preliminary report on the BOMEX sea-air interaction program

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Abstract

The principal objective of the Barbados Oceanographic and Meteorological Experiment (BOMEX) was to measure the rate of exchange of the "properties" heat, water substance and momentum between the tropical ocean and atmosphere over a 500-km square. The Sea-Air Interaction Program of BOMEX (called the "Core Experiment") determined the ship and aircraft array configuration and observation schedule during the period from 1 May to 2 July 1969. Intensive and in many cases redundant observations by several methods were made to permit for each property:

a) direct measurement of vertical eddy flux of the property in the surface layer of the atmosphere;
b) computation of horizontal flux divergence of the property in the lower 600 mb of the atmosphere, integrated over the array area;
c) vertical transport of the properties through the top surface of this volume due to the mean vertical velocity;
d) local rate of change of the volume integral of the property; and
e) internal sources and sinks (i.e. radiation, precipitation, stress).

Ranges of spatial resolution from 10 m to 500 km and temporal resolution from milliseconds to days are provided by the various sensor systems. Data reduction and analysis are underway. Preliminary results indicate that the goal of obtaining values of the significant energy transfer rates and conversions, with accuracy and resolution about an order of magnitude better than any previously available, will be attained. If so, a test of available parameterization formulae will be possible even under the relatively constant and uniform conditions over the tropical oceans.

1. Introduction

The Barbados Oceanographic and Meteorological Experiment (BOMEX) was a joint project of seven U. S. departments and agencies, conducted with the cooperation of the Government of Barbados during the period 3 May through 28 July 1969 (Kuettner and Holland, 1969). Data-gathering by ships, buoys, aircraft, balloons and satellites was concentrated in four periods of two to three weeks each.

During the first three periods (3–15 May, 24 May–10 June, 19 June–2 July) observations were concentrated in a 500 km × 500 km square east of Barbados and were scheduled to provide accurate statistical estimates of the sea-air exchange of mass, energy and momentum. In the fourth period (11–28 July) the ships and aircraft were employed in a more flexible manner to explore the structure of convective systems occurring in the Intertropical Convergence Zone and the adjacent Trades over the western Atlantic.

This report will be limited to the Sea-Air Interaction Program which is also referred to as the "Core" experiment of BOMEX. While many independent experiments were conducted on the various instrumented platforms in the BOMEX array by scientific groups from universities, government and private research organizations (BOMEX Project Office, 1969; BOMAP Office, 1969), the bulk of the total resources and effort were scheduled to serve the purposes of the Core experiment. In addition to the observations taken under the control of independent scientists, a large share will be directly contributory to the Core experiment.

In essence, the Core experiment consists of a comparison of fluxes of heat, water vapor and momentum from sea to air, averaged over the area of the BOMEX square, as estimated by three methods: a) those deduced from the budgets of these properties in a defined atmospheric volume; b) those deduced from direct measurements of the fluxes at points close to the air-sea interface; and c) those predicted by currently available synoptic-scale parameterization formulae. As an essential input to the energy budget, the long-wave and short-wave radiative energy flux and flux divergence were documented both at the interface and in the free atmosphere. Further to support the interpretation of the interface flux results, sufficient oceanographic data were collected to determine independently at least the gross magnitudes of the terms in the oceanic heat budget.

The 500-km square was conceived as an experimental prototype of the basic grid element of a global observation system. Synoptic observations of the type currently used in numerical weather prediction were obtained on the 500-km grid unit to permit testing of parameterization models. The experiment was also designed in such a way as to permit tests and intercomparisons of all available measurement techniques.

The plans for the BOMEX Core experiment were developed in considerable detail by Dr. Ben Davidson, Scientific Director of BOMEX up to the time of his death in December 1968 (Davidson, 1968). The basic design is an elaboration of the sea-air flux experiment carried out during the Indian Ocean Expedition in early 1964 (Fleagle *et al.*, 1967). It also responds closely to specific recommendations contained in the 1966 report "On the Feasibility of a Global Observation and Analysis Experiment" by the Panel on International Meteorological Cooperation of the U. S. National Academy of Sciences.

2. Experiment design criteria

Although Ben Davidson's written notes were not explicit on all points, it was evident that the following criteria governed the design of the Core experiment. When these criteria were applied in the detailed planning and implementation, a remarkable degree of continuity and full utilization of programmed resources were achieved.

a) Scale. The time scale corresponding to the 500-km length scale would be 14 to 28 hours assuming a mean wind or perturbation phase velocity of 5 to 10 m sec^{-1}. The accuracy criteria for sea-air fluxes should therefore apply to an averaging period which permits resolution of at least day-to-day variations. The supplies and ship deployment schedules permitted a maximum of about 30 days of intensive observations, allowing for resupply periods in port and maintenance and calibration days at sea.

b) Water vapor budget terms. The adequate measurement of the evaporation rate was taken as the anchor point for the design. Prior climatological estimates suggested evaporation rates in the range 4 ± 2 millimeters per day (mm d^{-1}) corresponding to a latent heat flux of 0.17 ± 0.08 cal cm^{-2} min^{-1}. It will be assumed that in undisturbed weather conditions the day-to-day changes are of the order of 10% of the mean although larger excursions may occur in disturbed weather (Garstang *et al.*, 1970). In order to resolve such changes the standard error of the 24-hour mean must be held below 0.4 mm d^{-1}. Since the sensible heat flux at the interface is normally only a few per cent of the latent heat flux, it is the accuracy of the latter which governs the accuracy of the total sea-air energy flux. The error limit of 0.02 cal cm^{-2} min^{-1} or 25 cal cm^{-2} d^{-1}, based on the estimated evaporation rate, will therefore be used in assessing the adequacy of all the observations.

c) Surface stress. A second high priority objective was the accurate measurement of surface stress. Although not strictly a part of the energy budget, this quantity plays a critical role in the "aerodynamic" estimates of heat and water vapor flux from mean profiles of temperature and humidity in the atmospheric surface layer, and also in the parameterization formulae. For this purpose measurements and intercomparisons of microscale eddy stress by a wide variety of methods were encouraged, and the criteria for mean wind, pressure and isobaric height measurements were governed by the requirements of the "geostrophic departure" technique (more generally, the momentum budget).

d) Precipitation. Because the planetary boundary layer in the tropics contains the normal trade-wind cumulus clouds including some rain showers, irreversible conversions of latent to sensible heat occur to some degree within the boundary layer. The season of the experiment was selected to avoid major tropical disturbances, and existing climatological information suggested that precipitation in this area and season would be generally much less than evaporation. Still, it was necessary to document the cloudiness and precipitation as completely as possible. Furthermore, it is clear that the difficulty of attaining satisfactory measurements of precipitation reinforces the requirement to evaluate the sensible heat budget with the same accuracy as the latent heat budget (i.e., ± 25 cal cm^{-2} d^{-1}).

