ON THE SCIENTIFIC REQUIREMENTS OF SEA SURFACE MEASUREMENTS FOR THE GARP TROPICAL EXPERIMENT

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SUMMARY

Sea surface measurements must serve the broad objectives of GATE - improved understanding of the role of the tropics in the global circulation and parameterization of the effects of cloud clusters in large scale numerical models - and contribute to the testing of specific hypotheses and models of disturbances: wave behavior, CISK, energy fluxes, and flux changes, parameterization of fluxes, and atmsopheric and oceanic boundary layer structure in disturbances. There is less need for accuracy in measurements than for budget studies such as BOMEX; however, measurements must be nearly continuous over periods as long as two to three weeks, and instruments and platforms must operate through some of the harshest conditions imaginable.

Fluxes of momentum, moisture, and heat are the most difficult and among the most important of measurements to be made. Based upon an intercomparison and evaluation of each of the four primary methods we recommend that fluxes be determined by the dissipation technique, with the bulk aerodynamic method used for back up and verification.

In addition to wind, temperature, and moisture, which are needed for dissipation fluxes, sea surface temperature, pressure, rainfall and radiation measurements will be made. Accuracies and sampling frequencies for all parameters except radiation are given. In addition to these core measurements we recommend that on a limited basis the spectrum of sea surface temperature should be determined by radiometric measurements from aircraft; that wave period and amplitude should be measured; and that the presence of spray should be monitored.

I. The Problem

A. Experimental objectives

Any consideration of scientific requirements for surface observations during GATE must begin with the pertinent objectives of the Experiment. J. S. Sawyer has stated these for the JOC (quoted in the Experiment Design Proposal, 1971).

> ...The primary aims of GATE are ... to extend our knowledge of those aspects of the meteorology of the equatorial belt which are essential for a proper understanding of the circulation of the Earth's atmosphere as a whole ...[and] to provide a basis upon which to develop appropriate schemes for estimating the effects of the smaller tropical weather systems on the larger scale circulations.
>
> ...[D]isturbances have important effects in producing transports of heat, momentum, and water vapor both vertically and horizontally. These must be taken into account by relating them to larger scale features of the atmospheric circulation which are adequately represented by the model. The GARP tropical Experiment has therefore been designed to provide a description of the internal structure of a number of cloud clusters, to estimate the vertical (and horizontal) transport of heat, moisture and momentum associated with the systems and to relate them to the movements of the tropical atmosphere on a larger scale. The experiment is exploratory in as much as no accepted conceptual model exists for a cloud cluster, and the experiment aims to describe the internal organization. However, the observational network in GATE will be designed to measure the bulk effects of a cloud cluster, such as the overall convergence into and divergence from it at various levels, the changes in the total vorticity of the circulation round it, the total release of latent heat and exchange of heat and water vapor between levels. An important aspect of the experiment will be the comparison of the observations with numerical calculations using dynamical models employing a fine grid. It is expected that the combined observational and theoretical approach will reveal significant aspects of the life cycle of cloud clusters with applications both to forecasting and to the understanding of the role of tropical disturbances in the general circulation of the atmosphere.
>
> The energy of tropical disturbances is largely derived from the heat input from the sea into the atmospheric boundary layer, most of it as latent heat. The energy released in a particular cloud cluster will not have been derived from the sea surface immediately beneath it, but will have been collected from a substantially wider area. Nevertheless, the effect of the cloud cluster

itself on the evaporation and heat transfer may be of significance and should be studied. Also, it is believed that the effects of frictional convergence in the atmospheric boundary play an important part in the control of the growth of organized convective systems (convective instability of the second kind - CISK) and some knowledge of the turbulent stresses in the boundary layer in different parts of the system is desirable.

Thus, although GATE is not primarily directed towards measurement of boundary-layer exchanges, measurements will be required from ships in order to establish variations in the boundary-layer fluxes of heat, water vapor and momentum which occur in association with cloud clusters - down draughts produced by the convective systems may be particularly effective in influencing the air-sea transfer processes.

Knowledge of the radiative flux divergence is of importance in the long-term control of the structure of the tropical atmosphere and may play a role in the maintenance of conditions in which convective disturbances can develop. It is therefore hoped that the GATE experiment will include sufficient radiation observations for an assessment of radiative flux divergence and its comparison with theoretical models.

