

Tropical Cyclone Genesis in a Global Numerical Weather Prediction Model

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ABSTRACT

The physical processes responsible for tropical cyclone genesis over the western North Pacific are investigated using the operational analyses of the U.K. Meteorological Office global model for the years 1992–93. The analyses are divided into two groups depending on whether a particular analysis led to the prediction of a real genesis in the atmosphere. Composites of the winds at 850 and 200 hPa from the analyses that fall into each of the two groups (the successful and failed predictions) are then made and compared.

It is found that about 3 days prior to genesis, the low-level trades north of the pregenesis vortex begin to strengthen. One day later, an upper-level westerly trough and/or the Tropical Upper-Tropospheric Trough (TUTT) starts to encroach toward the pregenesis cluster. The low-level trades near the cluster continue to intensify and a surge of southwesterly winds occurs to the south of the cluster. On the day before genesis, the southwesterlies become the dominant low-level feature. At the upper levels, the TUTT has moved to the northeast of the pregenesis vortex at this time. Most of these features are found to occur in a high percentage of the individual cases. Comparisons with the analyses that led to failed predictions also reveal these features to be statistically significant.

Calculations of the angular momentum (AM) fluxes suggest that at the low levels, the enhancement of the trades and the surge in the southwesterlies contribute to the spinup of the vortex primarily through two processes: the symmetric import of planetary AM and the asymmetric import of relative AM, with the former being more dominant. As the genesis time approaches, the contribution to the latter process by the trades becomes smaller relative to that by the southwesterlies. At the upper levels, the role of the TUTT or westerly trough is to reduce the export of planetary AM by the symmetric outflow. However, the contribution by the upper-level flow toward the genesis process appears to be minimal until the day before genesis. Comparisons with the analyses in the failed prediction category using individual cases again suggest that differences between the results in these two categories are statistically significant.

1. Introduction

Over the Tropics and especially along the monsoon trough or the intertropical convergence zone, cloud clusters constantly form and dissipate within a few hours to a day. However, some of them maintain their identity for over a day and finally become a tropical cyclone (TC). The question is, what are the conditions necessary to cause these latter clusters to develop into a TC, a process generally referred to as genesis?

An examination of the meteorological and oceanographic parameters near the locations of genesis led Gray (1979) to identify six climatological conditions that appear to be favorable for TC genesis. They include three thermodynamic parameters (high sea surface temperature and a deep ocean mixed layer, conditionally unstable atmosphere, and a moist lower troposphere) and three dynamic parameters (nonzero Coriolis param-

eter, strong low-level cyclonic shear and upper-level anticyclonic shear across the cluster at large distances, and small vertical shear near the center of the cluster). These parameters can be combined to form a seasonal genesis potential the distribution of which agrees very well with the seasonal distribution of the location of TC genesis. McBride and Zehr (1981) further identified the vertical shear to be the most important factor in distinguishing the disturbances that develop into TCs and those that do not. Pregenesis clusters tend to have strong positive (negative) zonal vertical shear at large distances to their north (south) but zero shear across their center. This implies strong cyclonic (anticyclonic) horizontal shear at the low (upper) levels. Love (1985a,b) proposed cross-equatorial surges as a mechanism for enhancing the low-level cyclonic shear, and Merrill (1988a) suggested the Tropical Upper-Tropospheric Trough (TUTT) to be the synoptic feature at the upper levels for enhancing the anticyclonic shear. In fact, Sadler (1976) has identified the TUTT as a precursor not only in the genesis but also in the intensification process.

Based on the results of the composite studies, Challa and Pfeffer (1980) and Holland and Merrill (1984) sim-

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ulated the genesis process and found that eddy fluxes of angular momentum at the upper levels appear to be most important in determining genesis. This contribution of the horizontal transport of angular momentum was verified by Lee (1989), who examined the analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF). Recently, Briegel and Frank (1997) further composited the ECMWF analyses from a few days before genesis to the genesis time and found large-scale characteristics associated with TC genesis similar to those from the composite studies of McBride (1981a,b). The most prominent features include the presence of an upper-level trough and low-level wind surges prior to genesis.

In all these previous studies, the focus has been on the synoptic-scale conditions present before genesis occurs. Although compositing actual observations may capture some of the pertinent features, whether these features can be identified from the analyses of a numerical weather prediction (NWP) model depends on the model resolution, initial guess field, analysis algorithm, etc. In other words, when such an analysis is used as the initial condition for the model, no TC may be developed in the subsequent integrations even though a TC may have formed in the real atmosphere. This inability to produce genesis could reflect a deficiency in the model physics. It also suggests that the analysis may be incorrect. On the other hand, if the model can produce a TC that is actually observed from a particular analysis, this analysis may be considered as a valid representation of the actual atmospheric conditions, assuming that the physics of the model is largely correct (to be justified later in this paper). Therefore, by comparing the two types of analyses (those that led to successful predictions of genesis and those that failed), the important physical parameters and processes may be identified. Of course, a third possibility exists in which the model produces a TC that is not observed. This again may result from an incorrect analysis. However, because the TCs predicted are fictitious, this case will not be considered further in the present study. The objective of this research is to utilize the NWP analyses to study the synoptic-scale features prior to genesis and the dynamical processes that lead to genesis. The ability of the NWP model to predict genesis or the quality of the analyses will not be evaluated.

The operational predictions from the U.K. Meteorological Office (UKMO) global model during 1992–93 for the western North Pacific (WNP) are used for this study. Details of the model can be found in Cullen (1993). The parameters employed are described in section 2. The methodology to identify successful and failed predictions of TC genesis is also given. Predictions made at 24, 48, and 72 h prior to genesis are examined. The composite synoptic-scale patterns from the operational analyses for each of these three forecast periods of both the successful and failed predictions are compared in section 3. Calculations of the angular momentum transports to deter-

mine their role in the genesis process are presented in section 4. A summary of the results together with a general discussion on the physical processes responsible for TC genesis are given in section 5.

2. Data and methodology

a. Data

Analysis and forecast fields of the UKMO model for the 1992 and 1993 are kindly provided by UKMO. The fields have a horizontal resolution of 2° lat \times 2° long. Parameters examined include the mean sea level pressure (MSLP) and 850- and 200-hPa zonal and meridional winds. The relative humidity fields have also been studied but were found to contribute little to differentiate between successful and failed predictions. This might be expected since the thermodynamic conditions for TC genesis stated by Gray (1979) are generally satisfied in the regions over the WNP where TCs typically develop (McBride and Zehr 1981). The moisture fields are therefore not studied further.

The Annual Tropical Cyclone Reports published by the Joint Typhoon Warning Center in Guam (JTWC 1992, 1993) are used to identify the successful and failed cases of the UKMO model predictions. For each TC, the first warning position given in the report is considered to be the location of genesis. Although this may not be the exact point when genesis occurred, it is the most consistent way to define the time of genesis. Locations prior to the first warning may be present in some cases but not in others. Because the systems at these earlier times are by definition quite weak, estimates of their intensity are bound to have appreciable errors. It would be very subjective and difficult to choose one of these locations as the genesis point rather than the first warning position. To avoid such ambiguities, the first warning position is therefore chosen.

b. Identification of genesis

To determine whether a particular forecast is successful in predicting genesis, the following procedure is employed, using the 24-h forecast as an example.

Suppose the first warning for a particular TC was issued at 0000 UTC on a given day D . For a 24-h forecast, the $T + 24$ h MSLP forecast made from the analysis at 0000 UTC on day $D - 1$ is examined. The MSLP forecast data at grid points within a square box of 16° lat \times 16° long centered on the grid point nearest to the first warning position are scanned. The absolute minimum is then identified. This minimum must then satisfy the requirement that its value is less than that of its neighboring 24 points. This requirement ensures that the grid point of absolute minimum represents a low pressure system that has a positive radial pressure gradient. If this is met, the value of the 850-hPa relative vorticity at this grid point is then checked using the

TABLE 1. The number of successful and failed predictions of genesis made by the UKMO model, the mean latitude and longitude of the cases in each category (numbers in parentheses indicating the standard deviation), and the percentage of successful predictions for TCs in the WNP in 1992–93.

