a review of the tropical boundary layer and cumulus convection: structure, parameterization, and modeling

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Abstract

Recent advances in our understanding of the boundary layer and cumulus convection in the tropics are reviewed. The review reflects the interactive nature of the atmosphere-ocean system. It discusses the observational picture of the atmosphere that is emerging from tropical field experiments, results of diagnostic studies of convective transports and structure, and the progress in both modeling and parameterizing convection and the tropical boundary layer.

1. Introduction

In 1971, the Scientific and Technical Activities Commission of the American Meteorological Society asked its technical committees to report on the state of their respective areas at the Annual Meeting of the Society. In the case of the Committee on Hurricanes and Tropical Meteorology, this resulted in the publication of "A Review of Hurricane and Tropical Meteorology" (Garstang, 1972). The present review is a continuation of this reporting request and the original paper by Garstang which was presented by Betts at the Annual Meeting in Honolulu, Hawaii, January 1974. Because of the recent nature of the previous review, this paper will deal only with a specific aspect of tropical meteorology: the boundary layer and cumulus convection.

The boundary layer can be defined as that part of the atmosphere where dynamical and thermodynamical effects generated at the surface are detectable. As such, under fair weather conditions, the boundary layer extends from the surface to the trade wind inversion. Under disturbed conditions, with enhanced cumulus convection, cloud-induced mixing reaches below cloud base and may finally couple sea surface processes with the high troposphere. By this definition the boundary layer can include both processes at the air-sea interface and cumulus convection extending through the entire tropical troposphere. This review will not attempt to cover such an all-embracing field. Instead, we will concentrate on those aspects of the boundary layer and convection that *reflect the interactive nature of the system*. In particular, we have reviewed work that deals with the interaction between the sea surface and the subcloud layer and between the cloud layer and the underlying subcloud layer and surface. Some 40 individuals actively engaged in research in these areas were asked to express their views on the progress of the field in their area of interest over the past three years. Responses were received from 40% of the scientists polled. The review which follows is materially influenced by these responses and their help is gratefully acknowledged.

2. The air-sea interface and the structure of the subcloud layer

a. Air-sea interface

During the past few years, it has become increasingly obvious that it is not enough to know only the sea surface temperature and stress distribution in order to determine the coupling between the ocean and the atmosphere.

From below, the sea surface characteristics are controlled by processes in each of three sub-layers:

i) The *wave-mixed layer* as the upper portion of the oceanic mixed layer is characterized by the fact that any thermodynamic property such as temperature or salinity which may be altered by atmospheric variables will be quickly and thoroughly stirred mechanically and mixed. The depth may vary from several centimeters to several 10s of meters depending on wind speed.

ii) The *diurnal thermocline* within the mixed layer is determined mainly by the influence of the diurnal heating cycle, with slightly stable stratification during the day time, and unstable stratification with nocturnal convection during the night time under undisturbed meteorological conditions; and also by the large-scale dynamic conditions. The depth of this layer may be of the order of 30–50 m.

iii) The bottom layer of the mixed layer is a *transitional layer* in which a balance must exist between the erosive effects of internal waves penetrating from below and the active top layer of the ocean. This layer is characterized by the dynamics of internal waves and by strong static stability.

To these layers and their dominant processes must be added knowledge of the wave field, latent heat flux, net radiation at the surface (see e.g. Paulson and Parker, 1972), radiation attenuation with depth, and the effects of precipitation on the sea surface. Recent observations (F. Ostapoff[1]) suggest that not only are the effects of precipitation on surface temperature and salinity marked but the effects of cumulus-generated downdrafts on the ocean surface are immediate and measurable. This has led to the suggestion that cold, cloud-induced "footprints" result which are yet to be observationally clearly delineated in space and time.

Estimation of the flux of moisture across the air-sea interface remains a serious unsolved problem for all but undisturbed conditions. Indirect estimates (see below) continue to indicate significant increases in evaporation under disturbed conditions. The dissimilarity between the temperature and moisture structure and fluxes in the air near the sea surface has now been well documented (Businger, 1972; Frisch and Businger, 1973; Grossman, 1973). Under fair weather conditions near the sea surface (<100 m) latent heat is transported primarily by small-scale phenomena with a plume or bubble structure, while sensible heat and momentum flux are due to a mixture of small-scale phenomena and some larger scale organization. Under disturbed conditions, as described below, this situation may change drastically with cloud convective downdrafts becoming the controlling mechanism.

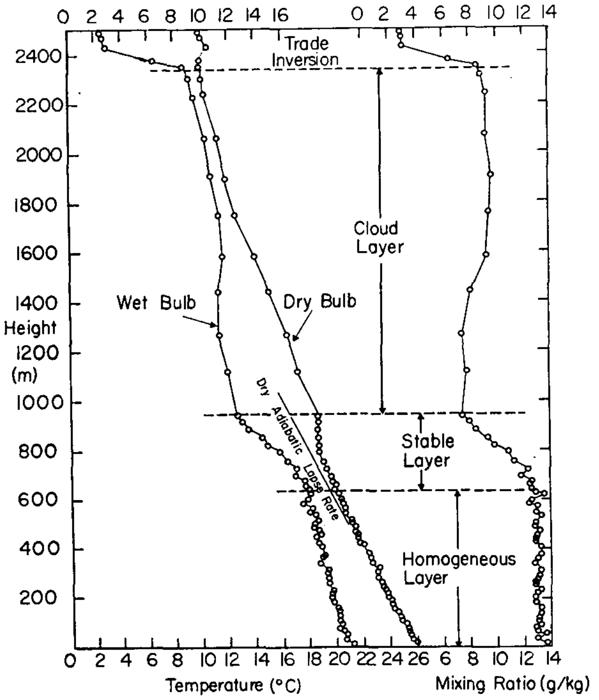

FIG. 1. (After Malkus) Structure of the undisturbed tropical atmosphere based upon aircraft soundings.

b. Subcloud layer

Riehl *et al.* (1951), Malkus (1956), and others have all documented the layered structure of the undisturbed trade wind atmosphere. Figure 1 shows:

i) the *surface layer* (0–100 m) with an adiabatic temperature gradient and a slight decrease in specific humidity with height resulting in slight static instability;
ii) a neutrally-stratified *mixed layer* extending to about 940 mb with an adiabatic temperature gradient but constant specific humidity distribution;
iii) a *transition layer* of nearly constant temperature distribution but marked decrease of moisture, about 100 m thick, and separating the regime of cloud convection above from that of dry convection and mechanical mixing below;
iv) a *cloud layer,* conditionally unstable, extending from the transition layer to the base of the inversion with a temperature gradient somewhat stronger than the moist adiabat;
v) the *trade wind inversion* atop the planetary boundary layer with a strong increase in temperature and decrease in humidity with height.

A significant advance has been the first systematic documentation of the changes in the dynamic and the thermodynamic structure of the subcloud layer with increasing convective cloud activity. These results have been obtained from two major field experiments: the Barbados Experiment (1968–1969), including BOMEX (1969), and the South Florida Seeding Experiment of 1971. Reports on this work were given by Garstang, Seguin, Echternacht and Fernandez-Partagas at the 8th Technical Conference on Hurricanes and Tropical Meteorology and summarized by Holland (1972).