B. Observational requirements

Much effort over the years has been directed toward explaining tropical weather in terms of waves. Although the focus of this wave school has recently shifted upward, there remains a good deal of interest in analyzing fluctuations of such surface parameters as pressure and wind.

In recent years several theories have been advanced to explain the existence and position of the ITCZ in terms of thermal instability related to sea surface temperature or convergence in the boundary layer related to Ekman transport, or some combination of these. The testing of these hypotheses imposes certain demands on the sea surface observational program.

The Interim Scientific and Management Group in its Experiment Design Proposal has discussed convective transport of energy in terms of four steps. It is the first of these steps - the transfer to the atmosphere of solar energy absorbed and stored in the upper layer of the sea-which concerns us here, because of reported order of magnitude increases in vertical flux within disturbances and complex interactions between the disturbance and sea surface fluxes.

Holland (1972), summarizing results from the BOMEX core experiment, argues that the observed boundary layer minimum of potential temperature, the fall off of the spectrum of temperature at frequencies below ∿1 cycle per 5 seconds (about 50 m wavelength) and the positive correlation of vertical fluctuations of wind with temperature and moisture - decreasing upward for temperature and increasing upward for moisture - can be explained in terms of a balance between two opposing processes. Long wave radiation, because it is controlled principally by the vertical moisture gradient, cools the boundary layer from above. This destabilization strengthens the larger scale eddies and increases the intensity of turbulence; however, the increased evaporation which results acts as a counter balance: increasing evaporation increases stability through cooling of the sea surface and the surface mixed layer of the sea. A third factor of importance in this system is the contribution of moisture to buoyancy, which up to the trade inversion typically is greater than the contribution of temperature. A too vigorous mixing may increase stability to the point where the buoyancy of moisture is suppressed.

Aircraft co-spectra of moisture and vertical wind, measured by Bean and by Miyake and Donelan (Donelan, 1970) below the trade inversion, showed a peak in the along-wind direction corresponding to wavelengths of about 1.2 to 1.9 km, changing little with height, and a sharper peak in the cross-wind direction which shifted from wavelengths of 100 to 200 m at 18 m above the sea to 500 to 1000 m at 150 m.

"The picture which emerges", Holland argues, "is one of highly elongated eddies carrying moist air up and dry air down, and having dimensions of the order of 1 to 3 km in the along-wind direction, or perhaps being even longer and oriented obliquely with respect to the wind. Their cross-wind structure seems to consist of an eddy spectrum containing a range of cross-wind scales, the scale which makes the principal contribution to the water vapor flux at each altitude increasing from about 100-200 m in the lowest 20 m to dimensions of the same order as the longitudinal wavelength as the cumulus base altitude is approached (about 500 m). These largest eddies may be in the nature of longitudinal roll vortices, with maximum energy in the cross-wind component, although the evidence on this is unclear. These eddies, in turn, contain a broad spectrum of smaller eddies, apparently in the nature of transverse vortices or plumes with predominant energy in the longitudinal direction and feeding directly on the mean shear." (Holland, 1972).

The boundary layer structure which Holland has described evidently plays an important role in determining fluxes of moisture, heat and momentum across the sea-air interface, and the redistribution of these properties within the boundary layer. Lettau (personal communication) has suggested that this boundary layer circulation of helical rolls may drive a similar circulation in the surface layer of the ocean, which, if it exists, would profoundly affect interface fluxes and the total surface heat budget. In fact, the existence of such a circulation would be confirmation of the atmospheric circulation. Lettau has suggested that precise low altitude aircraft bolometer measurements of the spectrum of sea surface temperature simultaneous with boundary layer measurements of turbulent co-spectra would constitute a sufficient test. A second matter of interest is how this model, based on measurements made in undisturbed conditions, behaves in the vicinity of a cluster. There the trade inversion is weakened or destroyed, middle and high level clouds intercept and reradiate long wave radiation, and convective downdrafts may transport large volumes of cold, dry air into the boundary layer.

