4. PRE-relative composite analysis

In order to depict the synoptic-scale environments within which PREs develop, PRE-relative composites are now presented for each of the three PRE categories. In the interest of brevity, composites are shown for T−12 h, T−0 h, and T+12 h in order to elucidate the synoptic-scale flow conditions prior to and during the PRE. The objective of the following analysis is to assess: dynamical mechanisms for forcing of ascent in the PRE region, the transport of TC moisture to the PRE region, and the impact of diabatic heating associated with the PRE and the TC on the upper-tropospheric flow. To accomplish this objective, plots displaying the evolution of the synoptic-scale environment on the 200-hPa and 925-hPa surfaces, respectively representing the upper and lower troposphere, are shown for each PRE category.

4.1 JR category

4.1.1 Synoptic-scale evolution

The composite evolution for the JR category is shown in Fig. 4.1. The antecedent 200-hPa flow, depicted at T−12 h, is dominated by a broad ridge that extends to the northeast of the composite TC location and a positively tilted trough located upstream (Fig. 4.1a). An anticyclonically curved 200-hPa jet streak is situated on the poleward flank of the ridge, with its core positioned well downstream of the trough axis (Fig. 4.1a). At T−12 h, a southward advancing 925-hPa baroclinic zone with an attendant region of frontogenesis is located to the northwest of the PRE initiation location (Fig. 4.1b). A localized region of PW values > 44 mm is evident ahead of the baroclinic zone, while the
TC and its attendant moisture plume, with PW values > 44 mm, are situated on the southwestern flank of a 925-hPa anticyclone (Fig. 4.1b).

Between T−12 h and T−0 h, the TC moves northwestward in the direction of the southeasterly 925-hPa geostrophic flow that extends on the western flank of the anticyclone from the eastern side of the TC circulation into the PRE initiation region (Figs. 4.1d,f). This southeasterly geostrophic flow contributes to the poleward progression of the TC moisture plume (PW values > 44 mm) into the PRE initiation region (Fig. 4.1d). In the presence of the TC moisture plume, the PRE is initiated within the equatorward entrance region of the anticyclonically curved 200-hPa jet streak and along the zonally oriented 925-hPa baroclinic zone (Figs. 4.1c,d). Southeasterly 925-hPa geostrophic flow directed perpendicular to the baroclinic zone within the PRE initiation region contributes to warm-air advection and frontogenesis over the PRE initiation region (Figs. 4.1d).

From T−0 h to T+12 h, as frontogenesis and warm-air advection persist along the baroclinic zone (Figs. 4.1d,f), additional forcing for ascent is indicated by a region of divergence extending poleward and eastward of the PRE initiation location within the equatorward entrance region of the 200-hPa jet streak (Figs. 4.1c,e). At T+12 h, the TC moisture plume continues to extend into the PRE initiation region as the TC moves toward the northwest on the western flank of the 925-hPa anticyclone (Fig. 4.1f).

4.1.2 Impact of diabatic heating on the upper-tropospheric flow

At T−12 h, a plume of low 250–200-hPa PV air extends poleward of the PRE initiation location toward the axis of the 200-hPa jet streak in connection with 200-hPa
irrotational wind vectors directed outward from a region of 700-hPa ascent centered just west of the PRE initiation location (Fig. 4.2a). This configuration of the irrotational winds is likely a reflection of divergent outflow associated with antecedent precipitation occurring prior to PRE initiation within the equatorward entrance region of the 200-hPa jet streak. At T=0 h and T+12 h, low-PV air, likely linked to diabatic heating associated with the PRE, extends from the PRE initiation region along the axis of the jet streak and contributes to a strengthened PV gradient within the jet streak (Figs. 4.2b,c). In association with the increased PV gradient, wind speeds within the core of the jet streak increase from 45–50 m s$^{-1}$ at T−12 h to > 50 m s$^{-1}$ at T−0 h and T+12 h (Figs. 4.2a–c).

