Baroclinic Dynamics of Simulated Tropical Cyclone Recurvature

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ABSTRACT

The mechanisms associated with tropical cyclone recurvature are investigated using a five-level primitive equation model and an idealized environment with characteristics observed in cyclone recurvature conditions. All cyclones moved generally with the flow in the lower and middle troposphere, but the precise motion occurs by a combination of divergence and of advection in both the horizontal and the vertical. The horizontal advection arises from a combination of the initial environmental flow and local changes from rearrangement of the potential vorticity field by cyclone–environment interaction (the so-called β effect). The balance between these mechanisms changes as the vortex recurves. Since the gradients of potential vorticity increase sharply poleward of the subtropical ridge, this is the preferred region for development of an anticyclonic gyre. This gyre is advected eastward and becomes the dominant anticyclonic system. Recurvature is aided by horizontal deformation of the cyclone in the vicinity of this gyre, and by the manner in which the vertical tilt of the vortex and local divergence fields vary as it moves through a changing vertical wind shears of the environment. Recurvature is sensitive to the degree of diabatic heating and to small meridional changes in the initial vortex location.

It is shown that recurvature can occur through an initially unbroken subtropical ridge, but that the presence of a midlatitude trough substantially enhances the potential for recurvature. However, while changes in the upper troposphere are indicative of recurvature potential, recurvature is accomplished largely by lower-tropospheric changes. An important component of this change is the development of a major anticyclone poleward and eastward of the cyclone. A recent observational study by Ford et al. concurs with this finding.

1. Introduction

Determining whether a tropical cyclone will recurve is a major forecast issue and most of the major track forecast errors occur in potential recurvature conditions (e.g., the annual reports from the Joint Typhoon Warning Center, Guam). For example, although cyclones normally move westward while equatorward of an unbroken subtropical ridge, occasionally they move straight through the ridge. Major forecast failures are often associated with "stair-stepping" and "looping," where a cyclone starts to recurve but then continues on a westward course.

Several observational studies have indicated the importance of interactions both with the subtropical ridge and with upper-tropospheric troughs in the midlatitude westerlies. George and Gray (1976) analyzed the changes in environmental wind fields prior to recurvature and found that the 200-hPa wind fields were significantly stronger from the west for recurving cyclones than those of the nonrecurring cyclones, and that these winds increased up to three days before recurvature. Chan et al. (1980) made a similar documentation of the characteristics of the environment of cyclones undergoing turning motion. These results are supported by later studies by Hodanish and Gray (1991) in which the cyclones began to recurve 1–2 days after westerly zonal winds in the upper troposphere penetrated to within 650 km of the cyclone center. Tropical cyclones that did not recurve experienced easterly zonal winds in this region.

An important finding from the composite analysis by George and Gray (1976) is that nonrecurring cyclones typically occur on the equatorward side of the easterly wind maximum in middle levels. As noted by Evans et al. (1991) and Holland and Evans (1992), this is a region of low, or perhaps reversed potential vorticity gradient so that the poleward "β drift" is inhibited. However, the recurving cyclones studied by George and Gray were located on, or poleward of the easterly wind maximum up to 3 days before recurvature. In this study we specifically address the recurvature potential of
cyclones in environmental flow conditions similar to those of George and Gray.

Holland (1984) used a composite study to show that the deep layer-mean flow averaged over the whole cyclone turned poleward and eastward ahead of the cyclone starting to recurve. He hypothesized that this resistance to recurvature arose from the tendency for the cyclone to propagate on the background vorticity field, and that recurvature would be rapid once it commenced. This was confirmed in a barotropic modeling study by Evans et al. (1991), who also found that cyclones could propagate through an idealized subtropical ridge and into the westerly flow.

More recently, Dong et al. (1991) studied tropical cyclone recurvature and environmental circulation features based on the Bureau of Meteorology Research Centre analyses of the SPECTRUM, TCM-90, and TYPHOON-90 data (Elsworth 1990). They showed that the presence of another cyclone, or other mesosynoptic-scale features in the near environment, could have a marked effect on the way in which a cyclone interacted with the subtropical ridge and midlatitude troughs during recurvature.

Krishnamurti et al. (1992) examined the recurvature of a typhoon as predicted by a high-resolution spectral model. They found that the tropospheric mean divergence and vorticity advection averaged out to 1000 km from the storm center in the forward and right quadrants changed consistently during recurvature. Much of the recurvature was attributed to the divergence field that arose from baroclinic, outflow-layer dynamics, and they considered that advection was not sufficient to produce the observed recurvature.