e) Mesoscale resolution. Parameterization of the effects of cumulus convection and rain showers has been attempted only in a very crude way in existing boundary layer models, and the effects of organized mesoscale convective systems have hardly been taken into account at all. It was clearly necessary to provide wind, temperature and humidity data, as well as cloud and precipitation data with sufficient resolution to permit estimates of the contributions of the variations on these scales to the area and time averages. This would be important not only in assessing the sampling error of the averaged synoptic-scale quantities, but also in explaining and perhaps ultimately remedying deficiencies in current boundary-layer parameterization models.

f) Observation system test. The Core experiment was intended also to serve as an engineering test of observational platforms, measurement techniques and operating procedures. Redundant and independent methods of measuring many of the parameters were employed systematically throughout the program. This was necessary in part because of the lack of certainty that the required results could be obtained with any single available system, but also because of the anticipated need for critical comparative data to support choices of observational tools for future experiments and networks. This objective was strongly favored by the choice of location and season. The accurate quantitative evaluation of observation system errors requires either very steady environmental conditions or very extensive statistical tests. The BOMEX Core experiment was a methodical, repetitive statistical experiment. It was conducted in a tropical region having minimal variances of most of the environmental variables, during the season when both extratropical perturbations and tropical disturbances have minimal probabilities. For the testing of parameterization models this environment provides only a highly restricted range of input and output variables. It consequently places extreme demands on observational accuracy for such tests. By the same token, however, it allows the systematic responses of the observation system to be isolated with unusual sensitivity. Thus it was appropriate that the expedition included experiments with a large number of relatively untested instruments, a situation which would be intolerable in an operation which had the gathering of environmental data as its sole objective.

3. Observational program

During the period 1 May through 2 July 1969, five vessels, provided by the Departments of Commerce and Transportation, were stationed at the corners and midpoint of a 500-km square whose sides were oriented parallel and perpendicular to the mean surface wind (Kuettner and Holland, 1969). The ships were equipped to take oceanic Salinity-Temperature-Depth ("STD") soundings; manual surface observations; continuous recordings ("BOOM") of surface meteorological parameters including sea surface temperature and solar and net radiation; free-balloon wind, temperature and humidity soundings ("RAWINSONDE"); and captive balloon time series of wind, temperature and humidity by means of a Boundary Layer Instrument Package ("BLIP"). The station ship data were recorded on magnetic tape by means of a Signal Conditioning and Recording Device ("SCARD") supplied and operated on each ship by the National Aeronautics and Space Administration.

During intensive observation periods, STD soundings were normally taken at 3- or 6-hr intervals to a depth of 1000 m and rawinsondes at 1-1/2 hr intervals to a pressure level of 400 mb, or about 7-km altitude. The BLIP system was only partially operational during the experiment. A principal mode was to raise the BLIP slowly to 700 m to obtain a vertical profile, then to hold it at 300 m for several hours.

The magnetic tapes from the fixed ships are being digitized and partially reduced at the NASA Mississippi Test Facility.

These observations provide the input data for the parameterization test. They also will permit the estimation of horizontal flux divergences of the measured properties in the atmosphere and ocean as well as vertical fluxes through the top surface of the atmospheric integration volume, and changes in internal storage within the volume. However, these estimates, even for synoptic-scale averages, will suffer from lack of spatial sampling density due to the small number of fixed ships in the array. Mesoscale time density was achieved, however, through the concentrated observation schedule.

To increase spatial density of sampling for the estimation of area-integrated horizontal flux divergence, advantage was taken of the Divergence Theorem (Green's or Gauss' Theorem) which requires measurements only along the perimeter. "Line integral" aircraft observations were taken during selected day and night periods. Several different flight patterns were executed, varying with respect to the number of aircraft, number of altitudes samples, and amount and type of calibration and intercomparison maneuvers. Aircraft of the Department of Commerce, the U. S. Navy and the National Aeronautics and Space Administration participated in the line integral flights. The altitude sampled most intensively by the aircraft was 300 m.

To improve the estimates of the "storage" or integrated "local change" terms in the heat and water vapor budgets, soundings were made at eight locations in the interior of the square near midday and midnight by means of "dropsondes" parachuted from U. S. Air Force aircraft flying at approximately 6 km altitude. The Air Force also provided once daily high-altitude photographic and radar coverage of the BOMEX square for use in estimating cloudiness, radiative flux divergence and precipitation.

Direct measurements of vertical eddy fluxes of heat, water vapor and momentum, as well as detailed vertical profiles of mean temperature, humidity and wind velocity in the lowest 30 m were made from the Floating Laboratory Instrument Platform ("FLIP"). A number of university and laboratory groups were represented in the FLIP personnel and instrumentation. Additional micrometeorological and mesometeorological measurements were made by Dr. Michael Garstang's group on the Florida State University "TRITON" buoy, on the ship *Rockaway* at the center of the BOMEX array and on the Island of Barbados.

Vertical eddy flux measurements were also made by instruments mounted on aircraft of the Department of Commerce Research Flight Facility (RFF), the National Center for Atmospheric Research (NCAR) and the Woods Hole Oceanographic Institution. A pattern flown numerous times by both the RFF and NCAR aircraft consisted of two 5-min runs, one along-wind and one across-wind, at each of three levels close to FLIP. The lowest level, 18 m, provided direct comparison with the water vapor flux measurements on FLIP. The other two, 45 m and 150 m, provide information on spectral changes with height, horizontal anisotropy and vertical flux divergence in the lower part of the planetary boundary layer. Other aircraft flight patterns were designed to explore the variation of microscale vertical velocity and humidity spectra and cospectra with height through the entire extent of the planetary boundary layer, diurnal variations, and horizontal variations over the BOMEX area.

4. Operational performance

The BOMEX field program was highly successful. Coordination of the 1500 people, 12 ships and 28 airplanes was remarkably smooth under the direction of Col. William Barney, Project Manager. During the entire 3-month period, the five fixed ships produced 2400 rawinsondes, 1400 STD soundings, 7000 hours of BOOM data and 700 hours of BLIP data. These records are contained in approximately 500 reels of SCARD tapes. Research aircraft flew more than 4000 hours on 500 missions covering more than a million miles. Nearly 500 successful dropsonde records were obtained. Two hundred thousand radar photographs were taken, of which 50,000 were taken with calibrated ground and ship-based radars at gain settings which were varied in pre-selected steps for quantitative precipitation analysis.

Difficulty was experienced with the deep-sea mooring systems which were intended to permit the five station ships to be anchored. Two failed in the first few days and all failed by the start of the third period. All ship crews were able to carry out their observation programs in a station-keeping mode, but this magnifies the problem of correcting surface and upper winds for ship motion.

During the first week various difficulties with the shipboard wind-finding systems prevented the collection of usable simultaneous sets from the five ships. The center ship was placed on a reduced rawinsonde schedule since the wind-finding radar interfered with other instrumentation. Wind data from this station are not essential for the volume budget analyses, but will be of value for the momentum and kinetic energy budgets.