Figure 2a–d shows that as the state of the atmosphere changes from undisturbed (Fig. 2a) with fair weather cumulus to strongly disturbed (Fig. 2d) with towering cumulus and cumulonimbus, the thermodynamic structure of the subcloud layer changes from unstable to stable. Surface temperature and humidity field measurements (Ulanski *et al.*, 1973) show that changes of 3–5 K of equivalent potential temperature occur with periods of 50–100 sec. Similar "saw-tooth" patterns were found by Gibson *et al.* (1971), Phelps and Pond (1971). The changes in θ_e described by Ulanski *et al.* (1973) and Bean *et al.* (1972) may be directly related to cumulus downdrafts; they are shown by Seguin (1972) to reach a maximum in the mid-subcloud region in the vicinity of showers. Garstang (1973) has suggested that cumulus and cumulus groups are largely self-limiting through interaction with the subcloud layer which results in (Fig. 3):

i) a dilution of the subcloud layer;
ii) a stable stratification of the subcloud layer.

The South Florida Cloud Seeding Experiments' results have shown, however, that cloud downdrafts very significantly change the velocity fields and hence the

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[1] Personal communication.

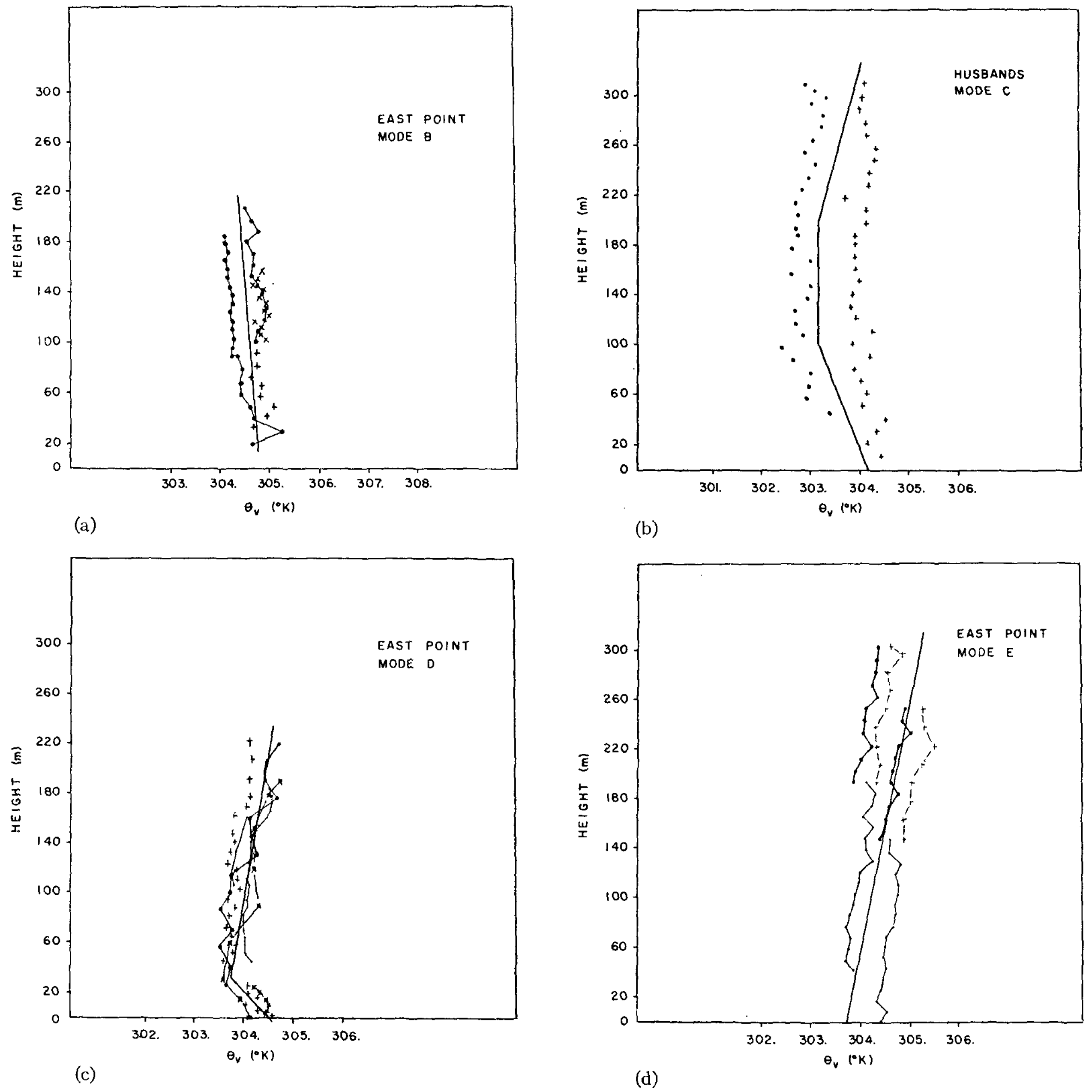
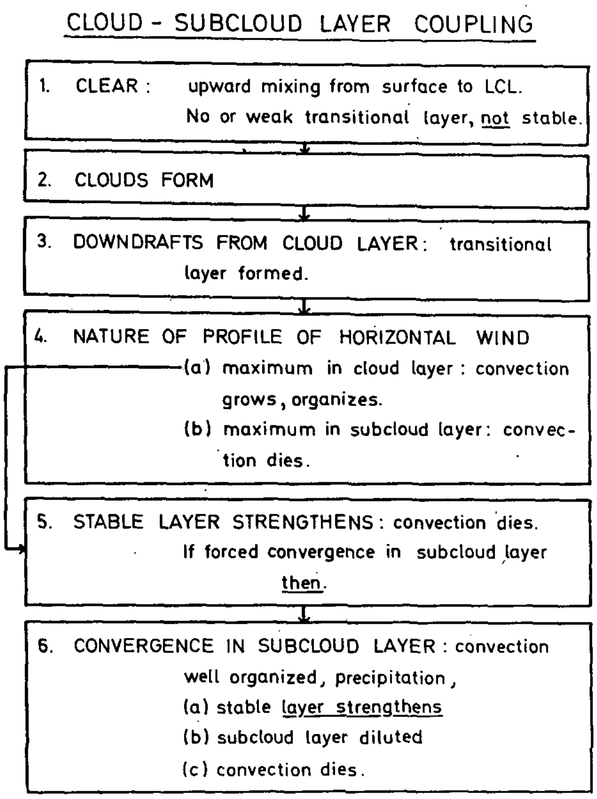


FIG. 2. Mean profiles of virtual potential temperature based upon a number of tethered balloon soundings with high resolution sondes: a) the undisturbed state, fair weather cumulus; b) a transitional state from undisturbed to disturbed conditions. Some shower activity with cumulus development up to 3 km; c) moderately disturbed, showers, groups of towering cumulus, some cumulonimbus, multilayered middle and high cloud; d) strongly disturbed, showers, cumulonimbus, low stratus and fracto stratus, multi-layered middle and high cloud.

fields of low level divergence. Figure 4a shows convergence of the order of 10^{-3} sec^{-1} with associated radar and rainfall isolines. One-half hour later, Fig. 4b shows divergence of the order of 10^{-3} while precipitation has reached its maximum rate of > 0.35 inch/5 min and radar echo intensities are at their maximum. It is not unimportant to note that the maximum precipitation rate coincides with the maximum value of the divergence. Prediction of fields of divergence based upon satellite imagery may require careful ground truth calibration before such estimates can be made with any reliability. Additionally, such intercomparisons must reflect the time and space scales measured by each system.

