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BOMEX: An Appraisal of Results

A major oceanographic and meteorological experiment provides scientific insights and administrative lessons.

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During the months of May, June, and July 1969 the observational phase of the Barbados Oceanographic and Meteorological Experiment (BOMEX) was carried out in the region of the tropical Atlantic to the east of the island of Barbados. The observations provided data for 100 investigations on a wide range of meteorological and oceanographic problems; about 45 of these investigations were led by scientists from universities and research institutes in the United States and Canada, an equal number were led by U.S. government scientists, and the remainder were led by scientists from industrial laboratories. The government of Barbados cooperated in the program through providing logistical facilities, and the Project Field Office was located at Seawell Airport, Barbados.

Observations were made from satellites, 12 oceanographic ships including the Navy floating instrument platform (*FLIP*), the Florida State University buoy *Triton*, and 28 aircraft. About 1500 persons participated in the program. The total expenditures associated with BOMEX have been in the neighborhood of $30 million, the largest part reprogrammed from federal agency budgets supporting the operations of the ships and aircraft used in the field observations. Included in this sum were grants made by the National Science Foundation, totaling $1.3 million, chiefly to university and institute scientists working on BOMEX projects.

This program has been a major scientific enterprise in which government, university, and industrial personnel have worked closely together. Further large field investigations of the atmosphere-ocean fluid dynamical system will be indispensable in order to extend the range of weather prediction, to anticipate the effects of increased pollution or other modifications of the air, sea, or land, and to develop an understanding of the mechanisms of climate change. It is important, therefore, to identify the chief scientific accomplishments of BOMEX and to assess the administrative lessons that may be useful in planning for future investigations.

This appraisal is based on (i) the initial published results from BOMEX, which have begun to appear in the literature within the last year; (ii) discussions carried on by the Barbados Oceanic and Meteorological Analysis Project (BOMAP) advisory panel of the U.S. committee for the Global Atmospheric Research Program (NASC/GARP) (*1*), of which I have been chairman; and (iii) personal participation in one BOMEX research program. It is limited to topics related directly to the primary goals of the program.

The story of BOMEX begins with discussions of the National Academy of Sciences (NAS) Joint Panel on Air-Sea Interaction in 1960 and 1961 (*2*). The panel recognized a critical lack of reliable, data, especially near-surfaced measurements of the vertical fluxes of water vapor, heat, and momentum or data relating these quantities to observations of wind speed, temperature, and humidity. The panel proposed, among several recommendations, that field studies be carried out to supply these data and to extend understanding of the physical processes of transfer at the sea surface. In 1966 the NAS Committee on Atmospheric Sciences report on the feasibility of a global observation and analysis experiment (*3*) called attention to the importance of such field investigations as a step in simplifying the processes of energy transfer for use in computer models of the general circulation of the atmosphere. A general plan for a series of field programs was described in that report. BOMEX provided the first opportunity to secure these data on a comprehensive scale, although pilot studies had been carried out as part of the International Indian Ocean Expedition by the University of Washington and the Woods Hole Oceanographic Institution in 1964 (*4*) and the Barbados Air-Sea Program of Florida State University in 1968 (*5*). Detailed plans for BOMEX were developed by the late B. Davidson (*6*), and progress reports have been published by Kuettner and Holland (*7*) and Holland (*8*).

BOMEX was conceived in 1961; an initial appraisal of results is possible in 1971. Perhaps the first conclusion to be drawn from BOMEX is that for an administratively complex research program the time elapsed from conception to assessment of results is equal to or greater than one decade.

