On the Mechanisms Affecting the Intensity Change of Typhoons Flo (1990) and Gene (1990)

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Abstract

The ECMWF/TOGA advanced analysis was used to study the mechanisms that affect the intensity of Typhoons Flo (1990) and Gene (1990). It is found that the intensification of both typhoons are associated with the effect of the upper-tropospheric systems. The rate of intensification of Typhoon Flo increased, as the outflow jet was enhanced by the TUTT cell to the east of Flo. The strong outflow carried the high potential temperature air out of the storm center effectively, and the compensated 400-hPa inflow helped to maintain the vertical wind shear for the development of the warm core in Flo. In addition, the low vertical wind shear and warm underlying SST were also favorable for the rapid intensification of Flo. On the other hand, the reintensification of Gene was associated with the interaction between a upper moving tough and the outflow of the storm. The case study indicates that the preexisting outflow helped Gene resisting the tilting effect from the increasing vertical wind shear. The interaction between the upper trough and Gene initiated the internal instability of the typhoon, thus resulting in the reintensification of Gene.

影響芙蘿及傑恩颱風強度改變之機制探討

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1. INTRODUCTION

Tropical cyclones are destructive weather systems in nature. An attack of a severe tropical cyclone to human residence usually causes serious property damage and heavy loss of life. Although numerical models have shown considerable skill in tropical cyclone track forecast, the intensity prediction of a tropical cyclone is still a challenge to meteorologists and weather forecasters.

It is well known that the ocean is a large energy reservoir for tropical cyclones, thus the sea surface temperature (SST) plays a crucial role in the determination of the maximum intensity of a tropical cyclone. Under such basis, an empirical maximum intensity of tropical cyclone for a given SST was derived by Merrill (1988). Moreover, a theoretical upper bound of tropical cyclone determined by the SST and the outflow temperature was proposed by Emanuel (1986), where a tropical cyclone is regarded as a Carnot heat engine, gaining energy from the disequilibrium between the air and ocean surface.

Besides the SST factor, in recent years, both observational and numerical studies have paid more attention to the external influences on tropical cyclone intensity. DeMaria et al. (1993) calculated the eddy flux convergence of relative angular momentum (EFC) at 200 hPa for the named tropical cyclones during the 1989-1991 Atlantic hurricane seasons. They showed that about one-third of the storms with enhanced EFC intensified just after the period of enhanced EFC. Most of the storms that did not intensify after the enhanced EFC usually experienced increasing vertical shears, moved over cool water, or became extratropical.

Because of the relative low inertial stability in the outflow layer, the upper-level momentum forcing was found to be able to affect the intensity of tropical cyclones (Holland and Merrill 1984). The interaction between the tropical cyclone outflow layer and the upper environmental features could provide the upper momentum sources for the development of tropical cyclones. The vertical derivative of the eddy flux convergence of angular momentum acts as a forcing function to increase inflow of moist air in the boundary layer and to pump drier air out in the outflow layer (Challa and Pfeffer 1980).

Molinari and Vollaro (1989,1990) found that the upper-level eddy flux convergence of angular momentum occurred during the intensifying period of Hurricane Elena (1985), indicating that the upper-tropospheric trough played an important role in the reintensification of Elena. Molinari et al. (1995) pointed out that the interaction of the outflow of Elena with the trough reduced the penetration depth of the upper westerly and the length of time during which the vertical wind shear occurred, therefore the destruction of Elena by the shear was prevented. Molinari et al. (1995) further suggested that the partial superposition of the upper-tropospheric trough on Elena initiated the wind-induced surface heat exchange mechanism (WISHE; Emanuel 1991) thus resulting in the reintensification of the storm.

The effect of vertical wind shear on tropical cyclone intensity was investigated by DeMaria (1996). DeMaria (1996) used a simple two layer model to show that the tilt of the upper and lower level PV produces a mid-level temperature decrease in the direction of the displaced upper PV and a temperature increase near the vortex center, which can act to increase the convection away from the storm center and thus inhibit the storm development.