By the second week of the first period full-scale operations were underway. A "data snatch" by Air Force aircraft permitted the first week's tapes to be taken to the NASA Mississippi Test Facility for a "quick look" at samples of the data. As a result a number of improvements in recording circuits and calibration procedure were made before the beginning of the second period. From then on the bulk of the scheduled observations were obtained with excellent quality.

One of the first and most important conclusions from BOMEX is that it can be done!

5. Some preliminary indications regarding data quality

The samples of data available so far are fragmentary and for the most part rather preliminary. Digitization of the fixed ship magnetic tape data is essentially complete and first-pass automatically reduced data are being reviewed. Fully reduced data are available only from manual records or strip charts. For the aircraft data reduction, programs have been developed and initial output is being checked while calibration studies are underway. We expect the flow of high quality reduced data to begin within the next few months and to be completed early in 1971.

a) Sea-air interface flux. My discussion of the data will begin with a unique experiment, which provided the only direct measure of the net energy flux at the air-sea interface, although by an indirect sensing technique. This was the twin-wave radiometer experiment conducted by Dr. McAlister of the Scripps Institution of Oceanography, utilizing a DC-4 aircraft (McAlister, 1969). From the difference in infrared radiance measured at two wavelengths, corrected for atmospheric attenuation and sky reflection, estimates were obtained of the temperatures at effective depths of 0.075 mm and 0.025 mm. From the gradient within the laminar sublayer of the ocean, the conductive heat flux can be readily calculated. Four successful flights were made in the vicinity of FLIP. In one unambiguous case, without rain-shower activity or electromagnetic interference, the heat flux in the "skin" of the ocean was 0.38 cal cm^{-2} min^{-1}, based on a series of several 30-sec samples measured over a 40-min period. The results are of a plausible order of magnitude, but do not yet constitute a sufficient basis for drawing any general conclusions.

b) Ocean temperature. The heat loss from the ocean surface can also be estimated, in principle, from the STD data, combined with the solar radiation data obtained at the fixed ship stations. Fig. 1 shows a temperature time-section constructed by Robert Landis using the radio-teletype reports received four times daily at Barbados from the *Discoverer* (station E) during the third period of the field expedition (Landis, 1970). Landis was able to estimate the diurnal variation in the heat content of the upper 30 m. The amplitude was about 800 cal cm^{-2} on four of the nine days for which the analysis could be done, and smaller on the other days. This is close to the total daily solar radiation at the sea surface in fair weather and for long-term equilibrium requires an average rate of heat loss from this layer, up and down combined, of 0.55 cal cm^{-2} min^{-1}.

There is evidence of substantial internal wave activity, possibly combined with mesoscale advective variations. These will introduce uncertainty in the estimates of the synoptic-scale horizontal heat flux divergence and rate of change of heat storage. Some aid in the analysis may be obtained from a few detailed aerial surveys of sea surface temperature and from a number of temperature array buoys operated by the U. S. Navy.

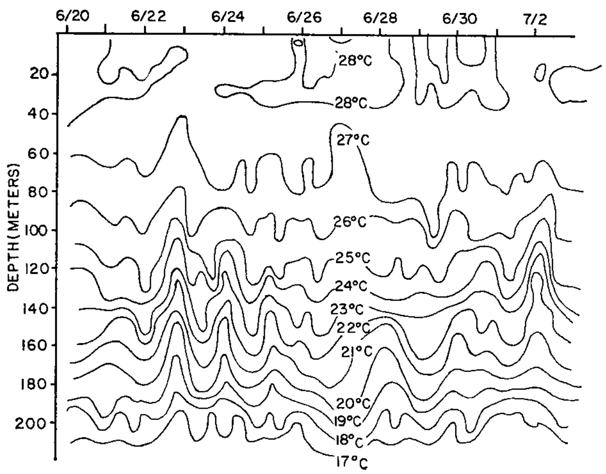

FIG. 1. Landis' time series plot of sea temperatures at station E (13°06′N, 53°51′W).

Useful estimates of the vertical eddy heat transfer should be derivable from a further study of the more abundant and more accurately reduced data from the magnetic tape records. In particular the diurnal variation of the vertical temperature gradient and heat storage will be analyzed in a deeper layer than that covered by Landis' analysis with the purpose of determining the magnitude of the errors by comparison with the more accurate atmospheric data. It is unlikely that the ocean heat budget analysis will meet the atmospheric criterion of ± 25 cal cm^{-2} d^{-1}. For example, if the integration were taken to a depth of only 100 m this would require day-to-day temperature differences accurate to ± 0.002C! Preliminary samples of carefully reduced STD data from the SCARD tapes suggests that instrumental errors may be nearly this small but that sampling errors due to short period perturbations may be much greater.

The heat given up by the ocean is approximately the sum of the net infrared radiative loss and the net latent heat of evaporation. Sensible heat input to the atmosphere and kinetic energy dissipation account for only a few per cent. The remainder of the discussion will be concerned with the latent heat budget because this is overwhelmingly the major part of the energy budget. The total sensible heat flux in the atmosphere next to the surface is ordinarily much smaller than the error limit of 25 cal cm^{-2} d^{-1} associated with the latent heat flux.

c) Vertical eddy flux of water vapor. Preliminary data on the microscale vertical eddy fluxes of water vapor in the surface layer have been obtained by several investigators based on measurements made with fast-responding vertical velocity and humidity sensors aboard FLIP (Paulson, 1969) and the RFF (Rinaldi, Lappe and Bean, 1969) and NCAR (Miyake and Donelan, 1969) aircraft. The amplitudes and spectra of vertical velocity and humidity, and their covariance and cospectra, appear to be generally consistent among the various measurement systems. Latent heat fluxes calculated from the aircraft covariance data are given in Table 1.

It was noted that the cospectral densities do not drop rapidly with decreasing frequency at eddy wavelengths of the order of 1 km and larger. This wavelength corresponds to eddy periods of 10 to 15 sec on the aircraft and several minutes on FLIP. At these low frequencies, the turbulence signals are overcome by extraneous variations. Thus the estimates reported so far, which imply evaporation rates of 2 to 4 mm d^{-1}, are most likely too low. The apparent changes with height, also, may reflect an increasing loss of covariance as the cospectral peak shifts to lower frequencies approaching that of the cumulus clouds. In any case, too few of these measurements have been analyzed so far to permit any general conclusions regarding the evaporation rate, or vertical flux divergence.

TABLE 1. Aircraft measurements of vertical eddy flux of latent heat (cal cm^{-2} min^{-1}).

Altitude (meters)	Miyake and Donelaw (27 May)	Rinaldi (17 May)
18	.10	
30		.17
45	.13	
150		.11
430		.04

d) Horizontal divergence. For the "integral experiment," the factors which will determine whether we succeed in attaining the required accuracy of the water vapor budget terms are the accuracies of the humidity and wind measurements and the success attainable in the quantitative estimation of precipitation. These involve primarily the line integral aircraft data, rawinsonde data, dropsonde data and radar data.

