

On the Formation and Structure of Tropical Hurricanes

By

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(This paper is a result of research carried out at the University of Chicago)

I. *Vertical Stability and Formation of Hurricanes.*

There is an almost complete agreement between meteorologists on the fact that the formation of tropical hurricanes is connected with the vertical instability in the tropical atmosphere. It is well known that in large tropical regions the potential wet-bulb temperature in the surface layers is higher than at somewhat greater elevations. Depending upon the actual content of moisture the vertical stratification is either unstable, or conditionally unstable in deep layers. In some cases with inversions characterized by decrease of humidity the stratification is convectionally (potentially) unstable.

In the extra-tropical regions one can occasionally observe the same types of vertical instability, but, as we shall see later on, the instability in these regions is usually characteristic of much thinner layers than in the tropics.

In order to find criteria for the seasonal variation of the vertical instability we shall at first consider the average temperature distribution over Swan Island ($17^{\circ}.5$ N, 84° W) in the Caribbean Sea. In fig. 1 the mean temperature at different levels over Swan Island in September and February is plotted on a tephigram. The data are taken from U. S. Weather Bureau's Monthly Weather Review. In the same tephigram the temperature of an air parcel lifted adiabatically from the sea surface to above the level

of 200 mb in the same months is given by the two dashed curves. In this process we assumed a relative humidity of 85 % at the surface and a temperature of 28° in September and 25° in February. As can be observed

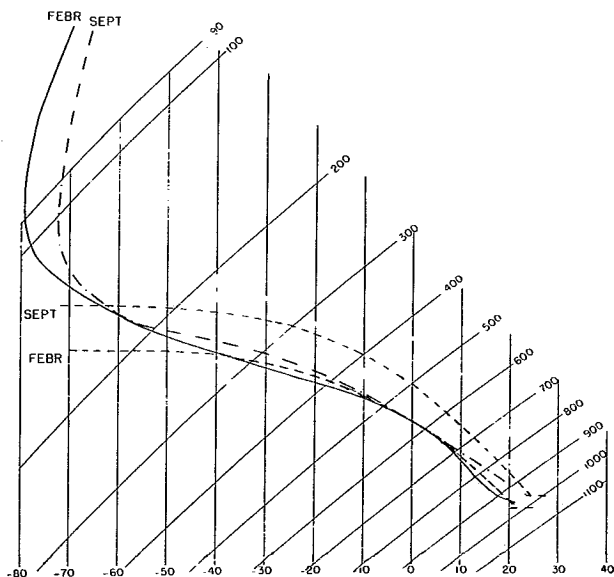


Fig. 1. Mean temperature over Swan Island (Caribbean Sea) in September and February compared with the temperature of an air parcel lifted adiabatically from the sea surface.

from the diagram the lifted air in September is much warmer than the surrounding air up to the level of about 160 mb. In February, however, the lifted air has approximately the same temperature as the surrounding air up to about 250 mb. Thus there is very little instability energy available in February, but a large amount in September. From the standpoint of the convective theory of tropical cyclones one can conclude, that *it is impossible for hurricanes to generate over the Caribbean Sea during the cold season.*

In order to study the possibility of hurricane formation in other regions of the Atlantic Ocean the same computation was made for the whole ocean north of the Equator. It is obvious that vertical instability is characteristic of the regions where strong outbreaks of deep polar air masses occur. However, the depth of the polar air masses showing vertical instability seldom exceeds 3—5 km over the regions with really warm water. Further on, the maritime polar air over the northern parts of the ocean

is characterized by strong convection because of the intense flux of heat and moisture from the relatively warm sea surface. An accumulation of strong instability is therefore not possible in cases of active outbreak of polar air.¹ Vertical instability up to a level of 10—12 km can therefore be expected only in the tropical or subtropical regions of the ocean.

