NOAA TM ERL NHRL-99

# NOAA Technical Memorandum ERL NHRL-99

**U.S. DEPARTMENT OF COMMERCE**
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Environmental Research Laboratories

# On the Role of the Organizational Period in the NHRL Circularly Symmetric Hurricane Model

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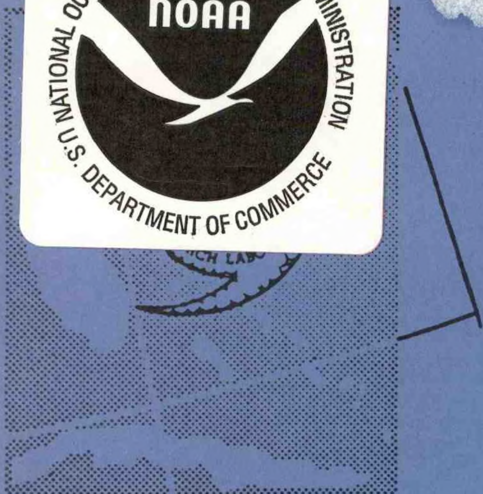

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Environmental Research Laboratories

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# ON THE ROLE OF THE ORGANIZATIONAL PERIOD IN THE NHRL CIRCULARLY SYMMETRIC HURRICANE MODEL

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March 1972

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# ON THE ROLE OF THE ORGANIZATIONAL PERIOD IN THE NHRL CIRCULARLY SYMMETRIC HURRICANE MODEL

Michael S. Moss and Stanley L. Rosenthal

The NHRL seven-level, circularly symmetric hurricane model is used in an attempt to ascertain the processes by which a weak tropical cyclone undergoes rapid development into a hurricane. Experimental results reveal that rapid development is primarily a manifestation of the formation of a deep moist layer.

## 1. INTRODUCTION

Numerous investigations (e.g., Riehl, 1954) have revealed that an incipient, relatively weak tropical cyclone must undergo a period of organization before rapid development into a hurricane. Due to sparse and uneven distributions of data over the tropical oceans, it has been difficult to determine the vortex structure changes that occur during this time and that render a vortex unstable. By controlled experimentation with numerical models, we may perhaps obtain a better understanding of this problem. It should be stressed that these models are highly idealized theoretical tools, and only very general qualitative comparisons can be made with real hurricanes. Therefore, the model results presented in this paper are tentative and represent some sort of "average" or "typical" hurricane.

The model used is the National Hurricane Research Laboratory (NHRL), seven-level, circularly symmetric hurricane model (Rosenthal, 1970). The model base state temperatures, potential temperatures, and relative humidities are nearly equal to those of the mean hurricane season (Hebert and Jordan, 1959) and are listed in table 1.

*Table 1. Base state values of height, pressure, temperature, potential temperature, and relative humidity .*

| Level | Height (m) | $\overline{p}$ (mb) | $\overline{T}$ (°K) | $\overline{\theta}$ (°K) | Relative Humidity (%) |
|---|---|---|---|---|---|
| 1 | 0 | 1015.0 | 301.3 | 300 | 90 |
| 2 | 1054 | 900.4 | 294.1 | 303 | 90 |
| 3 | 3187 | 699.4 | 282.6 | 313 | 54 |
| 4 | 5898 | 499.2 | 266.5 | 325 | 44 |
| 5 | 9697 | 299.2 | 240.8 | 340 | 30 |
| 6 | 12423 | 199.5 | 218.9 | 347 | 30 |
| 7 | 16621 | 101.1 | 203.1 | 391 | 30 |

The initial temperature field is specified by

$$\overline{T}_{i,j} = \overline{T}_i + T_* \left\{\cos\left(\frac{\pi}{\hat{r}}\right) r_j + 1\right\} \sin\left(\frac{\pi}{z_7}\right) z_i \ , \tag{1}$$

where i and j are the height and radial indices, respectively, $\overline{T}_i$ is the base state temperature, $T_* = 0.16°K$, $\hat{r} = 440$ km (the radial limit of the computational domain), and $z_7$ is the height of level seven. The initial pressure at level seven is taken to be the standard, base state value (table 1), and the hydrostatic equation is integrated downward to obtain the remainder of the initial pressure field. The gradient wind equation is then solved to obtain the initial tangential wind while the radial and vertical motions are initially zero. The initial specific humidity is horizontally uniform and equal to that of the base state.

The equations of motion and the thermodynamic equation are, respectively,

$$\frac{\partial M}{\partial t} = -u \frac{\partial M}{\partial r} - w \frac{\partial M}{\partial z} - fru + \frac{1}{\bar{\rho}} \frac{\partial}{\partial z} (\bar{\rho} K_Z \frac{\partial M}{\partial z})$$

$$+ \frac{K_H}{r} \frac{\partial}{\partial r} \left\{ r^3 \frac{\partial}{\partial r} (\frac{v}{r}) \right\}, \tag{2}$$

$$\frac{\partial u}{\partial t} = -u \frac{\partial u}{\partial r} - w \frac{\partial u}{\partial z} + \frac{M}{r} (f + \frac{M}{r^2}) - \theta \frac{\partial \phi}{\partial r} + \frac{1}{\bar{\rho}} \frac{\partial}{\partial z} (\bar{\rho} K_Z \frac{\partial u}{\partial z})$$

$$+ \frac{K_H}{r^2} \frac{\partial}{\partial r} \left\{ r^3 \frac{\partial}{\partial r} (\frac{u}{r}) \right\}, \tag{3}$$

and

$$\frac{\partial \theta}{\partial t} = -u \frac{\partial \theta}{\partial r} - w \frac{\partial \theta}{\partial z} + \frac{C_p}{\phi} \left\{ \frac{K_H}{r} \frac{\partial}{\partial r} (r \frac{\partial \theta}{\partial r}) + \frac{1}{\bar{\rho}} \frac{\partial}{\partial z} (\bar{\rho} K_Z \frac{\partial \theta}{\partial z}) \right\}$$

$$+ \frac{\dot{Q}}{\phi} . \tag{4}$$

Other pertinent equations include the hydrostatic equation,

$$\frac{\partial \phi}{\partial z} = - \frac{g}{\theta} , \tag{5}$$

a form of the continuity equation given by

$$\frac{\partial \bar{\rho} w}{\partial z} = - \frac{1}{r} \frac{\partial}{\partial r} (\bar{\rho} ru) , \tag{6}$$

with

$$\phi = C_p \left(\frac{p}{p_0}\right)^{R/C_p} , \tag{7}$$

and

$$\theta \phi = C_p T . \tag{8}$$

The symbols are as follows:

| | |
|---|---|
| $r$ | radius, |
| $z$ | height, |
| $t$ | time, |
| $u$ | radial velocity, |
| $v$ | tangential velocity, |
| $M = rv$ | relative angular momentum, |
| $w$ | vertical velocity, |
| $f$ | Coriolis parameter, |
| $\overline{\rho} = \overline{\rho}(z)$ | climatological density, |
| $K_Z$ | kinematic coefficient of eddy viscosity and diffusivity for vertical mixing, |
| $K_H$ | kinematic coefficient of eddy viscosity and diffusivity for lateral mixing, |
| $\theta$ | potential temperature, |
| $\dot{Q}$ | diabatic heating per unit time and mass produced by latent heat of condensation, |
| $c_p$ | specific heat capacity at constant pressure for dry air, |
| $R$ | universal gas constant for dry air, |
| $g$ | acceleration of gravity, |
| $p$ | pressure, |
| $p_0$ | 1000 mb, and |
| $T$ | temperature. |

