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VARYING STRUCTURE OF WAVES IN THE EASTERLIES

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Глава X. ДИНАМИКА АТМОСФЕРНЫХ ПРОЦЕССОВ В ТРОПИКАХ

Chapter X. DYNAMICS OF ATMOSPHERIC PROCESSES IN TROPICS

VARYING STRUCTURE OF WAVES IN THE EASTERLIES

H. RIEHL

Introduction

Weather disturbances of the tropics, especially waves moving westward in the tropical easterlies of summer, were first analyzed with data based on modern techniques of observation at the Institute of Tropical Meteorology, established at the University of Puerto Rico in the West Indies during World War II [1]. At that time radiosonde stations had been established in the Caribbean area. Use of radar made it possible for the first time to obtain wind observations in the upper troposphere regularly during cloudy as well as during clear weather.

Generally it had been assumed for many years that the kinetic energy of weather disturbances in the tropics is generated and maintained through liberation of latent heat of condensation. Yet, surprisingly, the new observations in the Caribbean revealed that the atmosphere frequently was denser in the rain areas connected with disturbances than on their outside. The wind data demonstrated that the waves, in such cases, increased in amplitude with height from the surface to the middle troposphere, and that the wave axes sloped toward the coldest air with elevation.

Thus, wind and temperature observations were consistent with an atmospheric model in which gradient wind balance was approximately maintained and which satisfied the theorem of conservation of potential vorticity. However, the energy cycle was obscure because the condensation was associated with dense rather than with light air. Apparently, the whole of such a weather disturbance required maintenance from the subtropical high pressure cells.

Because of this difficulty, the subject of understanding tropical weather disturbances advanced but little for a number of years. Recently, research concerning their nature has again increased. Tropical observation networks plus research opportunities with aircraft furnish enough data, at least in some situations, to permit more detailed examination of the waves than was possible in the early 1940's. Further, incorporation of tropical rainfall into numerical models of the general circulation has become an urgent problem, as Professor Mintz has demonstrated in his calculations presented at this conference. Finally, various numerical studies have been undertaken to learn about the transition from weak tropical disturbance to hurricane. These models generally predict a hurricane to form, whereas in reality only a very small fraction of the disturbances on the daily weather map do so intensify. Evidently, the constraints normally opposing intensification have not been included in the models so far proposed.

Purpose of this paper

The purpose of this discussion is to examine some recent data from the Caribbean in order to see what they indicate on the constraints against intensification and on the maintenance of waves in the easterlies.

Description of wave of August 1964

During the early part of August 1964, a wave travelled through the whole Caribbean. It was flown by two DC-6 aircraft from the Research Flight Facility of the United States Weather Bureau on 7 and 8 August. We shall concentrate on the missions flown on 8 August, when the disturbance was passing through the Western Caribbean.

Fig. 1 shows the regular rawinsonde network in operation in the Caribbean. At the time of the intercept the wave axis was situated near Swan Island and had passed Gran Cayman. At the latter stations, (Fig. 2) winds turned to northeast ahead of the wave axis and to southeast after its passage. The amplitude of the wind field was stron-

