GEOFISICA

INTERNACIONAL

REVISTA DE LA UNION GEOFISICA MEXICANA, AUSPICIADA POR EL INSTITUTO DE GEOFISICA DE LA UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO

Vol. 15 México, D. F., 1o. de abril de 1975 Núm. 2

A NOTE ON THE CISK MECHANISM IN THE TROPICS AND ITS ROLE IN DISTURBANCE FORMATION AND MAINTENANCE[1]

JOANNE SIMPSON*

RESUMEN

El concepto de CISK o "inestabilidad condicional de segunda clase" ha sido desarrollado para explicar el crecimiento de los sistemas de cúmulos y la intensificación de los disturbios tropicales hasta alcanzar el calibre de tormentas o huracanes. Se ha postulado al CISK como base para la parametrización de los procesos de cúmulos en modelos de gran escala. Su investigación tuvo importancia en el diseño y el análisis planeado del experimento GATE de 1974.

La médula del concepto del CISK incluye convergencia friccionalmente inducida en una capa fronteriza de Ekman, que se supone intensifica la convección, la cual a su vez estimula la convergencia de la capa fronteriza. Muchos modelos CISK hacen equivaler la capa de fricción Ekman con la capa inferior a la base de los cúmulos, en los trópicos. Este trabajo corrige este error mostrando que la capa fronteriza de fricción en los trópicos se extiende hasta la parte más elevada de los cúmulos. Varios diferentes tipos de interacciones de escalas en los trópicos se examinan. Se presentan aquí sugestiones específicas para ampliar el concepto CISK en relación a la agudización de las tormentas tropicales y a la parametrización de los procesos de los cúmulos.

---

[1] Research partly supported by the Global Atmospheric Research Program, National Science Foundation and the U. S. GATE Project Office, National Oceanic and Atmospheric Administration. Grant No. OCD74-21701, entitled "Cloud populations and their interaction with the boundary layer during GATE".

* *Department of Environmental Sciences, Center for Advanced Studies, University of Virginia.*

ABSTRACT

The concept of CISK, or "conditional instability of the second kind" has been advanced to explain the growth of cumulus systems and the intensification of tropical disturbances to storm or hurricane intensity. CISK has also been postulated as a basis for parameterization of cumulus processes in large-scale models. Its investigation played a role in the design and planned analyses of the 1974 GATE experiment.

The heart of the CISK concept involves frictionally driven convergence in an Ekman boundary layer, which is supposed to intensify convection, which in turn enhances the boundary layer convergence. Many CISK models equate the Ekman friction layer with the layer below cumulus base in the tropics. This paper corrects this error by showing that the frictional boundary layer in the tropics extends to cumulus tops. Several different types of scale interactions in the tropics are examined. Specific suggestions for broadening the CISK concept are made relative both to tropical storm deepening and to the parameterization of cumulus processes.

INTRODUCTION

A "conditional instability of the second kind", abbreviated to CISK, was proposed by Charney and Eliassen (1964). They postulated that under specifiable conditions, the synoptic and convective scales of motion could interact with one another in such a manner as to amplify each other and lead to the development and/or deepening of a tropical disturbance. The mechanism of interaction was hypothesized to be forced convergence in the lower frictional boundary region or Ekman layer, which the authors earlier (Charney and Eliassen, 1949) had expected to occur there when the relative geostrophic vorticity is cyclonic.

The basic equations of the CISK model are

$$-\mathrm{div}\, D = \frac{1}{2}\, \rho_o\, \zeta_g \sin 2\alpha \sqrt{\frac{2A}{f}} \tag{1}$$

or

$$w_o = -\frac{1}{\rho_o}\, \mathrm{div}\, D = \frac{1}{2}\, \zeta_g \sin 2\alpha \sqrt{\frac{2A}{f}} \tag{2}$$

where div D is the divergence of the horizontal mass flux D in the classical Ekman layer[2], ρ_0 is the mean density in the Ekman layer, ζ_g is the relative vorticity of the geostrophic wind; A is the kinematic eddy momentum exchange coefficient, f is the Coriolis parameter and w_0 is the vertical air motion at the top of the Ekman layer.