The local tendency of specific humidity is explicitly governed by the water vapor equation,

$$\bar{\rho}\,\frac{\partial q}{\partial t} = -\,\frac{1}{r}\,\frac{\partial \bar{\rho} uqr}{\partial r} - \frac{\partial \bar{\rho} wq}{\partial z} + \bar{\rho}\,\frac{K_H}{r}\,\frac{\partial}{\partial r}\,(r\,\frac{\partial q}{\partial r})$$

$$+\ \frac{\partial}{\partial z}\,(\bar{\rho} K_Z\,\frac{\partial q}{\partial z})\,, \qquad (9)$$

where q is the specific humidity.

The second and fourth terms on the right side of (9) represent vertical redistributions of the vapor in a column (neglecting transfers through the vertical boundaries of the column), and the first and third terms represent horizontal flux and diffusion of vapor, respectively, into the column. If there exists horizontal convergence of water vapor into a layer, i.e.,

$$\int_{z_i}^{z_{i+1}} \left\{-\,\frac{1}{r}\,\frac{\partial}{\partial r}\,(uqr) + \frac{K_H}{r}\,\frac{\partial}{\partial r}\,(r\,\frac{\partial q}{\partial r})\right\} dz > 0\,, \qquad (10)$$

and parcel ascent from the level $z_i$ is conditionally unstable, convection will originate from that layer.

The distinguishing aspect of this model is the parametric representation of the diabatic heating ($\dot{Q}$) produced by organized systems of cumulonimbi. This parameterization is achieved by a convective adjustment that may be generalized as follows. Suppose that existing cumulonimbi transport upward and condense a certain amount of water vapor in some period of time. Part of this condensate will be reevaporated and enrich the macroscale humidity as clouds dissipate. The remaining condensate falls as rain, and thus provides latent heat to the macroscale system. The reader is referred to Rosenthal (1970) for a detailed explanation of the convective adjustment.

The model storm's evolution is shown in figure 1, on which the maximum surface wind speed is plotted against time. During the "organizational period" (from 0 to 168 hours), a wind minimum occurs at 120 hours. From 120 to 192 hours, a gradual increase in intensity is observed and rapid development commences at 192 hours. By restoring, at selected times, a dependent variable to its initial value we may isolate the relative importance of its variations during the period involved. Therefore, experiments were performed in which at hour 120 or at hour 192 of the model storm the tangential wind, radial wind, potential temperature, and specific humidity were each replaced by their respective initial values. Table 2 lists the various experiments.

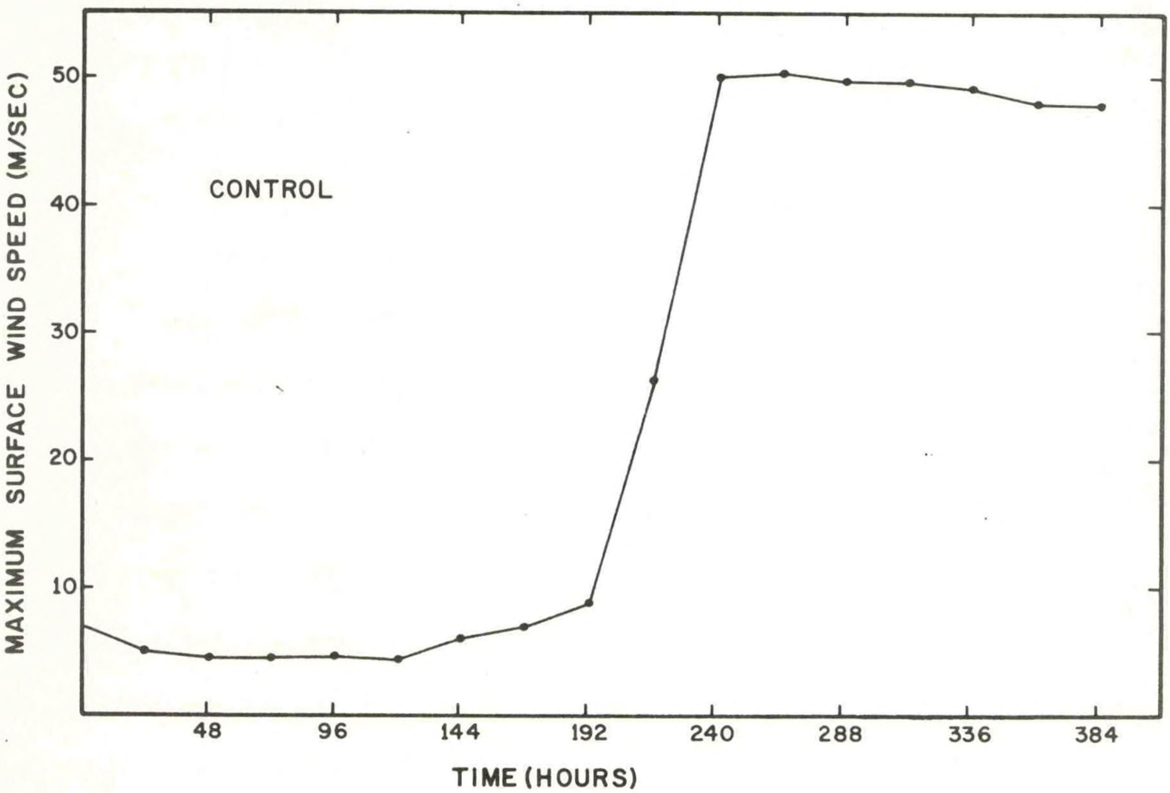


*Figure 1. Maximum surface wind as a function of time for the control experiment.*

*Table 2. Experiments (G-series) in which changes in the data field are introduced at 120 hours of the control experiment.*

| Exp.* | Tangential Wind | Radial Wind | Potential Temperature | Specific Humidity |
|---|---|---|---|---|
| G1 | restored to initial values | no change | no change | no change |
| G2 | no change | restored to initial values | Do. | Do. |
| G3 | Do. | no change | restored to initial values | Do. |
| G4 | Do. | Do. | no change | restored to initial values |
| G4A | Do. | Do. | Do. | restored to initial values above boundary layer (>1054 m); no change in boundary layer |

*The H-series experiments are the same, except that the changes are introduced at 192 hours of the control experiment.