Additionally at T−0 h and T+12 h, irrotational wind vectors, directed radially outward from the region of 700-hPa ascent overlying the PRE initiation location, point across PV contours from the region of low PV associated with the PRE toward the axis of high PV associated with the upstream trough (Figs. 4.2b,c). Within this configuration, the irrotational wind, which includes the diabatically driven divergent outflow associated with the PRE, acts to advect low-PV air poleward and contributes to the strengthening of PV gradients along the axis of the jet streak. The strengthened PV gradients are consistent with both the increase in maximum wind speeds and the strengthening of along-flow wind speed gradients within the jet entrance region at T−0 h and T+12 h (Figs. 4.2b, c). These flow changes within the jet streak are concomitant with the strengthening of 200-hPa divergence (Figs. 4.1a,c,e) and 700-hPa ascent (Figs. 4.2b,c) over the PRE initiation region between T−0 h and T+12 h.
4.2 SJ category

4.2.1 Synoptic-scale evolution

The composite evolution for the SJ category is shown in Fig. 4.3. At T−12 h, a 200-hPa trough approaches the PRE initiation region from the west, while a ridge extends poleward and eastward of the northeastward-moving composite TC (Fig. 4.3a). A southwesterly 200-hPa jet streak is situated poleward of the PRE initiation location in association with the strong geopotential height gradient that forms between the trough and the ridge (Fig. 4.3a). The TC circulation approaches a 925-hPa baroclinic zone accompanying the advancing trough, while a plume of deep moisture (PW values > 40 mm) extends poleward from the TC in association with strong southeasterly 925-hPa geostrophic flow on the eastern flank of the TC circulation (Fig. 4.3b).

The PRE is initiated beneath a region of divergence within the equatorward entrance region of the 200-hPa jet streak downstream of the approaching trough axis (Fig. 4.3c). Concurrently, at 925 hPa the circulation of the northeasterward-moving TC impinges upon the approaching baroclinic zone, establishing warm-air advection and frontogenesis over the PRE initiation region (Fig. 4.3d). Heavy rainfall is favored in the PRE initiation region as the TC moisture plume, with PW values > 44 mm, is transported poleward toward the region of implied lifting associated with low-level frontogenesis and upper-level divergence (Figs. 4.3c,d).

At 200 hPa, the continued eastward progression of the trough between T−0 h and T+12 h toward the slow-moving ridge extending to the northeast of the TC coincides with the strengthening of the southwesterly jet streak and an increase in divergence over the TC and the PRE initiation location (Figs. 4.3c,e). As the TC moves northeastward
between T−0 h and T+12 h, its circulation continues to interact with the 925-hPa baroclinic zone, resulting in strengthened frontogenesis over the PRE initiation region (Fig. 4.3f). Deep moisture, with PW values > 44 mm, continues to be transported into the PRE environment on the eastern flank of the TC circulation (Fig. 4.3f).

4.2.2 Impact of diabatic heating on the upper-tropospheric flow

At T−12 h, the 200-hPa jet streak is positioned poleward of the PRE initiation location in association with the 250–200-hPa PV gradient between the axis of high PV associated with the approaching trough and the low-PV outflow extending northeastward from the TC (Fig. 4.4a). The jet streak strengthens between T−12 h and T+12 h as the high-PV air associated with the trough advances to the east, and a plume of low-PV air, likely associated with diabatically driven outflow associated with the TC and PRE, extends poleward and eastward from the TC and the PRE initiation location along the axis of the jet streak (Figs. 4.4a–c).

Substantial divergent outflow associated with the PRE and TC is indicated at T−0 h and T+12 h by 200-hPa irrotational wind vectors that emanate outward from the maximum of 700-hPa ascent overlying both the TC and the PRE initiation location (Figs. 4.4b,c). The poleward and westward advection by the irrotational wind of low-PV air associated with the PRE and the TC toward the axis of high PV associated with the approaching trough leads to an increased PV gradient along the axis of the jet streak between T−0 h and T+12 h (Figs. 4.4b,c). The increased PV gradient contributes to strengthened maximum wind speeds (from 40–45 m s⁻¹ at T−0 h to 45–50 m s⁻¹ at T+12 h) and strengthened along-flow wind speed gradients within the jet entrance region (Figs.
4.4b,c). These flow changes associated with the jet streak between T−0 h and T+12 h coincide with the enhancement of 200-hPa divergence (Figs. 4.3a,c,e) and with the maintenance of 700-hPa ascent (Figs. 4.4a–c) over the TC and the PRE initiation location beneath the equatorward entrance region of the jet streak.

4.3 DC category

4.3.1 Synoptic-scale evolution

The composite evolution for the DC category is shown in Fig. 4.5. At T−12 h, the 200-hPa flow configuration is dominated by a region of geostrophic confluence downstream of the PRE initiation location, with a jet streak situated between an eastward moving downstream trough and a downstream ridge extending northeastward from the composite TC location (Fig. 4.5a). Compared with the JR and SJ category composites, the 200-hPa geostrophic flow upstream of the TC is weaker, owing to the lack of a strong upstream trough. At 925-hPa, a trough is situated poleward and eastward of the PRE initiation location at T−12 h, while a zonally oriented baroclinic zone, positioned poleward of the PRE initiation location, trails behind this trough (Fig. 4.5b). A plume of moisture (PW values > 36 mm) extends from the TC location along the baroclinic zone toward the axis of the 925-hPa trough (Fig. 4.5b).