Another point of view regarding the effect of eddy flux convergence of angular momentum on tropical cyclone intensity change was proposed by Merrill and Velden (1996). They used rawinsondes and cloud motion wind vector derived from geostationary satellite imagery to describe the three dimensional structure of the outflow layer of Supertyphoon Flo (1990). The net outflow at 6° latitude was found to occurred at higher levels and over an increasing range of potential temperature surfaces as Flo intensified. Merrill and Velden (1996) suggested that the enhanced EFC during the period after Flo's peak intensity may stimulate the outflow at the θ-level below the eyewall outflow, which favored more convection outside the eyewall and impeded the development of Flo.

The aforementioned studies have pointed out the importance of EFC, vertical wind shear, and the sea surface temperature to the intensity change of tropical cyclones. In this paper, the above three factors were evaluated to study the environmental influences on the intensity change of Typhoons Flo (1990) and Gene (1990). The data and analysis methods are introduced in section 2. Results for case studies of Typhoons Flo and Gene are presented in section 3. The effects from all factors affecting the intensity change of each typhoon are also discussed and compared to each other. The summary of this study is drawn in section 4.

2. DATA AND METHODOLOGY

2.1 Data

The ECMWF/TOGA (European Center for Medium Range Weather Forecasting/Tropical Ocean Global Atmosphere) advanced global analysis and the NCEP (National Centers for Environmental Prediction) weekly sea surface temperature analysis were employed for this case study. In addition, the Tropical Cyclone Motion field experiment (TCM-90; Elsberry 1990) post-processed analysis during 15-18 September 1990 was also used for data comparison.

The six-hourly ECMWF/TOGA advanced upper-level analyses on 1.125°x1.125° latitude-longitude grids are available in 14 pressure levels: 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 10 hPa. Twelve of the fourteen levels (from 1000 to 50 hPa) of the EC/TOGA advanced upper-level analyses were employed in this work. The TCM-90 data have a six-hour time resolution and a horizontal resolution of 0.5° latitude-longitude. The vertical resolution is 50 hPa from 1000 to 100 hPa.

2.2 Methodology

The analyses of this study contain the calculation of potential vorticity, the Eliassen-Palm flux, the eddy flux convergence of relative angular momentum, and the mean vertical shear. In addition, the azimuthal mean of the typhoon-relative radial and tangential wind, and the potential vorticity on both pressure and theta levels were also obtained.

The calculation of potential vorticity was taken on insentropic coordinates:

$$PV = -g\left(\frac{\partial p}{\partial \theta}\right)^{-1}\left[f + \left(\frac{\partial v}{\partial x}\right)_{\theta} - \left(\frac{\partial u}{\partial y}\right)_{\theta}\right],$$

where p is the pressure, θ is the potential temperature, f is the Coriolis parameter, u is the zonal wind, v is the meridional wind, and the subscript θ denotes the derivative taken along θ surfaces.

Following Molinari and Vollaro (1990), the eddy convergence of relative angular momentum is defined as

$$EFC = -\frac{1}{r^2}\frac{\partial}{\partial r} r^2 \overline{u_L' v_L'}$$

where u_L is the storm-relative radial wind, v_L is the storm-relative tangential wind, r is the radius, and the prime indicates the deviation from the azimuthal mean.

Both the eddy flux of momentum and heat can be combined in one form — the Eliassen-Palm (hereafter, E-P) flux. Following Molinari et al. (1995), the E-P flux divergence can be written as

$$\nabla \cdot \vec{F} = -\frac{1}{r}\frac{\partial}{\partial r} r^2 \overline{(\sigma u_L)' v_L'} + \frac{\partial}{\partial \theta}\overline{p' \frac{\partial \Psi'}{\partial \lambda}},$$

where

$$\vec{F} \equiv \left[-r\overline{(\sigma u_L)' v_L'} \ , \ \overline{p' \frac{\partial \Psi'}{\partial \lambda}}\right]$$

is the E-P flux vector, $\sigma = -\partial p / \partial \theta$ is the pseudo-density, u is the storm-relative radial velocity, v is the storm-relative tangential velocity, θ is the potential temperature, Ψ is Montgomery streamfunction, and λ is the azimuthal angle. The radial component of E-P flux represents the angular momentum flux, while the vertical component is the heat flux. Here, the E-P flux is calculated in a cylindrical coordinate, and the "bar" represents the azimuthal mean.

