Effect of Asymmetric Structure on the Intensification of Tropical Cyclones

Bao-Fong Jeng
Department of Meteorology
Naval Postgraduate School
Melinda S. Peng
Naval Research Laboratory
Monterey, CA

Abstract

The effect of planetary vorticity gradient (beta) and the presence of a uniform mean flow on the intensification of tropical cyclones are studied using a primitive equation model. The most intense storm develops on a constant f plane with zero mean flow and its structure is symmetric to the vortex center. The presence of beta effect or a mean flow induces asymmetric flow across the center of the vortex and inhibits the cyclone's intensification. The existence of asymmetric moisture convergence and momentum flux distribution resulted a phase shift exists between them and inhibits the development.

1. Introduction

Intensity prediction for tropical cyclones is a challenging task. Forecasts of tropical cyclone (TC) motion have shown significantly improved skill in past decades, but intensity forecasts have not improved (Elsberry et al. 1992). The lack of skill in intensity forecasts is partially a result of insufficient data and it may also be attributed to less research emphasis. Studies on TC's intensity change using analyzed data are focused mainly on the upper levels where satellite and aircraft data are available to compensate the shortage of conventional data on open tropical oceans. A number of studies have simulated the genesis and the evolution of TC using numerical models. The advantage of using numerical model is that many parameters related to storm's intensity can be analyzed in detail without the problem of insufficient data and poor data resolution.

Some studies suggested that small vertical shear in the environmental wind and a large inward eddy imports of angular momentum into the vortex center are favorable for tropical cyclone intensification (Pfeffer 1958, McBride 1981, Holland and Merrill , 1984). Tuleya and Kurihara (1981) investigated the effect of an environmental flow on the storm genesis. Their experiments produced storm genesis in an easterly vertical shear flow but not in a westerly shear or no-shear flow when the surface wind was easterly. The genesis mechanism required that the upper-level warming be in-phase with the low-level moisture convergence.

The effect of the planetary vorticity gradient on TC motion has been studied rigorously on a beta-plane (i.e., Madala and Piacsek 1975, Chan and Williams 1987, Fiorino and Elsberry 1989). The effect of beta on the development of tropical cyclones was also addressed by Madala and Piacsek (1975). In their simulations, a vortex on a beta-plane intensified at a slower rate than the one on an f-plane before the storm stage, but at the same rate thereafter. DeMaria and Schubert (1984) carried out tropical cyclone simulations using a three-layer spectral model and they found that the intensification rates for simulations on f-plane and beta-plane are very similar until 48 h. Afterwards, the intensity of the storm on an f-plane continued to intensity, while the storm on a beta-plane began to level off.

In this study, we will revisit some problems such as the beta effect and effect of an environmental flow on TC development. The numerical model and initial conditions are described in Section 2. A discussion on TC intensity in different environments is given in Section 3. Analysis of parameters that are related to the intensity are given in Section 4. Summary and conclusion are given in section 7.

2. Numerical model and initial conditions

The model used for this study is the Naval Research Laboratory limited-area primitive equation model (Madala et al. 1987). The model adopts a second-order finite difference scheme in flux form in space and a split-explicit leapfrog scheme in time. Physical parameterization of the model that are important for tropical cyclone simulation include the modified Kuo scheme (Kuo 1965,

1974) for cumulus convection and one-and-a-half order closure scheme for planetary boundary layer (Holt et al. 1990). The horizontal grid size is 0.5 degree in the latitude-longitude coordinate and there are 16 layers in the terrain-following vertical coordinate. The domain of the model covers an area of 45 degrees in the north-south direction and 70 degrees in the east-west direction.

The initial vortex is specified by a modified Rankine profile blended with the environment using a weighting function so that the tangential wind goes to zero at some radial distance. The maximum tangential wind speed equals 35 m/s at 1 degree away from the center on the lowest level and it decreases gradually with height, reaching zero at 100 hPa. The initial mass fields are in gradient wind balance with the wind field. The SST is set to constant of 29.5 °C throughout the domain during the integration to eliminate variation of the thermodynamic forcing as the vortex moves during the integration. The relative humidity is 95% at the first three lower pressure levels and decreases gradually to 10% at the top layer. All integration are carried out to 72 h.

