GLOBAL ATMOSPHERIC RESEARCH PROGRAM

GATE

ATLANTIC TROPICAL EXPERIMENT

This issue of *ATMOSPHERE-OCEAN* is devoted to the results of the Canadian participation in GATE (GARP Atlantic Tropical Experiment) which forms part of the Global Atmospheric Research Programme (GARP).

A Review of the GARP Atlantic Tropical Experiment (GATE)

R.J. Polavarapu
Atmospheric Environment Service
Downsview, Ontario

and

G.L. Austin
Stormy Weather Group, McGill University
Montreal, P.Q.

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ABSTRACT *The GATE experiment has provided a unique high quality data set for the tropical atmosphere and ocean. Progress in the analysis of the data has been considerable and is briefly reviewed here. The wider usefulness and availability of the data for other research studies is discussed.*

RÉSUMÉ *L'expérience tropicale atlantique du GARP a fourni des données uniques et de bonne qualité pour l'atmosphère et l'océan tropical. Le progrès des analyses des données est considérable et il est revu en bref. L'utilité des données pour d'autres études est discuté.*

1 Introduction

The Joint Organizing Committee of GARP states that "The Global Atmospheric Research Programme (GARP) is a programme for studying those physical processes in the troposphere and stratosphere that are essential for an understanding of:

(a) The transient behaviour of the atmosphere as manifested in the large-scale fluctuations which control changes of the weather; this would lead to increasing the accuracy of forecasting over periods from one day to several weeks;
(b) The factors that determine the statistical properties of the general circulation of the atmosphere which would lead to better understanding of the physical basis of climate".

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The combination of the major role of the tropics in the atmospheric energy balance and our relative lack of understanding of tropical atmospheric processes has resulted in special emphasis on the tropics in the planning of many of the GARP activities.

The GARP Atlantic Tropical Experiment (GATE), a major regional experiment of GARP, was carried out in the summer of 1974 under the aegis of the World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU). The experiment covered approximately one-sixth of the Earth's tropics, with emphasis on an area of about 500,000 km^2 located 1,000 km west of Senegal in the eastern Atlantic Ocean.

2 Scientific programme

The objectives of GATE are to explore the mechanisms by which the solar heat stored in the tropical oceans drives the global circulation of the atmosphere and to incorporate these mechanisms into numerical models.

The primary objectives of the Central Programme are:

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

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 and of the basic state in which they are embedded.

The second objective can be achieved by providing a good tropical data set and by an advance in parameterization techniques. The various scales of atmospheric phenomena in the tropics are depicted in Fig. 1.

The largest scale, the A-scale (10^3 to 10^4 km), which is called the "wave scale" includes easterly waves, Rossby-gravity waves and Kelvin waves. These waves have relatively long life-times, sometimes several weeks, as they travel considerable distances around the world.

The next smaller, the B-scale (10^2 to 10^3 km), is the important scale on which tropical "cloud-clusters" develop. They form the link between the short-lived smaller scale convective elements and the longer-lived tropical waves. The description of their structure and life cycle and the study of their role in the energetics of the tropical atmosphere comprise one of the main objectives of GATE, which has therefore sometimes been called a "cloud-cluster" experiment.

The C-scale (10 to 10^2 km), also known as the "meso-scale", includes structures of organized convection that form the sub-systems of the cloud-clusters.

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".

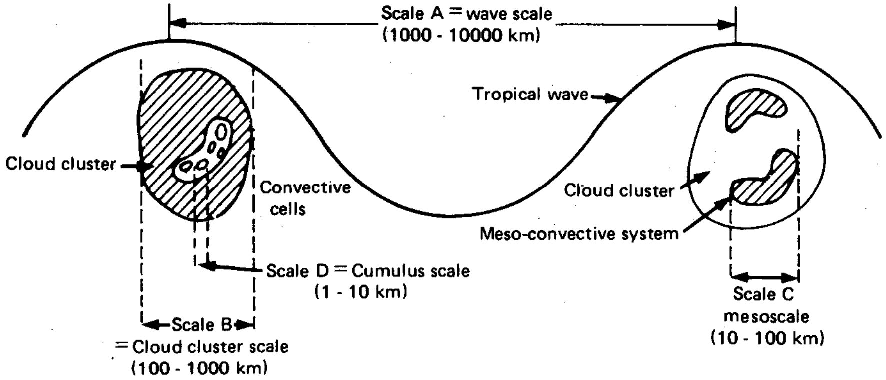

Fig. 1 Scales of atmospheric phenomena in the tropics.