The mean vertical wind shear was calculated by two difference methods. First, the vertical wind shear was obtained by taking the vector difference of the annular mean wind at 5°~7° radius between 200 hPa and 850 hPa (hereafter, referred as A-method). On the other hand, a three-point smoothing operator (Kurihara et al. 1993) was applied to determine the environmental wind field. The vector difference of the environmental wind at the typhoon center between 200 hPa and 850 hPa represents the second type of vertical wind shear of the environment (hereafter, referred as K-method).

3. RESULTS

3.1 Supertyphoon Flo (1990)

Flo formed southeast of Guam, and reached typhoon strength at 0600 UTC 15 September 1990. Thereafter Flo intensified rapidly and became a Supertyphoon at 1200 UTC 16 September. Before Flo recurved around the western edge of the subtropical ridge, it moved northwestward steadily. The peak intensity of Flo was observed at 0600 UTC 17 September. After reaching peak intensity, Flo accelerated northeastward and made landfall on the Japanese island on 19 September.

The r-θ cross section of 24-h potential vorticity tendency showed that the outflow layer potential vorticity decreased as Flo intensified (Fig. 1). In the early stage of the intensification, the evolution of potential vorticity (PV) in the outflow layer showed a high potential vorticity belt extended from an upper-tropospheric trough (TUTT) cell to the east of Flo to the north and west of the storm center (Fig. 2). The low PV air at the top of Flo was confined to the vicinity of the storm center. The outflow to the north of the storm center extended along the high PV belt. As Flo intensified, the low PV area expanded and the high PV belt was eroded by the low PV air advected outward form the storm center (cf. Wu and Emanuel 1994).

Not only did the TUTT provided an effective outflow channel for Flo, it also contributed to the upper-level eddy angular momentum forcing. During the period of interaction the value of the Eliassen-Palm flux divergence produced mean cyclonic angular momentum in the outflow layer (Fig. 3), and the Eliassen-Palm flux was dominated by the effect of the eddy momentum flux. The enhanced outflow (Fig. 4) had a positive contribution to the development of Flo because it helped to carry the high potential temperature air to the outer area, thus avoiding the subsidence near the typhoon center (as indicated in Holland and Merrill 1984). The enhanced upper-level outflow also invigorated the convection in Flo's core region.

Flo deepened rapidly after the outflow jet strengthened and the 400-hPa inflow appeared. The mid-level inflow and the upper-level outflow was favorable for the maintenance of the vertical shear required for the development of warm core. In addition to the enhanced outflow and the mid-level inflow, the warm sea surface temperature and the low mean vertical wind shear provided additional favorable conditions for the development of Flo (Fig. 5).

After two days of deepening, Flo reached peak intensity with a maximum surface wind of 75 m s^{-1}, then weakened rapidly. As Flo moved north into the mid-latitude westerly, Flo weakened due to the increasing vertical wind shear.

3.2 Typhoon Gene (1990)

The initial disturbance of Gene was formed at west-southwest of Guam and the maximum wind was less than 13 m s^{-1} for five days. Gene reached typhoon intensity at 1800 UTC 25 September 1990. It started to intensify again after 0000 UTC 26 September, and reached peak intensity with a maximum surface wind of 40 m s^{-1} at 1800 UTC 26 September. Gene moved northward before 0600 UTC September, then it recurved northeastward to the west of Okinawa. Finally, Gene made landfall on Japan at 0600 UTC 29 September.

As Gene intensified, the outflow layer PV decreased with time. On the other hand, the PV evolution on 350K surface showed low PV areas accompanied the outflow jets during Gene's intensification period and a positive PV anomaly associated with the mid-latitude trough existed to the northwest of Gene. As the trough approached Gene, an upper-level high PV strip extended southwestward to the northwest of the typhoon center (Fig. 6), and the maximum upper-level eddy flux convergence of angular momentum outside 6° latitude radius occurred. The mid-latitude trough continued moving east, and the upper-level EFC maximum shifted inward with time. The maximum value of EFC exceeded 20 m s^{-1} day^{-1} during the period when Gene interacted with the mid-latitude trough (Fig. 7).

Gene started to intensify when the 200 hPa maximum EFC shifted within the 7° latitude radius. After the mid-latitude trough passed over, the high PV strip split from the mid-latitude trough at 0000 UTC 27 September, then the intensification of Gene ceased.

