantic is a major unknown factor and increases the need for intercomparison. Quality control of land station data will have to be carried out by statistical techniques. Comparison of satellite winds and temperature/
humidity profiles with corresponding conventional data will involve a considerable amount of complex statistical work.

If all these types of data are successfully provided in the planned quantities and with the planned accuracies, and if the data requirements of the other subprograms are also satisfied, it will be possible to fulfill the scientific objectives, not only of this Subprogram, but of GATE as a whole; moreover, the way should then lie open for considerable advance in synoptic-scale tropical meteorology.

4. Data management

The most important Synoptic-Subscale Subprogram task during the field phase of GATE will be the near-real-time collection of GATE area data at the Synoptic-Subscale Subprogram Data Center (SSDC) at Bracknell, U.K., where a global, synoptic, near-real-time data bank is now operational. Thereafter the prime function of the SSDC will be to prepare in forms suitable for use by synoptic-scale scientists synoptic observations for the whole GATE area from WVR observing stations, GATE platforms, and satellites. The SSDC will use the existing routines of the operational, global, synoptic, near-real-time, data bank at Bracknell as a basis for the data organization method. For further details refer to the follow-up paper on the international operational plans for GATE.

5. Research participation

Information on research participation has been received from a considerable number of sources. See Table 6 and section 7 of GATE Report No. 6. It appears that most of the scientific objectives are covered by the proposed research programs.


References


Table 6. Organizations and institutes participating in research within the Synoptic-Subscale Subprogram

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<tr>
<th>Country</th>
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<tr>
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<td>Dirección de Hidrografia e Navegación.</td>
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**The Convection Subprogram**

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1 A former member of the ISMG.

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1. **Introduction**

The Convection Subprogram (CSP) is the broadest and most complex of the Subprograms because it utilizes a variety of observations on different scales to describe the state of convection. These data also provide a context for the work of the Boundary-Layer, Radiation, and a portion of the Oceanographic Subprograms. Likewise, the observations of the Synoptic-Scale Subprogram provide a context for interpreting the B-scale observations of the Convection Subprogram. Therefore, the CSP shares many observational objectives and data requirements with the other subprograms.

The focus of the CSP is on the cloud-cluster or B-scale ensemble convective and its two interactions: with the synoptic scale, and with organized mesoscale convection. The description of the smaller-scale interaction (C-scale to D-scale, or C:D) is also needed to assess the contribution of these fundamental components of the cumulus spectrum to the changes that occur on the A and B scale.

The objectives of the Convective Subprogram and the experimental design have been described by Rodenhouse and Betts (1974). A discussion of the scientific questions involved in this part of the Experiment has been written by Betts (1974). Ansenersen and Zipser (1974) have developed a plan for the use of aircraft to meet the objectives of the Convection Subprogram as well as those of the other subprograms.

2. **Objectives**

The scientific objectives of the CSP are:

1) to observe and describe the undisturbed state and the life-cycle of cloud clusters and mesoscale convection over the tropical ocean;

2) to study the interaction of convection between scales (B:C:D), with the boundary layer (as in CISK theories), and with the larger-scale systems such as the ITCC and tropical waves; and

3) to provide a data set for testing and developing models for convective interactions, including parameterization.

3. **Experimental design**

There are four fundamental concepts on which the experiment design of the CSP is based. The first is the B-scale budget experiment which has been the seminal convection experiment of GATE, (Kuettnner et al., 1972). The other experiments may be classified as the A-scale cloud cluster census, the study of mesoscale structure and organization, and the investigation of the physics and dynamics of individual cumulus clouds. These basic studies are discussed in turn.

a. **B-scale experiment**

The fundamental problem of the interaction between synoptic cumulus scales was investigated by Reed and Recker (1971), Yanai et al. (1973), Ogura and Cho (1975). These diagnostic studies were based on large-scale mass, heat, and moisture balance obtained from a network of upper-air stations such as described by Holland and Rasmussen (1973) in the BOMEX experiment and Austern et al. (1973) in the ATEX experiment.

These “budget studies” are based upon a set of averaged conservation equations; the thermodynamic energy equation in a slightly simplified form may be used as an example:

\[
\frac{\partial \theta}{\partial t} + \nabla \cdot (\mathbf{V} \theta) + \frac{\partial}{\partial p} (\mathbf{e} \theta) = \frac{\theta}{c_p} \dot{Q} - \frac{\partial}{\partial p} (\omega^* \theta) \quad (1)
\]

where

\[
\theta \quad \text{is the potential temperature},
\]

\[
\mathbf{V}, \omega \quad \text{are the velocity components in the } x, y, p \text{ coordinate system},
\]

\[
\dot{Q} \quad \text{is the net heating rate per unit mass due to precipitation, evaporation and radiational cooling},
\]

\[
\omega^* \theta \quad \text{is the vertical flux of heat due to turbulent transfer and cloud-scale vertical motion},
\]

and the averaging is taken over the horizontal area containing cumulus clouds; e.g. the neighborhood of a synoptic grid point. (Similar equations may be written for mass, momentum, and moisture conservation.) From the B-scale observations the left-hand side of (1) may be determined. The residual term, \(\dot{Q}_1\), is an estimate of the feedback of convective processes which drive the large-scale motion. Figure 10 shows a few examples of composite \(\dot{Q}_1\) for active and suppressed states.
the maximum possible contribution to the residual term. These conditions are usually associated with the cloud clusters of easterly waves and disturbances of the ITCZ. For these studies, soundings must extend from the surface through the outflow layer near 100 mb. The period between observations will be 3–6 hr. (For meso-scale studies a higher frequency is required.)

However, in order to understand the physical processes that contribute to these bulk measurements, it is necessary to examine some of these details of convection process, as well as bulk effects. Therefore, the residual term may be expanded

\[ Q_1 = L(c - e) - Q_R - \frac{c_p}{\theta} \frac{\partial H}{\partial \rho} \]  

(2)

where

- \( c \) = condensation rate
- \( e \) = evaporation rate
- \( Q_R \) = infrared radiational cooling rate
- \( H = \omega' \theta' \), the turbulent and cloud-scale heat flux.

To observe all these quantities throughout the cloud field and as a function of height is clearly beyond our capability. Therefore, two approaches will be taken. The first method uses a simplified model for convective clouds to develop an internally consistent solution for \( c, e, Q_R \) and \( H \) which also satisfies (2). Therefore, it is necessary to at least observe the integral of \( c - e \) or the precipitation \( (P_i) \) which represents the direct heating by convection. The precipitation estimate will be made by the overlapping radar observations in the B network (Fig. 12) as well as sample observations from ships and buoys and inferred estimates from satellites.

Furthermore, it is clear from (2) that the results from the other subprograms are needed to complete the calculation. The Boundary-Layer Subprogram will provide measurements of the boundary layer mass flux, the turbulent heat \( (H) \) and moisture flux \( (E) \) and the thermodynamic structure of the subcloud layer (Fig. 11). The infrared cooling rates as a function of height will be calculated and measured by the Radiation Subprogram. Since the individual observations will be very difficult to interpret because of sampling error, a selective composite will be made based upon synoptic meteorological fields, the location of the ITCZ and the axes of tropical waves. The description of these features will be provided by the Synoptic-Scale Subprogram.

The second approach to the problem of dissecting the terms in (2) relies upon direct sample measurements or an independent inference of the condensation and evaporation rate and the heat and moisture fluxes \( (c, e, H, \text{ and } E) \). Furthermore, in the models discussed above it is usually necessary to specify some additional parameters of individual clouds; e.g., liquid water content, entrainment, or cloud size. Sample measurements of all these parameters are discussed in later sections \( c \) and \( d \).

In addition to the calculation of the convective feedback, this data set will permit an assessment of the con-

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**Fig. 10.** Several different estimates of \( Q_i \): \( C_P \) Pacific easterly wave trough (Cho and Ogura, 1974); \( C_R \) Pacific easterly wave ridge (Cho and Ogura, 1974); \( Y \) Pacific composite (Yamai et al., 1973); \( HR \) ROMEX five-day composite (Holland and Rasmussen, 1973).

**Fig. 11.** A schematic view of the volume enclosed by upper air soundings. This volume is the basis for quantitative calculations of the heat, moisture, mass, and momentum balance (budgets). See the text for discussion and definition of symbols.
mesoscale substructures which make the major contribution to the net cumulus activity. On other occasions, the mesoscale features are isolated and less organized, but nonetheless intense.