Forecast period	Successful (category A)			Failed (category B)			Percentage of success
	Number of cases	Latitude (°N)	Longitude (°E)	Number of cases	Latitude (°N)	Longitude (°E)	
24 h	43	14.6 (4.9)	142.9 (15.9)	16	14.6 (5.4)	137.7 (15.2)	73%
48 h	27	13.2 (3.8)	142.2 (15.0)	32	15.6 (5.7)	140.5 (16.0)	46%
72 h	25	13.5 (4.3)	138.2 (14.2)	34	14.7 (5.1)	141.8 (15.1)	42%

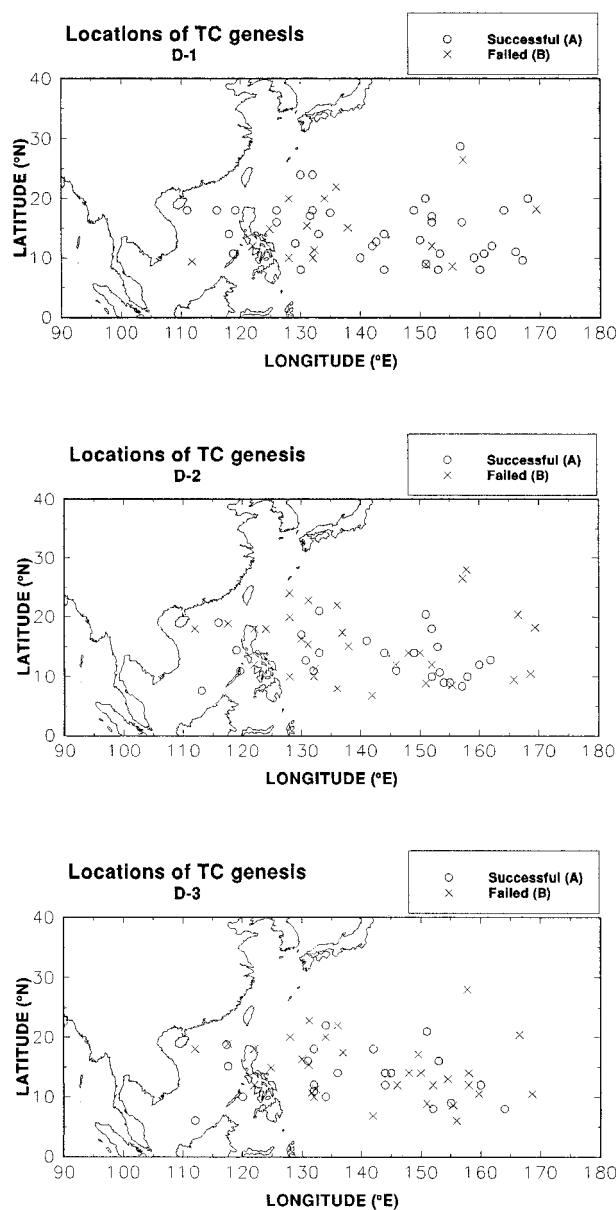


FIG. 1. Location of the genesis points for both successful and failed predictions made at 1 ($D - 1$), 2 ($D - 2$), and 3 ($D - 3$) days before genesis.

above procedure again, except now the maximum value and a negative radial gradient are required. A grid point that satisfies both the MSLP and relative vorticity requirements is then considered to be the genesis location. The 24-h forecast is then identified as a success case (category A) if the grid point is within $\pm 4^\circ$ lat of the warning position. Otherwise, the forecast is labeled as a failed case (category B). For the 48-h (72-h) forecasts, a similar procedure is used except that the $T + 48$ ($T + 72$) forecast made from the analysis on day $D - 2$ ($D - 3$) is examined.

As expected, the success rate decreases as the forecast time increases (Table 1). Over 70% of the genesis events in 1992–93 can be predicted from the 24-h forecasts. However, by 72 h, only less than 50% of the cases are predicted. This result suggests that the inherent signals at 48–72 h prior to genesis are not very strong so that small errors in the analyses could lead to failed predictions of genesis.

Although about 80% of TCs over the WNP form within the monsoon trough (Gray 1979), it is of interest to see whether the TCs in the two categories developed under different environments. Figure 1 gives the location of the TCs on the genesis day for both categories and for all the three forecast periods. No obvious difference in the genesis locations between the two categories can be discerned from each of the panels. In fact, the average latitude and longitude of the cases in each category (see Table 1) are very similar in both categories. Application of a two-sample t test (Panofsky and Brier 1958) on the mean locations of the two samples at each of the forecast periods indicates no significant difference between them. This suggests that differences in the composite flow fields between the two categories cannot be attributed to the different genesis mechanisms and should be due to differences in the analyses.

c. Compositing procedure

In section 3, the large-scale conditions associated with the successful and failed cases are composited and compared to identify the significant differences. The composites are made from the analysis and not the forecast fields. That is, using the same terminology described

above, for the successful and failed 24-h forecasts, the analyses at $D - 1$ are examined, and similarly for the 48- and 72-h forecasts.

All the composites are made relative to the genesis point (GP). For those in category A (successful cases), the GP is defined as the grid point identified through the procedure described in section 2b. Note that this choice of the center of the vortex may present a slight error in calculating the angular momentum transports (see section 4) because the GP may not coincide with the circulation center of the vortex in the analyses. However, since the GP is the grid point of highest vorticity and lowest pressure, it is likely that the two would be very close. Further, we are interested mainly in the large-scale patterns so that a slight shift in the center location should not be very important. Therefore, the GP is used as the center of the pregenesis vortex. For the failed cases (category B), it is sometimes difficult to identify the circulation center, which might be expected because, by definition, the analyses were incorrect (see the justification of this statement in section 3). Therefore, the first warning position is used as the GP. Because this position in general does not coincide with a grid point, the data are all interpolated using a bicubic spline so that the center grid point of the domain is always at the GP.

The domain of the composite is $\pm 14^\circ$ lat from the GP. The zonal and meridional winds for an individual case are first interpolated onto a 1° lat \times 22.5° azimuth polar grid and then converted to radial and tangential winds (for ease of calculation of angular momentum fluxes, see section 4). These wind components are then composited. Because all previous studies (e.g., McBride and Zehr 1981) suggest that winds at the lower- and upper-tropospheric levels are important for genesis, only those at 850 and 200 hPa are composited and examined.

The question of whether composite results are representative of the individual cases often arises. Two types of tests are used to address this question. In section 3, the steadiness of the winds is calculated. This parameter is defined as the ratio of the magnitude of the mean wind vector to the average speed of the wind at the same grid point without regard to direction for all individual cases. That is,

$$\text{steadiness} = \frac{|\mathbf{V}|}{V_m},$$

where V_m is the average wind speed of all the individual cases, \mathbf{V} the composite wind vector, and $||$ means the magnitude. A ratio close to 1.0 (or a percentage close to 100) therefore implies that the composite wind direction is representative of that of individual cases. An area with a large value of the steadiness suggests that the composite flow pattern within this area is meaningful. The two-sample t test is also performed at all grid points when studying the difference between the winds in the two categories. An area within which the t values

are greater than the threshold values for significance (at the 95% level) suggests that the difference in the flow patterns between the two samples in this area are not likely due to random chance. This test is again applied in section 4 to determine whether one term in the angular momentum flux equation is significantly larger than the other, or greater than zero, whichever is applicable.

3. General large-scale features

a. 24-h forecasts

A much stronger cyclonic 850-hPa flow can be found in the successful cases compared with the failed cases (Figs. 2a,b). Notice that the center of the circulation in category A is displaced to the south (and perhaps slightly east) of the GP. This is reasonable since the GP occurs 24 h after this analysis time. For the failed cases, only a broad circulation centered around 4° lat southeast of the GP can be found, with generally northeasterly or northerly winds over the GP.

To determine whether the strong trades to the north and southwesterly flow to the south of the GP in the successful cases did occur in most of the individual cases, the steadiness of the mean wind vector at each of the grid points is calculated. It can be seen from Fig. 2a that both the trades and the southwesterlies in the successful cases are very steady (with steadiness $> 80\%$). On the other hand, only the trades northeast of the GP are steady in the analyses that failed to produce genesis (Fig. 2b).

Therefore, the main differences in the 850-hPa wind fields between the two categories are a strong southwesterly flow south of the GP and easterly to northeasterly flow to the north and northwest (Fig. 2c). These differences are statistically significant at the 95% level based on the results of the t test. In fact, even the southerly flows to the southeast and east of the GP are significantly stronger in the successful cases. These results suggest that enhanced southwesterly flow (perhaps from a cross-equatorial surge, as suggested by Love 1985a,b) and/or enhanced trades are responsible for the genesis, a result consistent with previous composite studies.

