An Asymmetric Mechanism in the Interaction between Tropical Cyclones and Upper-Tropospheric Troughs

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Abstract

Many mechanisms have been proposed in earlier studies on the interaction between tropical cyclones and upper-tropospheric troughs. One of the mechanism, for example, postulated the divergence and convergence pattern associated with the upper-level trough can either enhance or hinder the vertical circulation and hence the intensity of the underlying tropical system. Another well known mechanism was the vertical shear of the mean winds can destroy the favorable condition for cooperative release of latent heat in the tropical storm.

In this review, observational and modeling evidence is given to support an alternate mechanism of the observed interaction between tropical cyclones and upper-tropospheric troughs. It can be inferred from observations and model simulations that there is a transverse secondary circulation around the outflow jet of tropical cyclones. It is postulated that the upward branch of the secondary circulation can be enhanced dynamically in the presence of an approaching trough. A deep circulation with convergence in the lower-troposphere and divergence in the upper-troposphere can then be induced in the region of the enhanced circum-jet secondary circulation. If the induced convection is located close enough to the central convective core, it is conceivable that the intensity of the tropical cyclone can be increased.

More case studies using high resolution remotely sensed data and numerical simulations in models with explicit cloud physics are necessary to further elucidate of this proposed asymmetric mechanism in the interaction between tropical cyclones and upper-tropospheric troughs.

I. Introduction

The interactions between tropical cyclones and their upper-level environments has been studied and analyzed since the early days of tropical analysis (Riehl 1954). It has been noticed that evolution and behavior of tropical disturbances can be greatly modified by the approaching upper-tropospheric troughs (UTT). Sadler (1976, 1978) showed that as an UTT aligns vertically with the underlying tropical cyclone the tropical cyclone weakens, whereas if a tropical cyclone is aligned with an upper-tropospheric ridge, it intensifies.

The outflow layer of tropical cyclones is generally anticyclonic, divergent on the synoptic scale, and considerably more asymmetric about the center than the middle and lower layers (Alaka 1961, Miller 1963, Black and Anthes 1977, Frank 1971, Shi et al 1990). The asymmetric outflow can be responsible for eddy fluxes of angular momentum comparable in magnitude to those of the tropical cyclone's symmetric radial circulation (Pfeffer 1958, Palmen and Riehl 1957, Molinari and Vollaro 1989, Shi et al 1997). Challa and Pfeffer (1980) showed that the angular momentum flux convergence measured from observational data can accelerate the development of a tropical cyclone in an axisymmetric model. Holland and Merrill (1984) argued that the anticyclonic outflow jet can become more unstable dynamically as compared to lower tropospheric cyclonic circulation as the storm intensifies. Molinari and Vollaro (1989) correlated the intensification of a tropical cyclone to the azimuthal mean convergence of eddy angular momentum flux. In these studies, the physical process allows the upper tropospheric forcing to affect the underlying tropical cyclone was attributed to the negative effects of the vertical shears or the positive effect of the vorticity spin-up. These mechanisms suggest symmetric responses, even though the asymmetric nature of the outflow layer was recognized.

An alternate explanation for the mechanism of the interaction is presented in this study, based on studies of Merrill (1984, 1988b), Rodgers et al (1990), Shi et al (1990), Rodgers et al (1991) and Shi et al (1997). Contrary to the axisymmetric response of tropical cyclones to upper-tropospheric ridges and troughs discussed in earlier literature, the interaction occurs through the secondary circulation around the tropical cyclone outflow jet or jets. Based on the evidence presented, it is plausible the upward branch of the circum-jet circulation can be strengthened as the outflow jet is accelerated by an approaching trough to induce deep convection. If the timing and location of the induced deep convection is cooperative with the organization of the tropical cyclone, intensification of the tropical cyclone can occur.

In the next sections, observational and model simulations will be presented to elucidate the proposed mechanism.

II. Observational Evidence

Studies based on analyzing remotely sensed total ozone anomalies and precipitation have suggested (1) that there is secondary circulation associated with the outflow jet of tropical cyclones, and (2) the convection or precipitation can be increased in the presence of approaching UTT in the regions of the upward branch of the secondary circulation. In the follows, observed characteristics and behavior of Hurricane Irene of 1982 and Hurricane Florence of 1988 will be discussed in the light of the proposed mechanism in the interaction between tropical cyclones and the UTTs.