Therefore, a comprehensive study of these convective scales is part of the CSP, and is closely related to the interests of the Synoptic-Scale Subprogram. The Synchronous Meteorological Satellite (SMS) is planned to provide the basic set from its geostationary orbit on the equator, (Fig. 13). The high-resolution visible (1/2 n mi) and infrared images will provide coverage of a major segment of the tropical Atlantic every 3 hr. In the region of the B-ships, observations will be nearly continuous—about once every 30 min.

In addition, the observations of the NOAA series, the ATS-3, and DAPP system of the U.S.A., and the METEOR satellites of the U.S.S.R. will be available. Since these satellites are polar orbiting, they provide images twice each day.

From these observations a comprehensive and nearly continuous record of convection will be available. These data will be used with additional data sources to construct composites of convection and cloud clusters and to describe their life cycle. In addition, the satellite record will be used for case studies and statistical analyses of the spatial variation of cloudiness. In the B-area the satellite view of the changes in cloud fraction and cloud height are a measure of intensity of convection which can be compared with surface observations. It will also be possible to use these data for estimates of precipitation over tropical oceans outside of the B-area of intense radar coverage. Calibration with observations within the array and with land stations is important, however.

Finally, the geostationary satellite will provide the basic resource for cloud-motion determination within the A-scale network. Again, a comparison of aircraft and upper-air soundings in the B-area with the cloud motions is needed.

c. Mesoscale experiments (C-Scale)

In the early studies of cloud clusters, it was already apparent that the intense zones of mesoscale convection which existed within the cluster probably accounted for the major contribution to the interaction with the larger scales (Martin and Suomi, 1972; Zipser, 1972). This has been confirmed by more recent studies (Madden et al., 1974). Furthermore, mesoscale convection is often organized outside of the cluster structure, and is sometimes the antecedent of a developing system or the remnant of a dying one.

The mesoscale experiments have been planned with two major components. The first is designed about the B-scale ship radars and high-resolution SMS satellite observations. These systems will identify convection at intervals of 15 and 30 min, respectively, which should easily resolve the spatial and temporal variations. Complementary data will be taken from the high-frequency...
surface (and boundary-layer) instrumentation. However, the spacing of these platforms is too great to resolve the complete meteorological fields of mesoscale features except when they drift past the observation point. Consequently, some high frequency but shallow upper air soundings are planned (80 min; surface—150 mb). These data will be analyzed in time series as case studies and by compositing many observations, assuming a time/space transformation.

During the third phase of the Experiment, however, a "C-scale" network has been designed with about 1/6 the enclosed horizontal surface area (Fig. 6 of a previous section). In this case, the high frequency data may be used with radar and satellite observations to isolate individual mesosystems and infer their development and interaction using equations of the type (1).

The second type of experiment designed to investigate the mesoscale is based on the use of several highly-instrumented aircraft in coordinated missions (Aamensen and Zipser, 1974). One type of basic mission is illustrated in Fig. 14. In this example, 4 to 6 aircraft will be scheduled to fly to the initial point (IP) and begin a survey of the convective feature. Because of the limitation upon aircraft endurance and the necessity to repeat the observational pattern several times, the box or "butterfly" flight pattern is limited to about 100 km on a leg. Therefore, the aircraft should be able to circumnavigate individual mesoscale features, but will not be able to study the entire cluster. The meteorological data from these flights will be used in computations similar
to the budget studies in the B-scale, but the observations will not be synchronous, and the vertical resolution will be quite coarse. On the other hand, the horizontal spatial resolution is much greater than the observations of the B-network.

During these flights there will be frequent opportunities to penetrate the region of organized convection as well as the quiescent region of the environment. Indeed, a number of other flights have been planned to make repeated penetrations of mesoscale structures which are embedded in a cluster or the ITCZ. It is particularly important to determine the relationship of the mesoscale convection to the cluster or ITCZ as distinct from interaction directly with the A-scale fields. The objective of these flights is to obtain the kinematic and thermodynamic structure of mesoscale convection and representative mass transports, vertical fluxes, and moisture (liquid and vapor) distribution. From these data and the supporting observations from the B-ships, the organization and life cycle of the mesoscale may be deduced. An extensive photographic record will be made to help connect these diverse sets of observations with the convection itself.

d. Experiments on the physics of clouds (D-scale)

The fundamental component of the interaction problem is the individual cumulus clouds. Therefore it may seem surprising that the focus of the GATE experiment is on the parameterization of convection and the interaction between scales, when cloud physics and microphysics are not well understood.

It is a fundamental assumption of the parameterization concept that the "important" effects of cumulus convection can be incorporated into the larger-scale models without the detailed knowledge of individual clouds and their microphysics. Certainly this is true to some extent. But as the models become more refined, the influence of such parameters as vertical distribution of cloud water content, evaporation of precipitation, and local wind shear become critically important. (For example, Simpson and Wiggert, 1969, or Takeda, 1971).

Therefore, selected experiments are planned to investigate the physics of clouds. The principal observing platform is the aircraft during its penetration into cumulus convection. The data will be collected both during "opportunity" flights which fortuitously enter clouds in the course of a mission, and during specially designed flights for frequent penetration at several different levels. In addition to conventional flight level data, other observations are planned: vertical motion from the gust probe, turbulent flux measurements, liquid and total water content, condensation and ice nuclei counts, and drop size spectra. (The latter measurement is also essential for radar calibration for rainfall estimates from the B-ships).

In addition, stereo cloud-photogrammetry will give a census of cloud characteristics to accompany the quantitative dynamics and cloud-physics measurements.

These direct observations may be used to compare with the results of diagnostic calculations for the bulk effects of convection. For example, a major question concerning the influence of cumulus on the synoptic scale is: How do the cumuli which occupy such a small fraction of the area distribute their concentrated heat, moisture, mass, and momentum to the synoptic scale? Many investigators have pointed to the compensating downdrafts as a possible explanation for the warming and drying of environment. Direct measurements of vertical mass flux in the clouds will be available from aircraft equipped with gust-probe instrumentation. These observations may be used with large-scale divergence measurements on the B-scale to infer the magnitude of the downdrafts and the results compared with alternative formulations of diagnostic models.

Other direct measurements of cloud structure, entrainment, liquid water content, and cloud-scale fluxes of heat and moisture can be used in this way to improve both the cloud models and the parametric representations of their collective effects on the larger scales.

4. Observations

The experimental design of the four basic experiments described in the previous section requires an interlacing set of measurements on different scales and frequencies. Furthermore, the objectives for which the experiments were designed require data from all the other subprograms.

This section briefly summarizes the observational requirements of the CSP by platform. A complete description is given by Rodenhuis and Betts (1974).

A/B Ships—Conventional meteorological surface observations every hour: pressure, temperature, dew point, wind, weather, precipitation, and cloud conditions. Special observations are taken for significant changes in these variables.

—Upper-air soundings every 3 hr to 70 mb: temperature, dew point, pressure (height), wind speed and direction. During non-intensive periods, the soundings will be made every 6 hr.

B Ships—In addition to the surface observations taken on A/B ships: Frequent (about every 3 min) surface meteorological observations of temperature, dew point, wind speed and direction.

—In addition to the upper-air soundings specified for A/B ships: selected ships will take soundings to 150 mb every 90 min during aircraft missions.

—Special observations: whole-sky photography, drop-size spectra and high-resolution precipitation measurements.

—Meteorological radar (3.2 and 5.7 cm) observations of intensity every 15 min in about 15 vertical steps and with a horizontal resolution of several kilometers.
Aircraft — (Boundary layer, cloud-layer, and high-level aircraft will be instrumented somewhat differently)
— Flight-level observations of wind speed and direction, temperature, moisture, pressure, and height from 10 long-range aircraft and 2 short-range aircraft.
— Dropsonde soundings from three aircraft; only two aircraft will record winds.
— Turbulent fluxes and cloud-scale vertical fluxes of mass, heat, moisture, and momentum from three aircraft equipped with gust-probes. In addition, one short-range aircraft will be capable of this type of measurement.
— Measurements of cloud-physics parameters: liquid and total water content, drop-size spectra, condensation, and ice nuclei from five aircraft.
— Cloud photography with nose- and side-viewing cameras; stereo photography from high-level aircraft.