After reaching the peak intensity, Gene moved northward into the mid-latitude westerly. It maintained a maximum surface wind of 40 m s^{-1} for 60 hours. During this period, the outflow of Gene was confined to the east of the typhoon center. Although the upper-level EFC increased again when an upper-tropospheric trough passed the north of Gene at 1200 UTC 27 September, the constricted outflow limited the intensification of the storm.

Gene decayed immediately after it reached Japan. The terrain effect and the moisture deduction were the major factors for the weakening of Gene.

3.3 Discussions

The results from the above case studies show that the upper environmental system played an important role in the development of both typhoons. The interaction between the upper environmental system and the tropical cyclone produced mean cyclonic angular momentum in the outflow layer of the tropical cyclones. It is found that in the intensification stages of both typhoons the effect of the upper eddy momentum flux was more important than the effect of the eddy heat flux.

According to the balanced vortex equations, the positive EFC produces a cyclonic vorticity tendency, and the vertical derivative of EFC can enhance the radial-vertical circulation inside the storm. We think that the strengthening of the radial-vertical circulation is more efficient than the spin-up of the upper-tropospheric tangential wind in the process of storm intensification. The increased low-level inflow acted to provide more moisture convergence. The extended upper-tropospheric outflow carried the high potential temperature air away from the storm center, avoiding the subsidence near the storm center. In addition, the enhanced outflow induced a compensated inflow near 400 hPa which could help to maintain the vertical shear needed for the development of the warm core.

In teory, the interaction between the upper-tropospheric system and the tropical cyclone can produce EFC which is favorable for the intensification of the tropical cyclone, but the approach of an upper-tropospheric trough aslo increases the vertical wind shear, which may be detrimental for its development. The result from the case study of Gene shows that the intensification is initiated before the trough moved over the north of the storm center. The interaction between the outflow of the tropical cyclone and the trough helped Gene to resist the effect of the vertical wind shear. However, after the trough has passed over, the outflow Gene was restricted by the strong northwesterly winds behind the trough, thus the development of Gene was limited.

4. SUMMARY

In this study, the EC/TOGA Advanced analysis was used to study the environmental influences on the intensity of Typhoons Flo (1990) and Gene (1990). The outflow structure, eddy momentum flux convergence, and the mean vertical wind shear were examined. The upper environmental features were shown to play a crucial role in the intensification of both typhoons.

After reaching typhoon strength, Flo continued deepening steadily. More rapid intensification of Flo occurred as the outflow was enhanced at 1200 UTC 15 September. The evolution of PV and wind fields in the outflow layer shows that the TUTT cell to the east of Flo provided an effective outflow channel for the outflow air. The stronger outflow can take the high potential temperature air away from the core region, avoiding the subsidence near the storm center, thus invigorating the eyewall convection, and strengthening the radial-vertical circulation. The increase of the low-level inflow can induce more moisture convergence and make the Ekman pumping more efficiently. On the other hand, the outflow also induced a compensated inflow near 400 hPa which could help to maintain the vertical shear needed for the development of the warm core.

The reintensification process of Gene appeared to be similar to that of Hurricane Elena (1985) as shown in Molinari et al. (1995). The interaction between the moving trough and Gene can be thought as the process of bringing two (upper and lower) positive PV anomalies closer to each other. As the distance between the two positive PV anomalies decreases, the total kinetic energy associated with the two PV anomalies increases. The increase of the low-level wind induces more evaporation from the sea surface, which invigorates more core convection. Therefore the stronger radial-vertical circulation and more low-level convergence can be triggered. The energy cycle, which operates like the wind-induced surface heat exchange instability (WISHE; Emanuel 1991), resulted in the intensification of Gene. As a result, the interaction between the two positive PV anomalies not only induced a transient growth of the total perturbation energy associated with the two systems, but also initiated the internal instability of the tropical cyclone. After the trough passed over the north of Gene, the strong northwesterly wind behind the trough restricted the outflow on the western side of the storm center, therefore impeded further development of Gene.

The above results also show that the upper eddy momentum forcing is more important than the upper eddy heat forcing as the two tropical cyclones intensified. In other words, the EFC can be regarded as a good indication of the effect of the upper environmental forcings. It is found in this work that the enhanced outflow is favorable for the intensification of tropical cyclones, and the constricted outflow inhibits the development of tropical cyclones. However, the existence of upper-level EFC does not ensure the strengthening of the outflow and the intensification of the tropical cyclone. The vertical wind shear also plays a subtle role, while the SST determines the effectiveness of the in-up-out circulation inside the tropical cyclone.