The central objective of BOMEX, narrowly stated, was to compare vertical fluxes measured on the synoptic scale over the tropical ocean using budget methods with independent measurements made by other methods. Most important was vertical vapor

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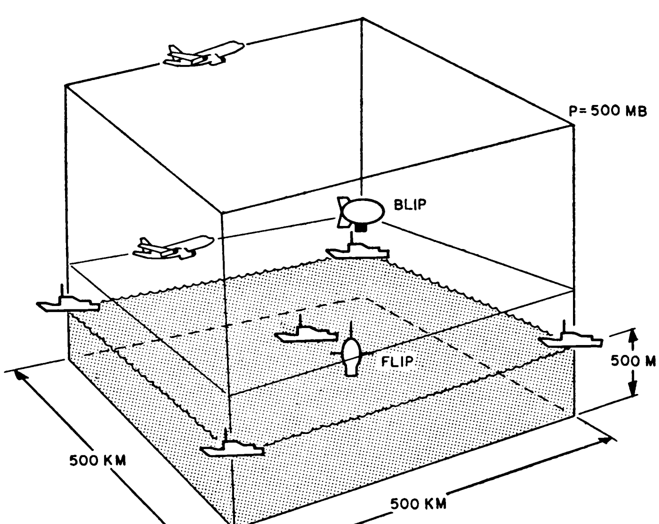
flux because of its dominance in supplying the energy which drives the atmosphere. The measurements on the synoptic scale have required, of course, an elaborate array of observing stations and central planning, field management, data processing, and analysis. This effort has come to be known as the "core" experiment, and it has required the bulk of the facilities, resources, and human energies devoted to BOMEX.

Flux measurements on smaller time and space scales have been carried out by small groups using single platforms, the manned buoy *FLIP*, and the unmanned buoy *Triton*, referred to earlier, and aircraft from the Department of Commerce Research Flight Facility (RFF), the National Center for Atmospheric Research (NCAR), and Woods Hole Oceanographic Institution. These small group programs were separately and independently funded, and they were only loosely linked administratively to the core experiment. In addition, a variety of specific research investigations were carried on by individual investigators and small groups utilizing BOMEX platforms or BOMEX data.

Core Program

The core program was designed to measure average values of flux over a 500-kilometer square, the nominal separation of synoptic observation points and of grid points for current general circulation models. Independent calculations were made from budget equations for the lower 500 millibars of the atmosphere and the upper 500 meters of the ocean as indicated schematically in Fig. 1. In order to obtain useful data, it was necessary to select an area of steady weather conditions, of uniform surface conditions, and with a high rate of evaporation. The region to the east of Barbados fulfilled these requirements, and the facilities and cooperation offered by the government of Barbados made this region an excellent choice for the experiment. Accurate results could be expected only with minimal precipitation, and consequently the program was scheduled for late spring. It was recognized that this was a restriction that tended to reduce the incidence of weather situations of greatest interest, but the highest priority was attached to getting the observations necessary to permit closure of the calculations. Reliable budget calculations were needed to provide unambiguous parameterization of the mean fluxes; more important, the data verified by the core experiment were needed for investigations of the properties of the smaller scale elements that participate in transport of water vapor, heat, and momentum. A variety of weather situations was anticipated, from steady winds and clear skies in early May, to intermittent incursions of organized cloud systems in July.

The most critical technical uncertainty associated with the core program was the accuracy of measurements of horizontal velocity divergence. Consequently, considerable redundancy was provided for in the observational program. On the basis of the results from