1. Hurricane Irene of 1982

Tropical cyclone Irene was first detected as a tropical disturbance off the African coast on 19 September 1981 and reached storm stage on 23 September. It reached a maximum intensity of 54 m/s on 28 September (Lawrence and Pelissier 1982) near 27°N and 57°W. Fig. 1 shows the position and intensity of tropical cyclone Irene, which stayed over open water with little low level environmental forcing before it moved over cooler ocean after 28 September Irene (Fig. 2, adapted from Fig. 16 of Rodgers et al, 1991).

During the period 24-26 September, a westerly UTT approached, intensified and merged with Irene. As the UTT was located approximately 500 km to the west of the center of Irene at 1200 UTC 26 September, the outflow jet was markedly accelerated with areas of high wind speed of more than 25 m/s extending around the northern quadrants. The evolution of Irene's convection (or precipitation) is shown in Fig. 3, where the average brightness temperature within a radius of 222 km from the center is used as an indication for convection. Fig. 3 shows that the central core brightness temperature T_{BB} (convection) decreased (increased) from 240 to 210°K between 24-27 September, which seemed to coincide with the general deepening of the tropical system. The intensification was correlated with the increase of the eddy momentum influx, indicating the interaction with the UTT.

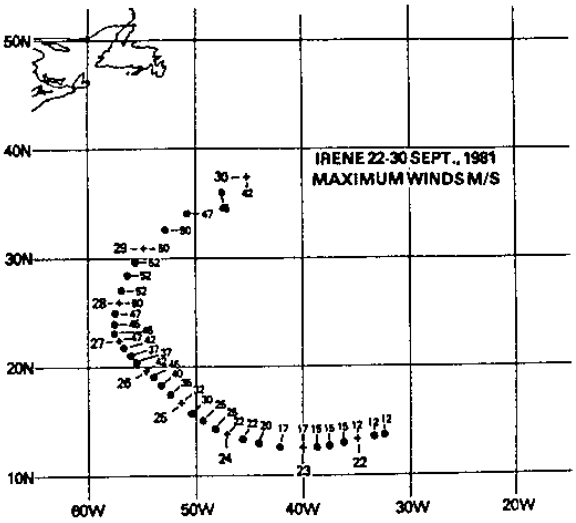

Fig. 1. Position and maximum winds (m/s) of Tropical Cyclone Irene (22-30 September 1981) every 6 h.

Ozone concentration in the lower stratosphere, below the photochemical ozone source region in the middle atmosphere and above the sink region below the tropopause, can serve as a tracer of circulation. Fluctuations in the total columnar amount of ozone were found to be primarily due to variations of tropopause height caused by three-dimensional transport at that level (Dobson et al 1946, Ohring and Muench 1960). Schubert and Munteanu (1988) found strong correlation between tropopause heights and the total ozone amount observed by Nimbus-7 Total Ozone Mapping Spectrometer (TOMS).

The distribution of anomalies in the TOMS total ozone amount surround a mature tropical cyclone, Hurricane Irene, and cloud-track