The CISK concept has been used extensively in many of the pioneering models of hurricane development (*cf.* Syono and Yamasaki, 1966, Ooama, 1969) and more recently (Rodenhuis, 1970) in an attempt to explain the early initiation of tropical disturbances from horizontal variations in latent heat release. It has also been called upon to explain tropical cloud clusters (Gray, 1967; Williams, 1970) and has been cited increasingly often relative to the GARP tropical experiment, GATE (for example, Atlas *et al.*, 1969). In virtually all of these efforts, the tropical Ekman layer has been thought of as occupying only about the lower 1 km of the atmosphere, coinciding very closely with the subcloud layer. In other words, the frictional inflow has been envisaged as mainly taking place in the surface mixed layer, feeding this moist subcloud air into the cumuli by a forced ascent w_0, at or near cloud base level.

THE TROPICAL EKMAN LAYER

The purpose of this note is to show that the concept of the CISK mechanism described above is erroneous and if there can be said to be an Ekman layer in the tropics, it in fact extends vertically throughout the entire depth of the moist or convective layer. Dispelling of the erroneous part of the CISK concept and reformulating it properly should, if pursued, pave the way to improved hurricane modelling, particularly of the formation stages.

The concept of a shallow tropical Ekman layer, confined mainly

---

[2] The classical Ekman layer is defined (see, for example, Hess, 1959, Section 18.7) as that portion of the air boundary layer, above the constant flux layer, in which the forces of pressure gradient, Earth's rotation and turbulent viscosity are in balance. The pressure gradient force and eddy momentum exchange coefficient are assumed constant with height, so that the wind profile is a clockwise spiral.

below cloud base, arose from a misinterpretation engendered in the original CISK paper by Charney and Eliassen (1964, *loc. cit.*) where equation (2) is written in the form.

$$w_o = \frac{1}{2} D_E \zeta_g \sin 2\alpha \tag{3}$$

where the authors define

$$D_E = \left(\frac{2A}{f}\right)^{1/2} \tag{4}$$

and state that D_E is "a measure of the depth of the Ekman layer". Using a middle-latitude value (from Brunt, 1939) of $A = 10\ m^2/sec$, they find at 15° latitude $D_E = 730$ m, which is roughly the height of cumulus base over the tropical oceans. In contrast, from classical Ekman theory (*cf.* Hess, *loc. cit.*) we find that the actual depth of the Ekman layer Z_E is

$$Z_E = \pi \left(\frac{2A}{f}\right)^{1/2} = \pi D_E \tag{5}$$

where Z_E is defined as that level where the actual wind first attains the direction of the geostrophic wind, which is, to all intents and purposes the geostrophic wind level. Throughout the depth Z_E Ekman theory shows a vertically integrated cross-isobar mass flux towards low pressure

$$D = \frac{1}{2} \rho_o u_g \sin 2\alpha \sqrt{\frac{2A}{f}} \tag{6}$$

where u_g is the geostrophic wind. At any level the cross-isobar flow is proportional to the wind component normal to the isobars, which may be shown to have its maximum value at Z_m where

$$Z_m = \frac{\pi}{4}\sqrt{\frac{2A}{f}} = \frac{Z_E}{4} \qquad (7)$$

Thus with even Brunt's old middle-latitude value of the eddy exchange coefficient we would get

$$Z_E = 2.3 \text{ km} \quad \text{and}$$

$$Z_m = 570 \text{ m}$$

Now, Riehl *et al.* (1951), found from budget considerations that eddy momentum exchange coefficients in the trades are much higher, as shown in Table 1.

Table 1

Austausch Coefficient of Momentum in the Pacific Trade (after Riehl *et al.*, 1951)

Level mb	μ gm cm $\sec^{-1}$
960	370
880	630
800	680
720	570

The rough nature of these figures still permits the concept of a μ roughly constant in the vertical; however, later studies (Charnock *et al.*, 1956) suggest that these values may be somewhat high and that $\mu \simeq 200$ gm cm $\sec^{-1}$ is conservative. With this, $A \simeq 20 \times 10^4$ cm^2 sec^{-1} and

$$Z_E \simeq 3.2 \text{ km}$$

$$Z_m \simeq 800 \text{ m}$$

This result would mean that if there is an Ekman layer in the tropics, it in fact comprises the entire depth of the moist layer and that, rather than ceasing near cloud base, the greatest cross-isobar flow occurs there and well up into the cloud layer. In view of Gray's work (1970) showing that cumulus clouds act as powerful "eddy" vertical transporters of horizontal momentum, the postulate that the tropical Ekman layer includes the cloud layer should surprise no one. But what is the actual observational evidence on the trade-wind boundary layer as a whole?