An important part of the parameterization problem involves expressing near surface turbulent transport of energy in terms of synoptic scale features and the structure of the underlying surface. The observational requirements of boundary layer parameterization are stated by the ISMG (1971) as follows:

> For parameterizing the boundary layer it is necessary to obtain the measured values for vertical mass ($\overline{w'V'}$), heat ($\overline{w'T'}$) and moisture ($\overline{w'q'}$) fluxes at different heights, over sea and over land, and in different latitudes, including the equator. The vertical range should be between a level just under the surface and a height of 1 to 3 km; observations of a continuous nature or at least at two to three hour intervals, are desirable. The heat conduction of the ocean surface as well as the horizontal advection must be known. Observations of the surrounding pressure field are desirable, as well as information about insolation and long-wave radiation.
>
> The mechanisms by which the latent heat of condensation is distributed to produce overall warming of the surrounding atmosphere is one of the unsolved problems of meteorology. For its solution the vertical massflux in cumulus towers as compared to the horizontal massflux due to boundary-layer convergence must be known. This requires extremely accurate boundary-layer measurements from ships and aircraft sampling active towers. This problem is also intimately connected with the CISK hypothesis.
>
> Another sub-problem of general importance is the determination of the turbulent flux of heat and water vapor from the sea surface under conditions of disturbed weather with high winds and sea state.

C. Ground rules

Deciding what is necessary and what is merely nice becomes much easier if judgements are made on the following bases:

(1) Surface measurements support the broad objectives of GATE - they are not an end in themselves.

(2) The need for accuracy is less than for budget studies such as BOMEX.

(3) Monitoring must be nearly continuous over periods as long as two to three weeks.

(4) Instruments must operate under some of the worst conditions imaginable: salt environment, high temperature and humidity, occasional immersion, and infrequent servicing by men who in the stress of these conditions may have little skill and less motivation.

II. Parameters

The ISMG Proposal lists five basic observable quantities - wind, air temperature, relative humidity, sea surface temperature, and pressure - and accuracies of these needed for GATE (Table 6, p. 81). However, the selection of these parameters and the determination of accuracies was based upon a general atmospheric rather than a specific level point of view. As the primary reference level for GATE, the surface should be specified to at least as high a degree of accuracy and resolution as all other levels. Additionally, some of the unique and important processes occurring at the surface cannot properly be described by the Proposal measurements alone. Therefore, the measurements recommended here will be both more detailed and more stringent in accuracy and resolution requirements than those recommended in the ISMG Proposal.

The rather broadly stated experimental goals of Section I explicitly identify several parameters which must be measured, among them pressure, wind speed and direction, rainfall, air temperature and humidity, radiation, sea surface temperature, and fluxes of heat, moisture, and momentum. Because fluxes are central to the sea surface measurement program and bear heavily on measurement of the remaining parameters, the four primary methods for measuring or estimating fluxes are discussed at some length in the sections which follow.

(1) Direct eddy flux measurement. Although attractive because it avoids the theoretical complications of all other methods, direct measurement has the following shortcomings: dependence of accuracy on vertical alignment;

sensitivity to ship or buoy oscillations; sophistication of instruments and need for calibration; expense. To our knowledge no instrument is presently available which would measure dependably, continuously, and accurately in the worst of conditions likely to be encountered during GATE.

(2) Profile. The development of stabilized floating platforms has made possible fairly accurate deep water measurement of fluxes over periods as short as several minutes (Hoeber, 1969; Paulson, Leavitt, and Fleagle, 1970). Redundancy is implicit, since partial failure of the system still allows use of the bulk aerodynamic method. However, the measurement of profiles imposes severe instrumental demands. Not only are vertical gradients generally small over the sea, the layer of largest gradient adjacent to the surface must be avoided because of fluctuating, unrepresentative winds over the moving waves (Roll, 1965a) and the debilitating influence of spray and waves on instruments. Users of the profile method must therefore either carefully match and cross-calibrate multiple sensor packages, or develop a mechanism for cycling a single package through several levels. In addition to these instrumental difficulties, there remain uncertainties in profile coefficients.