Changes in the velocity fields, which may in turn depend critically upon the magnitude and sign of the vertical shear of the horizontal wind, may be critical in the maintenance of fields of cumulus. Equally important, however, may be the input of sensible and latent heat across the air-sea interface in the immediate vicinity of the disturbance and the advection of sensible



CLOUD - SUBCLOUD LAYER COUPLING

1. CLEAR : upward mixing from surface to LCL. No or weak transitional layer, not stable.

2. CLOUDS FORM

3. DOWNDRAFTS FROM CLOUD LAYER: transitional layer formed.

4. NATURE OF PROFILE OF HORIZONTAL WIND
   (a) maximum in cloud layer : convection grows, organizes.
   (b) maximum in subcloud layer: convection dies.

5. STABLE LAYER STRENGTHENS: convection dies. If forced convergence in subcloud layer then.

6. CONVERGENCE IN SUBCLOUD LAYER : convection well organized, precipitation,
   (a) stable layer strengthens
   (b) subcloud layer diluted
   (c) convection dies.

FIG. 3. A possible sequence of events that reflect the feedback effects between cloud and subcloud layer. In the presence of shear, dynamic effects enter which can maintain the cloud or cloud system for a greater length of time.

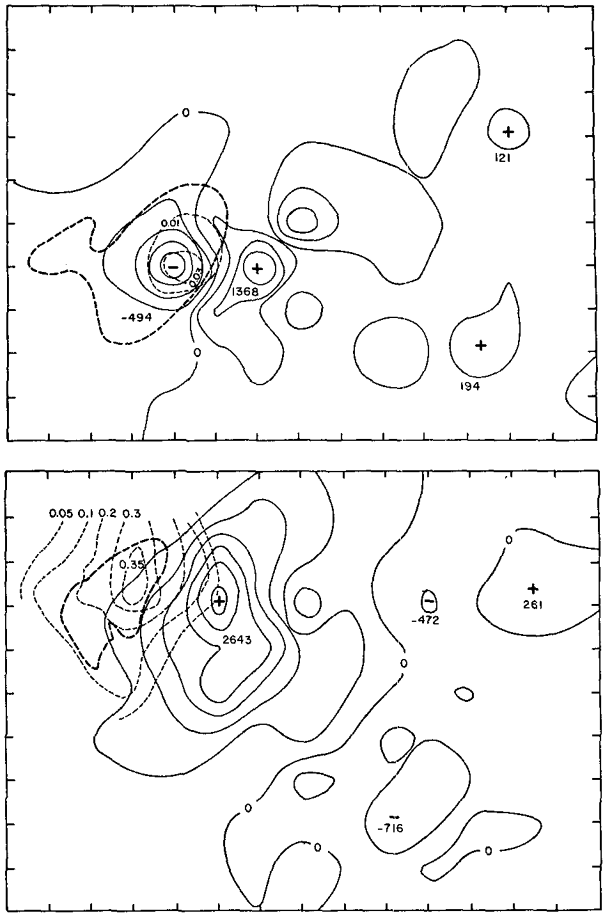


FIG. 4. Based upon a 4 × 4 mi grid of surface wind observations (20 ft towers) over a 200 square mile network (approximately the area shown in the diagrams) in the Everglades of South Florida. An objective numerical analysis generates a 1 × 1 mi grid of vectors from which surface divergence is computed [contours at intervals of 400 × 10^{-6} shown as thin lines: Numbers showing peak values of convergence (−) and divergence (+)]. A calibrated radar displays isoecho contours, and a 1 × 1 mi network of raingages yields the rainfall. In (a) rainfall (light dashed lines, maximum rate of 0.03 inch/5 min) and radar echo intensities (heavy dashed line) coincide with the region of maximum convergence. In (b), one half hour later, divergence dominates with much higher rainfall (0.35 inch/5 min) and radar echo intensities on one edge of the outflow region.

and latent heat into the cloud system from the surrounding areas. Calculations based upon the departures of the equivalent potential temperature observed by Ulanski *et al.* (1973), suggest that latent and sensible heat fluxes may increase by an order of magnitude at the sea interface in the presence of such downdrafts.

These observations have not yet shown what the spatial and temporal extent of the above described effects might be. Nor is it clear how different the structure of the subcloud air is over the continent vs over the oceans. Dugan (1973) and Betts *et al.* (1974), in an observational study based on the 1972 Venezuelan International Meteorological and Hydrological Experiment (VIMHEX), report clear evidence of cloud "roots" in the subcloud layer. In Fig. 5, Dugan presents evidence of modification of the subcloud layer by convection. The lower portion of what is frequently represented as the "constant θ" (see Fig. 1) layer is, in fact, slightly unstable during most of the convective period and becomes stable above z^*. Figure 6, from the same land experiment, shows a sequence of low level profiles of potential temperature through a major disturbance, which confirm the progressive stabilization of the lower atmosphere shown by Fig. 2.

It seems clear that the structure of the subcloud layer and the character of the sea surface can be largely controlled by interaction with the cloud layer. Furthermore, it would follow that the lifetime, and hence bulk effect, of a convective cloud system is similarly affected by these interactive processes.

Evidence of the existence and role of secondary flows such as helical rolls in the tropical subcloud layer remains inadequate. Field work carried out by the National Center for Atmospheric Research (under the direction of Zipser and LeMone) promises to yield additional information on this question.

3. Parameterization and modeling of the subcloud and cloud layers

We shall divide this field into five main topics which will deal with subcloud layer models, diagnostic models for convective transports and atmospheric structure, theoretical models, and finally, parametric models for moist convection. The coupling of convective models to the large-scale dynamics will not be discussed in any detail.

a. Models for a well mixed convective subcloud layer

This has been a period of rapid development. Betts (1971, 1973a), Deardorff (1972), Tennekes (1973), and Carson (1973) have all independently proposed mixed layer models following the earlier work notably of Ball (1960), and Lilly (1968). The papers by Tennekes and Carson were addressed only to a dry convection layer, those by Betts discussed both dry convection beneath an inversion and in the sub-cloud layer, and that by Deardorff was concerned with parameterizing the mixed layer for general circulation models. These models have shown how the height of the convective boundary layer is controlled in the absence of precipitation primarily by large-scale subsidence and the radiative and surface fluxes. They have also shown the complexity of the interactions that determine the fluxes from the surface.

Arakawa and Schubert (1974) have modified the model of Betts for use in their cumulus ensemble parameterization theory. They distinguish mixed layer height from cloud-base height, since in their theory the cloud base mass flux (and cloud population) are determined by an integral constraint over the whole cloud layer, whereas Betts (1973a) determined the convective mass flux through cloud base by a cloud-base boundary condition.

No adequate model exists for the transformation of the subcloud layer by precipitating convection primarily because the precipitation process and the downdraft circulation process is only now being observationally described and adequately understood.

