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# The Scientific Basis and Objectives of the U.S. Convection Subprogram for the GATE

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## Abstract

This paper discusses certain theoretical concepts underlying the GATE Convection Subprogram. It proposes a framework for the analysis, modeling and parameterization of scale-interactions, and comments on the testing and development of parameterization theories for moist convection using the observational and diagnostic studies which will stem from the field experiment.

## 1. Introduction

The GARP Atlantic Tropical Experiment (GATE) will take place during the period June–September 1974 in an area roughly 10S to 20N, 95W to 47E (GATE, 1972). GATE is an international program concerned with the interaction of convective cloud systems of all horizontal scales with their associated meteorological and radiation fields, and with the tropical Atlantic Ocean below. The GATE program is divided into five subprograms: synoptic-scale, convection, boundary layer, radiation, and oceanographic.

The purpose of this paper is to discuss the scientific basis and objectives of the United States participation in the Convection Subprogram (Betts, 1973c). An attempt will be made to define certain concepts underlying the subprogram and to discuss a strategy of observations and analysis. This paper is not a comprehensive survey of all aspects of the subprogram research effort. It is slanted towards the theoretical problem of understanding and parameterizing the transports by convective cloud systems of different scales. In all, some fifty research groups across the country are involved in the subprogram, which includes important studies in satellite meteorology, cloud physics, and radar meteorology. In this paper, many of these critical studies and analyses are only referred to briefly or alluded to in discussions of the data needed to test theoretical models of convection. It should not be overlooked that although our current theoretical concepts have guided the design of the experiment, it is the wealth of descriptive studies and analyses stemming from the GATE that will provide the observational basis for a deeper theoretical understanding of the interaction of convective cloud systems.

The general scientific background and objectives of the GATE including the Convection Subprogram are discussed in GATE Report No. 1 (1972). The plans for the United States participation in the GATE are outlined in a publication of the United States Committee for the Global Atmospheric Research Program (USC-GARP, 1971). More specific discussions on convection and its parameterization are contained in Yanai (1972), Bates (1972), Ogura (1972), and GARP (1972). A general review of the literature is not presented here.

## 2. Scale phenomena

### *a) The concept of scale*

The GATE may be described as a scale interaction experiment (see 3) and consequently, certain horizontal scales may be distinguished in the objectives, the field observations, and the analysis. Four scales are explicitly identified and defined in GATE (1972): these are shown in Table 1.

It is to be noted that the names for three scales (A, B, and D) are the names of meteorological phenomena having that scale, although the term mesoscale is not. In this paper, scales will be described by letter (A, B, C, D) when it is necessary to focus on measurements extending over a particular scale (which often are obtained by different platforms), and the name only when the focus is on a specific phenomenon. For example, the inner hexagon, the so-called B-scale ships (Fig. 1), will define a field on about the B-scale whether or not a cloud cluster of B-scale dimensions is there. However, convective organization may be present on the C-scale, and it will be important to study the interaction between the B- and C-scales using the B-scale ship data, and C-scale aircraft and radar data, even though no meteorological phenomena may be apparent with B-scale dimensions. The B-scale field may then be only a part of a larger (nearly homogeneous) A-scale field.

Associated with each different space-scale is a time-scale, and correspondingly a different frequency of observation is necessary for each space-scale. Table 2 lists a typical horizontal scale, a growth time for a phenomenon of that scale (rather idealized to preserve an order of magnitude separation), and a corresponding time interval, an order of magnitude less, which would be necessary to resolve the phenomena spectrally, and finally the sampling time expected in the GATE.

The growth times chosen in Table 2 may, for some purposes, be regarded also as advective time-scales: they are related to the corresponding space-scale by an advective speed of 7 m $sec^{-1}$. Some of the observational platforms, such as the ships, provide a nearly Eulerian data set, and a phenomenon must be resolved as it is advected through the network; other platforms such as the aircraft can follow a convective system and provide a data set which is more nearly Langrangian.

### *b) Observational objectives*

The first objective of the Convection Subprogram is to provide an observational description of convective phenomena of the B-, C-, and D-scales. A detailed outline of the proposed observations is contained in the United States Convection Subprogram (Betts, 1973c), and amplified in the International Scientific Management Group document (ISMG, 1974, The Convection Subprogram for GATE).

Fields on the A-scale will have the desirable time-resolution of 12 hours (Table 2), and the network will