Satellites — SMS (U.S.A.; geostationary) observations in the visible and infrared with highest resolution of 1 and 9 km, respectively, at the sub-satellite point. Maximum frequency of observation will be approximately once every 30 min.
— ITOS/NOAA (U.S.A.; polar-orbiting) observations in the visible and infrared. In addition, limited information on atmospheric temperature and moisture sounding and sea-surface temperature will be available.
— METEOR (U.S.S.R.; polar-orbiting) observations in the visible and infrared.
— Other satellite systems: the ATS-3 (U.S.A.; geostationary) observations in the visible are planned for direct readout in Dakar during

| Table 7. List of organizations or institutes participating in the convection subprogram. |
|---------------------------------------------|---------------------------------------------|
| **Country** | **Organization or Institute** | **Country** | **Organization or Institute** |
| Canada | McGill Weather Radar Observatory, Macdonald College, McGill University, Montreal, Physics Department, McGill University, Montreal, Department of Physics, University of Toronto | U.S.A. | Institute for Fluid Dynamics & Applied Mathematics, University of Maryland, College Park, Maryland, Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Coral Gables, Florida, Goddard Space Flight Center, NASA, Greenbelt, Maryland, National Center for Atmospheric Research, Boulder, Colorado, Atmospheric Physics & Chemistry Laboratory, NOAA, Boulder, Colorado, Boundary Layer Dynamics Group of the Weather Modification Program, NOAA, Boulder, Colorado, Center for Experiment Design and Data Analysis, NOAA, Rockville, Maryland, Experimental Meteorology Laboratory, NOAA, Miami, Florida, Geophysical Fluid Dynamics Laboratory, NOAA, Princeton, New Jersey, National Environmental Satellite Service, NOAA, Suitland, Maryland, Wave Propagation Laboratory, NOAA, Boulder, Colorado, Department of Physics, University of Puerto Rico, San Juan, Department of Environmental Sciences, University of Virginia, Charlottesville, Department of Atmospheric Sciences, University of Washington, Seattle, Department of Meteorology, and Space Science and Engineering Center, University of Wisconsin, Madison | |
| Federal Republic of Germany | Freie Universität Berlin, Institut für Physik der Atmosphäre, DFVLR, Oberpfaffenhofen, Meteorologisches Institut der Universität, Bonn | United Kingdom | Department of Meteorology, Imperial College, London, Department of Geophysics, University of Reading | |
| France | Laboratoire de la Météorologie, Dynamique du CNRS, Paris, Laboratoire d’ Dynamique et de Microphysique, de l’Atmosphère, University d’Clarmont-Serrand, Météorologie Nationale, Establissement d’Études et de Recherches Météorologiques, Boulonnais | U.S.S.R. | Central Aerological Observatory, Moscow, Hydrometeorological Center, Moscow | |
| Mexico | Dirección General de Geografía y Meteorología, Servicio Meteorológico Nacional, Tacubaya, D.F. | Multinational agencies | Bureau d’Études, ASECNA, Dakar, Senegal |
daylight hours. The DAPP (U.S.A.: polar-orbiting) has high-resolution capability in the visible and infrared and has an observational schedule similar to the ITOS/NOAA system.

5. Data Management

The data which were described in the previous section will be processed first by principal investigators and national processing centers. Within the 6–18 month period following the experiment, these data will be sent to the GATE Archives for distribution to interested scientists. The data will also be sent to the Convection Subprogram Data Center (CSDC) for further processing and international validation.

The CSDC will organize the data into data subsets which will be generally useful for the analysis of the CSP. These subsets will then be sent to the GATE Archives during the 6–30 month period following the experiment. Scientists who use these data sets will be able to obtain them directly from the Archive.

Some data sets (e.g., digitized satellite data) will go directly to the Archive, since further processing by the CSDC is not required. Furthermore, some data sets are so specialized (e.g., aircraft photography or some full-resolution aircraft measurements) that only a summary or selection of data will be in the Archive; the original data will be available from the principal investigator or national processing center. Nevertheless, the Archive remains the principal source for this information as well as for the primary data subsets.

The CSDC is located in Washington, D.C., at the Center for Experiment Design and Data Analysis. A more detailed description of the work of the CSDC is available in Rodenhuis and Betts (1974) and de la Moriniere (1974).

6. Participants

The data of the Convection Subprogram will be combined with the observations of the other subprograms to meet the GATE scientific objectives. However, there has been some attempt to recognize participating scientists who are interested in at least one of the problem areas described in section 3c. Table 7 is an incomplete list of institutions where these studies may be developed.

Acknowledgments: The International Working Group for the Convection Subprogram made several contributions to the definition of the observational program. The advisory group consists of: A. Betts, A. Borovikov, H. G. Fortak, K. Fraedrich, J. Holland, J. S. Marshall, R. Pearce, E. Zipser. In addition, I would like to thank Prof. Betts for a critical review of this manuscript.

References


The Boundary-Layer Subprogram for GATE

Heinrich Hoeber

International Scientific and Management Group for GATE

1. Objectives

To provide a description of the internal structure of cloud clusters is one of the central scientific objectives of GATE. This includes the description of conditions in the planetary boundary layer (PBL) of the tropics in relation to the clusters. In particular, the Boundary-Layer Subprogram has to provide information about those quantities which are of interest in models of both the boundary layer and convection. Different types of boundary layer models exist and must be tested, for instance those known as the resistance laws developed by Kazanski and Monin (1961), Blackadar and Tennekes (1968) and Zilitinkevich (1969, 1970), see GARP Publication Series No. 8 (1972), and a second group known as entity models (see, for example Tennekes, 1973).

These models, if applicable in the tropical PBL, would yield information on the surface fluxes of water vapor, sensible heat, and momentum, knowledge of which as lower boundary values is necessary for the integration of the energy budget equations. Moreover, the field of the surface stress is linked by theory to the cloud base mass flux, a quantity which is essential for the parameterization of convection. A similar consideration is part of the CIK hypothesis, where the vertical velocity at the top of the Ekman layer is also controlled by the PBL, i.e., by the vorticity of the surface geostrophic wind and the depth of the Ekman layer. The “critical latitude” concept assumes the depth of the Ekman layer to be dependent on the frequency of the wave disturbances in the boundary layer with a singularity at that latitude where the Doppler shifted wave frequency is equal to the Coriolis frequency.

It can, however, be predicted that a simple application of the existing models will not lead to success, as the PBL in the tropics reveals several peculiarities not considered so far. For instance transient phenomena will occur and the inertial terms of the equations of motion will be of the same importance as the Coriolis term. The development and decay of the convective systems will produce changes in the PBL structure which have to be observed. In particular, the interaction between the mixed layer and the cloud layer by mesoscale vertical circulation systems in connection with the cloud clusters will render the simplifying assumptions of the models on the vertical stratification within the boundary layer invalid.

A second problem area arises from the fact that interaction among motion systems of different scales will occur and has to be assessed quantitatively. This is a problem area in which the Boundary-Layer Subprogram cooperates closely with the Convection Subprogram. As a first step one can use those terms of the energy budget equations, which represent the fluxes achieved by subgrid scale eddies, to determine the effect of a smaller on a larger scale. Repeating the budget computations on different scales (from B- to D-scale, say) one gets first information about energy transfers from one scale to another. A better solution would be to look at the energy spectra in the wavenumber regime and how their shape is changed under the influence of interaction. This, however, is difficult to achieve considering the limited number of stations and the invalidity of Taylor’s hypothesis.

Finally, every model of the PBL must necessarily take into account the problem of the dynamics at low latitudes where the Coriolis parameter changes significantly, accelerations affect the boundary layer structure, and baroclinicity generated by cold ocean water has to be considered.

2. Experiment design

The existing models, although probably not adequate in the convective tropical atmosphere, will provide the firm basis from which the experimental design can be defined. This design must ensure measurements of a) the fluxes across the air-sea interface, b) the depth of the mixed layer and its time changes, c) the gradients of wind velocity, temperature, and humidity in the mixed layer, d) temperature and humidity changes in the transition layer and the depth of this layer, e) the height of convective cloud base, f) the gradients just above cloud base, g) the large-scale vertical velocity and the vertical velocity directly underneath clouds, h) the geostrophic and the thermal wind, i) the pressure fluctuations, and j) the roughness length. However, to improve the models and to consider the special circumstances in a tropical atmosphere, the plans require further that:

1) the time and space dependence of thermodynamic and dynamic variables be emphasized;
2) the vertical structure, in particular, of thermodynamic and dynamic variables be assessed with high resolution;
3) the height dependence of vertical fluxes be determined by aircraft and tethered balloons;
4) the radiative flux divergence be estimated (see Radiation Subprogram);
5) the development of mesoscale structures as possible forerunners of cloud clusters be observed;
6) all observations be classified according to the state of cloud convection and to their relative position to the convective system under investigation.

The PBL will be described in the context of develop-
ing and decaying cloud clusters, i.e. all the above quantities must be measured over a number of the 3- to 5-day cycles which correspond to the passage of B-scale systems. We must further acquire time series long enough and with such a resolution that spectra in the range of periods between seconds and four days can be studied. The network of B-scale ship stations plus the aircraft measurements will enable us to compute mass and energy budgets of volumes of different scales—B-scale, C-scale and possibly D-scale. And finally, the meridional extension of the network will be used to study all quantities, in particular the dynamic quantities, with respect to their latitude dependence at small Coriolis parameters.