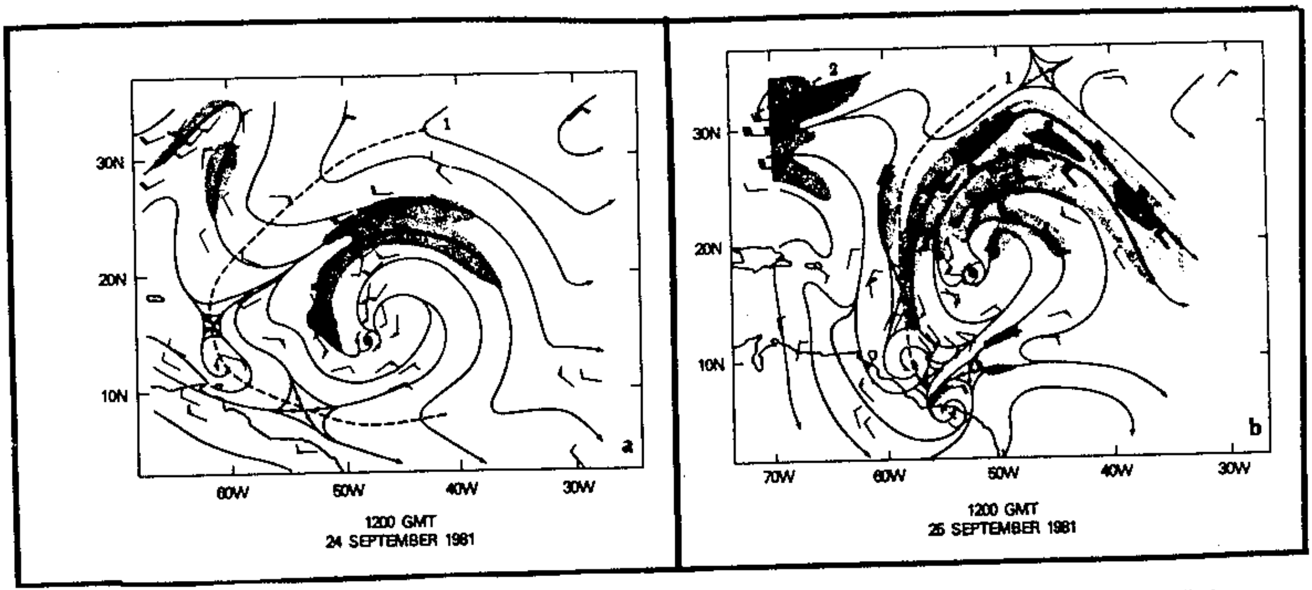

Fig. 2. Cirrus-level winds (m/s) and streamline analysis for Tropical Cyclone Irene at 1200 UTC 24 and 25 September 1981. Winds in shaded area exceed 25 m/s. Dashed lines denotes the upper-level trough.

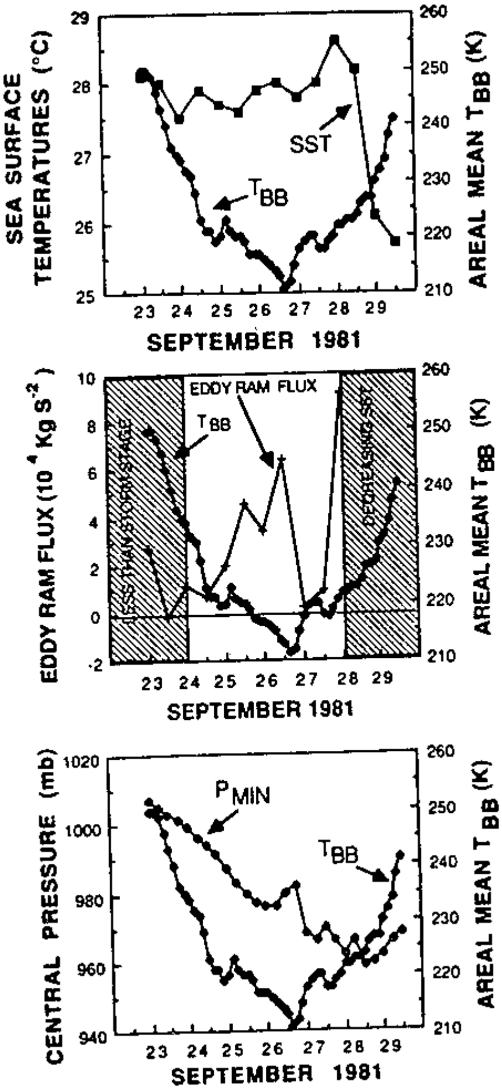

Fig. 3. Evolution of Irene's average brightness temperature (k) within 222 km of the center and (a) the sea surface temperature, (b) the eddy angular momentum flux (10^4 kg s^{-2}), and (c) minimum sea-level pressure.

