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Model hurricane formation in the presence of a basic state current[1]

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RESUMEN

Simulaciones numéricas con el modelo de área limitada del Laboratorio de Investigaciones Navales se llevaron al cabo, empleando las condiciones iniciales deducidas del análisis reticulado compuesto para racimos nubosos y depresión Atlántica pre-huracán de la Universidad del Estado de Colorado. Para cada tipo de perturbación las simulaciones fueron hechas con condiciones iniciales consistentes en el viento medio zonal sobrepuesto a la componente axi-simétirica del flujo alrededor del centro vorticoso. Estas simulaciones fueron comparadas con otras en que las condiciones iniciales fueron especificadas a partir del análisis reticulado en su plena complejidad tridimensional.

Cuando las asimetrías completas se retuvieron en las condiciones iniciales, tanto el racimo nuboso prehuracanado como la depresión prehuracanada se desarrollaron en un huracán maduro en las integraciones numéricas. Cuando las asimetrías, con excepción de las asociadas con el viento zonal medio, no estuvieron presentes en las condiciones iniciales, la depresión prehuracanada no mostró desarrollo significativo durante las 60 horas de integración, después de las cuales se intensificó ligeramente y el racimo nuboso prehuracanado se convirtió en una depresión débil.

Asociadas con las asimetrías ondulatorias en los campos iniciales de viento y temperatura, hay flujos torbellinarios de gran escala de momento angular y calor. Los datos revelan que éstos están organizados de tal manera como para inducir una circulación radial secundaria que recoge humedad a medida que gira hacia adentro sobre un gran trecho de océano y bombea aire seco hacia afuera en la troposfera superior y en la baja estratosfera. Postulamos que es esta circulación, la que inicialmente origina la convección sobre las aguas calientes oceánicas y dispara una cadena de eventos que finalmente conduce a la intensificación de la perturbación en un huracán. La ausencia de tales flujos cuando las condiciones iniciales consisten del viento medio zonal superpuesto a la componente axi-simétrica del flujo, es suficiente para impedir que la perturbación se intensifique en un huracán.

ABSTRACT

Numerical simulations with the Naval Research Laboratory limited area model were performed using initial conditions derived from gridded analyses of the Colorado State University composite Atlantic prehurricane cloud cluster and depression. For each type of disturbance, simulations were made with initial conditions consisting of the zonal mean wind superimposed on the axially symmetric component of the flow about the vortex center. These simulations were compared with ones in which the initial conditions were specified from the gridded analyses in their full 3-dimensional complexity.

When the full asymmetries were retained in the initial conditions, both the prehurricane cloud cluster and the prehurricane depression developed into a mature hurricane in the numerical integrations. When the asymmetries, with the exception of those associated with the zonal mean wind, were not present in the initial conditions, the prehurricane depression showed no significant development during the first 60 hours of integration, after which it intensified slightly, and the prehurricane cloud cluster developed into a weak depression.

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Associated with the wave-like asymmetries in the initial wind and temperature fields are large-scale eddy fluxes of angular momentum and heat. The data reveal that these are organized in such a way as to induce a secondary radial circulation which picks up moisture as it spirals inward over a large stretch of ocean and pumps dry air outward in the upper troposphere and lower stratosphere. We argue that it is this circulation which initially organizes the convection over warm ocean water and triggers a chain of events that ultimately leads to the intensification of the disturbance into a hurricane. The absence of such fluxes when the initial conditions consist of the zonal mean wind superimposed on the axially symmetric component of the flow is sufficient to keep the disturbance from intensifying into a hurricane.

1. Introduction

In two recent papers (Challa and Pfeffer, 1990; Pfeffer and Challa, 1992) the authors investigated the role of large–scale eddy processes in the transformation of Atlantic cloud clusters (D1) and depressions (D2) into hurricanes. This was done by integrating numerically the Naval Research Laboratory (NRL) limited area model (Madala and Chang, 1979; Madala *et al.*, 1987) using different initial conditions analyzed by Noel LaSeur (Pfeffer *et al.*, 1990) from the Colorado State University composite datasets of William Gray (McBride, 1981). With initial conditions specified from either the composite Atlantic prehurricane cloud cluster (D1) or depression (D2), a hurricane developed in the course of each model integration. With initial conditions consisting of only the axially symmetric components of the wind and moisture fields in the Colorado State datasets, the initial disturbances failed to develop, giving evidence that the wave–like asymmetries we removed may be necessary for hurricane development from Atlantic cloud clusters and depressions.

In using axially symmetric variables, we necessarily filtered out the zonal mean wind field, as well as the temperature field implied by the vertical shear of this wind, in addition to the wave asymmetries in the data. A number of colleagues have suggested that we investigate further whether the asymmetries associated with the meridionally and vertically varying zonal mean wind current, which is present in the original data, can contribute to the development of incipient tropical disturbances. A meridionally and vertically varying basic current can, for example, increase evaporation at the sea surface and enhance the Ekman layer convergence. It is possible, also, that it could contribute to the development of eddy fluxes of angular momentum and heat in the upper layers as the system evolves. The motivation for the present study is to determine whether the superposition of the varying zonal current on the symmetric vortex, in the absence of initial large–scale wave asymmetries, can lead to the formation of a hurricane. Accordingly, we present in this paper the results of an additional set of numerical integrations with initial conditions comprised of the zonal mean wind superimposed on the otherwise symmetric disturbance. As in our earlier work, the symmetric components of the wind and moisture fields were derived by azimuthally averaging these variables along concentric circles, the centers of which coincide with that of the vortex.

2. The NRL model and initial conditions

The Naval Research Laboratory limited area numerical model developed by Madala and Chang (1979) and Madala *et al.* (1987) is a three dimensional primitive equation model using sigma coordinates and an Arakawa C–grid (Mesinger and Arakawa, 1976) for discretization of the horizontal derivatives. In our application, we used 11 sigma layers and a 15–km horizontal resolution over a region extending 3240 km in both the meridional and zonal directions. The physical parameterizations in the model include the release of latent heat by non–convective and convective clouds (the latter using Kuo's, 1974 modified scheme), horizontal diffusion of momentum and, in the planetary boundary layer, surface friction and air–sea exchange of sensible heat and moisture using the bulk aerodynamic formula. For more details, the reader is referred to Challa and Pfeffer (1990), or to the original references cited above.