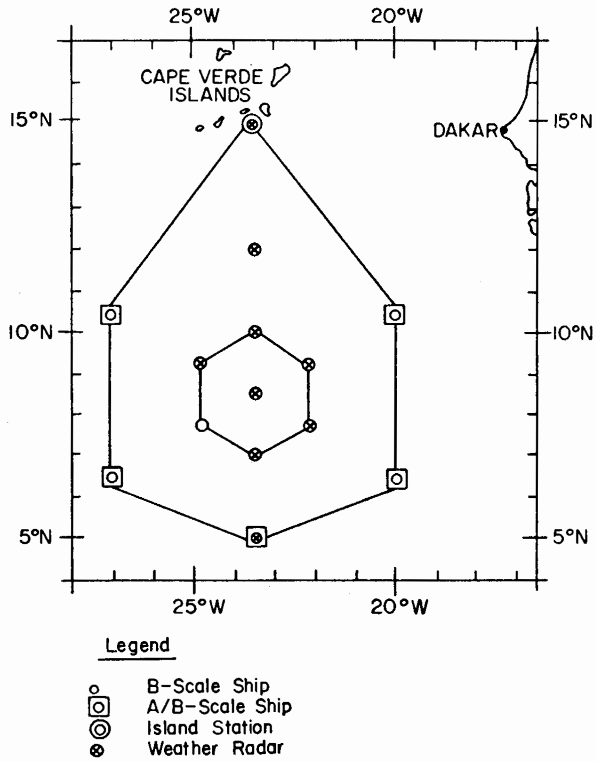


FIG. 1. Locations proposed for B and A/B-scale ships during Phases I and II of the GATE.

extend over a horizontal distance greater than $10^4$ km. On the B-scale, a sampling time of three hours approaches that required for spectral resolution. However, the B-scale ship network is rather small (diameter 300 km), and a "typical cloud cluster" of diameter 350 km will generally be advected through the B-scale ship array in a time period comparable to its growth time (Table 2). It follows that the A/B scale ships (Fig. 1), although their spacing is about 300 km, are critically important to case studies of the cloud cluster. Therefore, three hourly soundings from A/B-scale ships during intensive periods are planned. Three-hourly soundings are most critical for budget studies of cloud clusters: in undisturbed conditions, six-hourly sondes might be adequate, although they would not resolve the diurnal variation. However, the forecasting of cluster development may not be successful in GATE: if so, then only by continuous three-hourly sondes will we obtain adequate observations of the critical transition from undisturbed to disturbed conditions—the growth of clusters. However, the operational limitations of the observing ships, particularly the A/B-scale

TABLE 1: Scales of tropical disturbances.

| Scale | From (km) | To (km) | Name |
|---|---|---|---|
| A | $10^3$ | $10^4$ | Wave scale |
| B | $10^2$ | $10^3$ | Cloud cluster scale |
| C | 10 | $10^2$ | Mesoscale |
| D | 1 | 10 | Cumulus scale |

TABLE 2: Time scales (idealized) for tropical phenomena.

| Scale | Scale of phenomena | Growth time of phenomena | Sampling time for spectral resolution | Sampling time expected |
|---|---|---|---|---|
| A | 3500 | $5.10^5$ or 5 days | 12 hr | 12 hr |
| B | 350 | $5.10^4$ or 12 hr | 1½ hr | 3 hr |
| C | 35 | $5.10^3$ or 1½ hr | 10 min | 15 min to 1½ hr |
| D | 3.5 | $1.10^2$ or 10 min | 1 min | — |

ships, will not permit continuous three-hourly observations. An observational strategy for these ships must be devised that will provide a documentation of cluster development for some cases.

Individual phenomena on the A- and B-scales are resolved as they pass through a network. No meteorological network will exist on the C-scale, although aircraft will be vectored around individual C-scale systems (as, for example, a squall line). Each aircraft pattern will take 60–90 min, which is comparable to the growth time of the phenomena; hence, detailed resolution of the time dependence will not be possible. Radar observations, however, will map precipitating clouds every 15 min and the SMS-GOES satellite will map clouds from above in the visible and infrared about every half hour.

On the D-scale, measurements will be primarily line samples by aircraft, tethered balloon, and surface systems; time dependence will have to be inferred by statistical and composite studies.

## 3. Interactions

### *a) The concept of a scale interaction*

The concept of an interaction between different scales arises whenever averages over a certain scale length are defined (or implied, as, for example, by the choice of a grid length in a numerical model). Transports by processes on scales smaller than the averaging scale are then not resolved by the averaging fields. Denoting averages over this chosen scale by an overbar, and deviations from this average (or smaller scale) by a prime, one may write, for example, the equation for the moist static energy.

$$h = c_pT + gz + Lq,$$

with slight approximation, as

$$\frac{\partial \bar{h}}{\partial t} + \nabla\cdot(\overline{\mathbf{V}}\bar{h}) + \frac{\partial}{\partial p}(\bar{\omega}\bar{h}) = Q_R + \nabla\cdot(\overline{\mathbf{V}'h'}) + \frac{\partial}{\partial p}(\overline{\omega'h'}), \quad (1)$$

where $Q_R$ is the heating rate due to radiation. Similar expressions may be written for dry static energy and water vapor, each explicitly containing as well the net condensation of water (another source term). The correlation terms represent the collective effect of smaller scale transports on the averaged fields. These terms must be known if the time change of the averaged fields are to be computed. The parameterization problem is formally similar to the closure problem of turbulence theories. It is necessary to compute from given averaged fields the average transports due to smaller scale phenomena by using some physical model which relates the smaller scale processes to the averaged fields. In numerical modeling this is always necessary, since there is a lower limit of explicit resolution determined by the grid scale. In classical turbulence theories, it has often been supposed that the "eddy" transports are related to local gradients of the averaged fields. This is generally not true for the convective atmosphere (see, for example, Yanai *et al.*, 1973). There, clouds (the "eddies") can extend through the entire depth of the atmosphere, and are not controlled by gradients at any one level.

