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Figure 1.1: Schematic midtropospheric streamlines associated with a PRE ahead of TC Agnes (1972). Shaded regions indicate loci of heavy rainfall. Reproduced from Fig. 13 in Bosart and Carr (1978).

Figure 1.2: Conceptual model of the synoptic-scale environment associated with LOT PREs in advance of TCs, revised and updated from Bosart and Carr (1978). Position of TC is given by tropical storm symbol. Representative TC tracks are marked with solid blue arrows. Low-level (LL) features are representative of the 925-hPa level, midlevel (ML) features are representative of the 700-hPa level, and upper-level (UL) features are representative of the 200-hPa level. Boxed region indicates the area of the mesoscale and physiographic conceptual model shown in panel (b). Reproduced from Figs. 5.1 and 5.2 in C07.

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Figure 1.4: Schematic diagram of the radar-observed features of the (a) TL/AS and (b) BB patterns of extreme-rain-producing MCSs. Contours (and shading) represent approximate radar reflectivity values of 20, 40, and 50 dBZ. In (a), the low-level and midlevel shear arrows refer to the shear in the surface-to-925-hPa and 925–500-hPa layers, respectively, as discussed in section 4 of Schumacher and Johnson (2005). The dash-dot line in (b) represents an outflow boundary; such boundaries were observed in many of the BB MCS cases. The length scale at the bottom is approximate and can vary substantially, especially for BB systems, depending on the number of mature convective cells present at a given time. Caption and figure reproduced from Fig. 3 in Schumacher and Johnson (2005).

Figure 1.5: Schematic cross section of an elevated convective event taken parallel to a low-level jet (LLJ) across a surface frontal zone. Dashed lines represent typical θ_e values, the large stippled arrow represents the ascending LLJ, the thin solid oval with arrows represents the ageostrophic direct thermal circulation (DTC) associated with the upper-level jet (ULJ), and the dash-dotted oval with arrows represents the DTC associated with the low-level frontogenetical forcing. The area aloft enclosed by dotted lines indicates upper-level divergence; the area aloft enclosed by solid lines denotes the location of the ULJ. Note that in this cross section, the horizontal distance between the MCS and the location of the ULJ is not to scale. Caption and figure reproduced from Fig. 14 in Moore et al. (2003).

Figure 1.6: Conceptual model of transformation stage of ET in the western North Pacific, with labeled areas as follows: 1) environmental equatorward flow of cooler, drier air (with corresponding open cell cumulus); 2) decreased TC convection in the western quadrant (with corresponding dry slot) in step 1, which extends throughout the southern quadrant in steps 2 and 3; 3) environmental poleward flow of warm, moist air is ingested into TC circulation, which maintains convection in the eastern quadrant and results in an asymmetric distribution of clouds and precipitation in steps 1 and 2; steps 2 and 3 also feature a southerly jet that ascends tilted isentropic surfaces; 4) ascent of warm, moist inflow over tilted isentropic surfaces associated with baroclinic zone (dashed line) in middle and lower panels; 5) ascent (undercut by dry-adiabatic descent) that produces cloudbands wrapping westward and equatorward around the storm center; dry-adiabatic descent occurs close enough to the circulation center to produce erosion of eyewall convection in step 3; 6) cirrus shield with a sharp cloud edge if confluent with polar jet. Caption and figure reproduced from Fig. 5 in Klein et al. (2000).

Figure 2.1: Schematic illustration of the 200-hPa flow configuration for the three synoptic patterns associated with PREs: (a) JR, (b) SJ, and (c) DC. The PRE and TC locations are marked with the green star and the tropical storm symbol, respectively. Schematic streamlines are shown in black, and the jet streak is indicated by the red shaded area, with the “J” symbol marking the location of maximum wind speed.

Figure 3.1: The distribution of all PREs and PPTCs during 1988–2008 stratified by synoptic pattern. The gray bars indicate the number of PREs for each pattern, whereas the black bars indicate the number of TCs.