Initially, the vortex is placed at 20N. The beta effect will be studied by comparing integration with constant coriolis parameter f (group A) and with variable f (group B). To investigate the effect of an uniform environmental flow on TC's intensification, each group contains five cases with uniform flows U = -10, -5, 0, 5, 10 m/s, respectively.

3. Time evolution of the vortices in different environments

The time evolution for all the cases are depicted in Fig. 1. Note that the maximum intensity occurred in the case with constant f and zero mean flow. Comparing cases in Fig. 1a with 1b one can see that including the beta effect reduces the vortex's intensity. This can be illustrated most clearly with zero-mean-flow cases. The intensity of the vortex with constant f and zero mean flow weakens slightly during the model adjustment period before t = 12 h and then intensifies continuously to 940 hPa by 72 h. The cyclone remains roughly at the same location and has a fairly symmetric structure with respect to the center of minimum pressure (Fig. 2a). On the other hand, vortex in an variable f environment intensifies to its maximum strength at 36 h and then level off afterward. The wind field at the surface, that is, within the boundary layer, exhibits an asymmetry with a large cross-isobaric wind on the east and southeast side of the cyclone (Fig. 2b). This asymmetry is similar to the analysis of Hurricane Kelly (1979) by Black and Holland (1995). The upper level flow at 150 hPa, is asymmetric as the surface wind with a larger outflow in the southeastern quadrant (figure not shown).

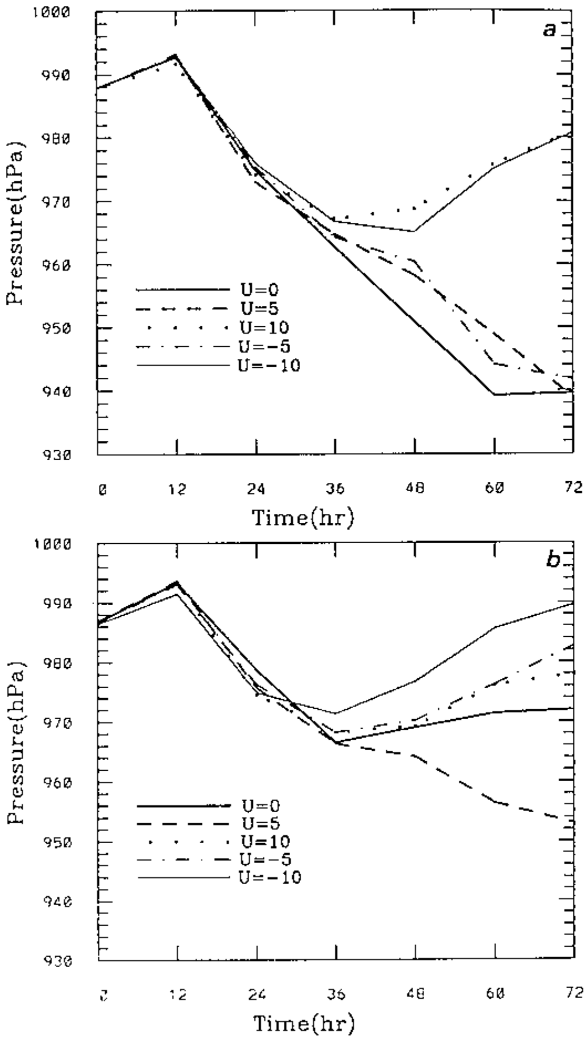


Fig. 1. Time evolution of the minimum MSLP of the vortex for the five cases with U = - 10, -5, 0, 5 and 10 m/s, a) constant f; b) variable f.

Comparing cases within each group shows that including a uniform mean flow also reduces the vortex's intensity. This effect is best illustrated with cases in group A (Fig. 1a) to exclude the beta effect. The evolution of TCs in different mean flows with a constant f diversify. In the zero-mean flow environment, the storm intensifies to 940 hPa at t = 72 h, the lowest in our experiments. Vortices with U = 5 and U = - 5 m/s have similar final intensity as the zero-mean flow case but the overall intensity is slightly weaker. With U = 10 and -10 m/s, vortices weaken after 36 h and 48 h, respectively. There is no significant bias in the direction of the mean wind on TC's intensification. However, the larger the mean wind speed is, the weaker the vortex is.