(3) Bulk aerodynamic. The bulk aerodynamic method has the advantages of simplicity, familiarity, and appropriateness to tropical conditions. In its simplest form it uses standard ten meter ship observations: momentum, heat, and moisture fluxes are given by

$$\begin{aligned} \tau &= \rho C_{10} U_{10}^2 \\ H &= \rho c_p C_{10} (T_o - T_{10}) U_{10} \qquad (1) \\ Q &= \rho C_{10} (q_o - q_{10}) U_{10} \end{aligned}$$

where C_{10} is the drag coefficient and the other variables have their conventional meaning. The bulk method is the most extensively used of all flux formulations, in numerical models of the boundary layer as well as in conventional flux studies. Garstang (1967) argues that the most restrictive of the assumptions upon which the method is based - that the turbulent exchange coefficients of momentum, heat, and water vapor are equal - are best met over the tropical oceans, particularly during disturbed weather, when the rather small departures from neutral stability which might occur are damped by the stronger turbulent mixing accompanying higher wind.

On the other hand it has been pointed out that the assumption of equivalence of eddy coefficients is invalid close to the surface where molecular transfer becomes important (Roll, 1965 b), and becomes increasingly questionable above because of buoyancy and pressure forces operating to change the scales of turbulence. (Businger, et.al., [1971] measuring fluxes and profiles over flat wheat stubble found a neutral lapse value of 1.35 for the ratio of heat to momentum eddy coefficients.) The bulk aerodynamic method also requires evaluation of the drag coefficient, about which there is a large cloud of uncertainty (Roll, 1965 b; Kraus, 1968). By definition, it depends on specification of bulk properties, and therefore may be poorly suited for revealing convective scale changes, and for accurately estimating stress when the surface wind is strong and gusty (Denman, 1972; Kraus, 1972). Wind speed, one of the most difficult measurements to make at sea, enters the bulk aerodynamic equation for stress as a squared term, and is present in all terms in any formulation where the drag coefficient is dependent on the Richardson number. This may be a critical limiting factor in an experiment such as GATE, where the ships will probably operate in a station keeping mode, adding ship motion errors to instrumental errors.

Results from BOMEX reinforce these reservations. Cain (1972) used surface winds measured by hot-film anemometers mounted on R. P. Flip to evaluate the drag coefficient. He concluded, "...due to the scatter in values of the drag coefficient obtained ... the bulk aerodynamic method should be used only as a very rough approximation to the wind stress, useful only because of its simplicity." Pond, Phelps, Paquin, McBean, and Stewart (1971) measured wind with a sonic anemometer mounted on Flip. The scatter of their drag coefficients for stress was somewhat smaller than Cain's, however, the drag coefficient computed for latent heat flux was 15% smaller than the coefficient for stress. Heat flux was so poorly related to $U\Delta T$ no estimate was made of the drag coefficient for sensible heat. Pond, et.al., concluded, "For the BOMEX data we must regard only the eddy flux values as reliable (to 10-15%) and accept the fact that the aerodynamic approach is not useful."

(4) Dissipation. In the fourteen years since it was first suggested by Deacon (1959) as a way of circumventing some of the difficulties of measuring wind at sea, the dissipation technique has rooted and flowered within a number of research groups and experimental situations. We develop the dissipation flux relations from the turbulent energy equation,

$$\frac{\tau}{\rho} \left|\frac{\partial U}{\partial z}\right| = \varepsilon + \frac{g\overline{\rho' w'}}{\rho} + \frac{1\partial}{\rho\,\partial z} (\overline{p'w'}) + \frac{\partial}{\partial z} (\overline{Pw'}), \qquad (2)$$

which equates the turbulent energy generation from the mean shear flow $\frac{\partial U}{\partial z}$ to the dissipation per unit mass plus the buoyancy production, the transfer to waves via the Miles mechanism, and the divergence of vertical flux of turbulent kinetic energy P (Kraus, 1968). Each of the last three terms ordinarily is small. Over the tropical ocean, with lapses neutral or near neutral, the buoyancy term can be neglected and at 6 to 10 m the wave generation term can be neglected. Although little is known about the last term, it is generally considered to be minor (Kraus, 1972). Thus, with the logarithmic law the dissipation can be expressed as

$$\varepsilon = \frac{1}{z\kappa} \left(\frac{\tau}{\rho}\right)^{3/2}, \tag{3}$$

where κ is the von Karman constant.