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Figure 3.3: Plots of TC tracks along with the geographic locations of PREs (green numbers) and associated TCs (red numbers) at the time of PRE initiation for (a) the JR pattern, (b,c) the SJ pattern, (d) the DC pattern, and (e) UC PREs. In each of the panels, the PREs and parent TCs are numbered in chronological order, with each number corresponding to a PRE–TC pair. The numbers corresponding to each pair can be found in the last column of Table I. Only the location of initial PRE for each TC is plotted.

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Figure 3.5: Box and whisker plots for each synoptic category and for all PREs showing (a) separation distance between the TC and PRE, (b) PRE longevity, (c) maximum PRE rainfall, and (d) lag time between PRE initiation and the passage of the TC over the latitude of PRE initiation. The whiskers indicate the maximum and minimum values, the top (bottom) of the box marks the third (first) quartile, and the line separating the light and dark blue denotes the median.

Figure 4.1: PRE-relative composites for 7 JR category PREs. The panels on the left show 200-hPa wind speed (shaded in m s^{-1} according to the color bar on the left), geopotential height (contoured in black every 10 dam), and positive divergence (contoured in red every $0.5 \times 10^{-5} \text{ s}^{-1}$ starting at $0.5 \times 10^{-5} \text{ s}^{-1}$) at (a) T-12 h, (c) T-0 h, and (e) T+12 h. The panels on the right show total PW (shaded in mm according to the colorbar on the right), as well as 925-hPa geopotential height (contoured in black every 2 dam), potential temperature (contoured in blue every 2 K), and Petterssen frontogenesis [contoured in white every $0.5 \times 10^{-1} \text{ K (100 km)}^{-1} (3 \text{ h})^{-1}$ starting at $0.5 \times 10^{-1} \text{ K (100 km)}^{-1} (3 \text{ h})^{-1}$] at (b) T-12 h, (d) T-0 h, and (f) T+12 h. The PRE initiation location is denoted by the green and white stars, and the composite TC location is marked by the tropical storm symbol.

Figure 4.2: PRE-relative composites for 7 JR category PREs showing 200-hPa wind speed (shaded in m s^{-1} according to the colorbar), 200-hPa irrotational wind vectors $> 5 \text{ m s}^{-1}$, 700-hPa ascent (contoured in red every $0.5 \times 10^{-3} \text{ hPa s}^{-1}$ starting at $-0.5 \times 10^{-3} \text{ hPa s}^{-1}$), and 250–200-hPa PV (0.5, 1, 2, 4, and 6 PVU contours shown in black) at (a) T-12 h, (b) T-0 h, and (c) T+12 h. The PRE initiation location is denoted by the green star, and the composite TC location is marked by the tropical storm symbol.

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Figure 5.1: The NHC Best Track positions for TC Rita during 19–26 September 2005 overlaid on the NPVU QPE analysis (shaded in mm according to the color bar) for 1200 UTC 24 September–0000 UTC 26 September 2005. The filled (unfilled) circles denote the 0000 UTC (1200 UTC) TC positions.

Figure 5.2: WSI NOWrad radar reflectivity mosaics (shaded every 5 dBZ) and 1000–500-hPa vertical wind shear $\geq 15 \text{ m s}^{-1}$ (half barb: 2.5 m s^{-1} ; full barb: 5 m s^{-1} ; pennant: 25 m s^{-1}) calculated from the NCEP 20-km RUC analyses at (a) 0000 UTC, (b) 0300 UTC, (c) 0600 UTC, (d) 0900 UTC, (e) 1200 UTC, and (f) 1500 UTC 25 September 2005. The TC location is denoted by the tropical storm symbol.