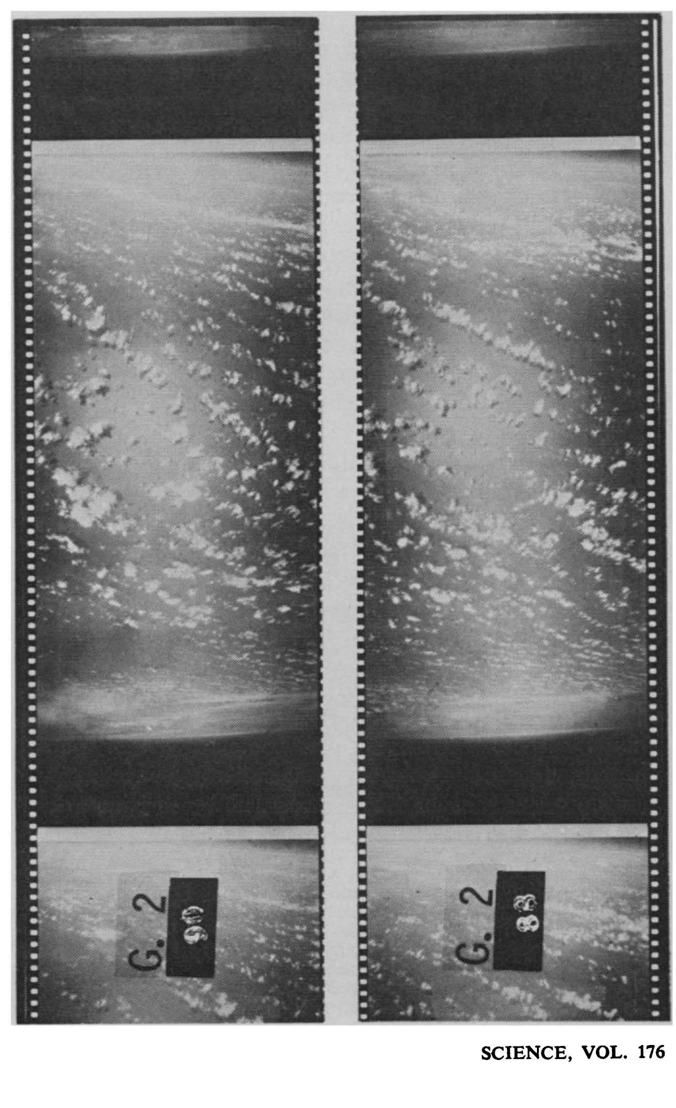


Fig. 1 (above). The basic BOMEX array of observing platforms centered at about 15°N, 57°W. Fig. 2 (right). Cloud distribution photographed vertically from a height of 15,000 meters at 1633 and 1635 Greenwich Mean Time on 2 July 1969 at approximately 16.6°N, 57.1°W. Each picture covers about 22 kilometers in the direction along the flight path in the center of the picture and extends from horizon to horizon in the lateral direction. Flight path was from right to left and was directed 20° south of west. Spacing of the centers of the photographs indicates the distance traveled by the plane in the elapsed time [from (*24*)].

22 to 26 June, the first to be thoroughly analyzed, it appears that budget calculations for the atmosphere and the ocean are in reasonable agreement and that the divergence measured by aircraft and from ship-based rawinsondes agreed well enough to permit vapor flux determinations with a time resolution of 24 hours, perhaps better, and a vertical resolution of 10 millibars (*9–11*). The average evaporation for this period of 6.0 millimeters per day appears accurate certainly within about 20 percent, probably somewhat better. The vertical profiles of mean divergence and of mean vertical eddy flux are of considerable interest in themselves, and they will be especially valuable if similar calculations can be provided for convective cloud systems or other smaller scale elements.

Aircraft Observations

Wind velocity determinations in which Doppler radar is used on aircraft over the sea have for many years been beset by an uncertainty of a meter per second or more. This translates into a divergence uncertainty for the BOMEX area of 2×10^{-6} sec^{-1} or more, which if systematic, is enough to seriously compromise mean flux calculations. However, this uncertainty can be avoided by using single aircraft to measure one-dimensional divergence along a straight flight track. There is a compensating uncertainty associated with change of velocity components with time, but this can be estimated. Development of this "trend method" of divergence measurement by Holland (*10*) offers an alternative to the measurement of the net rate of outflow from specified areas.