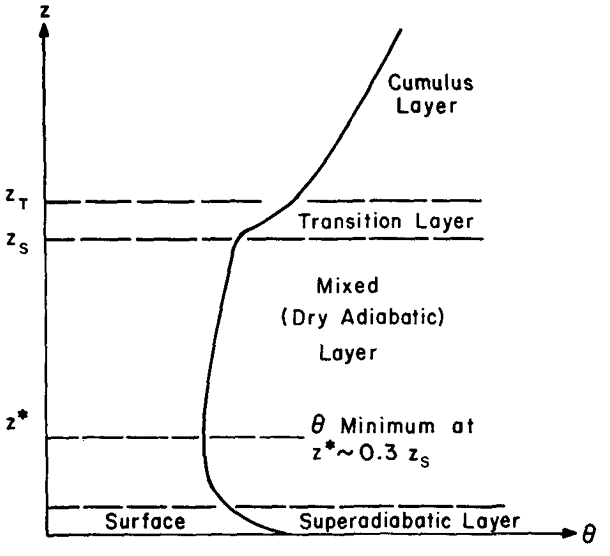


FIG. 5. Model subcloud layer structure for undisturbed conditions suggested by VIMHEX II data (Dugan, 1973).

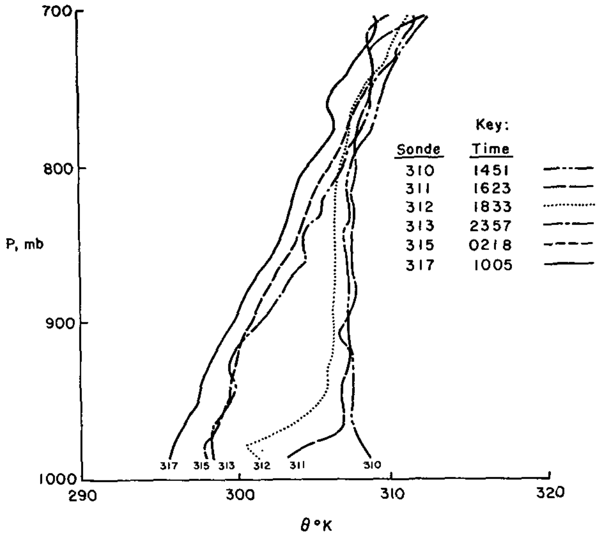


FIG. 6. Sequence of low level profiles of potential temperature, θ, from an undisturbed state through an intense disturbance over Venezuela (1–2 September 1972, from VIMHEX II data). Soundings 314 and 316 were omitted for clarity but fit the same pattern.

b. Diagnostic budget studies of convective transports

Direct observational studies of clouds either by aircraft observations or remote sensing by radar, have advanced considerably in the last few years. However, they have not yet had a major impact on tropical convection models. Much progress has been made in making closed diagnostic budgets of convective layers, and deriving the convective heat and moisture transports, sources and sinks, primarily by the techniques of averaging or compositing radiosonde data. These studies are proving very valuable in the further development of parametric models.

I) Undisturbed trades

Papers by Holland and Rasmusson (1973), Augstein *et al.* (1973), Nitta and Esbensen (1974), and Brümmer *et al.* (1974), have shown the vertical structure of the convective transports of heat, water, and momentum, derived from the atmospheric budget studies of the BOMEX and ATEX experiments. We now have a good observational picture of the structure of the planetary boundary layer during undisturbed tradewind conditions. The maintenance of the trade inversion by the upward transport and evaporation of liquid water predicted theoretically by Betts (1973a) has been confirmed.

II) Wave disturbances and clusters

Papers by Reed and Recker (1971), Nitta (1972), Williams and Gray (1973), and Yanai *et al.* (1973), have shown the structure of the convective heat source and moisture sink terms for precipitating convection and the associated vertical mass transports. This has provided an observational basis for the parameterization of convection in terms of mass transport in the middle and upper troposphere.

III) *Mesoscale cumulonimbus studies*

The structure of transports on the scale of mesoscale convective systems have been described by Zipser (1969) and Betts (1973b). Their chief contribution has been to show the important role of downdrafts on the cumulonimbus scale in determining the transports in and transformation of the lower atmosphere, as well as to provide evidence for mass transport parametric models.

Further interpretation of these observed transports has begun. Nitta (1974) and Ogura and Cho (1973) have used the spectral representation of a cloud ensemble (Arakawa and Schubert, 1974) to derive a population of model clouds from the diagnostically-derived budgets.

c. Diagnostic models of convective stratification

The diagnostic study of thermal and vapor stratification has advanced with the work of Aspliden (1971) and Betts (1973a, c). In the modeling of convective effects in large-scale models, one can either predict the transports, and deduce changes in stratification, or predict some quasi-equilibrium structure directly, thus implicitly specifying the transports with time. Haman (1969) discussed the relationship between stratification and transports by convective entrainment and detrainment. Observational studies from BOMEX, ATEX, and VIMHEX have confirmed that the cumulus population maintains an equilibrium structure. A lapse-rate model (Betts, 1973a) for the cumulus layer has been shown useful by diagnostic testing (Moore and Betts, 1974) using data from these experiments.

d. Convective models

A great deal of research is in progress on modeling moist convection with both theoretical and numerical models for the mesoscale, single clouds, and the cloud dynamical-microphysical interaction.

I) Analytic models

An important paper by Moncrieff and Green (1972) on the dynamic modeling of cumulonimbus convection theoretically coupled the heat and momentum transport by two-dimensional steady convection, using integrals of the vorticity and thermodynamic equations conserved along streamlines. The problem of the thermal instability of stratified shear flows has also been addressed by Asai (1970, 1972).

II) Mesoscale models

Mesoscale numerical models have been developed for a range of convective problems. Three-dimensional primitive equation models for dry convection (Deardorff, 1972) have been used to predict the statistics of the turbulence and also to compare the growth of the boundary layer with that predicted by the mixed layer parametric models (3a). This model has been adapted and extended by Sommeria (unpublished) to predict the spectrum of cumulus cloud development over the tropical ocean in the undisturbed tradewind regime. The results show promise in confirming the diagnostic transport studies for tradewind convection (3b). In a two-dimensional simulation of a cloud field over central Florida, Hill (1974) showed how the interaction between cumulus cells of different sites and stages of development suppressed some but led to enhanced growth of others by the incorporation of surrounding moisture anomalies from other cells. Pielke (1974) has developed a three-dimensional sea-breeze model, also for Florida, which has shown how the development and movement of thunderstorm complexes over the heated land are controlled by the strong boundary layer convergence in the sea-breeze fronts in the area of hurricane models. Orville *et al.* (1972) have published a paper on the simulation of hurricane rainband clouds and Anthes (1972) has modeled the three-dimensional asymmetric structure of the spiral bands of a tropical cyclone. Rosmond (1973) has proposed a linear stability model with parameterized cumulus convection and a variable eddy viscosity to explain the mesoscale cellular convective patterns which are frequently observed over the ocean.

III) Cloud models

The two major developments are the beginnings of three-dimensional numerical cloud convection models, and also of models that couple the microphysics and dynamics. In the first group, there has been some progress (Miller and Pearce, 1974; Pastushkov, 1973; and Steiner, 1973) as well as advances in two-dimensional modeling (Takeda, 1971; Soong and Ogura, 1973; Hane, 1973; Schlesinger, 1973; Chang and Orville, 1973). Fox (1972) has tackled the classical problem of a three-dimensional dry thermal and successfully simulated the low Reynolds number flow. He also points out the inadequacies of the eddy viscosity method, and the problems of simulating a high Reynolds number flow.