Figure 5.3: NCEP 1° GFS analysis at 0000 UTC 25 September of: (a) 200-hPa geopotential height (contoured in black every 10 dam) and wind speed (shaded in m s^{-1} according to the color bar); (b) total PW (shaded in mm according to the color bar) overlaid with 925-hPa geopotential height (contoured in black every 3 dam), potential temperature (contoured in blue every 3 K), and Petterssen frontogenesis [contoured in white every $2 \text{ K (100 km)}^{-1} (3 \text{ h})^{-1}$ starting at $1 \text{ K (100 km)}^{-1} (3 \text{ h})^{-1}$]; and (c) 700-hPa geopotential height (contoured in black every 3 dam), potential temperature (contoured in red every 3 K), \mathbf{Q} vectors ($10^{-11} \text{ K m}^{-1} \text{ s}^{-1}$; reference vector at the bottom of the panel), and \mathbf{Q} -vector divergence (shaded in $10^{-15} \text{ K m}^{-2} \text{ s}^{-1}$ according to the color bar). The TC and PRE locations are denoted by the tropical storm symbol and the star, respectively.

Figure 5.4: Skew T - $\log p$ plots showing temperature (black line in $^{\circ}\text{C}$), dewpoint (dashed red line in $^{\circ}\text{C}$), and wind (barbs in m s^{-1} according to the convention in Fig. 5.2) at 0000 UTC 25 September 2005 for (a) Omaha, NE (OAX), and (b) Chanhassen, MN (MPX). The PW and CAPE values for each location are indicated at the top of each panel.

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Figure 5.6: NCEP 20-km RUC analyses of 925-hPa potential temperature (contoured in gray every 3 K), Petterssen frontogenesis [contoured in red every $3 \text{ K (100 km)}^{-1} (3 \text{ h})^{-1}$ starting at $1 \text{ K (100 km)}^{-1} (3 \text{ h})^{-1}$], and winds $\geq 7.5 \text{ m s}^{-1}$ (barbs according to the convention in Fig. 5.2) overlaid on WSI NOWrad radar reflectivity mosaics (shaded in dBZ according to the color bar) at (a) 0000 UTC, (b) 0300 UTC, (c) 0600 UTC, and (d) 1200 UTC September 2005. Cross sections A–B and C–D are indicated in panels (c) and (d). The TC location is denoted by the tropical storm symbol.

Figure 5.7: Vertical cross sections generated from the NCEP 1° GFS analyses showing potential temperature (contoured in blue every 3 K), Petterssen frontogenesis [contoured in red every $2 \text{ K (100 km)}^{-1} (3 \text{ h})^{-1}$ starting at $1 \text{ K (100 km)}^{-1} (3 \text{ h})^{-1}$], mixing ratio (shaded in g kg^{-1} according to the color bar), and the flow in the plane of the cross section (vectors with the horizontal component in m s^{-1} and the vertical component in hPa s^{-1} ; reference vectors are at the bottom of each panel) at (a) 0000 UTC, (b) 0600 UTC, and (c) 1200 UTC 25 September 2005. The cross-section locations are indicated in Figs. 5.6a,c,d, respectively.

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Figure 5.9: Ten 36-h backward kinematic air parcel trajectories ending within the PRE region at 0600 UTC 25 September 2005 overlaid on the NCEP 1° GFS total PW analysis at 1800 UTC 23 September 2005 (shaded in mm according to the color bar on the left). The red (black) numbers denote the ending (beginning) point of each trajectory. Trajectories 1–5 begin at 850 hPa and trajectories 6–10 begin at 700 hPa. The white circles mark the 0000 UTC 25 September and 0000 UTC 24 September air parcel positions. The air parcel pressure values (hPa) are shaded according to the color bar at the bottom. For reference, the track of TC Rita subsequent to 1800 UTC 23 September 2005 is indicated by the blue arrow, and the positions of TC Rita at 1800 UTC 23 September, 0000 UTC 25 September, and 0600 UTC September 2005 are marked by the tropical storm symbols. The dashed blue line indicates the location of the 925-hPa baroclinic zone at 0600 UTC 25 September.