## 2. EXPERIMENTS ALTERING TANGENTIAL WIND, RADIAL WIND, AND POTENTIAL TEMPERATURE

Experiments G1 and H1 (fig. 2) reveal that replacing the tangential winds with initial values alters the rate of development but not the ultimate intensity of the model storm. Since the initial tangential winds are greater than those at 120 hours, frictional convergence of water vapor is increased (Rosenthal, 1971; Rosenthal and Moss, 1971) in experiment G1, and development is more rapid than in the control. For experiment H1, the delayed development is explicable by the reverse of the arguments cited above.

These results are consistent with previous calculations. An experiment in which the initial winds were twice those of the control (Rosenthal, 1971) revealed that the vortex development was characterized by a much shorter organizational period but with only a small deviation in peak intensity from the control. Anthes et al. (1971) cite similar results obtained from other models.

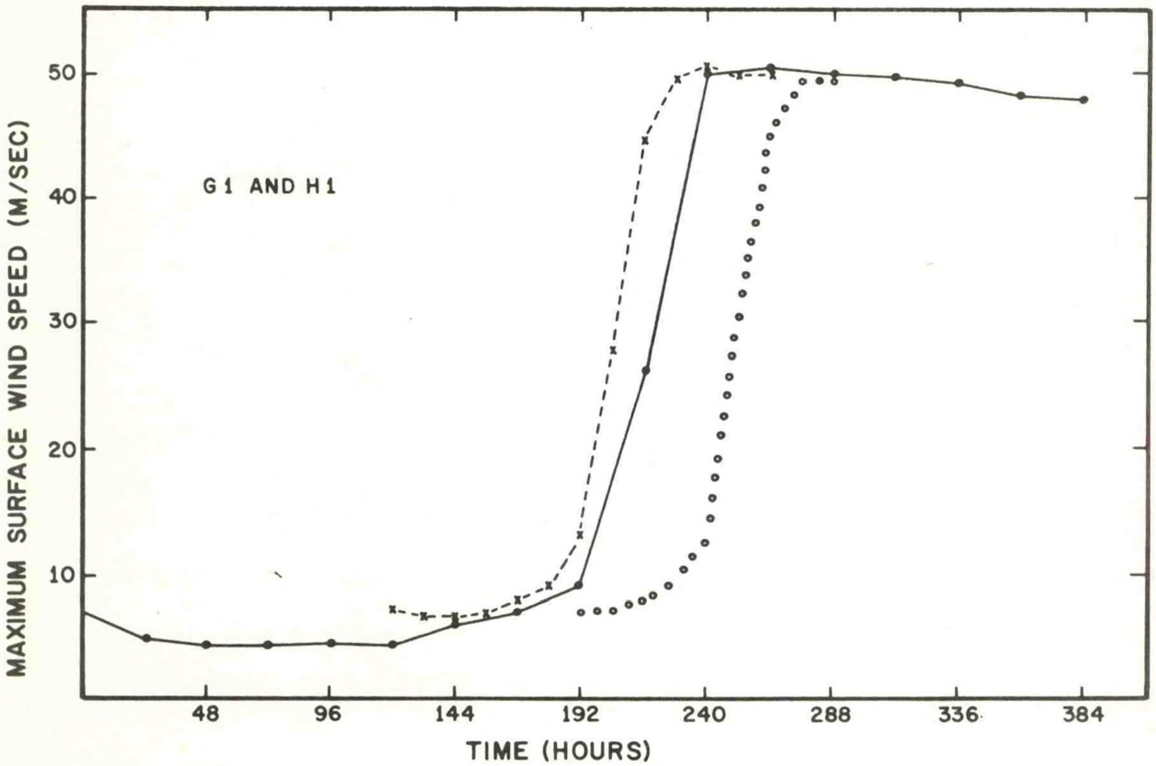


*Figure 2. Maximum surface wind as a function of time. Control data are solid lines, experiment G1 dashed lines, and experiment H1 circles.*

The absence of transverse circulations at the start of experiments G2 and H2 does not significantly disrupt the storm's development (fig. 3). The generation of frictional inflow occurs very rapidly and is primarily determined by the strength of the tangential wind (Rosenthal and Moss, 1971). The mechanism by which this occurs may be demonstrated as follows.

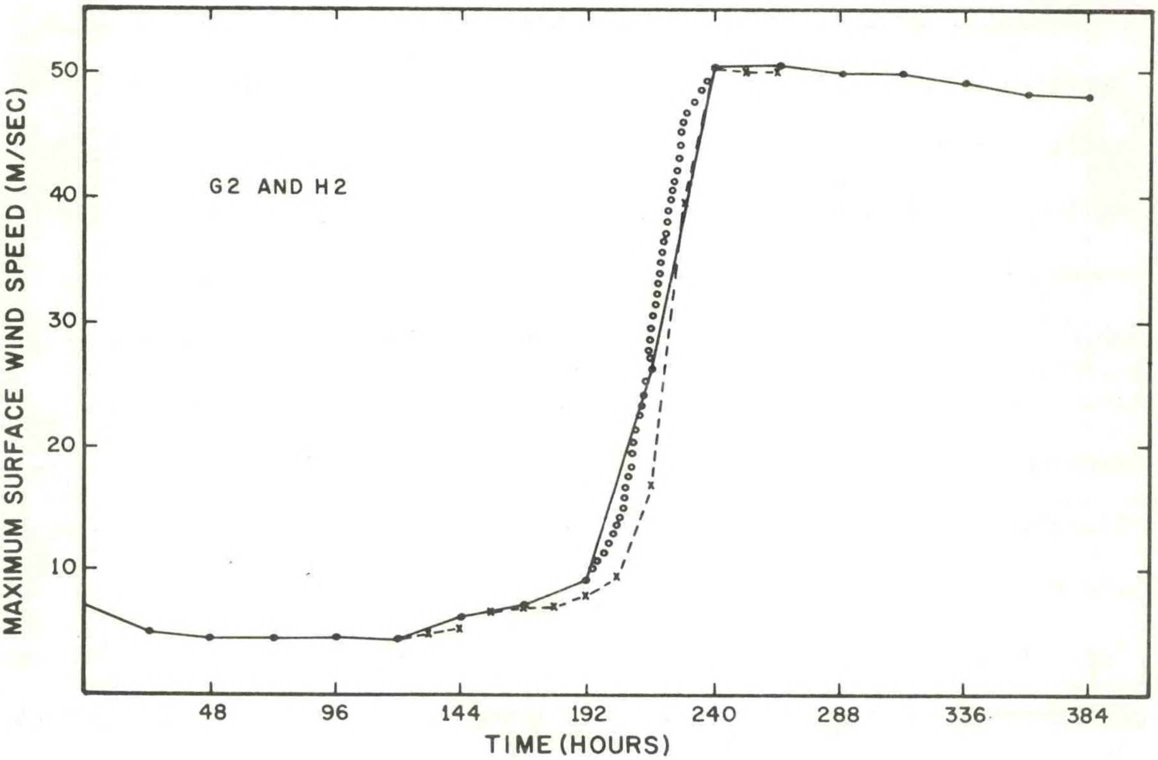


*Figure 3. Maximum surface wind as a function of time. Control data are solid lines, experiment G2 dashed lines, and experiment H2 circles.*

In the absence of radial motion, (2) and (3) at the bottom surface become[1]

$$\frac{\partial M}{\partial t} = \frac{1}{\bar{\rho}} \frac{\partial}{\partial z} (\bar{\rho} K_Z \frac{\partial M}{\partial z}) + \frac{K_H}{r} \frac{\partial}{\partial r} \left\{ r^3 \frac{\partial}{\partial r} (\frac{M}{r^2}) \right\}, \tag{11}$$

and

$$\frac{\partial u}{\partial t} = \frac{M}{r} (f + \frac{M}{r^2}) - \theta \frac{\partial \phi}{\partial r} . \tag{12}$$

Surface drag in (11) quickly produces significant negative angular momentum tendencies, and the rotational forces in (12) are, therefore, decreased. In the model, therefore, this tends to produce $\frac{\partial u}{\partial t} < 0$, and radial inflow is established.[2] Qualitatively, through the neglect of inflow, we have increased the effect of surface drag on the angular momentum tendency, and this then allows inflow to redevelop quickly.