Thus, changes in the upper troposphere occur some days before recurvature; the cyclone has a tendency to resist these changes in the large-scale “steering” flow, by continuing on a westward trajectory; and potential recurvature conditions are associated with major forecast failures. Although some of the problems arise from the lack of adequate data in the cyclone vicinity during recurvature, we suggest that insufficient attention has been given to the dynamics of cyclone recurvature in a baroclinic environment. In a previous study (Wang et al. 1993, hereafter referred to as WHL), we found that tropical cyclone motion in a baroclinic environment can be sensitive to the diabatic heating and the vertical structure of both the vortex and its environment. This study extends our previous work and that of DeMaria (1985), Evans et al. (1991), and Holland and Evans (1992) to consider the interactions between a baroclinic vortex, zonal ridge, and westerly trough in idealized conditions similar to those described in the above observational studies. Our aim is to examine the detailed interactions that occur and to elucidate potential mechanisms responsible for recurvature.

The next section describes the numerical model used in this study. The motion of a tropical cyclone in the vicinity of an idealized subtropical ridge is analyzed in section 3. Section 4 contains an investigation of the motion of a cyclone in the vicinity of a ridge with a midlatitude westerly trough. Our findings and conclusions are summarized in section 5.

2. Experimental design

The experimental design follows that of WHL; azimuthally symmetric, baroclinic vortices are superimposed onto an idealized environment and integrated with a five-level, primitive equation model with CISK-type heating (section 2a). Several numerical experiments are used to diagnose the vortex—environment interactions. Two vortices with different vertical structure are used (section 2b). The environments include an unbroken subtropical ridge (section 2c) and a midlatitude trough (section 2d). Both f-plane and β-plane (valid at 20°N) configurations of the model are used, with and without diabatic heating. The codes designating these experiments are summarized in Table 1.

a. Description of the model

The three-dimensional model (WHL) uses the nonlinear, primitive equations on a β plane formulated with Cartesian and σ coordinates. The model consists of five layers with Δσ = 0.2 in each layer. Horizontal velocity and potential temperature are defined in the middle of each layer and the vertical velocity at the layer interface. The horizontal mesh consists of 151 × 131 grid points with a uniform grid spacing of 40 km.

The explicit time-split algorithm of Gadd (1978) is used for the model time integration. The trapezoidal forward—backward scheme of Gadd (1980) is adopted for the adjustment stage. Horizontal differencing uses a centered finite-differencing scheme with second-order precision, and the vertical differencing is identical to that used in Arakawa and Lamb (1977). The advection stage utilizes a fourth-order Lax—Wendroff scheme with splitting in x and y directions. The time step is set at 150s for both stages.

For upper and lower boundary conditions, we require that fluid particles do not cross the σ = 0 and σ = 1

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<th>Table 1. Description of the experiments used.</th>
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<td>STR1–5: Vortex located in an idealized subtropical ridge environment (Table 2 and Fig. 2).</td>
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<td>TR1–4: Vortex located in an idealized subtropical ridge and midlatitude trough environment (Table 3, Fig. 3).</td>
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All experiments are on a β plane with diabatic heating unless otherwise designated by one of the following prefixes:

F: Denotes f-plane experiment.
B: Denotes β-plane experiment.
H: Denotes experiment with diabatic heating from the CISK parameterization.
NH: Denotes no diabatic heating.
surface, that is, $d\sigma/dt = 0$ at $\sigma = 0$, 1. Sponge layers are applied to the model’s lateral boundaries as used by Wang and Li (1992). Wave reflection near the boundary is avoided by using a method of “circling smoothing” (WHL).

The model equations do not include moist processes and diabatic heating occurs by the CISK-type parameterization described in WHL. WHL showed that diabatic heating was not essential to the maintenance of a stable vertical structure and that the general characteristics of adiabatic and diabatic motion were similar. For this investigation we are interested in the comparison between vortices with and without diabatic heating and consider that the simplified parameterization used here is suited to this task. So that we can isolate the impact of heating on the vortex alone, we constrain the heating to the region within 400 km of the cyclone center. This ensures that other aspects, such as heating in the monsoon trough or in developing $\beta$ gyres, do not affect the interpretation. Further studies of the detailed impact of cumulus parameterization on tropical cyclone recurvature in full numerical simulations are needed.

The subgrid-scale horizontal diffusion of momentum and heat is calculated in the manner given by Smagorinsky et al. (1965). Vertical diffusion of momentum and heat is accomplished by the eddy diffusion coefficient method. The exchange of momentum at the surface is parameterized by the bulk aerodynamic method. All experiments with no diabatic heating have the diffusion and surface friction reduced by 75%.

b. Vortex structure

The symmetric vortices are spun up on an $f$ plane centered at 20° N and in an environment at rest. By varying the vertical heating profile, we obtained the two vortices shown in Figs. 1a,b. Vortex A consists of a deep cyclonic circulation overlayed by a shallow anticyclone (Fig. 1a), while vortex B has a deeper and more intense upper anticyclone (Fig. 1b). The two vortices included with slightly different intensities: 27 m s$^{-1}$ and 987 hPa for A, compared to 32 m s$^{-1}$ and 979 hPa for B, but the major difference lay in the depth and extent of the upper anticyclone (Fig. 1c).

