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Multi-scale drivers of PM2.5 and PM10 extremes in the Valley of Mexico: Synoptic regimes, boundary-layer stability, and ENSO modulation

stage two

Context & Objective

Monthly Structuring and Baseline Episode Climatology (2012–2024)

- Fixed event definition: monthly p90 (2012–2024, daily city mean).
- Characterize episode climatology (frequency, severity, duration).
- Recompute and refine monthly Z500′ composites.
- Assess seasonal structuring of event-related circulation patterns.
- Prepare a clean baseline for Stage 3 (synoptic regime analysis).

Data & Methodology

Daily PM time series + NARR 500 hPa reanalysis (2012–2024)

- **PM data:** Daily city-mean PM10 and PM2.5 concentrations from CDMX monitoring network (4,749 days, 2012-2024).
- **Reanalysis:** NARR 500 hPa geopotential height (Z500), zonal (U) and meridional (V) wind fields; 2.5° × 2.5° grid over Mexico domain (12-33°N, 120-85°W).
- **Event definition**: A day is classified as an extreme event if PM ≥ 90th percentile of its calendar month (p90 monthly).
- **Composites:** Z500 anomaly (Z500′ = Z500 - monthly climatology) averaged over all event days.
- **Significance:** Two-sample Welch t-test (event vs. non-event days) at each gridpoint; stippling marks $p < 0.05$.
- **Ranking:** Months ranked by frequency (event-day count) and severity (mean exceedance above p90).

Table 1. Monthly 90th-percentile thresholds for PM10 and PM2.5, 2012–2024.

Month	PM10 p90 (µg/m³)	PM2.5 p90 (µg/m³)
January	78.9	41
February	76	35.7
March	68.3	32.8
April	69.6	37.1
May	72.9	40.3
June	52.2	28.9
July	47.5	25.4
August	42.3	23.3
September	44	26.2
October	52.5	28
November	67	36
December	84.7	43.6

Part I: Event Climatology

Frequency, severity, and persistence of p90 extreme PM days

Event-Day Frequency by Year (2012-2024)

Sharp decline after 2013 suggests improving air quality

- PM10 peaked at 94 event-days in 2012 and 78 in 2013; by 2023 only 1 event-day remained.
- PM2.5 peaked at 75 event-days in 2013; down to 3 by 2023.
- Strong declining trend across both pollutants, especially post-2016.
- 2019-2024 contribute very few events → composite maps are dominated by early-period (2012-2017) atmospheric patterns.