The evaporation accuracy criterion of 0.4 mm d^{-1}, with a water vapor content of the order of 10 mm in the lowest 100 mb of the atmosphere leads to a limit of 4% per day on the error in the vertical integral of the divergence, horizontal advection and local time derivative terms through this depth. For a depth of 500 mb, the corresponding water vapor content is on the order of 20 mm (liquid equivalent) and the error limit 2% per day.

The divergence error must therefore be held to 4×10^{-7} sec^{-1} provided at least four independent increments are averaged vertically. Since we are using the line integral technique, this requires that the average velocity along each side of the BOMEX square be accurate to ± 0.1 m sec^{-1}. Aircraft parameters such as heading, air speed, ground speed and drift angle were recorded at a sufficient frequency to obtain on the order of 100 to 500 independent measurements of the wind on each leg. Thus random errors in the individual readings as large as ± 1 m sec^{-1} can be tolerated as long as systematic errors in the wind component transverse to the aircraft heading are kept an order of magnitude smaller.

Robert Reeves of the National Hurricane Research Laboratory has analyzed line integral data collected by Navy aircraft on four consecutive nights. Straight level legs were flown at 300 m altitude along a 180 km segment on each side of the BOMEX square. At the midpoint of each side of the square (H, I, J and K) a sounding was made as follows. At each of six levels up to 3000 m, a 2-min leg was flown along the side of the BOMEX square, the aircraft was turned 180° and a second leg flown in the opposite heading. The sounding at point H was performed both at the beginning and end of the circuit. These "reciprocal heading" pairs can be used to estimate the drift angle error.

Table 2 shows the computed divergences before and after correcting for this error. On each night approximately 500 readings of the relevant flight parameters were recorded manually, of which roughly 300 were calibration readings taken during the soundings and 200

TABLE 2. Divergences computed from hand-tabulated ASN-41 on-board computer winds (U. S. Navy Aircraft WC-121).

Date	Divergences from uncalibrated data	Divergences from calibrated data
31 May	$+3.0 \times 10^{-6}$ sec^{-1}	$+0.8 \times 10^{-6}$ sec^{-1}
1 June	$+10.9 \times 10^{-6}$	$+1.1 \times 10^{-6}$
2 June	$+12.7 \times 10^{-6}$	$+0.4 \times 10^{-6}$
3 June	$+7.4 \times 10^{-6}$	$+1.6 \times 10^{-6}$
Avg.	$+8.5 \times 10^{-6}$	$+1.0 \times 10^{-6}$
St. Dev.	3.7×10^{-6}	0.4×10^{-6}

were line integral readings. The standard deviation of 4×10^{-7} sec^{-1} for the corrected divergences of the individual nights is encouraging, since this must include both real and error variance.

The RFF aircraft participating in line integral flights had rapid automatic recording systems in place of the manual recording employed in the Navy aircraft. Flight patterns using multiple aircraft flying on opposite sides of the square simultaneously were also carried out in order to minimize time changes during the divergence measurement. In these cases extensive intercomparison legs were flown by pairs of aircraft. The data tapes from these missions are in process of reduction by the National Hurricane Research Laboratory with assistance of the Research Flight Facility.

Turning to the ship rawinsondes, the accuracy in wind velocity and divergence attainable with these systems is not yet known. The criteria are similar to those for the aircraft, i.e., the combination of 15 runs per day at two ends of each side, plus some tens of independently observed winds in the vertical, produce a statistical sample of comparable size. The two systems play different roles in the analysis, the aircraft providing dense sampling in the horizontal directions at a limited number of times and altitudes, the rawinsondes giving dense coverage of time and altitude at a limited number of locations.

Reduction of random errors to 1 m sec^{-1} will not be as difficult as reduction of systematic errors to 1/10 this magnitude. Fortunately numerous measurements were made by aircraft at the ships' stations so that the winds measured by the two systems can be corrected to a common basis.

A valuable resource in refining the divergence estimates is the fact that the radiosonde temperatures are very accurate. Average day to night differences during the third period, for example, based on radioteletype reports from three of the ships, are mostly between 0.0 and 0.2C at 850, 700 and 500 mb. Standard deviations for the whole period are of the order of 1C.

There is good reason to hope, therefore, that the temperature data can be used to estimate vertical velocity by the "adiabatic method." This method is best in stable, dry layers where the vertical gradient of potential temperature is large, and turbulent mixing and radiative cooling rates small. These conditions are most likely to be satisfied above the top of the planetary boundary layer. The ability to measure temperature changes with an accuracy of a few tenths of a degree on individual observations and probably better than ±0.1C for 24 hour averages, would then permit highly accurate vertically integrated divergence estimates. For example, even with the average moist-adiabatic lapse rate of 6.5C km^{-1} at the 500-mb level, an integrated divergence of 2% per day, which implies a vertical displacement of 10 mb in 24 hr, would lead to a local temperature change of about 0.7C. This method can be used to calibrate the systematic errors of the shipboard wind-finding systems, including the effects of orientation errors, heading errors and ship velocity errors. It is hoped that residual errors will not preclude obtaining useful vertical profiles of the horizontal divergence from the shipboard wind observations.

e) Humidity. The errors in water vapor storage and advection will depend primarily on the accuracy of the humidity measurements, since wind data adequate for the divergence computations will be more than adequate for the advection. Thus the errors in either the 24-hour time derivative or the 500-km gradient must be held to 2% of the water vapor content integrated through 500 mb. For derivatives taken over shorter times, the accuracy requirements would be more stringent.

Fig. 2 shows a comparison between aircraft soundings taken by the RFF in a pre-BOMEX test in August 1968. Two humidity instruments on the same aircraft are compared. Both types are installed on all three of the RFF aircraft used in BOMEX. An ascent curve and a descent curve of relative humidity are shown for the infrared hygrometer (IRH) and the optical dew-point hygrometer

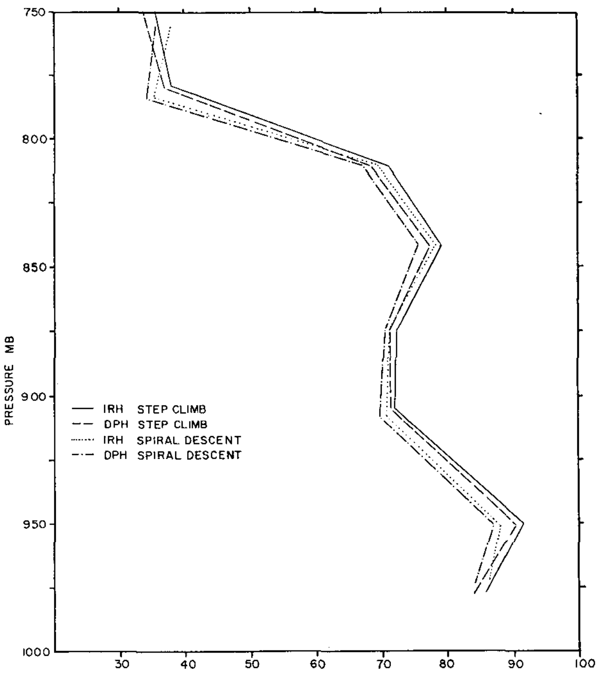

FIG. 2. RFF pre-BOMEX aircraft infrared (IRH) and dew point (DPH) hygrometer soundings.

