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MID-TROPOSPHERIC VENTILATION AS A CONSTRAINT ON HURRICANE DEVELOPMENT AND MAINTENANCE

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As is well known, the primary energy source for hurricanes is latent heat of condensation. In the model picture, release of latent heat in an organized pattern leads to vertical expansion of the air columns in which the release occurs. This increases the potential energy, and raises the height of isobaric surfaces in the upper troposphere thus initiating outflow aloft toward colder areas and, in the manner of the simple heat engine, compensatory inflow near the ground toward the area of ascent. Gradually, the main body of the volume occupied by a storm should fill with air which has originated in the subcloud layer.

From this description it would seem that the vertical temperature structure within hurricanes should be governed by the sensible and latent heat content of air in the subcloud layer. Data from NHRP flights have confirmed that there is a tendency in this direction--i.e., the temperature increases inward from the outskirts of a storm across the rain area toward the eye at all heights. Nevertheless, temperatures observed at various altitudes and especially in the middle troposphere, both in mature and immature hurricanes, are noticeably colder in the bulk of the rain area than would be demanded if the lower atmosphere were composed entirely of air raised from the vicinity of the surface.

As an example, consider the temperature range found at different flight levels in hurricane Carrie, 1957 (fig. 1). In this diagram, temperatures for each level of reconnaissance have been entered for the eye, the point of maximum wind, and the outer rain area. At the time these data were obtained, Carrie was a mature small hurricane with well developed eye and central pressure of about 960 mb. Figure 2 shows similar temperature ranges for hurricane Daisy on September 25, 1958 when the storm was immature, and on September 27 when it was mature and very intense.

The relative coldness of hurricane rain areas in the middle troposphere may be ascribed to any one of three factors. First, the difficulty may be entirely instrumental, i.e., the temperature elements of the aircraft may either have had erroneous calibrations or the thermistor elements were measuring the temperature of the precipitate rather than air temperature. Second, the coldness could result at least partly from a real heat exchange between high and middle troposphere. Water at first freezes in the upper layers releasing latent heat of fusion. Later, as the frozen hydrometeors fall below the freezing level, heat is abstracted from the mid-tropospheric air at temperatures just above freezing to accomplish the melting process. Finally, it may be that the mid-tropospheric layer does not contain entirely air drawn from the surface but that it consists of a mixture of air partly drawn from below and partly advected laterally into the storm. From the known vertical temperature structure of the air outside the storm (fig. 3) and various temperature profiles through hurricanes, it is evident that such lateral advection would practically always import air cooler than that rising from the subcloud layer; hence the temperature of the mixture would be held to a value below that given by the moist adiabatic ascent of surface air.

The first factor cannot be fully evaluated at this time. But it can be stated that no evidence has been found of systematic error in aircraft thermometer readings. Temperatures measured by the aircraft have been in good agreement with temperatures at radiosonde stations overflown by the aircraft enroute to and from hurricanes. Moreover, the trends of temperature measured by three different elements -- two of the reverse flow type well protected from wetting by the precipitate -- were substantially in agreement both inside and outside of rain areas.

The second factor also cannot be completely evaluated as yet except to state that cooling through melting is not likely to account fully for the deviation of mid-tropospheric temperatures from those prescribed by the moist adiabatic ascent of surface air.

It is the main point of this paper to demonstrate that, irrespective of the possible importance of the effects just discussed, independent evidence exists confirming that lateral advection of mid tropospheric air from the outside toward the interior of a storm does occur. If the advection were zero, then the radial component of motion calculated in a polar coordinate system moving with the storm should vanish in the middle troposphere, since this layer is located between the primary ageostrophis inflow at low levels and the outflow at high levels. It is either an explicit or implicit assumption of most hurricane models that such is the case. Actually, however, the relative indraft did not vanish in the middle troposphere in the cases observed so far by NHRP Figure 4 shows the relative inflow components obtained at 14,000 ft in hurricane Carrie. We note a prominent movement of environmental air through the storm; air entered into the forward quadrants and exited through the rear quadrants. Thus, although the net ageostrophic circulation was very small at the level considered, the vortex was <u>ventilated</u> by invading colder masses of air and this, by lowering the temperature in the interior, reduced the efficiency of the primary mass circulation from the subcloud layer in maintaining the hurricane. Only near the eye wall itself is there evidence of temperatures corresponding to moist adiabatic ascent from the surface.