The initial conditions for the integrations with the full asymmetries were discussed in detail by Challa and Pfeffer (1990). Here, we show, for D1 (Fig. 1) and D2 (Fig. 2) at 150, 200 and 250 mb, the initial distributions of v'_ϑ and v'_r, where v_ϑ and v_r are the tangential (positive counterclockwise) and radial (positive outward) components of the wind measured in a cylindrical coordinate system centered at the vortex center, and the primes represent departures from the azimuthal mean. Also shown in these figures are the products $-r^2 v'_\vartheta v'_r$ where r is radius. The radii of the two circles in each panel are 600 and 1200 km. Inspection of the figures reveals the existence of a negative covariance of v'_ϑ and v'_r along the outer circle in both D1 and D2, implying an inward eddy flux of angular momentum across that circle. It is not difficult to deduce

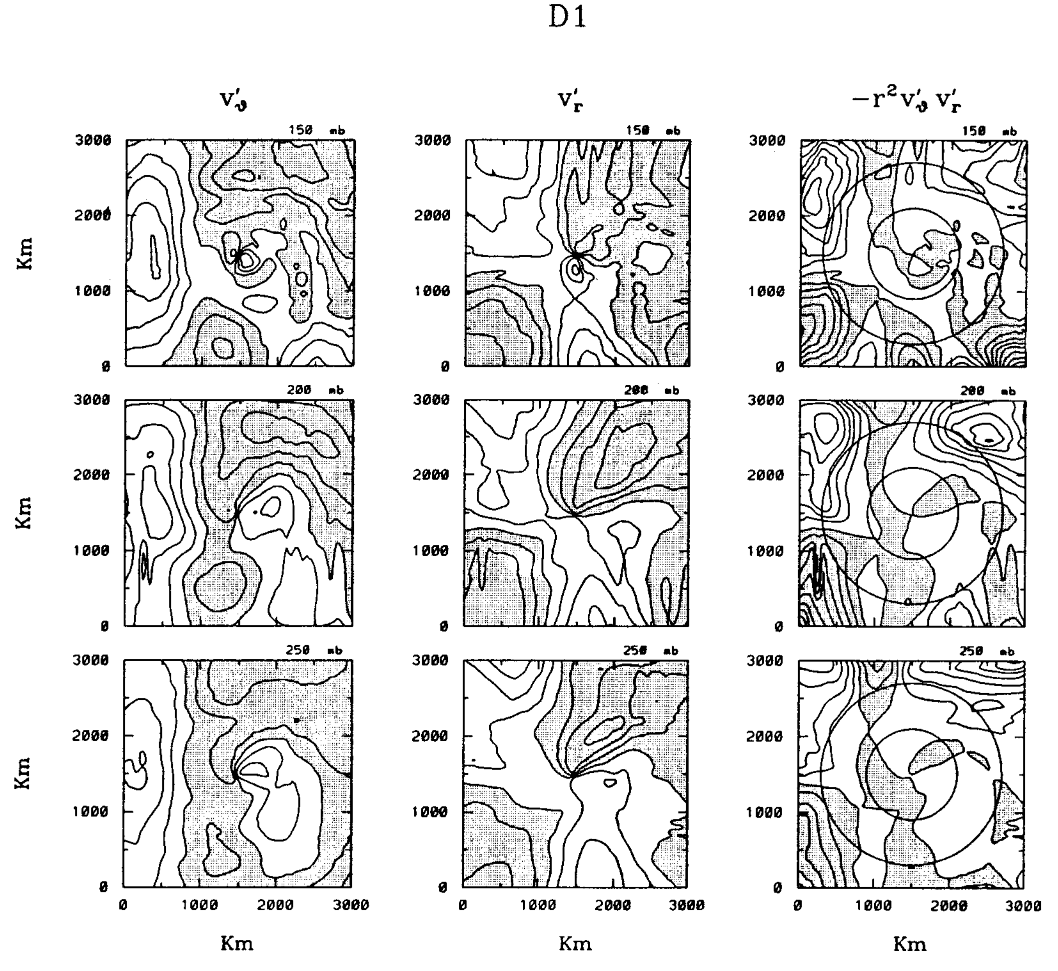

Fig. 1. Horizontal distributions of v'_ϑ, v'_r and $-r^2 v'_\vartheta v'_r$ at the initial time at 150, 200 and 250 mb for the prehurricane cloud cluster (D1) which is centered in the middle of each box. Contour interval for v'_ϑ and v'_r, 4m s^{-1}. Contour interval for $-r^2 v'_\vartheta v'_r$, 4000 deg^2 m^2 s^{-2}. The shaded regions represent clockwise tangential velocity, outward radial velocity and outward eddy flux of angular momentum.

from these figures that there must be a large–scale covergence of the eddy flux of momentum in the upper troposhere over the region enclosed by the two circles. As discussed by Pfeffer and Challa (1992), such an eddy flux distribution contributes to the driving of a secondary vertical circulation with inflow along a broad stretch of warm ocean, upward motion near the center of the disturbance and outflow aloft.