In addition to measuring mean values of the atmospheric variables, aircraft instrumentation on an NCAR plane and an RFF plane were used by Miyake *et al.* (*12*) and Bean *et al.* (*13*) to measure fluctuations in the frequency range from 10^{-3} hertz to 10 or 100 hertz. These data provide eddy fluxes and other turbulence statistics. Flights at various heights in the planetary boundary layer reveal interesting properties of mesoscale structures (*14*). Some of these are revealed in Fig. 2. Cloud photographs of this type have been used by BOMAP in analysis of period 3, but much more remains to be reported concerning analysis of mesoscale properties.

Vertical Flux Comparisons

Surface layer fluxes were measured for limited periods by several methods. In addition to the budget calculations for the atmosphere and the ocean, the covariance method was applied to measurements made on board RFF and NCAR aircraft flying as low as 18 meters and also on the two buoys, *FLIP* and *Triton* (*12, 13, 15, 16*). Calculations based on the rate of dissipation were made from *FLIP* data (*17*), and profile measurements were made from the two floating platforms (*18*). Substantial differences occur between the independent calculations. There are, no doubt, instrumental and analytical sources of some of these differences; but Fig. 3 shows substantial differences between the fluctuations of humidity and of temperature and indicates that the mechanism of heat flux in the surface layer differed from the mechanisms of vapor and momentum flux. The points in Fig. 3 represent 11 runs totaling 608 minutes during the period 3 to 12 May 1969. This evidence from BOMEX studies by Phelps and Pond (*15*) and Donelan (*19*) has helped to shift the focus of scientific attention from the surface layer to the entire planetary boundary layer and to interaction of the boundary layer and the free atmosphere.

Boundary Layer Structure

Aircraft observations of the planetary boundary layer have revealed that organized mesoscale structure is characteristic of the planetary boundary layer. Preferred dimensions of mesoscale elements are greater in the along-wind direction than in the cross-wind direction (*12, 14*). An example of the horizontal distribution of vertical velocity and humidity observed by an RFF plane at 150 meters is shown in Fig. 4. Much