One might, in fact, view this scale interaction as three problems, each involving the parameterization of one scale in terms of the next larger one. The ultimate problem to be solved in this hierarchy of studies is that of defining the interactions between cloud-clusters and large-scale systems, the evolution of which we wish to predict.

The magnitude of the scientific programme made it necessary to break it down into five subprogrammes: The Synoptic-Scale Subprogramme; the Convection Subprogramme; the Boundary-Layer Subprogramme; the Radiation Subprogramme; and the Oceanographic Sub-programme. The central programme and the subprogrammes are described by Kuettner (1974), Parker (1974), Rodenhuis (1974), Hoeber (1974), Kraus (1974) and Philander (1974).

3 Field phase of GATE

To understand the interrelations between the various scales of motions and convective organization, the field phase of GATE was carried out in the summer of 1974. During the experiment, weather systems were observed by satellites, planes, ships, and a network of land stations reaching from the west coast of Latin America eastward to the east coast of Africa, between 10°S and 20°N as shown in Fig. 2.

Nearly a thousand land stations provided surface weather and rainfall reports. A smaller network of stations – generally about 500 km apart – took upper-air soundings of temperature, air pressure, humidity, and wind twice each day.

Of the 38 participating ships from ten nations, about half were stationed at points 500 to 1,000 km apart across the Atlantic Ocean, and measured sea-surface temperature, wind speed, barometric pressure, temperature, and humidity near the sea surface and in the upper air.

To study the internal structure of tropical cumulus clouds and cloud-clusters, fourteen ships were concentrated within an area of about 500,000 km^2 in the eastern Atlantic, 1,000 km from the African coast, as shown in Fig. 2. The hexagonal area was bounded by six Soviet ships. Within

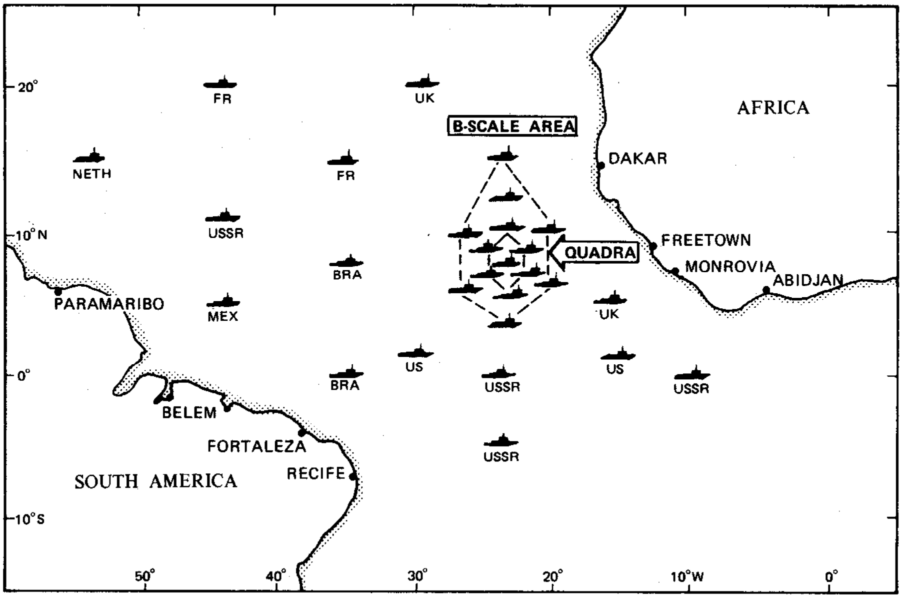

Fig. 2 Ship array in Phase 1 of GATE.

the hexagon was an even denser formation of seven ships from the United States, the Soviet Union, Canada, and the Federal Republic of Germany, stationed about 150 km apart. The Canadian Coast Guard Ship *Quadra* was one of the seven key ships stationed in that core area.