At 200 hPa, the flow is primarily easterly in the southern half of the domain for both categories (Figs. 3a,b) although it is much steadier than in category A, as can be seen from the area enclosed by the 80% steadiness contour. In addition, a distinct trough can be seen to the northeast of the GP in category A, with anticyclonic cells to the northwest and east. This pattern resembles very much the schematic provided by Sadler (1976), who proposed the presence of an upper-level trough as a major factor in genesis. The trough identified in Fig. 3a is therefore either a westerly trough or a TUTT. In the failed cases, only a broad anticyclone can be found (Fig. 3b). Although the steadiness of the winds in this northeast quadrant is not high ($< 50\%$), the absence/presence of a trough is the main distinguishing and sta-

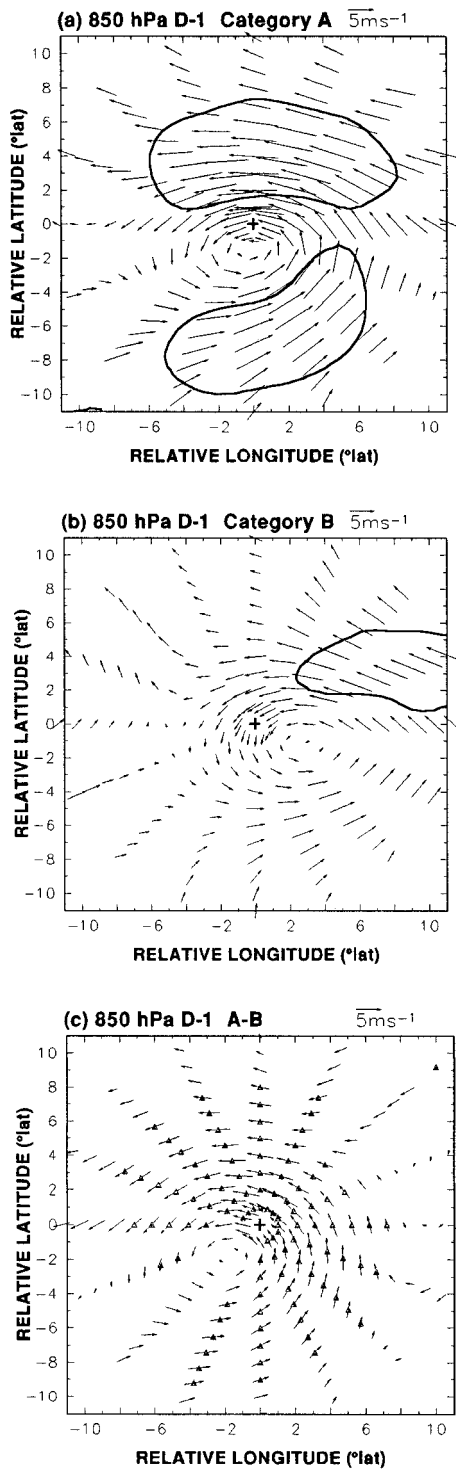


FIG. 2. (a) Composite 850-hPa wind vectors at $D - 1$ for the successful 24-h forecasts (category A); (b) as in (a) except for category B; (c) difference vectors [(a) minus (b)]. The (+) sign indicates the location of the GP. The thick line in (a) and (b) is the 80% wind steadiness contour (see text for how this is calculated). The triangles in (c) indicate grid points where the mean winds of the two categories are significantly different at the 95% level (based on the t test) in at least one of the wind components (zonal or meridional).

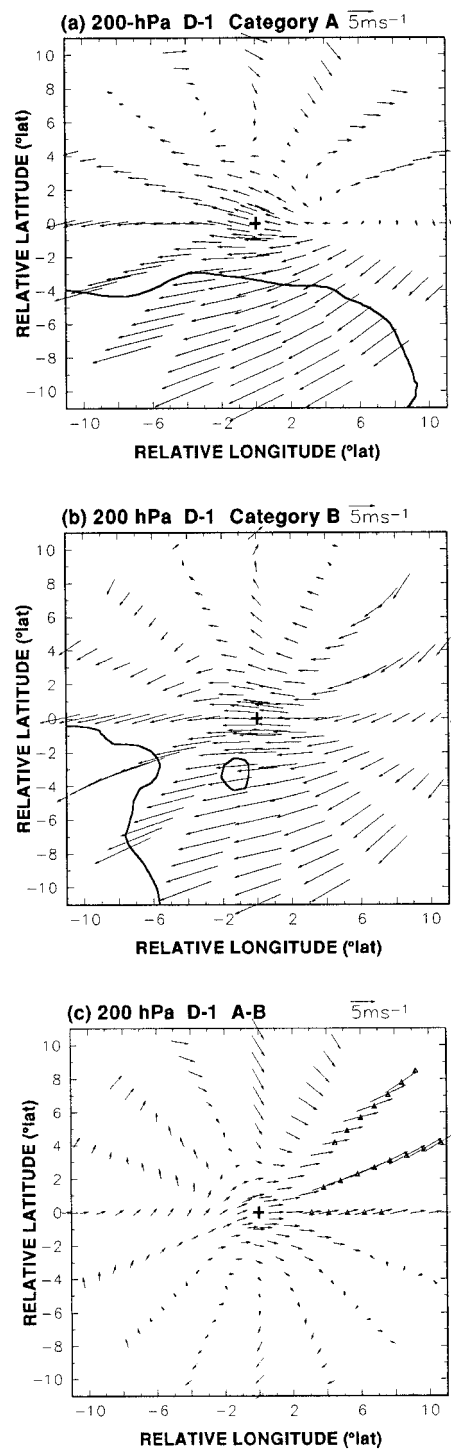


FIG. 3. As in Fig. 2 except for the flow at 200 hPa.

tistically significant feature between the two categories (Fig. 3c). Strong southwesterly flow to the east and northeast at 200 hPa therefore appears to be crucial in the genesis process.

One important dynamic feature associated with TC genesis discussed by Gray (1979) and McBride and Zehr

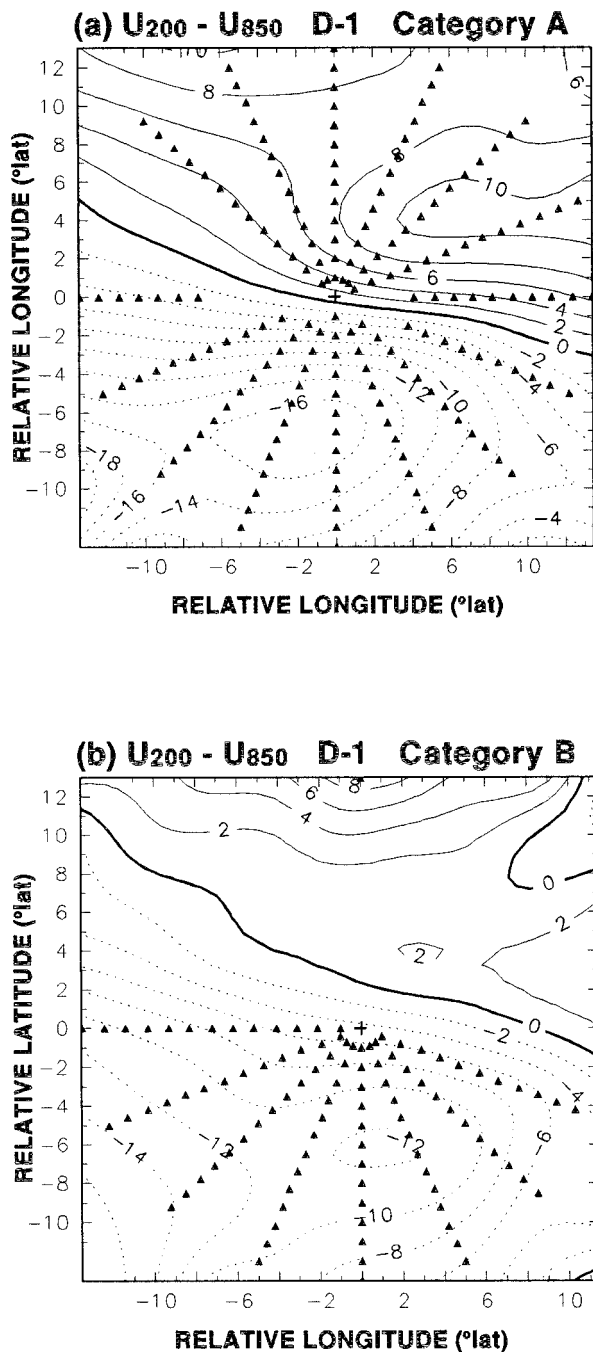


FIG. 4. (a) Zonal wind shear between 200 and 850 hPa at $D - 1$ for the successful 24-h forecasts (category A); (b) as in (a) except for category B. The (+) sign indicates the location of the GP. The triangles indicate grid points where the mean zonal wind shear is significantly different from zero at the 95% level (based on the t test). Unit: m s^{-1} .