The PRE is initiated within the equatorward entrance region of the 200-hPa jet streak, downstream of a weak 200-hPa short-wave trough, and along the 925-hPa baroclinic zone, while a plume of moisture, characterized by PW values > 40 mm, advances poleward and eastward from the TC (Figs. 4.5c,d). Warm-air advection and frontogenesis at 925 hPa over the PRE initiation region are evident at T−0 h and T+12 h.
as southerly geostrophic flow, situated between the circulation of the poleward-moving TC and a 925-hPa anticyclone to its east, impinges upon the 925-hPa baroclinic zone (Figs. 4.5d,f).

As the downstream trough moves eastward, confluent 200-hPa geostrophic flow is maintained poleward of the PRE initiation location between T−0 h and T+12 h (Figs. 4.5c,e). In conjunction with the persistent confluent flow, the equatorward entrance region of the 200-hPa jet streak and an attendant region of 200-hPa divergence remain positioned over the PRE initiation region at T+12 h(Fig. 4.5e). As the TC continues to move poleward between T−0 h and T+12 h, frontogenesis and warm-air advection at 925 hPa are maintained as the TC circulation interacts with the baroclinic zone (Fig. 4.5f). The moisture plume continues to advance northeastward from the TC along the baroclinic zone and extends toward a region of 925-hPa geostrophic confluence situated to the east of the PRE initiation location (Fig. 4.5f).

4.3.2 Impact of diabatic heating on the upper-tropospheric flow

At T−12 h, the 200-hPa jet streak is situated poleward and eastward of the PRE initiation location between the region of high 250–200-hPa PV associated with the downstream trough and the region of low 250–200-hPa PV that extends to the northeast of the TC (Fig. 4.6a). As the axis of high PV associated with the downstream trough moves eastward at T−0 h and T+12 h, low-PV outflow associated with the TC and the PRE extends poleward toward the confluent jet entrance region (Figs. 4.6b,c). The poleward extension of low-PV air at T−0 h and T+12 h occurs as 200-hPa irrotational wind vectors, linked to the diabatically driven divergent outflow associated with TC and
PRE, point outward from the region of 700-hPa ascent overlying the TC and the PRE initiation location (Figs. 4.6b,c). The irrotational wind is directed from the region of low PV toward the region of high PV associated with the weak upstream short-wave trough (Figs. 4.6b,c). This configuration of the irrotational wind vectors indicates the poleward and westward advection of low-PV air, which contributes to the localized strengthening of the PV gradient within the entrance region of the jet streak between T−12 h and T+12 h (Figs. 4.6a–c). The locally strengthened PV gradient results in the slight backbuilding of the jet streak and acts to strengthen along-flow wind speed gradients within the jet entrance region (Figs. 4.6a–c). This evolution of the structure of the jet streak was concurrent with the enhancement of 200-hPa divergence (Figs. 4.5a,c,e) and 700-hPa ascent (Figs. 4.6a–c) at T−12 h and T+12 h within the equatorward entrance region of the jet streak.
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 the color bar on the left), geopotential height (contoured in black every 10 dam), and positive divergence (contoured in red every 0.5 \(\times\) \(10^{-5}\) s\(^{-1}\) starting at 0.5 \(\times\) \(10^{-5}\) 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 \(\times\) \(10^{-1}\) K (100 km\(^{-1}\) (3 h))\(^{-1}\) starting at 0.5 \(\times\) \(10^{-1}\) K (100 km\(^{-1}\) (3 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 $> 5$ m s$^{-1}$, 700-hPa ascent (contoured in red every $0.5 \times 10^{-3}$ hPa s$^{-1}$ starting at $-0.5 \times 10^{-3}$ 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.
Figure 4.3: As in Fig. 4.1, except for 17 SJ category PREs, and frontogenesis in panels (b), (d), and (f) is contoured every $0.3 \times 10^{-1}$ K (100 km)$^{-1}$ (3 h)$^{-1}$ starting at $0.3 \times 10^{-1}$ K (100 km)$^{-1}$ (3 h)$^{-1}$.
Figure 4.4: As in Fig. 4.2, except for 17 SJ category PREs.
Figure 4.5: As in Fig. 4.3, except for 9 DC category PREs.
Figure 4.6: As in Fig. 4.2, except for 9 DC category PREs.