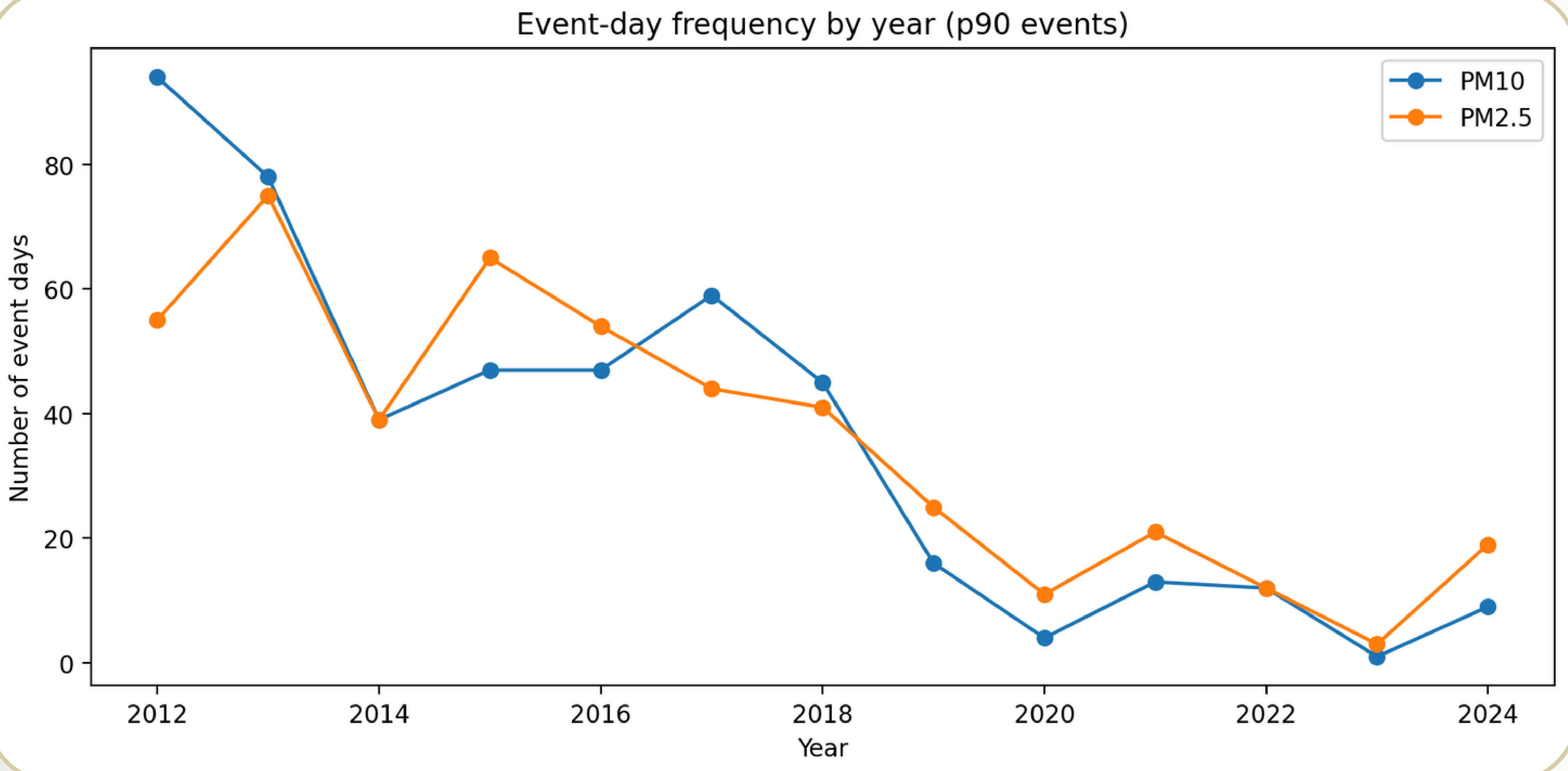

Figure 1. Annual frequency of PM10 and PM2.5 p90 event-days (2012–2024).

Year × Month Heatmaps of Event-Day Counts

Where and when do extreme days cluster?

- PM10: strongest clustering in Mar-Apr 2013 (12-15 days/month) and Aug–Sep 2012 (13 days each).
- PM2.5: notable cluster in Mar-May 2013 (11–15 days) and Jun–Oct 2015 (7-8 days/month).
- Post-2019, virtually all months show 0–2 event-days → confirms the declining trend is broad-based, not month-specific.

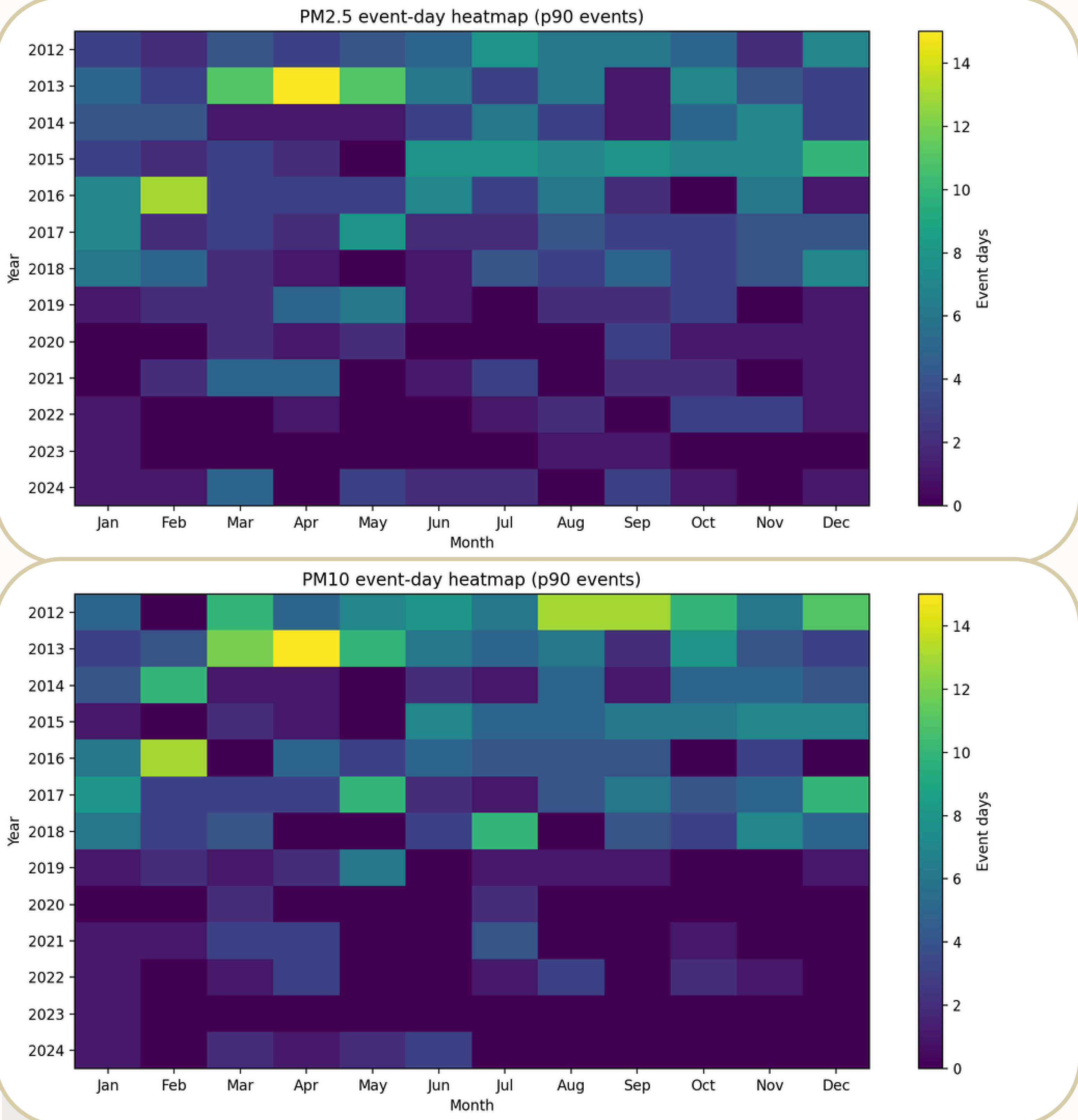

Figure 2a/2b. Year × month heatmap of PM2.5 and PM10 p90 event-day counts (2012–2024).