(1981) is minimal vertical shear near the center and large shear in the surrounding flow. The difference between the 200- and 850-hPa zonal winds indeed gives the expected results (Figs. 4a,b). For the successful predictions, the composite analysis shows the zero line being

very close to the GP with strong negative (positive) shear to the southwest (northeast). A strong horizontal gradient of the vertical shear can also be found in the vicinity of the GP. Notice that the magnitude of the vertical shear is significantly (statistically) different from zero at large radii, in agreement with previous studies. On the other hand, over the GP in the failed cases, the vertical shear is negative and is only weakly positive to its north. In addition, only the area of negative shear (south of the GP) is statistically significant.

To summarize, these results suggest that the large-scale dynamical conditions of the atmosphere prior to the development of a TC in the model are consistent with those from previous composite studies of observational data and analyses from NWP models. More importantly, they highlight the fact that if the analysis is incorrect, no genesis can be developed in the model. This, a posteriori, justifies our assumption that the model physics is largely correct so that comparing the analyses of the successful and failed predictions can provide an understanding of the physical processes involved in genesis. It should also be pointed out that the composite results are all statistically significant so that they should be representative of the individual cases.

b. 48-h forecasts

Similar to the results for the successful 24-h forecasts, the 850-hPa composite analysis at $D - 2$ for category A indicates strong easterly flow to the north and southwesterly flow to the south (Fig. 5a). Notice that both features have a steadiness of greater than 80%. The center of the pregenesis vortex can also be seen to be located about 3° lat south-southeast of the GP. On the other hand, the 850-hPa flow for the failed predictions gives only a broad-scale cyclonic flow (Fig. 5b), with a weak circulation center at around the same location as that for the failed 24-h predictions (see Fig. 2b). Notice also the flow to the north of the GP is southeasterly instead of easterly as in category A. None of the mean winds in Fig. 5b has a steadiness greater than 80%. Comparing Figs. 2b and 5b, it appears that in both sets of failed predictions, the UKMO analysis correctly identified the large-scale monsoon trough near the latitude of the GP but failed to capture the pregenesis vortex, which is present in the analyses that produced the successful predictions. The difference between the analyses shown in Figs. 5a and 5b suggests that for the 48-h predictions, surges in the trades appear to be more important than those from the cross-equatorial flow (Fig. 5c). Notice that the largest difference is to the north and near the GP. Results of the t test also confirm that the most statistically significant difference between the two categories is in the area of the trades.

Similar to category A at 24 h, the 200-hPa flow for the successful predictions indicates strong easterly flow south of the GP (Fig. 6a). A broad ridge exists north of the GP with a hint of a trough to the northeast (resem-

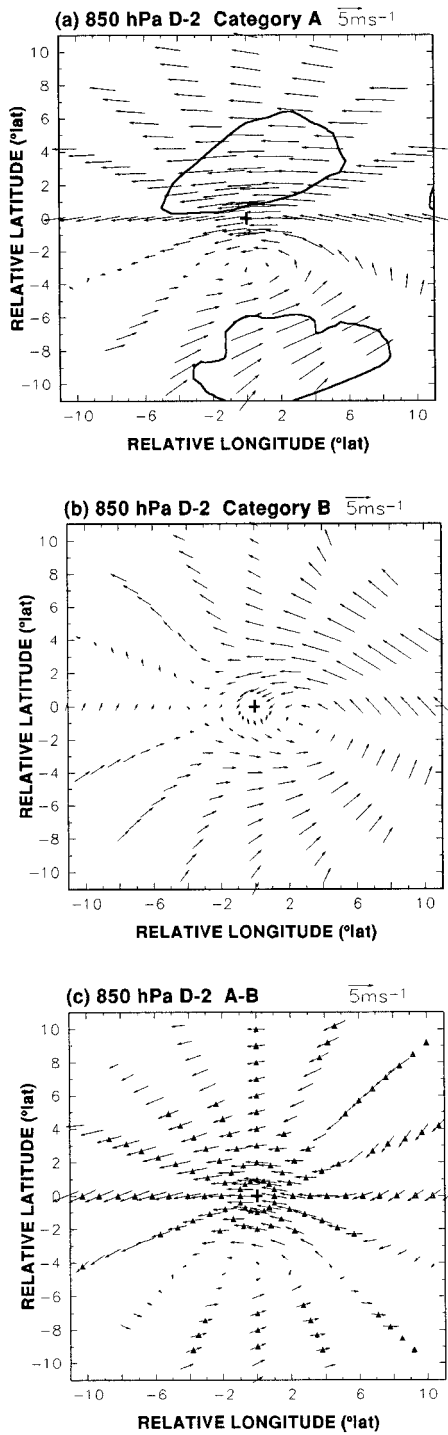


FIG. 5. As in Fig. 2 except for the 48-h forecasts. Note the absence of the 80% steadiness contour in (b).

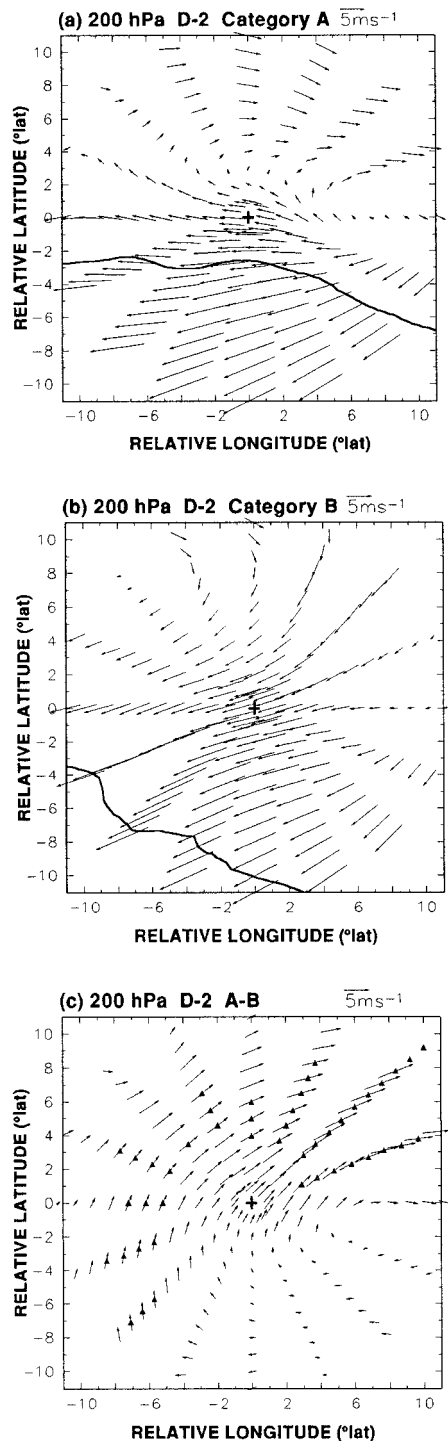


FIG. 6. As in Fig. 2 except for the 200-hPa flow and the 48-h forecasts.

bling that of the TUTT) and one to the northwest (probably a midlatitude trough). The configuration in Fig. 6a suggests a diffluent flow around the GP, thus favoring the exhaust of excess heat from the convection (as suggested by Sadler 1976) or the export of anticyclonic

angular momentum (as suggested by Challa and Pfeffer 1980). Notice again that the easterly flow is the most steady. For the failed predictions, northeasterly flow prevails throughout much of the domain (Fig. 6b) but this flow is generally quite variable (since the steadiness is

generally $<80\%$ throughout the domain except at the southwest corner). The main difference between the flow in these categories is thus a strong southwesterly flow to the north and east of the GP (Fig. 6c), which is consistent with Merrill's (1988b) finding. In addition, the southerly flow to the west and southwest of the GP is also significantly different between the two categories. This suggests a more anticyclonic flow around the area where a TC would likely form within the next 2 days.

The vertical zonal wind shear between 850 and 200 hPa again shows very similar results as those for the 24-h forecasts. These shears will therefore not be shown.

c. 72-h forecasts

Whereas the $D - 3$ 850-hPa composite wind analysis for the $T + 72$ successful predictions gives essentially the same results as those for the $T + 24$ and $T + 48$ forecasts, the center of the pregenesis vortex is farther away from the GP, about 5° lat to the southeast (Fig. 7a). This means that generally speaking, the center of a cluster migrates northwestward and then northward to the GP from 72 h before genesis occurs. Notice also that the southwesterly flow is much weaker than the easterly flow to the north. Indeed, the area with a steadiness in the wind greater than 80% now exists only north of the GP.