In the GATE, the left-hand side of Eq. (1) may be computed from the measurement of fields averaged on a certain scale, although sometimes it will be necessary to assume that point measurements are representative of an area. If the radiation fields are measured or computed, the smaller scale "eddy" transports may be found as a residual. Some direct measurements of these smaller scale transports will be made by platforms such as the aircraft and boundary layer systems; these will give insight into the physical processes. Generally, however, we shall have fields on a certain scale, and the smaller scale transports and source terms derived as residuals from budget calculations using equations like Eq. (1). This data set will comprise a description of an interaction, based on observation. The theoretical closure problem of relating the derived eddy transports and source terms to the larger scale fields will still remain.

Since the interactions between phenomena of different scales in the tropics are not well understood, it seems helpful to conceptually structure the data analysis in a manner that is directly applicable to the closure problem discussed above, and in particular to the test and development of parameterization theories. In particular, one may hypothesize that a control by the larger scale of the smaller scale can always be identified, simply because if such a control cannot be identified, then the effects of the smaller scale phenomena cannot be parameterized in terms of the larger scale.

### *b) Simple model of a two-scale interaction*

Fig. 2 illustrates this concept by formally dividing a scale interaction into:

1) a large-scale control of the smaller scale "clouds";
2) a feed-back of the smaller-scale transports to the large-scale.

An objective of the Convection Subprogram is, therefore, to analyze the scale data to determine these controls and feedbacks for each interaction. The controls suggested in Fig. 2 are not necessarily correct, but represent hypotheses which may be tested. Of the larger-scale controls, destabilization by low level convergence is perhaps the only one that is well understood. Other controls need to be defined and described in the GATE, by identifying the static and time dependent meteorological fields associated with a particular scale and type of convection. For example, how does vertical shear control convection?

The "feed-back" is simply the smaller scale transports, sources or sinks of mass, enthalpy, water vapor, momentum, and kinetic energy by the convective phenomena (see 3a); and these can be made quantitative by

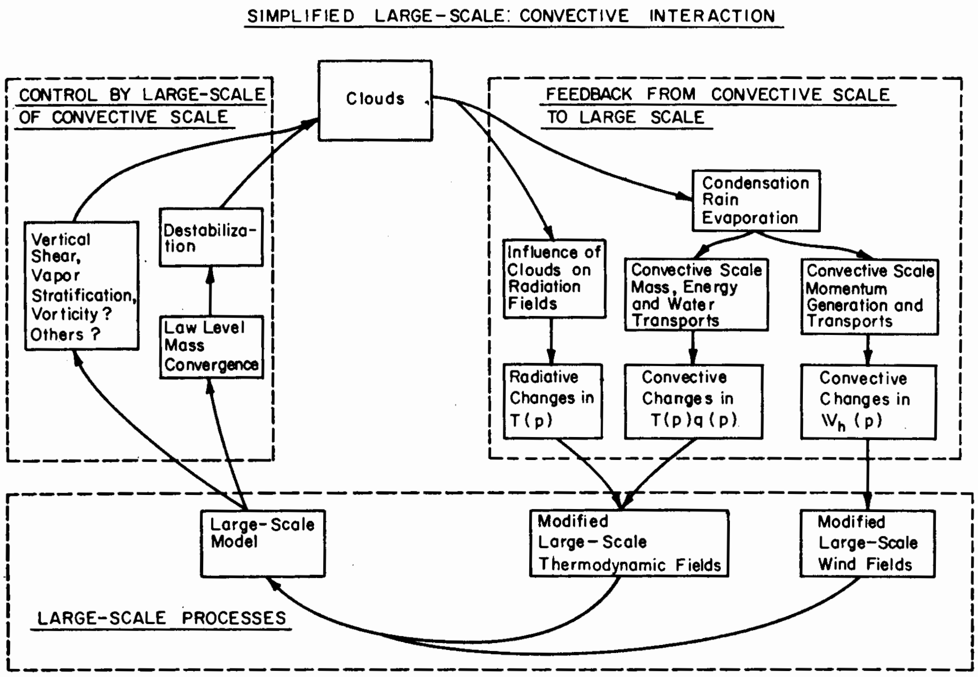


FIG. 2. Simplified diagram of interaction between the large-scale and the convective scale showing the controls by the large-scale and the feedback to the large-scale due to convective scale transports and transformations.

budget calculations [as in Yanai *et al.* (1973), Holland and Rasmusson (1973), and Augstein *et al.* (1973)] using the large-scale data.