Experiments G3 and H3 reveal that slight alterations of the potential temperature do not result in significant modifications of the development of the hurricane (fig. 4).[3] The implication is that the changes in temperature configurations during the organizational period are not particularly important for the onset of rapid development. Yanai (1964) observed that development of a strong warm-core in the upper troposphere occurred during the period of rapid intensification. Experiments G3 and H3 appear to be consistent with this observation.

[1]The vertical motion, w, is equal to zero at the lower boundary.

[2]The reader is referred to Rosenthal (1970) for an explanation of the computation of the surface pressure gradient force in the model.

[3]The initial vortex is generally a few degrees cooler than is the vortex when these experiments are started.

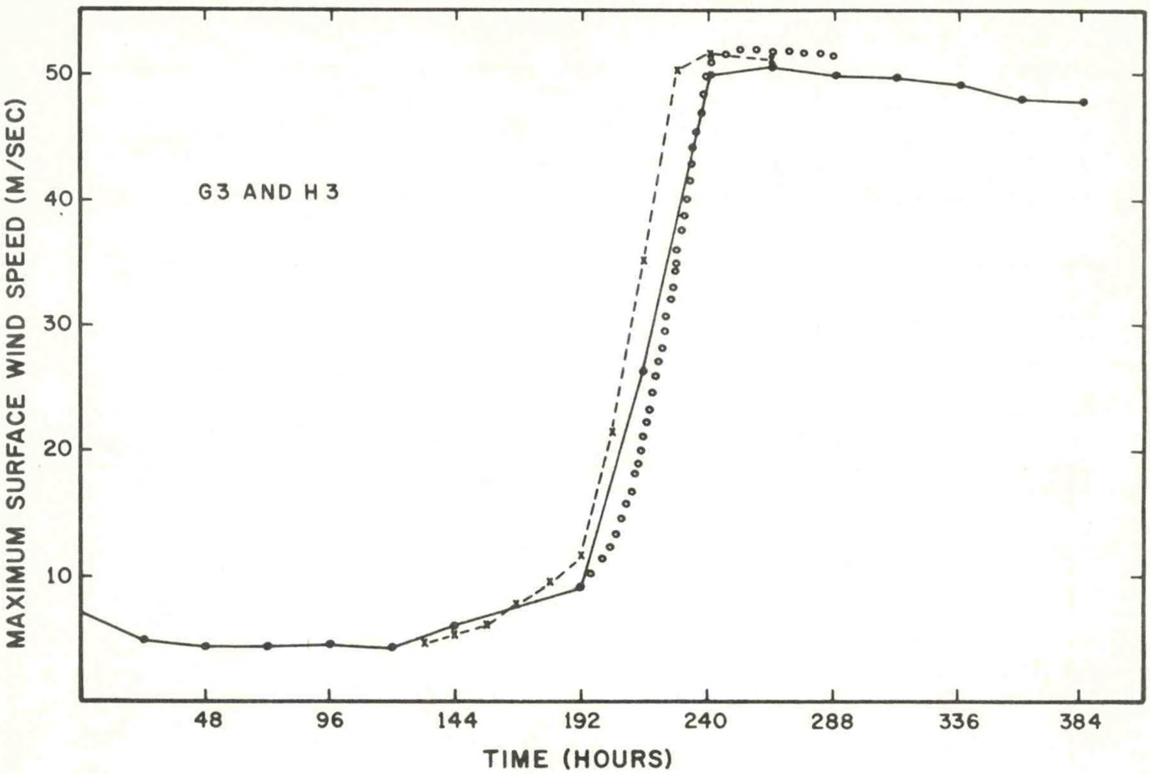


*Figure 4. Maximum surface wind as a function of time. Control data are solid lines, experiment G3 dashed lines, and experiment H3 circles.*

Although the temperatures in the upper troposphere are generally slightly decreased at the start of experiments G3 and H3, the partitioning of released latent heat between the lower and upper troposphere is also changed (see Rosenthal (1970) for details); therefore, relatively more heat is applied to the upper troposphere. This then tends to counteract the alterations in temperature imposed by the experimental procedure.

### 3. EXPERIMENTS ALTERING SPECIFIC HUMIDITY

Careful inspection of the control experiment during the organizational period shows that the changes in humidity are considerably more impressive than are the changes of other dependent variables. Figures 5, 6, and 7 illustrate the evolution of the distribution of relative humidity

