5. Discussion, Conclusions, and Suggestions for Future Work

5.1 Discussion of Multiscale Analyses

Similarities and differences between the two multiscale analyses [TC Camille (1969) and TC Danny (1997)] will be presented in this section. As was documented earlier in this thesis, TC Camille produced a high-impact flooding event over west-central Virginia in the 12-h period starting 0000 UTC 20 August, whereas TC Danny underwent inland reintensification while moving across the Carolinas on 24 July 1997. The most notable similarity between the two TCs is that both storms crossed the Appalachian Mountains and interacted with an equatorward entrance region of an upper-tropospheric jet located poleward over the northeast United States. Although a maximum wind speed in the upper-tropospheric jet poleward of TC Camille and TC Danny was 45 m s^{-1} and 35 m s^{-1}, respectively, TC Danny was situated closer to the equatorward entrance region of the weaker upper-tropospheric jet than TC Camille was to the stronger upper-tropospheric jet. Accordingly, TC Danny was able to interact with the equatorward entrance region of the weaker upper-tropospheric jet more directly.

The presence of a lower-tropospheric baroclinic zone associated with a surface frontal boundary was observed in both TC cases as well. A surface cold front associated with the TC Camille case was important throughout the inland flooding event over west-central Virginia. In addition to the synoptic-scale ascent beneath the equatorward entrance region of the upper-tropospheric jet poleward of TC Camille, frontogenesis along the lower-tropospheric baroclinic zone associated with the surface front forced additional ascent over Nelson County, the area that received copious amounts of rainfall during the inland flooding event (maximum rainfall of 690 mm over Massies Mill, Virginia, during the 12-h period stated in section 3.1.2). A stationary surface front observed in the TC Danny case had an associated lower-tropospheric baroclinic zone that was located over Virginia. In addition to synoptic-scale ascent in the equatorward entrance region of the upper-tropospheric jet, frontogenesis along the lower-tropospheric baroclinic zone forced additional ascent around the circulation of TC Danny as the TC moved into northeastern North Carolina on 24 July.

A highly moist environment (PW > 50 mm) was an additional similarity between the two TC cases, but the moist conditions played different roles in each case. A moist, southerly flow ahead of TC Camille likely provided sufficient instability in west-central Virginia to promote the development and maintenance of heavy rainfall and convection. In the case of TC Danny, PW values exceeding 50 mm were located around the TC circulation and promoted the initiation and maintenance of convection prior to and during its inland reintensification. Available observed soundings exhibited a moist and unstable environment within which TC Danny was embedded.

One of the main differences between the TC Camille and TC Danny cases was the orientation of the midlatitude flow poleward of each TC. A broad, closed-off upper-level low associated with a quasi-stationary extratropical cyclone to the northeast of TC Camille prohibited inland reintensification from occurring. In addition, a quasi-stationary positive PV anomaly was coincident with the broad upper-level low. This synoptic setup is similar to the “northeast” pattern described by Harr et al. (2000), in that it is characterized by a quasi-stationary midlatitude system to the northeast of a poleward-moving TC. The strong confluent zonal flow into which a TC enters was a determining factor explaining why the TC does not intensify significantly (Harr et al. 2000). In this setup, minimal baroclinic development occurs, which leads to a minimal strengthening of the TC (Harr et al. 2000). Conversely, TC Danny had an upper-tropospheric trough to the northwest, which was coincident with an upper-tropospheric positive PV anomaly. Hanley et al. (2001) found that this setup could produce a "favorable distant interaction" between a TC and an upper-tropospheric positive PV anomaly. The comparable size of the positive PV anomaly and TC Danny was important in minimizing adverse effects of vertical wind shear on the TC circulation. Bosart et al. (2000) showed that ascent associated with a positive PV anomaly likely acts to organize deep convection, thereby resulting in an upscale development of convection into clusters. As a result of this upscale development, the positive PV anomaly becomes comparable in size to the clustered area of deep convection (Molinari et al. 1995, 1998; Bosart et al. 2000). The comparably sized positive PV anomaly would likely exhibit less vertical wind shear and would therefore be more favorable for TC intensification (Molinari et al. 1995, 1998; Bosart et al. 2000).