Fig. 3 carries the definition of controls a step further by formalizing the logical structure of recent parameterization theories. A simplified two-scale interaction (which one may think of as a large-scale: convective scale) is again shown and the time-scale separation shown in Table 2 is made explicit. The cloud scale dynamics and transports have a much smaller time scale ($\tau_2$) than that of the large scale ($\tau_1$). The *static large-scale fields* (e.g. stratification, shear field) influence the cloud dynamics (and therefore, the depth of the cloud layer, updraft, and downdraft transports, etc.). This will be called a *static control:* these static large-scale fields control the vertical structure of the convective transports by a cloud type because, during the lifetime of each cloud, the large-scale field changes only a little. Conversely, the magnitude of the convective transports (for example, the number of clouds) is related, not to the vertical stratification, but to the large-scale dynamics, and in particular to that *time dependence of the large-scale fields* which would occur if the convective transports momentarily ceased. For example, suppose a large-scale mean ascent sets a rate of destabilization; the atmosphere maintains a structure only slightly unstable to cumulus convection by balancing the large-scale cooling with a compensating convective heating rate. This will be called a *time-dependent control* by the large-scale fields. This concept has a good observational basis, since a characteristic thermodynamic stratification is observed while cumulus convection is in progress (Ludlam, 1966) despite forcing by the large scale. This state of quasi-equilibrium between the large-scale time dependent control and the convective feedback (Betts, 1973a; Arakawa and Schubert, 1974) seems possible because of the separation of time scale ($\tau_2 << \tau_1$). Whenever the large-scale fields change (a slow process), the convective processes rapidly

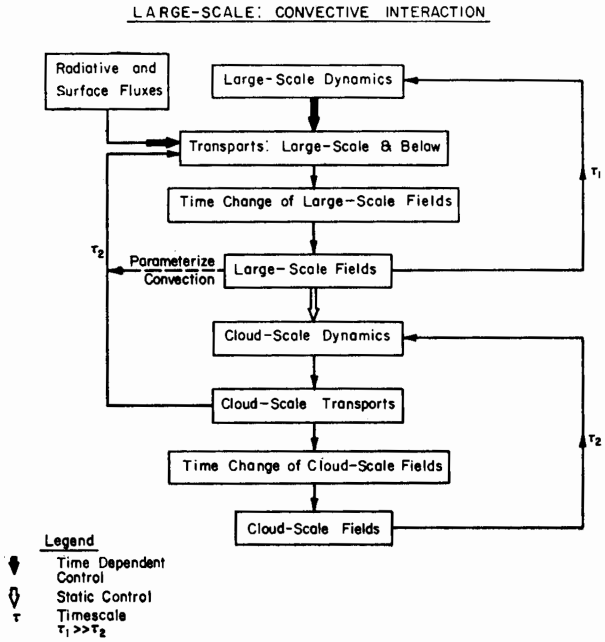


FIG. 3. Schematic diagram of a two-scale interaction between the large-scale and the convective scale, showing time-scale separation, and static and time-dependent controls of the convective scale by the large-scale.

restore some equilibrium convective structure. One can envision a large-scale field with a thermal and wind shear structure balanced on the large scale—although with convection in progress, this balance involves both the convective heat and momentum transports.

Although a sharp time-scale separation is an idealization, the concept of balanced states is likely to be useful as a first approximation, as elsewhere in meteorology.

*c) Extension of the simple model*

Figs. 2 and 3 are oversimplified; Fig. 4 is probably more realistic. It is modeled on Fig. 3 but identifies separately the A-, B-, C-, and D-scales. Convective phenomena on the B-, C-, and D-scales certainly exist, but the relative importance of different interactions is not known: this is a purpose of the GATE. We shall use the notation of an A:B interaction.

In multiscale interactions of this kind, it becomes important whether the feedback from the smaller scale is positive or negative. If the feedback is positive, then an instability peculiar to that scale interaction can give rise to convective organization with that particular scale. Examples are the hurricane (instability probably due to B:C interaction), and the squall line (instability probably due to C:D interaction). Positive feedback from the smaller scale raises questions about the concept of downscale control (that is, of the smaller scale by the larger) which was hypothesized in the previous section. For example, if a squall line is a C:D instability, then the control of the C-scale by the B-scale may be small compared with the positive feedback from the D-scale. In this case, where the upscale feedback is strong and the downscale control weak, then it may not be possible to parameterize the phenomena solely in terms of the larger scale meteorological fields: the ocean surface interaction might, for example, be important.

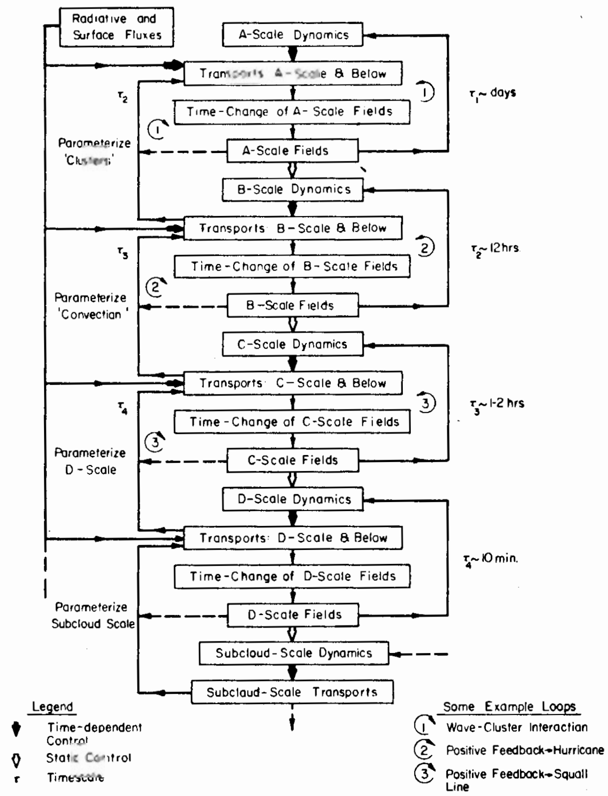


FIG. 4. Schematic diagram of multiscale interactions A:B:C:D showing some possible feedback loops.