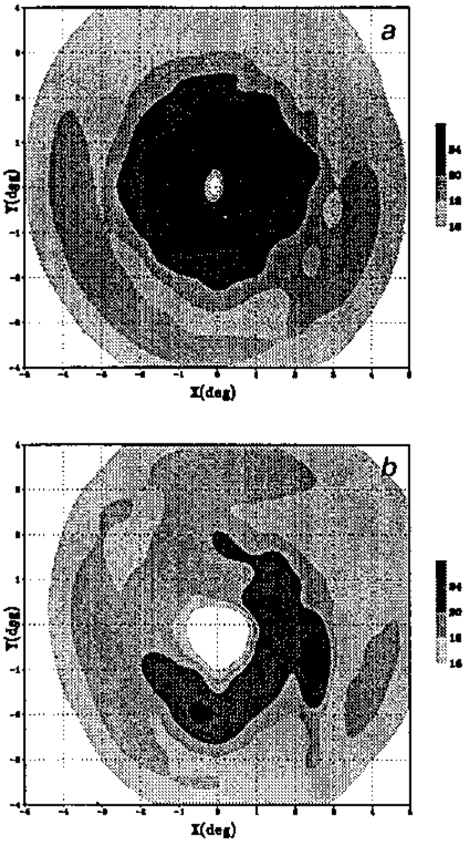


Fig. 2. Surface isotachs at t = 60 h with zero mean flow and a) constant f and b) variable f.

The TCs in group B with variable f intensify at the same rate as in group A before 36 h (Fig. 1b). Beyond that point, four cases cease to intensify while the vortex with U = 5 m/s continues to intensify slightly, reaching a MSLP of 953 hPa at 72 h. The intensity of the TC with U = 0 reaches 972 hPa and the TC with U = -10 m/s has the weakest intensity of 990 hPa, while the remaining two cases cluster around 980 hPa. Comparing individual cases between groups A and B indicates that cases in group A in general have higher intensity than cases in group B. Therefore, the beta effect is not favorable for TC intensification, as discussed in more detail for the zero-mean-flow cases. Except for the case of U = 5 m/s with variable f, the presence of a mean flow is not favorable for TC development. The evolution of the TCs with different basic flow diversify after 36 h, a similar pattern obtained by Tuleya and Kurihara (1981) in their simulations of storm genesis. Similarly, they also found a higher intensity with a uniform flow of 5 m/s.

4. Analysis

To understand the dynamics associated with these intensity differences, some properties are examined in the following subsections.

a) Precipitation

It is commonly known that a storm's intensity is closely related to its precipitation. The maximum of 12 h accumulated precipitation amount (including both convective and non-convective rain) for each case is shown in Fig. 3. Since the 12-h `accumulated' rain amount is compared with the intensity, the lag effect of rain amount with the intensity change (Rao and MacArthur 1994) has already been included. The accumulated precipitation has a positive correlation with the intensity change. Between the two groups, the precipitation amounts are larger with constant f. Within each group, the precipitation amounts associated with different mean flows are also positively correlated with their intensities. For example, the highest intensity obtained in group B with U = 5 m/s is a result of having the largest precipitation between 60 h and 72 h among all cases in the same category (Fig. 3b). Similarly, the two weakest storms in group A with westerly and easterly mean flow of 10 m/s have significantly smaller rainfall amount between 60 and 72 h.