Another difference between the TC Camille and TC Danny cases was a thermal advection pattern in the equatorward entrance region of an upper-tropospheric jet. Cold-air advection in the lower-troposphere analyzed poleward of TC Camille acted to oppose ascent in the middle and upper troposphere beneath an equatorward entrance region of an upper-tropospheric jet. This situation suggests that the ascent associated with frontogenesis observed along a lower-tropospheric baroclinic zone was an important forcing mechanism in the inland flooding that occurred during TC Camille's transit across the central Appalachian Mountains. In the TC Danny case, on the other hand, lower-tropospheric warm-air advection, although weak, was analyzed northeast of TC

Danny and acted to force ascent beneath an equatorward entrance region of an upper-tropospheric jet. The ascent associated with this area of warm-air advection not only favored the development of rainfall and convection around TC Danny's inner core, but also to the northeast of TC Danny as well. The area of rainfall to the northeast of TC Danny contributed to a diabatically driven upper-tropospheric outflow. Negative PV advection by the irrotational wind in this diabatically driven outflow acted to strengthen the cross-jet PV gradient poleward of TC Danny. This strengthened PV gradient was associated with a strengthening of the upper-tropospheric jet poleward of TC Danny and with increased ascent over the storm.

Effects of vertical wind shear were an important difference between the two cases as well. Within several days after making landfall, TC Camille had weakened into a tropical depression and headed into an environment where vertical wind shear started to tilt the TC circulation. A broad positive PV anomaly to the northeast of TC Camille strongly influenced the TC circulation as the storm traversed the Appalachian Mountains. As previously mentioned, the reduced vertical wind shear associated with the comparably sized positive PV anomaly affecting TC Danny was favorable for its inland reintensification. In the case of TC Camille, a broad PV anomaly meant that stronger shear was present, which prevented the redevelopment of the TC. Prior to its inland reintensification, TC Danny spent several days in an environment that was characterized by low shear. This environment was very important in preserving the preexisting vortex of the TC and the associated rainfall and convection. As TC Danny moved toward the Carolinas, vertical wind shear values increased from 2.5 m s^{-1} to 5 m s^{-1} and were coincident with an organization and development of convection near the center of the TC circulation. Diabatic heating associated with the convection favored the development of PV and cyclonic relative vorticity toward the surface, which strengthened the TC vortex and subsequently led to its inland reintensification. By the time TC Danny encountered higher vertical shear than when the TC was over Alabama and Georgia, the diabatically driven outflow associated with the TC negated the effects of vertical wind shear.

A process unique to the TC Camille case was an orographic enhancement of rainfall induced by upslope flow across the Blue Ridge Mountains over west-central Virginia during the inland flooding event associated with the storm. Locations in Nelson County that received copious amounts of rainfall were on south- and southeast-facing slopes, indicative of the importance of orography in this inland flooding event. An analysis of the Big Thompson flood from 31 July 1976 (Caracena et al. 1979) showed that mountainous terrain was key to that inland flooding event. Physical mechanisms leading to its severity were a prolonged upslope flow and a continuous replenishment of moisture and instability by the larger-scale flow (Caracena et al. 1979). These physical mechanisms were similar to the TC Camille case, and the flooding associated with TC Camille was exacerbated by frontogenetically forced ascent along a lower-tropospheric baroclinic zone.

The TC Camille inland flooding case closely resembled a "frontal" pattern for flash-flooding-producing MCSs (Maddox et al. 1979), where warm, moist air is transported by a lower-tropospheric jet toward a west–east quasi-stationary lower-tropospheric baroclinic zone. In addition, the synoptic setup in the TC Camille case was similar to a DC category PRE described by Moore (2010). A DC category PRE develops beneath an equatorward entrance region of an upper-tropopsheric jet positioned within a region of upper-level confluent flow associated with a trough-over-ridge pattern situated downstream of a TC (Moore 2010). This type of PRE is associated with deep moist southerly flow on the eastern flank of the TC circulation that is transported into the PRE region (Moore 2010). Synoptic-scale ascent beneath the equatorward entrance region of the upper-tropospheric jet is reinforced by subsynoptic-scale ascent associated with frontogenetical forcing and warm-air advection (Moore 2010).