Thus, the relative strength of different interactions is an important objective of the Convection Subprogram. At times, certain scales of organization, such as the C-scale, may not exist, and the interaction problem may simplify to B:D. The larger the separation of space and time-scales, the simpler the scale interaction problem is likely to be.

*d) Analysis objectives*

It will be clear from this discussion that a further set of Convection Subprogram objectives, after providing an observational description of the scale phenomena (see 2b), is to analyze these data to provide a description of scale interactions: that is, the controls and feedbacks from one scale to another. Although all interactions between adjacent scales are identified separately for logical completeness in the U.S. Convection Subprogram (Betts, 1973c), all are not equally important GATE objectives. The focus of the experiment and its basic design is the cloud cluster or B-scale. Thus, the two interactions of primary importance are A:B (wave:cluster), which should be explicitly resolved by the ship network and by some numerical models, and B:C (cluster:mesoscale), which is the target of the intensive aircraft studies within the B-scale ship array. The C:D (mesoscale:cumulus) interaction, despite its probable importance, will of necessity receive less intensive study, as will studies of smaller scale.

Analysis procedures will differ by scale, according to the resolution of data available. On the A- and B-scales, and to a more limited extent the C-scale, case studies will be possible. Some time averaging of sonde data may, however, be necessary for B-scale budgets. For B-scale studies of regional differences, for some C-scale studies, and for most D-scale studies, composite methods will be used. Examples in the recent literature on the large-scale are Williams and Gray (1973), Reed and Recker (1971), Yanai *et al.* (1973), and on the mesoscale, Betts (1973b). Case studies are clearly important, as they are free from the ambiguities of compositing; but the composite problem must be studied since the characteristics of "mean" systems are needed for modeling studies. This relates back again to the question of controls, since if different categories of mesoscale systems yield different budgets, then what controls the category must be determined.

Other interactions than the scale interactions discussed above will be studied in the GATE. For example, the interaction between the tropical and the mid-latitude circulations is part of the Synoptic-scale Subprogram.

The interaction between cloud layer and the subcloud layer (an interaction between two vertical domains) is an object of both the Convective and the Boundary Layer Subprograms. The interaction of convection on all scales and the radiation fields is an object of the Radiation Subprogram. The interaction between convection and diurnal controls (a time rather than space interaction) may also be important.

## 4. Modeling of interactions

A distinction may be drawn between the description of an interaction (based on the analysis of the observations; see Section 3) and the modeling of an interaction (which includes the parameterization of convection). This distinction is a little blurred because the analysis (discussed above in 3) is based on concepts derived from the parameterization objective, since one major purpose for which the analyzed data set will be used is to test parameterization models. Conversely some components of a parameterization theory can usually be tested diagnostically. However, the development of a model for a scale interaction and for parameterization involves additional factors or assumptions beyond the simple analysis of an interaction. Nevertheless, this further step is necessary, since analysis alone will not provide an adequate understanding of an interaction: the consequences must be modeled. In several respects, the analyzed data set will go far beyond our current models, and will provide the observational basis for further model development.

### *a) Modeling objectives*

The Convection Subprogram is concerned with four aspects of modeling:

1) the numerical simulation of convective phenomena;
2) testing prognostic parameterization models;
3) diagnostic tests of models;
4) analytical dynamic models of convection.

The first three objectives represent decreasing orders of complexity. For example, the realism of a numerical model of any convective scale depends on the structure and assumptions of the model as well as on the prediction of subgrid scale transports by its parameterization scheme. A prediction model can be tested as a complete unit by comparison of the observed and predicted fields of motion or precipitation (the observed precipitation being estimated by radar or satellite). This will not be discussed in this paper.

A parameterization scheme for subgrid-scale convection can be tested directly by comparing the subgrid-scale transports predicted by the scheme with the convective transports derived for this scale. This is a direct comparison of a computed "feedback" with that observed (3), and in the GATE this can be done using the B-scale ship data. Similarly, if the parametric model predicts a cloud population (or other observable quantity) for the parameterized scale, this can be compared with the corresponding atmospheric cloud fields. This represents a test of the "control" aspect of the parametric model. Finally cloud models and the simplified parametric versions of them usually have components which can be tested diagnostically using atmospheric data.

The development of analytical dynamic models for convective systems is still in its infancy. Some progress has been made towards the classification of specific dynamic regimes in terms of a synoptic-scale Richardson number (Moncrieff and Green, 1972). Further development of dynamic models using exact integrals of the equations of motion is necessary to relate the structure of convective systems to the flow in which they are embedded, and to predict the convective transfers of heat and momentum.

The focus of the U.S. Convective Subprogram is on those studies which will help test and develop models which parameterize C- and D-scale convection in terms of A- and B-scale models. However, since the smallest grid length currently envisaged for tropical models is 100 km, which is a little coarse to resolve the lower end of the B-scale (100–1000 km), it is also necessary to test models which parameterize cloud clusters. Within the A/B ship array, the data will be adequate to initialize and test short period predictions of a B-scale model (grid length $\sim$50 km), which parameterizes the C- and D-scale convection. It may be necessary to test the A-scale models within the same A/B array although satellite data may provide adequate validation throughout the A-scale domain.