winds at 1200 UTC 25 September 1981 are plotted in Fig. 4 (Adapted from Fig. 11 of Rodgers et at (1990)). The anomalies were obtained by subtracting the climatological TOMS observed amount for a given day and location from the observed amount. In Fig. 4 the location of the sea-level pressure minimum is noted with the tropical cyclone sign. The single outflow jet originated from the west of the center, bending anticyclonically around the northern quadrants. Symbols A and B in Fig. 3 denote the approximate entrance and exit region of the jet, respectively. Just to the west of the jet entrance region, the anomalous total ozone amount has a local maximum of 4 Dobson units (DU), indicating a low tropopause or downward transport. A local minimum of -4 DU is located to the east of the entrance region just north of the storm center, suggesting a downward transport. From these two implied vertical transport, mass continuity requires a radially outward flow above the outflow jet and a radially inward flow below the jet. Thus, the inferred transverse circulation is thermally direct, i.e., upward with anticyclonic shear and downward with cyclonic shear. Near the jet exit region, the indication of the secondary circulation is discernible.

The pattern of total ozone anomalies around Hurricane Irene is very similar to what was observed with the majority of mature western Atlantic tropical cyclones (Rodgers et al, 1990). Fig. 5 (adapted from Fig. 15 of Rodgers et al, 1990) shows the average total ozone anomalies for 16 Atlantic hurricanes south of 35°N in the months of July-September 1979-

1982. In the composite figure the center of the hurricanes is placed at the center and the pattern is rotated that the direction of motion is 360°. Some details are lost due to the composite, nevertheless, there is a distinct wave pattern in the total ozone anomalies near tropical cyclones with a minimum of -4 DU near or just to the right quadrants and a maximum of +8 DU to the left forward quadrant. This pattern is very similar to that of Hurricane Irene shown in Fig. 4.

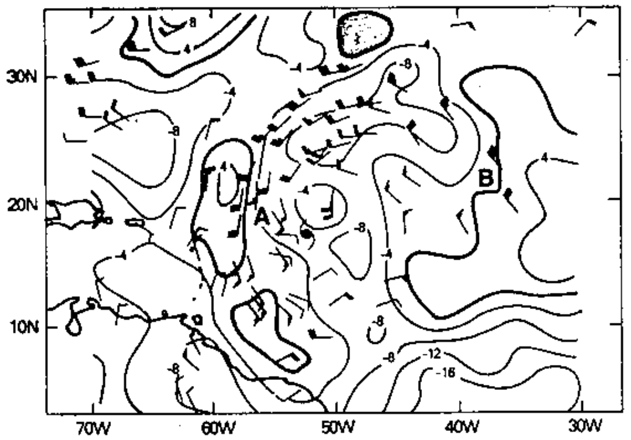

Fig. 4. Cirrus-level winds (m/s) and TOMS measured total ozone anomalies (4 DU interval) near local noon on 25 September 1981. Positive total ozone anomalies are shaded. A and B locate, respectively, the jet entrance and exit region.

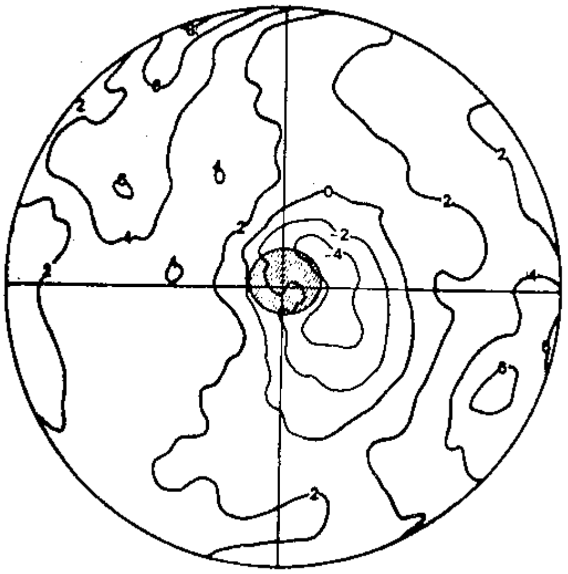

Fig. 5. The mean Nimus-7 TOMS measured total ozone anomalies (2 DU interval) for 53 western Atlantic tropical cyclone observations (16 tropical cyclones). The storm motion is rotated to the top of the plot.