The Kolmogoroff law relates the spectrum of energy in the inertial subrange of isotropic turbulence to wave number k, dissipation, and a universal constant K:

$$\phi(k) = K\varepsilon^{2/3}k^{-5/3} \tag{4}$$

Combining (3) and (4) and noting that by definition $\tau = -\overline{u'w'}$, we get

$$-\rho\overline{u'w'} = \tau = \rho K^{-1} (\kappa z)^{2/3}k^{5/3}\phi(k). \tag{5}$$

Since we seldom have the temporally and spacially continuous observations that are needed to specify the spectrum $\phi(k)$, structure functions are defined which exploit known dynamic or kinematic relationships between wave numbers and frequencies (Kraus, 1972). Cain (1971) discusses three primary structure functions which are based on differencing measurements of two sensors aligned along the mean horizontal wind, differencing measurements of two sensors aligned across the mean wind, and differencing successive measurements made by a single sensor. The latter method is based on Taylor's hypothesis, that the local frequency of turbulent eddies is equal to their streamwise wave number times the speed of the mean flow. It has the obvious advantage of requiring only one set of sensors; recent users include Cain (1971), Pond et.al., (1971), and Denman (1972).

Pond et.al., present a single sensor structure function for the down stream velocity spectrum $\phi(k)$, defined as

$$D_{uu}(r) = \overline{[u(x+r) - u(x)]^2} = 4.02K\varepsilon^{2/3}r^{2/3}, \tag{6}$$

where $r = -Ut$, by Taylor's hypothesis. Substituting the expression for dissipation from Equation (3) and reordering gives the following expression for the horizontal stress:

$$\tau = \rho(4.02K)^{-1} (z\kappa)^{2/3} (Ut)^{-2/3} D_{uu}. \qquad (7)$$

The structure function for scalar properties γ (temperature or humidity) is

$$D_{\gamma\gamma} = \overline{[\gamma(x+r) - \gamma(x)]^2} = 4.02K_\gamma N_\gamma \varepsilon^{-1/3} r^{2/3}, \qquad (8)$$

with K_γ the Kolmogoroff constant for scalar fluctuations.

N_γ, the dissipation of the scalar fluxes, is set equal to production

$$-\overline{w'\gamma'} \frac{\partial\overline{\gamma}}{\partial z} = N_\gamma. \qquad (9)$$

In analogy to the logarithmic law for velocity we have for the vertical gradient of the mean scalar $\overline{\gamma}$

$$\frac{\partial\overline{\gamma}}{\partial z} = \frac{\gamma^*}{z} = -\frac{\overline{w'\gamma'}}{(\kappa u^*)} \cdot \frac{1}{z} = - \frac{\overline{w'\gamma'}}{\kappa z\sqrt{\tau/\rho}}. \qquad (10)$$

Combining Equations (10) and (9) gives for the dissipation of scalar fluxes N_γ

$$N_\gamma = \frac{(\overline{w'\gamma'})^2}{\kappa z\sqrt{\tau/\rho}}, \qquad (11)$$

which, when combined with Equations (8) and (3) yields an expression for the scalar flux

$$\overline{w'\gamma'} = (4.02K_\gamma)^{-1/2} (\kappa z)^{1/3} (Ut)^{-1/3} D_{\gamma\gamma}^{1/2} (\frac{\tau}{\rho})^{1/2}. \qquad (12)$$

The expressions (7) and (12) for fluxes of momentum, moisture, and heat have been modified by Pond et.al., (1971) to include the buoyancy term of the turbulent energy equation. Pond et.al., also discusses the Kolmogoroff constants K and K_γ, both of which seem now to be fairly well established.

The dissipation technique, and the assumptions upon which it rests, were quite extensively tested by several research groups during BOMEX. Except for temperature, spectra and cospectra generally had well defined inertial subranges. (Phelps and Pond, 1971; Pond et.al., 1971; Cain, 1971). It has been suggested by Phelps and Pond that the anomalous behavior of temperature is related to the long wave radiative influence on temperature gradients and large scale fluctuations which becomes important when moisture content is high. However, they also point out that the high frequency end of their temperature spectrum appeared to be at the edge of an inertial subrange. Gibson, Stegen, and Williams (1970) looked at this high frequency portion of the temperature spectrum, up to the viscous cut off. The shape of their spectrum indicated an inertial subrange, but anisotropy was indicated by a skewed distribution of the temperature distribution. However, Holland (1972) reports that Wyngaard has suggested the skewness resulted from an instrumental effect. Predictably, in view of this spectral behavior, the dissipation method during BOMEX compared well with eddy correlation and profile methods in estimating momentum and moisture fluxes, but stumbled on sensible heat. Holland (personal communication) has suggested that estimates of sensible heat flux might be improved if sampling occurred at ten times the "natural" frequency $\frac{U}{z}$. A second possibility for improving estimates of sensible heat flux is use of the Bowen ratio, which Pond et.al., found to be quite constant at 0.10 for their BOMEX data.