Mean Exceedance Above p90 by Month

How far above the threshold do extreme days go?

- PM10: January has the highest mean exceedance (12.7 μg/m³), followed by May (11.7) and April (11.4).
- PM2.5: January also dominates (10.9 μg/m³), with May as a distant second (10.5).
- Summer months (Jun-Sep) show the lowest exceedances (4-7 μg/m³ for PM10; 3-4 μg/m³ for PM2.5).
- The dry season (Nov-May) produces not only more events but also more severe events.

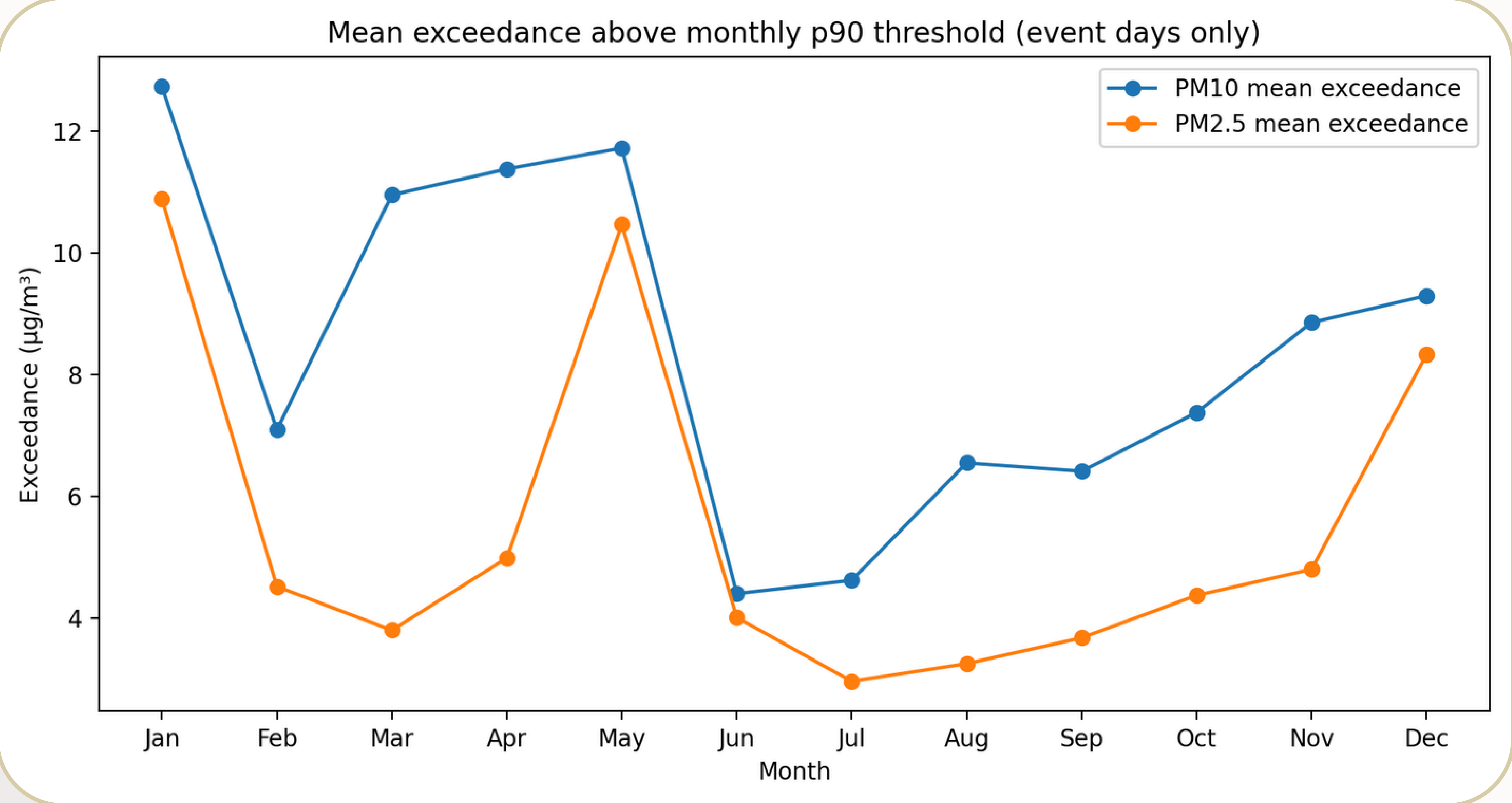

Figure 3. Mean exceedance above the monthly p90 threshold by calendar month (PM10 and PM2.5).

Episode Persistence: Run-Length Statistics

Multi-day pollution episodes are common in the dry season

- PM10: 250 episodes total; mean duration = 1.9 days, p90 duration = 3 days, max = 10 days.
- PM2.5: 286 episodes; mean = 1.6 days, p90 = 3 days, max = 10 days.
- Most episodes are 1-2 days, but ~10% persist for ≥3 days.
- Multi-day episodes suggest sustained synoptic forcing (persistent ridges), not just daily fluctuations.