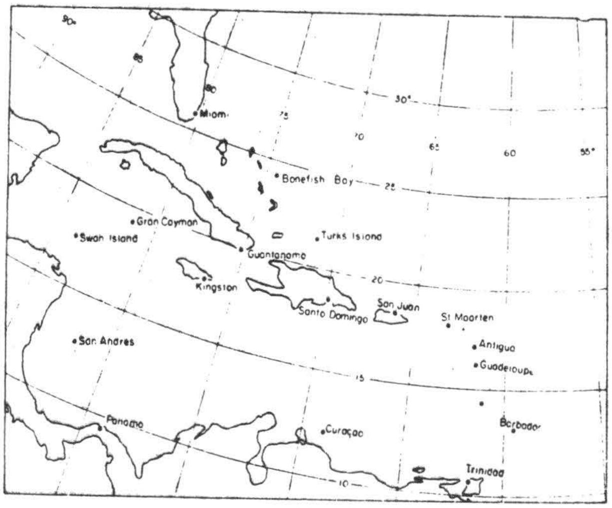

Fig. 1. Rawinsonde network in the Caribbean area

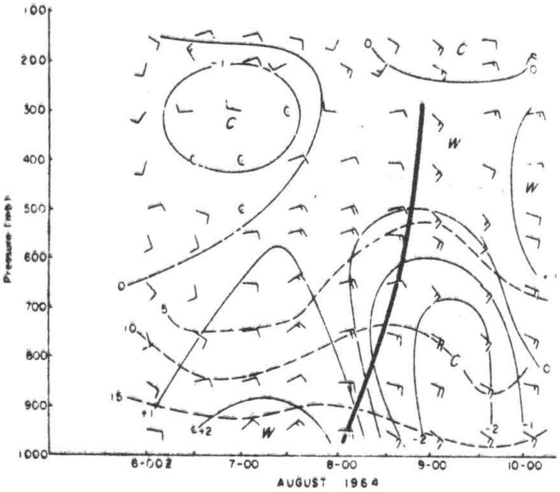

Fig. 2. Time cross-section of winds, temperature and moisture at Gran Cayman during passage of wave in the easterlies (axis drawn heavy). Specific humidity lines in g/kg, dashed. Isotherms (°C), solid, are deviations from the mean at each level

gest near 600—500 *mb*, decreasing from there both toward the ocean and toward the high troposphere. The wave axis passed 6—12 hours later at upper than at low levels, which means that it sloped eastward with height, because the disturbance moved westward across the station.

Plan of flight missions

The extent of a wave in the easterlies is so great, that many aircraft would be required to cover such a system sufficiently, if computations were to be performed in general Eulerian coordinates. With a small number of aircraft, the best procedure is to select a problem within the flight capability, and to design a mission accordingly. In this case it was judged best to try and fly along an air

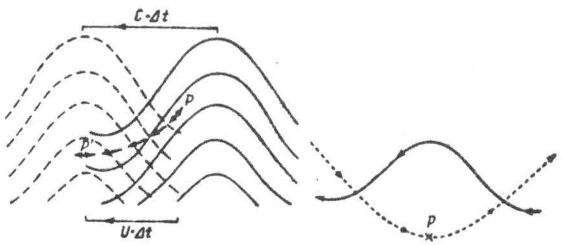

Fig. 3. Model showing air east of wave trough in the easterlies being overtaken by trough (left); streamline (solid) and trajectory relative to waves (dashed) for wave moving faster than basic easterly current [2] (right)

trajectory with the purpose of examining the dynamic and thermodynamic transformations of the air entering into and becoming the bad weather area. If, in the first approximation, we assume the wave to be in steady state and moving at a constant rate (which was not altogether true), we can determine the trajectory of the air in a coordinate system fixed in the wave axis.

Phase and amplitude of a relative trajectory, compared to the streamlines, depends on whether the wave travels faster or slower than the basic easterly current. Our wave was moving with a velocity near 10 $m\ sec^{-1}$, a very fast rate and well in excess of the basic current. Air initially west of the trough is overtaken by it, so that some time later it will be in the trough (Fig. 3). A relative streamline, or trajectory for a steady state system, appears on the right in the figure.

It was attempted to fly along such a relative trajectory. Since the aircraft had stayed overnight at Jamaica, that is to the east of the wave, the planes would first enter the trajectory on the eastern end at two levels, fly to the western end, change flight altitudes and return to the eastern end. This manoeuvre was executed with flight altitudes at 950, 850, 750 and 640 *mb*. The aircraft then left the area flying westward.

Observed wind field and cloud patterns

Data gathered during the missions were time, location of aircraft, temperature, moisture, wind direction, wind speed, radar altitude, and horizontal and vertical radar rain cloud presentation. Two cameras also took continuous cloud movies.