The work by Riehl *et al.* (1951, *loc. cit.*) clearly showed that in the Pacific trade cross-isobar flow toward low pressure occurred up to levels close to 3 km. At 700 mb, trajectories and streamlines closely paralleled the height contours and geostrophic balance became a good approximation. However, the vertical wind profile did not exhibit an Ekman spiral. On the contrary, the wind direction varied little with height[3] and the height contours rotated counter-clockwise with elevation into alignment with the wind field, as illustrated in Figure 1. This height variation of the pressure field clearly violates one of the basic assumptions of classical Ekman theory.

However, since the meteorologically important feature of an Ekman layer is the frictionally forced divergence or convergence and its interaction with cumuli, perhaps we may usefully broaden the concept of an Ekman layer to include the tropical moist layer and also broaden the CISK concept to consider more realistically the interaction between the cumuli and larger scales of motion. We shall now consider the impact of the broader concepts upon several classes of models of tropical circulations and upon our views concerning the interactions of the several scales of motion.

---

[3] Gray (1967) has found an average 10-14° veering of the wind in the lowest kilometer in both the tropical Atlantic and tropical Pacific (in the latitude belt 10-30°N). That the wind becomes very nearly constant in direction above 1000 m should *not* be interpreted that this level is the top of the Ekman layer; flow across the isobars toward low pressure extends much higher (*cf.* Riehl *et al.,* 1951; Colón, 1960).

IMPACT ON MODELS OF LARGE-SCALE TRADE-WIND DYNAMICS

Fifteen years ago I (Malkus, 1956) put forward a simplified two-dimensional model of the trades which in broad outline was confirmed by observational studies (Colón, 1960) and more sophisticated numerical modelling (Pike, 1968). Briefly, the gist of the model is that the diabatic heating by the cumuli produces hydrostatically the downstream drop in surface pressure which accelerates the flow against turbulent friction. The accelerative effect of the heating function slightly overbalances the frictional retardation so that the tradewinds speed up downstream and thereby undergo subsidence. The subsidence maintains the trade-wind inversion and on the average acts as a brake upon convection. Hence a stable interaction between the cumuli and the planetary trades was deduced which helped to explain the unusual wind steadiness. This steadiness, however, not unexpectedly breaks down above the cloud tops. The two-dimensionality of the model precluded the investigation of the effects of lateral wind shear, which were thought to be comparatively small. It is now possible to re-examine these, in terms of the broadened CISK concept.

Using Fig. 1, we see that the relative vorticity of the geostrophic wind is virtually all in the latitudinal shear, with a magnitude just a little less than 1 m $\sec^{-1}$ per degree latitude. Introducing this number into equations (2) and (5) combined we obtain an average divergence in the Ekman layer of just under 10^{-6} $\sec^{-1}$. The calculations of Riehl *et al.*, showed that this is about the measured amount of the mean divergence in the lower 300 mb, within the errors of the calculation. This agreement tells us nothing startlingly new about the poleward half of the trades except to fill in some important mechanistic linkages. It confirms Gray's suggestion that the vertical momentum transport function of the cumuli is vital and indicates that a mechanism maintaining the divergence, hitherto deduced from observations and a simplified model, may be frictional forcing as well as downstream heating. It should be emphasized that the diabatic heating by the clouds is primary, however, for that maintains the downstream pressure force. No air flow can ever be *driven by* fiction, although friction can cooperate with heating to preserve or accelarate it. In this case, the cumulus and the planetary scales of motion are cooperating to maintain divergence in the boundary layer and to maintain a steady condition, which is quite a different interaction from that occurring in the equatorward portion of the trades and yet again from that in disturbances.

