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SECTION 3

PHYSICAL PROCESSES RELEVANT TO NUMERICAL WEATHER PREDICTION OVER THE TROPICS

3.2 PARAMETERIZATION OF SHALLOW AND DEEP CONVECTION

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CONTENTS

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Introduction

There have been several recent reviews of research into the role of tropical convection and its parameterization in large-scale numerical models (e.g. Yanai 1975; Ogura 1975; Betts 1974). In addition one of the objectives of GATE was to collect a data set suitable for the test and development of such parameterization schemes (GATE Report No 7). This work is just beginning as the GATE data is archived. We shall not therefore attempt to review the literature; and it is also premature to assess the attainment of this GATE objective. Rather we shall discuss the problems in convective parameterization which seem of current importance with particular emphasis on the papers presented at the study conference. We shall then list some topics which deserve further research, and attempt to draw some conclusions relating to FGGE.

3.2.1 Physical processes and their parameterization

3.2.1.1 General considerations

The need for the parameterization of convection in numerical models arises because all models, whether grid-point, spectral, or of some other type, are capable of resolving only those scales of motion above a certain spatial (and temporal) limit. In grid-point models the minimum resolved spatial scale is approximately twice the grid length; in spectral models it is the shortest wavelength retained in the spectral truncation. (The errors associated with the smallest resolved scales are large, however, and the scales which can be regarded as ***adequately*** resolved do not extend down to cover the whole range of resolved scales). In the atmosphere systems exist on a complete range of space scales from the global down to the molecular; furthermore systems on different scales interact with each other, often very strongly and in a way which decisively influences the development on any particular scale. It is thus not possible simply to ignore in a numerical model systems on scales below those which are resolved if the real atmosphere is to be properly simulated. It is necessary to represent the interaction with the scales resolved in the model of processes on unresolved scales.

This problem is a particularly difficult and important one in the simulations of the tropical atmosphere owing to the prevalence of penetrative convection, a process which, through latent heat release, plays a major controlling influence, certainly in modifying and often in initiating disturbances on the meso-scale and sometimes the synoptic scale, e.g. West African disturbance lines, disturbances on the ITCZ and tropical cyclones. This contrasts with the situations in mid-latitudes where the evolution of cyclones is determined primarily by larger scale processes which are adequately resolved in numerical models

Since the percentage area of the tropics occupied at any time by a given type of convection is small, a first requirement is the establishment of selective criteria for the occurrence of these different types of convection; this is an essential part of the parameterization procedure. Some parameterization schemes are based on the assumption that deep convection must occur whenever conditional instability is set up. However, over large areas of the tropical atmosphere a state of conditional instability is observed to persist for long periods without the occurrence of convective activity. A state of conditional instability is clearly necessary for deep convection to occur; it cannot however be a sufficient condition. The establishment of criteria sufficient for the occurrence of deep convection is thus an essential requirement of an adequate parameterization scheme.

The next question which must be answered is 'Given that deep convection is occurring in a particular grid area, what form will it take and what are the appropriate adjustments which must be made to the grid-scale parameters?' Our knowledge of convection in the tropics suggests that the scales involved extend from that of isolated showers e.g. showers over land associated with diurnal heating, to extensive cumulonumbus with associated squall lines and various meso-scale organizations of these clouds e.g. West African disturbance lines and incipient tropical cyclones. Systems such as the latter exist on scales which overlap the lowest resolved spatial scales of many prediction models; it is to be expected that the accurate parameterization of such organized systems must differ, perhaps substantially, from that of shower populations. The criteria for the occurrence of deep convection must therefore, if they are to be accurately applied, provide also a specification of the particular type of convection which is to be parameterized. It is only on the basis of this that the appropriate parameterization can be selected.

No existing schemes include such a detailed specification of different deep convection types.

3.2.1.2 Parameterization schemes for large-scale models

Parameterization schemes may be defined by:

(i) the criteria for convection to occur,
(ii) the nature of the sub-grid-scale model used and
(iii) the closure conditions, or assumptions used to relate quantitatively the large-scale and sub-grid-scale models.

Schemes used recently in large-scale models for simulation of the tropical atmosphere which are described here are:

(i) Manabe et al. (1965): used in the GFDL model,

(ii) Kuo (1974) (a development of that of Kuo 1965): used in the FSU model by Krishnamurti et al. (1975),

(iii) Arakawa and Schubert (1974) (a development of Arakawa (1969) and Ooyama (1971)): used in the UCLA model,

(iv) Ceselski (1974) (combining features of Kuo (1965) and Arakawa (1969)): used in tropical prediction experiments with the model of Krishnamurti et al. (1973).

(v) Rowntree (1973) (version of Arakawa (1969)): used in the tropical version of the 11-layer general circulation model of the U.K. Meteorological Office (Lyne and Rowntree (1976)).