Many papers have been published on the modeling of cloud microphysics: Cotton (1972a, b), Árnason and Greenfield (1972), Murray and Koenig (1972), Clark (1973), Ogura and Takahashi (1973), Silverman and Glass (1973). However, our understanding has not progressed to the point where we have a realistic parameterization of rain for inclusion in the cloud models of large-scale parameterization theories.

In the area of one-dimensional cloud models, Holton (1972) has shown how to include the effect of the nonhydrostatic pressure perturbation. The debate on the applicability of one-dimensional entrainment models which are widely used in parametric theories has continued with numerous contributions, particularly by Warner (1970, 1972) and Simpson (1971, 1972). Additional observational evidence has been presented by McCarthy (1974) for this simplification, and against it by Warner (1973) from cloud droplet spectrum studies. However, the use of the concept in parametric cloud models has continued because of its simplicity (e.g. Lopez, 1973).

e. Parameterization models

Prior to 1970, efforts at parameterization of the convective transfer of temperature and moisture in conditionally unstable atmospheres could be divided basically into two main categories: 1) hurricane development models (Charney and Eliassen, 1964; Kuo, 1965; Ooyama, 1969; etc.); and 2) general circulation, extended-range forecast models (Manabe *et al.*, 1965; Bushby and Timpson, 1967; Arakawa *et al.*, 1968; Oliger *et al.*, 1970; etc.). The tropical cyclone development parameterization schemes stressed that the convection being parameterized was deep, organized, and undiluted moist convection, while the forecast and general circulation models (except Arakawa's) developed quick acceptable methods of convective adjustment which conserved energy. The drawbacks of these models have become clearer as the theoretical basis for parameterization theories has evolved (Arakawa and Schubert, 1974; Betts, 1974), and as recent observational papers by Gray (1973), Betts (1973b), and Yanai *et al.* (1973) have emphasized the importance of the re-evaporation of cloud and rain water, environmental subsidence, and the effects of entrainment and detrainment in determining the properties of the post-cumulus environment. The questions that remain are two-fold: what is the relative role of the different processes that control enhanced convection (such as low level convergence, atmospheric destabilization, and wind shear) and what are the resulting transports and sources of heat, water, and momentum by the cloud population? Many papers have appeared which address some of these questions (Ooyama, 1971; Betts, 1973a; Fraedrich, 1973, 1974; Kurihara, 1973; Kuo, 1973; Kreitzberg and Perkey, 1973; Arakawa and Schubert, 1974). Other papers have compared different parameterization methods (Krishnamurti and Moxim, 1971; Elsberry and Harrison, 1972; Ceselski, 1973). Probably the major development in this area has been the ensemble model by Arakawa and Schubert (1974), which predicts a spectrum of clouds and their thermodynamic transports from the large-scale forcing functions. Predictive and diagnostic testing of this model are in progress. At present, the modeling of momentum transport by convection and the control of convection by shear remain largely unresolved, as does the adequate parameterization of the water transports in precipitating clouds.

4. Large scale boundary layer models

Low level, perhaps subcloud layer convergence has emerged progressively as critical to convective cloud growth and maintenance. The concept of CISK, that condensation heating is induced by large-scale boundary layer convergence, has been applied to tropical wave development. Yamasaki (1969, 1971), Hayashi (1971a), Murakami (1972), and Lindzen (1974) have found several modes with most unstable growth rates in the synoptic-scale wave range. However, Chang (1971) and Williams and Robertson (1973) found that there is no preferred scale for wave growth. All these works have used either an Ekman-layer or a surface-layer type parameterization. Recent work by Chang and Piwowar (1973), using a boundary layer parameterization that includes the temporal acceleration effect, also produces no preferred growth scale. From this and the smallness of the growth rates, Chang and Piwowar suggest that CISK is not the initiation mechanism for tropical synoptic-scale waves.

The mid-latitude Ekman layer is subjected to modification as the flow approaches the equator. Both temporal acceleration and advective acceleration may make this modification quite drastic. In the presence of synoptic-scale wave oscillations, the temporal acceleration may be important, and the boundary layer becomes a quasi-Stokes type layer near the equator with a transition zone between it and the more-poleward quasi-Ekman layer. This transition zone is around a latitude where Coriolis frequency equals the wave frequency. Drastic change in flow structure with maximum boundary layer pumping may occur here, depending on the depth of the boundary layer and the mode of symmetry of the waves. In the presence of cross-equatorial mean flow, advective acceleration may become important and an "advective boundary layer" may result downstream from the equator. This advective boundary layer meets the mid-latitude Ekman layer in a transition zone farther downstream where large structure change and maximum boundary layer pumping also occur.

The maximum vertical motions at the top of the boundary layer in the flow transition zones for both types of boundary layer are found to be due to local increase of the boundary-layer depth. Theories have been proposed using CISK-type heating and strong nonlinear process in the boundary layer as the basic mechanisms to explain the formation of the ITCZ due to these flow transition zones.

The work of Holton *et al.* (1971) and Yamasaki (1971) demonstrated that moving, quasi-nondivergent flow fields aloft could possess boundary layer flow with strong convergence or divergence near a "critical latitude," suggesting a simple explanation for the location of ITCZ clusters. Charney[2] alternatively considers the Holton *et al.* (1971) mechanism to be one for selecting the frequency of disturbances moving along a pre-existing ITCZ latitude circle.

This theory of Holton *et al.* (1971) has been modified by Hayashi (1971b) and Chang (1973) to include limits on the layer depth, and Mahrt (1972) has studied a "slab" model of mixed layer flow of finite depth. Mak (1974) has assessed the modifying role of horizontal momentum advections while Young (1973a) has given isallobaric solutions that are appropriate poleward of the ITCZ. Young found that pumping by the unbalanced component of flow exerted a retarding influence

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[2] Private communication.

in the frictionless pumping. Mak (1974) found analytically that a planetary boundary layer can indefinitely extend to higher elevations if and only if the interior flow is of inertial character. Furthermore, it was found that pronounced frequency dependence in PBL is a more general property than the critical latitude effect would imply.

Charney (1973) has shown that the lessened efficiency of the low latitude "Stokes layer" pumping also occurs when the scale of a moving disturbance is made smaller. As a consequence, a simple CISK model exhibits maximum growth rate at a realistic scale.

In examining the effects of inertial or advective accelerations, Kuo (1971) found that the increasing importance of inertial acceleration with decreasing radius in the boundary layer (BL) of a vortex gives rise to a sinusoidal variation of the velocity profile essentially of an Ekman type, although the BL in the outer region of the vortex has only an ordinary BL structure. Thus, the inertial acceleration does not give a qualitatively different structure from a linear Ekman theory in this flow.

The study of mixed layer models for both momentum and heat is progressing rapidly at the present time. Most models assume that the mixed layer is "entraining" at its top (the inversion). The validity of this assumption for upward mean motion across the inversion has not been established. A key question for the modeling of the wind is the determination of a proper "stress boundary condition" at the inversion; current models vary considerably in terms of continuity of stress vs continuity of horizontal velocity. GATE measurements should be immensely helpful here.

Kuo (1973) has shown that stable stratification produces buoyancy and pressure gradient modifications which depend upon latitude and frequency in a complicated way. One result is that strong low-level lifting cannot occur equatorward of typical ITCZ latitudes. Kuo's study included the dynamics of flows driven by low-level baroclinity impressed by sea-surface temperature gradients. Young (1973b) has found that the baroclinic modifications for a neutral boundary layer depend strongly upon the depth of influence: the boundary layer flow baroclinic component is toward cold air when the baroclinic layer is sufficiently thin, and vice-versa when it is thick.