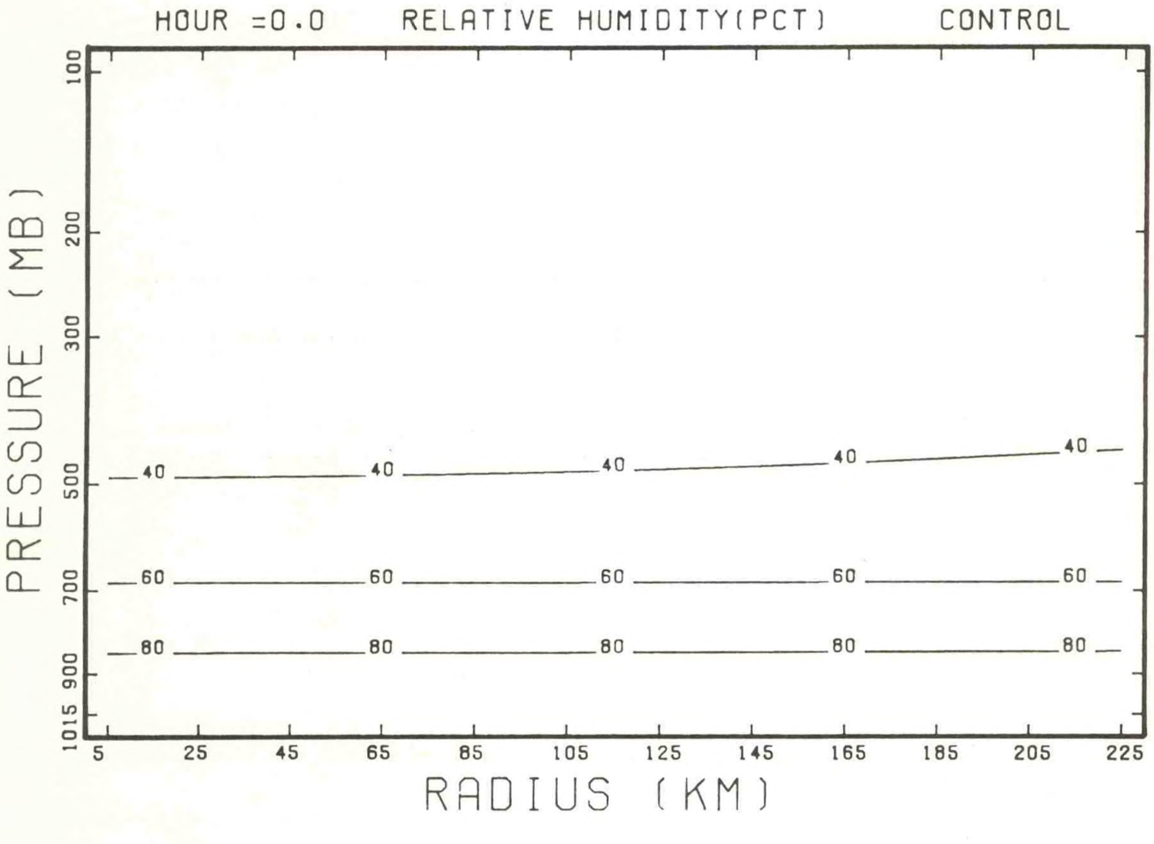


*Figure 5. Cross section of relative humidities at 0 hours of the control. Isohumes are in percent. (Ordinate values of pressure are assumed to correspond to the heights given in table 1, and are so scaled. This assumption is approximately valid during organization because the pressure changes at a constant height are minimal.)*

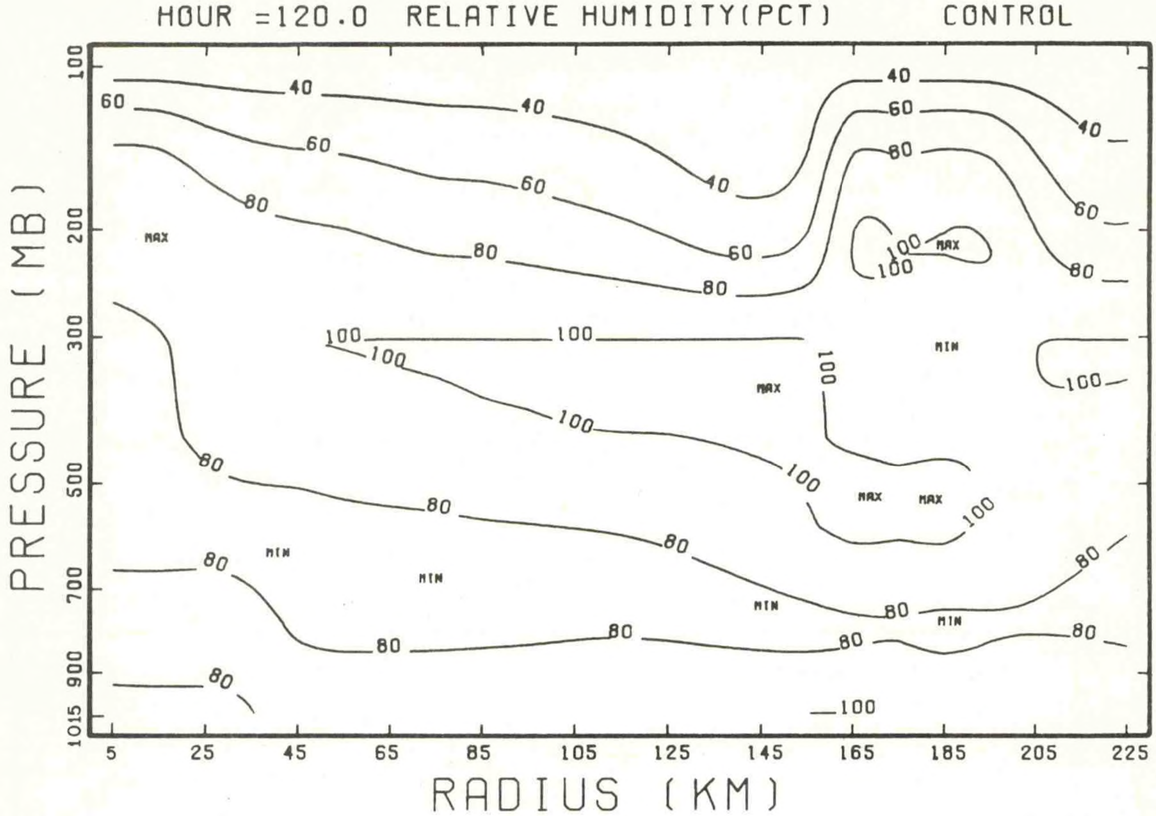


*Figure 6. Cross section of relative humidities at 120 hours of the control. Isohumes are in percent. (Ordinate labeling same as fig. 5.)*

for the control. Initially, the humidity profiles are nearly horizontally uniform.[4] At 120 hours, the depth of the moist layer has increased and

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[4]The initial (as compared with base state) relative humidities are calculated from the ratio of the horizontally uniform specific humidities to the saturation specific humidities derived from (1). This explains the small deviations from horizontal uniformity.

saturation (to be interpreted as stratus-type cloud) is evident in some regions of the middle troposphere. By 192 hours, the moisture shows further increases, and the middle tropsopheric region of saturation is more widespread. This sequence is consistent with Riehl's (1954) hypothesis that the principal role of the organizational period in real storms is to form a deep moist layer from an initial moisture distribution that is relatively dry aloft.