We can get a simple picture of the average conditions if we start from the water temperature, assume, as before, that the surface air has the same temperature and an average humidity of 85 % and lift the air adiabatically to the condensation level, then moist-adiabatically to the level of 300 mb (9—10 km). Comparing the temperature T' of the lifted air with the average temperature T at the same level we get a temperature difference $T'-T$, which gives a rough indication of the vertical instability. If $T'-T$ is positive, then there is instability energy available up to the level in question.

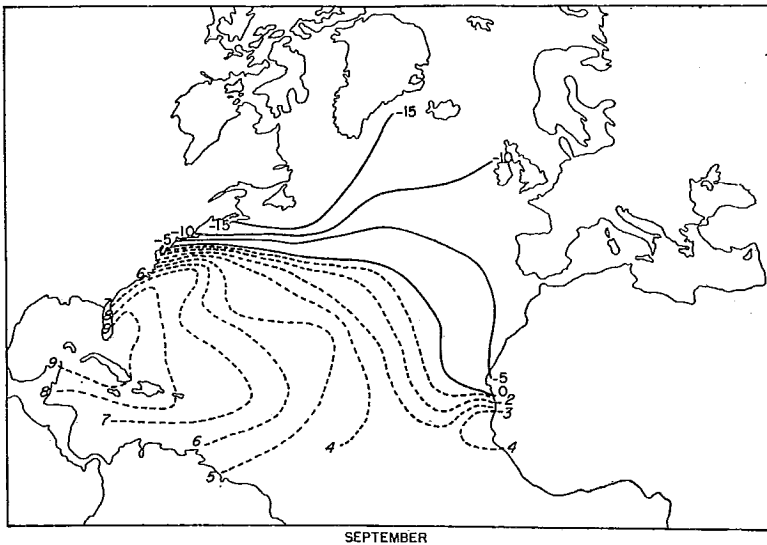


Fig. 2. Difference in temperature between the air lifted adiabatically from the sea surface to the level of 300 mb and the air at the same level over the North Atlantic ocean in September.

In fig. 2 this computation has been done for September, using the surface temperature of the Atlantic Ocean and the average temperature

¹ In the coastal regions of NW Europe the polar air sometimes shows a practically moist adiabatic lapse rate up to about 7 km connected with heavy instability showers.

at the 300 mb level along the meridian 80° W computed from data published by the U. S. Weather Bureau. For September one can observe a large area of instability over the region limited in the north by the zero line of the temperature difference $T' - T$. Off the west coast of Africa the instability is rather weak and limited to a small area, but over the western part of the tropical and subtropical ocean it is large. The maximum instability can be observed over the West Indies, the Gulf of Mexico and the Gulf Stream region off the south-east coast of the American continent. The corresponding map for February in fig. 3 shows only a very weak instability over the West Indies and surrounding seas, but stability

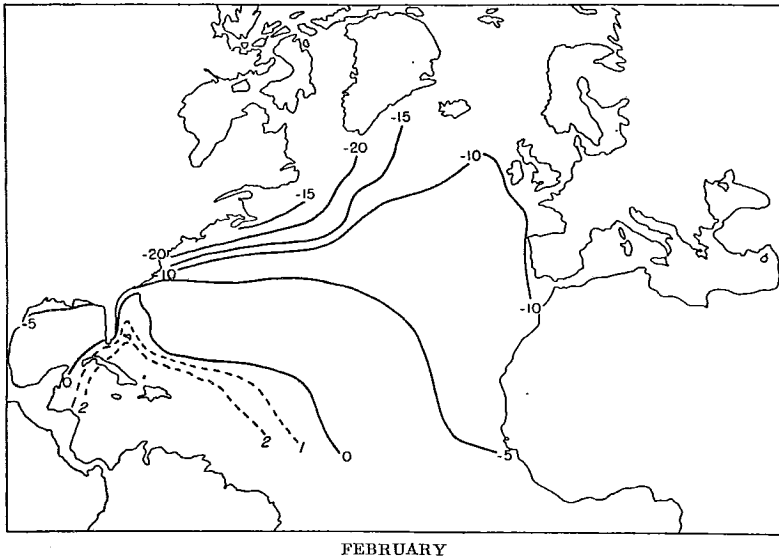


Fig. 3. Difference in temperature between the air lifted adiabatically from the sea surface to the level of 300 mb and the air at the same level over the North Atlantic ocean in February.

over all other regions. The stability over Northern Atlantic is very pronounced both in summer and winter.