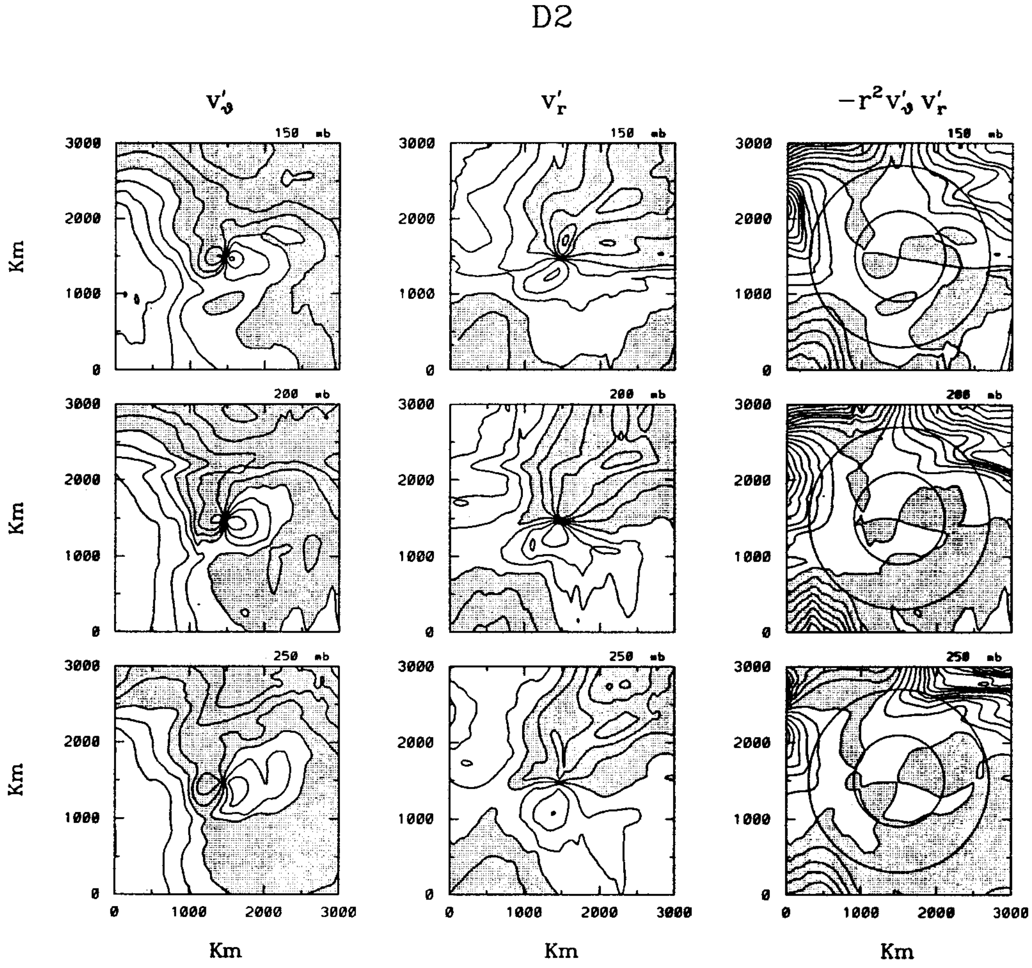

Fig. 2. Same as in Fig. 1 but for the Atlantic prehurricane depression (D2).

The initial conditions for the numerical experiments with the zonal mean wind superimposed on the axially symmetric vortex were obtained as follows. The gridded eastward and northward components of the wind were averaged in the east–west direction across the grid at each latitude and altitude. The resulting zonal mean wind fields for D1 and D2 are shown in Figures 3 and 4, respectively. In both cases, easterlies prevail at all latitudes at the lowest levels and at the uppermost level. In between, westerlies are found in the northern sector spreading southward and increasing in magnitude with height up to 200 mb. The zonal mean of the meridional component of the wind over the region is very small in comparison with the zonal component. The component wind fields shown in Figures 3 and 4 were added to the azimuthal means of v_ϑ and v_r (Challa and Pfeffer 1990, Fig. 3) to obtain the initial wind field for the new integrations. The corresponding temperature field was obtained by using the nonlinear balance equation and the hydrostatic equation.

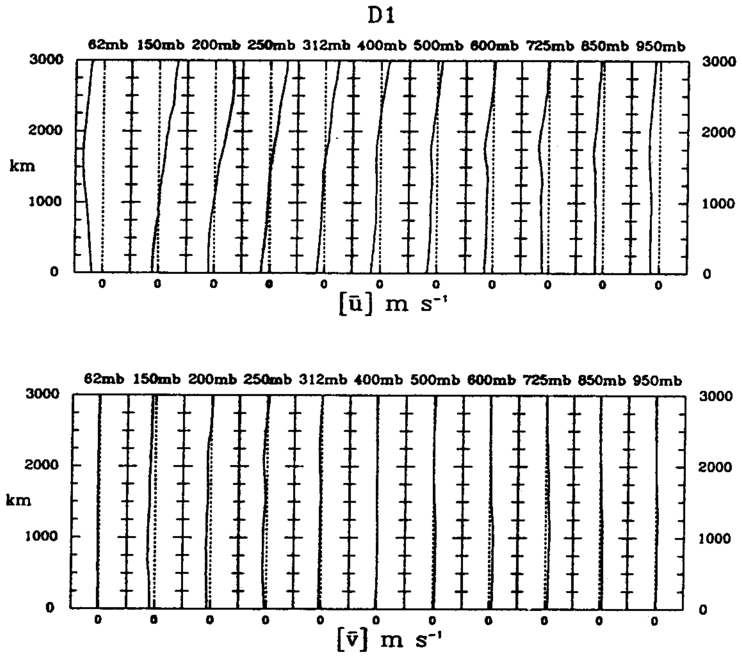

Fig. 3. Meridional variation of the zonally averaged eastward [*u*] and northward [*v*] velocity components at each model level at the initial time for the Atlantic prehurricane cloud cluster (D1). Here, the square brackets represent a zonal mean. The meridional extent of the domain is shown on the ordinate, with the disturbance centered in the middle. The range of velocities along the abscissa for each level is -20 m s^{-1} to +20 m s^{-1}, with zero represented by a dashed line.