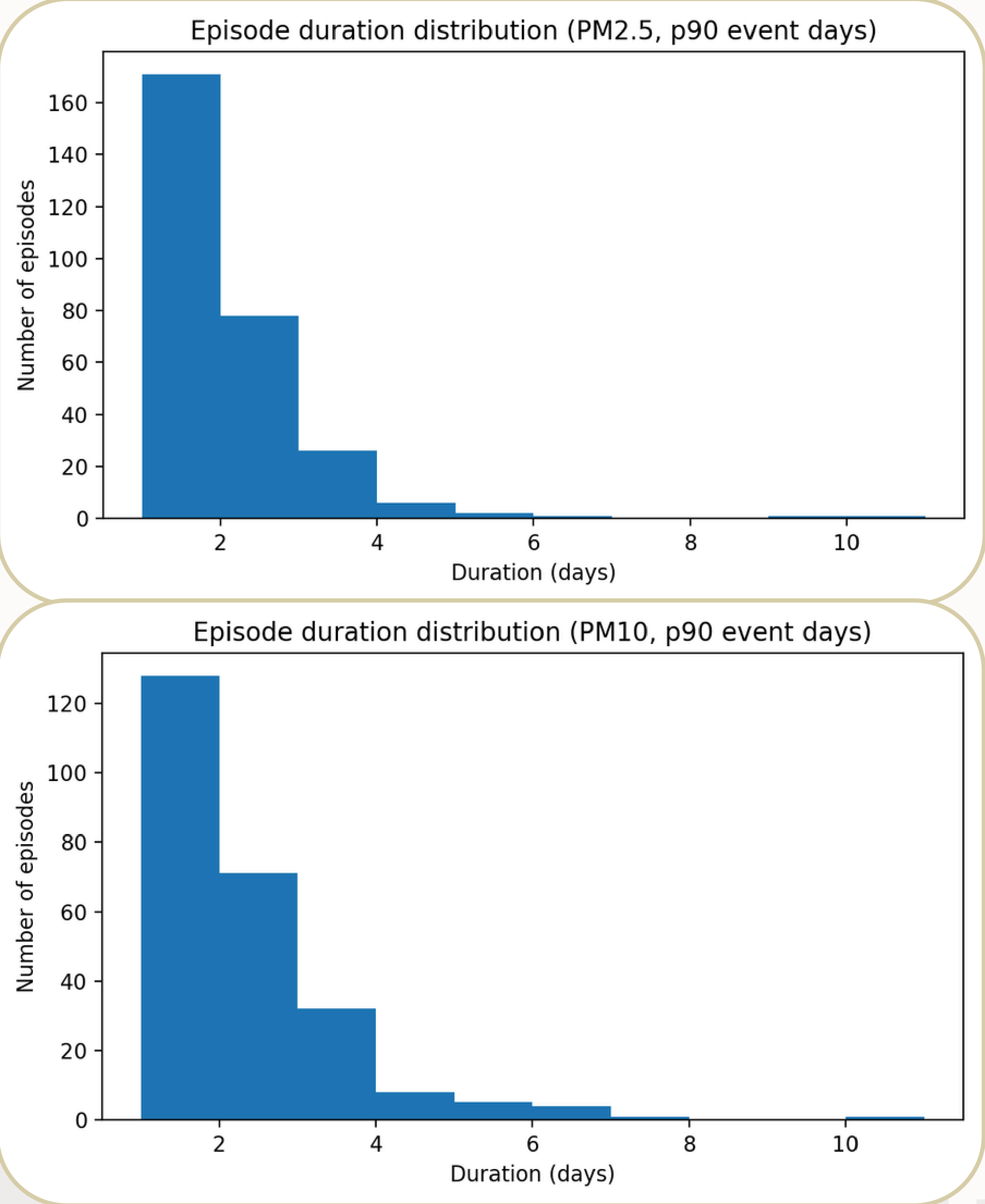

Figure 4. Episode duration distribution for PM2.5 and PM10 p90 events.

Part II: Synoptic Composite Analysis

What does the upper atmosphere look like on extreme PM days?

- Z500 anomalies (Z500′) reveal large-scale ridges and troughs.
- Positive anomaly (warm colors) → ridge → subsidence → stable atmosphere → PM accumulation.
- Negative anomaly (cool colors) → trough → instability → better ventilation.
- Stippling = statistically significant difference from non-event days ($p < 0.05$, Welch t-test).

Monthly Z500′ Composites During PM10 p90 Event Days

Dry-season months (Nov–May) show coherent positive anomalies over Mexico

- Dec-Feb: Strong positive anomalies centered over north-central Mexico; extensive stippling
- Mar-Apr: Moderate positive anomalies; significant but less intense.
- May-Sep: Weak or negative anomalies → no coherent synoptic signal.
- Oct: Transitional; weak positive anomaly beginning to build.
- Valley of Mexico consistently sits under the southern flank of the ridges during dry-season events.