In the tropical atmosphere, baroclinity and stable stratification are closely related and are highly variable in space. Thus, the true character of their influence will not be known definitely for some time.

5. Concluding remarks

Perhaps the most significant fact evident from the aspect of tropical meteorology which has been reviewed is that experimentation and theoretical modeling are working in close concert with discernible and encouraging results.

The structure of the subcloud layer is described in a range of atmospheric conditions. The feedback effects between the cloud layer, the subcloud layer, and the surface are beginning to be clearly documented in observations. Theory, encompassing these effects, exists and is already yielding encouraging results.

Where uncertainty lies, the questions are being framed with some precision. Hope, therefore, exists that the answers will be forthcoming. From the observational side, the GATE offers an exceptional opportunity to answer many of these questions. Simultaneously, a large number of scientists are now actively engaged in grappling with the theory of the tropical boundary layer.

Our optimism must be tempered with the knowledge that what is emerging is evidence of a highly coupled, highly nonlinear system. If steady state conditions prevail at all, they exist only for the undisturbed state. For the disturbed conditions, intricate feedback effects exist and make it difficult, if not impossible, to integrate over large areas. Processes on the scale of the cumulus cloud, characteristically "sub-grid" scale, may control mass, energy, and momentum fluxes. Interaction between these scales and the ocean are just being revealed. It appears inevitable that coupled dynamic models must be developed for both the oceanic and the atmospheric boundary layers. While there is great hope that GATE may provide many new and critical data, it is perhaps already apparent that certain key elements such as surface pressure fields may not be described with all the necessary precision.

On balance, however, we must conclude that since this Committee last reported upon the state of hurricane and tropical meteorology, progress has been substantial. We expect this progress not only to continue but to accelerate over the next few years.

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References

Anthes, R. A., 1972: Development of asymmetries in a three-dimensional numerical model of the tropical cyclone. *Mon. Wea. Rev.*, **100**, 461–476.

Arakawa, A., A. Katayama, and Y. Mintz, 1968: Numerical simulation of the atmosphere. *Proc. of WMO/IUGG Symposium on Numerical Weather Prediction*, Tokyo, Meteor. Soc. of Japan, IV (7)–IV (8–12).

——, and W. Schubert, 1974: Interaction of a cumulus cloud ensemble with the large-scale environment. Part I. *J. Atmos. Sci.*, **31**, 674–701.

Árnason, G., and R. S. Greenfield, 1972: Micro- and macrostructures of numerically simulated convective clouds. *J. Atmos. Sci.*, **29**, 342–367.

Asai, T., 1970: Stability of a plane parallel flow with variable vertical shear and unstable stratification. *J. Meteor. Soc. Japan*, **48**, 129–138.

——, 1972: Thermal instability of a shear flow turning the direction with height. *J. Meteor. Soc. Japan,* **50,** 525–532.

Aspliden, C., 1971: On energy distribution in the tropical atmosphere. Ph.D. Dissertation, Florida State University, 232 pp.

Augstein, E., H. Riehl, R. Ostapoff, and V. Wagner, 1973: Mass and energy transports in an undisturbed Atlantic trade-wind flow. *Mon. Wea. Rev.,* **101,** 101–111.

Ball, F. K., 1960: Energy changes involved in disturbing a dry atmosphere. *Quart. J. Roy. Meteor. Soc.,* **86,** 483–494.

Bean, B. R., R. O. Gilmer, R. L. Grossman, R. E. McGavin, and C. Travis, 1972: An analysis of airborne measurements of vertical water vapor flux during BOMEX. *J. Atmos. Sci.,* **29,** 860–869.

Betts, A. K., 1971: Relating the non-precipitating convective boundary layer to the large-scale motion field. Presented at the 52nd Annual Joint Meeting of the AGU and AMS.

——, 1973a: Non-precipitating convection and its parameterization. *Quart. J. Roy. Meteor. Soc.,* **99,** 178–196.

——, 1973b: A composite mesoscale cumulonimbus budget. *J. Atmos. Sci.,* **30,** 597–610.

——, 1973c: A relationship between stratification, cloud depth and permitted cloud radii. *J. Appl. Meteor.,* **12,** 890–893.

——, 1974: The scientific basis and objectives of the U.S. Convection Subprogram for the GATE. *Bull. Amer. Meteor. Soc.,* **55,** 304–313.

——, F. J. Dugan, and R. W. Grover, 1974: Residual errors of the VIZ radiosonde hygristor as deduced from observations of the sub-cloud layer structure. *Bull. Amer. Meteor. Soc.,* **55,** 1123–1125.

Brümmer, B., E. Augstein, and H. Riehl, 1974: On the low level wind structure of the Atlantic trade. *Quart. J. Roy. Meteor. Soc.,* **100,** 109–121.

Bushby, F. H., and M. S. Timpson, 1967: A ten-level model and frontal rainfall. *Quart. J. Roy. Meteor. Soc.,* **93,** 1–17.

Businger, J. A., 1972: Turbulent transfer in the atmospheric surface layer. Workshop on Micrometeorology. Amer. Meteor. Soc., August 14–18, Boston, Massachusetts.

Carson, D. J., 1973: The development of a dry inversion capped convectively unstable boundary layer. *Quart. J. Roy. Meteor. Soc.,* **99,** 450–467.

Ceselski, B. F., 1973: A comparison of cumulus parameterization techniques in a numerical integration of an easterly wave. *Tellus,* **25,** 459–478.

Chang, C. P., 1971: On the stability of low-latitude quasigeostrophic flow in a conditionally unstable atmosphere. *J. Atmos. Sci.,* **28,** 270–274.

——, 1973: A dynamical model of the intertropical convergence zone. *J. Atmos. Sci.,* **30,** 190–212.

——, and T. M. Piwowar, 1974: Effect of a CISK parameterization on tropical wave growth. *J. Atmos. Sci.,* **31,** 1256–1261.

Chang, S. W., and H. D. Orville, 1973: Large-scale convergence in a numerical cloud model. *J. Atmos. Sci.,* **30,** 947–950.

Charney, J. G., 1973: Movable CISK. *J. Atmos. Sci.,* **30,** 50–52.

——, and A. Eliassen, 1964: On the growth of a hurricane depression. *J. Atmos. Sci.,* **21,** 68–75.

Clark, T. L., 1973: Numerical modeling of the dynamics and microphysics of warm cumulus convection. *J. Atmos. Sci.,* **30,** 857–878.

Cotton, W. R., 1972a: Numerical simulation of precipitation development in supercooled cumuli. Part I. *Mon. Wea. Rev.,* **100,** 757–763.

——, 1972b: Numerical simulation of precipitation development in supercooled cumuli. Part II. *Mon. Wea. Rev.,* **100,** 764–784.

Deardorff, J. W., 1972: Parameterization of the planetary boundary layer for use in general circulation models. *Mon. Wea. Rev.,* **100,** 93–106.

Dugan, F. J., 1973: The thermodynamic structure of the cumulus sub-cloud layer. Atmospheric Science Paper No. 205. Colorado State University, 97 pp.

Elsberry, R. L., and E. J. Harrison, Jr., 1972: Effects of parameterization of latent heating in a tropical prediction model. *J. Atmos. Sci.,* **3,** 255–267.