Figure 5 similarly reveals marked ventilation in hurricane Daisy on August 25, 1958. In this case, the ventilation took place crosswise from the right to the left semicircle - in this case northeast to southwest--across the hurricane which was moving northwestward about 4 kts. In contrast, Carrie--moving WNW at a rate of 12 kts--was ventilated from front to rear (northwest to southwest). On August 27, (fig. 6) Daisy had attained maximum intensity and was moving NNE about 8 kts. Ventilation occurred prominently from front to rear quadrants with pronounced outlfow occurring only in the right rear quadrant. The hurricane accelerated markedly on August 28. When intercepted by the NHRP aircraft on the day it was moving at a rate of 23 kts with strong ventilation from front to rear (fig. 7). It is of interest in this connection that maximum winds in Daisy exceeded 120 kts on August 27 but were barely above 100 kts on August 28.

The foregoing demonstrates that ventilation exists and may act as a constraint upon the hurricane heat engine. Quantitatively ventilation may be defined as $M(Q - Q_o)$ (cal/time), where M is the mass laterally entering a hurricane in the middle troposphere, Q the heat content of this air per unit mass at the periphery of the storm, and Q_o the heat content of the air in the subcloud layer. Maintenance and growth of a warm core will depend at least partly on the magnitude of the ventilation compared to the heat input by the primary mass circulation. Calculation of the effect for the hurricane vortex, similar to the computation for Bonefish Bay, fig. 8, during hurricane Daisy, is planned for all cases where suitable data from NHRP flights are available. This should bring out the extent to which this type of constraint limits growth rates and to what extent it can account for the fact that, given apparently similar conditions otherwise, some disturbances become hurricanes of great intensity, while others acquire only tropical storm or minimal hurricane strength.

A study of synoptic conditions related to varying rates of ventilation is also planned. At this time we merely wish to point out that the ventilation effect must be large if the basic current in which a hurricane is located, is strongly baroclinic in the middle troposphere. In such a current the suggested requirement for maximum storm growth (zero ventilation) can be realized only over a shallow vertical layer.

LEGENDS

Figure 1. Horizontal temperature gradients at various levels of

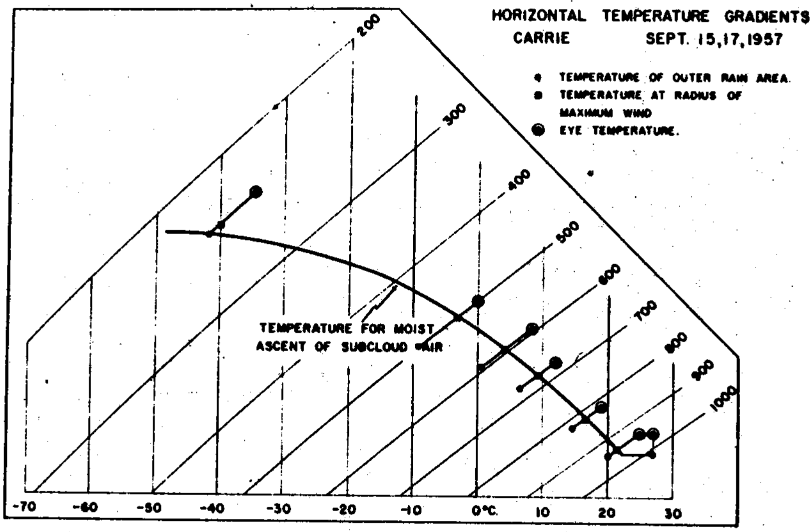

Fig. 1. Horizontal temperature gradients at various levels of reconnaissance in Hurricane Carrie, September 15, 17, 1957.

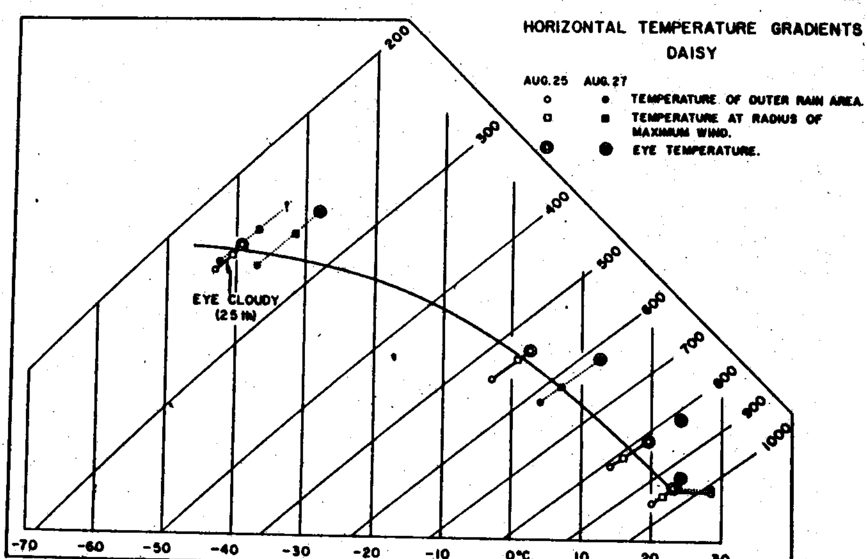

Fig. 2. Horizontal temperature gradients at various levels of reconnaissance in Hurricane Daisy, August 25th and 27th, 1958.