These two types of vortices enable us to examine the effects of vertical structure of tropical cyclones during recurvature. Unless otherwise stated, vortex A is used in all general experiments. Ueno (1991) indicated that the method of parameterizing the diabatic heating can be expected to have an effect on vortex motion through both asymmetric heating and differential changes in the vortex structure. The experiments used here have been carefully designed so that changes in the overall vortex structure in the lower levels are not a dominant component of the cyclone motion. The heated vortices start at a steady state and do not change markedly during integration. We also note that the adiabatic vortex experiments have all diffusion reduced by 75%. As a result there is little change in the lower-tropospheric structure during the experiments described here. Major changes that occur in the vertical tilt and in the upper troposphere are specifically discussed as appropriate in the text.

c. Subtropical ridge environment

The idealized environment consists of a subtropical ridge with no zonal variation constructed from

$$u(y, \sigma) = u_m \sin \left( \frac{2\pi(y-y_0(\sigma))}{L_y} \right),$$

where $u_m$ is the maximum value of the zonal wind, $L_y$ is the width of the model domain (5200 km), and $y_0(\sigma)$ is the initial distance of the vortex center equatorward of the subtropical ridge at each $\sigma$ level. The expressions for $y_0(\sigma)$ are given in Table 2 and the corresponding zonal winds and potential vorticity gradients in the $y-\sigma$ plane are drawn in Fig. 2. The mass and thermal structure consisted of geostrophic and thermal wind balance based on the mean tropical sounding of Gray et al. (1975). This meridional structure is similar to the idealized fields constructed by DeMaria (1985), Evans et al. (1991), and Holland and Evans (1992).

Five benchmark experimental configurations are used (STR1–5; Table 2, Fig. 2). STR1 (STR2) has no vertical shear of the environment with the initial vortex center 600 km equatorward (poleward) of the lower-level ridge axis (Fig. 2). The remaining three experiments use a ridge that is tilted toward the equator with the initial vortex location at several positions on or equatorward of the lower-level ridge axis. In all of these cases the sense of the vertical wind shear is westerly and the horizontal gradient of potential vorticity (vector arrows in Fig. 2) is directed poleward in the vortex vicinity.

The maximum zonal wind $u_m$, which also gives the strength of the horizontal shear [Eq. (1)], is set at 12 m s$^{-1}$ in STR1–4, and at 16 m s$^{-1}$ in STR5. Thus, STR5 contains a westerly flow over the cyclone at upper levels and also has stronger horizontal and vertical shear than do the other configurations.

d. Midlatitude trough environment

For the examination of the effects of midlatitude troughs, a perturbation is introduced onto the idealized subtropical ridge configuration described in the previous section (Fig. 3). The corresponding wind fields are

$$u = \left[ \bar{u} + u_0 \sin \frac{2\pi(y-y_0)}{L_y} \right] f(\sigma),$$

$$v = v_0 \frac{\cos \frac{2\pi(x-x_0)}{L_x}}{L_x} F(\sigma),$$
where $\bar{u} = 2 \text{ m s}^{-1}$, $u_0 = 7.5 \text{ m s}^{-1}$, $v_0 = 4 \text{ m s}^{-1}$, $L_v = 6000 \text{ km}$, $L_x = 5200 \text{ km}$, $x_0 = 1/2 L_x$, $y_0 = 1/2 L_v + 600\sigma$, and $F(\sigma) = 2 - \sigma$. The equatorward tilt of the subtropical ridge is the same as that shown in Fig. 2a and the additional vertical shear, $F(\sigma)$, is introduced to concur with the observational results of Chan (1984) and Hodanish and Gray (1991). This relation enhances the westerly vertical shear on the poleward side of the subtropical ridge, but introduces an additional easterly vertical shear on the equatorward side.

The four benchmark experiments (TR1–4) use vortex A with diabatic heating and are located initially as shown in Table 3. We note also that the trough is a Rossby wave and drifts slowly westward during the experiments. This westward movement does not affect the generality of our findings.

**Table 2.** Distance (km) from the cyclone core to the subtropical ridge axis, $y_0(\sigma)$, for each of the subtropical ridge experiments. STR1–2 contain no vertical tilt of the ridge; the ridge axis in STR3–4 tilts equatorward, as shown in Fig. 2.