Conceptual models of the aforementioned similarities and differences between the two TC–jet interaction cases, in addition to other important tropospheric features and processes unique to each case, are found in Figs. 5.1a,b. The conceptual model in Fig. 5.1a that characterizes the TC Camille heavy rain event could be used as a source of forecast guidance for future events that may resemble a "Camille-like" situation. If upper-level flow poleward of a TC that crosses the central Appalachian Mountains is characterized by an upper-tropospheric jet located within a region of upper-level confluent flow across the northeast United States, a heavy rain event is likely, with the rainfall especially heavy in orographically favored regions (Fig. 5.1a). This confluent flow also contains an upper-tropospheric positive PV anomaly coincident with a broad, upper-level low located over southeastern Quebec and an upper-level high off the southeastern United States coast (Fig. 5.1a). Cold air-advection upstream of this confluent flow and beneath an equatorward entrance region of an upper-tropopsheric jet (Fig. 5.1a) acts to suppress ascent beneath this jet-entrance region. This cold air-advection is located on the cold side of a west–east oriented quasi-stationary lower-tropospheric baroclinic zone located across the Mid-Atlantic region. The warm side of this quasi-stationary lower-tropopsheric baroclinic zone is characterized by moist, low-level southerly flow on the eastern flank of the TC circulation (Fig. 5.1a). Forcing for ascent in the area of heaviest rainfall is associated with frontogenesis along this lower-tropospheric baroclinic zone. Additional ascent is forced by an upslope flow induced by mountainous terrain across the central Appalachian Mountains (Fig. 5.1a).

Prognoses of future events that may resemble a “Danny-like” situation could benefit from using the conceptual model displayed in Fig. 5.1b. Prior to interacting with the poleward midlatitude flow, a TC is embedded within a low-shear and moist environment (Fig. 5.1b) that acts to help preserve a preexisting vortex and convection associated with a TC. As the TC moves toward the east, convection around the TC circulation starts to organize and develop as a result of a favorable moist thermodynamic environment characterized by deep instability. This organization of convection leads to an increase in maximum heating at midlevels. Below the level of maximum heating, cyclonic relative vorticity and PV increases, which enables the TC vortex to strengthen. The TC subsequently reintensifies as upper-level features (e.g., upstream positive PV anomaly and poleward upper-tropopsheric jet) provide forcing for favorable synoptic-scale ascent over the TC circulation (Fig. 5.1b). Negative PV advection by the irrotational wind in diabatically driven outflow associated with the TC (Fig. 5.1b) acts to enhance a cross-jet PV gradient poleward of the TC. This enhanced PV gradient strengthens an upper-tropospheric jet and increases ascent over the TC. Frontogenesis along a lower-tropospheric baroclinic zone and warm-air advection northeast of the TC (Fig. 5.1b) provide additional forcing for ascent around the TC circulation.

5.2 Conclusions

The main objectives of this research were to: (1) document the synoptic-scale environment and underlying mesoscale processes responsible for inland flooding associated with TC Camille (1969) and the inland reintensification of TC Danny (1997); (2) explain similarities and differences between the TC Camille and TC Danny cases; and (3) document important physical mechanisms and processes that lead to various impacts associated with inland TC–midlatitude jet interactions. To accomplish these objectives, important tropospheric features and processes were identified in each case using reanalysis datasets, observational data, and a PV analysis perspective. TC Camille produced a high-impact inland flooding event over west-central Virginia on 20 August 1969, where 690 mm of rain fell over Massies Mill, Virginia, in the 12-h period starting 0000 UTC 20 August. TC Danny, on the other hand, underwent significant inland reintensification over the Carolinas on 24 July 1997, where its minimum central MSLP decreased from 1012 hPa to 1000 hPa and its maximum sustained wind speed increased from 20 kt to 40 kt in the 18-h period starting 0000 UTC 24 July.