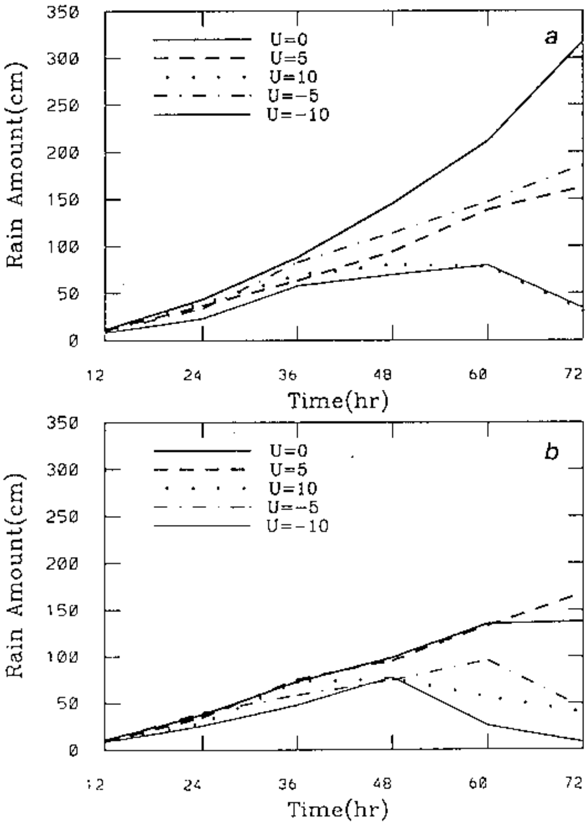


Fig. 3. Time evolution of the maximum 12 h accumulated precipitation amount corresponding to Fig. 1.

b) Wavenumber-one asymmetry

It is well known that interaction between the symmetric circulation and the planetary vorticity gradient (variable f) generates a wavenumber-one circulation with the ventilation flow oriented in the direction of TC's motion. When a basic flow is included along with a planetary boundary layer, interaction between the vortex and mean flow also generates a wavenumber-one asymmetry. Therefore, to explore mechanisms associated with interaction between the vortex and the planetary vorticity gradient and an environmental mean flow, we will examine the asymmetric circulation of the vortex. This is done by transforming the wind field to polar coordinates centered at the geopotential minimum at each level. Fourier analysis along the azimuthal direction is then performed to obtain the wavenumber-one circulation. The motion of the vortex at each time is subtracted from the total wind field before fourier analysis is carried out.

After careful examination of these flow patterns and comparison of them with the intensity change, we observe that the wavenumber-one circulation associated with intensifying TC has its circulation center close to the center , while a weakening or non-intensifying TC has a wide range of ventilation flow across the center. The intensifying situation is illustrated by the zero-mean flow case with constant f at 48 h in Fig. 4a. Since the planetary vorticity gradient induces a wavenumber-one gyres with their circulation centers lie far away from the TC's center (Peng and Williams, 1990), the effect of beta generate a larger ventilation flow (Fig. 4b). Interaction of a mean flow with a symmetric vortex also induces ventilation flow when the surface friction is present and therefore, is not favorable for TC's development. This is illustrated with U equals`10 m/s and a constant f at 48 h (Fig. 4c). To demonstrate the relationship between asymmetric circulation and the development of TC, the time mean of the area-averaged across-the-center flow and the final MSLP is plotted in Fig.5. There is a linear relation between them. Cases with constant f (marked with `x') have smaller across-the-center flow and deepen to lower minimum MSLP. We further hypothesize that a large ventilation flow generates a more asymmetric distribution of the basic energy source and inhibit cyclone's development.