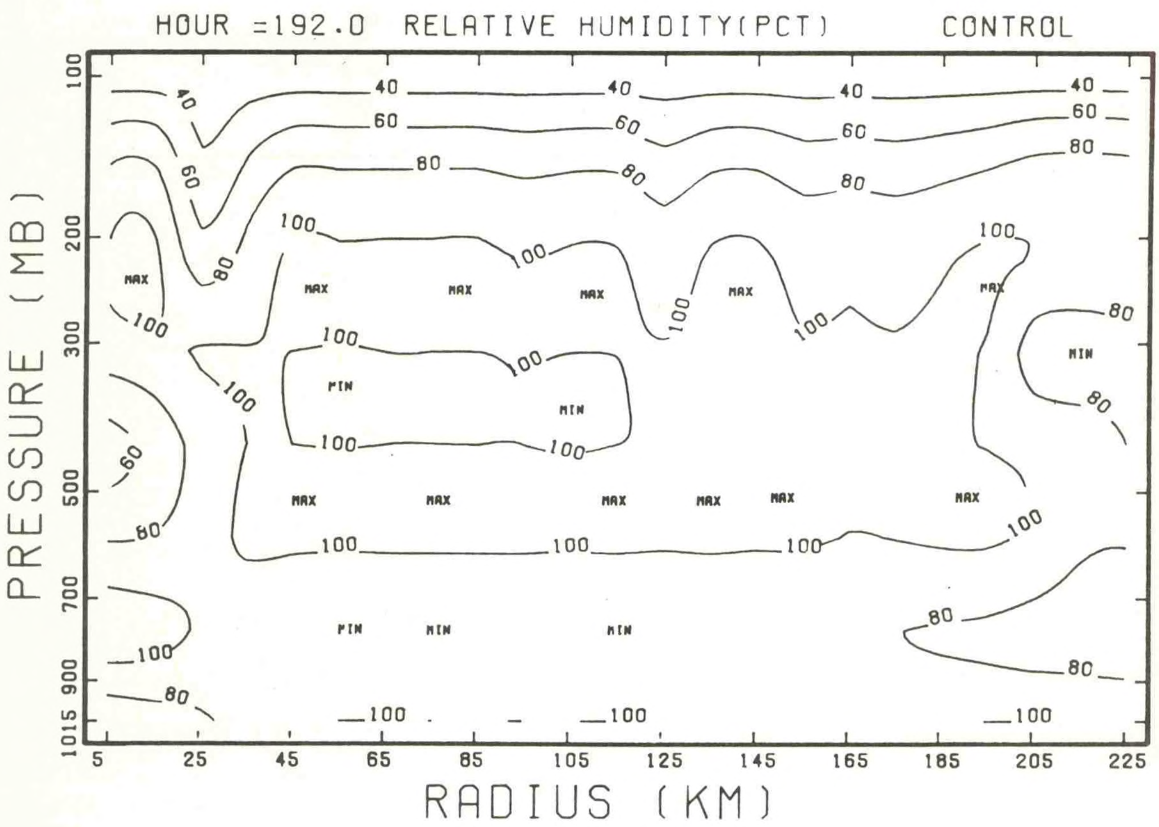


*Figure 7. Cross section of relative humidities at 192 hours of the control. Isohumes are in percent. (Ordinate labeling same as fig. 6.)*

When the specific humidity is restored to its initial value in experiments G4 and H4, there results a significant modification in the storm development (fig. 8). Experiments G4A and H4A (where the specific humidity is only altered above the boundary layer) reveal that the response of experiments G4 and H4 is due mainly to the deletion of moisture above the boundary layer (cf. figs. 8 and 9). Rosenthal (1970) found that when the initial relative humidity was 90 percent everywhere, the model storm developed more rapidly with only a very short organizational period.

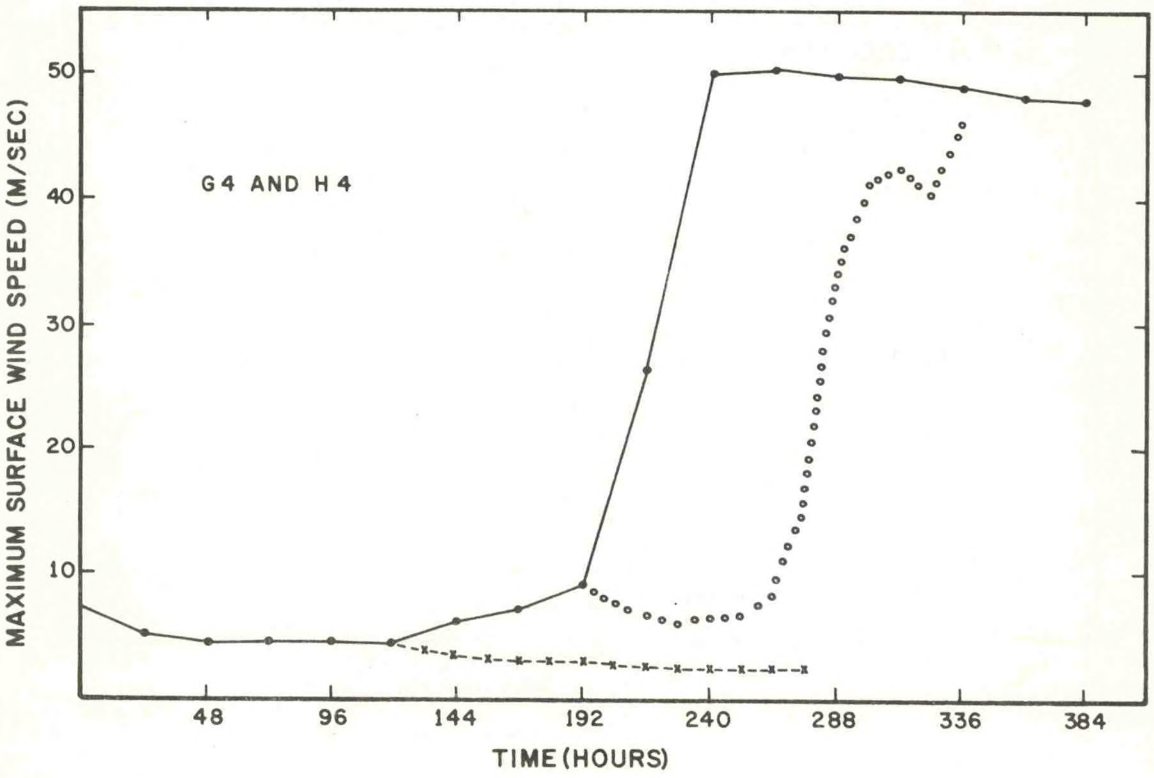


*Figure 8. Maximum surface wind as a function of time. Control data are solid lines, experiment G4 dashed lines, and experiment H4 circles.*

In the real atmosphere, the establishment of a deep moist layer during organization implies that cumulus clouds may entrain relatively moist air making their net condensation greater and their growth to cumulonimbus more likely. Although model clouds are undilute, the partitioning of condensate between precipitation and reevaporation in a convective column depends on the difference between the cloud and environmental humidities (Rosenthal, 1970). With a dry upper level