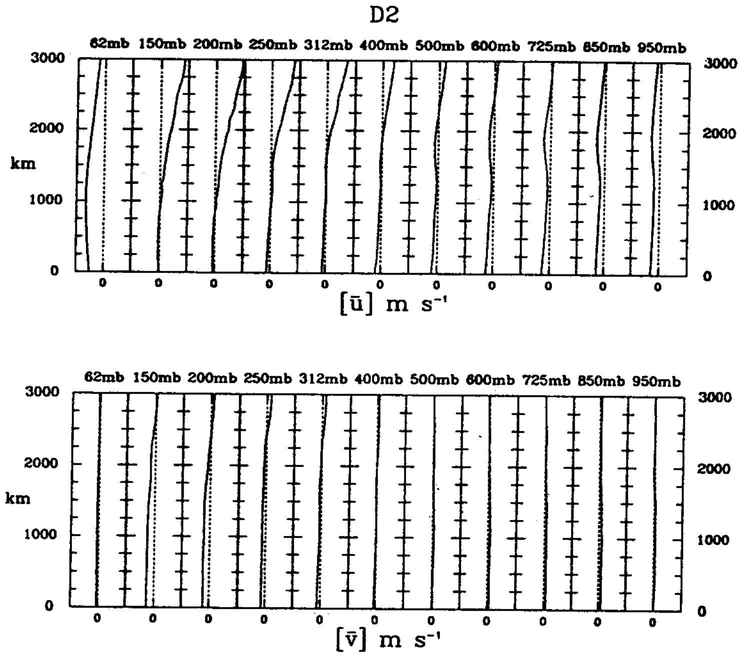

Fig. 4. Same as Fig. 3 but for Atlantic prehurricane depressions (D2).

3. The radial diagnostic circulation equation

The equation governing the secondary radial circulation in a vortex in hydrostatic and gradient wind balance (Eliassen, 1952; Kuo, 1956) may be written in cylindrical coordinates as follows:

$$A\frac{\partial^2\psi}{\partial p^2}+2B\frac{\partial^2\psi}{\partial r\partial p}+C\frac{\partial^2\psi}{\partial r^2}-\frac{4B}{r}\frac{\partial\psi}{\partial p}-(\frac{1-\kappa}{p}B+\frac{C}{r})\frac{\partial\psi}{\partial r}$$

$$=\frac{Rr}{p}\frac{\partial}{\partial r}(\frac{\overline{Q}}{c_p}-\frac{1}{r}\frac{\partial r\overline{v_r'T'}}{\partial r})$$

$$+r\frac{\partial}{\partial p}[(f+\frac{2\overline{v_\vartheta}}{r})(\overline{F}-\frac{1}{r^2}\frac{\partial r^2\overline{v_\vartheta'v_r'}}{\partial r})] \tag{1}$$

where

$A=(f+\frac{2\overline{v_\vartheta}}{r})(f+\frac{\partial\overline{v_\vartheta}}{\partial r}+\frac{\overline{v_\vartheta}}{r})$	Dynamic Stability Parameter
$B=-(f+\frac{2\overline{v_\vartheta}}{r})\frac{\partial\overline{v_\vartheta}}{\partial p}=\frac{\alpha}{\theta}\frac{\partial\overline{\theta}}{\partial r}$	Baroclinic Stability Parameter
$C=-\frac{\alpha}{\theta}\frac{\partial\overline{\theta}}{\partial p}$	Static Stability Parameter

Here, p pressure, T temperature, θ potential temperature, α specific volume; ψ is the Stokes stream function (given by $\overline{v}_r=(1/r)\partial\psi/\partial p$ and $\overline{\omega}=-(1/r)\partial\psi/\partial r$, where $\omega\equiv dp/dt$ and t is time); Q is the diabatic heating rate per unit mass, F the azimuthal component of the boundary layer friction force per unit mass, f the Coriolis parameter, R the gas constant for dry air, c_p the specific heat capacity of the air at constant pressure, $\kappa=R/c_p$; the overbar represents an azimuthal mean and the primes designate departures from this mean. In Eq (1) we have neglected the vertical eddy fluxes of angular momentum and heat.

For observed values of the atmospheric variables in developing hurricanes $AC>B^2$, so Eq (1) is elliptic. With ψ taken to be zero at the bottom and top of the atmosphere, at the axis of the vortex and at some great distance from the axis, this equation can have a non-trivial solution only when one or more of the forcing functions on the right hand side are non-zero. The forcings are seen to involve diabatic heating, friction and eddy fluxes of heat and momentum. In the following section, we shall compare the efficacy of each of these processes in two sets of integrations — one with asymmetric initial conditions, and the other with initial conditions consisting of the symmetric components of the meteorological variables superimposed on the zonal mean wind and temperature fields.

4. Results

Figure 5 shows time variations of the minimum surface pressure in the two sets of numerical integrations. The symbol ZS designates an integration with the initial conditions consisting of the zonal mean wind superimposed on the azimuthal mean circulation. It is clear that both the D1 and D2 disturbances developed into a hurricane only when the full asymmetric structure was present in the initial conditions (solid curves). This is shown even more vividly in Figures 6 and 7, which compare, for the D1 and D2 cases, respectively, the development of the surface

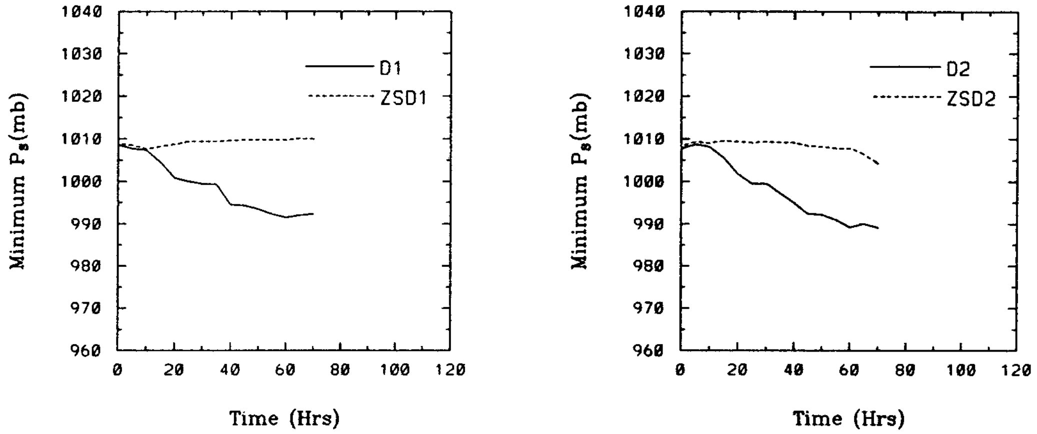

Fig. 5. Time variations of the minimum sea level pressure in numerical simulations with initial conditions corresponding to the Atlantic prehurricane cloud cluster (D1) and depression (D2) with and without fully asymmetric initial wind fields. The prefix ZS denotes an integration with initial conditions consisting of the zonal mean current superimposed on the azimuthal mean circulation.