The two case studies in this paper qualitatively evaluate the mechanisms affecting the intensity change of Flo and Gene, such as the SST, the vertical wind shear, and the EFC. More quantitative investigations on the interaction of all factors may not be an easy task. It is hoped that a systematic combination of the observational analyses and numerical model experiments can help improving our understanding on the interaction between the tropical cyclone and its environment, and aid in the prediction of the tropical cyclone intensity.

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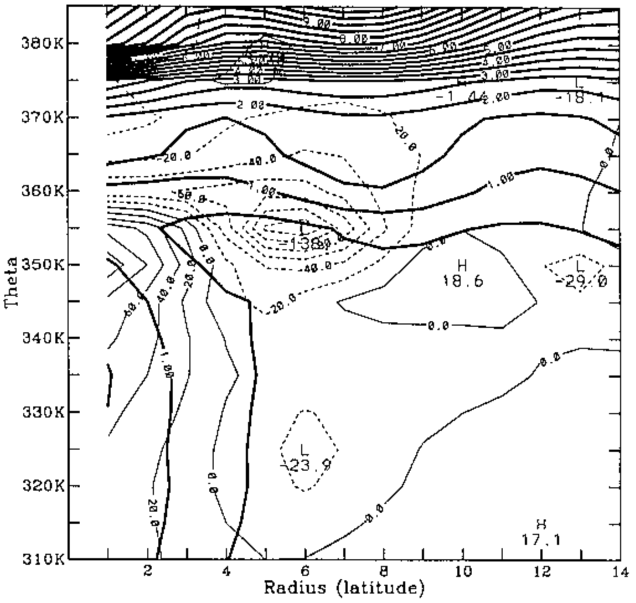

Figure 1. Radius and potential-temperature cross section of the 24-h axisymmetric mean PV (bold contours) and the percent change in axisymmetric PV for a 24-h period (thin contours; negative values are dashed) for Typhoon Flo from 1200 UTC 15 September through 1200 UTC 16 September, 1990.

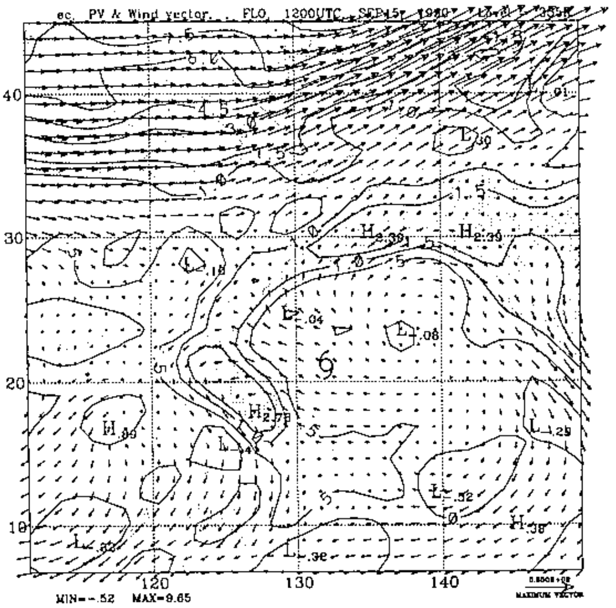

Figure 2. Wind vectors and potential vorticity on the 355 K isentropic surface at 1200 UTC 15 September, 1990. Potential vorticity values greater (smaller) than 1.5×10^{-6} m^2 Ks^{-1} kg^{-1} (1.5 PVU) are contoured at a 1.5 PVU (0.5 PVU) increment, and values greater than 1 PVU are shaded. The location of Typhoon Flo is indicated as the tropical cyclone symbol.