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<tr>
<td>$y_0(\sigma)$</td>
<td>600</td>
<td>−600</td>
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**Fig. 1.** Azimuthal wind fields (contour interval 2 m s$^{-1}$, dashed lines are negative) for the symmetric vortices used in all experiments: (a) vortex A, (b) vortex B, and (c) difference fields of $A - B$. 
3. Vortex motion in the vicinity of an idealized subtropical ridge

a. Barotropic subtropical ridge

The tracks\(^1\) of vortex A at \(\sigma = 0.9\) for several experiments using a barotropic subtropical ridge environment are shown in Fig. 4. On an \(f\) plane the vortex drifts equatorward while south of the ridge (Fig. 4, FSTR1) and in the opposite direction while poleward of the ridge (Fig. 4, FSTR2). On a \(\beta\) plane the vortex drifts poleward and westward, regardless of its location relative to the subtropical ridge or the presence of diabatic heating (Fig. 4, BSTR1, 2; BNSTR1, 2). However, the vortex poleward of the subtropical ridge drifts 200–300 km farther poleward in 72 h compared to the same vortex on the equatorward side of the ridge.

These results are consistent with the well-known vortex movement arising from interactions with the potential vorticity gradient and provide an extension of the findings by DeMaria (1985) into a barotropic environment with a baroclinic vortex. On an \(f\) plane for

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\(^1\) All vortex locations are determined from the local maximum of relative vorticity using the method of Wang and Zhu (1989).
STR1 (Fig. 5a) the relative vorticity field reflects advection of the initially zonal environmental vorticity to produce a vortex couplet with the anticyclone located southwest of the cyclone. The result is an equatorward and eastward drift of the vortex relative to the initial environmental flow in Fig. 4. For the vortex poleward of the subtropical ridge, the gyre generation (not shown) and drift are in the same sense as for the $\beta$ effect.

We note that this $f$-plane motion involves modification of the environmental potential vorticity field, and is thus different to the motion arising from an equivalent gradient of earth vorticity, which cannot be changed. Ulrich and Smith (1991) have shown that cyclone-scale horizontal shear flow can be substantially modified by this interaction. For Fig. 5a the horizontal shear in the environmental flow is not strong and the barotropic subtropical ridge--scale environment is not

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<td>DSR</td>
<td>1200</td>
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**Fig. 3.** Environmental flow at the middle model level ($\sigma = 0.5$) arising from superposition of a westerly trough and vertical wind shear on the idealized subtropical ridge: (a) vector arrows (max, 21 m s$^{-1}$); (b) streamlines; (c) potential vorticity (contour interval $5 \times 10^{-8}$ K kg$^{-1}$ m$^2$ s$^{-1}$) together with vector arrows indicating the gradient (max $4.6 \times 10^{-11}$ K kg$^{-1}$ m$^{-1}$ s$^{-1}$).
substantially modified, so that the analogy to $\beta$-plane motion is justified. Other experiments with stronger horizontal and vertical shear, described later, contain substantial modification of the ridge environment.

Since the earth vorticity gradient is larger than that for the environment in these experiments, the vortex equatorward of the subtropical ridge on the $\beta$ plane develops a $\beta$-gyre structure (Fig. 5b). But this structure is weakened by the impact of the environmental relative vorticity field. Climatological results reported by Evans et al. (1991) and analyses from the TCM-90 field experiment in the western North Pacific (R. Elsberry 1993, personal communication) indicate that the relative vorticity gradient may exceed $\beta$. In such cases, a net equatorward drift of tropical cyclones relative to the large-scale flow can be expected.

In agreement with our findings in WHL, changing the vertical structure of the initial vortex made very little difference to the motion for experiments STR1–2 (not shown). We thus conclude that the changes in vertical structure of the vortices used here have little impact on their motion in a barotropic environment. Other studies by Wang and Li (1992) indicate some motion sensitivity arising from the changes of integrated net angular momentum. We do find some sensitivity to diabatic heating, however, particularly for vortices equatorward of the subtropical ridge (Fig. 4, BSTR1 and BNHSTR1). This supports the findings by WHL, Heckley et al. (1987), and Ueno (1991) that tropical cyclone motion may be sensitive to the type of diabatic heating in potential recurvature situations. The mechanisms are elaborated in the following section.

b. Baroclinic subtropical ridge

The observational studies discussed in the introduction all found significant changes in upper-tropospheric zonal winds to the poleward side of tropical cyclones one or two days prior to recurvature. We examine this process by locating the vortices differentially relative to a tilted subtropical ridge (Fig. 2).

![Figure 4](image)

Fig. 4. Tracks of vortex A, with 12-h positions indicated, for the barotropic subtropical ridge environment of experiments STR1–2: with diabatic heating on an $f$ plane (FSTR1, FSTR2); with diabatic heating on a $\beta$ plane (BSTR1, BSTR2); adiabatic motion on a $\beta$ plane (BNHSTR1, BNHSTR2). Note that in this and all subsequent figures only a small part of the 6000 km × 5200 km model domain is shown.