Documentation of both TC–jet interaction cases showed that each TC was situated underneath an equatorward entrance region of an upper-tropospheric jet. In addition to being positioned beneath an equatorward entrance region of an upper-tropospheric jet, both TCs interacted with a lower-tropospheric baroclinic zone associated with a surface frontal boundary. Furthermore, TCs Camille and Danny were embedded within a highly moist environment, which likely provided instability that supported the initiation and maintenance of convection.

Important differences between the TC Camille and TC Danny cases included the orientation of the upper-level flow poleward of each TC. Specifically, the location and large spatial scale of a quasi-stationary upper-tropospheric positive PV anomaly to the northeast of TC Camille was deemed to have a negative influence on the TC. This negative influence was due to strong vertical wind shear induced by the quasi-stationary positive PV anomaly, which acted to tilt and weaken the circulation of the storm. A positive PV anomaly to the northwest of TC Danny interacted favorably with the TC by forcing synoptic-scale ascent over the TC circulation. The effects of increased vertical wind shear over TC Danny were negated by diabatically driven upper-tropospheric outflow from TC-related heavy rainfall that acted to build a ridge near the storm center. Furthermore, a thermal advection pattern beneath the equatorward entrance region of an upper-tropospheric jet poleward of TC Camille acted to suppress ascent in the region where cold-air advection was indicated. In the TC Danny case, warm-air advection acted to force ascent beneath the equatorward entrance region of an upper-tropospheric jet.

Conceptual models characterizing the two case studies show important synoptic-scale and mesoscale mechanisms and processes that lead to various inland impacts associated with TC–midlatitude jet interactions. “Camille-like” events, which can lead to severe inland flooding, are characterized by a synoptic setup where warm, moist southerly flow ahead of a TC is directed toward a lower-tropopsheric baroclinic zone beneath an equatorward entrance region of an upper-tropopsheric jet located within an upper-level confluent flow. Synoptic-scale ascent over the area of heaviest rainfall is reinforced by frontogenetically forced ascent along a lower-tropospheric baroclinic zone and in the equatorward entrance region of the upper-tropopsheric jet. An upslope component of the wind induced by mountainous terrain leads to orographic enhancement of rainfall in the area of heaviest precipitation.

"Danny-like" events, which can reintensify inland, are characterized by a prior low-shear environment that helps to preserve the preexisting vortex and convection associated with a TC. The presence of moisture and instability can help to organize and reinvigorate deep convection around the TC. An increase in the convection can be linked to an increase in diabatic heating at midlevels and to an increase of cyclonic relative vorticity and PV below the level of maximum diabatic heating. Synoptic-scale ascent ahead of an upstream positive PV anomaly and in the equatorward entrance region of an upper-tropospheric jet poleward of the TC can provide a favorable environment for the TC to reintensify. Negative PV advection by the irrotational wind strengthens a poleward cross-jet PV gradient and the associated upper-tropospheric jet and enhances ascent over a TC. Frontogenesis and warm-air advection northeast of the TC also force ascent around the TC circulation.