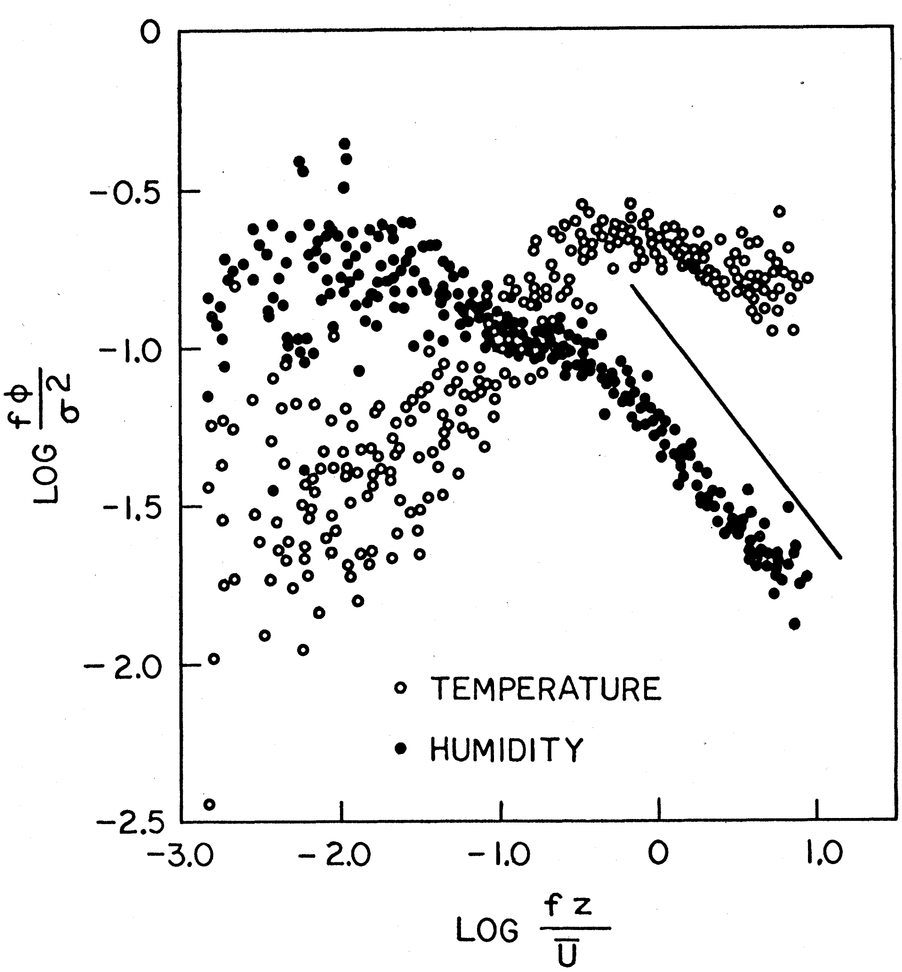


Fig. 3. Normalized temperature and humidity spectra determined by Phelps and Pond (*15*) from observations made on board *FLIP* at a height of 8 meters. The straight line has a slope of $-2/3$, corresponding to the Kolmogoroff law; *f*, represents frequency; *z*, height $\overline{U}$, mean wind velocity; ϕ, spectral density; and σ^2, the variance of fluctuations.

of the record is dominated by fluctuations with horizontal scales of 1 to 2 kilometers, and at these scales vertical velocity and humidity are positively and strongly correlated.

Detailed time series observations of wind direction and speed, temperatures, and humidity together with a number of vertical soundings were made at heights up to 250 or 500 meters by means of the boundary layer instrument package (BLIP) supported by a tethered balloon. The plan had been to fly this instrument from each of the fixed ships for extended periods throughout the BOMEX observation period. A number of difficulties were encountered with this system which stemmed from the fact that it had not been field-tested prior to BOMEX; but in the end some 700 hours of data of good quality have been secured, mostly at two sites. Time series observations were made also on *FLIP* and on each of the fixed ship stations; these observations describe boundary layer structure and its change with time. The evidence so far available emphasizes that more or less orderly mesoscale structures—helical rolls, plumes, and vortices—were general features of the planetary boundary layer. They contributed directly to total vertical flux of water vapor and momentum, and they appeared to strongly modulate the higher frequency components, with high frequency upward flux being concentrated in regions of mesoscale upward motion.

These results lead to a fairly simple conceptual model of air flow in the planetary boundary layer over the tropical oceans, which have been discussed by Fleagle (*14*) and by Kuettner (*20*). The model is idealized and, of course, accounts for only part of the weather states encountered in BOMEX. One may visualize (Fig. 5) a series of helical rolls side by side filling the planetary boundary layer. Representative lateral dimensions of individual rolls are 1 to several kilometers, with the height ranging from ½ to 1 or 2 kilometers. Lateral velocities close to the sea surface below the center of the roll are about 1 m sec^{-1}, and maximum vertical velocities are 0.5 m sec^{-1}, as is shown in Fig. 4. These quantities have been measured from *FLIP* and from aircraft, and the cloud bands that form above the lines of convergence are visible on many aerial photographs (Fig. 2). We may infer from these measured characteristics of the boundary layer circulation certain aspects of the energetics of the flow. Water vapor is picked up by the air sweeping laterally across the sea surface and is concentrated in the areas of converging flow, as is suggested in Fig. 5. The high humidity here makes these regions slightly unstable statically; the resulting buoyant energy, organized by the boundary layer circulations, is added to the helical circulation along the line of convergence. In addition, higher frequency turbulence occurs preferentially in these regions of higher humidity.