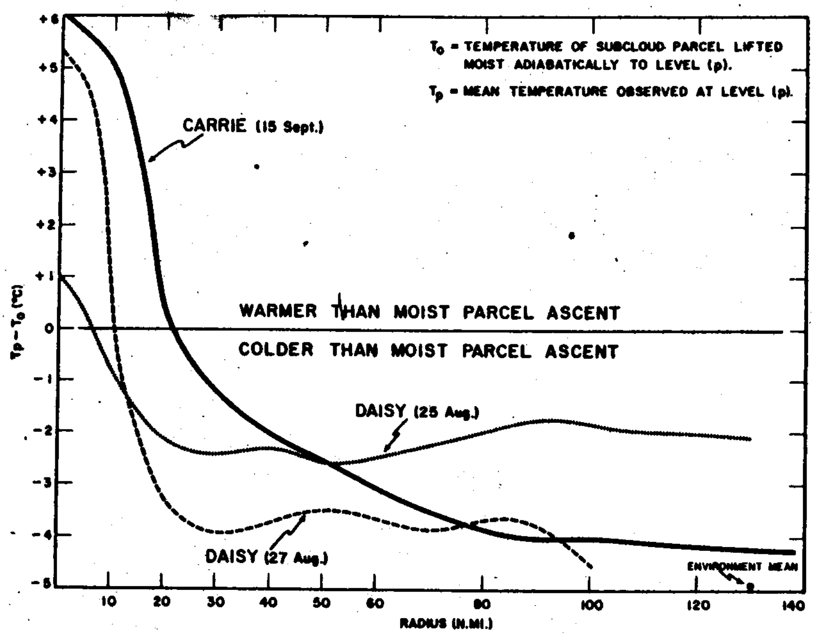

Fig. 3. Deviation of temperature in mid-troposphere from that of air which ascends moist adiabatically from the subcloud layer to the reference level.

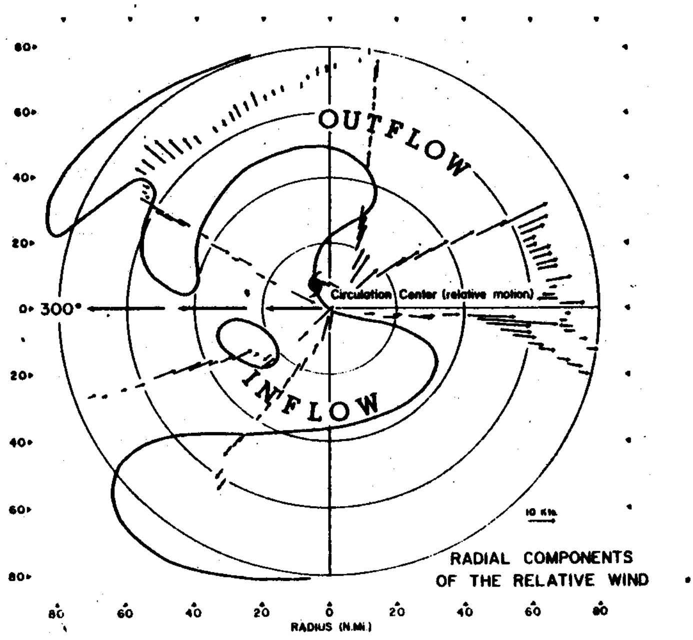

Fig. 4. Mid-tropospheric ventilation, Hurricane Carrie, September 15, 1957. Radial components are for winds relative to the moving center.