Many other studies of atmospheric convection will also be carried out using the GATE data by the scientists of the participating countries.

### *b) Existing parameterization theories*

There have been several schemes suggested for the parameterization of moist convection. Early schemes included moist adiabatic adjustment (Manabe *et al.*, 1965), those relating to the convergence of water vapor into an atmospheric volume (Kuo, 1965), or boundary-layer convergence (Ooyama, 1964, 1969; Ogura, 1964; Charney and Eliasson, 1964, and many others). More recently, models for a cumulus population have been suggested (Arakawa, 1971; Ooyama 1971; Arakawa and Schubert, 1974), Betts (1973a) has produced a parameterization for the non-precipitating convective boundary layer.

Fig. 3 can be used to discuss parameterization models. It presents a two-scale interaction between a large-scale and a cloud-scale. All current models greatly simplify the cloud-scale component and do not explicitly compute time dependent cloud-scale fields: their objective is to compute cloud-scale transports using the simplest possible cloud model. Static and time dependent controls can be distinguished in all models, although at present both are usually based only on the thermodynamic fields.

For example, convective adjustment schemes included the time-dependent control by adjusting the lapse rate back to a moist adiabat, whenever the large-scale fields produced a layer unstable to moist convection, while the static control was included implicitly by adjusting over the unstable layer. Kuo's scheme computed the convergence of water vapor in unit time into a grid volume (a time-dependent control), and then partitioned this into a vertical distribution of heat and vapor using a "static" cloud model. Arakawa's theory uses a cloud ensemble model, which determines the depth over which the convective modification takes place for each cloud scale by the calculation of the equilibrium height of a parcel ascending with entrainment from the mixed layer. With additional conditions on detrainment and precipitation, the vertical structure of the transports for every "cloud class" is completely determined—this is the static control. The time dependent control is imposed a little more implicitly by imposing a balance condition (see 4c). This is an integral constraint on the time change of the large-scale thermodynamic fields. Referring to Fig. 3, we see that this constraint can specify the magnitude of the cloud-scale transports which feed back to the large-scale in terms of large-scale processes.

The next section discusses the testing of these models. No existing models have attempted to parameterize the multiscale interactions B:C:D shown in outline in Fig. 4 (see 4f).

### *c) Testing parameterization theories*

The object is to determine how well current models for parameterizing moist convection over the tropical oceans predict the observed convective heat and water budgets. One may assume that if these bulk budgets are not predicted with some realism, then that parameterization scheme will have only limited value in a prognostic model. One can first ask whether a scheme predicts the gross value of the convective heat sources, and then the correct vertical distribution of heat source and vapor sink. This comparison is relatively straightforward once the data has been analyzed: the observed controls and feedback from a convective scale can be compared with the model controls and model convective transports.

These studies will cover a wide range of scale, from large-scale models (grid length say 250 km, which will only resolve well the A-scale) to mesoscale models (with a fine mesh of a few kilometers to resolve the C-scale). Most current parameterization theories are intended to derive the collective effects of clouds (D-scale) from A-scale parameters. This simplification was discussed in 3b, and in a later section (4f) some possible extensions are considered. This section will comment on the testing of some of the models currently in use.

*Adjustment to moist adiabat.* The tropical atmosphere is usually conditionally unstable and rarely approaches the moist adiabatic structure, so that adjustment to such a structure involves too large a change in the vertical temperature and humidity profiles (Krishnamurti *et al.*, 1971). This procedure can hardly be validated, although the gross heating of the atmosphere can be compared with values deduced from budget studies.

*Kuo's method.* This method predicts the vapor and enthalpy changes produced by convection, by partitioning the net vapor convergence into a volume into a vapor input and a condensation. The comparison with the B-scale budgets is straightforward, although it already seems likely that this method in general underestimates the convective heating, which can be comparable with the vapor convergence (Betts, 1973b; Yanai *et al.* 1973).

*Boundary layer convergence methods.* The convective heating function computed from the boundary layer convergence of mass or water vapor can be compared with the observed heating function. Methods of this kind are undoubtedly not too unrealistic, since low level convergence is a destabilizing mechanism generating precipitating convection. However, the vertical distribution of heating is hard to specify, and correspondingly, the constraints on the stratification are ill-defined.

In some CISK theories, a relationship is assumed between boundary layer frictional convergence and low level vorticity; convection is parameterized in terms of the frictional convergence. Measurements of surface stress, low-level vorticity, boundary layer convergence, and convective budgets will allow comparison with the theory.

*Cumulus ensemble models.* The models proposed by Ooyama (1971), Arakawa (1971), and Arakawa and Schubert (1974) for the parameterization of cumulus convection in terms of a population of clouds or cumulus ensemble need more detailed discussion.

Ooyama computed the transports by a population of "bubbles," given their number and level of origin. This is not yet a closed parameterization scheme since the large-scale fields do not specify the model "dispatcher function." It this sense, this approach addresses the feed-back aspect of the interaction problem, but not that of control. The theory can be used diagnostically to study the vertical structure of convective transports.