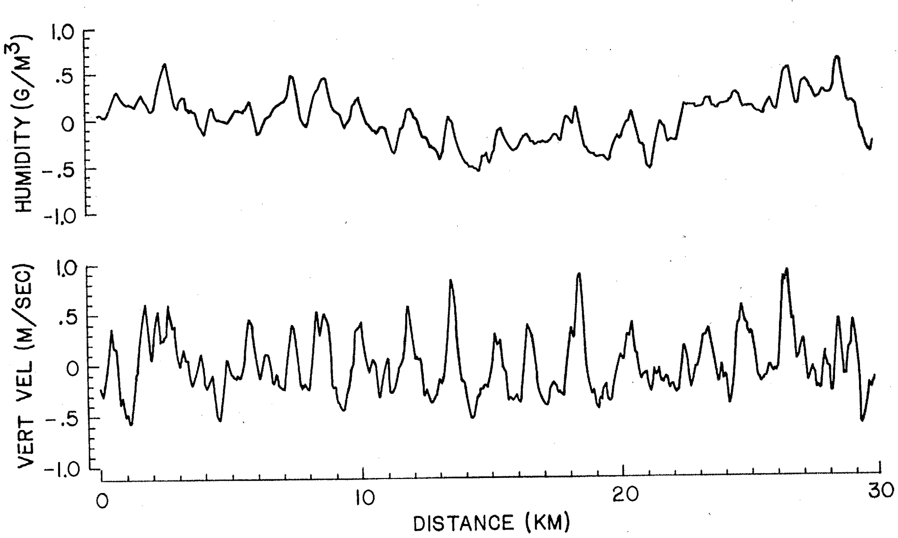


Fig. 4. Vertical velocity in meters per second and humidity variations from the mean in grams per cubic meter observed on a crosswind flight by the Research Flight Facility at a height of 150 meters on 11 May 1969. Data have been smoothed by a 3-second running mean (data tape provided by BOMAP office, processed by Rinaldi Associates).

Successes

Analysis of BOMEX data is now moving at full pace; some results are in, and it is possible to identify the following major results.

1) Vertical vapor flux on the synoptic scale can be evaluated with reasonable accuracy in undisturbed periods by budget equations applied to both the atmosphere and the ocean (*9, 10, 21*).

2) Vertical flux of water vapor, heat, and momentum and other turbulence statistics can be determined reliably from aircraft observations as well as from fixed platforms (*12, 13, 15, 16*).

3) Temperature spectra in the surface layer exhibit maximum energy at about 1 hertz, while humidity and velocity spectra exhibit maximum energy at about 10^{-3} to 10^{-2} hertz (*15, 19*). These frequencies correspond to horizontal dimensions of roughly 10 meters for temperature fluctuations and 1 to 5 kilometers for humidity fluctuations. This striking difference, which had not been found over land or in other overwater observations, indicates dissimilarity in the transfer mechanisms of water vapor and temperature.

4) The planetary boundary layer is characterized by mesoscale structure of dimensions of 1 to 5 kilometers. In part these appear to be helical rolls of the character predicted by the theory of Ekman instability (*14, 20, 22*).

Apart from the specific scientific results achieved so far, BOMEX has great value as a data source for other investigations and as a test bed for new instrumentation and for new forms of coordination or management of field programs. The following instances are especially notable.

1) BLIP has been demonstrated to be capable of observing mesoscale structures in the planetary boundary layer.

2) Lidar aircraft observations have been demonstrated to be capable of detecting aerosol distribution.

3) The most complete set of intercomparisons of turbulence statistics has been acquired.

4) A unique set of the most complete tropical ocean and atmosphere data has been provided.

5) There is now evidence that a complex field program requiring coordination of aircraft, ship, and buoy observations can be planned and carried out successfully (*23*).

6) Development of the Center for

Experimental Design and Data Analysis (CEDDA) (*23*) provides a vital capability for planning and for data analysis in other large field programs.

Criticisms of BOMEX

BOMEX has been criticized on many grounds, and I now address myself directly to the most important of these issues. This is not to take on the role of defender of BOMEX, but rather to identify some of the weaknesses of the program in order to contribute to more effective planning for the Atlantic Tropical Experiment (GATE) or other large-scale field programs. I shall also discuss some of the earlier criticisms of BOMEX which, in my opinion, were not well founded.