![Figure 5](image)

Fig. 5. Relative vorticity fields (contour interval $5 \times 10^{-9}$ s$^{-1}$, dashed is anticyclonic) at $\sigma = 0.5$ after 48-h integration of vortex A with diabatic heating equatorward of the subtropical ridge (STR1): (a) on an $f$ plane; (b) on a $\beta$ plane.
All vortices move through the axis of the initially unbroken ridge (Fig. 6), and those that recurve accelerate eastward and poleward. Notice that the vortex in STR4 recurves within 60 h, despite its being initially located equatorward of the ridge at all levels (Fig. 2). This vortex also moves more rapidly poleward than do those in STR3 and STR5. This is consistent with STR4 containing both a stronger potential vorticity gradient and a weaker vertical wind shear than both STR3 and STR5 (Fig. 2). Increased westerly shear reduces the poleward drift by vertical coupling within the tilted vortex and by changing the potential vorticity gradient.

We find in these experiments a nonlinear coupling between the vortex and subtropical ridge environment, which results in marked changes to the environment and development of a major anticyclone several thousand kilometers to the east of the vortex. Fiorino and Elsberry (1989) and Smith and Ulrich (1990) have shown that advection of earth vorticity produces the anticyclonic gyre that develops on the eastern edge of a cyclone in an atmosphere at rest. The subtropical ridge substantially modifies the potential vorticity field to produce a weak gradient equatorward of the ridge axis and a strong gradient on the poleward side (Fig. 2). Thus, as a cyclone approaches the subtropical ridge, the anticyclonic gyre develops poleward of the ridge axis and is advected eastward by the westerly flow (Fig. 7).

A combination of strong environmental shear enhanced by the developing anticyclonic gyre introduces a shearing deformation on the cyclone, especially in midlevels (Fig. 8). The strongest shearing deformation occurs for cyclones located near to, or recurring past

![Fig. 6. Tracks of vortex A with heating on a β plane for STR1 and STR3, 4, 5 (solid lines) and without diabatic heating for STR3 and STR5 (dashed lines). The tracks are located relative to the initial position of the subtropical ridge axis at σ = 0.5 (horizontal line) and 12-h positions are indicated.](image)

![Fig. 7. Tracks of vortex A and its anticyclonic gyre at σ = 0.5 (dashed lines) and σ = 0.7 (solid lines) for (a) STR3 and (b) STR5. Centers are located relative to the initial position of the subtropical ridge axis at σ = 0.5 (horizontal line). The first location of the anticyclonic gyres is at 6 h, thereafter all positions are at 6-h intervals.](image)
Fig. 8. Vertical structure of the relative vorticity field (contour interval $5 \times 10^{-6} \text{ s}^{-1}$, dashed is anticyclonic) for STR5 after 48-h integration on a $\beta$ plane. The bottom right panel is an EOF reconstruction of the mean field surrounding a tropical cyclone in the western North Pacific 24 h before recurvature from Ford et al. (1993).
movement of the cyclone past the ridge axis and subsequently to rapid recurvature.

In all experiments conducted in this study, the gyre becomes the dominant anticyclonic system and is located up to 2000 km from the cyclone. This is a major finding, one which has considerable implications for the processes that cause recurvature of tropical cyclones. The vertical structure for STR5 after 48-h integration (Fig. 8) indicates the variation of vortex deformation and strength of the anticyclonic gyre with height that is typical of the other cases, except that vortices located farther from the subtropical ridge remain more symmetric.

Composite studies by George and Gray (1976) and others have emphasized the role of a developing mid-latitude trough in the upper troposphere west of the cyclone as a precedent for recurvature. However, these composites also contain evidence of the dominant anticyclone that has been noted here. A recent example from Ford et al. (1993) is provided in the bottom right panel of Fig. 8. Ford et al. used the first 45 EOFs from the Navy Global Band Analyses to reconstruct the characteristic relative vorticity field surrounding recurving cyclones in the western North Pacific. Their fields are at 700 hPa and should be compared to the $\sigma = 0.7$ panel immediately above. Given the idealized nature of our study, the relationship is quite remarkable. Relative to the cyclone: both panels contain a strong anticyclone located 1000–1500 km to the northeast and extending eastward; a tongue of anticyclonic vorticity extends around the east and equatorward; and there is a broad region of low anticyclonic vorticity to the northeast. Ford et al. find that the anticyclone is present up to 4 days before recurvature and intensifies with time. It is absent for non-recurving cyclones.

Substantial modification of the subtropical ridge by the anticyclonic outflow occurs in the upper levels (Fig. 8). We find no evidence, however, that this has a marked effect on the vortex motion, which seems to be dominated by the lowest three layers. The development of convection and asymmetric diabatic heating from the associated divergence fields (Krishnamurti et al. 1992) may be important contributors but are specifically excluded from the CISK-type parameterization scheme used in this study.