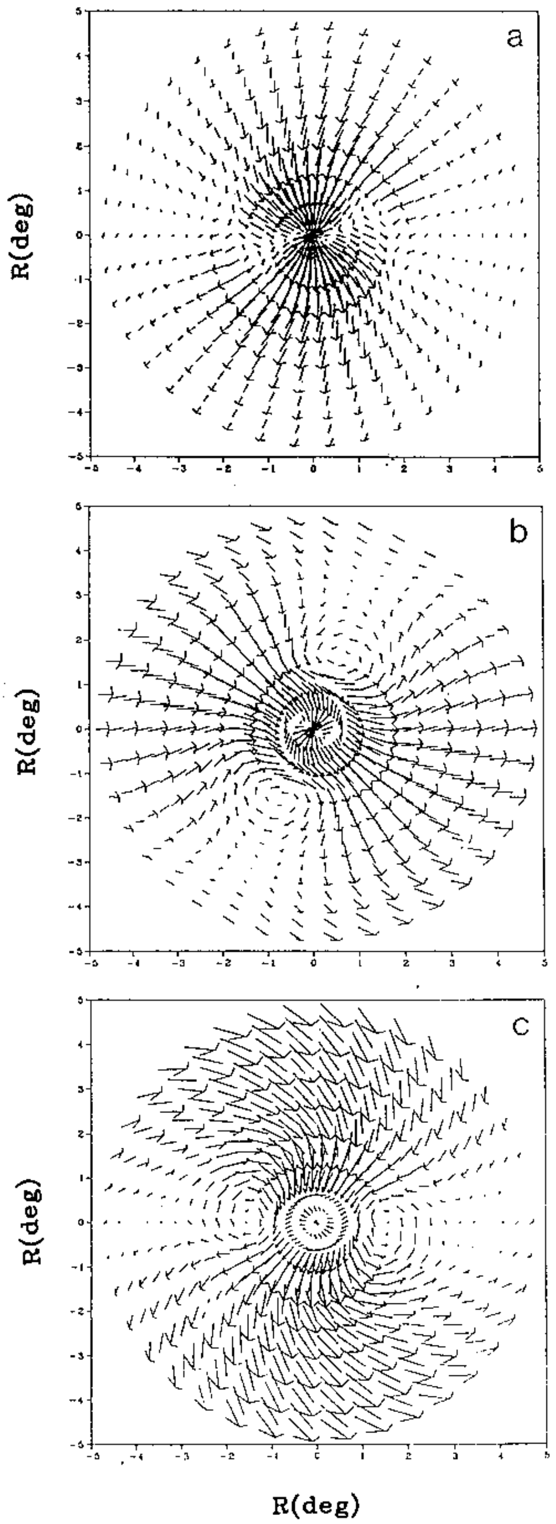


Fig. 4. Wavenumber-one asymmetric wind field for vortex with U = 0 at t = 48 h; a) with constant f, an illustration for intensifying vortex, b) with variable f, an illustration for non-intensifying vortex, and c) with constant f and U = 10 m/s.

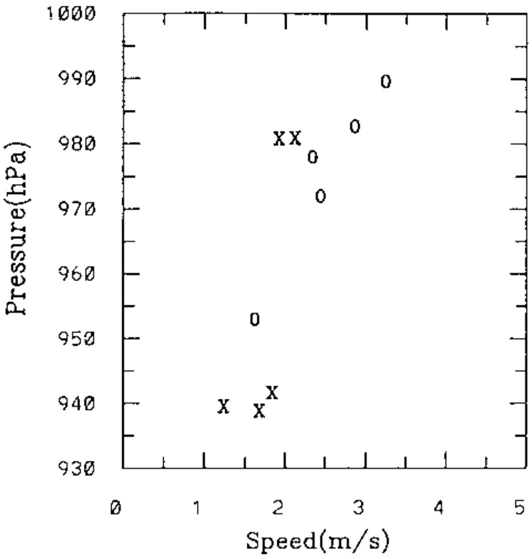


Fig.5. Minimum MSLP and the time-averaged across-the-center flow speed for each case. The `0's represent cases with variable f and the `x's represent cases with constant f.

c) Surface momentum stress (and latent heat flux)

The basic energy source for TC's intensification is the latent heat flux from the ocean which is induced by the perturbed momentum flux onto the ocean. To investigate the beta effect on this energy source first, two cases with zero-mean flow but with a constant f and variable f, respectively, are compared. The distributions of surface momentum flux at t = 48 h for U = 0 with constant f (Fig. 6a) is quite symmetric with respect to the center, while with variable f the momentum flux is highly asymmetric (Fig. 6b). This asymmetry indicates a momentum flux maximum in the southeast quadrant of the cyclone. The wavenumber-one wind circulation induced by the beta effect without a mean flow is oriented from the southeast toward northwest. The entrance region of this ventilation flow in the southeast quadrant generates the largest momentum flux in the same quadrant. The latent heat flux has the same distribution as the momentum flux and, is therefore, not shown here.

The effect of mean flow on the distribution of momentum flux is illustrated in Fig. 7 by cases with U = 10 and -10 m/s and constant f at 48 h. The largest wind stress is located in the southwest quadrant for a westerly flow and northeast quadrant for a easterly flow, both in the entrance region of the mean flow. The maximum region remains roughly in the same quadrant for each case. Therefore, the presence of a mean flow, as does the planetary vorticity gradient, induces an asymmetry in the momentum flux. This asymmetric distribution of the momentum and the heat source is not favorable for TC's intensification as will be explained in next subsection.