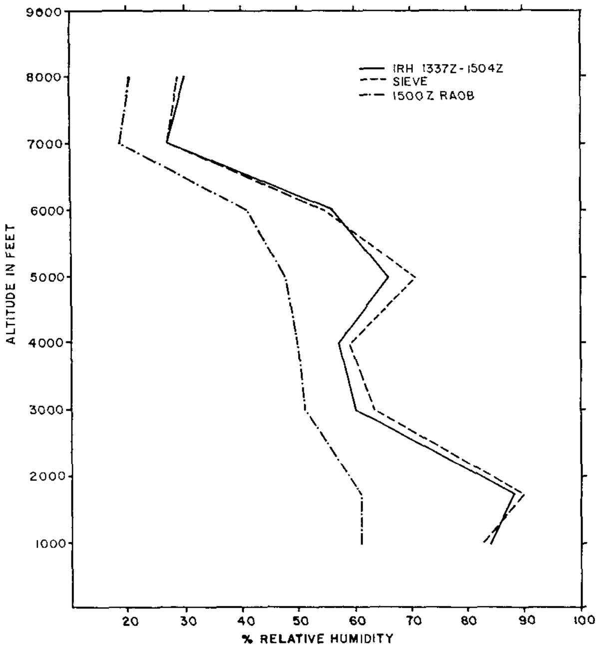

FIG. 3. RFF pre-BOMEX aircraft infrared (IRH) and molecular sieve humidity soundings and radiosonde (RAOB) humidity.

(DPH). The results are typical of the observations made during BOMEX in showing agreement between the two systems to about 3 to 5%. Fig. 3 shows a comparison, made during the same August 1968 mission, between the infrared hygrometer and a series of total water sample measurements made on the same aircraft by Dr. Östlund of the University of Miami using a molecular sieve sampler. Also shown on this figure is the relative humidity sounding obtained simultaneously by a radiosonde released from the ship *Discoverer* at the same location. Again the two aircraft measurements agree within 5%. The radiosonde reports a relative humidity lower by 10 to 20% than those measured by all the aircraft instruments.

The aircraft humidity data apparently meet the accuracy requirement. Systematic errors can be reduced to a per cent or two by means of the extensive calibration opportunities incorporated in the instruments, recording system and operating procedures. Random errors are of the order of 3% and will be reduced an order of magnitude by averaging over the large number of data points recorded.

The radiosonde discrepancy shown in the 1968 test has proven not to be an isolated phenomenon. It is apparent that the carbon hygristor, housed in a rather narrow transverse duct covered with translucent plastic at the top of the radiosonde, is warmed by the Sun, causing it to measure low relative humidity. Table 3 shows the dew-point difference between the 1200 GMT (8:20 a.m.: sunlight) and 0000 GMT (8:20 p.m.: dark) soundings taken on the *Oceanographer, Rockaway* and *Discoverer* during the third BOMEX period, based on the radioteletype messages received in the field. The systematic excess of nighttime over daytime dew points, ranging up to 10C, is larger than the average difference between ships or between periods on the same ship. The difference in integrated moisture content is of the order of 3 to 10 mm, far too great to be accounted for by diurnal variations of precipitation, especially since the differences occur even in the most undisturbed weather conditions.

Further evidence is provided by the dropsonde data. One of the features of the dropsonde program was the execution of a "calibration" series once in every 4-day intensive observation period. This consisted of a series of eight dropsonde releases over about a 3-hr period in close proximity to the *Mt Mitchell* while the regular rawinsondes were being released from the ship. Fig. 4 shows the dew-point difference, dropsonde minus radiosonde, as a function of time of day, at selected pressure levels for 10 pairs of nearly simultaneous soundings. The 8 a.m. data resemble the night-day differences in showing a dew-point deficit of 1 to 9C in the radiosonde relative to the dropsonde.

The dropsonde has a rate of descent on the order of 9–10 m sec^{-1} compared to the radiosonde ascent rate of

TABLE 3. Mean diurnal humidity differences, 0000Z–1200Z, 18 June to 3 July 1969.

	Oceanographer 17.3N, 54.0W					*Rockaway* 15.0N, 56.5W					*Discoverer* 13.0N, 54.0W				
	T	T_D(00)	ΔT_D	ΔX	ΔRH	T	T_D(00)	ΔT_D	ΔX	ΔRH	T	T_D(00)	ΔT_D	ΔX	ΔRH
Surface	27.0	23.5	−0.1	−0.1	−1	27.4	23.5	0.3	0.3	1	26.9	23.0	0.0	0	0
1000	25.8	22.7	3.2	3.2	15	26.3	22.6	1.1	1.1	5	25.6	21.9	1.1	1.1	5
850	15.6	12.4	4.5	2.9	22	17.0	12.7	2.4	1.6	11	17.4	10.5	0.6	0.5	3
700	8.1	−5.9	3.5	0.6	6	9.1	−5.2	0.9	0.3	3	8.7	−2.5	5.7	1.7	17
500	−8.1	−15.0	10.4	1.5	36	−6.7	−19.1	−1.3	−0.2	−4	−6.2	−20.9	5.0	0.5	11

T temperature, C
T_D dew point, C
ΔT_D dew point difference, C
ΔX mixing ratio difference, gm kg^{-1}
ΔRH relative humidity difference, %

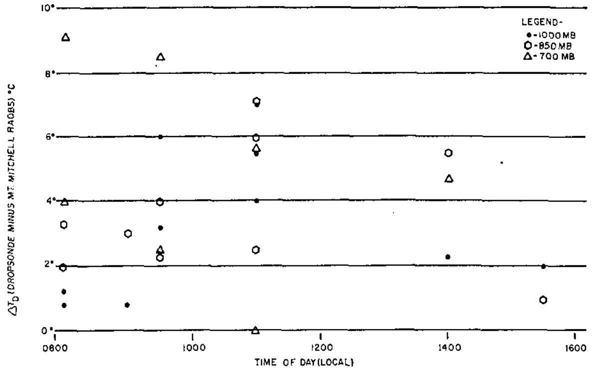

FIG. 4. Dew point temperature differences, °C (dropsonde minus *Mt. Mitchell* radiosonde).

3–5 m sec^{-1}. The dropsonde hygristor is exposed to the external air stream instead of being housed in a duct. The effect seems to be to cause the dropsonde humidities to be more accurate than those of the radiosondes.

Other evidence pointing to a radiosonde dew-point deficit of the order of 5C or greater in sunlight has been found in the climatological records of Equatorial Pacific stations, in comparative test data obtained with an optical dew-point sonde by Brousaides of the Air Force Cambridge Research Laboratories (Harney, 1970; Brousaides, 1970), and in a series of comparative tests with modified and unmodified radiosondes conducted in Miami under the direction of Mr. Feodor Ostapoff of the Sea-Air Interaction Laboratory.