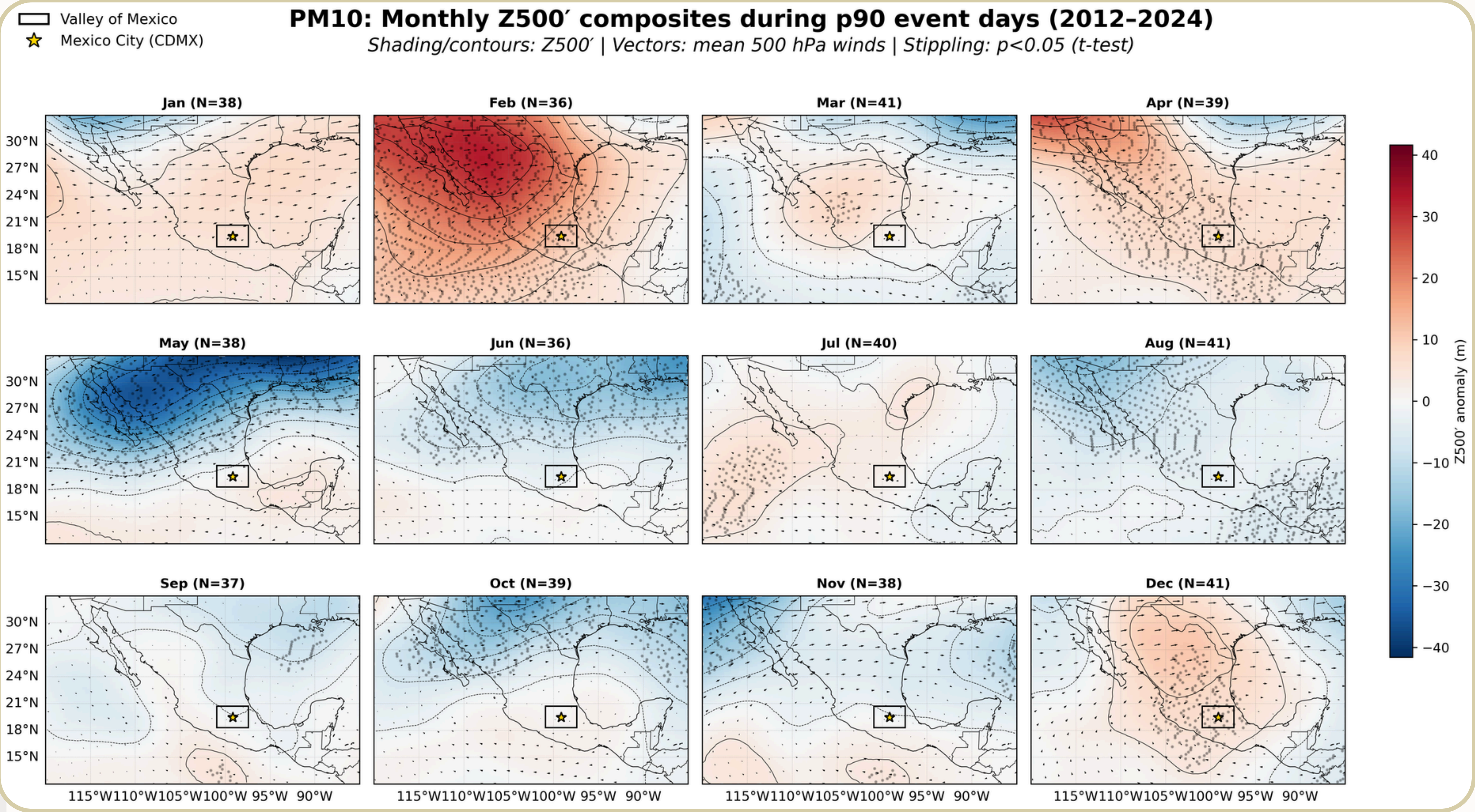

Figure 5. Monthly Z500′ composites during PM10 p90 event days (12-panel).

Monthly Z500′ Composites During PM2.5 p90 Event Days

Similar structure to PM10 but with stronger winter signal

- Dec-Feb: Strongest positive anomalies and most extensive stippling among all months.
- Pattern closely mirrors PM10, confirming both pollutants respond to the same synoptic forcing.
- Summer months show no coherent signal (as with PM10).
- Key difference from PM10: PM2.5 composites in spring (Mar-Apr) show weaker anomalies than PM10, suggesting PM10 spring events are additionally driven by surface sources (fires, dust), not just atmospheric stagnation.