Fig. 4 shows the track of the aircraft in relative coordinates and the wind field at two levels. At 640 *mb* a closed circulation was present, as happens frequently in waves in the easterlies in the middle troposphere. Looking along the aircraft path (Fig. 5) the winds relative to the wave have been plotted at 850 and 640 *mb*. It is seen that the aircraft manoeuvre actually caught the relative motion quite well. Of course, it is impossible to

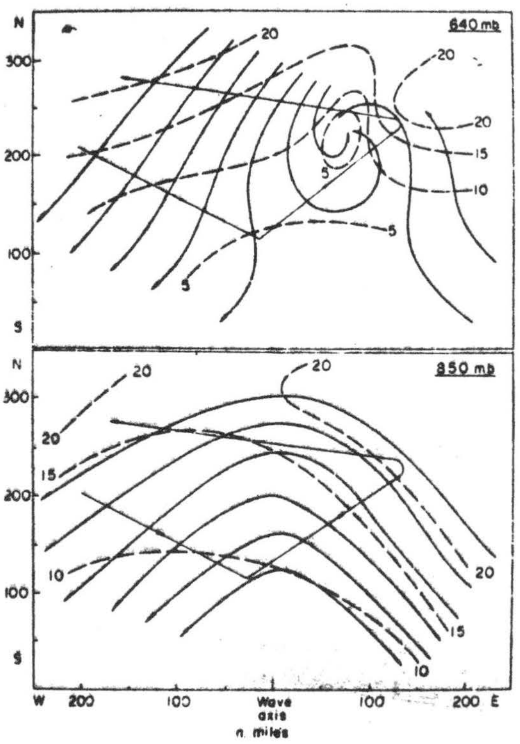

Fig. 4. Streamlines and isotachs (knots), also aircraft path, at two levels on 8 August, 1964

do this perfectly at all heights, because of some turning of wind direction with height. The assumption must be made that air moving into the flight section has undergone the transformations observed along the section, so that advection perpendicular to the flight path may be neglected. From Fig 2. the vertical wind shears were very small;

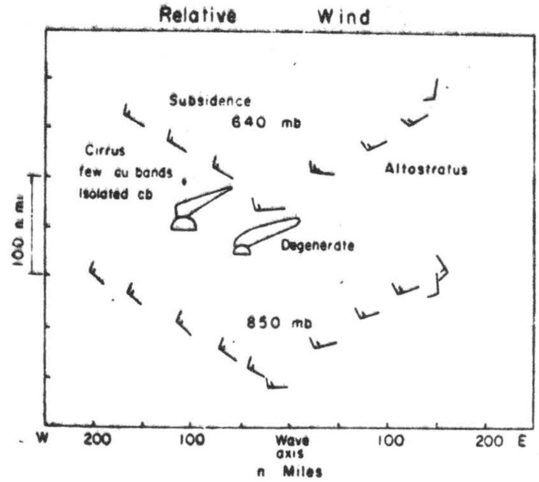

Fig. 5. Winds relative to wave at two levels and cloud pattern

distortion of vertical columns was as little as can ever be hoped to be found in a synoptic-scale weather disturbance. Under these circumstances, and in view of the considerable north-south extent of the wave plus the homogeneity of the tropical atmosphere flowing into the disturbance, this assumption is considered to be well justified.

Turning to the cloud patterns, cumulus clouds were largely suppressed along the northwestern portion of the flight, indicative of subsidence. Following the trajectory from there, the air moved toward somewhat lower latitudes but also to higher relative vorticity in the trough itself. The change in flow curvature dominated the vorticity distribution, so that the absolute vorticity increased as the air approached the trough.

Thus, convergence started west of the surface position of the wave axis and became strong close to the axis. Isolated cumulonimbi with very large shearing anvils and a great deal of isolated cirrus was first observed. The cloud mass increased toward the wave axis. The anvils became less distinct and the cumulonimbus clouds assumed a degenerate appearance. East of the wave axis the vorticity of the air continued to increase, going toward higher latitudes and toward the high relative vorticity associated with the closed circulation aloft. The cumulonimbus clouds died away on th's part of the trajectory, as did almost all convective activity. Instead, the air first became very hazy and then the cloud mass became stratiform to terminate in a very extensive sheet of altostratus — with extent of at least 300 × × 300 *km* — with base near 700—650 *mb*, top near 300 *mb*. Light rain was falling from the altostratus. The transition in cloud type was most remarkable.