2. Hurricane Florence of 1988

Compared to Hurricane Irene, Hurricane Florence was relatively short-lived after its genesis from a stationary coastal front (Fig. 6). One of the most striking behavior of Florence was the sudden development around 12 UTC 9 September of a convective cell to the northwest of the center, which eventually grew stronger and large than the original central convective core. The evolution of the explosive growth of the convection is depicted by the GOES infrared imagery of Florence between 0200 and 1200 UTC 9 September in Fig. 6 (adapted from Fig. 7 of Rodgers et al 1991). The outflow jet, combined with the jet stream from an approaching UTT is outlined by the packed isotherms to the northwest of the convection. The changes in these white contours of the VISSR infrared water-vapor (6.7 μm) brightness temperature between 258 and 264 K hint the sinking of dry air just to the west of the outflow jet. This is again suggests the interaction of Florence with the UTT through the secondary circulation around the outflow jet core, consistent with what the total ozone anomalies imply in Hurricane Irene.

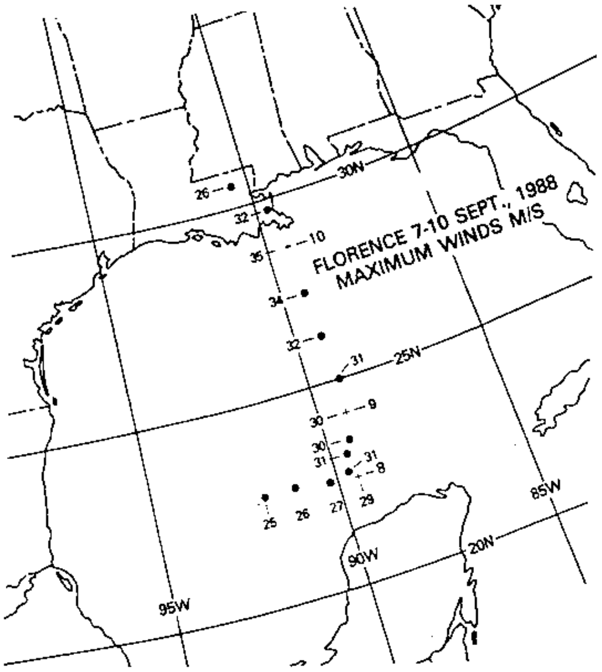

Fig. 6. Position and maximum winds (m/s) of Tropical Cyclone Florence (8-10 September 1988) every 6 h.