pressure field with ZS and with fully asymmetric initial conditions. When fully asymmetric initial conditions were used, the cloud cluster and the depression each developed into a hurricane. At the end of 70 hours of integration, the minimum surface pressures were 991.5 and 989.0 mb, and the local wind maxima at $\sigma = 0.95$ (not shown here) were 44 m s^{-1} and 46 m s^{-1}, respectively. With ZS initial conditions, on the other hand, the local wind maximum at $\sigma = 0.95$ in the cloud cluster (D1) decreased from its initial value of 9.7 m s^{-1} and the surface pressure never dropped below 1009 mb. With similar initial conditions, the local wind maximum at $\sigma = 0.95$ in the tropical depression (D2) never exceeded 18.5 m s^{-1} and the surface pressure never dropped below 1004.2 mb during the course of the 70 hour integration, including the period of intensification which occurred during the last 10 hours when the vortex slowed down and began to recurve. These results give evidence that the asymmetries associated with the superposition of the zonal mean current on the symmetric circulation do not play the same role as do the wave asymmetries. The latter appear to be crucial for the development of a hurricane from Atlantic prehurricane cloud clusters and depressions.

As discussed previously by the writers (Pfeffer and Challa, 1992 and references therein), wave asymmetries in prehurricane cloud clusters and depressions are associated with inward eddy fluxes of heat and angular momentum about the axis of the vortex. These fluxes drive a weak, but organized, radial circulation with inward motion over a broad stretch of warm ocean, upward motion with a maximum near the vortex center and outward motion aloft. The inward motion serves to pick up the moisture necessary to fuel the intensification of the storm. The stream function for this circulation can be determined by solving equation (1) governing the secondary circulation induced by sources of heat and momentum in a balanced vortex. Since this equation is a linear elliptic equation for observed atmospheric parameters in developing tropical disturbances, one can assess the contribution of each of the forcing functions that appear on the right hand side of the equation by solving it with that one as the only forcing function, setting the others to zero, as done by Pfeffer and Challa (1992). The total radial circulation is then given as the sum of these component solutions. The forcing functions that appear in the radial circulation equation are due to diabatic heating, frictional dissipation and eddy fluxes of heat and angular momentum. In Figures 8 and 9 we present the component solutions associated with each of these forcing functions at different times during the early development of the prehurricane cloud cluster and depression. The cross–sections on the left are for ZS initial conditions and those on the right are for initial conditions which include the wave asymmetries. Figures 8a and 9a, in particular, show the radial circulations forced by the initial eddy fluxes of heat and momentum in the D1 and D2 cases, respectively. In both cases the circulation is negligible when ZS initial