In summary, the cloud films show suppressed cloudiness in the northwest, then convective cloudiness increasing toward the wave axis, becoming degenerate and finally going over into a stable cloud form, altostratus, in the most intense part of the wave east of the axis.

Evidence from the vertical scan radar supports the deductions from the cloud films. In Fig. 6 we see several pictures of this radar presentation at selected intervals. The radar scan extends to 50 *km* from the aircraft. Echoes reaching above the freezing level have been shaded heavy to convey an impression of the altitude of the echoes. Along the northwestern part of the trajectory echoes at first were few and low. Near the wave axis convective clouds with radar tops near 300 *mb* appeared. Then the presentation takes on a stratified character. After some holes in the clouds it indicates a complete stratus deck with a level top near 300 *mb*. It should be noted that on the films the highest cloud usually appears directly

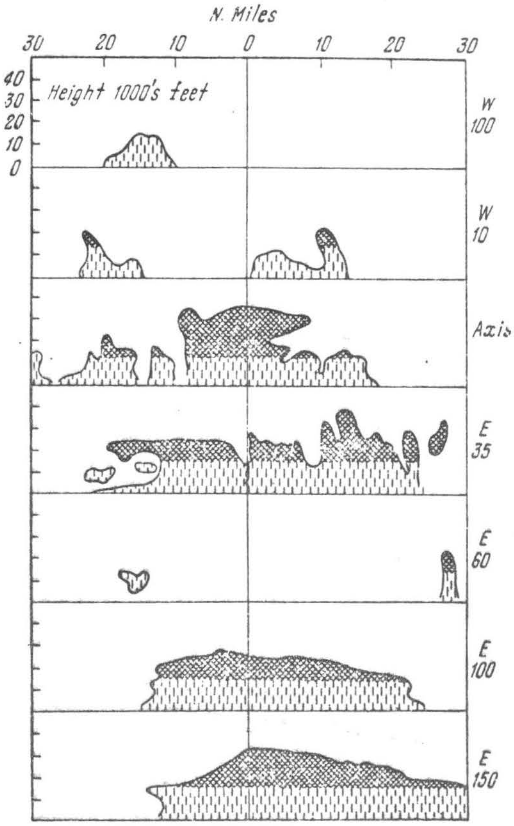

Fig. 6. Vertical scan radar presentation of rain clouds at indicated distance from wave axis (on right). Echoes above freezing level shaded heavy

above the aircraft. But this is due to attenuation and scattering of the electrical energy reflected from more distant points.

Thermodynamic transformations

If the air moves along the relative trajectory under conservation of potential vorticity, and if individual fluid sheets remain stratified so that they retain their identity, the trajectories will bend upward as indicated in Fig. 7.

Assuming these paths are realistic, the vertical profile of equivalent potential temperature (θ_e) observed at the westernmost or initial end of the trajectory should change to the profile marked «no mixing» in Fig. 8. It has often been assumed that this type of transformation actually occurs, perhaps with mixing through of warm cumulus towers added. Nevertheless, as Fig. 8 demonstrates, this solution is erroneous. θ_e did increase above 800 *mb*. But it also decreased markedly below 800 *mb* right down to the ocean. The final profile approaches a constant value of θ_e, indicative of vertical mixing superimposed on the general ascent under influence of synoptic-scale

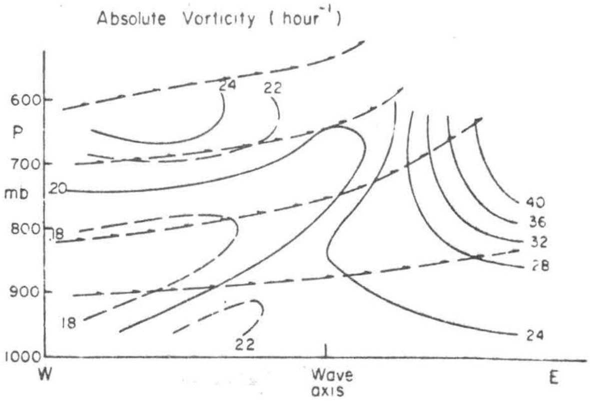

Fig. 7. Vertical cross section of absolute vorticity along relative trajectory and paths (with arrows) which air would follow if the potential vorticity was conserved and if individual fluid strata remained unmixed