The strength of the cyclone decreases as the anticyclone develops; after 48-hours integration, the relative amplitudes of the cyclonic vortex and its anticyclonic gyre at $\sigma = 0.5$ are 573:40 for STR1, 472:48 for STR3, and 244:50 for STR5. Similar proportions are found at the lower levels, but the amplitude of the anticyclone does not vary as much. Our model results (not shown) suggest that the weaker cyclonic structure arises from the strong vertical wind shear, which tilts the vortex and prevents an accumulation of the upper-tropospheric warming required to maintain a large pressure deficit and strong vortex in the lower troposphere.
vortex movement relative to westerly vertical shear. Since the major difference between vortices A and B are in the strength of the upper-tropospheric anticyclone (Fig. 1), the results in Fig. 10 indicate that the influence of the upper-tropospheric anticyclone described by Wu and Emanuel (1993) is of minor direct importance.

4. Vortex motion in the vicinity of an idealized midlatitude westerly trough

The environmental configuration and the four basic experiments in this section have been described in section 2d and Table 3. We note that the trough propagated slowly westward during each of the experiments, the results therefore will not necessarily be applicable to rapidly moving and developing midlatitude trough conditions.

The tracks from all experiments displayed considerable similarity to those of real tropical cyclones, as indicated by Figs. 11a, b. Recurvature consisted of deceleration followed by rapid acceleration into the westries and the more equatorward vortices recurve farther westward, but also at a lower latitude. In comparison to the unbroken ridge environment discussed in the previous section, the presence of a midlatitude trough induced recurvature of vortices initially located at much lower latitudes. This concurs with the observational findings of many previous studies (e.g., George and Gray 1976).

Fig. 11. Tracks of vortex A from a range of initial locations relative to the idealized subtropical ridge and trough: (a) a selection of locations with the dashed lines used for ease of differentiating tracks; the inset indicates the growth of the meridional (dashed) and zonal (solid) separation in time for the vortices indicated by A, B, and C; (b) TR 1, 2, 3, 4 (Table 3), with diabatic heating (solid lines) and adiabatic (dashed lines). The tracks extend over 96 h with locations every 12 h.
a. Track sensitivity

Strong sensitivity to initial conditions is apparent in Fig. 11, even for the relatively static synoptic conditions in our idealized model. The most rapid separation of vortex centers occurs during and after recurvature; little change occurs in the first 24 h, during which the asymmetries associated with cyclone motion developed. The greatest track sensitivity arises from meridional displacements of the initial vortex (inset to Fig. 11a), which produce marked differences in both meridional and zonal location. Smaller sensitivity is found for zonal displacements in the initial vortex location. For example, an eastward displacement of 200 km from location A to B in Fig. 11a, resulted in a final zonal/meridional separation of 350/100 km; the same displacement equatorward from A to C produced a final separation 1150/650 km.

Substantial sensitivity also was found to diabatic heating for those vortices in the region where recurvature might or might not occur (TR1, 2 in Fig. 11b). Vortices initially located nearer to the subtropical ridge, which recurved quickly, were less sensitive to diabatic heating (TR3, 4 in Fig. 11b). Changing the vertical structure to that of vortex B made almost no difference to the motion for the recurring systems (Fig. 12). Maximum sensitivity to vertical structure was found for the vortex in easterly vertical shear (TR1 in Fig. 12).

b. Diagnosis

The environmental changes seen by the recurring vortex are summarized by the flow fields for TR3 in Fig. 13. At 36 h before recurvature ($t = 24$ h) the upper-tropospheric flow to the poleward and westward side of the vortex has turned westward within 750 km. By 12 h before recurvature ($t = 48$ h), the westerly flow is impinging on the vortex in the upper troposphere and lies near the vortex in lower levels. After recurvature ($t = 72$ h) the vortex is embedded in a deep southwesterly airstream. The upper-tropospheric precursor to recurvature is very similar to the observational studies by Gray and his collaborators (George and Gray 1976; Chan et al. 1980; Holland 1984; Hodanish and Gray 1991), in which recurvature began once westerly winds penetrate within 700 km of the cyclone center in the mid-upper troposphere. This change in the poleward and westward quadrant therefore can be considered as an indicator of the cyclone moving into an environment suitable for recurvature.

Quite interesting changes occur also in the cyclone core, which cannot be adequately resolved by current observing systems. These are seen by the flow averaged over 150-km circles centered on the vortex in Fig. 14. TR1 moves continuously westward without recurvature. The remainder represent different times relative to recurvature; the vortices in TR2, 3, and 4 are, respectively, 24, 12, and 0 h before recurvature in Fig. 14a and 0, 12, and 24 h after recurvature in Fig. 14b (note that TR2 and TR4 are different experiments, so that the analyses at recurvature time in Figs. 14a,b also differ in detail). The non-recurring vortex in TR1 experiences a flow from the southeast at all levels and both times, although the upper levels become more southerly as the vortex approaches the trough.