Arakawa's parameterization theory is a closed model for the large-scale: convective interaction. A cloud population is determined by specifying a precise balance for each class of "cloud" (identified in terms of a fractional rate of entrainment, $\lambda$). This balance is expressed mathematically as

$$\frac{\partial A(\lambda)}{\partial t} = \left(\frac{\partial A(\lambda)}{\partial t}\right)_{LS} + \left(\frac{\partial A(\lambda)}{\partial t}\right)_{Cu} = 0 \qquad (2)$$

where $A(\lambda)$, called by the author a cloud "work function," is an integral representing the kinetic generation for a given cloud class interval $d\lambda$ per unit cloud-base mass flux (essentially an area on a tephigram between the environment and the ascending parcel curve for that entrainment rate). The subscripts $_{LS}$ and $_{Cu}$ denote the large scale and cumulus processes which are assumed to be in a quasi-equilibrium on time scales larger than the time taken by the cumulus ensemble to reach equilibrium in the absence of large-scale forcing.

The theory "solves" the question of large-scale controls by demanding that the stratification should be maintained [in the sense specified by Eq. (2)] in the face of large-scale destabilization (the time-dependent control). This maintenance is achieved through the use of a cloud ensemble model which specifies the vertical distribution of heat and vapor sources in terms of a cloud base mass flux distribution [$m_B(\lambda)$], mixed layer properties, and the environmental stratification. Once $m_B(\lambda)$ is determined by the balance condition, the convective transport and source terms can be computed.

The large-scale fields can, however, change since the constraint imposed is only an integral constraint. Further, certain classes of cloud can cease to exist if the integral inversion which determines $m_B(\lambda)$ gives no solution for a value of $\lambda$.

The aspects of this theory which need to be tested are:

i) the predicted distribution of the convective heat source and vapor sink;
ii) the cloud model and ensemble model;
iii) the balance condition.

Test (i) is the critical test of the use of the theory for parameterizing moist convection, as indicated earlier. If comparison with observations is satisfactory, then this is a useful parameterization model, although it is not necessarily true that either the cloud model or the balance condition are individually correct. Conversely, if the budget comparison is poor, at least for some categories of convection, then one must ask if the failure is due to an oversimplified cloud model, or whether the balance condition is incorrect.

The cloud population model (ii) is based on a very simple cloud model containing a direct updraft which condenses water, and through a circulation, warms and dries the environment. A simple parameterization determines the fraction of condensation precipitated; the detrainment of the remaining liquid water at an upper level of thermal equilibrium cools the environment by evaporation and also moistens it. This is an oversimplification (see 4f), but it contains the basic mechanisms for heating and cooling, drying, and moistening the environment. The cloud population model itself can be tested either by using the same cloud ensemble model diagnostically (see 4d), or by simulating numerically cloud lifecycles.

The balance condition (iii) can be tested by computing $A(\lambda)$ as a function of time, and studying its time dependence in relation to the large-scale processes tending to produce changes.

*Other lapse rate adjustment methods.* Although adjustment to a moist adiabat is an unsatisfactory method of parameterization in the tropics, adjustment to a lapse-rate structure which is consistent with a cloud model remains an encouraging possibility. The way in which the convective stratification is controlled during the scale interaction is not yet clear, but this is likely to be an important constraint, and one which is not explicitly incorporated into Arakawa's theory. One theory of this kind is Betts (1973a), although this is restricted to non-precipitating cumulus convection (that is, shallow clouds). The model transports and lapse-rate structure can, therefore, be tested during periods of shallow cumulus convection. This theory uses a kinetic energy equation and a relation related to enthalpy transport based on a simple cloud model of a single scale (or $\lambda$) to specify a time-dependent lapse-rate structure consistent with the cloud model. The general concept of a quasi-equilibrium (see 3b) between large-scale forcing (long time-scale) and convective transports (small time-scale) is used, so that as the cloud layer deepens, the model cloud scale and stratification change in balance. In contrast, Arakawa's theory, by preserving $A(\lambda)$, constrains the stratification rather indirectly. Although a single cloud scale related to cloud layer depth is probably adequate for shallow clouds, for a deep layer, a population may be needed.

*d) Diagnostic models*

The analysis of the GATE convection data and the testing of parameterization models will involve many diagnostic studies. The diagnostic testing of cloud ensemble models has already been mentioned. Yanai *et al.* (1973) have shown how certain bulk properties $m_c(p)$, $T_c(p)$, $q_c(p)$, $l(p)$ (respectively cloud mass flux, temperature, water vapor, and liquid water) can be determined from large-scale budgets. The liquid water content depends on the microphysics parameterization. For a cloud ensemble, the transports are completely specified in terms of the cloud-base mass flux distribution function, $m_B(\lambda)$, the parameterization of the microphysics, and the thermodynamic properties of the environment. This problem can be inverted to give $m_B(\lambda)$ from the observed convective transports and the environmental stratification (Ogura and Cho, 1973; Nitta, 1974). This inversion will give $m_B(\lambda)$, $m_c(p, \lambda)$, $T_c(p, \lambda)$, $q_c(p, \lambda)$, and $l(p, \lambda)$. These are model quantities in $\lambda$-space which represents both a fractional entrainment rate, and a detrainment level (at "cloud-top" based on thermal equilibrium). It could be interpreted in terms of observed cloud-top, or cloud radius (assuming entrainment is proportional to cloud radius). On this basis, the observed cloud population statistics could be compared with those predicted. However, the model contains no cloud lifecycle, and in particular, no moist downdrafts comparable with the assumed moist updraft, so the model can only interpret these real processes, which detrain air over the cloud life-cycle at many levels, in terms of its degree of freedom ($\lambda$). In practice, therefore, one must try to derive correlations between model quantities and cloud field statistics observed by satellite or radar.