Fox, P. G., 1972: Numerical simulation of three-dimensional, shape preserving convective elements. *J. Atmos. Sci.,* **29,** 322–341.

Fraedrich, K., 1973: On the parameterization of cumulus convection by lateral mixing and compensating subsidence. Part I. *J. Atmos. Sci.,* **30,** 408–413.

——, 1974: Dynamic and thermodynamic aspects of the parameterization of cumulus convection. Part II. To be published in *J. Atmos. Sci.*

Frisch, A. S., and J. A. Businger, 1973: A study of convective elements in the atmospheric surface layer. *Boundary Layer Meteor.,* **3,** 301–328.

Garstang, M., 1972: A review of hurricane and tropical meteorology. *Bull. Amer. Meteor. Soc.,* **53,** 612–630.

——, 1973: *Proc. Mainz Symposium on Atmospheric Boundary Layer.*

Gibson, C. H., C. A. Friehe, and S. O. McConnell, 1971: Measurements of sheared turbulent scalar fields. Paper presented at Agard Specialists Meeting on Turbulent Shear Flows, London, England.

Gray, W. M., 1973: Cumulus convection and larger-scale circulations. I. Broadscale and mesoscale considerations. *Mon. Wea. Rev.,* **101,** 839–855.

Grossman, R. L., 1973: An aircraft investigation of turbulence in the lower layers of a marine boundary layer. Ph.D. dissertation, Dept. of Atmospheric Science, Colorado State University, 166 pages.

Haman, D. K., 1969: On the influence of convective clouds on the large-scale stratification. *Tellus,* **21,** 40–53.

Hane, C. E., 1973: The squall line thunderstorm. Numerical experimentation. *J. Atmos. Sci.,* **30,** 1672–1690.

Hayashi, Y., 1971a: Large-scale equatorial waves destabilized by convective heating in the presence of surface friction. *J. Meteor. Soc. Japan,* **49,** 458–466.

——, 1971b: Frictional convergence due to large-scale equatorial waves in a finite depth Ekman layer. *J. Meteor. Soc. Japan,* **49,** 450–457.

Hill, G. E., 1974: Factors controlling the size and spacing of cumulus clouds as revealed by numerical experiments. *J. Atmos. Sci.,* **31,** 646–673.

Holland, J. Z., 1972: The BOMEX Sea-Air Interaction Program: Background and results to date. NOAA Tech. Memo. ERL BOMAP-9, 34 pages.

——, and E. M. Rasmusson, 1973: Measurements of the atmospheric mass, energy and momentum over a 500-kilometer square of tropical ocean. *Mon. Wea. Rev.,* **101,** 44–55.

Holton, J. R., 1972: Waves in the equatorial stratosphere generated by tropospheric heat sources. *J. Atmos. Sci.,* **29,** 368–375.

——, J. M. Wallace, and J. A. Young, 1971: On boundary layer dynamics and the ITCZ. *J. Atmos. Sci.*, **28**, 275–280.

Kreitzberg, C. W., and D. J. Perkey, 1973: Modeling the effects of the release of potential instability on mesoscale circulations. WMO/IAMAP Symposium on Mesoscale Meteorological Systems and Fine Mesh Modeling. May, 1973, Reading, England.

Krishnamurti, T. N., and W. J. Moxim, 1971: On parameterization of convective and non-convective latent heat release. *J. Appl. Meteor.*, **10**, 3–13.

Kuo, H. L., 1965: On formation and intensification of tropical cyclones through latent heat release by cumulus convection. *J. Atmos. Sci.*, **22**, 40–63.

——, 1971: Axisymmetric flows in the boundary layer at the Equator. *J. Atmos. Sci.*, **28**, 20–41.

——, 1973: Planetary boundary layer flow of a stable atmosphere over the globe. *J. Atmos. Sci.*, **30**, 53–65.

Kurihara, Y., 1973: A scheme of moist convective adjustment. *Mon. Wea. Rev.*, **101**, 547–553.

Lilly, D. K., 1968: Models of cloud topped mixed layers under a strong inversion. *Quart. J. Roy. Meteor. Soc.*, **94**, 292–309.

Lindzen, R. S., 1974: Wave-CISK in the tropics. *J. Atmos. Sci.*, **31**, 156–179.

Lopez, R. E., 1973: A parametric model of cumulus convection. *J. Atmos. Sci.*, **30**, 1354–1373.

Mahrt, L. J., 1972: A numerical study of the influence of advective accelerations in an idealized, low-latitude, planetary boundary layer. *J. Atmos. Sci.*, **29**, 1477–1484.

Mak, M-K., 1974: On the frequency dependence and dynamics of accelerating neutral planetary boundary layers. *J. Atmos. Sci.*, **31**, 475–482.

Malkus, J. S., 1956: On the maintenance of the trade winds. *Tellus*, **8**, 335–350.

Manabe, S., J. Smagorinsky, and R. F. Strickler, 1965: Simulated climatology of a general circulation model with a hydrologic cycle. *Mon. Wea. Rev.*, **93**, 769–798.

McCarthy, J., 1974: Field verification of the relationship between entrainment rate and cumulus cloud diameter. *J. Atmos. Sci.*, **31**, 1028–1039.

Miller, M. J., and R. P. Pearce, 1974: A three-dimensional primitive equation model of cumulonimbus convection. *Quart. J. Roy. Meteor. Soc.*, **100**, 133–154.

Moncrieff, M. W., and J. S. A. Green, 1972: The propagation of steady convective overturning in shear. *Quart. J. Roy. Meteor. Soc.*, **98**, 336–352.

Moore, D. A., and A. K. Betts, 1974: Diagnostic tests of models for the thermal structure of the non-precipitating convective boundary layer. Atmospheric Science Paper No. 217, Colorado State University, 61 pages.

Murakami, T., 1972: Equatorial tropospheric waves induced by diabatic heat sources. *J. Atmos. Sci.*, **29**, 827–836.

Murray, F. W., and L. R. Koenig, 1972: Numerical experiments on the relation between microphysics and dynamics in cumulus convection. *Mon. Wea. Rev.*, **100**, 717–732.

Nitta, T., 1972: Energy budgets of wave disturbances over the Marshall Islands during the years of 1956 and 1958. *J. Meteor. Soc. Japan*, **50**, 71–84.

——, 1974: Observational determination of cloud mass flux distributions. Submitted to *J. Atmos. Sci.*

——, and S. Esbensen, 1974: Heat and moisture budget analysis using BOMEX data. *Mon. Wea. Rev.*, **102**, 17–28.

Ogura, Y., and H. R. Cho, 1973: Diagnostic determination of cumulus cloud populations from observed large-scale variables. *J. Atmos. Sci.*, **30**, 1276–1286.

——, and T. Takahashi, 1973: The development of warm rain in a cumulus model. *J. Atmos. Sci.*, **30**, 262–277.

Oliger, J. E., R. E. Wellck, A. Kasahara, and W. M. Washington, 1970: Description of NCAR global circulation model. Publication of Lab. of Atmospheric Science, NCAR, Boulder, Colorado, 94 pp.

Ooyama, K., 1969: Numerical simulation in the life cycle of tropical cyclones. *J. Atmos. Sci.*, **26**, 3–16.

——, 1971: A theory of parameterization of cumulus convection. *J. Meteor. Soc. Japan*, **49**, 744–756.