IMPACT ON MODELS OF TROPICAL DISTURBANCES AND HURRICANES

The CISK model has been used by many authors (e.g. Rodenhuis, 1970) to examine the instability responses of the tropical easterlies to horizontal variations in latent heating. A thin frictional boundary layer is envisaged below cloud, which affects the free atmosphere above only by the imposition of a w_0 at or near cloud base. The remainder of the free atmosphere, in which the latent heat release takes place is treated by means of balance equations. The work described in this article has shown that this idealization, separating into two superposed layers the regions of frictional convergence and of latent heat release is such a vast oversimplification as to be physically incorrect and probably more misleading than helpful in understanding the origins and behavior of tropical waves.

The proper question to be addressed is a much more complex and difficult one, namely how do cumulus convection and convergence interact in the entire moist layer? This is firstly a problem for the numerical modellers of single clouds and mesoscale cloud groups; for some years the former have been working up to the point where convergence may be superimposed on the model cumulus in various stages of its development. My own experience (Malkus and Williams, 1963) strongly suggests that the most important effect of convergence upon cumuli is to produce wider towers, which are then able to penetrate to greater heights without dilution. This subject still awaits definitive research and hopefully will be clarified in analyses of the GATE data.

To make the linkage to disturbance growth, a very small but perhaps useful step has been taken by Holton (1970). He assumes a heating function varying sinuosidally with downstream distance, that has an assumed dependence on height. With this he shows that the ensuing Rossby waves forced by these heating patterns have many characteristics of observed easterly waves. Later, when the relationship between convergence and convection can be specified, it may be possible to put into such a model the feedback between the wave development and the latent heat release. It is not now, however, clear that the frictionless equations of motion may be used to describe the evolution of tropical waves; it may be necessary to at least parameterize the vertical transport of horizontal momentum by the cumuli, as well their latent heat release.

In the case of hurricane models, virtually all of them have had the problem of developing, without fail, a mature hurricane despite wide variations in assumptions and initial conditions. Nature's problem appears to be just the reverse one, namely for every 100 or so seedlings, only about ten develop and we find that the important question is not why are there hurricanes but why are there so few hurricanes? (Malkus, 1957).

It is doubtful that convective momentum transports can be neglected at any stage in hurricane modelling, as included in the more sophisticated studies (Rosenthal, 1970) which demonstrate the need for these transports both explicitly and also implicitly in the differencing scheme. Furthermore, in a hurricane, the Ekman layer and the inflow layer are virtually *never* coincident. The Ekman layer is essentially the whole troposphere, while the inflow becomes increasingly concentrated at low levels as the storm deepens.

We can now see a major reason for many of the models' too great ease of deepening. Using the CISK concept, they start way beyond the no-return point in hurricane development. That is, they incorporate in the initial stage a set of key features that nature herself arrives at only in the final stages of tropical storm intensification. These models start out with a forced frictional convergence only in a very shallow "boundary layer" fixed in depth, to coincide with the subcloud layer. Then they put all this moist convergent air immediately into penetrative undilute "hot towers" (Ooyama, 1969) which release the latent heat according to various parameterization schemes. The latent heat release starts a central pressure drop, which intensifies the inflow, the heat release, etc. It is no wonder that the inflow remains confined to low layers as the storm invariably deepens.

In our analysis of real hurricanes (e.g., Riehl and Malkus, 1961) we found that in the early stages, the inflow often extends up to as high as 500 mb and cumuli of all sizes are found. A sure sign of deepening to full hurricane (and perhaps also both a necessary and a sufficient condition) is the compression of the inflow until it mainly comprises just the very moist subcloud air, which then and only then enables virtually all the ascent to concentrate in wide undilute "hot towers". In the next generation of models, it would be desirable not to assume these concentrations as initial conditions, but to attempt to predict how they come about, starting from a weak, deep inflow and a heating function characteristic of mainly entraining cumuli with a few hot towers. If these models could be used to learn just what factors must be present or absent for the concentration process to proceed, we might hope to learn why the proper "cooperation" between scales of motion is such a rare phenomenon. This goal will be a difficult one to achieve; its accomplishment can be greatly aided if part of the GATE analyses are, as planned, focussed on elucidating the relationship between convergence, cumulus width, their latent heat release and their vertical momentum transport, in a hierarchy of tropical weather conditions ranging from suppressed to highly disturbed.