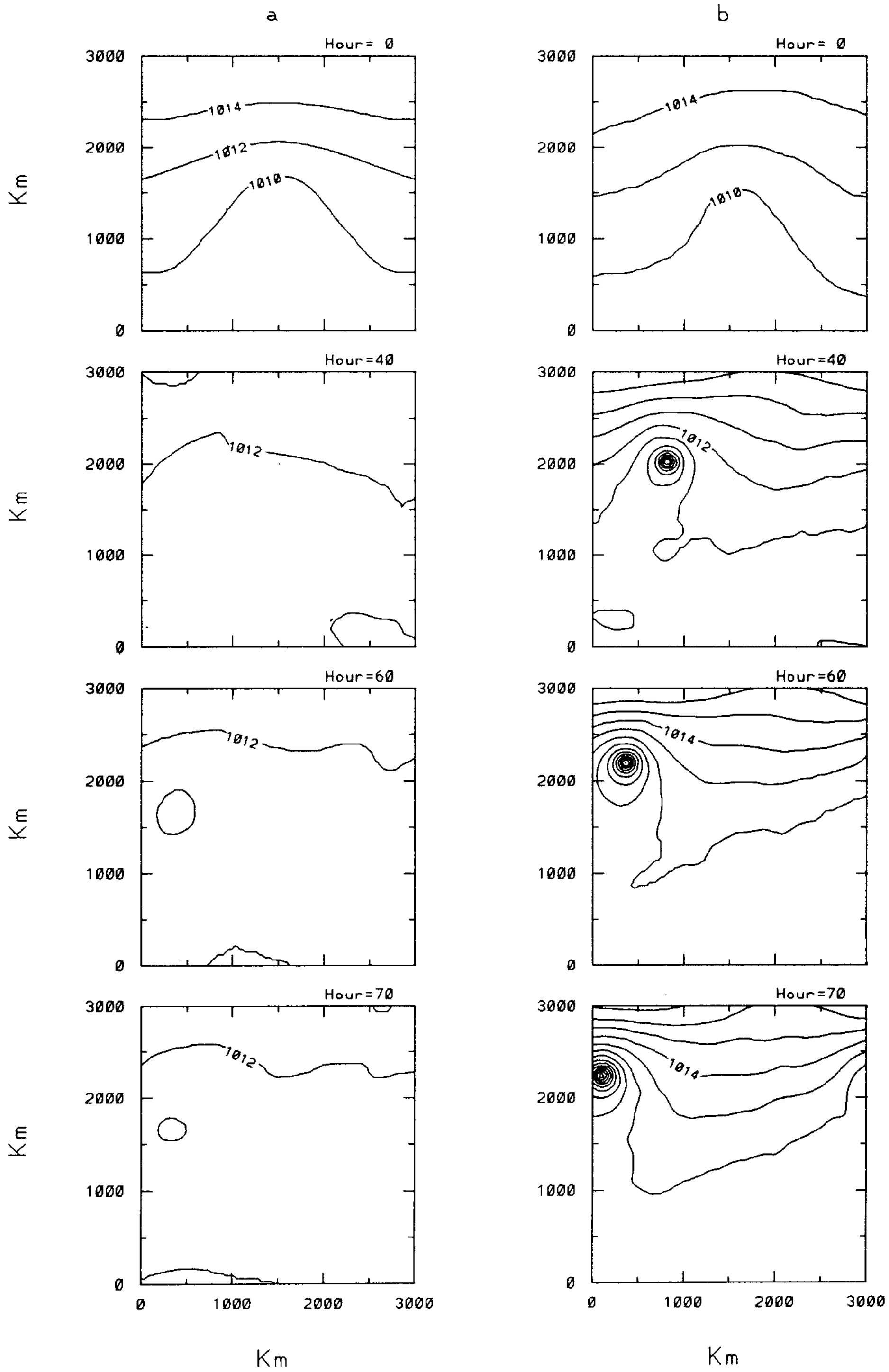

Fig. 6. Surface pressure distribution at t = 0, 40, 60 and 70 hours in the numerical integrations with initial conditions corresponding to the Atlantic prehurricane cloud cluster a) with ZS initial conditions and b) with fully asymmetric initial conditions. Contour interval = 2 mb.

conditions are used. With the wave asymmetries present, however, there is an organized radial circulation with maximum inflow at the surface over a very large area and maximum outflow around 200 mb. Initially, there are no circulations induced by diabatic heating or friction in the model, so none are presented here. The eddy induced radial circulations at the end of 10 hours of integration are given in Figures 8b and 9b and at the end of 20 hours in Figures 8e and 9e.

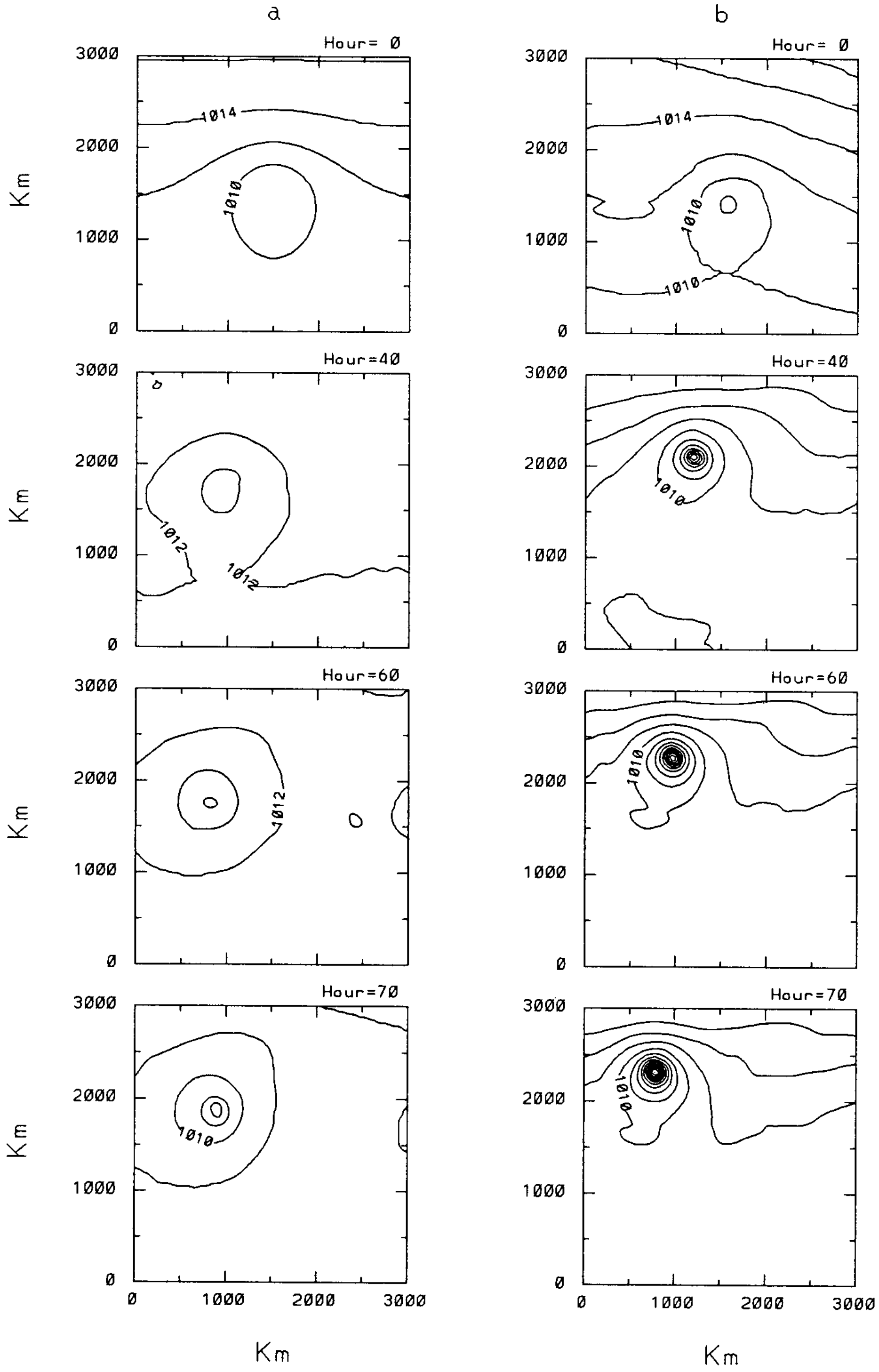

Fig. 7. Same as Fig. 6 but for the Atlantic prehurricane depression.

These figures reveal that this component of the circulation is sustained throughout the period under consideration when wave asymmetries are present initially, but that no significant eddy induced circulation develops with ZS initial conditions.