3. The measurements

The observational program for the PBL investigations concentrates on the East Atlantic Array of the GATE network (see Fig. 1). Here the best equipped research vessels will be stationed, and the area is well within reach of aircraft operating from Dakar. Figure 15 shows the ship network and the observational systems for the Boundary-Layer Subprogram for the third phase of GATE as an example; it also contains information on oceanographic measurements. For more details reference is made to GATE Report No. 5 (Hoeber, 1973).

The most important measuring systems for the PBL investigations are the following:

Shipborne tethered balloons carrying up to five sondes at different levels for the measurement of wind speed and direction, temperature, humidity, and pressure. Sampling frequency: 1 per 4 sec; height range: 50 to 1200 m; max. endurance: 24 hr. Six systems are available. They will be operated in either a fixed level mode or in a profiling mode. An additional tethered balloon system (on board HECLA, third phase) will be capable of measuring small scale fluctuations of vertical and horizontal wind components, temperature, and humidity, and thus eddy correlation fluxes up to cloud base.

Free-rising sondes ("structure sondes") for the measurement of the fine structure of the vertical temperature and humidity profiles up to 3000 m. Sounding frequency: 1 per 3 hr intermittent with 3-hourly routine soundings. Three systems will be available on C-scale ships, i.e., only in the third phase.

Free-rising balloons tracked from C-scale ships by radar or optical theodolite for the measurement of the vertical wind profile up to 2000 m. Sounding frequency: 1 per 30 min. Four systems available, but third phase only.

Acoustic echo sounding by ship-born equipment for measurements of subcloud wind profiles and structures of atmospheric layers. One system on board Oceanographer.

Aircraft equipped with high response sensors for temperature, humidity, horizontal and vertical wind components, in addition to inertial platforms which allow determination of turbulent energy and momentum fluxes around and underneath the clusters. Three aircraft so equipped are committed (see Fig. 7 and Table 4). Their range will permit four to six hours of operations within the B-scale area during each mission.

Buoys for the measurement of surface variables, i.e. mean wind velocity, temperature, and humidity, as well as turbulent fluxes of sensible and latent heat and momentum. Three systems for flux measurements (two

![Fig. 15. Meteorological and oceanographic observing systems of research ships in the inner East Atlantic Array for phase III. Surface buoys, tethered balloons, structure sondes, and low-level windfinding systems support the Boundary-Layer Subprogram; current meters, STDs (salinity, temperature and depth sounders), wave-measuring buoys, and towed probes are part of the Oceanographic Subprogram.](image-url)
thereof only for one phase) and four for average quantities will be deployed.

In addition, the routine surface observations of all ships serve the PBL investigations by providing the large-scale pressure, temperature, and wind fields, estimates of sea surface waves and the bulk fluxes. Satellite images and radar observations will help locate the centers of convective activity. Infrared radiative temperature measurements from aircraft and satellites will yield information on large and mesoscale sea surface temperature fields.

The large number of different measuring systems on ships and aircraft makes a careful intercomparison mandatory. The plans provide for three intercomparison periods for B-scale ships where emphasis is put on the sounding systems, routine surface instrumentation, and flux-measuring systems. Aircraft will intercompare as often as possible, for instance during the ferry flights from Dakar to the B-array.

4. The data

The data set necessary to achieve the scientific objectives has been defined and is described in detail in the Boundary-Layer Subprogram (Hoeber, 1973). The data management plans require that the National Processing Centers deliver their PBL data for international validation to the Subprogram Data Center which in the case of the Boundary-Layer Subprogram has been established in Hamburg in cooperation with the Deutscher Wetterdienst (German Weather Service), the Meteorologisches Institut der Universität Hamburg, and the Institut für Radiometeorologie und Maritime Meteorologie an der Universität Hamburg. Emphasis in this Subprogram will be put on the data in their original form with high resolution in space and time in order to enable the user to study time and space scales at his own discretion. The exception will be aircraft gust probe data and other eddy correlation data which will be reduced by averaging. More details of the data handling can be found in the GATE Data Management Plan (de la Morinie, 1974).

5. The participants

Table 8 comprises those institutions which are actively participating in the Boundary-Layer Subprogram during the field phase of GATE. In several cases the activities overlap with either the Oceanographic or the Convection Subprogram. The table does not consider those groups or individuals who have shown their interest in working on the PBL data after the field phase; such a list would be both very voluminous and incomplete, as the interest is growing everyday.

**Table 8. List of institutes participating in the Boundary-Layer Subprogram during the field phase of GATE.**

<table>
<thead>
<tr>
<th>Country</th>
<th>Organization or Institute</th>
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<tbody>
<tr>
<td>Canada</td>
<td>Atmospheric Processes Research Branch, Atmospheric Environment Service.</td>
</tr>
<tr>
<td></td>
<td>Department of Oceanography, U. of British Columbia.</td>
</tr>
<tr>
<td>Federal</td>
<td>Institut für Meereskunde, U. of Kiel.</td>
</tr>
<tr>
<td>Republic of</td>
<td>Meteorologisches Institut, U. of Hamburg.</td>
</tr>
<tr>
<td>Germany</td>
<td>Institut für Radiometeorologie und Maritime Meteorologie, U. of Hamburg.</td>
</tr>
<tr>
<td></td>
<td>Institut für Meteorologie, U. of Mainz.</td>
</tr>
<tr>
<td>France</td>
<td>Laboratoire de la Méteorologie Dynamique, Paris.</td>
</tr>
<tr>
<td>United</td>
<td>Meteorology Division, Chemical Defence Establishment, Porton Down.</td>
</tr>
<tr>
<td>Kingdom</td>
<td>Meteorological Research Flight, Meteorological Office.</td>
</tr>
<tr>
<td></td>
<td>Department of Meteorology, Imperial College, London.</td>
</tr>
<tr>
<td>U.S.A.</td>
<td>Space Science and Engineering Center, U. of Wisconsin.</td>
</tr>
<tr>
<td></td>
<td>Department of Environmental Sciences, U. of Virginia.</td>
</tr>
<tr>
<td></td>
<td>Department of Meteorology, Texas A &amp; M University.</td>
</tr>
<tr>
<td></td>
<td>Department of Atmospheric Sciences, U. of Washington.</td>
</tr>
<tr>
<td></td>
<td>Wave Propagation Laboratory, NOAA, Boulder.</td>
</tr>
<tr>
<td></td>
<td>Boundary Layer Dynamics Group, Office of Weather Modification, ERL/NOAA, Boulder.</td>
</tr>
<tr>
<td></td>
<td>National Hurricane Research Laboratory', NOAA, Miami.</td>
</tr>
<tr>
<td></td>
<td>Center for Experiment Design and Data Analysis, NOAA, Washington.</td>
</tr>
<tr>
<td></td>
<td>National Center for Atmospheric Research, Boulder.</td>
</tr>
<tr>
<td></td>
<td>Institute of Atmospheric Physics, Academy of Science, Moscow.</td>
</tr>
<tr>
<td></td>
<td>Main Geophysical Observatory, Leningrad.</td>
</tr>
<tr>
<td></td>
<td>Leningrad Hydrometeorological Institute, Leningrad.</td>
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</tbody>
</table>

Acknowledgment. The ISMG, in preparing the Boundary-Layer Subprogram for GATE, was assisted by an international Advisory Group with the members E. Augustin, N. L. Byzova, M. Dupuy, M. Garstang, H. Hinzpeter, J. Z. Holland, M. Miyake, Y. Ogura, R. J. Polavarapu and N. Thompson. I wish to thank the members for their lively interest and their excellent cooperation during the planning phase.

References


The Radiation Subprogram for GATE

Helmut Kraus

International Scientific and Management Group for GATE

1. Scientific objectives

In the attempts to assess the influence of the smaller-scale tropical weather systems on the larger-scale circulations and finally to find out how to parameterize the subscale effects, radiative processes play an important role. This can be considered from different viewpoints.

The very general one is that radiation is the primary energy source for the generation and maintenance of atmospheric motion and the development of dynamic systems. Obviously there exists a considerable feedback of these systems to radiative fields, and the need for a better understanding of their interplay leads to a strong emphasis on studies about the interaction of radiative processes and the dynamics of the atmosphere. This interaction is of increasing importance with increasing scale of the system considered. But this does not exclude the significance of radiative processes for small-scale motions at all. Thus it has been frequently pointed out that, for example, radiative flux divergences play a considerable role in boundary layer processes and that there may be a strong direct influence of radiative cooling on single cumulus clouds in certain situations.