It is obvious that the water temperature cannot vary very much from day to day. The temperature at the 300 mb level, however, shows rather large aperiodical variations, at higher latitudes and in winter. At lower latitudes the variations are not very pronounced, if we do not consider the variations in connection with hurricanes which will be discussed later. Over the Northern Atlantic the temperature variations, however, cannot

be so large that a real instability from the sea surface up to 300 mb could develop. It is therefore obvious that the region of instability indicated in fig. 2 and 3 never can be extended very much to the north, but that there can be some aperiodic variations within the region of vertical instability. Thus, there can be important changes from year to year or from day to day depending upon rather small variations in the upper air temperature or in the water temperature. H. REEBEL (2) has emphasized the importance of cold upper troughs as a destabilizing factor.

It might be pointed out that the figures 2 and 3 are computed under the assumption that there is no zonal temperature gradient at the 300 mb level. This is certainly not true, but the zonal variations of the temperature in the upper atmosphere are not likely to introduce any essential changes in our picture of the instability distribution.

The maps in fig. 2 and 3 give a good indication of those regions in which the vertical instability, necessary for formation of tropical hurricanes, is available. They also show *why no hurricanes can be expected over the eastern Atlantic and why the hurricanes, formed farther to the west, generally reach their greatest intensity over the West Indies and the Florida region.* Furthermore, the maps show *why there must be a pronounced seasonal variation of the frequency of hurricanes and why there can be practically no hurricanes during the cold season.* A hurricane, once formed in the region of the unstable stratification must start to weaken and fill when it moves out from the region of high water temperature.

According to all observations no hurricanes can be formed in the immediate vicinity of the Equator. Every hurricane represents an area of large cyclonic vorticity produced in connection with the convergence of air. That means that it is necessary to have an initial vorticity in the region of the hurricane formation. According to the vorticity theorem given by C.-G. ROSSBY (3) the individual change of the vorticity relative to the earth is, if we neglect the change in latitude, determined by the formula

$$(1) \quad \frac{d\zeta}{dt} = - (\zeta + 2 \omega \sin \varphi) \operatorname{div}_H \mathbf{V},$$

where ζ is the relative vorticity, ω the angular velocity of the earth's rotation, φ the latitude and $\operatorname{div}_H \mathbf{V}$ the horizontal divergence. In order to form a strong vortex in the area of the converging air it is necessary that

the Coriolis parameter $2\omega \sin \varphi$ exceeds a certain value because the pre-existing relative vorticity ζ cannot be very great.

Considering the conditions discussed above, it is possible to segregate the regions of the earth where hurricane formation can be expected. From the discussion of the surface temperature of the Atlantic Ocean and the temperature in the upper atmosphere as a function of latitude one can conclude that hurricanes can be formed only in the oceanic regions outside the vicinity of the Equator where the surface water has a temperature above $26\text{--}27^\circ\text{C}$.

In fig. 4 the principal hurricane paths on the earth according to H. BYERS (1) are indicated with arrows. In the same figure the isotherms of the surface water during the warmest season according to H. U. SVERDRUP, M. W. JOHNSON and R. H. FLEMING (5) are drawn. From the map we can clearly see that *all regions without hurricanes are characterized by relatively low water temperature*. Very characteristic is the entire area