Studies are underway to develop a method of correcting and analyzing the humidity data which will eliminate or sidestep the systematic error and reduce the random error to an acceptable level. Random errors are increased by this phenomenon since it is turned off or reduced by cloud shadows falling on the sonde. A likely implication is that the radiosonde data cannot be used to compute accurate time derivatives over periods other than nighttime periods or multiples of 24 hours.

For the storage term in the water vapor budget, the time derivative of the volume integral must be evaluated. If only the radiosonde data from the five ships were used, 15 observations per day at the corner ships and 8/day at the center ship, there would be 68 observations scheduled in a 24-hr period and somewhat fewer in practice. Thus random errors as large as ± 3 mm in the integrated water vapor, or ± 0.6 gm kg^{-1} in the average specific humidity through the lowest 500 mb in individual soundings, can be tolerated.

f) Precipitation. Finally we come to the most difficult term in the moisture budget, namely the precipitation. With values potentially ranging up to several cm, this term can overshadow all others. Yet the highly sporadic, localized nature of tropical precipitation renders it virtually impossible to obtain good statistical averages in time or space.

The ships were equipped with raingages, but numerous previous tests and experiments have failed to suggest a design and exposure which would guarantee data with the accuracy of 0.4 mm d^{-1} at rates of the order of 10 mm d^{-1}, even at the location of the raingage, not to mention the estimation of area averages. The most accurately measured amount is zero, with both the measurement error and the sampling error due to mesoscale variability increasing with the amount of precipitation.

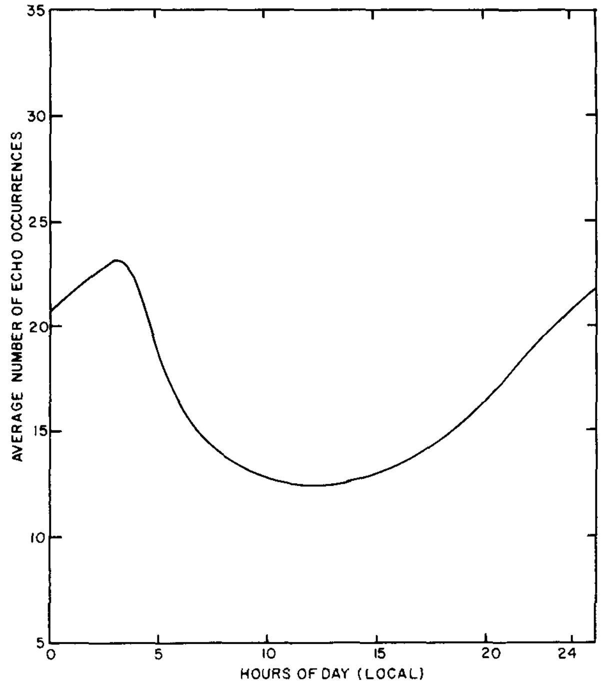

FIG. 5. Diurnal variation in occurrence of cloud radar echoes, 25 May to 3 June and 18 July to 27 July 1969 (U. S. Army Radar, Barbados).

Radar scope photographs are being used as the primary source of information for deducing area averages of precipitation. Digitization of the cloud-echo data is underway at present. The attainable accuracy is not yet known. As a minimum the radar pictures, aided by satellite and aircraft cloud photographs, should permit reliable identification of those cases with much less than 1 mm of precipitation in a 24-hr period. In such cases the evaporation can be computed accurately, provided the other terms are determined with acceptable accuracy. In cases of very heavy precipitation it is not expected that the radar data will permit computation of the evaporation to ± 0.4 mm d^{-1}. In fact, if the evaporation rate, either assumed or based on eddy-flux or profile measurements, is treated as an input variable, the water vapor budget method may give more accurate estimates of the larger amounts of precipitation than will the available direct observations.

Fig. 5, constructed by Dr. Michael Hudlow, then of the U. S. Army, based on a preliminary study of photographs taken at the Army radar station in Barbados, shows the diurnal variation of the number of cloud echoes appearing on the scope. In agreement with other studies of clouds and precipitation over the tropical ocean, this shows a pronounced nocturnal maximum. The number of echoes is roughly twice as great at 3 a.m. local time as at noon. If this is taken to imply a diurnal variation of precipitation rate, it would lead to the expectation of a minimum humidity in the cloud layer at the end of the precipitation peak, and a gradual buildup during the day. The sizes and intensities of these echoes during most of the days used in the study appear to be incapable of accounting for more than a fraction of a mm per day, so that this pattern is confounded with, but not the cause of, the observed day–night difference in radiosonde humidities.

The radar is useful also in indicating at what altitude it may be permissible to neglect vertical transport of heat and moisture by convection, and the depth of the layer within which latent heat conversion to sensible heat is occurring. Fig. 6 shows the observed cumulative frequency distribution of echo heights during portions of BOMEX periods 2 and 4. During the May–June period the most common height was in the neighborhood of 10,000 ft (3 km), but roughly 10% of the echoes penetrated the 20,000 ft (6 km) level. The fraction of the area covered by such penetrations would, of course, be much smaller than 10%. When such penetrations are extensive, the upward transfer of water substance in

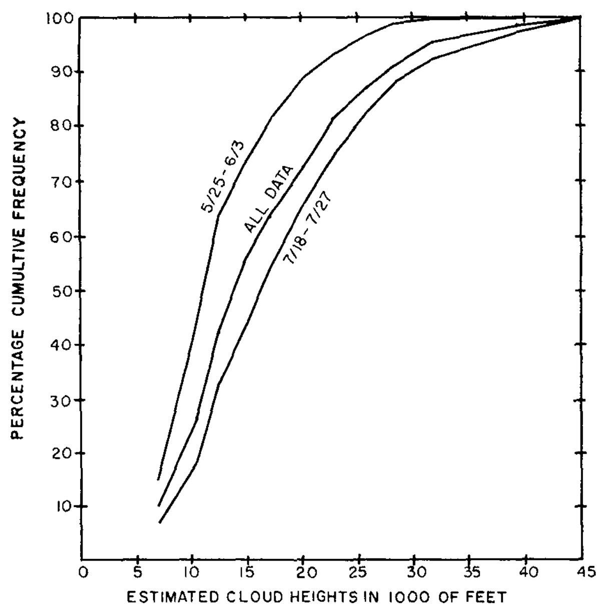

FIG. 6. Cumulative frequency distribution of cloud radar echo heights, 25 May to 6 June and 18 July to 27 July 1969 (U. S. Army Radar, Barbados).

liquid and vapor form can become large enough to affect the water vapor budget. Precipitation falling back through the integration volume could also appear at the surface without having contributed to the sensible heat content of the volume. The Core experiment was not designed to cope with situations involving extensive convection reaching outside the planetary boundary layer and such situations were, in fact, rare during the first three BOMEX periods. Nevertheless some of the measurable terms, such as the synoptic scale horizontal divergences of mass, water vapor flux and heat flux would be of particular interest during such occasions.