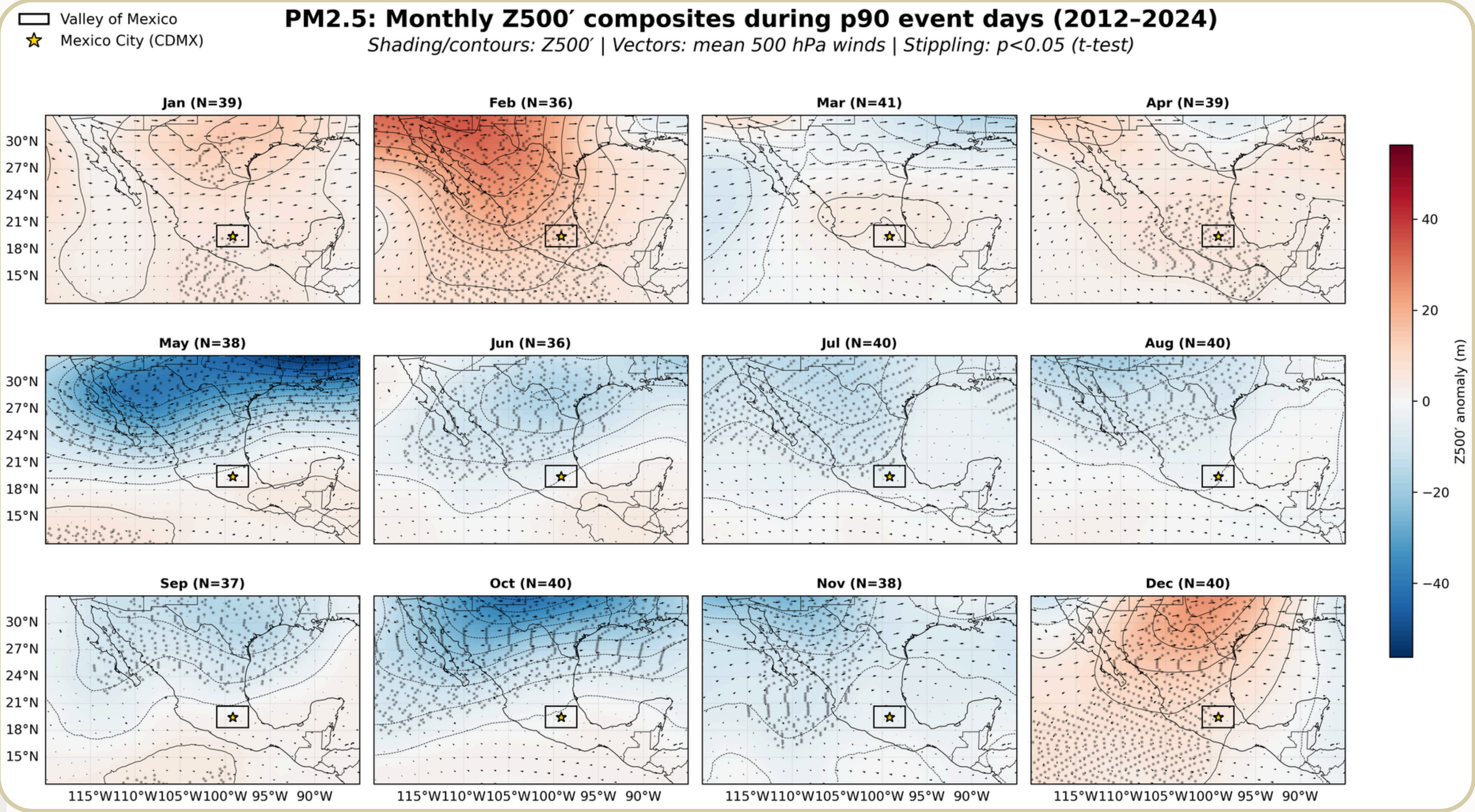

Figure 6. Monthly Z500′ composites during PM2.5 p90 event days (12-panel).

Part III: Focused Analysis - Top Months

Zooming in on the 4 months with highest event-day frequency and severity

- Top 4 months by frequency (PM10): Mar, Jul, Aug, Dec (41-40 event-days).
- Top 4 months by severity (PM10): Jan, Apr, May, Mar (exceedance 11–13 µg/m³).
- Top 4 months by frequency (PM2.5): Mar, Jul, Aug, Oct (40-41 event-days).
- Top 4 months by severity (PM2.5): Jan, May, Apr, Dec (exceedance 5–11 µg/m³).

Z500′ Composites – Top 4 Months by Event-Day Frequency (PM10)

Mar, Jul, Aug, Dec

- December: Strongest ridge of all panels (≈+12 m), extensive stippling → classic winter stagnation pattern.
- March: Moderate positive anomaly over central Mexico; dry-season + incipient fire season.
- July: Less significant positive anomaly → summer events are not driven by ridges; likely local/mesoscale causes during monsoon breaks.
- Contrast: Clear dichotomy between dry-season (coherent synoptic signal) and wet-season (no signal) top months.