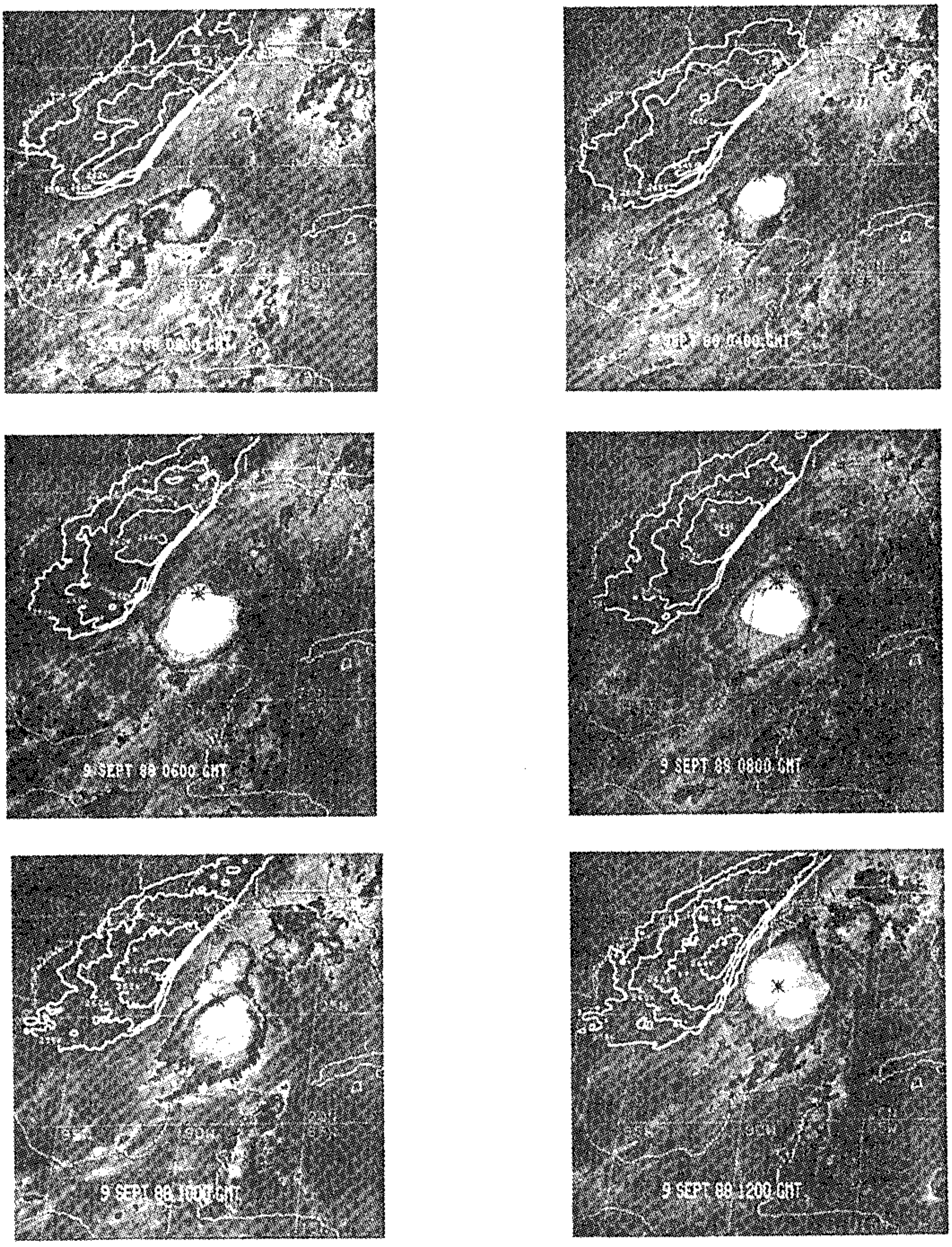

Fig. 7. GOES VISSR infrared (11.5 µm) image of Tropical Cyclone Florence between 0200 and 1200 UTC 9 September 1988. The white contours depict the 6.7 µm brightness temperature between 258-264 K at 2 K interval.

III. Numerical Model Results

Numerical models was used to further investigate the asymmetric mechanisms in the interaction of tropical cyclones and the UTTs. First, the structure of the outflow layer in an idealized tropical cyclone was examined to assess whether the proposed interaction is dynamically plausible. Then numerical simulation of the response of Hurricane Florence of 1988 to a approaching UTT in the westerly was presented.

1. Model Simulated Outflow Structure

In a typical tropical cyclone environment with zero mean wind, a generic tropical cyclone was initialized in a hydrostatic numerical model , the NRL NORAPS, using parameterized physics and a horizontal resolution of approximately 40 km (Shi et al 1990). The simulated outflow consists of asymmetric anticyclonic circulation with a outflow jet, contributing up to one half of the total angular momentum transport in the outflow layer. There are secondary transverse circulations around the jet (Fig. 8) similar to those associated with midlatititude westerly jet streaks. In the jet entrance region, the secondary circulation is thermally direct, i.e., the ascending motion is located on the anticyclonic shear side of the jet and the descending branch is located on the cyclonic shear side. In contrast, the secondary circulation is thermally indirect in the jet exit region. Both the relative humidity and potential vorticity field are consistent with the secondary circulation. It was also shown in Shi et al (1991) that a stronger tropical cyclone has stronger outflow jet and a stronger secondary circulation. These characteristics are in agreement with observed features of the tropical cyclone outflow discussed above.

Two sets of sensitivity simulations were conducted in Shi et al (1990) to test the symmetric and the asymmetric response of the model tropical cyclone to upper tropospheric forcing. In the first experiment, the outflow layer of the quasi-steady tropical cyclone was forced to be more divergent. In response, the model tropical cyclone intensified for additional 10 hPa in 36 h. Additional numerical experiments demonstrated that the deep convection play a central role in linking the upper level divergence to lower tropospheric convergence and hence the deepening. In the second experiment, the outflow jet was accelerated due to a numerical nudging. It was found that precipitation due to the induced convection occurred where upward branches of the secondary circulation were located in both the entrance and exit regions of the outflow jet (Fig. 9).