Vessels in the eastern Atlantic array used radars, upper-air sounding systems, and sensors held aloft by tethered-balloons and mounted on booms extending forward from the ships, to measure winds, air pressure, temperature, humidity, rainfall and precipitation, solar and infrared radiation, and sea-surface temperature. Instruments were lowered into the sea to measure ocean temperature, salinity, and currents. Some 65 moored buoys were deployed by the GATE ships to gather data on temperature, salinity and currents in the ocean, make weather observations near the sea-surface, and serve as reference points for navigation.

Along the Equator, roving and stationary oceanographic vessels gathered data on coastal and equatorial currents, the equatorial undercurrent, and other aspects of tropical ocean circulation. Ocean studies within the concentrated array focussed on the processes in the uppermost layer of the ocean where the effects of local atmospheric conditions are most felt – surface and internal waves, oceanic fronts, and the development of the mixed layer.

Flying at altitudes from 100 m to more than 10 km, 13 instrumented-aircraft from five nations gathered atmospheric and ocean measurements, principally over the concentrated array. They probed the cores of cloud-clusters, investigated the Inter-Tropical Convergence Zone (levels of the atmosphere where high winds bring clouds together), ocean waves and surface temperatures, radiation, tropical disturbances and dust layers moving off the African continent, day-night weather changes in the coastal area, and other atmospheric phenomena.

Six kinds of spacecraft scanned the entire experimental area furnishing day-and-night information on cloud systems, their liquid water content, the height and temperature of cloud tops, the speed and direction of cloud movement, air temperature and moisture and sea-surface temperatures.

The experiment was divided into three 21-day experimental periods (Phases 1, 2 and 3) scheduled between 26 June and 19 September, 1974. In addition there were three intercomparison periods for checking instrument packages on each ship with those on the other ships.

Nations that provided ships or aircraft for the GATE project were: Brazil, Canada, France, the Federal Republic of Germany, the German Democratic Republic, Mexico, the Netherlands, the United Kingdom, the Soviet Union, and the United States.

The field phase of GATE may indeed be termed a major scientific step forward. In addition, however, it is a remarkable example of how different nations of the world are able to co-operate in a full and friendly manner to achieve a common scientific goal.

4 Data management

The National Processing Centre (NPC) of each participating country has processed the data it collected and deposited them in the five international Subprogramme Data Centres (SDC's): (a) Synoptic Subprogramme Data Centre (SSDC), Bracknell, U.K.; (b) Convection Subprogramme Data Centre (CSDC), Washington, D.C., U.S.A.; (c) Boundary-Layer Subprogramme Data Centre (BSDC), Hamburg, F.R.G.; (d) Radiation Subprogramme Data Centre (RSDC), Leningrad, U.S.S.R.; (e) Oceanographic Subprogramme Data Centre (OSDC), Brest, France. The Subprogramme Data Centres have validated the data and deposited them in the World Data Centres located in Asheville, U.S.A., and Moscow, U.S.S.R., from which they are available to users of all nations.

5 Canadian contribution

The Scientific programme carried out on board the Canadian Coast Guard Ship *Quadra* represents the major Canadian contribution to GATE. In this article we have emphasised the papers appearing in this issue of *ATMOSPHERE-OCEAN*. The programme included:

1. hourly surface observations;
2. upper-air soundings every 3 h;
3. radar mapping of precipitation areas every 5 min;
4. measurement of boundary-layer profiles at the surface and from a tethered-balloon;

5. measurement of radiation components at the surface including cloud photography;
6. measurement of salinity-temperature-depth profiles including sea-surface temperature.