Again the potential value of the highly accurate radiosonde temperatures must be mentioned. It may be that in just those conditions when the precipitation rate is comparable to the evaporation rate, the sensible heat budget will provide the most accurate estimate of the latent heat conversion and hence the precipitation. In this case the precipitation is neither so small as to be negligible nor so large as to dominate the water vapor budget. However, condensation of only 2 mm of precipitation within the lowest 500 mb would release enough heat to raise the mean temperature 1C. Such effects would be readily distinguishable from those due to any credible sea-air flux of sensible heat. The third BOMEX period contained some days in which situations of this type may have occurred. A major problem will be to determine whether the precipitation was so unevenly distributed as to prevent adequate sampling of the temperature effect by the BOMEX instrumentation.

6. Analysis plan

The plan for the completion of the Core experiment analysis is to carry out the atmospheric budget computations, oceanic heat budget computations, eddy flux analysis and parameterization experiment concurrently. The results of the four independent efforts, with respect to the energy and momentum transfer rates at the sea-air interface, will confront one another and after a period of adjustment, some conclusions will emerge:

a) regarding the magnitude and variabilities of the various transfer rates in this part of the tropical ocean in this season of the year;

b) regarding the accuracy, efficiency, reliability and relative merit of the various measurement techniques employed;

c) regarding the adequacy and deficiencies of currently available parameterization models; and

d) regarding the physics of the tropical air-sea system.

The atmospheric integral experiment is the most ambitious part of the analysis program. It is presently planned to carry out the integrations using pressure deficit from sea-level pressure as the vertical coordinate. Fig. 7 shows this "p^*" coordinate system. In this system the integration "volume" is actually a constant

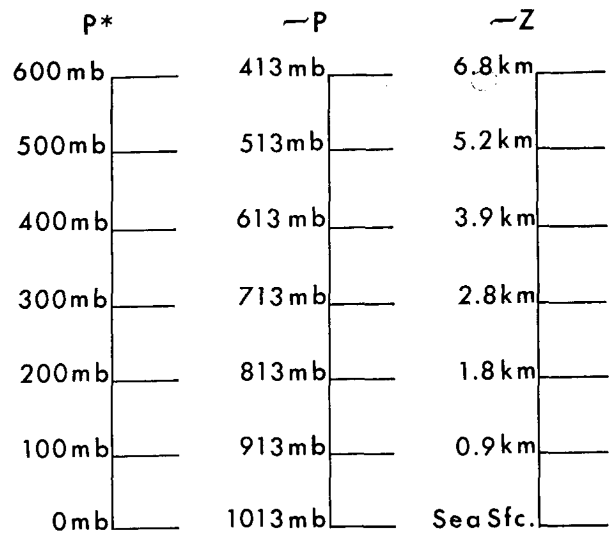

FIG. 7. "p^*" coordinate system, where $p^* = p_0 - p$.

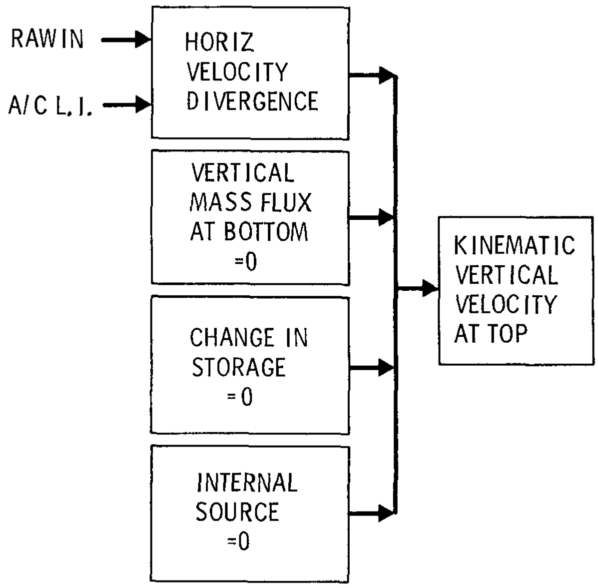

FIG. 8. Mass budget analysis plan.

mass, and the mass budget becomes a simple conversion formula between horizontal divergence and vertical velocity, as shown in the flow chart in Fig. 8.

Combining the heat budget and mass budget analyses as shown in Fig. 9 permits optimum vertical distributions of both vertical velocity and horizontal divergence to be developed, making use of both the "kinematic" and "adiabatic" methods. The vertical integration will be based on 25-mb slices. All the data analyses will be oriented towards developing minimum-error estimates of the necessary mean values, gradients, and time derivatives within each 25-mb slice, making use of all available data in that slice. Estimation of the errors at each stage will also be emphasized.

The heat storage (local time derivative) term, radiative cooling rate and latent heat conversion will be estimated for each slice in the same way for both the volume integration and the adiabatic vertical motion calculation. However, instead of calculating the horizontal flux divergence directly from the wind and temperature observations, only the advective part will be calculated at this stage, using the mean wind and the horizontal temperature gradient. The residual temperature change in each slice except that at the sea surface will be assumed to be due to adiabatic vertical motion. The mean vertical velocity is obtained by dividing this residual temperature change by the appropriately averaged vertical temperature gradient. Differences between slices will provide estimates of the horizontal divergence.

The two vertical profiles of vertical velocity and horizontal divergence obtained by the adiabatic and kinematic (mass budget) methods will be combined with suitable weighting factors. The kinematic data will most likely be favored in the turbulent mixed layer where entropy is not conserved, mean velocities are small and aircraft data are relatively plentiful. The adiabatic method should receive greatest weight in the upper, dry, stable regions, and therefore in the total volume integral.

The optimized distributions of horizontal divergence and vertical velocity will then be combined with the mean temperature in each slice to obtain the divergence contribution to the horizontal heat flux divergence, and the contribution of the mean vertical velocity to the vertical heat flux, respectively. All terms will be integrated over p^* to obtain the corresponding integral budget terms. The residual will be an estimate of the sea-air flux of sensible heat.

In the event that the surface heat flux estimate falls well outside the plausible range set by the microscale eddy flux measurements, the probable sources of error will be investigated. If extensive precipitation is indicated by the radar and satellite data, revised estimates

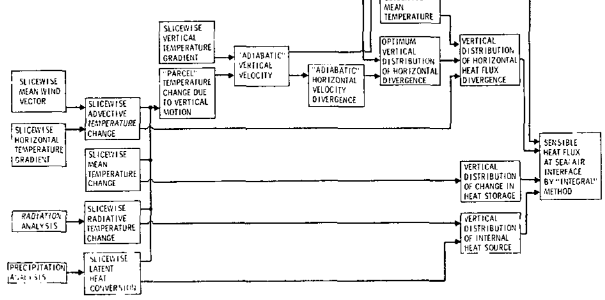

FIG. 9. Mass and heat budget analysis plan.