Partial results from the Bahama Banks Experiment of 1971, kindly loaned by Miyake, are, if anything, more encouraging than results from BOMEX; an inertial subrange appears to be present in spectra of moisture, temperature, and each velocity component.

III. Recommendations

The primary advantage of the dissipation technique over the bulk aerodynamic technique is its dependence on a universal constant (which is fairly well known) instead of an uncertain coefficient (which is a function of height and surface structure at least). It is far less demanding of instrumental sophistication and technique than the profile method; and more forgiving than either bulk or profile methods of errors in wind speed, which over the ocean are compounded by wobbles and unknown translational motions of the platform. We consider these advantages to be decisive, and therefore propose to estimate fluxes using the dissipation technique.

The bulk aerodynamic method will serve to back up and verify dissipation estimates of fluxes; comparisons with the dissipation technique may lead to improvements in both methods.

Besides wind, air temperature, and moisture (which are needed for dissipation fluxes) sea surface temperature, pressure, rainfall, and radiation measurements will be made. Accuracies and sampling frequencies for all parameters except radiation are given in Table 1. These accuracies and frequencies are governed by the needs of flux estimations in the case of wind, temperature, and moisture. Sea surface temperature, although not needed for dissipation estimates of the scalar fluxes, is included because of its importance to the oceanographic subprogram, and the parameterization of fluxes, its control on stability, and the need to explore interactions between sea surface temperature, boundary layer structure, and convection. Accurate surface pressure is important as a reference for soundings, but if measured to the accuracy specified it will also give insight on the response of the surface wind field to unbalanced pressure forces. With data from the Boundary Layer Instrumentation System, it is possible to vertically integrate cross-isobar flow and so arrive at an estimate of the boundary layer stress, independent of the dissipation estimate. The requirements for accuracies in estimating divergence and vorticity are noted separately in Table 1. Radiation is not considered explicitly as specifications have already been made.

For removing the effects of platform oscillation from observations of wind and rainfall and for correction of wind spectra which close to the surface may show some influence of waves we recommend monitoring wave period and amplitude. The laboratory experiments of Okuda and Hayami (1959), showing a sharp increase in evaporation rate as wind speed exceeds the threshold for spray formation, suggest that the presence of spray should also be monitored.

TABLE 1

SEA SURFACE MEASUREMENTS FOR GATE

PARAMETER	PURPOSE	ACCURACY	SAMPLING FREQUENCY	REMARKS
horizontal wind speed	fluxes	±3% (abs)	1 $\sec^{-1}$	
	divergence	±.5m/sec (abs)*	1 hr^{-1}	
wind direction	fluxes	2-3° (abs)	1 $\sec^{-1}$	
	divergence	3° (abs)*	1 hr^{-1}	
moisture	moisture flux	0.1°C (dewpt) (abs)	1 $\sec^{-1}$	same level as wind
air temp	heat flux	0.1°C (abs) 0.02°C (rel)	∿ 10 $\sec^{-1}$	same level as wind
sea surface temp	boundary layer dynamics	0.01°C (rel)	∿ 10 $\sec^{-1}$	aircraft mounted radiometer; simultaneous with aircraft spectral measurements of w', T', q'; occasional basis
	fluxes; oceanographic program	0.05°C (abs) 0.02°C (rel)	1 $\sec^{-1}$	
pressure	stress non-geostrophic pressure forces	.1 mb (abs)	.02-.04 $\sec^{-1}$	long sampling frequency smooths high frequency ship-oscillations
rain	heat budget	.5 mm	8 day^{-1} or more	

*based on ship spacing of 150 km, disturbance divergence of 10^{-5} $\sec^{-1}$, 10% accuracy in the measurement of divergence, and an error of .2 - .3 m/sec resulting from platform drift.

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