Diagnostic studies of convective stratification are also needed to provide an observational basis for this aspect of parameterization theories. Betts (1973d) has indicated how simple one-dimensional cloud models may be used to classify convective stratifications, and explore the relationship between cloud fields and stratification. This approach may also expose the limitations of simplified cloud models which do not include possible static controls such as the shear field.

*e) Cloud models*

The dependence of cumulus ensemble models on their cloud model and on their formulation of the cloud microphysics indicates a pressing need to understand the vertical transports on the cloud scale. The GATE will not provide a comprehensive set of observations on the D-scale, but sufficient data will be obtained to advance cloud simulation studies and microphysical studies. Direct measurements in cloud of vertical fluxes, turbulent fields, droplet spectra, and liquid water content are needed to estimate the cloud: environment interaction processes and the structure of vertical transports of heat, vapor, liquid water, and momentum by individual clouds.

The literature on cloud dynamical-microphysical models is growing very rapidly: recent publications include Árnason and Greenfield (1972), Murray and Koenig (1972), Cotton (1972), Clark (1973), Lopez (1973), Ogura and Takahashi (1973), Schlesinger (1973), Soong and Ogura (1973), and Steiner (1973).

*f) Improvement of parameterization theories*

The GATE will provide an observational base for the development of improved models for predicting convective transports from the large-scale four-dimensional fields. However, even after the GATE observational and analysis programs have been completed, this will remain a formidable task. We cannot indicate here what needs to be done, but can point out some of the limitations of current models which have influenced the design of the Convection Subprogram.

Current parameterization theories are based almost entirely on thermodynamic controls and transports, since momentum and vorticity transports by convection and the control of convection by the shear or vorticity fields is not understood. These budgets and controls are an important exploratory aspect of the GATE.

The current theories have not included convective downdrafts, which represent a cumulus-scale circulation of comparable importance to the updraft. These are particularly important for the modeling of precipitating convection, and for its interaction with the boundary layer (Zipser, 1969, Betts, 1973b). The simple detrainment of liquid water at a level (followed by a hypothetical evaporation and rapid mixing with the environment at that level) is not equivalent to a vertical downdraft transport which modifies the environment over a deep layer (as does the updraft). The presence of the earth's surface as a lower boundary where downdrafts diverge introduces the further possibility of one convective system forcing the growth of another by imposing a convergence-divergence pattern on the sub-cloud layer; this is a mesoscale:cumulus interaction.

Fig. 4 shows schematically the multiscale interactions from the A-scale down to the D-scale. It is not yet known what the role of C:D interactions and instabilities is, and whether these present problems for parameterization in terms of B-scale fields. The current theories have assumed essentially that the D-scale convection (a cloud population) is uniquely determined by the A- and B-scale fields; the theories do not include a mesoscale organization of any kind (Fig. 3). In the design of the GATE, it seems wise to assume the converse—that mesoscale organization is important, and does affect the convective budgets. The purpose of B-scale, and even more so of C-scale budget studies, is to determine the importance of mesoscale organization and interactions. Formally, this can be discussed, using Arakawa's theory. Using the simple cloud ensemble model there are no nontrivial solutions to the homogeneous equation

$$\left(\frac{\partial A(\lambda)}{\partial t}\right)_{Cu} = 0 \qquad (3)$$

so that the cloud field is forced by the large-scale term $(\partial A(\lambda)/\partial t)_{LS}$ of Eq. (2). If a more complex ensemble model was constructed, containing mesoscale:cumulus interactions and instabilities, then Eq. (3) might have nontrivial solutions, even in the absence of large-scale forcing. The traveling squall line is an example of a C:D scale instability for which the large-scale forcing may not be significant. Parameterization must then include the controls on this instability. A related possibility is that some forcing terms (radiation and surface fluxes, for example) may be very strongly coupled to mesoscale convection, so that they cannot be parameterized without predicting the level of organization on the mesoscale. For these reasons, the modeling of cloud clusters and mesoscale convection are important objectives.

Any diurnal control on the convection must also be well predicted by a parameterization theory: thus, the description of the diurnal interaction is important.

In conclusion, it must be stated that there is no guarantee that the atmospheric system on these scales is transitive: that is, more than one cloud field may be possible for a given large-scale field. The formal similarity to determining the general circulation, given certain external controls, is apparent.

## 5. Final remarks

This paper has reviewed the major objectives of the U.S. Convection Subprogram for the GATE. The corresponding international subprogram plan and operational plan have been drafted, and are available to the scientific community. The GATE is a major component experiment in GARP, and its success will be an advance both in international cooperation and in our understanding of the tropical atmosphere.

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