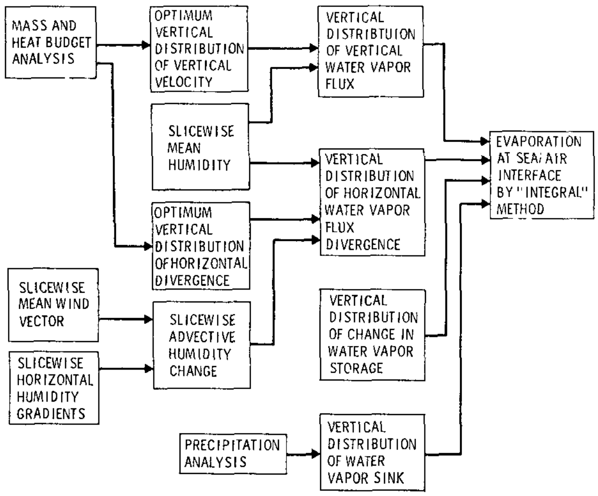

FIG. 10. Water vapor budget analysis plan.

of the latent heat conversion will be made with surface heat flux as an input quantity based on the eddy flux analysis.

The water vapor budget analysis, shown in Fig. 10, will thus have the benefit of the optimized divergence and vertical velocity distributions obtained from the mass and heat budgets. The precipitation input to the water vapor budget can also reflect any feedback from the heat budget as discussed in the previous section.

Similar synoptic-scale budget analyses will be carried out for mechanical energy and momentum. The latter will have surface stress as its output, for comparison with the microscale measurements.

Within this scheme, the objective of the analysis of surface-layer turbulent eddy flux data will be to develop estimates of area averages for comparison with the results of the integral budget analysis. In making such extrapolations, one approach which comes to mind is to establish semiempirical relationships of the measured fluxes to the immediate governing conditions, then to construct weighted area averages taking into account the area distribution of the governing variables.

The parameterization test is being carried out by Dr. Joseph Pandolfo of the Center for Environment and Man. An area in which additional effort may be undertaken is that of synoptic-scale parameterization of mesoscale exchange and conversion rates, in the event that the model containing only microscale turbulence fails to account for the observed rates.

7. Concluding remarks

It appears likely, though not yet certain, that the accuracy criterion of ± 25 cal cm^{-2} d^{-1} for the sea-air energy flux averaged over the 500-km BOMEX square and over a 24-hr period will be attained or closely approached. In other latitudes and seasons the environmental ranges may well be an order of magnitude larger than those existing in the BOMEX area during the first three periods of BOMEX, i.e., several mm d^{-1} for evaporation, several hundred cal cm^{-2} d^{-1} for total energy, several tenths of degrees for ocean temperature, several degrees for air temperature, several times 10^{-6} sec^{-1} for divergence. Under such conditions the observational requirements for parameterization model testing would be far less stringent and could probably be met with fewer observations per day, with ship-only or aircraft-only arrays, or with less sophisticated instrumentation. The problem of resolving the evaporation in the presence of precipitation would, of course, remain equally severe. We hope that the information and procedures developed in the course of analyzing the BOMEX data will be useful both in providing critical data for the design of such experiments and in maximizing the effectiveness of the data-gathering effort expended in the field.

Acknowledgments. I am indebted to DeVer Colson for the preparation of Table 3 and to Terry de la Moriniere for Figs. 8, 9 and 10. No account of the success of BOMEX would be complete without mention of the brilliant performance of the Project Manager, Col. William Barney, and the tremendous personal support given by Dr. Robert M. White, Administrator, Dr. John Townsend, Deputy Administrator, and Dr. Richard Hallgren, Assistant Administrator for Environmental Systems, ESSA. The project as a whole was directed by Dr. Joachim Kuettner. Beyond this the individuals who have given generously of their time and effort are too numerous to mention here. Financial support for the experiment was provided by seven agencies of the U. S. Government. And, of course, it should never be forgotten that Dr. Ben Davidson created the BOMEX Sea-Air Interaction Program.

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announcements

NASA research announcements

The National Aeronautics and Space Administration has adopted a new method of summarizing research projects within the agency to facilitate the exchange of ideas among researchers and project managers.

A 267-page publication, entitled *Research and technology: Objective and plan,* includes research currently in progress throughout NASA. It replaces the *NASA Flash Index* published in previous years. The RTOP summary lists the FY 1970 projects of three major elements of NASA—Advanced Research and Technology, Manned Space Flight, and Tracking and Data Acquisition. Copies may be purchased for $3.00 from the U. S. Department of Commerce, Clearinghouse for Federal Scientific and Technical Information, Springfield, Va. 22151. The accession number is N-7029204.

Scientific exchange to Soviet bloc

The National Academy of Sciences is now accepting applications from American scientists for professional visits to the USSR or Eastern Europe during the 1971–1972 academic year.

Under the program, scientists may visit Bulgaria, Czechoslovakia, Poland, Romania or Yugoslavia for one month. Visits of 3–12 months for research in these countries and the USSR are also open.

Deadline for applications is 23 November. Contact the National Academy of Sciences, Office of the Foreign Secretary, USSR/EE, Washington, D. C. 20418.

Interdepartmental program at Johns Hopkins

An interdepartmental graduate training program for the study and management of the atmospheric environment has been formed at the Johns Hopkins University following a $230,000 grant from the U. S. Public Health Service. The program will draw from the Department of Geography and Environmental Engineering, Chemistry, Environmental Medicine, and Environmental Health.

The program for the master's degree is intended to prepare students for careers in air pollution control, while the doctoral program stresses the need for fundamental research in the definition and solution of problems in air pollution control. Students at both levels are required to take a core seminar in which outside speakers will present various aspects of air pollution research and control. A broad range of courses on the biological, chemical, and physical aspects of pollution is available; students will elect courses related to their special interests.

New courses offered in the program are air pollution control and strategy, air pollution instrumentation laboratory, aerosol physics, atmospheric dispersion, biological effects of air pollution, and chemistry of atmospheric contaminants.

Applicants should contact Dr. Jerome Gavis, Department of Geography and Environmental Medicine, The Johns Hopkins University, Baltimore, Md. 21218.

Films

The oceanographer in the polar regions (16mm, 29 min, color, sound, on loan from Public Affairs of all Naval Districts) explains how Navy oceanographers study the ice, surface atmosphere, and the polar seas.

The weather eye (16 mm, 13 min, color, sound, 1969, $5.00 rental from U. S. Atomic Energy Commission or National Film Board of Canada, CFI, 1762 Carling Av, Ottawa 13, Canada) is the story of the design, development and fabrication of SNAP-19, a small, long-lived, radioisotope-fueled nuclear generator. The film describes SNAP-19's role as auxiliary power supply to produce electricity aboard a Nimbus weather satellite. As the orbiting Nimbus monitors changing weather patterns in the Earth's atmosphere, SNAP-19 helps power the data-gathering instruments and transmitters that supply information continually to meteorologists on Earth.

(More **announcements** on page 910)