The structure of the simulated outflow jets and the results of the sensitivity test discussed above lend strong possibility of the proposed asymmetric interaction between tropical cyclones and UTTs.

2. Response of Hurricane Florence of 1988 to an UTT

The observed response of Hurricane Florence has been described above. A model simulation of Florence was conducted to isolate the effect of the approaching UTT on the behavior of Florence (Shi et al 1997). The NRL NORAPS was employed with a horizontal

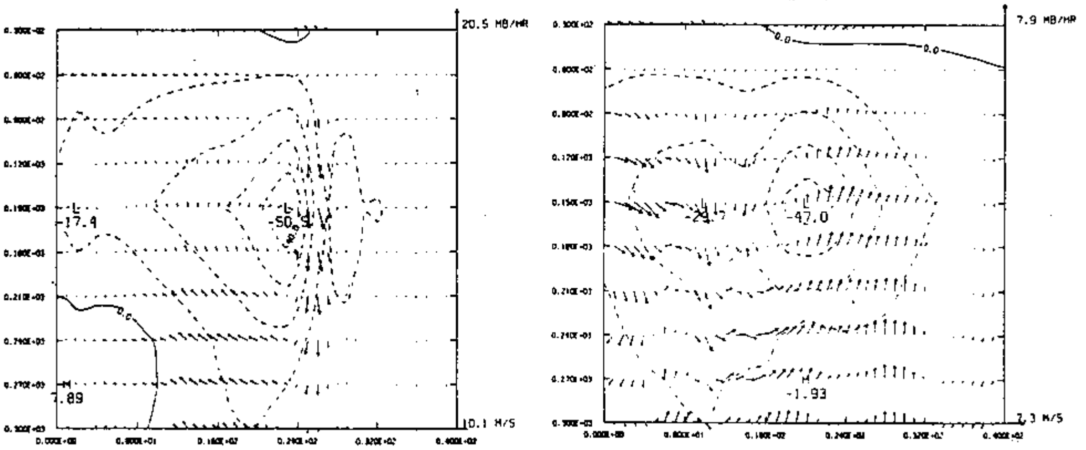

Fig. 8. Vertical cross-sections, covering 400 km and 30-300 mb, perpendicular to the outflow jet in the entrance (left panel) and exit (right panel) region. The isotachs at a 10 m/s interval show the horizontal winds normal to the plane. The vectors are formed by horizontal winds in m/s tangential to the plane and vertical velocities in mb/h.