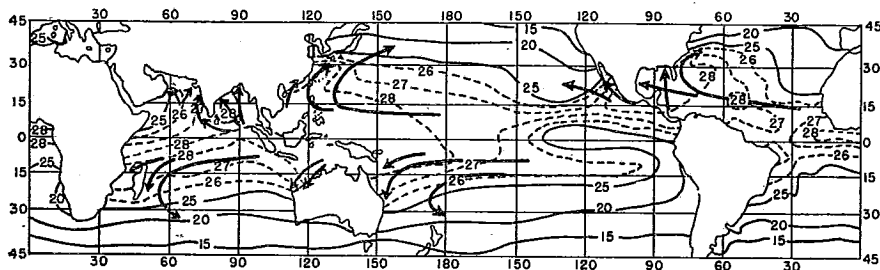


Fig. 4. Principal hurricane paths and surface water temperature during the warmest season.

of the southern Atlantic and eastern Pacific where the temperature is lower or just around the critical value. Over the entire eastern Pacific there is only one relatively small hurricane region, viz. along the west coast of Central America, and just here the temperature definitively exceeds the critical temperature ($26\text{--}27^\circ\text{C}$).

It might be pointed out that the arrows, indicating the principal paths of hurricanes, in some regions end in areas with lower temperature than the critical. This is quite natural because a hurricane, once formed, cannot immediately die, if it moves out from the region of high water temperature. Rather often the tropical hurricanes are transformed to extra-tropical cyclones and receive new energy when they invade the regions of preexisting fronts.

It is obvious that these two conditions for formation of hurricanes are necessary but not sufficient. There must at least be one condition more, because tropical hurricanes are rather rare phenomena in the hurricane regions. We are not going to discuss the other conditions here, but refer to a paper by H. RIEHL (2) concerning this problem.

It is obvious that the convective theory for formation of tropical cyclones includes that surface air with high potential wet-bulb temperature in a hurricane must be lifted to a considerably high level (around 10 km or more). The inner part of a fully developed hurricane must therefore be filled by moist air with a potential wet-bulb temperature corresponding to that of the surface layer. This warm moist air is quite different from the much warmer but dry air regularly found in the »eye» of a fully developed tropical hurricane.

In CuNb clouds lower air is lifted under unstable conditions. However, temperature observations in high CuNb clouds indicate that the air there usually is denser than what could be expected from the simple theory for the formation of convective clouds. According to recent theories the ascending air in a rising CuNb cloud mostly is strongly mixed with air from higher levels with a potentially lower temperature. In the case of a tropical cyclone the air, however, is lifted over such a large area that no stronger mixing with the surrounding air is possible. One can therefore conclude that in this case the inner part of the ascending air column must consist of potentially very warm surface air.¹

II. Vertical Structure of Hurricanes.

The severe hurricane which formed on September 11, 1947 east of Martinique in French West Indies and moved by September 17 over Florida and penetrated into the lower Mississippi valley on September 20, gives a good opportunity for a study of the upper temperature field in a hurricane. In fig. 5 the surface map for September 17, 06³⁰ GMT, and the path of the hurricane are given. At the time of the map the surface centre was about 955 mb deep over the sea east of the coast of Florida. The temperature distribution in the vicinity of the hurricane at the levels of 500, 400 and 300 mb is represented in fig. 6—8 where the isotherms are drawn with the aid of the radiosonde stations operating over the south-

¹ See E. J. SCHACHT (4).