(vi) Gilchrist: used in the 5-layer general circulation model of the U.K. Meteorological Office (Corby et al. (1976)) (a development of the diffusive convection scheme of Corby et al. (1972)).

These schemes will now be described in terms of their criteria for convection, sub-grid-scale model, and closure conditions.

(i) Manabe et. al. (1965)

Criteria: Super-adiabatic lapse rate (moist adiabatic if saturated, dry if not). The definition of saturation is modified in some versions to, say, 80% relative humidity with corresponding modification of the critical lapse rate.
Model: Redistribution of heat and moisture with adjustment of the lapse rate to the appropriate critical lapse.
Closure conditions: Energy conservation.

(ii) Krishnamurti et al. (1975) (version of Kuo (1974))

Criteria: Vertical structure conditionally unstable and positive, vertically integrated moisture convergence.
Model: Heating and moistening of the environment by mixing with a model cloud.
Closure conditions: Cloud cover determined by area over which moisture convergence can generate cloud. An empirical assumption for the heat and moisture mixing coefficients, dependent on cloud cover.

(iii) Arakawa and Schubert (1974)

Criteria: Conditionally unstable, solutions to closure exist (see below).
Model: Mass flux calculated assuming a spectrum of cloud sizes with entrainment rates depending on the cloud size. Cloud mass detrained when buoyancy reaches that of environment also with modification of environment by compensating subsidence.
Closure conditions: The mass flux distribution over the cloud spectrum is determined by conservation of a cloud work function representing the cloud buoyancy.

(iv) Ceselski (1974)

Criteria: Upward motion at 900 mb with parcel from the lowest layer buoyant at next layer up.
Model: Mass flux calculated with entrainment and three possible cloud depths depending on parcel buoyancy. Environment modified by compensating subsidence, detrainment and partial evaporation of cloud, depending on cloud cover as defined in Kuo's scheme, at detrainment level. For deep convection a direct downdraught from the middle to lower troposphere is modelled.
Closure conditions: Initial mass flux equated to large-scale 900-mb ascent. Empirical assumptions for entrainment rates and for proportions of the deep convective downdraught assumed to be moist.

(v) Rowntree (1973)

Criteria: Parcel slightly buoyant in one layer is still buoyant in the layer above.
Model: Mass flux calculated for an ensemble of parcels with a vertical entrainment profile. The detrainment of smaller clouds at zero buoyancy is assumed to enhance the ensemble mean buoyancy; the convective depth is limited by that of an undilute parcel and by a minimum mass flux. Environment modified by compensating mass fluxes and evaporation.
Closure conditions: Empirical assumptions for the entrainment rate, the relation of the initial ensemble size to the vertical structure and the evaporation.

(vi) Gilchrist (see Corby et al. (1976))

Criteria: Parcel slightly buoyant in one layer is still buoyant in the layer above.
Model: Initial mass flux with no entrainment and with detrainment determined by the parcel's buoyancy at next level. Environment modified by mixing with this detrained air, evaporation of precipitation and compensating subsidence.
Closure conditions: The dependence of initial mass flux on parcel buoyancy and boundary layer depth and detrainment rates determined from single-column experiments.

While no attempt is being made here to discuss these differences in detail, it may be noted that only one of these schemes (Ceselski's) makes allowance for a deep downdraught as opposed to subsidence between adjacent layers and that none allow for the convective transfer of momentum (but see 3.2.2.4). Several of the schemes restrict the base of convection to the boundary layer whereas convection is observed with its roots at higher levels (e.g. during GATE as described by Simpson and Simpson (1975)). Several schemes include a low-level convergence or a similar parameter as an explicit criterion. It is not obvious that this is essential in a large-scale model because large-scale vertical motions can affect the convective process through modification of the temperature and moisture structure. However, Ceselski (1974) found that in prediction experiments, omission of such a criterion tended to produce a moisture-related disturbance.

3.2.1.3 Convective transport processes

The thermodynamic transports by convection have been studied extensively using diagnostic methods and the concept of vertical mass transport by convection (e.g. Yanai et al., 1973; Williams and Gray 1973). Spectral cloud models have been used to interprete further the transports in terms of a cloud population (Ogura and Cho 1973, Nitta, 1975).