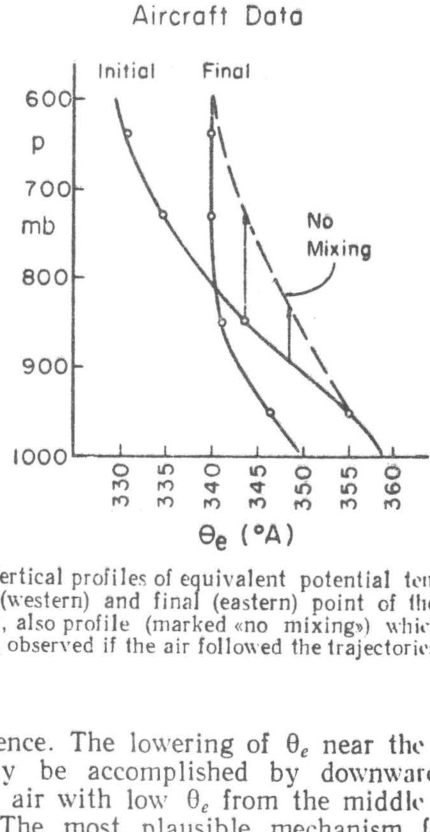

Fig. 8. Vertical profiles of equivalent potential temperature at initial (western) and final (eastern) point of the relative trajectory, also profile (marked «no mixing») which should have been observed if the air followed the trajectories of Fig. 7 strictly

convergence. The lowering of θ_e near the ground can only be accomplished by downward transport of air with low θ_e from the middle troposphere. The most plausible mechanism for this descent to be possible is evaporation of rain falling from the leaning cumulonimbus clouds and from the altostratus clouds.

Fig. 9 shows the transformation of the Gran Cayman radiosonde observation before and after wave passage, roughly corresponding to beginning and terminal point of the trajectory. Aircraft data are given with dashed lines for comparison. Again we observe the decrease of θ_e in the low layers, and the increase higher up. Because

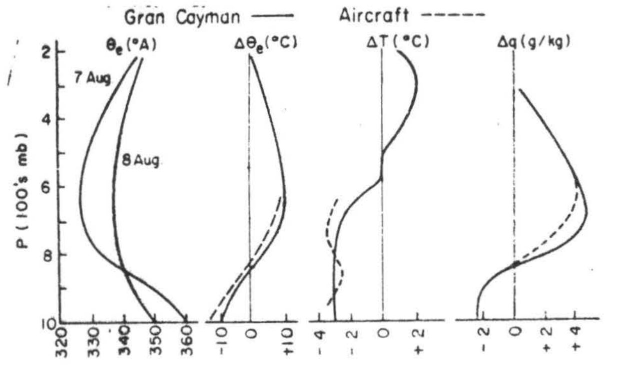

Fig. 9. Comparison of Gran Cayman radiosonde observations on 7 August 1200 GMT and on 8 August 1200 GMT. Left: profiles of equivalent potential temperature. Center and right: difference in equivalent potential temperature, temperature and specific humidity from 7 to 8 August (data on 7 August subtracted from those on 8 August).

of the general convergence at low levels, a net increase of θ_e took place in the whole column between the ocean and the high troposphere. We are not merely dealing with a vertical rearrangement of a given air column.

The two components producing the change in the θ_e-profile are plotted on the right. Most of the variation in θ_e is determined by the moisture change—a general increase to near saturation above 700 *mb* and a remarkable lowering by 2 *g/kg* near the ocean. Temperature decreased up to 600 *mb*, but it increased higher up in the layer occupied by the stratus.