Figure 5.10: 200-hPa irrotational wind vectors ($> 5 \text{ m s}^{-1}$; reference vector is at the bottom of each panel), 200-hPa wind speed (shaded in m s^{-1} according to the color bar), 700-hPa ascent (contoured in red every $5 \times 10^{-3} \text{ hPa s}^{-1}$ starting at $-5 \times 10^{-3} \text{ hPa s}^{-1}$), and 250–200-hPa PV (0.5, 1, 2, 4, and 6 PVU contours shown in black) generated from the NCEP 1° GFS analyses at (a) 0000 UTC, (b) 0600 UTC, and (c) 1200 UTC 25 September 2005. The TC and PRE locations are denoted by the tropical storm symbol and the star, respectively. Cross-section E–F is indicated in panels (a) and (c).

Figure 5.11: Vertical cross sections generated from the NCEP 1° GFS analyses showing potential temperature (contoured in gray every 3 K), ascent (contoured in red every $5 \times 10^{-3} \text{ hPa s}^{-1}$ starting at $-5 \times 10^{-3} \text{ hPa s}^{-1}$), PV (shaded in PVU according to the color bar), and horizontal wind speed (contoured in black every 10 m s^{-1} starting at 30 m s^{-1}) at (a) 0000 UTC and (b) 1200 UTC 25 September 2005. Panel (b) also shows positive 12-h potential temperature changes (contoured in green every 0.5 K starting at 1 K and every 1 K starting at 3 K) between 0000 UTC and 1200 UTC 25 September. The cross-section location is indicated in Figs. 5.10a,c.

Fig. 5.12: The NHC Best Track positions for TC Ernesto during 29 August–3 September 2006 overlaid on the NPVU QPE analysis (shaded in mm according to the color bar) for 1200 UTC 30 August–1200 UTC 1 September 2006. The filled (unfilled) circles denote the 0000 UTC (1200 UTC) TC positions. The inset in the upper-left corner shows NPVU QPE analysis (shaded in mm according to the color bar) for 1200 UTC 30–1200 UTC 31 August 2006.

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Figure 5.15: Skew T - $\log p$ plots showing temperature (black line in $^{\circ}\text{C}$), dewpoint (dashed red line in $^{\circ}\text{C}$), and winds (barbs in m s^{-1} according to the convention in Fig. 5.2) at 1800 UTC 30 August 2006 for (a) Greensboro, NC (GSO), and (b) Newport, NC (MHX), and at (c) 0000 UTC 31 August 2006 for GSO. The PW and CAPE values for each location are indicated at the top of each panel.

Figure 5.16: Vertical cross sections generated from the NCEP 20-km RUC analyses showing potential temperature (contoured in blue every 3 K), Petterssen frontogenesis [contoured in red every $2 \text{ K (100 km)}^{-1} (3 \text{ h})^{-1}$ starting at $1 \text{ K (100 km)}^{-1} (3 \text{ h})^{-1}$], mixing ratio (shaded in g kg^{-1} according to the color bar), horizontal wind speed (contoured in green every 10 m s^{-1} starting at 30 m s^{-1}), and the flow in the plane of the cross section (vectors with the horizontal component in m s^{-1} and the vertical component in hPa s^{-1} ; reference vectors are at the bottom of each panel) at (a) 1800 UTC 31 August and (b) 0000 UTC 31 August 2006. The green “J” indicates the location of maximum horizontal wind speed. The cross section locations are indicated in Figs. 5.14b,c, respectively.

Figure 5.17: Total PW (shaded in mm according to the color bar) and 1000–100-hPa VIMF vectors ($\text{kg m}^{-1} \text{ s}^{-1}$; reference vector in the center) and VIMF convergence (contoured in blue every $5 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$ starting at $-5 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$) generated from the 20-km RUC analyses at (a) 1800 UTC 30 August, (b) 2100 UTC 30 August, (c) 0000 UTC 31 August, and (d) 0600 UTC 31 August 2006. The centroid of the PRE is marked by the white star, and the TC location is denoted by the tropical storm symbol.