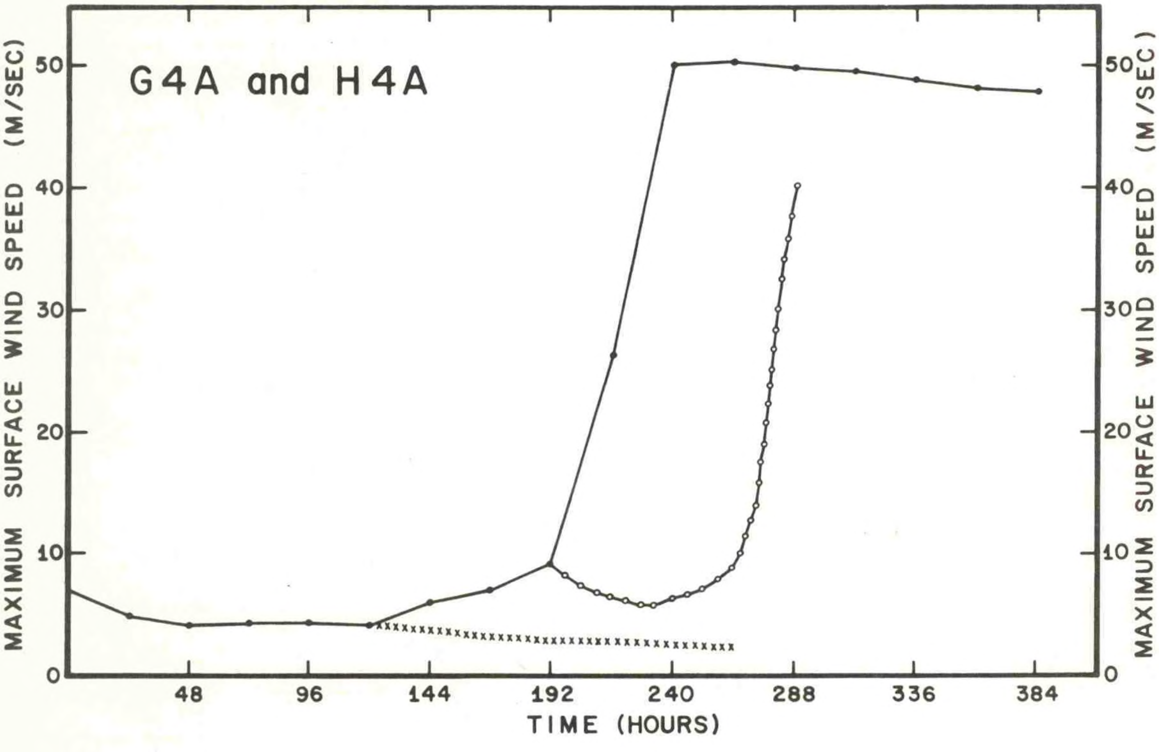


*Figure 9. Maximum surface wind as a function of time. Control data are solid lines, experiment G4A dashed lines, and experiment H4A circles.*

environment, a greater proportion of the condensate is reevaporated and less of the condensate is realized as rain (latent heat). The rainfall rates for the nondeveloping experiments are considerably less than the control (figures not shown), confirming that less latent heat is available to the model vortex in the absence of a deep moist layer.

At the start of experiment G4, a deep moist layer is lacking (fig. 10; note the similarity to fig. 5), and the tangential winds are

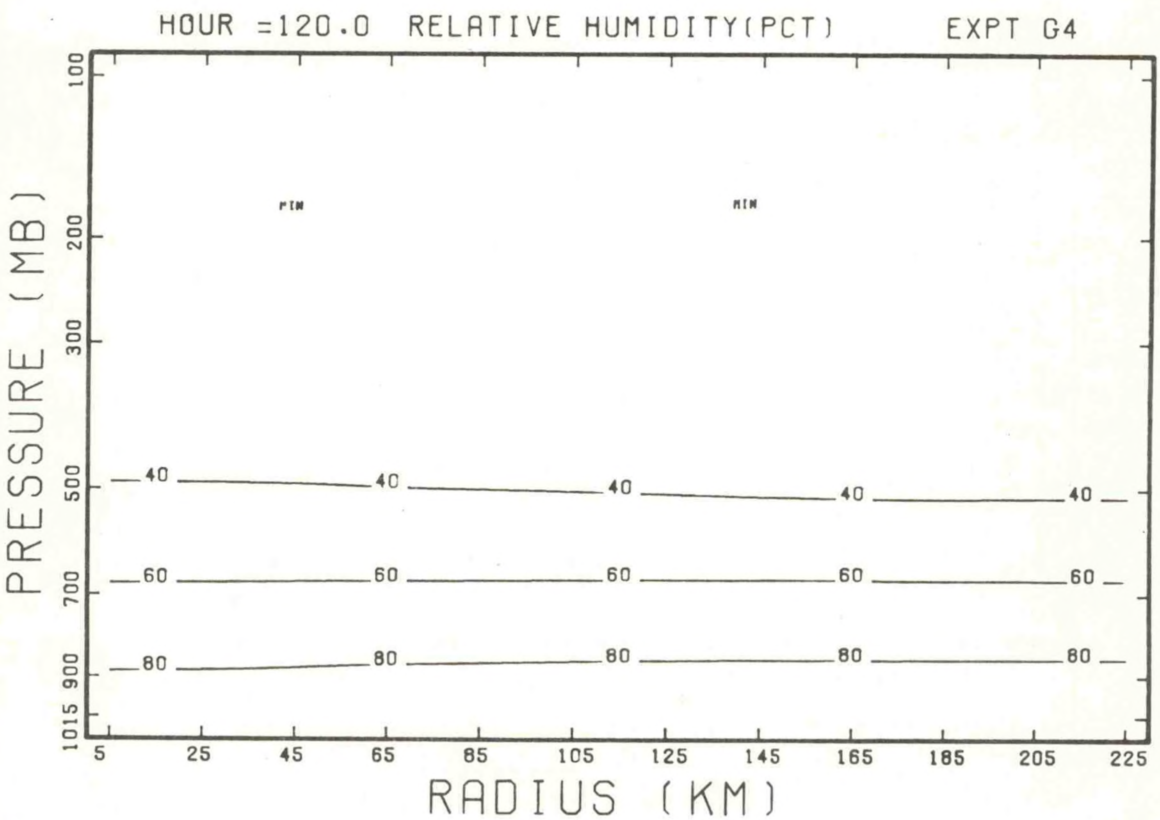


*Figure 10. Cross section of relative humidities at 192 hours of experiment G4. Isohumes are in percent. (Ordinate labeling same as fig. 5.)*

smaller than those of the control at the initial instant. Hence, the failure of the storm to develop during the time span of the experiment (6 days) is not surprising. A deep moist layer is also lacking at the start of experiment H4 (fig. 11). However, in this case, rapid development does occur. Here, the tangential wind is greater and frictional inflow is quickly produced. Root-mean-square (RMS) deviations of