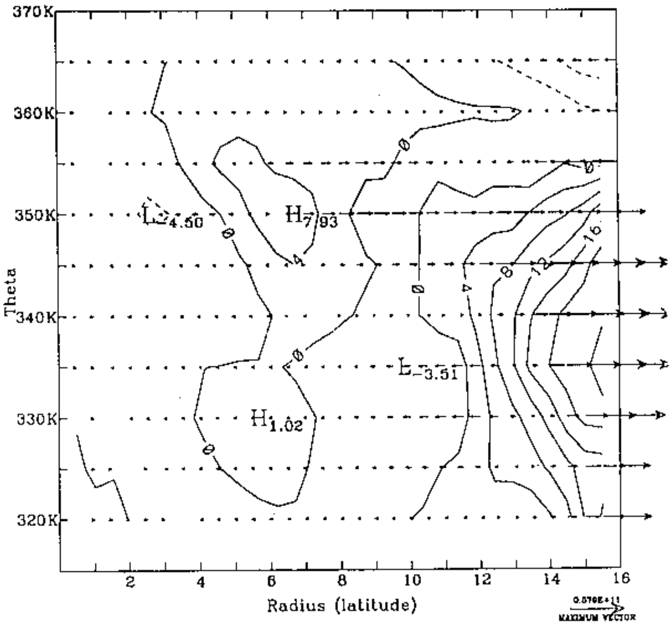

Figure 3. Radius and potential-temperature cross sections of Eliassen-Palm flux vectors and their divergence at 1200 UTC 15 September. The contour interval is 4×10^4 Pa m^2 K^{-1} s^{-2}, and negative contours are dashed.

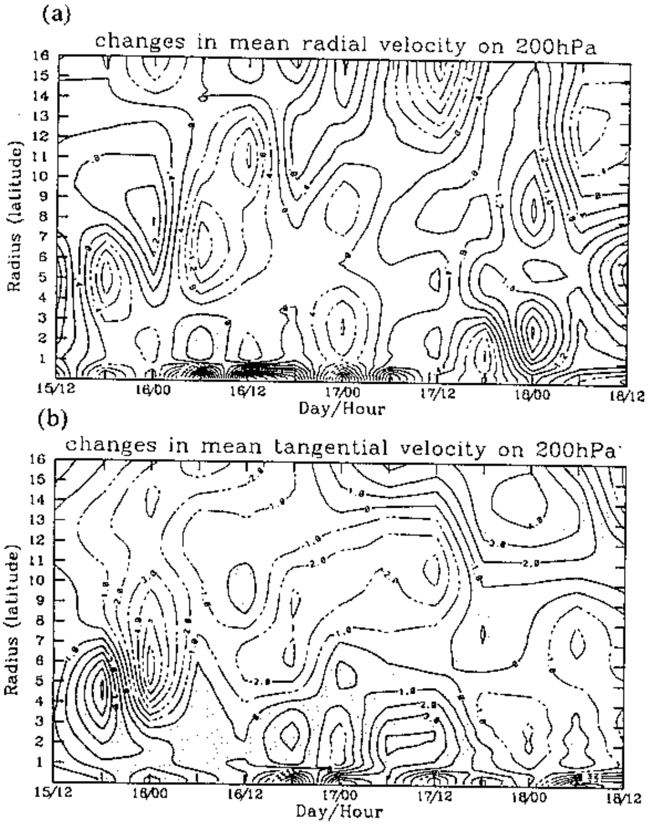

Figure 4. Changes in azimuthal mean winds of Typhoon Flo (1990) at 200 hPa for 6 h ending at the time shown: (a) radial wind (contour interval of 0.4 m s^{-1}) and (b) tangential wind (contour interval of 0.4 m s^{-1}). Positive values are shaded, and negative contours are dashed.