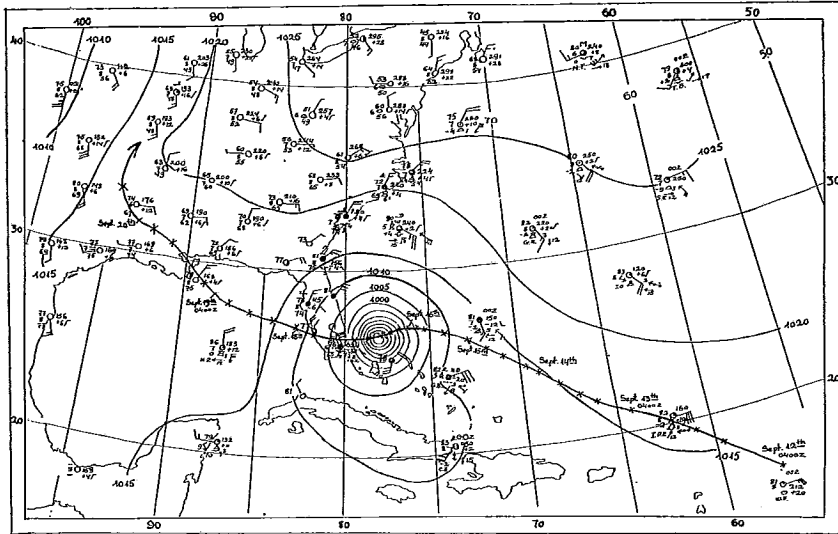


Fig. 5. Surface weather map for September 17 1947, 06³⁰ G.M.T. and the path of the hurricane between September 12 and 20, 1947. The centre of the hurricane at the time of the map is 956 mb deep.

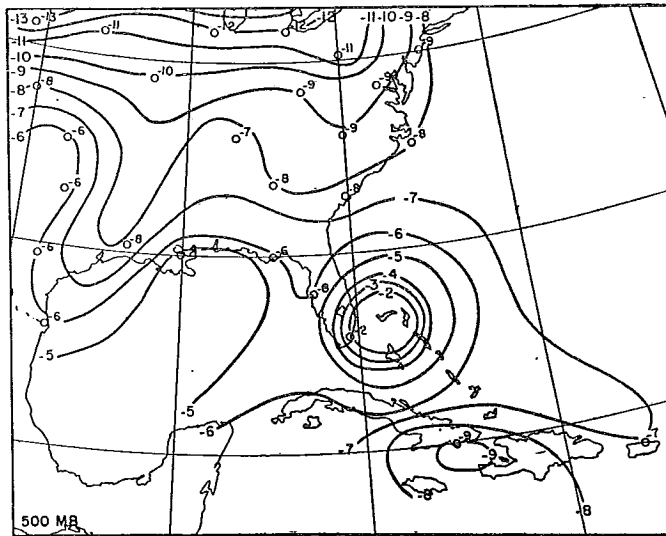


Fig. 6. Temperature at the 500 mb surface September 17 1947, 03 G.M.T.

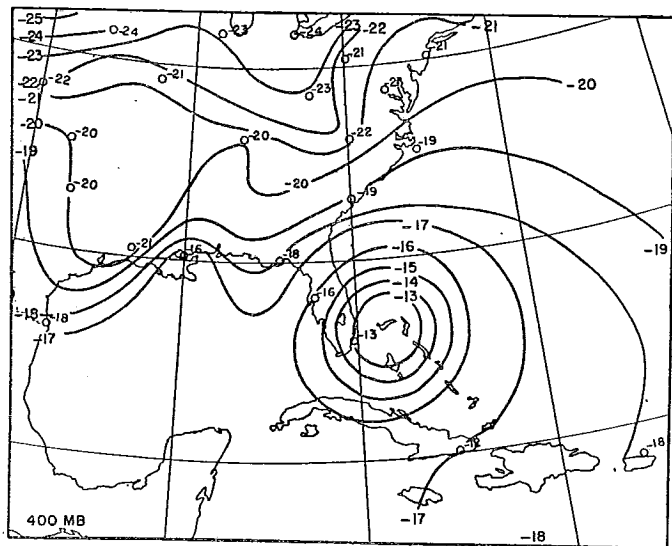


Fig. 7. Temperature at the 400 mb surface September 17 1947 03 G.M.T.