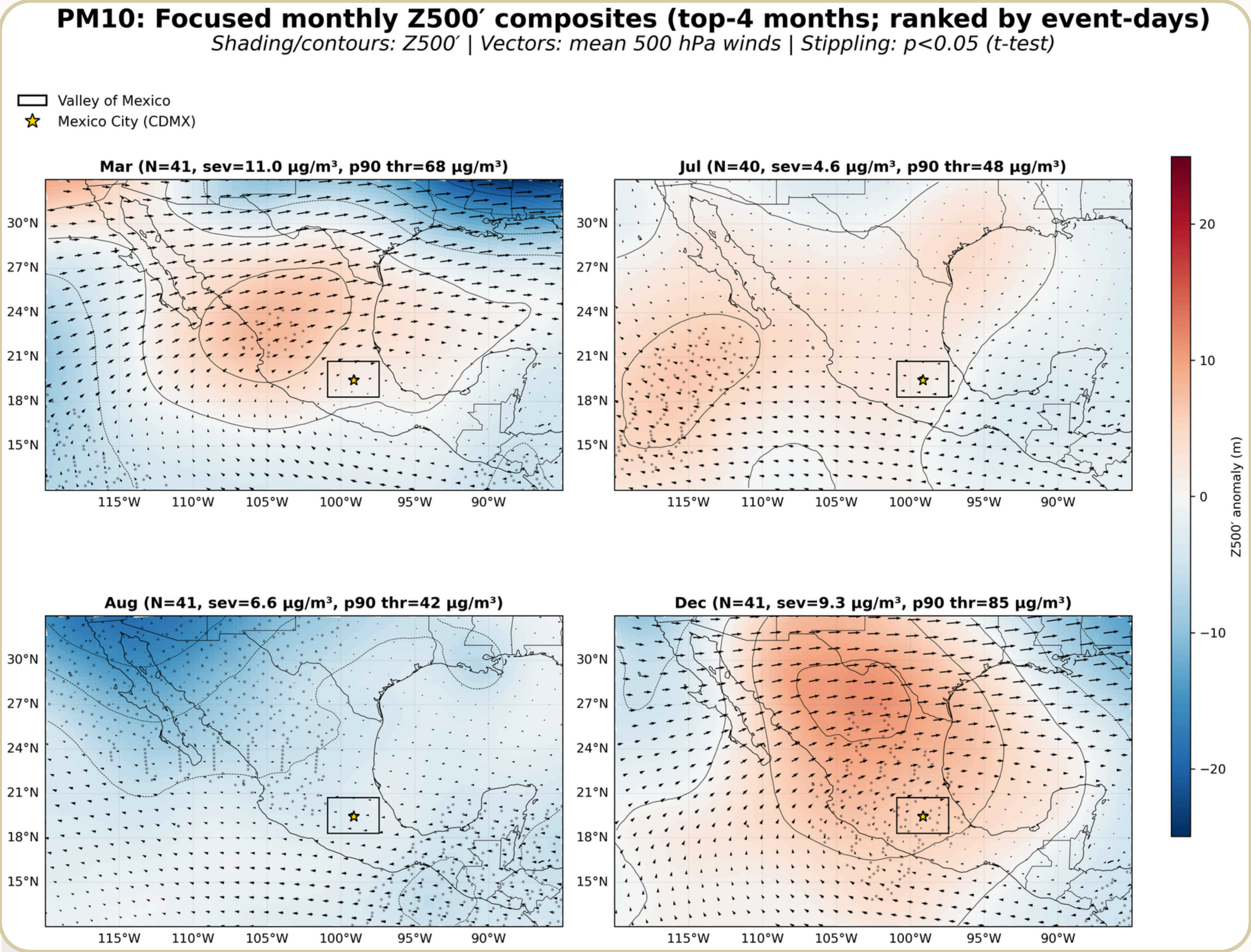

Figure 7. Z500′ composites for top 4 months ranked by event-day frequency (PM10).

Z500′ Composites – Top 4 Months by Severity (PM10)

Jan, Mar, Apr, May

- All 4 months fall in the dry season (Nov-May corridor).
- January: Small ridge anomaly → subsidence-driven inversions.
- March: Combined fire emissions + moderate ridge → high severity.
- April: Broad positive anomaly; contributes to fire-season PM accumulation.
- May stands out with a distinct ridge-trough dipole: a deep coastal trough (-30 to -40 m) along the Pacific coast channels southwesterly flow aloft toward the Valley of Mexico, concentrating subsidence over the basin.
- All panels show statistically significant positive Z500′ over the Valley of Mexico.

