The Boundary-Layer Subprogram for GATE

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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 CISK 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 baroclinity 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-

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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-borne 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

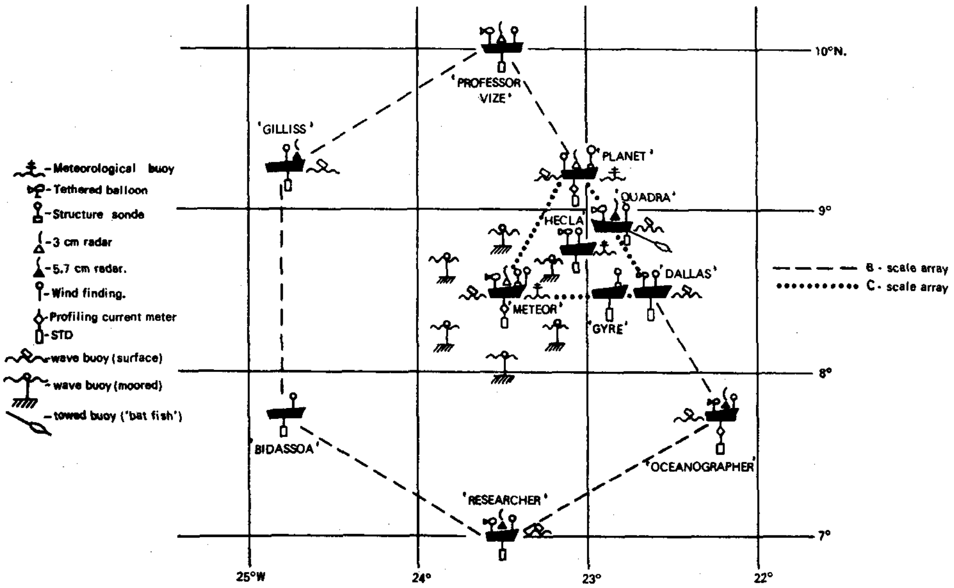

FIG. 15. Meteorological and oceanographic observing systems of research ships in the inner East Atlantic Array for phase III. Surface buoys, tethered balloons, structure sondes, and low-level windfinding systems support the Boundary-Layer Subprogram; current meters, STDs (salinity, temperature and depth sounders), wave-measuring buoys, and towed probes are part of the Oceanographic Subprogram.

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 Moriniere, 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.

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

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