The 850-hPa analysis for the failed predictions is quite different from those for the $T + 24$ or $T + 48$ forecasts. The monsoon trough now lies to the west of the GP where only an area of confluence can be found (Fig. 7b). Note also that the southwesterly flow is about the same order of magnitude as in the analysis for the successful predictions. However, the winds are generally more variable in individual cases since none of the composite winds has a steadiness of greater than 80%. Therefore, the main difference between the two categories is the enhanced trades to the north and west of the GP (Fig. 7c). This is the area where the t test suggests that there is only less than 5% chance that the difference between the winds in the two categories can be attributed to random chance.

The 200-hPa flow for the $T + 72$ h forecasts in the two categories does not show much difference, with generally easterlies especially south of the GP. It appears that 3 days before genesis, the upper-level flow does not have much of a contribution.

d. Summary

Based on these results, the following scenario probably describes the large-scale dynamic conditions from about 3 days prior to genesis to the time of genesis. At around $D - 3$, low-level trade winds to the north of a pre-existing cluster embedded in a monsoon trough begin to strengthen, increasing the cyclonic vorticity associated with the cluster. At this time, the upper-level

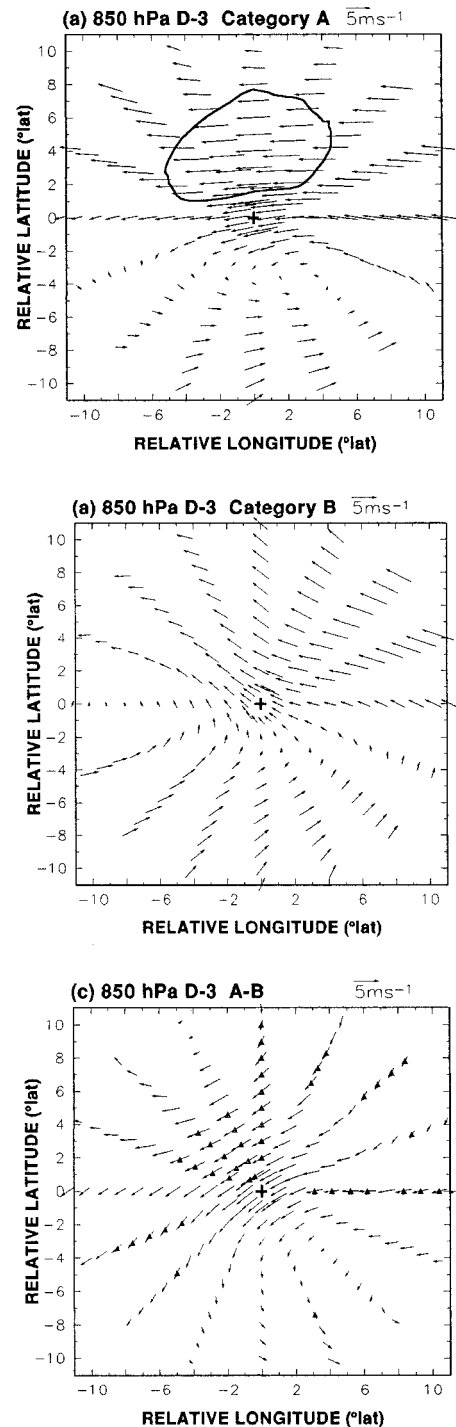


FIG. 7. As in Fig. 2 except for the 72-h forecasts. Note again the absence of the 80% steadiness contour in (b).

flow is generally easterly. A day later, the low-level southwesterly flow to the south of the cluster also intensifies (probably as a result of a cross-hemispheric surge). This couples with the enhanced trades to the north to form a cyclonic vortex. During this time, the

prevailing easterly flow has advected the cluster westward. Note that although the easterlies north of the vortex may be related to its movement, the fact that most of the pregenesis vortices in *both* categories were westward-moving suggests that the trades north of the vortex found in the analyses that led to the successful predictions are actually strengthened by the larger-scale environment. This point is further substantiated by the result that, within the entire northern sector, the winds in the two categories are significantly different from each other.

At the upper levels, the subtropical ridge migrates southward so that westerly flow appears at around 10° lat from the cluster. This southward movement of the ridge is apparently related to the encroachment of a trough from the west and/or the TUTT from the northeast. This juxtaposition of the upper- and lower-level flows gives a weak vertical shear near the genesis point but a strong positive (negative) shear to its north (south). Twenty-four hours prior to genesis, the southwesterly surge intensifies further so that a strong low-level cyclonic vortex develops just south of the genesis point. The midlatitude upper-level trough or the TUTT is now located to the northeast of the cluster. This configuration not only gives a minimum vertical shear near the center of the system but also allows a strong spinup at the low levels. As a result, a tropical cyclone develops within 24 h.

Although many of the elements described above have been found by previous researchers, the comparison between the analyses that led to successful and failed predictions identifies the important features that are necessary for the genesis of a tropical cyclone. They include the enhancement of the low-level trades at the early stage of pre-genesis, and a southwesterly surge at low levels as well as an encroachment of a trough and/or TUTT at the upper levels near the time of genesis. It should also be pointed out that these results should be representative of the situation in individual cases since differences in these features between the two categories are found to be statistically significant to at least the 95% level.

Pfeffer and Challa (1980) suggested that angular momentum transport at the upper levels is the main physical mechanism that causes a cloud cluster to develop into a TC. Holland and Merrill (1984) also proposed this transport to be important in the intensification process. Therefore, calculations on the different components of angular momentum transport are made in the next section to determine the validity of these hypotheses.

4. Angular momentum transports

a. The components

The absolute angular momentum m is defined as

$$m = vr + \frac{1}{2}fr^2, \quad (1)$$

where v is the tangential wind, r the radius, and f the Coriolis parameter. To study the various contributions to the change in angular momentum (AM), one can separate the wind components into the symmetric and asymmetric parts (denoted by an overbar and a prime, respectively). Thus, the two wind components can be written as

$$\begin{aligned} u &= \bar{u} + u', \\ v &= \bar{v} + v', \end{aligned}$$

where u is the radial component.

The AM flux across a circle centered on the TC at radius r is then given by

$$M(r) = \frac{\int_0^{2\pi} \left(vr + \frac{fr^2}{2} \right) ur \, d\theta}{\int_0^{2\pi} r \, d\theta}. \quad (2)$$

Substituting the wind components then gives

$$M(r) = r\bar{u}\bar{v} + r\overline{u'v'} + \frac{f_0 r^2 \bar{u}}{2} + \frac{r^2 \overline{fu'}}{2}, \quad (3)$$

where f_0 is the Coriolis parameter at the center of the system. The overbar indicates an azimuthal average.

In the present study, the symmetric and asymmetric radial and tangential winds of individual cases are first calculated before the computation in (3) is made. This differs from the method used by Merrill (1988a), who separated the asymmetric flux term $r\overline{u'v'}$ into resolved and residual components. However, the interpretation for the latter is quite difficult and does not add much in the present study because every case of the composite contains the same number of data points so that no sampling problem exists as in Merrill's (1988a) study.

The AM transport into or out of the disturbance therefore consists of the four terms on the right-hand-side of (3), namely, the symmetric relative angular momentum (RAM) flux, the asymmetric or eddy RAM flux, the symmetric Coriolis torque, and the asymmetric or eddy Coriolis torque, respectively. Adding the first and third (second and fourth) terms gives the total symmetric (asymmetric) flux. Here it is assumed that frictional losses are negligible since only the 850- and 200-hPa flows are considered.

In the following calculations, all the flux terms are calculated using the GP (defined in section 2) as the center of the (polar coordinate) system.

b. 24-h forecasts

Recall from Fig. 2a that the 850-hPa flow for category A is strongly cyclonic and quite symmetric. As a result, the symmetric flux dominates over the asymmetric term (Fig. 8a), with the former being much more negative (i.e., an AM import). Beyond about 7° lat radius, the