The component radial circulations induced by Ekman layer frictional dissipation at the end of 10 hours of integration are shown in Figures 8c and 9c, and those at the end of 20 hours in Figures 8f and 9f. With the exception of Figure 9c, it is clear that the Ekman circulations are more intense and have their rising branches closer to the vortex center when wave asymmetries

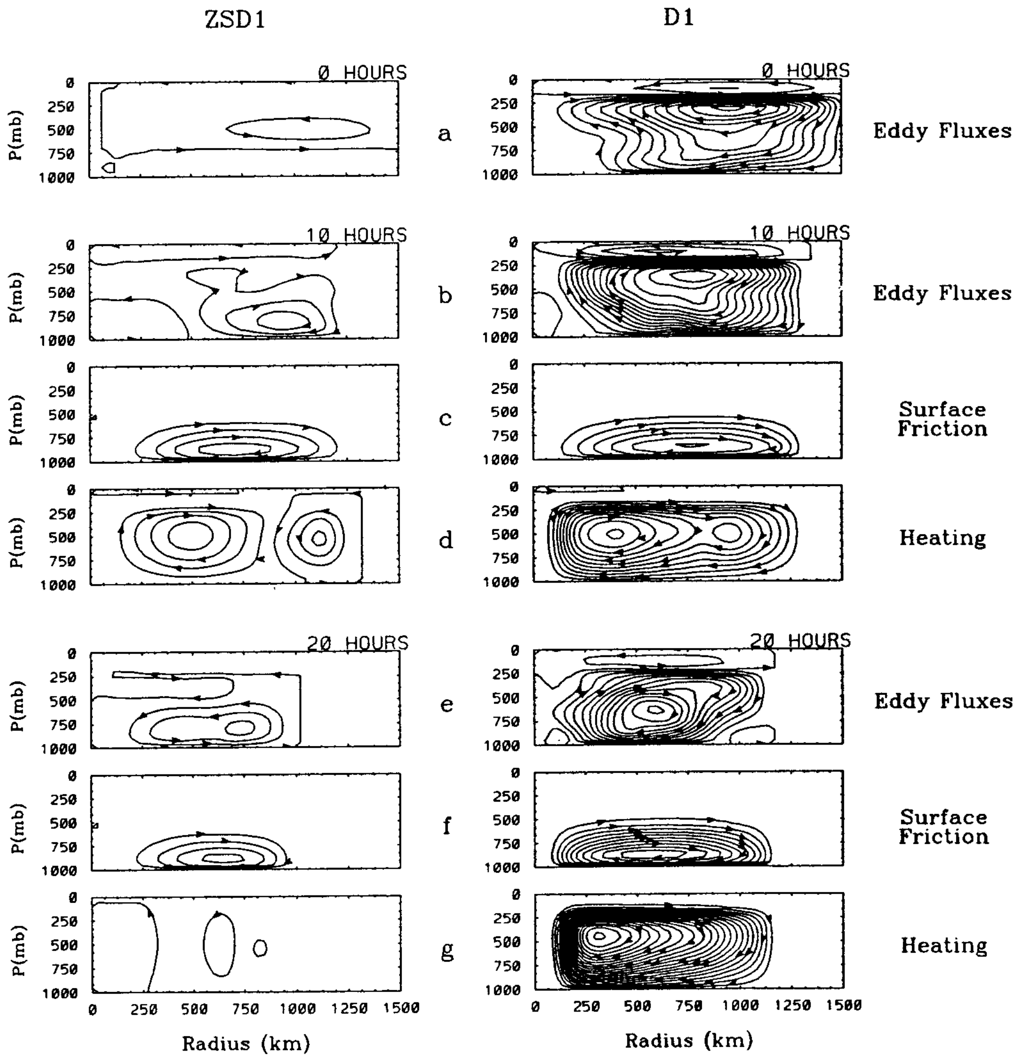

Fig. 8. Components of the stream function ψ induced individually by the combined eddy fluxes of heat and momentum, by surface friction and by diabatic heating at time $t = 0$, 10 and 20 hours in the numerical simulations with initial conditions corresponding to Atlantic prehurricane cloud clusters with full asymmetries (D1) and with ZS initial conditions (ZSD1). Panel (a) represents the component induced by the combined eddy fluxes of heat and momentum at the initial time. Panels (b), (c) and (d) at 10 hours and (e), (f) and (g) at 20 hours respresent the components induced individually by the combined eddy fluxes, by surface friction and by diabatic heating, respectively. Contour interval for panels (a), (b), (c), (e) and (f), 2.5×10^8 newtons s^{-1}; contour interval for panels (d) and (g), 15×10^8 newtons s^{-1}.

are present than when they are absent. Figures 8d and 9d show the component radial circulations induced by diabatic heating at the end of 10 hours, and Figures 8g and 9g show them at the end of 20 hours of integration. In each case, the circulation is much more vigorous and intensifies with time, and the vertical branch of the circulation is closer to the vortex center when the wave asymmetries are present. In the absence of wave asymmetries, the diabatically induced circulation is weaker at 20 hours than it is at 10 hours because, in the absence of the eddy fluxes, the moisture supply is inadequate to sustain this process at a sufficiently vigorous level.