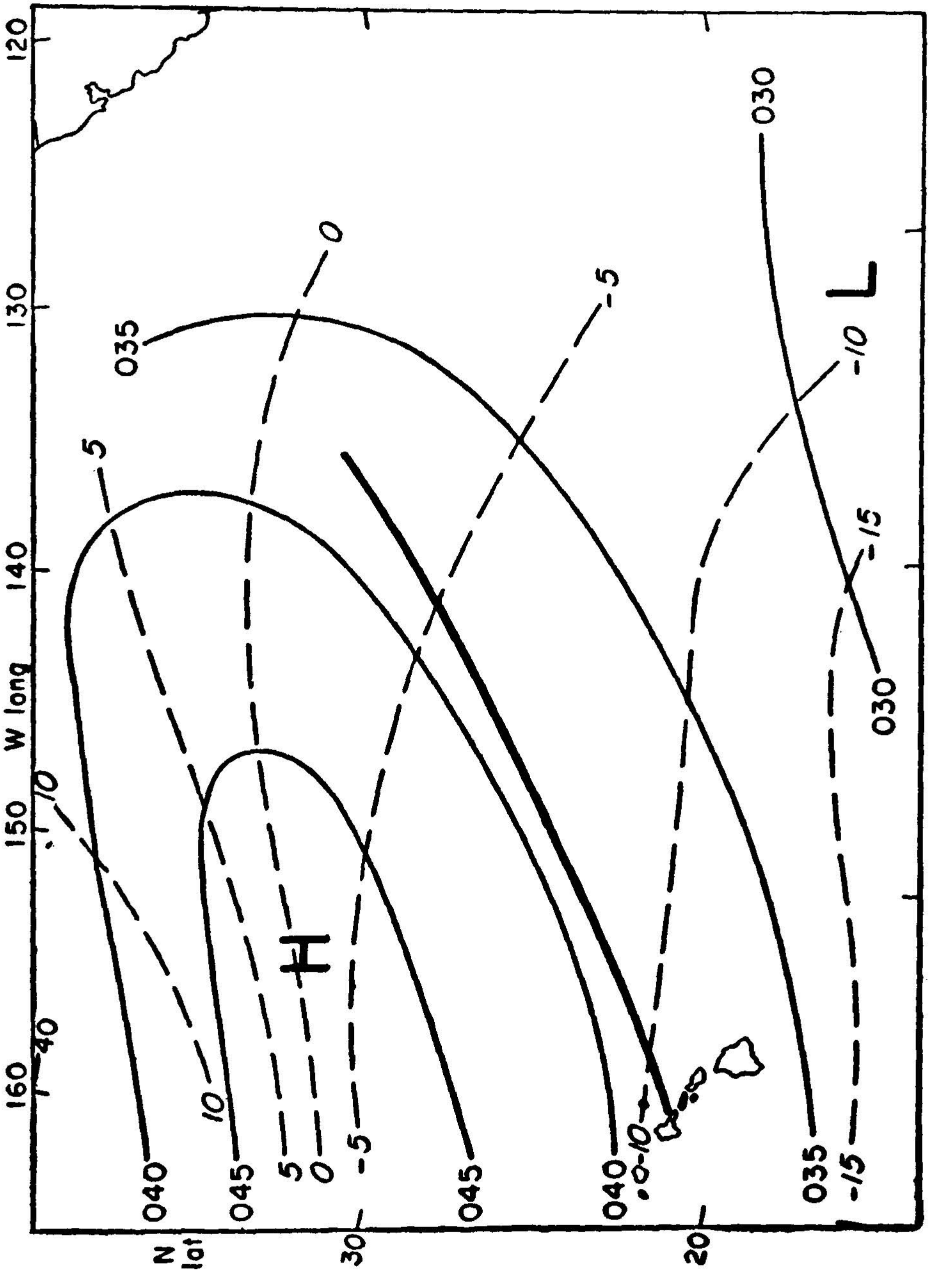
120
130
140
150
160
W long
N lat
30
20
040
045
5
0
-5
045
040
-10
035
-15
035
030
030
-15
-10
-5
0
5
10
40
10
H
L

Figura 1

BIBLIOGRAPHY

ATLAS, D., N. LASEUR, D. LILLY, S. MANABE, C. NEWTON and K. OOYAMA, 1969. Report of the working group on cumulus convection. U. S. Committee for the Global Atmospheric Research Program. *Unpublished manuscript on file at the National Academy of Sciences* – National Research Council.