Some of the significant aspects of the Canadian programme can be briefly described. A major contribution was provided by the radar on board *Quadra*. Radar pictures were transmitted in near real-time from *Quadra* to the GATE operational Control Centre, Dakar, Senegal, to assist in the planning and operation of the GATE experiment, particularly the aircraft programme. It has been acknowledged by WMO that without the radar pictures and the communications support given by *Quadra*, the aircraft programme would have been far less effective.

The Canadian programme was one of the most extensive conducted during GATE. Activities carried out on *Quadra* that were in addition to the regular programme, and usually only conducted from 1–5 other ships, are identified with an asterisk (*).

The radar was used mainly for mapping rainfall rates at 5-min intervals in horizontal layers approximately 1 km apart and with a spatial resolution of approximately 2 km × 2 km. The data were recorded both on photographs and on magnetic tape. An additional use for the radar was in tracking 104 of the scheduled 504 radiosonde flights in order to* compare the winds derived from radar and very low frequency (VLF) navigation system used aboard *Quadra* to monitor upper-air flights. All flights were* processed for mandatory and significant levels; about 90% were also processed with 5-mb resolution. The wind data from radar-tracking were recorded at 1-min intervals.

The main contribution from the boundary-layer programme was the operation of a shipborne tethered-balloon carrying two sondes at different levels. With this system wind speed and direction, temperature, humidity and pressure were measured from the sea surface to the cloud base, as shown by Mickle and Davison (1979). The same system was also used to monitor the fluctuations in the above meteorological parameters keeping one sensor in the mixed layer and the other sensor in the cloud layer. Surface-layer* profiles of wind and temperature were also measured from sensors mounted on a boom extending from the bow of the ship (Fig. 3).

The radiation components measured on board *Quadra* were the *total radiation ($Q\downarrow$), *net all-wave radiation (Q^*), using two sensor-halves and also a single sensor, incoming solar radiation ($K\downarrow$), reflected solar radiation ($K\uparrow$), and outgoing surface long-wave radiation ($L\uparrow$). The *incoming long-wave radiation ($L\downarrow$) was obtained as ($Q\downarrow - K\downarrow$). All-sky photographs were taken every 5 min.

The net radiation was measured by two different techniques to aid an assessment of errors. From these measurements Polavarapu (1978) showed that the net radiation measured by a single sensor was undervalued during the day-time by up to a maximum of 3% due to the screening of part of $Q\downarrow$ by the

Fig. 3 The Canadian Coast Guard Ship *Quadra*.

ship's superstructure. As a result the net radiation data obtained with the single sensor were not archived in the WDC's. However, care must be used in comparing the net radiation data from *Quadra* with that from other ships, since their Q^* measurements were made with a single sensor.

The accurate measurement of net radiation at sea is very difficult. However, Polavarapu (1979) using the *Quadra* data showed that Q^* can be estimated from measurements of $K\downarrow$ or $Q\downarrow$ to the same accuracy as that of measurement. Polavarapu (unpub.) also showed that in calm waters, such as the Atlantic Ocean in the GATE area, the albedos evaluated from measurements of $K\downarrow$ and $K\uparrow$ are in good agreement with those obtained theoretically. Hence, the measurement of $K\uparrow$ in calm waters is not necessary. However, the albedo data from some of the other ships seem to be in error since the bow of the ship is within the view of the sensor used to measure $K\uparrow$.

The validated radiation data from *Quadra* have been used by Cram and Hanson (1977) as an independent check in validating the American data.

The atmospheric long-wave radiation data were used by Davies and Uboegbulam (1979) to check their parameterization schemes for estimating long-wave radiation from the atmosphere.

The oceanography programme mainly consisted of measuring the temperature and salinity of the upper 500 m of the ocean every 3 h throughout the three phases of GATE. During Phase 3, a special device* known as the porpoising batfish was towed to measure salinity and temperature as a function of depth and horizontal distance. A surface mooring* was also deployed with 4 current meters and a chain of thermistors to continuously monitor the changes in the upper layers of the ocean.