(i) Shallow convection

Holland and Rasmussen (1972), Augstein et al. (1973) and Nitta and Esbensen (1974) have all presented diagnostic studies of shallow trade cumulus convection. Betts (1973, 1975) discussed the interpretation and modelling of shallow non-precipitating convection. A consistent description of the thermodynamic transports emerges which is supported by three-dimensional simulations of a shallow cumulus field (Sommeria, 1976). The clouds are typically negatively buoyant at cloud-base, become buoyant through the condensation in the lower part of the cumulus layer of liquid water which they advect upwards to be evaporated in the upper part of the cumulus layer, where the cumulus clouds overshoot into a stable layer (such as the trade inversion). Although the clouds do not precipitate, the downward energy transport associated with this process of condensation, upward transport and evaporation of liquid water dominates over the upward sensible heat transport so that the lower cumulus layer is warmed while the upper part is cooled. In the trade inversion the inversion is thus maintained by a balance between subsidence warming and cooling by both convection and radiation processes. The convection mass transport model appears to be an adequate model for this process, and the coupled transport of water vapour. Betts (1976a) discussed how these transports could be coupled to a mixed subcloud layer.

One unresolved question is whether an ensemble model is needed to parameterize these shallow cumulus transports. Fraedrich (1976) has suggested that a cloud population be specified empirically as opposed to the internal specification using a quasi-equilibrium assumption proposed by Arakawa and Schubert (1974). Betts (1975) suggested that it might be sufficient to specify the cloud mass flux profile.

Momentum transport by shallow cumulus is not well understood: the three-dimensional simulations may suggest a formulation. We also do not know whether parameterizations should take account of mesoscale organizations such as cloud streets. The coupling of the radiation and convection fluxes needs careful study, since for the shallow boundary layer it may be simpler to parameterize the diabatic processes together.

(ii) Deep convection

The transport processes by deep convection are made more complex by the precipitation process. The vertical liquid water flux is difficult to parameterize and both the weight of liquid water and the evaporation of falling rain can drive strong downdrafts. The organization and intensity of the updraft-downdraft structure is not well understood, and many parametric models neglect downdrafts. Garstang and Betts (1974) emphasized the important effect of downdrafts on boundary-layer structure. Betts (1976b) has used a simple diagnostic downdraft model to examine the transformation of the boundary layer, and found that for organized mesoscale systems over Venezuela, the precipitation driven downdraft originated from a layer above the subcloud layer (typically 850-700 mb). Downdrafts clearly played an important role in convection in the GATE area (Seguin and Garstang, 1976).

One-dimensional models cannot adequately formulate the effects of pressure perturbations, or the role of vertical shear on updraft-downdraft structure and the vertical transport of horizontal momentum although simple formulations have been suggested (Ooyama (1971), Fraedrich (1974)). It appears that a distinction can be made between the structure of deep convection in unsheared flow and in flow with vertical shear. In unsheared deep convection the updrafts and downdrafts in three-dimensional simulations are highly time-dependent and the convective transport could be regarded as an unorganized stochastic process (Miller and Pearce, 1974). The vertical axial symmetry of the flow does not allow a net transfer of momentum. By contrast, in vertically sheared flow, deep convection may become organized with a quasi-steady propagating updraft and downdraft system. As in the unsheared case upper level warming and moistening and low level downdraft cooling and drying are also features of this convection. Two dynamically distinct regimes of organised deep convection have been identified analytically, one which moves at a speed close to the mid-level mean-flow speed (Moncrieff and Green, 1972) and another which propagates relative to the flow at all levels (Moncrieff and Miller, 1976). In the latter paper a three dimensional simulation was used to study the dynamical structure and transports of the propagating convection (a developing squall-line).

This organization has important implications for the flux structure of heat, moisture and momentum, all of which can be explicitly formulated in terms of the mean flow; this means that the flux structure representation for use in parameterization has a fundamentally different form from a stochastic representation. In particular, counter-gradient momentum and horizontal vorticity transport which effect an increase in mean flow shear and kinetic energy; this contrasts distinctly with the concept of momentum mixing by convection. As regards large-scale models in general this transfer regime shows that momentum transport parameterization should be approached with caution.

Further work is needed to incorporate these concepts into a practical parametric model for deep convection. Similarly, the representivity of counter-gradient momentum transport in the tropics should be established; there is considerable evidence that it features in squall line systems in Venezuela (Betts et al. 1976) W. Africa.

3.2.1.4 Development and testing of parameterization models

(i) Dynamics of idealized tropical disturbances

Limited area models describing the dynamics of tropical phenomena such as easterly waves, hurricanes and monsoon disturbances may be more sensitive to the parameterization scheme used than global scale (coarse-grid) models. Anthes (1976) has shown marked changes in hurricane development result from different parameterizations of the heating function.

The need to understand the dynamics of tropical disturbances suggests the use of idealized models in which the dynamic response to convective scale transports can be studied in detail. The effects of downdraft heat and moisture transports and the role of momentum transfer in these phenomena are as yet unknown but should be established and included if necessary in convective parameterization schemes. The role of convection in hurricane formation and development needs further study. Likewise heat and moisture transfers and momentum transport which may be countergradient will influence the growth and structure of baroclinic and barotropic disturbances.