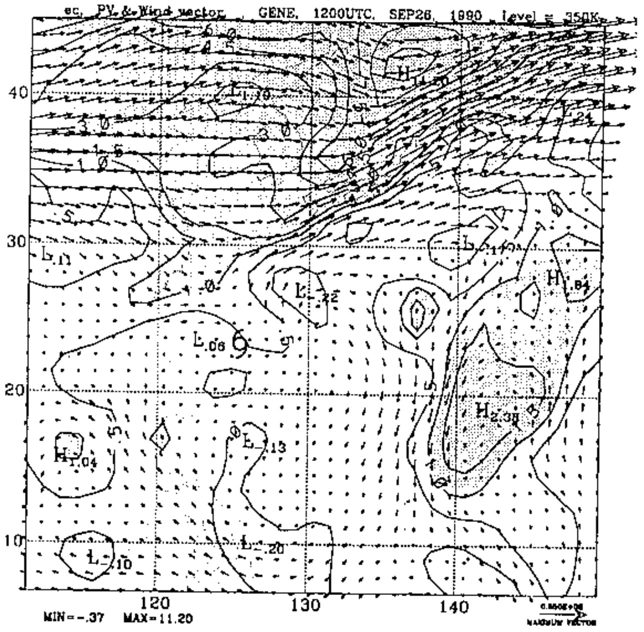

Figure 6. Wind vectors and potential vorticity on the 350 K isentropic surface at 1200 UTC 26 September, 1990. Potential vorticity values greater (smaller) than 1.5×10^{-6} m^2 Ks^{-1} kg^{-1} (1.5 PVU) are contoured at a 1.5 PVU (0.5 PVU) increment, and values greater than 1 PVU are shaded. The location of Typhoon Gene is indicated as the tropical cyclone symbol.

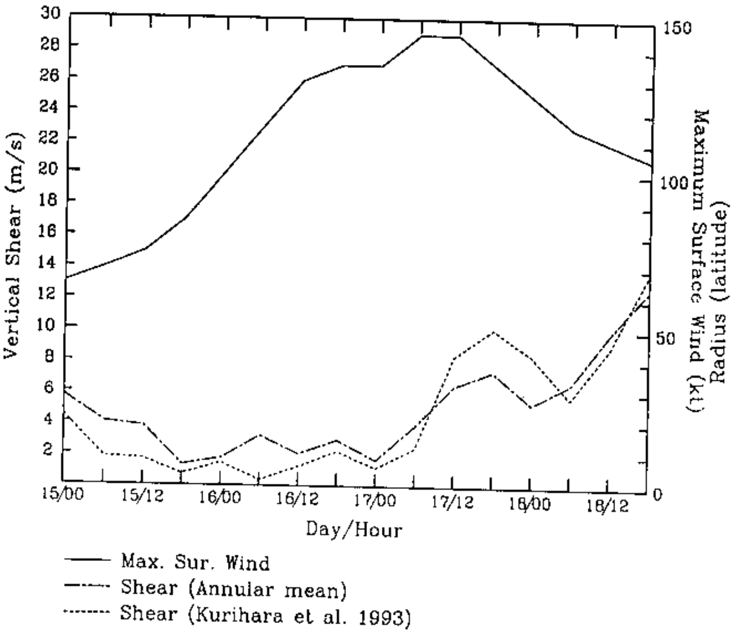

Figure 5. Time variation of the vertical wind shear obtained from the A-method (dash-dot) and K-method (small dashes), and the best track maximum surface wind (solid) from JTWC for Typhoon Flo (1990).

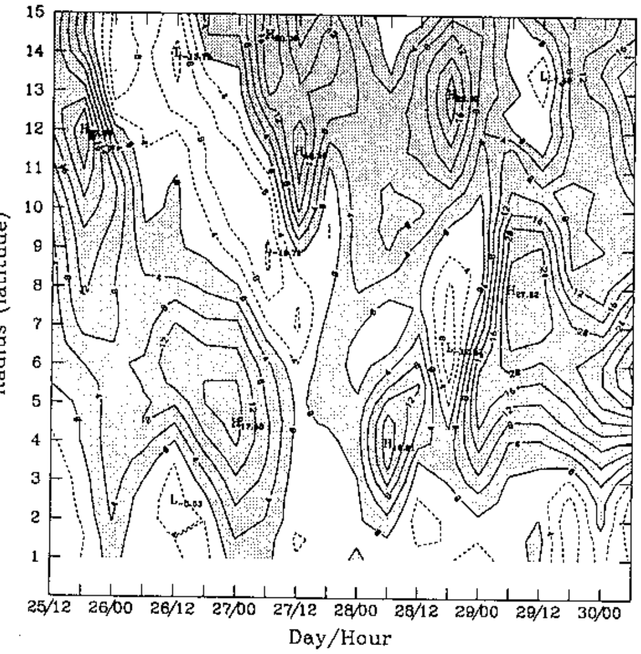

Figure 7. Time series of the eddy flux convergence of the angular momentum at each radius at 200 hPa for Typhoon Flo (1990). The contour interval is 4 m s^{-1} day^{-1}, and negative values are dashed. Positive values are shaded.