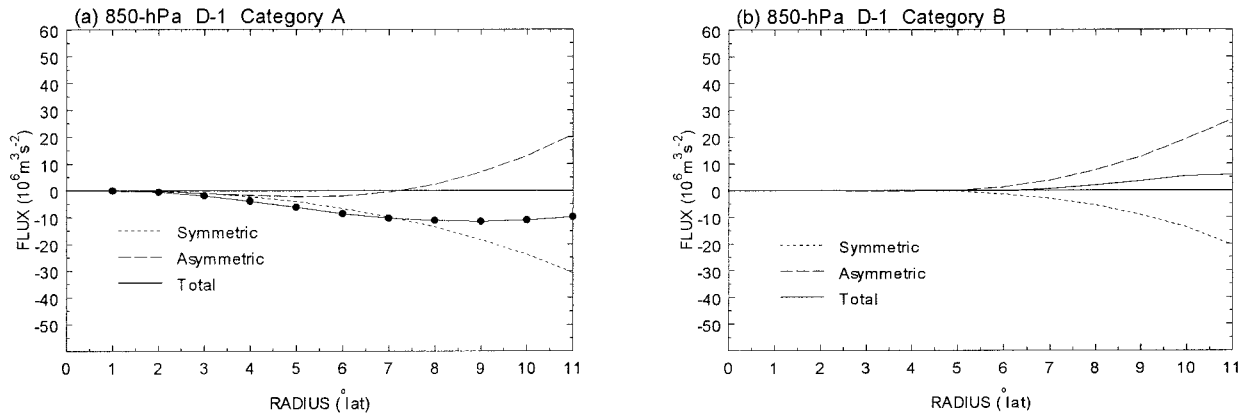


FIG. 8. Symmetric (short-dashed), asymmetric (long-dashed), and total (solid) fluxes of angular momentum at 850 hPa and $D - 1$ for the 24-h forecasts in (a) category A and (b) category B. The dots in (a) indicate that at these radii, the total RAM flux is significantly different from zero at the 95% level (based on the t test). At no radius in (b) is this condition satisfied.

asymmetric flux becomes positive. The net result is therefore an import of angular momentum. A t test of the total angular momentum flux suggests that it is significantly different from zero at all radii. Note that the t test for the total flux at small radii still gives a statistically significant value even though the flux is close to zero because the standard deviation is quite small and the number of cases is large (39). In any case, the composite result should hold for individual cases. For category B, the symmetric and asymmetric fluxes almost cancel each other so that the net AM flux is very small (Fig. 8b). In fact, at no radius is the total flux significantly different from zero.

A breakdown of the symmetric terms for category A shows the Coriolis torque to be dominant especially at large radii (Fig. 9). This domination is statistically significant beyond 6° lat. Since f_0 is constant, this result suggests that a stronger symmetric inflow contributes

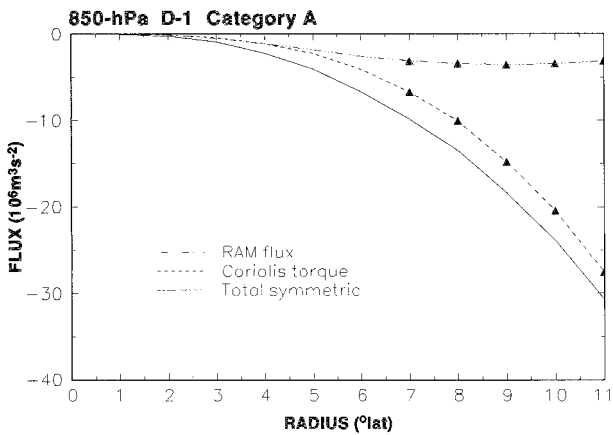


FIG. 9. Symmetric RAM flux, Coriolis torque, and total symmetric AM flux at 850 hPa and $D - 1$ for the 24-h forecasts in category A. The triangles indicate that at these radii, the symmetric RAM flux and the Coriolis torque are significantly different from each other at the 95% level (based on the t test).

significantly to the spinup of the low-level vortex. Indeed, the values of \bar{u} are two to four times larger in category A than those in category B (Fig. 10). The fact that the symmetric Coriolis torque is the most important term also explains why it is difficult for a cloud cluster at very low latitudes to become a TC.

The reason for the relatively small contribution of the asymmetric terms is because the eddy Coriolis torque actually exports AM from the system (Fig. 11a). Thus, part of the import of the eddy RAM flux is negated by the eddy Coriolis torque. For category B, both asymmetric terms are positive and no import of eddy RAM flux occurs (Fig. 11b).

Thus, the enhanced trades and southwesterly flow in the lower troposphere identified in Fig. 2a contribute toward the spinup of the cloud cluster through two processes: the symmetric import of the earth AM through a strong inflow and the eddy import of RAM. In the latter, the southwesterly flow appears to be more important since the import of eddy RAM covers a much larger area south of the GP (Fig. 12). Indeed, the area to the southwest of the GP has the largest cluster of

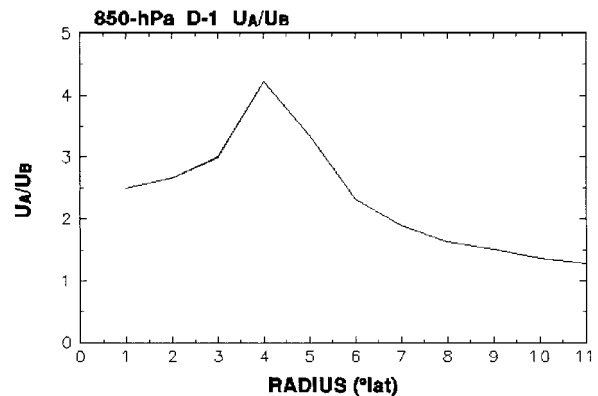


FIG. 10. Ratio of category A to category B composite symmetric 850-hPa radial winds at $D - 1$ for the 24-h forecasts.

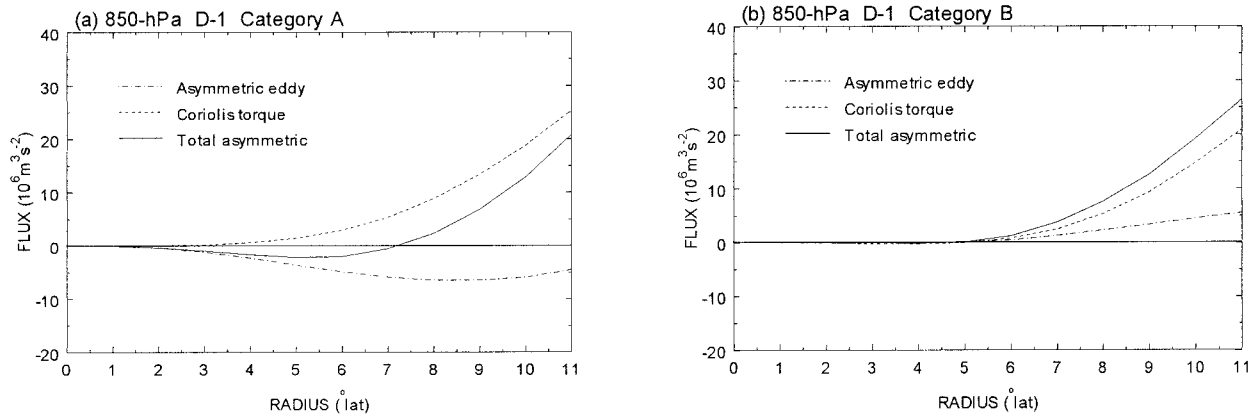


FIG. 11. Eddy RAM flux, eddy Coriolis torque, and total asymmetric AM flux at 850 hPa and $D - 1$ for the 24-h forecasts in (a) category A and (b) category B.

points where the import is significantly different from zero. Although the symmetric flow in category B still imports earth AM, its magnitude is much smaller. In addition, the absence of the import of eddy RAM due to an incorrect analysis also resulted in the failure of the model to predict genesis.

At 200 hPa, even though the asymmetric term is negative, the dominance of the (positive) symmetric term implies a net export of AM in both categories (Figs. 13a,b). Notice also that the export due to the symmetric term is larger for category A at all radii (Fig. 13c) although the difference is small (only about 10% of the actual export). However, the import of eddy RAM is

larger for the successful predictions at radii $>7^\circ$ lat. Of the four terms in (3), only the symmetric Coriolis torque is positive but its large magnitude overwhelms that of the other three terms (Figs. 14a,b). This result is consistent with those of previous studies (e.g., Holland 1983; Merrill 1988a). The dominance of the symmetric Coriolis torque is due to the strong mean outflow at this level, which is actually stronger in category A (Fig. 15). As a consequence, the symmetric Coriolis torque is larger in this category. Merrill (1988b) also found a similar result. Notice also from Fig. 13c that the stronger mean outflow also results in a larger symmetric RAM export in category A.

Thus, these results suggest that the role of the eddy RAM import at the upper levels is not to increase the cyclonic circulation of the system. Rather, it serves to mitigate the effect of the symmetric Coriolis torque, which exports large quantities of AM out of the system.

To summarize, the spinup of a cloud cluster is apparently due to two processes: (a) a large symmetric low-level import of the earth AM and (b) a negative eddy flux of RAM, both resulting from the enhanced trades and the southwesterly surge at the low levels. The role of an upper-level trough (westerly trough or TUTT) is to reduce the export of cyclonic momentum due to the mean export of the earth momentum at that level.