As the other vortices approach recurvature, the upper-tropospheric flow turns more poleward and then becomes westerly at and beyond the recurvature point. The cyclone motion is closely aligned with the mean flow over the core in the lower troposphere. Thus, the motion lags considerably behind the changing upper-flow regime, and the vortices consistently move to the left of, and slower than the deep-layer flow. The degree of leftward deviation increases near recurvature and is similar to observational findings by Gray and collaborators for the mean flow over a larger domain of up to 800-km radius from the center.

Such motion to the left of the deep-layer mean flow has been associated with the addition of a $\beta$-effect type propagation onto a mean environmental flow (e.g., Holland 1984; DeMaria 1985; Evans et al. 1991). We see that the leftward deviation of the vortex from the mean flow over the core (which includes the $\beta$ drift) is a result of the anticyclonic turning of the winds with height that is characteristic of tropical cyclone environments near to the subtropical ridge. When the true advecting layer from 850–500 hPa is chosen, this deviation largely disappears in our modeling results. This suggests that past efforts to find a cyclone motion deviation from a defined steering layer may be biased by the choice of layer. In this study, while changes in the
Fig. 13. Total streamlines at $\sigma = 0.3$ (left panels) and $\sigma = 0.9$ (right panels) after integration of TR3 for 24, 48, and 72 hours. The domain shown is 4000 km $\times$ 4000 km.
upper troposphere might be indicative of potential recurrvature, the recurrvature is achieved by changes in the lower-middle troposphere. Such lower-tropospheric changes may in part reflect the upper changes.

Holland (1984) also argued that the highly divergent outflow and frictional boundary layers should be excluded from the layer-mean steering and advocated use of a 850–300-hPa layer. The cases presented here and in WHL, together with the forecasting study by Velden and Leslie (1991) indicate that Holland chose too deep a layer and that the region from 850–500 hPa might be more appropriate.

While the upper-tropospheric flow does not have a direct role in moving the vortex, it does have an important secondary effect arising from the manner in which the vortex is tilted by the vertical wind shear. In WHL we showed that the adiabatic secondary circulation associated with the vortices in this modeling system arose from their tilted structure. As the vortex tilts downshear, the divergence associated with the vorticity advection induces an ascending motion branch on the downshear side and descending motion upshear from the vortex center. The vorticity changes from vertical advection and divergence in these branches helps maintain a vertical vortex structure and changes the degree of cyclone motion from horizontal advection alone. Since the recurring vortices move through a variety of vertical shears in their environment, this mechanism can be expected to contribute to changes in the cyclone motion.

The contribution of divergence and vertical advection to the adiabatic vortex motion is indicated by the cross sections of vertical motion for TR3 in Fig. 15. Initially, the vortex tilts westward in the prevailing easterly shear. The induced secondary circulation (Fig. 15, t = 24 h) produces upward motion ahead of and slightly to the right of the vortex. The associated divergence and vertical advection effects lead to faster westward motion than that obtained from horizontal advection alone. Vertical coupling helps to advect the surface center poleward. As the vortex approaches recurrvature, it tilts eastward. As a result, the induced secondary circulation weakens (Fig. 15, t = 72 h), then becomes aligned across the direction of motion to contribute to a more rapid recurrvature than would occur from advection alone. The eastward tilt is maintained following recurrvature and contributes to upward motion ahead of and to the right of the direction of motion (Fig. 15, t = 72 h). This helps accelerate the vortex toward the east and maintains a trajectory slightly eastward of the advecting flow in low levels, as does coupling between layers in the tilted vortex.

The effects of vortex deformation described in section 3 also apply to the recurving vortices here. The trough/ridge environment produced less vortex deformation than did the subtropical ridge environment in section 3, however.

5. Conclusions

We have investigated the recurrvature of tropical cyclones by use of a five-level, primitive equation model and several idealized environments in which the vertical wind shear, subtropical ridge, and midlatitude trough are varied to simulate observed conditions associated with recurrvature. We have shown that a cyclone can recurve through an initially unbroken subtropical ridge, but that the presence of a midlatitude trough substantially enhances the recurrvature potential. The process is sensitive to the degree of diabatic heat-
Fig. 15. Adiabatic vertical motion (contour interval $5 \times 10^{-4} \text{ s}^{-1}$, dashed is upward) for vortex A in TR3 along the direction of motion (left panels) and perpendicular to the motion (right panels) for $t = 24$, 48, and 72 hours.
ing of the vortex, the vertical and horizontal structure of the environment, the meridional location of the cyclone, and, to a lesser degree, the vertical structure of the cyclone.