A more specific viewpoint exists in regard to the (slightly simplified) budget equations of thermodynamic energy and latent heat of water vapor (see for example Yanai et al., 1973)

\[
Q_1 = \frac{\partial \theta}{\partial t} + \nabla \cdot \mathbf{q} \mathbf{v} + \frac{\partial \bar{w}}{\partial p} = Q_R + L(c - e) - \frac{\partial}{\partial p} \frac{\bar{q} \omega}{\rho}
\]

(1)

\[
Q_2 = -L \left( \frac{\partial q}{\partial t} + \nabla \cdot q \mathbf{v} + \frac{\partial \bar{w} q}{\partial p} \right) = L(c - e) - L \frac{\partial}{\partial p} \frac{\bar{q} \omega}{\rho}
\]

(2)

The notation is conventional with \( s = \) dry static energy \( = e_s T + gz \) and \( q = \) specific humidity. The bar means a horizontal average over a certain area, which scale has to be defined for each specific investigation. With the right sides considered as the influence of subscale effects on the prognostic terms in the scale under consideration, the role of \( Q_s = \) area mean of radiative heating rate, becomes obvious. The magnitude and importance of \( Q_s \) compared with the apparent heating \( Q_1 \) and the apparent sink of latent heat \( Q_2 \) of the large-scale motion system became clear from various recent investigations of cumulus ensembles and areas in which mean values were formed for B-scale (100–1000 km) dimensions. Figure 16 presents an example from a study by Yanai et al. (1973) using Marshall Islands data. The integral

\[
\frac{1}{g} \int_{p_{top}}^{p} (Q_1 - Q_2 - Q_s) dp = - \frac{1}{g} \frac{h}{\omega} = F(p)
\]

(3)

from the top of the atmosphere down to a certain pressure level \( p \) represents the total vertical eddy transport of moist static energy \( h = e_s T + gz + Lq \) at \( p \) which can be considered as a measure for the activity of cumulus convection. Since \( Q_s \) is of the same order of magnitude as \( Q_1 - Q_2 \) in Fig. 16 and also in other studies (Nitta and Esbensen, 1973; Reed and Johnson, 1974), the significance of the B-scale radiative heating profile for budget and interaction studies in investigations of cumulus cloud ensembles is obvious. Figure 17 shows a comparison between \( F(p) \) computed according to Eq (5) after Yanai et al. (1973) and the vertical flux evaluated with the assumption \( Q_s = 0 \). This together with the fact that \( Q_s \) is not a rather constant quantity but very sensitive to the state of the atmosphere, especially to clouds, explains the significance of the study of the \( Q_s \) profiles during GATE.

Profiles of radiative fluxes include the boundary values at the top of the atmosphere to be measured by satellites and at the sea surface to be measured from on board the ships. These surface boundary values also represent an important input to the Boundary Layer Subprogram and to the Oceanographic Subprogram as a means to assess the surface energy balance and the energy input into the mixed layer of the ocean. Top atmospheric and surface boundary values also allow to compute the bulk radiation budget of the whole atmosphere for different scales as an associated experiment.

\(^{1}\) On leave from Meteorologisches Institut der Universität München.
FIG. 16. Scientific and observational objectives of the RSP. The quantities indicate (except $Q_0$, $Q_2$, $H_0$, $E_0$, and $B_0$) will be measured or computed within the efforts of the RSP. Most of them are explained in the text (see Sections 1 and 3). $a =$ surface albedo, $\lambda =$ wavelength, $\theta =$ zenith angle, $\phi =$ azimuth angle.

Thus the central objectives of the Radiation Subprogram (RSP) are focused on B- and C-scale studies of the large-scale radiative heating profiles and on the net radiation and its components at the ocean surface, the latter also as an essential input for air-sea interaction studies within the Boundary Layer and Oceanographic Subprograms. Figure 16 shows these objectives in a simple scheme. They will be assessed mainly for the GATE B-scale area, providing an essential input to the budget and interaction studies of the B- and C-scale triangles (see Convection Subprogram). It is planned that measurements and analysis within the RSP will lead to a determination of $Q_0(p)$ with the following resolution of time ($t$) and space: $\Delta t = 0.12$ hr and $\Delta x = \Delta y = 100$ to 500 km for B-scale investigations and $\Delta t = 3$ hr over a horizontal scale $< 100$ km for C-scale investigations. In both kinds of studies $\Delta p = 200$ mb will be used in order to achieve an accuracy of radiative heating rate

$$\left( \frac{\partial T}{\partial t} \right)_{rad} = - \frac{g}{c_p} \frac{\Delta Q^*}{\Delta p}$$

($Q^* =$ total net radiation) of 0.2 C/d or about 10% of the net radiative heating. For the surface fluxes the resolution in space is given by the surface network (see Fig. 18 and the more detailed information in the Ship Operations Plan), the resolution in time will be 1 hr for most purposes. In most cases the hourly mean values of surface fluxes will be gained by continuous recording or using high sampling rate (e.g. 60 per hour). Their error is expected to be smaller than (10 mly min$^{-1} + 5\%$ of the true value).

2. Parameterization

The determination of the profiles of the large-scale heating rates will depend on measurements as well as on rather sophisticated analysis efforts, finally on parameterization methods which are still under development. At this decisive point the RSP is exactly in the same position as the Convection Subprogram and the Boundary-Layer Subprogram: there are first approaches to the parameterization problem in all three fields, promising results (in both the Boundary-Layer Subprogram and the RSP for rather undisturbed areas) were obtained during the last years, but the final methods of coping with the strongly disturbed conditions, and with perhaps very different regimes of convection which are expected in GATE, have yet to be developed.

In principle there would be three ways to assess the four-dimensional radiative fields as we need them in GATE:

1) The first way is a pure interpolation method using measurements of radiative fluxes from all platforms and other data (e.g. cloudiness) to decide about variations between the measured points. But this approach is not applicable since the ratio of measured to needed data is too small.

2) The second way is to compute the whole field by radiative transfer calculations using actual parameters (distribution of temperature, humidity, clouds, aerosol). The measured values will then serve to check the computed fields and to update them at critical points. This method is obviously applicable for rather undisturbed situations. But it will mean
a very great effort for disturbed situations, when the atmosphere even between the active convective cells also shows a rather complicated cloud structure.

3) We must bear in mind that the data which can be measured, even using as many platforms as available in GATE, represent only a small amount of the data necessary to describe the whole field, and that for the application of the GATE results in numerical models nearly no direct measurements of the radiative fluxes will be available. Therefore the best way to use the data measured in GATE seems to be for the development of parameterization methods. The next step is then to apply these methods in order to assess the profiles of $Q_a$ for all the B- and C-scale areas (triangles) for which budgets will be computed. This can be done if the independent large-scale variable or variables (parameters) by which radiation heating is parameterized (e.g. type of cloud fields) can be obtained in sufficient resolution for the whole area.

There are several parameterization methods which will be further developed and used for the analysis efforts of the RSP in the above mentioned sense. They are not completely independent from each other since the physics of radiative transfer is basically taken into account in all of them. Besides, of more or less simplified computations from state parameters (this is not the place to refer to the numerous publications) there are two special parameterization efforts which should be mentioned here, the compositing technique and the regression technique.

The “compositing technique” (Cox, 1972 and 1973) assumes that with rather small variations of temperature and humidity, clouds are the primary modulator of radiative divergence in the tropics. Thus cloud properties (type, fractional cover, height of base and top, and optical thickness) are the main independent parameters to construct the tropospheric radiation field. For infrared radiation the scheme can be established by a rather straightforward coordination of measured (by aircraft and radiometers) heating-rate profiles and observed (e.g. from satellites) types of cloud fields. For solar radiation the problem is far more complicated because of the influence of the elevation angle of the sun and of the more complicated optical properties of clouds. Therefore, the investigations for establishing the method must take into account existing models of shortwave absorption for clear sky as well as for different types of clouds. Once the solar and infrared “models” of heating rate profiles which are dependent on cloud type are established, they can be applied to the large-scale cloud fields to be observed during GATE. The heating-rate fields can then be composited from the “models.” It is obvious that the experiment must be conducted in a way that measurements by aircraft and radiometers will be obtained for as many typical cloud fields as possible.

The “regression technique” computes the total infrared radiative heating as a sum over the radiative heating in special preselected wavebands, which are representative for the whole spectrum. The weighting coefficients for these wavebands are determined by regression from measured values of total and spectral heating rates.