Figure 5.18: Two sets of fifteen 36-h backward kinematic air parcel trajectories ending within the PRE region at (a) 925 hPa and (b) 400 hPa at 0000 UTC 31 August 2006 overlaid on the NCEP 1° GFS total PW analysis at 1200 UTC 29 August 2006 (shaded in mm according to the color bar on the left). The air parcel pressure values (hPa) are shaded according to the color bar at the bottom of each panel. The red (black) numbers denote ending (beginning) point of each trajectory. The position of the surface thermal boundary associated with the PRE cold pool at 0000 UTC 31 August is indicated by the dashed blue line. The position of TC Ernesto at 1200 UTC 29 August 2006 is indicated by the tropical storm symbol.

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Figure 5.23: *GOES-12* IR ($\sim 11 \mu\text{m}$) satellite imagery at (a) 1800 UTC 23 October, (b) 0000 UTC 24 October, (c) 0600 UTC 24 October, and (d) 1200 UTC 24 October 2005. The “W” and the “ α ” symbols indicate the positions of TC Wilma and TS Alpha, respectively. [Images courtesy of the National Climatic Data Center (NCDC) GIBBS web site at <http://www.ncdc.noaa.gov/gibbs/>].

Figure 5.24: WSI NOWrad radar reflectivity mosaics (shaded in dBZ according to the color bar) at (a) 1800 UTC 23 October, (b) 0000 UTC 24 October, (c) 0300 UTC 24 October, (d) 0600 UTC 24 October, (e) 1200 UTC 24 October, and (f) 1800 UTC 24 October 2005.

Figure 5.25: As in Fig. 5.3, except for 1800 UTC 23 October 2005, and the position of TS Alpha is indicated by the “ α ” symbol.

Figure 5.26: 850-hPa geopotential height (contoured in black every 2 dam), potential temperature (contoured in blue every 2 K), Petterssen frontogenesis [contoured in green every $1 \text{ K} (100 \text{ km})^{-1} (3 \text{ h})^{-1}$ starting at $1 \text{ K} (100 \text{ km})^{-1} (3 \text{ h})^{-1}$], and positive potential temperature advection (shaded in 10^{-5} K s^{-1} according to the color bar) generated from the NCEP 1° GFS analyses at (a) 1800 UTC 23 October, (b) 0000 UTC 24 October, (c) 0600 UTC 24 October, and (d) 1200 UTC 24 October 2005. Cross section A–B is indicated in panel (c).

Figure 5.27: As in Fig. 5.16, except generated from the NCEP 1° GFS analysis at 0600 UTC 24 October 2005. The star denotes the position of the PRE. The cross section location is indicated in Fig. 5.26c.

Figure 5.28: As in Fig. 5.17, except generated from the NCEP 1° GFS analyses at (a) 1800 UTC 23 October, (b) 0000 UTC 24 October, (c) 0600 UTC 24 October, and (d) 1200 UTC 24 October 2005.

Figure 5.29: As in Fig. 5.18, except all trajectories end at 600 hPa at 0600 UTC 24 October 2005, and the PW analysis at 1800 UTC 22 October is shaded. The dashed blue line denotes the axis of maximum radar reflectivity values associated with the PRE at 0600 UTC 24 October. The red “ α ” symbol denotes the position of TS Alpha at 1800 UTC 22 October.

Figure 5.30: As in Fig. 5.10, except for (a) 1800 UTC 23 October, (b) 0600 UTC 24 October, (c) 1200 UTC 24 October, and (d) 1800 UTC 24 October 2005.

Figure 6.1: Conceptual model of the synoptic-scale environment of JR category PREs showing 200-hPa geopotential height (solid black contours), 200-hPa wind speed (gray shading; “J” symbol marks the location of maximum wind speed), low-level (i.e., 925-hPa) streamlines (red indicates warm advection, blue indicates cold advection), the low-level jet (large red arrow), the low-level baroclinic zone (stationary front symbol), and PW (values > 50 mm shaded in blue). The position of the TC is indicated by the tropical storm symbol, and the maxima and minima in low-level geopotential height are indicated by the “H” and “L” symbols, respectively.

Figure 6.2: As in Fig. 6.1, except for the SJ category.

Figure 6.3: As in Fig. 6.1, except for the DC category.