Other measurements from *Quadra* included* true wind speed and direction (compensated for the ship's movement),* air temperature and dew point measured from the sensors mounted on the boom which extended from the bow of the ship (Fig. 3). The surface boom measurements were made to minimize the effect of the ship's environment on the data. Sea-surface temperature was measured by four different methods namely, *surface float, *infrared thermometer, bucket samples and salinity-temperature-depth soundings. In addition to the standard rain gauge measurements, the *intensity of precipitation was recorded using a specially made dual-funnel rain gauge. The *beginning and ending times of precipitation events were also recorded with an electronic device.

6 Progress in GATE-related research

Since the final GATE data sets have become available only recently it is premature to make a critical review of progress of GATE-related research. However, a brief review is helpful in identifying the future needs for meeting the central programme objectives of GATE. Some of the highlights of progress to date are compiled from published results in GATE (1975), the U.S. GATE Central Program Workshop (GATE, 1977) as well as from scientific presentations made in conferences such as the WMO Technical Conference on GATE Data Utilization and the 11th Technical conference on Hurricanes and Tropical Meteorology. These comments will, of necessity, reflect the personal biases of the authors.

a *Boundary Layer*

The three Phases of GATE were characterized by very limited ranges of wind speed, stability (always slightly unstable), and sea-surface temperature. A simple bulk aerodynamic approach for calculating the fluxes has proven to give satisfactory results on the average. Nevertheless, more detailed studies of the turbulence structure of the surface layer show that individual averages up to 1 h, under seemingly similar situations, indicate fluxes that differ by a factor of two. Hence, it seems that the structure of the surface layer is not uniquely determined by the mean quantities alone. A beginning has been made to analyze this structure in more detail by considering possible effects of the height of the boundary layer and the large-scale convergence or divergence on the surface layer. It may well be that this type of investigation will lead to a better insight into the mesoscale interaction with the surface layer as well as with the mixed layer as a whole.

The structure of the mixed layer has been described by data from tethered-balloon systems (Canada; F.R.G.; U.S.A.; U.K.; U.S.S.R.) structure sondes, radar-tracked targets, pilot balloons, acoustic sounders, and aircraft. Analyses to date show a high degree of agreement among this wide variety of measurements. There was remarkable agreement in the vertical distribution of the fluxes as calculated from aircraft, tethered-balloon measurements and the budgets.

The structure of convection is still poorly understood. Plume-like convection elements are a dominant feature in the slightly unstable mixed layer; sometimes they penetrate the mixed layer and trigger convective clouds. Dynamical models to understand the convective plumes are yet to be developed.

A valuable data set has been collected within the boundary layer which has led to an improved understanding of the structure of the tropical boundary layer. Some insight has been gained into the interaction between the boundary layer and the larger mesoscale phenomena.

b *Radiation*

The basic radiation data set is composed of observations of upward and downward short-wave and long-wave fluxes made from ship, balloon, aircraft and satellite platforms. The data set is of sufficient quality to specify the radiative flux divergence to within ±0.2°C/day/200 mb at specific times and locations.

In order to ensure consistency between the surface, aircraft, radiometersonde, and satellite radiation data sets, a systematic comparison of appropriate data needs to be made.

It has been established that the vertical profiles of radiative heating are substantially different in the disturbed and undisturbed regions[1]. The studies to date have shown that the different heating profiles can have a significant effect on the synoptic-scale wave dynamics.

The emissivities of cirrus clouds and high middle clouds were observed to be significantly higher than expected. Cloud and cloud-free radiation differences are as large as the infrared cooling itself. These cloud and cloud-free differences may contribute a significant feedback to the mesoscale circulations.

In the ship array, the dust aerosols were more plentiful than sea salt particles below cloud base on most days. At levels above 900 mb, very few salt particles were observed, but the dust particles, which can act as ice nuclei, were quite numerous during major outbreaks.