Fig. 18. B-scale area ship distribution for phases 1 and 2 and planned radiation measurements from these ships. Scheme according to the latest ISMG ship distribution status.
Smith (1974), for example, uses the relationship

\[
\left[ \frac{\partial T}{\partial t}(\rho) \right]_{\text{TOTAL}} = \sum_{i=1}^{8} \alpha_i \frac{\partial T}{\partial t}(\rho, \Delta \lambda_i)
\]  

(5)

where the \( \alpha_i \) are the weighting coefficients and the \( \Delta \lambda_i \) are five spectral intervals including the window region and absorption bands of \( \text{H}_2\text{O} \) and \( \text{CO}_2 \). The experiments specially used for this technique will mainly be conducted from aircraft and satellites. They will enable the determination of the atmospheric transmission functions needed for the computation of the heating rate profiles for the specified spectral regions from state parameters. They will also provide the spectral heating rates and the total rate as a basis for the determination of the weighting coefficients. Once the transmission functions and the weighting coefficients are established for special types of cloudiness the total heating rate profile can be computed by the linear equation (5) using measurements of temperature, humidity, and cloud distribution as they can be derived, for example, from satellite experiments. Besides Smith, Ellington and Gille (unpublished) proposed a similar regression technique.

This is not the place to explain the analysis methods in sufficient detail. More information about parameterization of radiative processes was presented for example by Rodgers (1972). The problem of the cloudy atmosphere in relation to radiative transfer is well treated (e.g. Feigelson, 1973). More direct details concerning the GATE Radiation Subprogram can be found in GATE Report No. 4 (Kraus, 1973), and more recently in the Report of the Second Informal Planning Meeting for the RSP (1974).

3. Experimental design

This section contains a compilation of the experimental contributions to the RSP. It should be seen together with the scientific objectives sketched in Fig. 16.

The surface energy balance (serving as a boundary value of the \( Q_k \) profiles and for the Boundary-Layer Subprogram and the Oceanographic Subprogram) is formed by the surface net radiation \( Q_n \), the heat flux \( E_h \) below the surface, and the turbulent fluxes of sensible \( (H_0) \) and latent \( (E_0) \) heat in the air. An essential task of the RSP is to assess \( Q_n \). Basic measurements to do this will be performed from at least 27 ships. This (ideally) will give hourly mean values of \( Q_n \) and its components, the short-wave (in Fig. 16 indicated by K) and longwave (indicated by L) irradiances from above (4) and below (7), for almost the whole ship network. The surface observations will also help to assess the \( Q_n \) profiles by bulk measurements of atmospheric turbidity (made by photometers and phyrheliometers with filters from many ships) and cloud observations with all-sky and movie cameras. Figure 18 shows the B-scale area ship distribution for phases 1 and 2, and the planned radiation measurements from these ships. Note that there will be some changes in the inner hexagon in phase 3 (see Fig. 6 in the Central Program section).

The measurements of the profiles of radiative heating rate will be made by radiometers and aircraft. Sondes will be launched from 11 ships, mainly infrared sondes with a schedule according to the occurrence of the different types of cloud fields. Some daytime infrared sondes will be flown on an experimental basis. The aircraft will collect far more data than the sondes by using upward and downward looking broadband hemispheric pyranometers and pyrgometers and numerous spectral radiometers. The operational preparations have led to certain aircraft patterns which will best serve the scientific goals of the RSP.

Satellite measurements will be of critical importance by providing high resolution images in the visible and infrared range, (e.g. by the Visible and Infrared Spin Scan Radiometer on SMS-A) as an essential input into the parameterization schemes, by measuring irradiances and radiances for radiation balance computations and by special remote sounding experiments. There is a serious impact on the plans by the delayed launching of SMS-A and Nimbus F; but there are possibilities of recovering by using other satellites (especially Meteor 16 and 17, Nimbus 5, NOAA-2 and 5, DMSP, and ATS-5).

4. Data management and analysis

Data management within the National Processing Centers (NPCs) and the Subprogram Data Centers (SDCs) is a service to the international scientific community. The essential tasks are to assemble data, to validate them, and to produce validated and complete data sets as a basis for scientific analysis. The Radiation SDC will be in Leningrad at the Main Geophysical Observatory of the Hydrometeorological Service of the U.S.S.R.

5. Research participation

The institutes listed in Table 9 will participate in the experimental program and in the analysis efforts. The plans for the latter ones are already well developed along the lines described in Sections 1 and 2.

<table>
<thead>
<tr>
<th>Country</th>
<th>Organization or Institute</th>
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<tbody>
<tr>
<td>Canada</td>
<td>Atmospheric Environment Service</td>
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<tr>
<td>France</td>
<td>Centre Technique et du Material, Météorologie Nationale, Trappes</td>
</tr>
<tr>
<td></td>
<td>Laboratoire d’Optique Atmosphérique</td>
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<tr>
<td></td>
<td>Université de Lille</td>
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<tr>
<td>F. R. G.</td>
<td>Meteorologisches Institut der Universität München.</td>
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<tr>
<td></td>
<td>Institut für Meteorologie, Universität Mainz</td>
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<tr>
<td></td>
<td>Institut für Meereskunde der Universität Kiel</td>
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<tr>
<td></td>
<td>Institut für Geophysik und Meteorologie der Universität Köln</td>
</tr>
<tr>
<td></td>
<td>DFVLR-Institut für Physik der Atmosphäre, Oberpfaffenhofen</td>
</tr>
<tr>
<td>Mexico</td>
<td>Instituto de Geofísica, Universidad de Mexico</td>
</tr>
</tbody>
</table>

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Table 9. (continued).
Countries and institutes or organizations in the radiation subprogram.

<table>
<thead>
<tr>
<th>Country</th>
<th>Organization or Institute</th>
</tr>
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<tbody>
<tr>
<td>Netherlands</td>
<td>Koninklijk Nederlands Meteorologisch Instituut, De Bilt</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>Meteorological Office, National Institute of Oceanography, Wormley</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>Meteorological Research Flight, Farnborough Clarendon Laboratory, University of Oxford</td>
</tr>
<tr>
<td>U.S.A.</td>
<td>NOAA, Atlantic Oceanographic and Meteorological Lab., SAIL, Miami</td>
</tr>
<tr>
<td>U.S.A.</td>
<td>NOAA, National Environmental Satellite Service, MSL, Washington</td>
</tr>
<tr>
<td>U.S.A.</td>
<td>NOAA, Atmospheric Physics and Chemistry Laboratory, Boulder</td>
</tr>
<tr>
<td>U.S.A.</td>
<td>NASA-Goddard Space Flight Center, Greenbelt National Center of Atmospheric Research, Boulder</td>
</tr>
<tr>
<td>U.S.A.</td>
<td>The Eppley Laboratory Inc., Newport Department of Atmospheric Science, Colorado State University, Fort Collins Department of Oceanography, University of Miami Institute for Fluid Dynamics and Applied Mathematics, University of Maryland</td>
</tr>
<tr>
<td>U.S.S.R.</td>
<td>Main Geophysical Observatory, Leningrad Institute of Physics, Leningrad University Central Aerological Observatory, Moscow Institute of Atmospheric Physics, Moscow Institute of Atmospheric Optics, Academy of Sciences, Tonom</td>
</tr>
</tbody>
</table>

More details about all aspects of the RSP including the supporting programs using satellites, aircraft and ships as operational platforms can be found in GATE Report No. 4, and in the Report of the Second Informal Planning Meeting for the RSP.

Acknowledgments. The ISMG, in preparing this program, was assisted by the members of the GATE Radiation Working Group of the Radiation Commission of IAMAP (T. H. Vonder Haar, Chairman; H. J. Bolle; K. Hanson; C. D. Walshaw; V. P. Zhvalev) and by other experts, especially by S. K. Cox, K. Ya. Kondratyev, and E. Raschke. The author wishes to express his thanks to all of them for their excellent cooperation.

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The Oceanographic Subprogram

G. Philander

*International Scientific and Management Group for GATE, World Meteorological Organization*

1. Introduction

The GATE Oceanographic Program is a study of the response of the ocean-to-atmospheric forcing on various scales, and thus capitalizes on the detailed information about the forcing functions, particularly the surface winds, that will be available during GATE. Oceanic studies are usually divided into two groups: 1) studies of the (small scale) physical processes that determine the structure of the upper ocean which interacts with the atmospheric boundary layer, and 2) studies of the (large scale) oceanic currents and the coupling between these currents and the surface winds. Two sets of studies, which are discussed in detail in Sections 1 and 2 are of course closely related. For example, the depth of the mixed layer of the ocean depends on the structure of the thermocline below the mixed layer; in other words, on the large-scale oceanic circulation. Furthermore, horizontal advection by currents, and upwelling—a consequence of divergent surface currents—can critically affect the temperature and salinity distribution in the surface layers. Upper layer (small-scale) processes in turn have to be parameterized in models of the large-scale oceanic circulation because they are responsible for...
the transfer of significant amounts of heat, salt, and momentum.