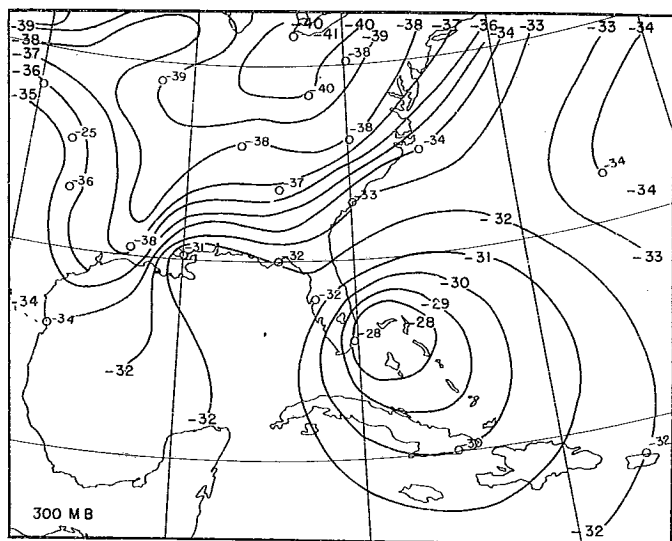


Fig. 8. Temperature at the 300 mb surface September 17 1947 03 G.M.T.

eastern part of the U.S. At all three levels the temperature in the hurricane area is higher than in the surroundings, the temperature difference being about 4° . Below the level of 500 mb the temperature difference decreases downward, so that at the level of the 700 mb surface the air in the cloud region of the hurricane has almost the same temperature as the surrounding air at the same level.

In order to get an average picture of the temperature distribution in the hurricane the mean temperature for the four days September 17—20 was computed at the standard isobaric surfaces 850, 700, 500, 400, 300 and 200 mb for every 100 km distance from the actual location of the hurricane centre. For this computation only observations at 0300 GMT were used. Further, the hurricane was regarded as a symmetric vortex, which obviously is correct only as a very rough approximation. Unfortunately no observations were available from a distance less than about 200 km from the centre.

For construction of a complete cross section through the storm it is necessary to have some data concerning the vertical temperature distribution in the central part (the «eye» of the hurricane). Because no observations were made in this important part it was necessary to use earlier observations and try to accommodate them to our special case. The most complete sounding through the eye of a Florida hurricane which was available was that of October 19, 1944, 0500 GMT in Tampa, Florida. This sounding was therefore used in order to give a picture of the whole temperature field in a cross section through the hurricane for the time September 17—20, 1947. However, the use of this important sounding from a different hurricane makes it impossible to treat the case, studied here, quantitatively.

The result of the computation is given in fig. 9 which then represents a cross section through a somewhat idealized, quite symmetric tropical hurricane. The dashed lines in fig. 9 are isotherms for every 5° C, the thin solid lines are isentropes and the heavy lines indicate the boundary between the central core of the storm (the eye) and the region of ascending moist air or the tropopause surfaces in the upper part of the figure.

This picture of the hurricane shows us a vortex with a warm core consisting of ascending moist air and inside it another still warmer, but much drier air originally produced by strong subsidence. Outside this warm and dry eye the warm and moist air together with the surrounding colder air represents a relatively strong solenoid field where a direct solenoidal circulation

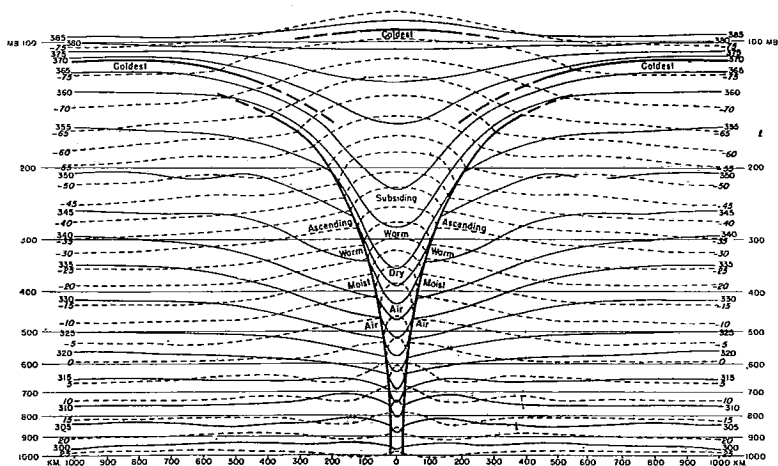


Fig. 9. Vertical cross section through the hurricane for the time September 17—20 1947. Dashed lines indicate temperature, thin solid lines potential temperature and heavy solid or dashed lines either the boundary of the «eye» of the hurricane or tropopause surfaces.