Model calculations in the dust layer indicate that solar radiation may produce warming of 2°C per day from 900 to 500 mb during intense dust outbreaks near the coast of Africa. It is not yet clear to what extent this heating is compensated by long-wave radiational cooling.

c *Convection Studies*

Case studies of convection have led to some clarification of the relationship between the mesoscale fields and the distribution and intensity of precipitation[2]. However, due to the lack of economical techniques to reduce the labour required to integrate the satellite, radar, synoptic and aircraft data, the effort required for these studies remains high.

Compositing studies have led to some progress in establishing the relationships between the forcing synoptic-scale waves and the convective activity. It is now fairly clear that the vertical motion fields associated with the easterly waves have an enhancing effect on convective activity. The case-to-case variability is very large, however, and the utility of these results in a short-term predictive scheme is probably quite limited.

Attempts to parameterize the convection, i.e. to relate mean properties of the convective activity (e.g. vertical mass transports) to the larger scale, have met with some success and some difficulties. Clearly the problem reduces to two factors.

1. To what extent do the large-scale fields force the convection and give predictable amounts of convective activity?
2. To what extent can the effects of these convective elements on the larger-scale fields be predicted?

It is an added difficulty in these studies that these two questions are interlocked, so that one is frequently faced with disentangling the two questions at the same time. There seems, however, little doubt that these questions are tractable with the radar, satellite, synoptic and boundary-layer data sets available.

[1]See, for example, Cho et al. (1979).
[2]See, for example, Mower et al. (1979).

d *Synoptic-Scale Studies*

The testing of the parameterization schemes mentioned above in large-scale models has been given some attention. It is not easy, however, to separate problems related to data initialization, the accuracy of the parameterization, and problems in the physics of the numerical models. More work is needed to devise diagnostics to clarify the situation.

Since final high quality data sets have only recently become available and several large groups are currently working on these problems there is a reasonable expectation that the amount of activity in this area will be significant for the next few years. It is to be hoped that this will lead to significant improvements in the modelling and numerical forecasting of tropical weather systems.

e *Oceanography*

The two objectives of the GATE oceanography programme were to study the upper layers of the tropical ocean with a view to evaluating the effect of weather systems on that layer, and to study the tropical currents and their variability.

The results published so far seem to indicate little response of the upper ocean to small-scale weather systems but rather seem to depend on long time-scale events of a duration measured in weeks. This would seem to suggest that the major surface layer features including sea-surface temperature are determined by changes in the mean currents. Data analysis to discover whether the seasonal movement of the Inter-Tropical Convergence Zone has any effect on the oceanic fields has not as yet been published to the authors' knowledge but is clearly an interesting problem.

7 Impact of GATE on Canadian meteorology

Clearly the objectives of GATE, particularly those directed towards improving long-range numerical weather prediction, have an immediate impact on meteorologists working in any part of the world. A different aspect of GATE, and one we believe is not sufficiently well known to Canadian meteorologists, is the quality and quantity of data archived as part of the GATE experiment. These data sets may be very easily obtained and allow studies involving simultaneous boundary-layer, radiation, oceanographic, aircraft, satellite, radar and synoptic data sets. The quality of the data is generally very high and the spatial and temporal resolutions are much better than any comparable set for mid-latitudes of which we are aware. The geostationary satellite data, for example, are considerably better than the mid-latitude sets because of the more nearly vertical viewing angle and also may be obtained very easily. Similarly the synoptic data have a 150-km grid at the centre of the array and a 3-h time scale.

We believe, therefore, that the GATE data should not only be used for studies directed towards the objectives of GATE but also as a data test bed for developing procedures, techniques and analyses in other areas of meteorology. The GATE data set is an extremely valuable resource which should be more widely used by the meteorological community if the considerable expense and effort expended in its collection are not to be wasted.

Scientists wishing to use the GATE data are encouraged to communicate directly with any of the authors of the papers in this issue of *ATMOSPHERE-OCEAN* or to write directly to Mr Bob Williams, WDC-A, GATE, Federal Building, Asheville, NC 28801, to obtain a catalogue of the available data.

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