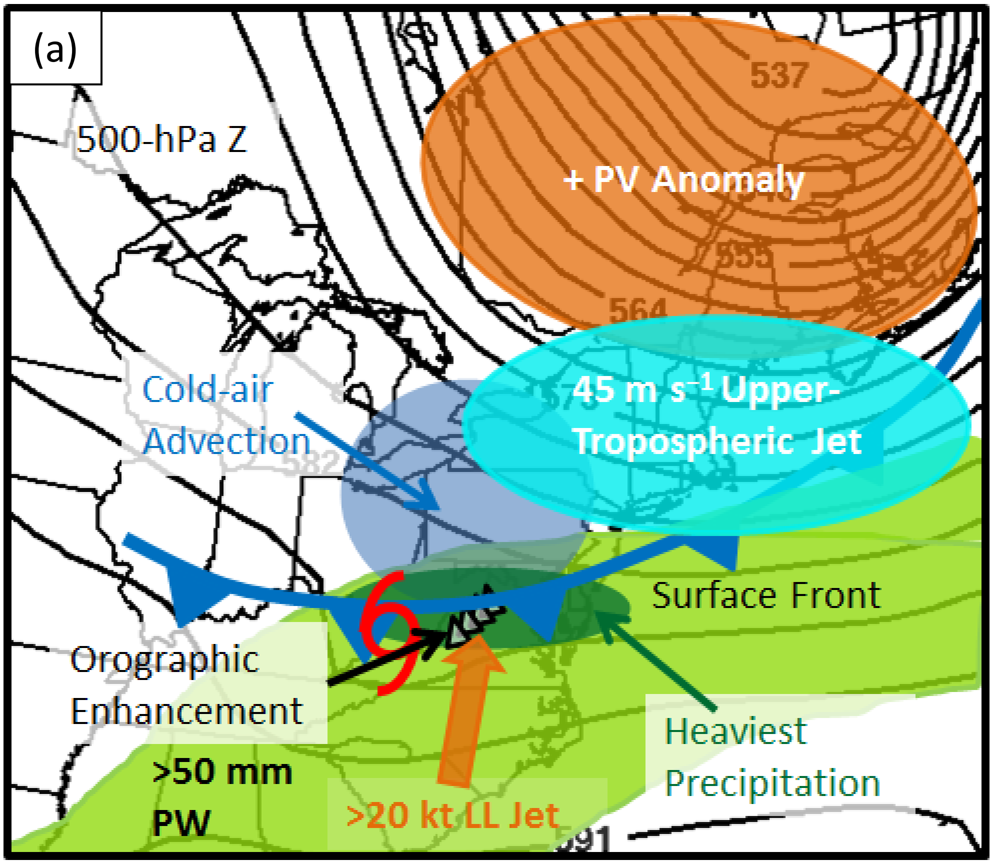
5.3 Suggestions for Future Work

Although this thesis documented insight into mechanisms and processes associated with TC–midlatitude jet interactions, future opportunities remain to better understand relative contributions from important tropospheric features and processes associated with these interactions. For the TC Camille case, high-resolution modeling would offer an effective method for determining the relative contributions of the orography of the Blue Ridge Mountains, an upper-tropospheric jet, and a lower-tropospheric baroclinic zone. For the TC Danny case, high-resolution modeling would offer an effective method for determining the relative contributions of diabatic heating, an upper-tropospheric jet, and an upper-tropospheric positive PV anomaly.

As was used in a previous study (Hanley et al. 2001), EFC calculations of angular momentum quantified an interaction between a TC and an upper-tropospheric trough. Particularly for the TC Danny case, EFC calculations over a 300–600-km radial range would quantify the strength of the interaction between the TC and the upstream upper-tropospheric trough and associated positive PV anomaly. Then calculations could confirm the "favorable distant interaction" between TC Danny and the positive PV anomaly hypothesized to have taken place during the TC's inland reintensification. A similar analysis using EFC calculations for the TC Camille case could provide insight into the factors that prevented the TC from undergoing inland reintensification.

Recalling the Evans et al. (2011) study documented in section 1.4, the inland reintensification of TC Erin over Oklahoma was found to have been impacted by anomalous wet months preceding the event. As found by Shen et al. (2002), inland reintensifying TCs have occurred in situations where the underlying surface has high heat conductivity and is relatively moist. In light of these two studies, analysis of the soil moisture along the track of TC Danny may prove to be important in explaining its inland reintensification. The PRE observed over North Carolina (section 4.1.2), a day prior to TC Danny moving across the area, may have led to favorable surface latent heat fluxes that served as an important element in the inland reintensification of the TC.

A list of inland reintensifying TCs (Table II) presented in section 4.1.3 provided a first-order historical perspective of the TC Danny case, but a further analysis of this case list provides the opportunity for future research. Specifically, a documentation of all important tropospheric features and processes in each TC case could reveal similarities between these cases.