One criticism of BOMEX has been that the flux measurements made on *FLIP* and by aircraft were not integrated with the core program. The two programs were managed by separate government agencies, the Department of the Navy and the Department of Commerce. *FLIP* was available only during the month of May; BLIP was operated sporadically, and aircraft observations from an inertial platform were made only occasionally.

Schedules for the *FLIP* program were established to accommodate the greatest number of individual programs, rather than to insure accurate and reliable flux measurements as a basis for comparison. As a result, crucial data are lacking for making comparisons; and for much of the period of BOMEX no surface layer flux measurements are available from *FLIP* or from aircraft. The fundamental point is that existing mechanisms for federal interagency coordination are inadequate to mount a program of the scope and complexity of BOMEX.

This leads to more general criticism: (i) that planning was begun too late, on too small a scale, (ii) that insufficient resources were directed toward instrument testing and calibration, and toward quick verification of data; and (iii) that crucial decisions on funding, on development, and on management of facilities were late. These defects did indeed occur. They were, however, inevitable in view of the limited resources and the necessity for creating de novo an effective management structure. It was clear to me, as chairman of the BOMEX advisory panel and later of the BOMAP advisory panel, that most of the defects of management were beyond the control of those directly responsible. In fact, the leadership of this program has been outstanding; R. M. White, R. Hallgren, and B. Davidson, and, later, J. Kuettner, J. Holland, and W. Barney, who played vital leadership roles in implementing the program, all deserve great credit for bringing BOMEX through some very treacherous waters. This is not to say that administrative improvements could not have been made. Perhaps it would have been better to have delayed the whole program until an effective interagency management structure and adequate funding were assured. If this had been done, the program may well have never been carried out, and this would have been a heavy cost to subsequent research programs. Earlier appointment of the advisory panel would have been beneficial through contributing to the planning phase and through emphasizing the needs for central management, instrument testing, and data processing. But Monday-morning quarterbacking is an easy sport.

A fundamental controversy has centered on the technical question of whether or not horizontal velocity divergence could be measured on the synoptic scale with adequate accuracy. Some atmospheric scientists have held that wind velocity measurements are inherently so inaccurate or unrepresentative that the budget method could not be applied successfully. Without going into detail here, the results from the core experiment reported by Rasmussen (*9*) and Holland and Rasmussen (*10*) indicate that divergence was measured accurately enough to calculate vertical water vapor flux. On the basis of these results, this criticism should no longer be considered valid for undisturbed periods, and it seems likely that a similar result will be found for disturbed conditions. The sampling problem in the latter case may be much more severe than in the undisturbed case.

Another source of criticism has arisen from the claim that the most important problems are related to understanding the physics of moist convection and the interaction of scales of motion rather than the processes of the planetary boundary layer in undisturbed conditions. I agree with this view. The issue, however, is not so easily disposed of; it is a tactical one of the size of the research step that should be attempted from a particular starting point. Decisions are bound to be somewhat subjective. I would simply call attention to the fact that BOMEX was planned to include both undisturbed and somewhat disturbed periods. Also, it is important to recognize the need for verifying the methods of measurement of divergence on a variety of scales and for developing confidence in