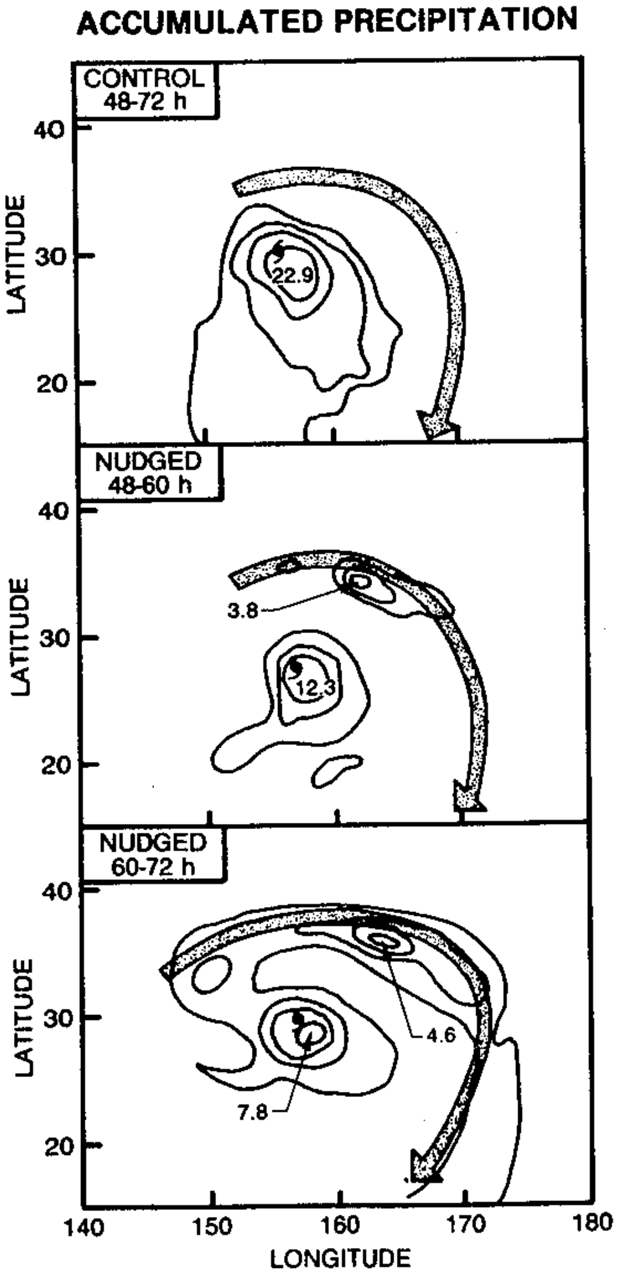

Fig. 9. The location of the idealized outflow jet and accumulated precipitation for the control (upper panel) and the accelerated jet experiment (lower panels).

resolution of 25 km and 22 levels in the vertical. The model was initialized from the NCEP (formally NMC) analysis valid for 00 UTC 9 September but enhanced with 51 dropsonde observations (Shi et al 1996).

The control experiment in Shi et al (1977) reproduced the observed intensity and track of Florence. The structure of the model outflow layer of Florence was first dissected. It was found that there was a single outflow jet into the westerly and that there was a circum-jet secondary circulation in the jet entrance region. The humidity and potential vorticity fields were consistent with the three-dimensional transport in the outflow layer. The most interesting results was the sudden increase and then decrease of the total inner core convective (as implied by the precipitation rate) where the UTT moved into a juxtaposition. In a supplementary experiment, the dynamic and thermodynamic signature of the UTT in the initial field was significantly weakened. The sudden convective increase did not occur (Fig. 10) and the eddy momentum flux was considerably reduced compared to the control. Because of the relatively coarse resolution and the cumulus parameterization in the model, the exact manner of the induced convective burst could not be resolved explicitly. These numerical experiments, however, suggested that the UTT had a definite impact on the model tropical cyclone.

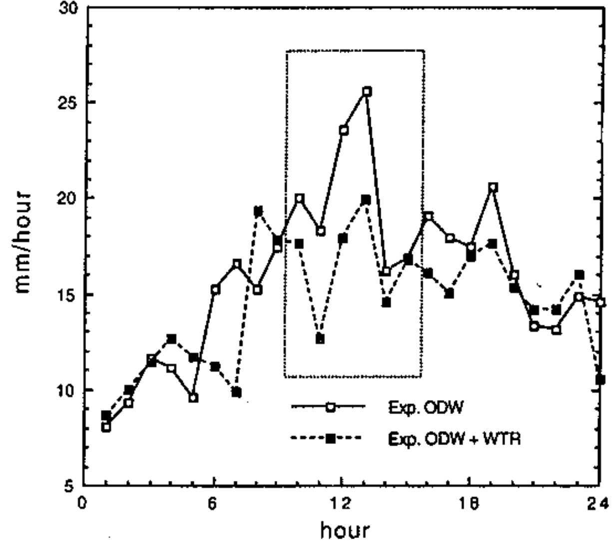

Fig. 10. Mean convective rainfall rates inside a 2x2° box around the center for the simulated Hurricane Florence (1988) with (solid) and without (dashed) the upper tropospheric trough.

IV. Summary

Observational and modeling studies presented above have shown an alternate mechanism that may play a role on the interaction between tropical cyclones and the UTTs. The proposed mechanism was based on the existence of a transverse secondary circulation around the outflow jet. As the outflow jet was channeled by the jet stream associated with an UTT, the secondary circulation would also be enhanced. The enhanced upward branch of the secondary circulation could initiate new or additional deep convection in the convectively unstable tropical atmosphere. Providing the deep convection occurred near the inner core, an intensification of the tropical cyclone could follow.

Further study using high resolution remote sensing means and numerical models with explicit clouds can further substantiate and quantify the asymmetric mechanism in the interaction between tropical cyclones and upper-tropospheric troughs presented here.

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