Both components of the Oceanographic Subprogram contribute to the Central Program. The experiment on upper layer processes will provide estimates of the flux of momentum and of sensible and latent heat across the air-sea interface. Without knowledge of these fluxes a study of atmospheric convection will not be possible. The experiment on the tropical current system will clarify the role of these currents in determining the sea-surface temperature, which is known to influence the atmospheric circulation, and in particular the position of the ITCZ. Of special interest is equatorial upwelling with which is associated a band of anomalous cold water along the equator. This cold water not only suppresses atmospheric convection locally but also affects the atmospheric circulation in mid-latitudes (Rountree, 1972).

To meet the above objectives (and the others which will be described shortly) 27 of the vessels that will occupy assigned positions during GATE will make routine (3 hour) measurements of the temperature and salinity fields to a depth of 500 m. They will also make sections on their way to and from port; some of them will, in addition, measure currents and surface waves. These platforms will be complemented by nine research vessels roving in support of the oceanographic program, by arrays of instrumented moorings, and by aircraft equipped to measure the sea-surface temperature and surface wave field.

2. The experiment on upper layer processes

a. C-scale experiment

It is the object of this experiment, which will be conducted during Phase III, to elucidate the physical processes that determine the structure of the upper ocean. The experiment concentrates on the following phenomena.

Surface waves. Most of the momentum transferred to the ocean by the surface wind-stress is used to generate surface gravity waves. (For a review of the literature see Kraus, 1972). Numerical methods for the prediction of these waves have been developed but a data set is needed to test these models and to make possible improved parameterization of air-sea momentum transfer. The goals of the experiment require an array covering scales between 40 and 300 km. (These correspond to the estimated response scales of different regions of the wave spectrum). Figure 15 shows the positions at which the wave-rider buoys, and pitch-and-roll buoys (which are tethered to a ship) will be deployed. To overcome spatial aliasing problems, measurements will also be made with airborne laser instruments.

Mixed layer development. Some of the energy of the surface waves is transformed into turbulence when the waves break, some of the energy is transferred to a drift current. The vertical shear of this current and the breaking waves are sources of mechanical energy to mix the surface waters of the ocean. These are only some of the physical processes that models of the mixed layer should include; the absorption of available kinetic energy by inertial waves and the kinetic energy release associated with the shear at the interface of the mixed layer and the stably stratified fluid below are two further ones. The models recently proposed by Pollard et al. (1973), and Denman and Miyake (1973) both include only some of the above mechanisms. Neither includes effects associated with internal gravity waves or horizontal inhomogeneities such as fronts. Yet both yield plausible predictions concerning the development of the seasonal thermocline. There is obviously a need for more data to test these models, and for an experiment to reveal the relative importance of the various mixing processes.

The measurements in support of this experiment will be made from the platforms shown in Fig. 19. These include routine 3-hourly STD casts from on board the stationary vessels (note that the Quadra is free to rove for 50% of the time), and routine Profiling-Current-Meter measurements to a depth of 200 m from on board the Meteor, Planet and Cyre. There will, in addition, be high-resolution measurements with the following special instruments on board the Discovery and the Quadra: towed STD's (or batfish) that poirpoise between the surface and 200 m; and dropsondes (or free-fall devices) that make microstructure measurements which include the temperature, vertical gradient of the temperature, and vertical shear of the currents. Note that three of the instrumented moorings, those marked C on Fig. 19 and referred to as cyclosondes, have current meters that move continuously along the mooring-lines between the surface and 200 m every 30 min. Most of the moorings will have instruments to make meteorological measurements at the surface.

Internal gravity waves. The mooring marked F1 in Fig. 19 is a two-legged mooring, instrumented with current-meters and temperature sensors between the surface and a depth of 200 m along each leg, and along a 400-m horizontal line joining the two legs. This mooring and its companion marked F2 will permit determination of the frequency and wavenumber spectrum of internal gravity waves in two dimensions at scales upward of a few hundred meters. The other measurements to be made in the C-scale array will make possible the correlation of frequency spectra on scales between 3 and 40 km. Because of the detailed surface-wind information that will be available, a study of the effect of changes in the surface winds on the spectral properties of internal gravity waves will be attempted. It will be possible to investigate the interaction of internal gravity waves with the vertical shear of the current, and with surface gravity waves.

Fronts. Spatial variation of the surface winds implies a non-zero wind-stress curl and consequently Ekman divergence or convergence which may give rise to large horizontal gradients in the near-surface temperature.
field. (There are, of course, alternate mechanisms for the generation of fronts; see for example Hoskins and Bretherton, 1972). The dynamics of a front, the possibility of it being baroclinically unstable, and the manner in which it affects the upper ocean, will be investigated in the C-scale area during Phase III. To achieve these aims airborne radiation thermometer measurements over the whole C-scale area will complement the measurements by the roving vessels Discovery and Columbus Iselin and other platforms shown in Fig. 19.

b. Mixed layer budget study

This experiment will provide an accurate estimate of the heat and moisture fluxes across the air-sea interface on the B-scale and will thus contribute directly to an improved understanding of tropical convection in cloud clusters. The routine 3-hourly STD or hydrocasts on board the A/B-, B- and C-scale ships will make such estimates possible because the heat and salt budget of the mixed layer of the ocean can be related to the precipitation and to the sensible and latent heat exchange between the ocean and atmosphere (Ostapoff et al., 1973). The great variability in the surface salinity field on spatial scales of 15 to 30 km, the scale of convective elements, and a scale smaller than the spacing of B-scale platforms, may cause the local budget calculations to be subject to aliasing errors. There will, for this reason, be a detailed mapping of the temperature and salinity distribution in the A/B-B-scale area. This will be done on four occasions, between the phases of GATE, by B- and C-scale vessels sailing along parallel tracks 25-km apart and dropping XBT's every 10 km. There will, in addition, be a detailed mapping of the mixed layer during phase III by the Quadra and Discovery, which will tow porpoising STD's, and by the Columbus Iselin which will use a newly developed acoustic instrument (see Figs. 19 and 20).

c. Latitudinal variations of upper layer processes

It has been pointed out that upper-layer processes depend on the structure of the thermocline below the mixed layer. In the tropics the thermocline varies considerably with latitude. (Alternate bands of eastward and westward currents have been inferred from these variations). The result of the C-scale experiment may therefore not be representative of upper-layer processes over the whole tropical ocean. (The results will definitely not be valid at the equator where there is often no mixed layer at the surface, but where there is usually one below the core of the Equatorial Undercurrent). There will, for this reason, be a study of latitudinal variations of the upper-layer processes. Its measurement program will use selected A-scale ships, particularly the platforms along 23.5W (see Fig. 20). Special micro-
structure measurements will be made at the equator with
towed S1D's and free-fall devices (described earlier) from
on board the Discovery and Atlantis II.

3. Study of the tropical oceanic circulation
a. Description of the tropical current system

The major components of the current system in the
tropics are the coastal (boundary) currents, the zonal
equatorial currents that have been measured directly, and
the alternate bands of eastward and westward flowing
water that have been inferred from measurements of the
density field and calculations of the associated geo-
stric currents. The eastward currents are at first sur-
prising because the prevailing winds are westward and,
for this reason, are known as Countercurrents. Sverdrup
(1947), however, explained that the distribution of
gestrophic currents is a consequence of the curl of the
wind stress, rather than the intensity and direction of
the winds. A rigorous comparison between these theo-
retical results and measurements has however never been
possible since neither the winds nor the currents are
known with sufficient accuracy at the moment. It is one
of the objectives of the GATE Oceanographic Sub-
program to provide a quantitative description of the
tropical currents and to test these theories. Measurements
of the geostrophic currents will be made by ships on
their way to and from assigned positions before and
after each phase of GATE. Figure 21 gives an example
of the area to be covered by such measurements. Direct
measurements of the currents will be made from the in-
strumented moorings shown in Fig. 20.

b. A/B-scale dynamic response study

Because measurements along some of the tracks shown
in Fig. 21 will be repeated at various stages of GATE, it
will be possible to study the coupling between the entire
tropical current system and the large-scale wind system,
at low frequencies. An investigation of the dynamic
response of the extra-equatorial ocean at high frequen-
cies will be conducted in the A/B-scale area. This region
is particularly suitable for a study of the adjustment
problem (for recent reviews of theoretical work on the
response of the ocean to transient atmospheric storms
see Kraus, 1972; and Blumen, 1972) because in this
region it should be possible to associate uniquely the ob-
served oceanic perturbations with local forcing events:
there is a high probability that atmospheric disturbances
will be channeled along the predominantly zonal ITCZ
while neighboring latitudinal belts will be free of inten-
sive meteorological events. Current measurements from

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Fig. 20. Moorings, instrumented with current meters and temperature sensors, for the Equatorial and A/B-scale Experiments. The dashed lines across the equator denote tracks along which the Capricorne (10W), Discovery (22W), Alexander von Hum-
boldt (36W), and Columbus Iselin (28W) will make repeated sections.
moorings in the C-scale (Fig. 19) and A/B-scale (Fig. 20) areas will furnish information about the generation of gravity and inertial waves; routine density measurements from C, A/B- and B-scale ships will make possible a study of the ultimate adjustment of the ocean to a state of geostrophy.