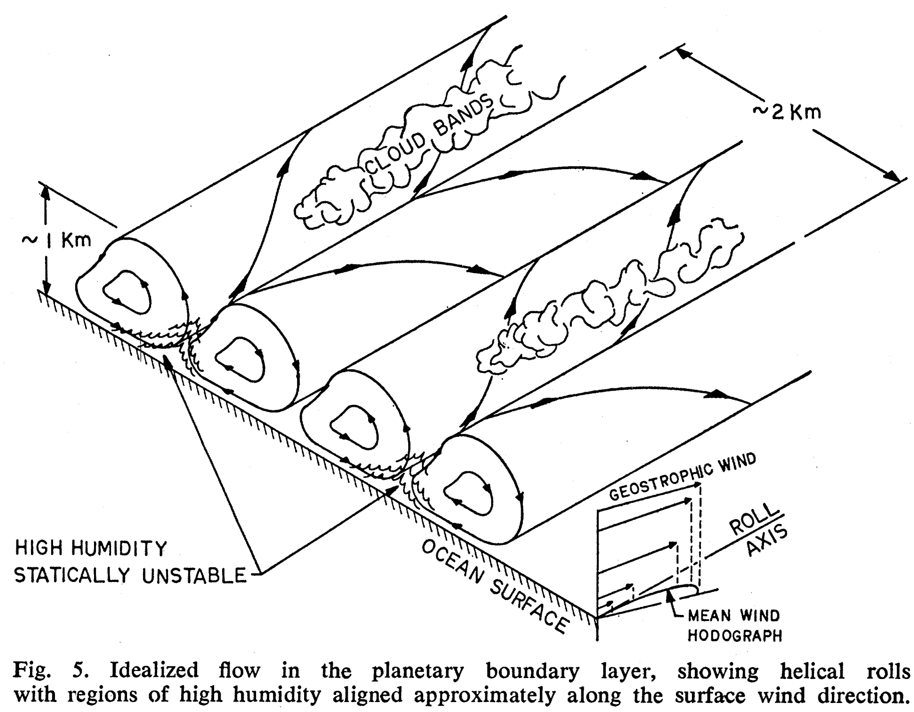


Fig. 5. Idealized flow in the planetary boundary layer, showing helical rolls with regions of high humidity aligned approximately along the surface wind direction.

coordinating the engineering, logistic, and data quality control aspects of a complex field program. The experience from BOMEX will be of great value in planning the GATE program. It seems doubtful that we could have undertaken the GATE program without the lessons—scientific, technical, and managerial—learned in BOMEX.

A related criticism has concerned the strategy of deployment of ships and aircraft in order to observe and measure moving and transitory weather elements. It has been held that the observational network of fixed ships and patterned aircraft flights should have been replaced by a flexible scheme for identifying and following discrete convective disturbances. On the other hand, the argument is persuasive that the range of scales can best be handled through a homogeneous set of observations made at fixed points and at regular time intervals. Only in this way does one have the freedom to average over sufficient data to reduce observational uncertainty. In addition, the logistic problems of a fully flexible observation system would be formidable and might well lead to serious interruptions or ambiguities in data.

Finally, the most persistent criticism has been that BOMEX is *big science*, and that we should abjure big science because in these projects scientists lose control, scientific objectives are subverted, and budgets are diverted from science to technology. There is no question that for nearly every scientist the personal joys of little science are greater than those of big science. However, the question we have to consider is what are the crucial problems and what programs are required to attack them. For atmospheric scientists there can be no avoiding the conclusion that the crucial scientific questions require extensive data collection which can be carried out only by groups of scientists and technicians working within a well-organized and well-managed program. To move in the opposite direction condemns us to working on trival problems with diminishing public support.

Summary

Results to date from the Barbados Oceanographic and Meteorological Experiment (BOMEX) are adequate to permit certain generalizations which should be valuable in planning for subsequent large field programs. Vertical fluxes of water vapor, heat, and momentum can be determined with useful accuracy within the surface layer by several methods either from fixed platforms or from aircraft or both. New insights into the structure of the planetary boundary layer over the tropical ocean have been developed. The experience gained in planning and executing the field program and in processing and analyzing data demonstrates that a large, complex field program can be successfully carried out by the coordinated efforts of government, industry, and university scientists, administrators, and technicians. Serious deficiencies of the BOMEX program can be attributed to the fact that federal interagency coordination of funding and field management was inadequate. Other criticisms which have been directed at BOMEX are less valid.

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