(a)
500-hPa Z
+ PV Anomaly
537
555
564
45 m s-1 Upper-Tropospheric Jet
Cold-air Advection
582
Surface Front
Orographic Enhancement
Heaviest Precipitation
>50 mm PW
>20 kt LL Jet
591

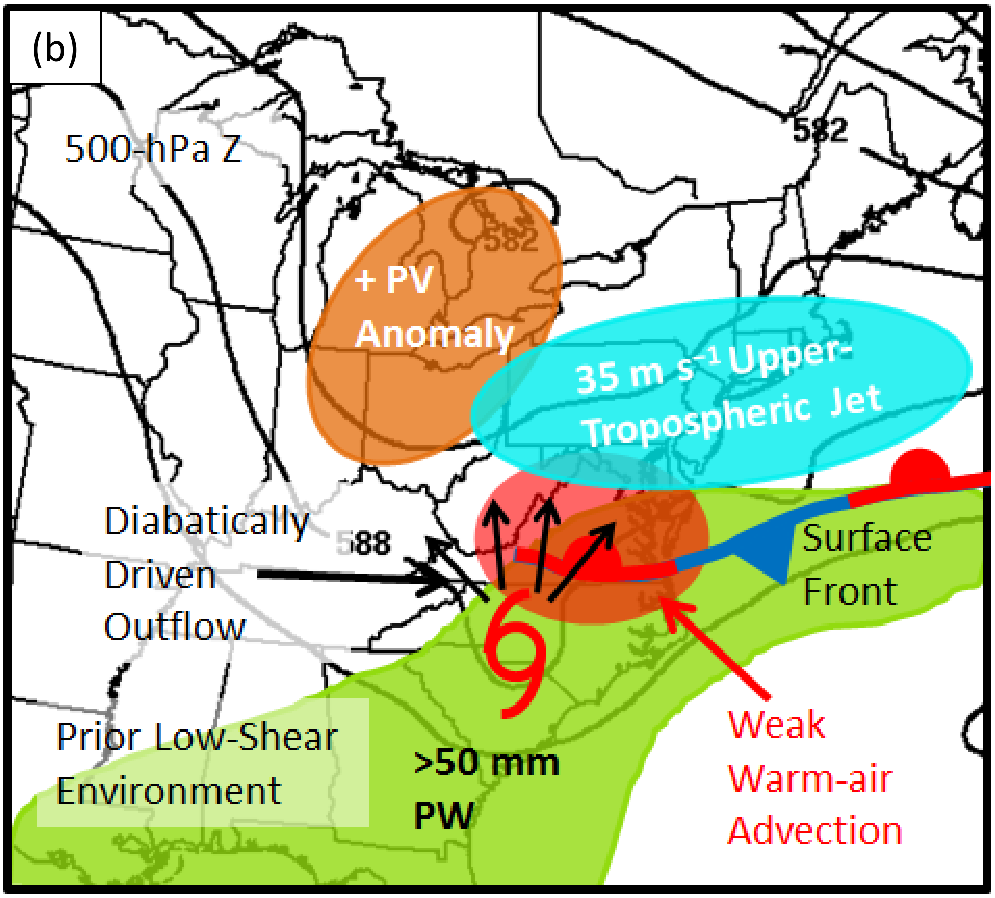


Fig. 5.1. Conceptual models depicting important mechanisms and processes leading to (a) “Camille-like” and (b) “Danny-like” events. For both conceptual models, 500-hPa geopotential height is indicated by solid black contours, the positive PV anomaly is shaded in orange, the upper-tropospheric jet is shaded in light blue, regions of warm-air advection and cold-air advection are indicated by red and blue shaded regions, respectively, and areas of PW exceeding 50 mm are shaded in light green. The red TC symbol indicates the position of the TC. (a) Low-level jet is indicated by the orange arrow. The placement of orography is indicated by the triangular symbols. The approximate area of heaviest rainfall is indicated by dark green shading. (b) Diabatically driven outflow is indicated by the black arrows emanating from the TC.