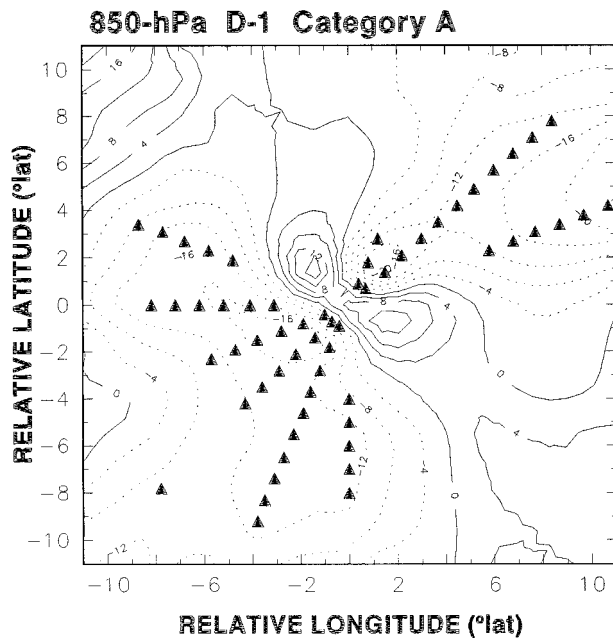


FIG. 12. Eddy RAM flux distribution at 850 hPa and $D - 1$ for the 24-h forecasts in category A. The triangles indicate grid points where the eddy RAM flux is significantly different from zero at the 95% level (based on the t test). Unit: $10^6 \text{ m}^2 \text{ s}^{-2}$.

c. 48- and 72-h forecasts

The AM fluxes at 850 hPa associated with the analyses in both categories for the 48- and 72-h forecasts give essentially similar results as those for the 24-h forecasts described in section 4b. One pertinent feature worth noting is that the areal extent of negative eddy fluxes of RAM for the successful 48- and 72-h predictions increases in the northeast but decreases in the southwest. The magnitude to the northeast is also large, especially at 72 h (cf. Figs. 16 and 12). However, results of the t test show that more points to the southwest actually have values significantly different from zero. These results

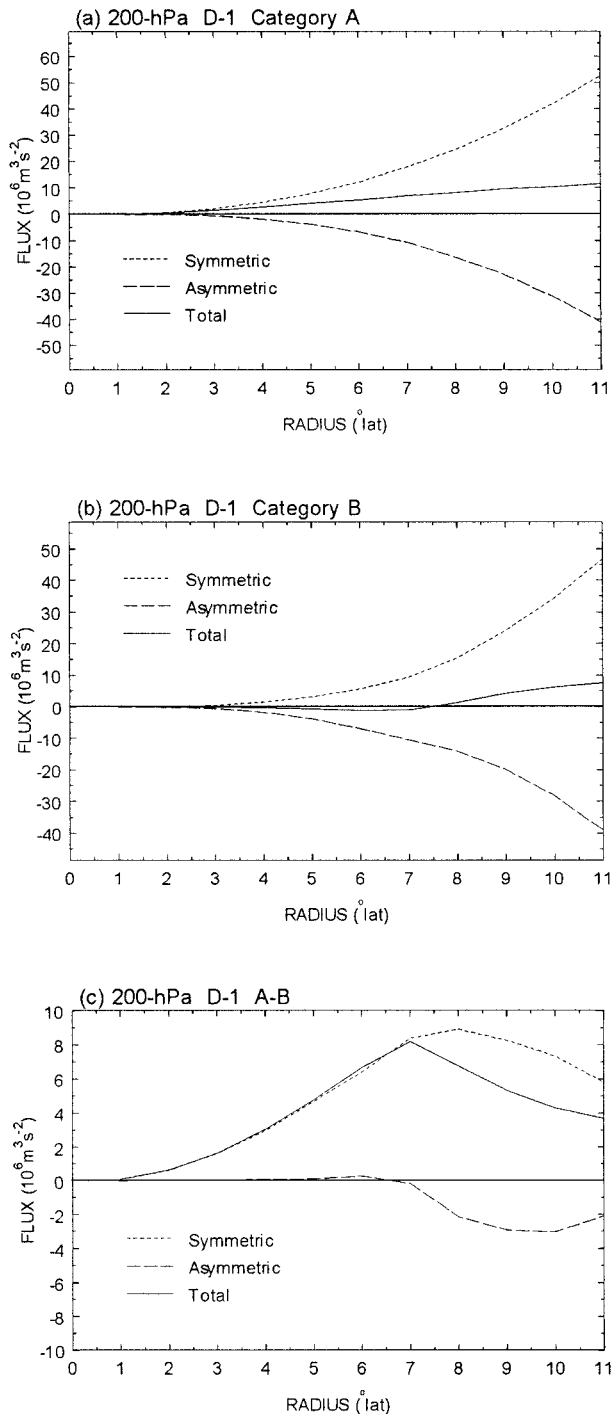


FIG. 13. Symmetric, asymmetric, and total fluxes of angular momentum at 200 hPa and $D - 1$ for the 24-h forecasts in (a) category A and (b) category B. The difference between the two categories (A-B) is shown in (c).

suggest that although the observations in section 3 seem to imply enhanced trades as being more important than the southwesterly flow at these times prior to genesis, the latter is still a significant contributor.

At 200 hPa, differences between the two categories are not as large as those for the 24-h forecasts. The symmetric Coriolis torque again overwhelms the other three terms. It appears that the flow at 200 hPa 2–3 days prior to the formation of a TC does not have much contribution toward the genesis process.

5. Summary and discussion

a. Summary

This study utilizes the analyses and forecasts of the UKMO global model in 1992–93 to study the physical processes responsible for TC genesis over the western North Pacific. Analyses that led to successful and failed predictions of the formation of actually observed TCs are compared. Assuming that the physics of the model is largely correct (which is justified a posteriori from the results), these comparisons can highlight the important features present in the analyses that allowed the model to make the successful predictions. The results show that indeed the composite analyses for these two categories of predictions differ significantly.

At the 850-hPa level, enhancements of the trade winds and surges in the southwesterlies appear to be the main distinguishing features. The former appears to be more important at 2–3 days prior to genesis. As the time of genesis approaches, the latter becomes more prominent. At 200 hPa, the analyses that led to successful 24-h predictions show a trough to the northeast of the pregenesis cloud cluster but none is observed for those of the failed predictions. However, at longer forecast intervals, the upper-level features are not significantly different in the two types of analyses.

Computations of angular momentum fluxes from the analyses in the two categories show that the earth's rotation plays a very important role. At the low levels, the main contribution to the spinup of the pregenesis cluster is the symmetric Coriolis torque due to a strong inflow. The symmetric and eddy fluxes of relative angular momentum (the latter resulting from the enhancement of the trades and/or surges in the southwesterlies) only play a secondary role. On the other hand, the eddy Coriolis torque actually exports angular momentum. At the upper levels, the presence of a trough to the northeast of the pregenesis cluster 24 h prior to genesis serves to mitigate the effect of the large symmetric Coriolis torque, which exports large amounts of angular momentum due to a strong outflow.

These results are generally consistent with those obtained previously from composite studies. The important synoptic-scale features present prior to genesis appear to be the enhancement of low-level trades and surges in the low-level southwesterlies, as well as the presence of an upper-level trough to the northeast of the pregenesis cloud cluster. The strengthening of the winds at the low levels serves two purposes. An increase in inflow leads to import of the earth's rotation, which is necessary

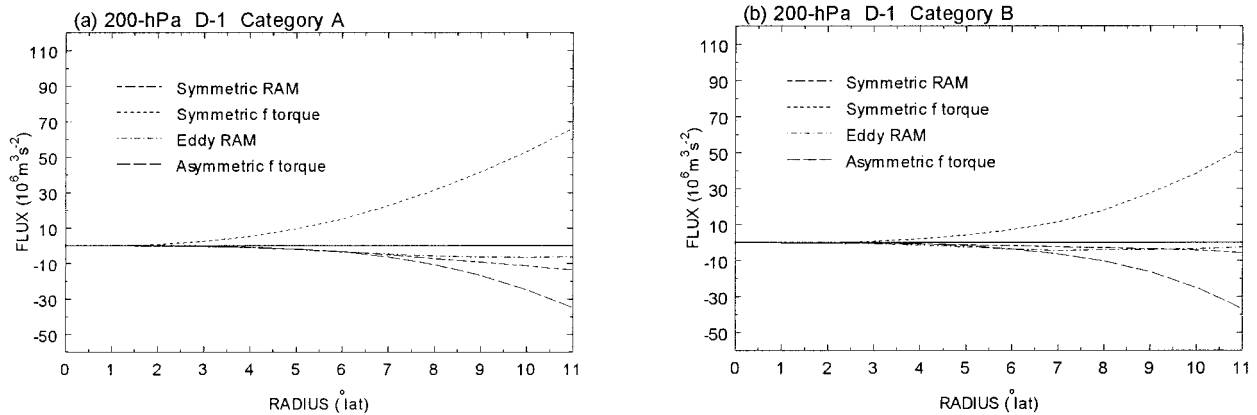


FIG. 14. Symmetric and eddy RAM flux and Coriolis torque at 200 hPa and $D - 1$ for the 24-h forecasts in (a) category A and (b) category B.