BRUNT, D., 1939. *Physical and Dynamical Meteorology,* Cambridge, Cambridge University Press, 428 pp.

CHARNEY, J. G. and A. ELIASSEN, 1949. A numerical method for predicting perturbations. *Tellus, 1:* 38-54.

CHARNEY, J. G. and A. ELIASSEN, 1964. On the growth of the hurricane depression, *Jour. Atmos. Sci.,* 21: 68-75.

CHARNOCK, H., J. R. D. FRANCIS and P. A. SHEPPARD, 1956. An investigation of wind structure in the trades: Anegada, 1953. *Phil. Trans. Roy. Soc.* London, A249: 179-234.

COLON, J., 1960. On the heat balance of the troposphere and water body of the Caribbean Sea. *National Hurricane Res. Proj.,* Rep. No. 41. U. S. Dept. of Commerce, Washington, D.C., 41 pp.

GRAY, W. M., 1967. Global view of the origin of tropical disturbances and storms. *Atmos. Sci.* Paper No. 114. Dept. of Atmos. Sci., Colorado State Univ., Ft. Collins, Colo., 105 pp.

HESS, S. L., 1959. *Introduction to Theoretical Meteorology.* Henry Holt and Co., New York, 362 pp.

HOLLAND, J. and E. M. RASMUSSEN, 1973. Measurements of the atmospheric mass, energy and momentum budgets over a 500-kilometer square of tropical ocean. *Monthly Weather Rev.,* 101: 44-55.

HOLLAND, J. and E. M. RASMUSSEN, 1974. Reply to H. Riehl. *Monthly Weather Rev.,* 102: 527-532.

HOLTON, J. R., 1970. On the theory of easterly waves. *Extended Abstracts,* Symposium on Tropical Meteorology, June 2-11, 1970, Univ. of Hawaii, Honolulu, Hawaii, EIII-1-EIII-3.

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

MALKUS, J. S., 1957. The origin of Hurricanes. *Scientific American,* 197: 33-39.

MALKUS, J. S. and R. T. WILLIAMS, 1963. On the interaction between severe storms and large cumulus clouds. *Severe Storms,* Meteor. Monographs 5 (27): 59-64.

OOYAMA, K., 1969. Numerical simulation of the life of tropical cyclones. *Jour. Atmos. Sci.,* 26: 3-40.

PIKE, A. C., 1968. A numerical study of tropical atmospheric circulations. Inst. of Atmos. Sci., Univ. of Miami. *Rep. of Contract No. F19628-68-C-0144,* 125 pp.

RIEHL, H., T. C. YEH, J. S. MALKUS and N. E. LASEUR, 1951. The north-east trade of the Pacific Ocean. *Quart. Jour. Roy. Met. Soc.*, 77: 598-626.

RIEHL, H. and J. MALKUS, 1961. Some aspects of hurricane Daisy, 1958. *Tellus,* 13: 181-213.

RODENHUIS, D. R., 1970. The effect of horizontal distribution of latent heat release upon the growth of tropical disturbances. *Extended Abstracts,* Symposium on Tropical Meteorology, June 2-11, 1970, University of Hawaii, Honolulu, Hawaii, EI-1-EI-6.

ROSENTHAL, S. L., 1970. A circularly symmetric primitive equation model of tropical cyclone development containing an explicit water vapor cycle. *Monthly Weather Review,* 98: 643-663.

SYONO, S. and M. YAMASAKI, 1966. Stability of symmetrical motions driven by latent heat release by cumulus convection under the existence of surface friction. *Jour. of the Meteor. Soc. of Japan,* 44: 353-375.

WILLIAMS, K., 1970. Characteristics of the wind, thermal and moisture fields surrounding the satellite-observed mesoscale trade-wind cloud clusters of the western North Pacific. *Extended Abstracts,* Symposium on Tropical Meteorology, June 2-11, 1970, Univ. of Hawaii, Honululu, Hawaii, D IV-I-DIV-6.