tends to intensify the vortex. The energy of this solenoid field is taken from the latent heat of the water vapour released through the condensation. The strong solenoid field in the innermost part of the storm at the boundary of the eye, however, is the result of an indirect circulation and therefore consumes kinetic energy. *The very high temperatures in the eye are the resulting effect of the tendency to establish a combined hydrostatic and geostrophic-cyclostrophic balance.*

It is interesting to compare the picture of a tropical cyclone with the corresponding picture of an extra-tropical cyclone of the symmetric type (without warm sector). In fig. 10 a west-east cross section through such a cyclone over the southwestern part of the U.S. for November 4, 1946 is reproduced. In the extra-tropical cyclone the core of the vortex is cold and the direct solenoidal circulation therefore tends to diminish the intensity of the vortex. However in the upper atmosphere (in the stratosphere) the central part is warmer than the surrounding air. *This upper warm core in the tropopause depression which is so characteristic of the extra-tropical cyclones corresponds to the warm eye of a tropical hurricane.* The boundary of the eye in fig. 9 can therefore be regarded as some kind of

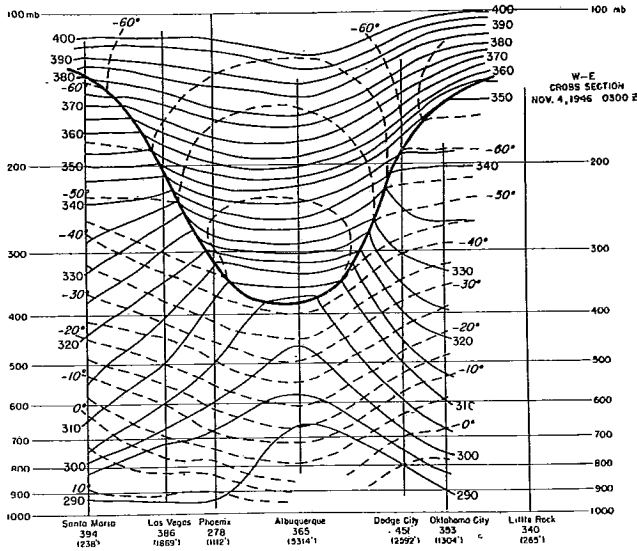


Fig. 10. Vertical W-E cross section through an extra-tropical cyclone with cold core over the south-western U.S. November 4 1946, 03x G.M.T. Dashed lines indicate temperature, solid thin lines potential temperature and heavy solid line the tropopause.

a new-formed lower tropopause which in cases of fully developed hurricanes sometimes reaches the earth's surface.

For the understanding of the source of energy of the tropical cyclones this difference in temperature distribution is essential. The symmetric extra-tropical cyclone is a vortex where the solenoid field is approximately balanced by the combined Coriolis and centrifugal force and where every direct solenoidal circulation counteracts the vortex. The tropical cyclone, on the contrary, is a vortex where the solenoid field also is approximately balanced by the combined Coriolis and centrifugal force, but where every direct solenoidal circulation tends to intensify the vortex.¹ *The tropical cyclone furnishes its own solenoid field as far as it remains over a region where the surface air has a higher potential wet-bulb temperature than the upper air up to a high level.* The tropical hurricane, once formed, therefore cannot die before traveling into a region where the surface temperature is low enough to change the cyclone into a cold vortex. Such a change happens

¹ Because of the difference in latitude and dimensions, the Coriolis force is more important in the extra-tropical cyclones; the centrifugal force in the tropical cyclones.

outside the hurricane regions previously discussed. It can be pointed out that over the oceans there must be an equilibrium between the kinetic energy destroyed by the friction and that produced through the direct solenoidal circulation. Therefore there must always be an upper limit for the depth of a hurricane which depends upon the instability energy of the atmosphere and the friction. Over land where the surface friction is much stronger than over the oceans no real hurricanes can exist for any great length of time.

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