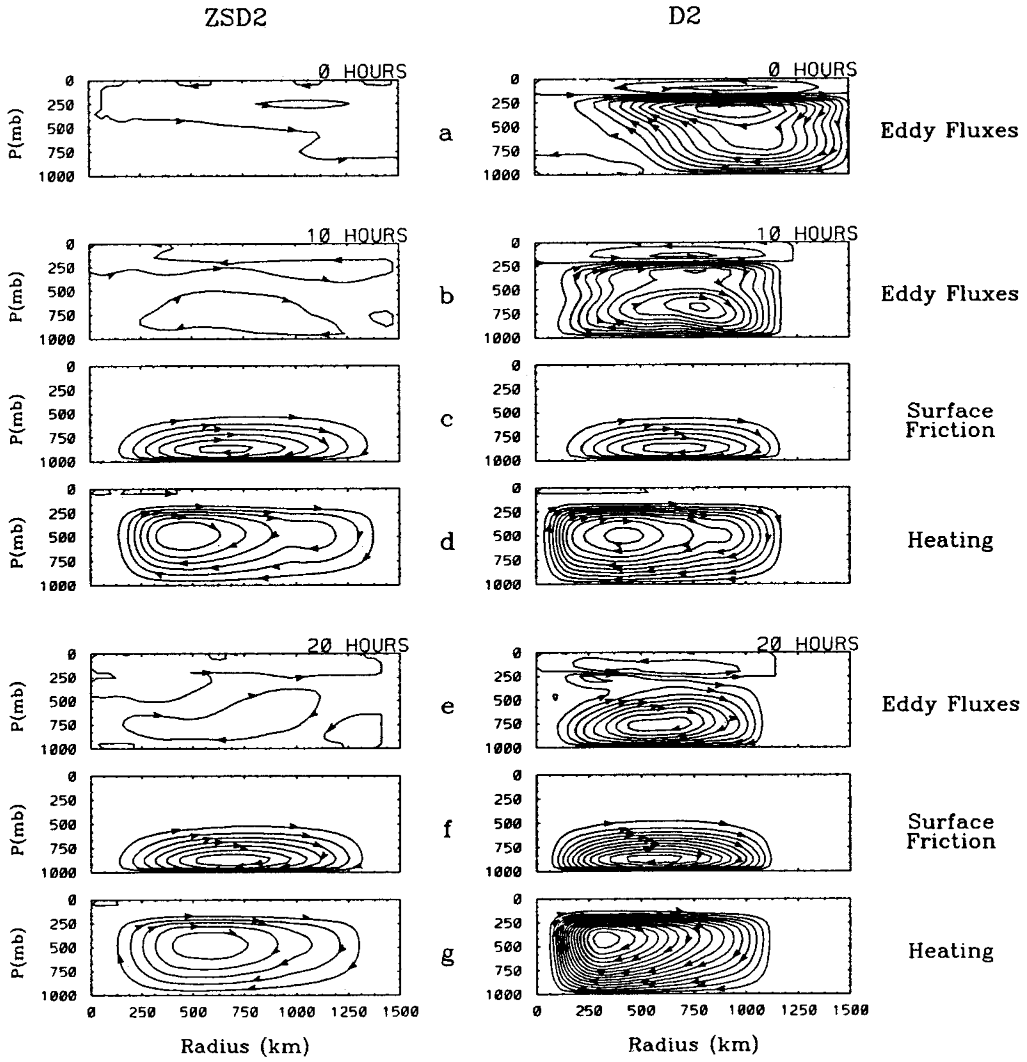

Fig. 9. Same as Fig. 8 but for the Atlantic prehurricane depression.

5. Interpretation and conclusion

Our interpretation of the results in the preceding section is that the wave asymmetries found in the composite datasets corresponding to Atlantic prehurricane cloud clusters and depressions act as catalysts. In particular, the eddy fluxes of heat and momentum associated with these asymmetries induce a weak, but persistent, radial circulation with inflow over a broad stretch of warm ocean. This inflow picks up water vapor and concentrates it near the vortex center, where the release of latent heat of condensation serves as an even more intense driving force that accelerates the radial circulation and, through the Coriolis force, intensifies the surface vortex. This in turn increases the Ekman pumping, and therefore the inflow of water vapor, adding further fuel for intensification of the disturbance.

By way of contrast, the asymmetries associated with the meridional and vertical variation of the zonal wind do not induce a significant radial circulation. Ekman pumping in the ZS case cannot by itself concentrate enough moisture to generate an increasingly intense differential heating, radial circulation and vortex. We conclude that it is the eddy induced radial circulation associated with synoptic-scale wave asymmetries that intensifies Atlantic cloud clusters and depressions to the threshold value required for self sustained growth to hurricane strength. The small number of cloud clusters and depressions that form hurricanes in nature is most likely due to the low probability of having a mid to upper level synoptic event of sufficient intensity juxtaposed on one of the many such disturbances that pass through warm waters.

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REFERENCES

Challa, M. and R. L. Pfeffer, 1990. Formation of Atlantic Hurricanes from Cloud Clusters and Depressions, *J. Atmos. Sci.*, **47**, 909-927.

Eliassen, A., 1952. Slow Thermally or Frictionally Controlled Meridional Circulations in a Circular Vortex. *Astrophys. Norveg.*, **5**, 19-60.

Kuo, H. L., 1956. Forced and Free Meridional Circulations in the Atmosphere. *J. Meteor.*, **13**, 561-568.

Kuo, H. L., 1974. Further Studies of the Parameterization of the Influence of Cumulus Convection in Large-Scale Flow. *J. Atmos. Sci.*, **31**, 1232-1240.

Madala, R. V. and S. W. Chang, 1979. A Vectorized Three-Dimensional Operational Tropical Cyclone Model. *Proceeding of the Scientific Computer Information Exchange Meeting*, Livermore, CA, 1979.

Madala, R. V., V. C. Mohanty, S. C. Madan, R. K. Paliwal, V. B. Sarin, T. Holt and S. Raman, 1987. Description of Naval Research Laboratory Limited Area Weather Prediction Model. *NRL Memorandum Report* 5992.

McBride, J., 1981. Observational Analysis of Tropical Cyclone Formation. Part I: Basic Description of Datasets. *J. Atmos. Sci.*, **38**, 1117-1131.

Mesinger, F. and A. Arakawa, 1976. Numerical Methods Used in Atmospheric Models. *WMO Garp Publication Series No. 17*, **1**, 43-62.

Pfeffer, R. L., M. Challa, N. LaSeur and W. Gray, 1990. Composite Atlantic Tropical Disturbance Structure: Developing and Non-Developing Disturbances. *FSU Publication*, 96 p.

Pfeffer, R. L. and M. Challa, 1992. The Role of Environmental Asymmetries in Atlantic Hurricane Formation. *J. Atmos. Sci.*, **49**, 1170-1178.