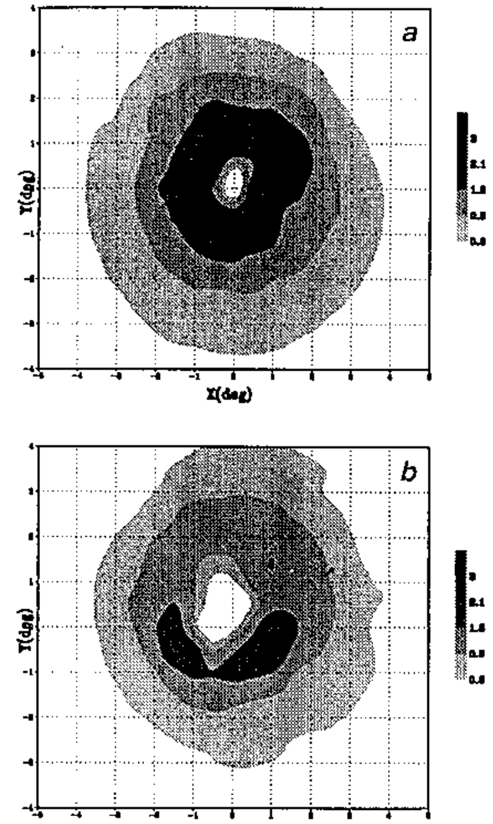


Fig.6. Surface momentum flux (newtons/m^2) at t = 48 h with U = 0, and a) constant f, b) variable f.

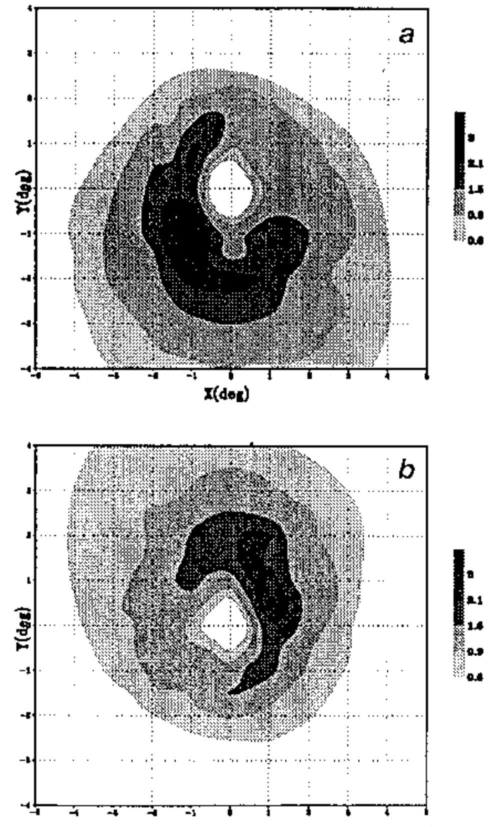
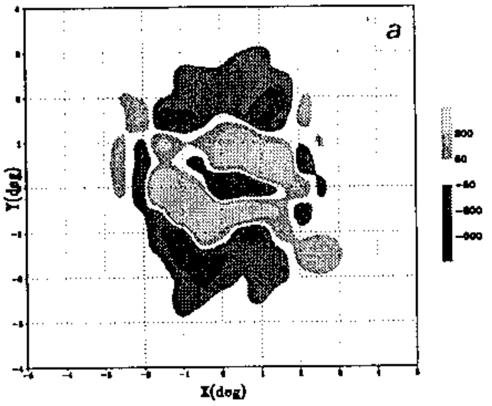


Fig. 7. Same as in Fig. 6 except for vortices with constant f and a) U = 10 m/s, b) U = -10 m/s.

d) Low-level moisture convergence

The core intensity of a TC depends directly on the moisture convergence (Gray 1968). To explore the relation between the asymmetric circulation, the distribution of momentum flux and the intensity change, we compute the moisture convergence on 850 hPa level for each case every 12 h. For the vortex with constant f that is intensifying, the moisture convergence field has a rather symmetric distribution around the TC's center (Fig. 8a), while the moisture convergence for a vortex in a variable f environment that is not intensifying is asymmetric with respect to the center (Fig. 8b). The location of maximum moisture convergence is, in general, located at the in-flow region of the asymmetric wavenumber-one circulation. This is illustrated by the case shown in Fig. 8b for which the wavenumber-one wind field is given in Fig. 4b. When the orientation of the asymmetric flow rotates with time, the location of the maximum moisture convergence changes accordingly.