Fig. 2 indicated that the disturbance attained its greatest intensity near 600—500 *mb*; the Swan Island time section (not reproduced) corroborates the Gran Cayman data. The largest wave amplitude thus occurs near the levels of temperature anomaly reversal in Fig. 9. Thus the data are still consistent with a model of large-scale quasi-gradient motion obeying the baroclinic vorticity theorem. The thermal wind, integrated from the ocean to 200 *mb*, vanishes (using the temperature curve of Fig. 9), and this is in agreement with the wind observations.

Using the principle of conservation of heat, budgets of sensible and latent heat can be constructed, so that the changes in θ_e, temperature and moisture shown in Fig. 9 are individually satisfied. Such budgets were constructed for a volume extending from the ocean to 600 *mb*, and moving along the relative streamline with the average speed of the relative wind. The details of these calculations will be presented elsewhere. They are based on a model of vertical mixing, in which ascent is concentrated in warm cumulus towers and descent is effected through evaporation of raindrops into unsaturated air in the layer below 700 *mb*. Satisfactory computational results were obtained with this model. About 50% of the condensed moisture was required for evaporation. In the whole layer from 1000 to 600 *mb* condensation and evaporation were nearly equal, so that no net heating from release of latent heat took place below 600 *mb*. The entire net heat release was restricted to the upper troposphere, where (Fig. 9) corresponding warming took place. In spite of the large evaporation, the downdrafts led to drying out of the low troposphere and they therewith stopped the possibility for formation of cumulus clouds and penetration of the troposphere with air of high θ_e from the ocean surface. This consequence of the mixing was demonstrated spectacularly by the rise of cloud base from about 600 *m* west of the wave axis to over 3000 *m* in the area of the closed circulation aloft.

Production of kinetic energy

The model of vertical mixing, together with the temperature anomaly distribution of Fig. 9, may be used also to estimate the production of kinetic energy in the wave. At low levels the cold air sinks under the influence of evaporation from falling rain, while the mass in the ascending cumulus towers moves at nearly adiabatic temperatures. This vertical rearrangement contributes to release of kinetic energy. Further, we saw that the upper altostratus deck was warmer than the atmosphere ahead of the wave so that, above 600 *mb*, the ascent also takes place at relatively warm temperatures. Thus, the entire system acts to generate kinetic energy. Numerically, the release in the volume considered was about 3 watts m^{-2}. If half of the dissipation of kinetic energy through friction takes place in the surface boundary layer and half in the free atmosphere, as often assumed, the production is sufficient to sustain a root-mean-cube wind of 9 $m\ sec^{-1}$ in the surface layer. The observed root-mean-cube wind at 950 *mb*, the lowest flight level, was 8 $m\ sec^{-1}$; it follows that the computed production was ample to maintain the disturbance.

Conclusion

It turns out that a model of a wave in the easterlies with convergence and superimposed vertical mixing can explain the maintenance of the energy of the waves, without need for recourse to external energy sources as often thought necessary. Further, the drying out and cooling of the low atmosphere by the downward spreading air with low θ_e from the middle troposphere provides a constraint against intensification of a wave. As θ_e decreases in the subcloud layer and the whole atmosphere becomes increasingly stably stratified, it is no longer possible for cumulonimbus towers to shoot up from the ground to the high troposphere in the convergence zone. Convective penetration is suppressed, and therewith the general tropospheric warming required for the transition from wave to hurricane stage cannot occur. Essentially, this is the equivalent of a polar air mass moving into the center of a tropical disturbance; only in this case the air suppressing strom development came from above.

While the mechanism discussed is not advanced as the unique way for maintaining stable disturbances in the tropics, it is nevertheless difficult to avoid the conclusion that the meso-structure of the clouds in tropical disturbances may have a decisive influence on their larger-scale structure and maintenance.

It will not be a very simple task to represent tropical clouds and precipitation by statistical parameterization in models of the disturbances or of the general circulation. Clearly, however, this must remain a primary objective, and it is hoped that the present study has contributed to determining the kind of transformations which, ultimately, must be summarized statistically. It appears essential that the physical situation must be closely observed and analyzed over a wide spectrum of individual cases. Evidently, this is a large and challenging task which requires broad international cooperation for its accomplishment.

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Discussion

K. Ooyama and L. Berkofsky took part in the discussion.

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