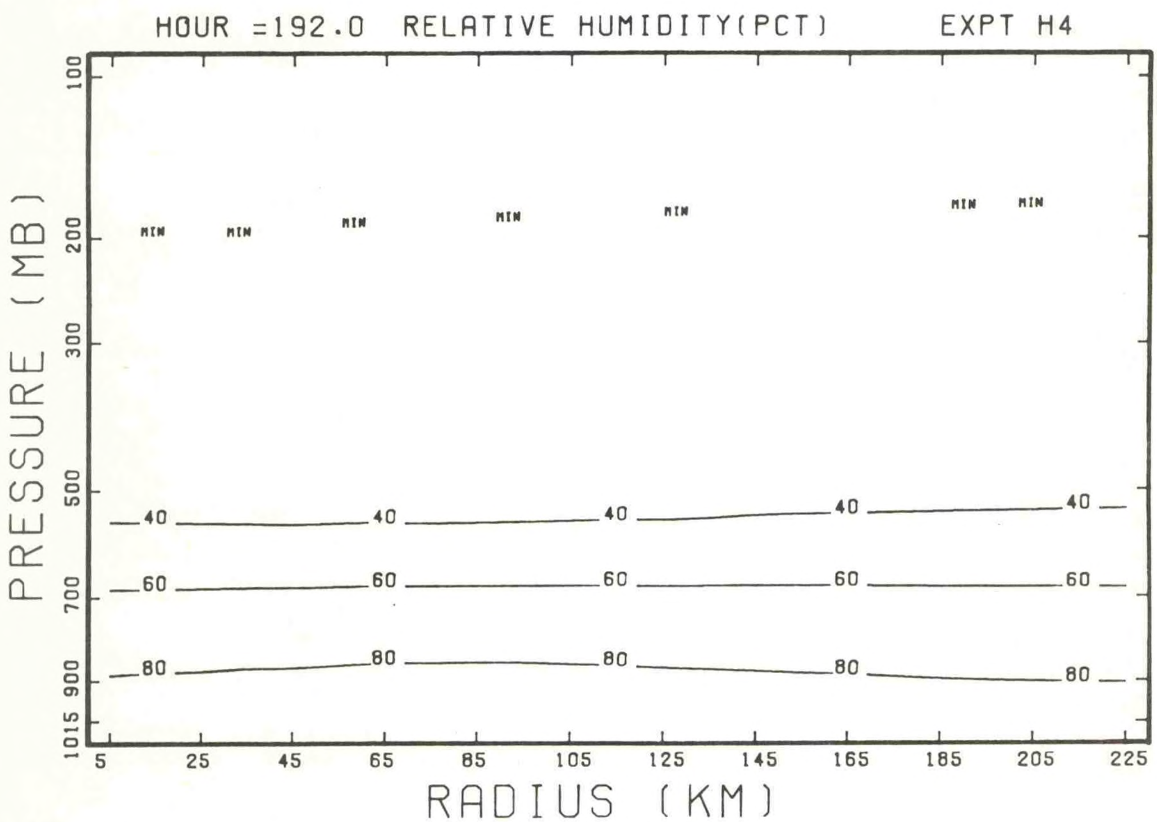


*Figure 11. Cross section of relative humidities at 192 hours of experiment H4. Isohumes are in percent. (Ordinate labeling same as fig. 5.)*

the relative humidity from the control at 192 hours and the maximum surface winds for experiment H4 are depicted in figure 12.[5] Rapid development roughly corresponds to a minimum in the humidity deviations, indicating that such development is coincident with the formation of a moisture field compatible with that of the control (at 192 hours).

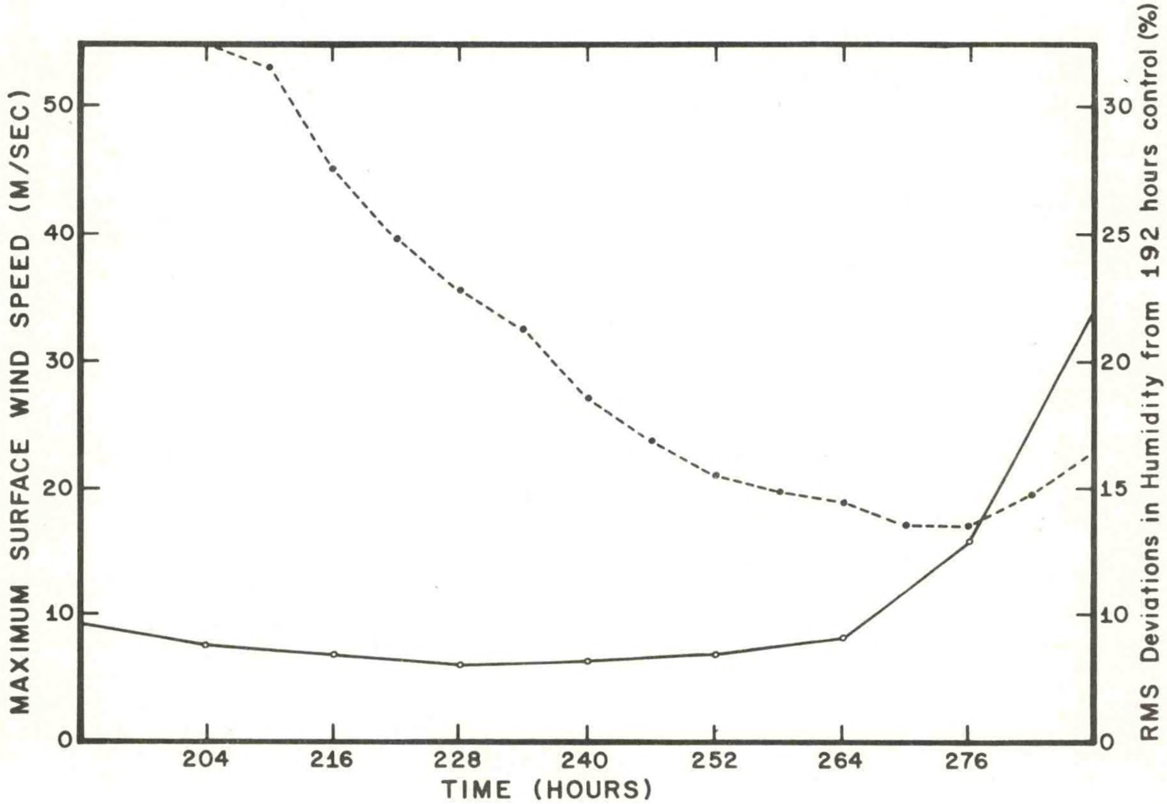


*Figure 12. Maximum surface wind and RMS relative humidity deviations from 192 hours of the control as a function of time for experiment H4. Maximum surface winds are shown by solid lines, and RMS deviations by dashed lines.*

[5]The initial boundary layer humidities are relatively moist (table 1). Therefore, the percent of humidity changes is very small throughout the storm's life cycle.

## 4. SUMMARY AND CONCLUSIONS

During the "organizational period" of the model hurricane, friction reduces the gradient winds at the surface to subgradient values. This induces low-level inflow that results in the horizontal convergence of water vapor and, therefore, to cumulus convection. The condensate in these cumuli is largely evaporated into the dry upper level environment. There is little rain, but the macroscale humidity increases. Eventually, the troposphere becomes extremely moist and large amounts of latent heat are imparted to the upper troposphere, thus inducing the development of a warm core. Surface pressures are decreased, especially towards the storm center where the upper level heating is most pronounced. The horizontal convergence of water vapor is concomitantly increased, implying more vigorous convection that ultimately results in rapid development.

The numerical experiments discussed here indicate that rapid development can only occur after the deep moist layer has been produced, and that the changes that occur to other meteorological variables during the organizational period are important only to the degree that they feed back on the moisture field. A more intense vortex results in more rapid development, because the horizontal convergence of water vapor develops more rapidly; therefore, less time is required to create large moisture contents to great heights.

## 5. ACKNOWLEDGMENTS

Computations were performed at the NOAA computer complex, Suitland, Maryland. Access to the computer facility is via a terminal located at NHRL in Miami, Florida.

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