As discussed in previous subsection, the distribution of momentum and latent heat flux is asymmetric with respect to the center when either a mean flow or the beta effect is present. Since the region of maximum momentum flux stays roughly in the same location, when the asymmetric circulation rotates, it shift the maximum moisture convergence region away from the energy source region (the momentum and heat flux). Figures 6, 7 and 8 demonstrate this out-of-phase relation between the surface momentum flux and the low-level moisture convergence region that is not favorable for TC's intensification. The more symmetric distribution of the moisture convergence and the momentum flux, illustrated by Figs. 6a and 8a, is more favorable for the development of TCs because the heat and momentum source region would overlap the region of moisture convergence where precipitation occurs.



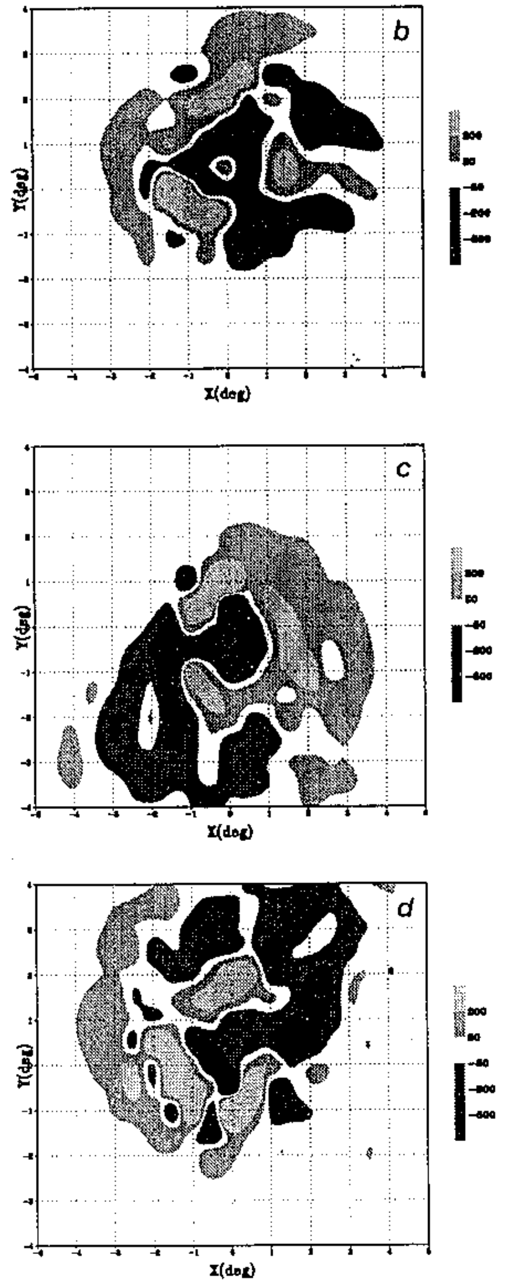


Fig. 8. Moisture convergence at 850 hPa corresponding to cases shown in Fig. 6 (a and b) and Fig. 7(c and d).

6. Summary and Conclusion

A limited-area primitive equation model is used to study the dynamics associated with the intensification of tropical cyclones in different environmental flows and with different coriolis parameters.

An intense storm is associated with large precipitation amount, upper-level divergence and low-level moisture convergence. The dynamics associated with an intensifying vortex and a non-intensifying vortex lies in the degree of asymmetry in its horizontal structure. An intensifying cyclone is associated with a small ventilation flow in its wavenumber-one circulation that allows a more symmetric distribution of the surface momentum flux and low-level moisture convergence around the center. The presence of planetary vorticity gradient and a large mean flow in the environment are not favorable for tropical cyclone's development by inducing a larger ventilation flow across the storm center. A large ventilation flow generates a large asymmetry in the momentum flux and moisture convergence around the center. The region of maximum moisture convergence always lie in the inflow region of the wavenumber-one wind circulation. When the wavenumber-one circulation rotates with time, the maximum moisture convergence rotates accordingly, resulting a separation between region of maximum moisture convergence and region of maximum momentum flux. This mechanism is induced both by the planetary vorticity gradient and the presence of a basic flow and inhibits the intensification of tropical cyclones.

The results obtained in this study may be useful for bogussing procedure in a numerical baroclinic model. To allow a vortex with the same intensity in a baroclinic model, the vortex included initially would be less intense within a weaker background flow than within a stronger background flow.

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