(ii) Comparisons between large scale models and real data

Although to some extent it is possible to assess the validity of convective parameterization techniques by their behaviour in simple, idealized situations, the final test of the validity of a parameterization for a large-scale model is its ability to give a realistic prediction. The ability should be tested both against climatology (can the scheme give realistic temperature and moisture fields, rainfall distribution and kinetic energy spectra in the long period mean?) and in short-term prediction. In the context of GATE, the latter is of more concern though clearly GATE phase-mean data can be valuable in assessing climatic simulations for that particular area.

In order that useful tests against GATE data can be made on a day-to-day basis the model must be sufficiently complicated to give realistic simulations, and the initial data, analysis methods and model initialization must be of good quality.

Short term predictions have been made using GATE data at a number of centres, (e.g. at Florida State University (Krishnamurti and Pan, 1976), GFDL (Princeton), the UK Meteorological Office (Lyne et al. 1975), and the Hydrometeorological Centre of the USSR (Sitnikov and Rubinshtein, 1975)). Detailed comparison of the results against GATE ship data have been made by Rowntree (1976). He found that the model performance was sensitive to the magnitude of the initial mass flux in its prediction of the rainfall distribution over the GATE ship array in 20° – 26°W and that the flow pattern in this region was substantially modified by inclusion of a momentum convection formulation in which momentum was transferred upwards by cloud updrafts and downwards by the compensating large scale environmental subsidence. The consequent reduction of vertical shear by this down gradient transfer was apparently harmful to the quality of the forecast over West Africa and the East Atlantic but did help to suppress the over development of waves in the central and west Atlantic.

A preliminary diagnostic study of the comparison and verification of different parameterization techniques (moist convective adjustment, CISK - type methods by both Kuo and Rosenthal) based on GATE observational data has been made by Degtyaryov and Sitnikov, 1976. Synoptic and upper air data of AB ships for Phase I and Phase II of GATE were used. It is desirable to compare the convective transports and source terms predicted by models with those derived diagnostically from the data fields (GATE report No. 7). This awaits further analysis of the GATE B-scale data.

(iii) Comparison between observations, detailed cloud or meso-scale models and parametric schemes.

Parametric models of an individual cloud or a cloud population (individual clouds interacting with each other within a larger mesoscale region) should be compared with the detailed numerical models and both of them with real data for a variety of conditions.

Two examples illustrate this procedure:

(a) Cloud models describing the detailed cloud structure evolution, dynamics and microphysics have the disadvantage that their complexity makes their incorporation into parameterization schemes difficult. Therefore, analytic models which relate the flux structure of the convection to the mean flow in a parametric fashion have been tested: Moncrieff and Miller (1976). The design of these idealized models retain as far as possible the basic dynamic processes relating directly to the large scale parameters (convective available potential energy, vertical shear). Likewise the validity of an idealized, dynamical model has also been tested against observed systems in Venezuela (Betts, Grover and Moncrieff, (1976).

(b) Sommeria (1976) has modelled a field of shallow cumulus clouds and the statistics have been compared with observed turbulent fluxes (Lemone and Pennell, 1976). These results can also be compared with simpler parametric schemes (Betts, 1975; Fraedrich, 1976).

Observational studies can however provide extensive phenomenological information such as the statistics of individual clouds and the cloud population (heights, areas, lifetimes, distribution). These should be compared with the statistics produced by both detailed model simulations and parametric models.

3.2.2 Recommendations

3.2.2.1 Future research

Research in the areas discussed in 3.2.1.4 are essential to improve current parameterization models and our ability to simulate and predict the tropical atmosphere. These areas were:

(i) The study of the dynamics of idealized tropical disturbances with particular emphasis on the convective-dynamical coupling.

(ii) The testing of large-scale models by the comparison of predictions with real data, and of predicted model convective transports with those found by diagnostic budget studies using the same data base.

(iii) The development of improved understanding of cloud-scale transports by the comparison of detailed non-hydrostatic cloud models, analytic or parametric models, and observations.

It is recommended that the GATE data base be fully utilized to study these questions. Despite the apparent complexity of the problems, it seems likely that significant progress will be made in the next five years.

3.2.2.2 FGGE

One additional unresolved question is that of the space- and time-scale of the proposed FGGE observations. The initial GATE studies on convection and parameterization will be focused on the B scale area using data with spacing about 150 km and every 3–6 hours. We do not yet know whether it will be possible to parameterize the mesoscale convection using data of this scale, because of the strong non-linear meso-synoptic interaction. Even if this is accomplished it may be some step up in scale to the proposed FGGE resolution (which will be rather variable in space 12 hrs in time). It is unlikely that parameterization on this scale will be possible until our understanding of the dynamics of tropical disturbances (section d(i)) advances. The GATE data base provides a means of addressing this problem, but the results may not be available in the planning stage of FGGE.

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