This dynamic response study in the A/B area will yield a crucial parameter for the study of the budget of the mixed layer (also to be conducted in the A/B-scale area) namely the vertical velocity at the bottom of the mixed layer, and the amount of salt thus convected into the mixed surface layer. Given the latter quantity, and the measured salinity structure of the mixed layer, it will be possible to infer the amount of rainfall over the A/B area.

c. Equatorial Experiment

The Equatorial Experiment, to be conducted within 3° latitude of the equator, will concentrate on a study of the Equatorial Undercurrent. The mean state of this current is well known (for a recent review of the literature see Philander, 1973) and there are numerical models capable of simulating many of the observed structural features associated with the mean state. There is, nonetheless, a need for measurements to clarify certain aspects of the dynamics of the Undercurrent; for example, is the zonal pressure gradient the primary source of momentum? There is also a need for a data set to test the numerical models. Furthermore, very little is known about the westward Intermediate Equatorial Current below the eastward Undercurrent, and its role in the tropical oceanic circulation is unclear. The measurements to be made during the Equatorial Experiment will provide answers to the above questions. This, however, is not the primary aim of the experiment.

The Equatorial Experiment has been designed to determine the spatial and temporal scales of transient equatorial phenomena (both neutral and unstable waves), and to study their interaction with the equatorial currents. There is, unfortunately, very little information about these waves that can be used in the design of the experiment. A 22-day current meter record obtained in the spring of 1970 at a depth of 120 m at 1N 150W showed a near linear increase in the zonal velocity at that position (Taft et al., 1974). This has been interpreted as a meridional displacement of the core of the Undercurrent, suggesting that it meanders. There are theoretical indications that the horizontal shear of the Undercurrent is such as to cause waves with a growth rate of approximately ten days, a wavelength of about 700 km, and a period of 22 days. (The waves propagate eastward at a speed less than that of the core of the Undercurrent). Perturbations antisymmetric about the equator have the largest growth rates so that these instabilities will indeed cause the Undercurrent to meander.
Further mechanisms for the generation of trapped equatorial waves include the following: sudden changes in the local atmospheric forcing; the presence of waves in the local surface winds; the current meter record of Taft et al., 1974, gave clear indications of waves with a period of four to five days forced by oscillations in the meridional component of the surface wind; non-local forcing such as storms coming off the South American continent in mid-latitudes. These storms could generate Kelvin waves that travel northward along the coast of South America as far as the equator and then eastward along the equator). Because the spatial and temporal scales of the forcing functions are not known, analytical results concerning these trapped equatorial waves cannot be used to predict their wavelengths and frequencies. Indeed, it is even questionable whether these analytical models (Lighthill, 1969; Moore, 1968; Gill, 1973) are relevant to the Atlantic; they neglect the equatorial currents with which are associated strong horizontal and vertical shears.

The only available estimate for the longitudinal wavelength of transient equatorial phenomena is approximately 700 km. Platforms will therefore be spaced in such a manner as to ensure resolution of waves with a longitudinal wavelength between 200 and 2000 km (see Fig. 22). The use of towed STD's on two of the mobile ships Discovery and Atlantis II, and measurements from on board the roving Trident will improve the spatial average. The core of the experiment will be conducted during Phase II in the region west of 22W because the smooth bottom topography in this region (smooth relative to the topography immediately east of 22W), is an important factor in the installation of moorings, and because perturbations associated with the southern coast of West Africa will not affect equatorial phenomena at these longitudes.

The meridional spacing of moorings (see Fig. 20) is such as to ensure resolution of the Equatorial Undercurrent and of trapped equatorial waves (which have an amplitude that decays rapidly with latitude). The vertical spacing of current meters on each mooring has been determined on the basis of what is known about the vertical distribution of currents near the equator, and, to a lesser extent, on the basis of what is thought to be the vertical modal structure of neutral equatorial waves. The horizontal currents will be measured continuously to a depth of 500 m with Profiling Current Meters (Düing and Johnson, 1972) at the moorings marked P in Fig. 20. The vessels making repeated meridional sections along 28W (Columbus Iselin) and 26W (Alexander von Humboldt), and near 10W (Capricorn), and the vessels stationed on the equator at 29W (Anton Dorn) and 23.5W (Akademien Kurchatov) will convert their relative velocity measurements to absolute velocity measurements by using the P moorings as reference buoys.

Lighthill (1969) has suggested that the westward traveling equatorial waves, on reaching the western extreme of the oceanic basin, give up their momentum to the coastal current at the boundary, the northward flowing Brazilian coastal current in this case. This current

![Fig. 22. Measurements on the equator.](image-url)
is of course also affected by the local winds. It should, however, be possible to distinguish between the effects of the local winds and those of westward traveling equa-
torial waves on the Brazilian coastal current because the
monsoons that generate the waves occur only in the Gulf
of Guinea, far from the Brazilian coast. (This distinction
is possible in the Atlantic but not the Indian Ocean). An
experiment to monitor the transport of this coastal cur-
current would therefore be extremely valuable, and will be
conducted by the ships Mariano Mutamoros and Gyre.

4. Data management
The Centre Oceanologique de Bretagne in Brest, France,
will be the international data center for the Oceanog-
ographic Subprogram. All Oceanographic data, including
high resolution data obtained with special instruments,
will be available at the resolution provided by the prin-
cipal investigators. The high resolution data will also be
available in reduced form: towed STD measurements, for
example, will be averaged in such a manner as to pro-
vide data similar to those obtained by conventional
STD casts at fixed points; data from the surface wave
experiment will be available as banded spectra.

5. Participating institutions
Table 10 lists some of the institutions participating in
the field phase of the Oceanographic Subprogram.

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Table 10. Countries and institutes or organizations partici-
   pating in the field phase of the oceanic subprogram.

<table>
<thead>
<tr>
<th>Country</th>
<th>Institute or Organization</th>
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</thead>
<tbody>
<tr>
<td>Brazil</td>
<td>Univ. of Sao Paulo; Hydrographic Office, Rio de Janeiro</td>
</tr>
<tr>
<td>Canada</td>
<td>Univ. of British Columbia; Bedford Institute of Oceanography</td>
</tr>
<tr>
<td>F.R.G.</td>
<td>Univ. of Hamburg; Univ. of Kiel</td>
</tr>
<tr>
<td>France</td>
<td>Centre Oceanologique Bretagne; O.R.S.T.O.M. (Abidjan)</td>
</tr>
<tr>
<td>G.D.R.</td>
<td>Institut fur Meereskunde, Warnemunde</td>
</tr>
<tr>
<td>Mexico</td>
<td>Univ. of Mexico; Secretaria de Marina</td>
</tr>
<tr>
<td>Netherlands</td>
<td>Koninklijk Nederlands Meteorologisch Instituut</td>
</tr>
<tr>
<td>United</td>
<td>Univ. of Liverpool; Univ. of Southampton; Institute of Oceanographic Sciences (Godalming)</td>
</tr>
<tr>
<td>Kingdom</td>
<td></td>
</tr>
</tbody>
</table>
| U.S.A.      | Univ. of Miami; Univ. of Rhode Island; Texas A and M Univ.; Woods Hole Ocean-
              | ographic Institution; National Oceanic and Atmospheric Administration (Miami,            |
              | Rockville, Seattle)                                                                      |
| U.S.S.R.    | Hydrometeorological Service; Arctic and Antarctic Research Institute (Leningrad);      |
              | Institute of Oceanology (Moscow); Ukrainian Academy of Sciences; Atlantic Research      |
              | Institute of Marine Fisheries and Oceanography                                          |

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