Although there are substantial differences of detail, our analysis indicates that the vortex motion arises from the baroclinic motion mechanisms described by Wang et al. (1993). In a vertical wind shear, the cyclones tilt, then develop a secondary circulation that maintains a stable, tilted configuration. They then move predominantly with the mean lower and midtropospheric flow over their core. This advecfing flow consists of the initial environment plus modifications arising from readjustments of the potential vorticity as the cyclone and environment interact. One such adjustment is the so-called $\beta$ effect, in which the potential vorticity of the environment is advecf and deformed by the cyclonic circulation. The anticyclonic gyre becomes established on the poleward side of the subtropical ridge and is advected eastward to become the dominant anticyclonic circulation. This anticyclone is present in observational studies of tropical cyclone recurvature, but its role in recurvature has generally been neglected in favor of the upper-tropospheric changes poleward and westward of the cyclone. As the cyclone approaches recurvature, horizontal shearing deformation produces a Kirchhoff-type interaction (Ritchie and Holland 1993) in which the elongated vortex rotates about itself to increase the rate of recurvature.

The relative importance and effect of these processes varies according to the cyclone and ambient conditions. One illustrative example for a cyclone recurring ahead of a midlatitude trough (experiment TR3) is provided in Fig. 16. This cyclone started equatorward of the subtropical ridge in an east-southeasterly flow with eastward vertical wind shear (panel 1 in Fig. 16); the environmental (ENV) advecfing flow in the lower-midtroposphere is slightly poleward of westward; an additional weak poleward drift due to potential vorticity (PV) effects is reinforced by contributions from induced divergence (DIV) and tilting of the vortex (TILT), so that a northwestward movement results.

As the cyclone approaches the subtropical ridge (panel 2 in Fig. 16), a strong anticyclonic gyre develops just poleward of the ridge axis and to the east of the cyclone. This gyre is advected eastward and becomes the dominant circulation in the ridge. Thus, the total environment has been modified with the result that the vortex moves on a more poleward path (ENV). A local tendency to drift along and westward of the PV gradient is still maintained (PV). Substantial horizontal shearing deformation of the cyclone occurs, which leads to a reinforcement of the anticyclonic gyre and to an eastward motion tendency for the cyclone (DEF). The cyclone also experiences an increasing westerly vertical wind shear and tilts to the east. This induces an eastward motion tendency from low-level convergence (DIV) and by retardation of the poleward movement of the surface center by vertical interaction (TILT).

After recurvature (panel 3 in Fig. 16), the vortex lies in a sheared southwesterly flow. It tilts and deforms to the poleward and eastward, producing a southeastward motion tendency (DEF, TILT). The induced divergence fields (DIV) accentuate the northeastward motion of the vortex from the environmental flow (ENV). The movement associated with continuing adjustments of the environmental potential vorticity field in the cyclone vicinity remains to the north-northwest (PV).

Diabatic heating has potential to change the characteristics of the recurvature from changes to the cyclone structure, stratiform cloud that develops along the deformation zone ahead of a recurring cyclone, and overall changes to the large-scale flow. In this study we have restricted ourselves to consideration of the diabatic effects on the vortex alone by use of a CISK-type parameterization within 400 km of the cyclone center. We confirm the findings by Wang et al. (1993) that diabatic heating is not essential to the movement of a baroclinic cyclone. In comparison to adiabatic conditions, the major impact of such diabatic heating is to reduce the vertical tilt of the vortex. For the environments examined here, this results in a slightly slower motion directed to the right of the adiabatic vortex track and thus increased potential for recurvature. The results
for the CISK-type parameterization used here thus indicate a sensitivity to diabatic heating that calls for further investigation. In particular, moist convection responding to induced convergence and vertical motion, and to developing, large-scale asymmetries, may produce substantially different responses.

We have found substantial sensitivity to changes in meridional location of the vortex at the initial time. For example, after allowing 24 h for the initial adjustment, an initial 200-km meridional displacement lead to a zonal/meridional separation of 1150/650 km after a further 72 h. The forecasts are much less sensitive to zonal displacements. These results indicate that subtle errors in either the cyclone location or the equatorward extent of midlatitude westerly flow may result in large track forecast errors. An additional consideration, not examined in this paper, is the potentially large impact of variations in horizontal storm structure.

We conclude that the observational findings by Gray and collaborators, that significant changes in the upper tropospheric zonal wind fields to the poleward side of tropical cyclones occur one to two days before recurvature, should be taken as indicative of the movement of the cyclone into a region where recurvature is possible. Our findings suggest that the vorticity and environmental changes in middle and lower levels may be more important for general environmental interactions leading to recurvature. Changes to the east of a cyclone moving near to a subtropical ridge may be the most important in some circumstances. These findings concur with the recent study by Ford et al. (1993) and may be found in the results of previous studies by George and Gray (1976) and Chan (1984).

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