Orville, H. D., W. J. Chang, and F. J. Kopp, 1972: A numerical experiment on the simulation and modification of hurricane rainband clouds. Report 72-12, Institute of Atmospheric Sciences, South Dakota School of Mines, 80 pp.

Pastushkov, R. S., 1973: The effect of vertical wind shear on the development of cumulus clouds over mountains. *Izv. Acad. Sci., USSR, Atmos. Ocean. Phys.*, **9**, 5–11.

Paulson, C. A., and T. W. Parker, 1972: Cooling of a water surface by evaporation, radiation and heat transfer. *J. Geophys. Res.*, **77**, 491–495.

Phelps, G. T., and S. Pond, 1971: Spectra of the temperature and humidity fluctuations and of the fluxes of moisture and sensible heat in the marine boundary layer. *J. Atmos. Sci.*, **28**, 918–928.

Pielke, R., 1974: A three-dimensional numerical model of the sea breezes over South Florida. *Mon. Wea. Rev.*, **102**, 115–139.

Reed, R. J., and E. E. Recker, 1971: Structure and properties of synoptic scale wave disturbances in the Equatorial Western Pacific. *J. Atmos. Sci.*, **28**, 1117–1133.

Riehl, H., T. C. Yeh, J. S. Malkus, and N. E. La Seur, 1951: The North-East trade of the Pacific Ocean. *Quart. J. Roy. Meteor. Soc.*, **77**, 598–626.

Rosmond, T. E., 1973: Mesoscale cellular convection. *J. Atmos Sci.*, **30**, 1392–1409.

Schlesinger, R. E., 1973: A numerical model of deep moist convection: Part I. Comparative experiments for variable ambient moisture and wind shear. *J. Atmos. Sci.*, **30**, 835–856.

Seguin, W. R., 1972: A study of the tropical oceanic subcloud layer. Ph.D. Dissertation. Dept. of Meteorology, Florida State University, 221 pp.

Silverman, B. A., and M. Glass, 1973: A numerical simulation of warm cumulus clouds: Part I. Parameterized vs. non-parameterized microphysics. *J. Atmos. Sci.*, **30**, 1620–1637.

Simpson, J., 1971: On cumulus entrainment and one-dimensional models. *J. Atmos. Sci.*, **28**, 449–455.

——, 1972: The global energy budget and the role of cumulus clouds. NOAA Tech. Memo., ERL WMPO-8.

Soong, Su-Tzai, and Y. Ogura, 1973: A comparison between axisymmetric and slab-symmetric cumulus cloud models. *J. Atmos. Sci.*, **30**, 879–893.

Steiner, J. T., 1973: A three-dimensional model of cumulus cloud development. *J. Atmos. Sci.*, **30**, 414–435.

Takeda, T., 1971: Numerical simulation of a precipitating convective cloud: The formation of a "long-lasting" cloud. *J. Atmos. Sci.*, **28**, 356–376.

Tennekes, H., 1973: A model for the dynamics of the inversion above a convective boundary layer. *J. Atmos. Sci.*, **30**, 558–567.

Ulanski, S. L., R. K. Hadlock, and M. Garstang, 1973: The role of convection in surface property and velocity fluctuations. *Boundary-Layer Meteor.*, **6**, 183–195.

Warner, J., 1970: On steady-state one-dimensional models of cumulus convection. *J. Atmos. Sci.*, **27**, 1035–1040.

——, 1972: Comment "On cumulus entrainment and one-dimensional models". *J. Atmos. Sci.*, **29**, 218–219.

——, 1973: The microstructure of cumulus cloud: Part IV. The effect on the droplet spectrum of mixing between cloud and environment. *J. Atmos. Sci.*, **30**, 256–261.

Williams, K. T., and W. M. Gray, 1973: Statistical analysis of satellite-observed trade wind clusters in the Western North Pacific. *Tellus*, **25**, 313–336.

Williams, R. T., and T. G. Robertson, 1973: Effect of horizontal wind shear on CISK. Paper presented at the Fall Annual Meeting of the Amer. Geophys. Union, San Francisco. Abstract published in *Transaction*, **54**, 1093.

Yamasaki, M., 1969: Large-scale disturbances in the conditionally unstable atmosphere in low latitudes. *Papers in Meteorology and Geophysics*, **20**, 289–336.

——, 1971: Frictional convergence in Rossby waves in low latitudes. *J. Meteor. Soc. Japan*, **49**, Special Issue, 691–698.

Yanai, M., S. Esbensen, and J. Chu, 1973: Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *J. Atmos. Sci.*, **30**, 611–627.

Young, J. A., 1973a: A theory for isallobaric air flow in the planetary boundary layer. *J. Atmos. Sci.*, **30**, 1584–1592.

——, 1973b: Theoretical models of boundary layer pumping at low latitudes. Presented at Eighth Tech. Conf. on Hurricanes and Tropical Meteorology, Miami, Florida.

Zipser, E. J., 1969: The role of organized unsaturated convective downdrafts in the structure and rapid decay of an equatorial disturbance. *J. Appl. Meteor.*, **8**, 799–814.

announcements

World Weather Program plan for 1975

The World Weather Program Plan for Fiscal Year 1975, recently transmitted to Congress, details federal programs to extend the time range and scope of weather predictions, to assess the impact of atmospheric pollution, to study the feasibility and consequences of weather modification, and to encourage international cooperation in meeting the meteorological needs of all nations.

The World Weather Program is an international effort, coordinated by the World Meteorological Organization. U.S. participation in the program is coordinated by the Commerce Department's National Oceanic and Atmospheric Administration. Other agencies contributing are the Departments of Defense, State, and Transportation, the Atomic Energy Commission, Environmental Protection Agency, National Aeronautics and Space Administration, and National Science Foundation.

The annual report describes current and planned activities of federal agencies participating in the Program. Immediate gains in weather predicting are being made through increased computer use, which will in time produce long-term gains in both immediate and extended range prediction of global weather conditions and in the assessment of the impact of man's activities upon climate and weather.

Field investigations for the Global Atmospheric Research Program Atlantic Tropical Experiment (GATE) were conducted from 15 June through 23 September in a 50-million-square-kilometer area of tropical land and sea extending from the eastern Pacific Ocean to the western Indian Ocean. The primary purpose of GATE was to collect the massive quantities of simultaneous observations required to enable scientists to understand tropical weather phenomena, describe them in mathematical terms, and develop improved models for computer weather forecasting.

Work is also underway in planning other regional GARP experiments such as the Air Mass Transformation Experiment slated in the westernmost Pacific Ocean, the Monsoon Experiment which will study the properties of air masses over the Arabian Sea during the southwest monsoon season, and the Polar Experiment, concerned with energy transfer processes in the polar regions. The target date for a global observation experiment is 1978.

U.S. activities in the World Weather Program for the coming year includes the initiation of an operational geostationary satellite system for more effective environmental warnings. A portion of the system was realized on 17 May with the launching of NASA's new Synchronous Meteorological Satellite-1. A second, similar satellite is scheduled to be launched later this year. In cooperation with other nations, it is planned that five such satellites will eventually be operational. Work will also continue on the expansion of a baseline monitoring network, and the U. S. will offer continued assistance to developing nations for their participation in the World Weather Watch, a program in which member nations of the World Meteorological Organization make available the basic meteorological and related environmental information needed by each to support its weather services and research.

The *World Weather Program for Fiscal Year 1975* is available for $1.00 from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

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