to spin up the cluster. The inflow also converges the cyclonic shear associated with the trades and southwesterlies. The outflow at the upper levels is actually not conducive to the spinup of the system because it exports the earth's angular momentum. The upper-level trough to the northeast of the cluster serves to reduce this detrimental effect through an import of cyclonic momentum.

b. Discussion

Previous studies of TC genesis using NWP analyses (e.g., Lee 1989; Briegel and Frank 1997) have all assumed that the model was capable of predicting the genesis of a TC based on these analyses. However, this study shows that some analyses could be erroneous so that the model would not be able to predict genesis based on these analyses. Although the failure of the model to predict genesis may result from insufficient physics in the model, the fact that the analyses that led to successful predictions show features that are consistent with previous observational studies lends credence to the valid-

ity of the assumption that the model physics is largely correct. Therefore, these latter analyses could be considered to be a largely true representation of the atmospheric conditions prior to the genesis of a TC. Furthermore, the composite results presented in this paper have been verified using statistical tests so that they should be valid even in individual cases.

Although the large-scale features of the environment prior to genesis are generally consistent with those previously found (e.g., McBride and Zehr 1981a,b; Love 1985a,b), some new results have been identified. First, the relative importance of the enhancement of the trades and the southwesterly surge at the low levels varies with

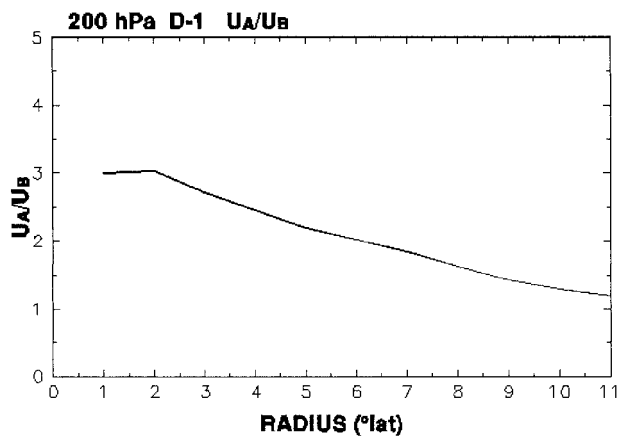


FIG. 15. As in Fig. 10 except for the radial winds at 200 hPa.

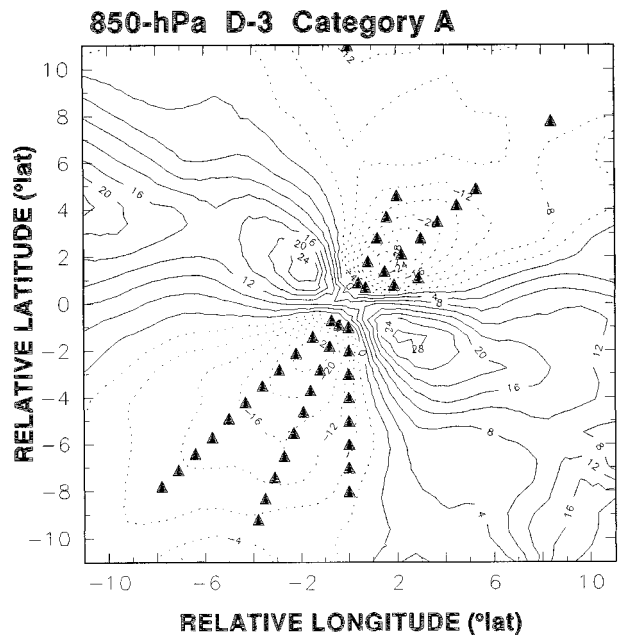


FIG. 16. Eddy RAM flux distribution at 850 hPa and $D - 3$ for the 72-h forecasts in category A. The triangles indicate grid points where the flux is significantly different from zero at the 95% level (based on the t test). Unit: $10^6 \text{ m}^2 \text{ s}^{-2}$.

the length of time prior to genesis. The trades appear to be more important in providing the initial spinup but the southwesterly surge becomes more dominant 1 day before genesis. Second, although previous studies have identified the TUTT as a main feature prior to genesis (e.g., Sadler 1976), the composite study here shows the actual flow patterns at various times prior to genesis, which indicate a migration of the TUTT and/or the mid-latitude trough. Further, computations of the momentum fluxes have illustrated the relative importance of the various flux terms.

Thus, NWP analyses can be used as an additional source of data for the study of TC genesis. This is especially important since data are always sparse over the ocean. However, the results from this study illustrate that not all analyses can be used. The model forecasts must be examined to make sure that the analyses are close to a true representation of the conditions in the real atmosphere.

Because this study was performed using only 2 yr of data, further studies should be made with more recent forecasts and for TCs in other ocean basins. Using more recent forecasts will determine whether the results obtained in this study will change due to different analysis and/or forecast techniques. Studies using TCs from other basins will show whether differences exist in the genesis mechanism for TCs in different basins. For example, most of the TCs in the western North Pacific develop within the monsoon trough, whereas those in the west Atlantic generally form from easterly waves. These will form the future direction of this study.

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REFERENCES

- Briegel, L. M., and W. M. Frank, 1997: Large-scale influences on tropical cyclogenesis in the western North Pacific. *Mon. Wea. Rev.*, **125**, 1397–1413.
- Challa, M., and R. L. Pfeffer, 1980: Effects of eddy fluxes of angular momentum on model hurricane development. *J. Atmos. Sci.*, **37**, 1603–1618.
- Cullen, M. J. P., 1993: The unified forecast/climate model. *Meteor. Mag.*, **122**, 81–94.
- Gray, W. M., 1979: Hurricanes: Their formation, structure and likely role in the tropical circulation. *Meteorology over the Tropical Oceans*, D. B. Shaw, Ed., Royal Meteorological Society, 155–218.
- Holland, G. J., 1983: Angular momentum transports in tropical cyclones. *Quart. J. Roy. Meteor. Soc.*, **109**, 187–209.
- , and R. T. Merrill, 1984: On the dynamics of tropical cyclone structure changes. *Quart. J. Roy. Meteor. Soc.*, **110**, 723–725.
- Joint Typhoon Warning Center, 1992: 1992 annual tropical cyclone report, U.S. Naval Oceanography Command Center, 269 pp. [Available from COMNAVMARIANAS Box 12, FPO, AP 96536-0051.]
- , 1993: 1993 annual tropical cyclone report. U.S. Naval Oceanography Command Center, 243 pp. [Available from COMNAVMARIANAS Box 12, FPO, AP 96536-0051.]
- Lee, C. S., 1989: Observational analysis of tropical cyclogenesis in the western North Pacific. Part I: Structural evolution of cloud clusters. *J. Atmos. Sci.*, **46**, 2580–2598.
- Love, G., 1985a: Cross-equatorial influence of winter hemisphere subtropical cold surges. *Mon. Wea. Rev.*, **113**, 1487–1498.
- , 1985b: Cross-equatorial interactions during tropical cyclone genesis. *Mon. Wea. Rev.*, **113**, 1499–1509.
- McBride, J. L., 1981a: Observational analysis of tropical cyclone formation. Part I: Basic description of data sets. *J. Atmos. Sci.*, **38**, 1117–1131.
- , 1981b: Observational analysis of tropical cyclone formation. Part III: Budget analysis. *J. Atmos. Sci.*, **38**, 1152–1166.
- , and R. Zehr, 1981: Observational analysis of tropical cyclone formation. Part II: Comparison of non-developing versus developing systems. *J. Atmos. Sci.*, **38**, 1132–1151.
- Merrill, R. T., 1988a: Characteristics of the upper-tropospheric environmental flow around hurricanes. *J. Atmos. Sci.*, **45**, 1665–1667.
- , 1988b: Environmental influences on hurricane intensification. *J. Atmos. Sci.*, **45**, 1678–1687.
- Panofsky, H. A., and G. W. Brier, 1958: *Some Applications of Statistics to Meteorology*. Pennsylvania State University, 224 pp.
- Sadler, J. C., 1976: A role of the tropical upper tropospheric trough in early season typhoon development. *Mon. Wea. Rev.*, **104**, 1266–1278.