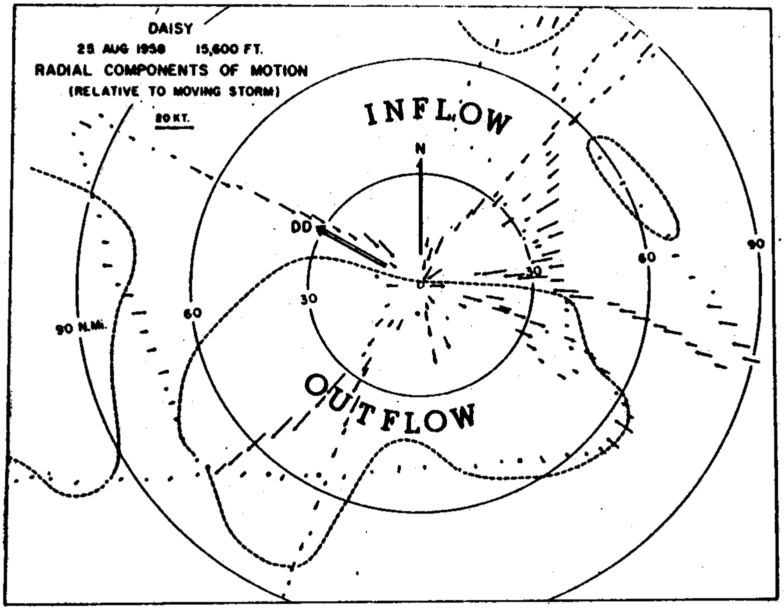

Fig. 5. Mid-tropospheric ventilation, Hurricane Daisy, August 25, 1958. Radial components are for winds relative to the moving center.

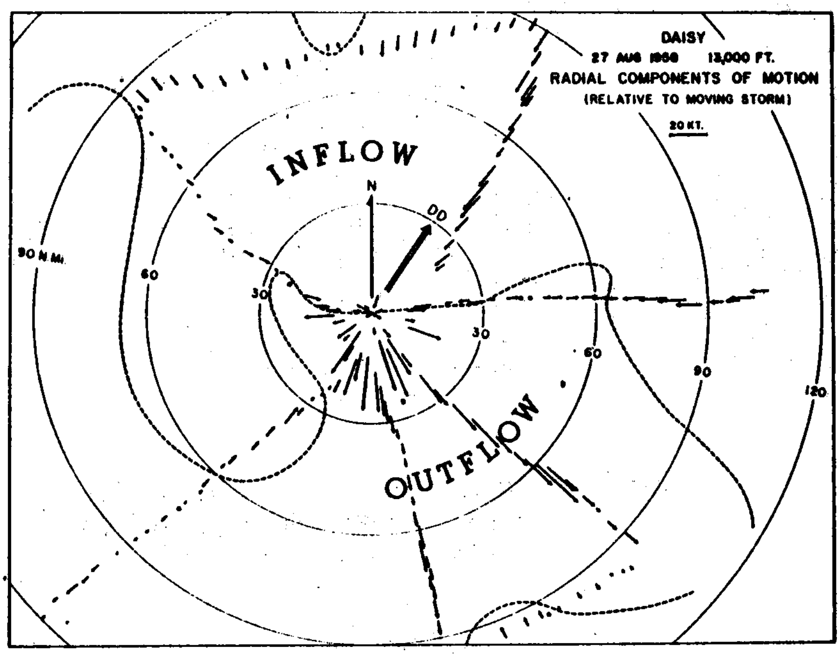

Fig. 6. Mid-tropospheric ventilation, Hurricane Daisy, August 27, 1958. Radial components are for winds relative to the moving center.

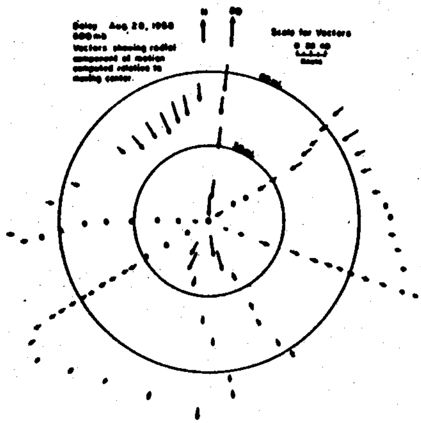

Fig. 7. Mid-tropospheric ventilation, Hurricane Daisy, August 28, 1958 Radial components are for winds relative to the moving center.

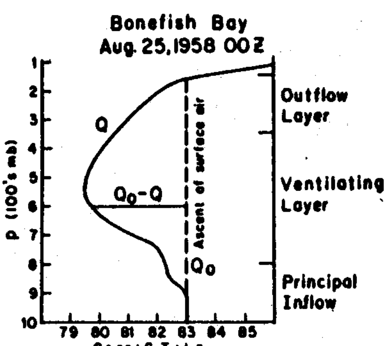

Fig. 8. Ventilation computation for Bonefish Bay during Hurricane Daisy, August 25, 1958.