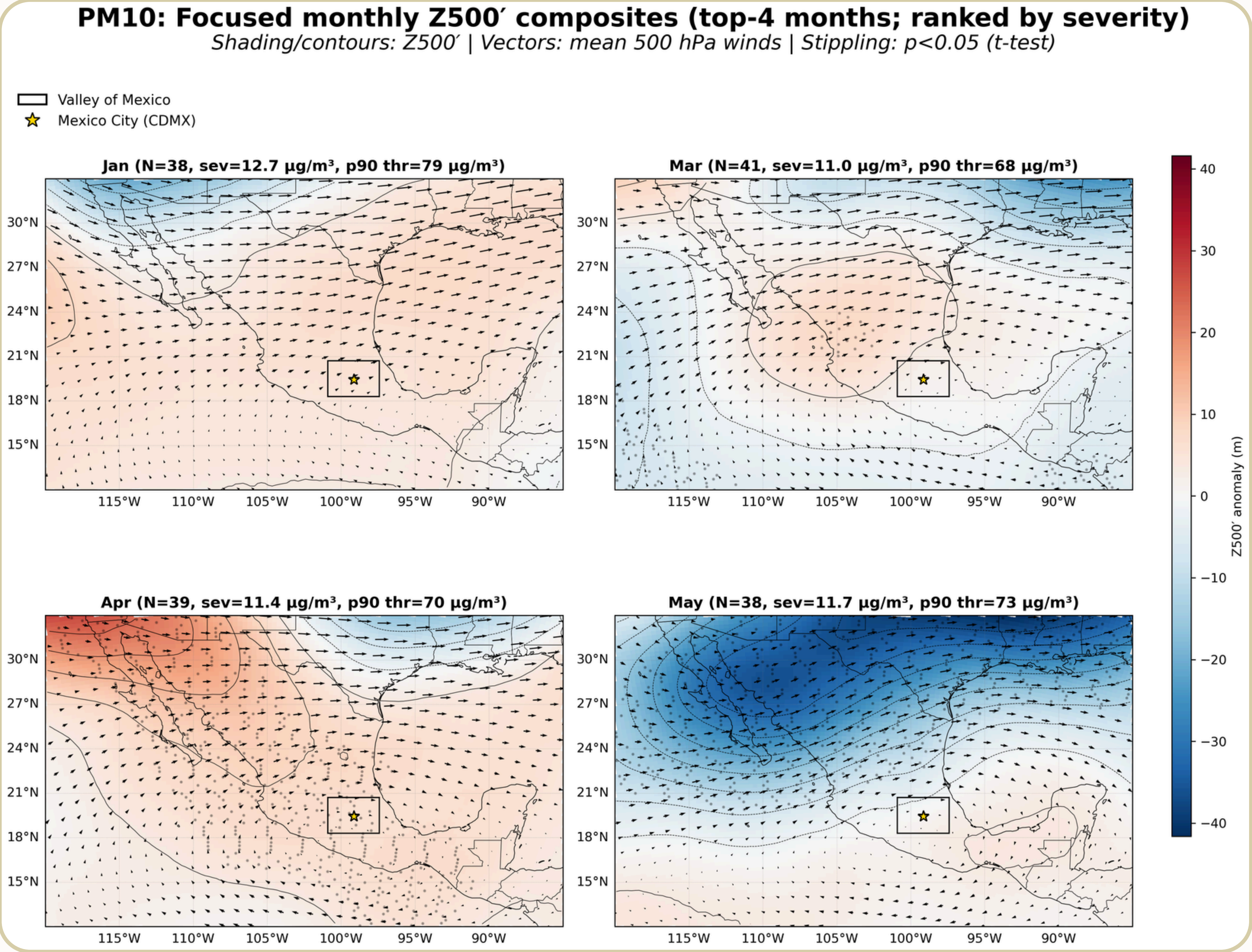

Figure 8. Z500′ composites for top 4 months ranked by severity (PM10).

Z500′ Composites – Top 4 Months by Event-Day Frequency (PM2.5)

Mar, Aug, Oct, Dec

- Similar pattern to PM10: dry-season months show ridges (mostly seen in December), wet-season months do not (especially August).
- PM2.5 events in October show a very mild positive anomaly in the southern part of the country→ early dry-season signal.

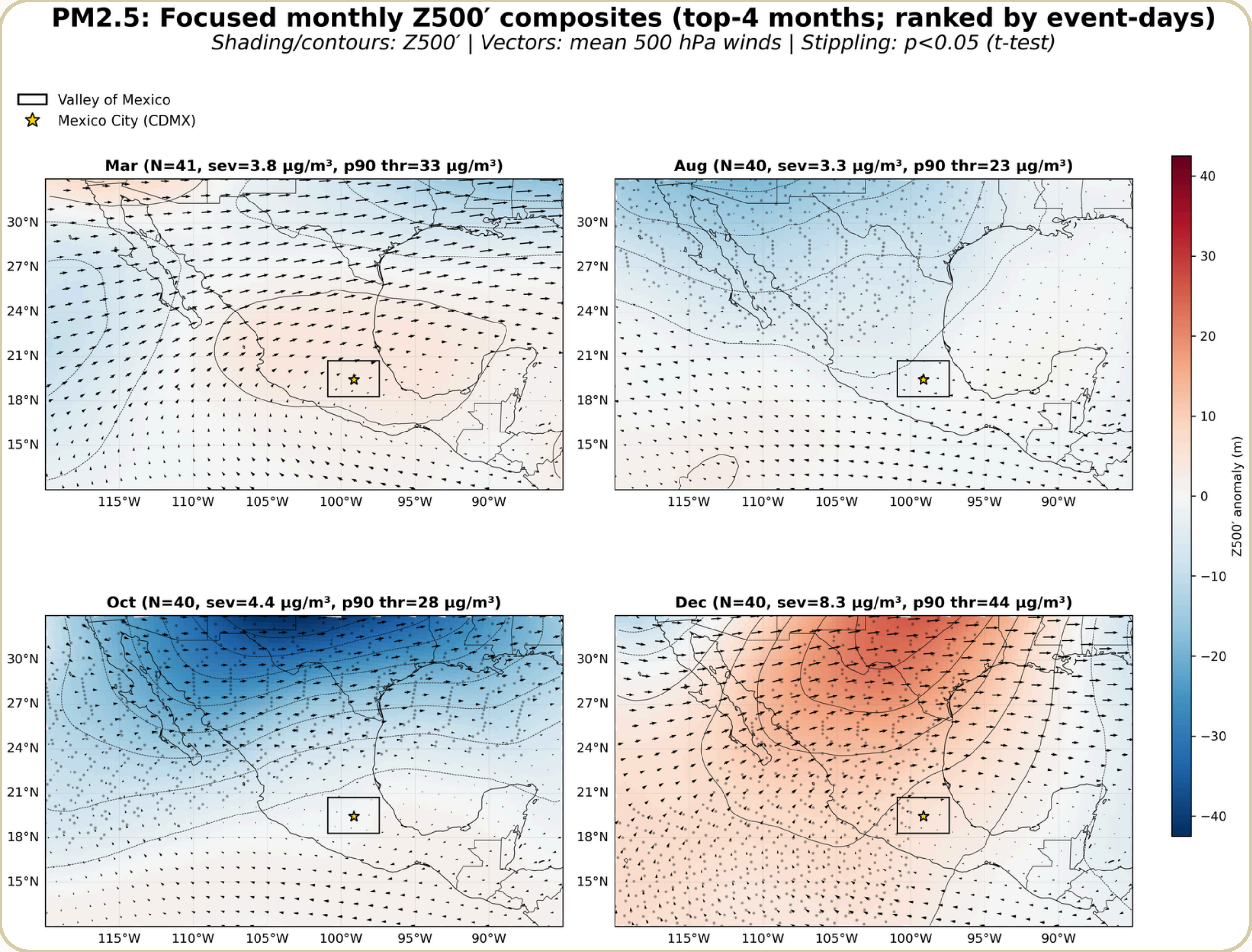

Figure 9. Z500′ composites for top 4 months ranked by event-day frequency (PM2.5).

Z500′ Composites – Top 4 Months by Severity (PM10)

Jan, Apr, May, Dec

- January dominates with the highest severity (10.9 μg/m³).
- December: Strong ridge with significant stippling.
- PM2.5 severity is heavily weighted toward winter → secondary aerosol formation under cold, stable conditions.

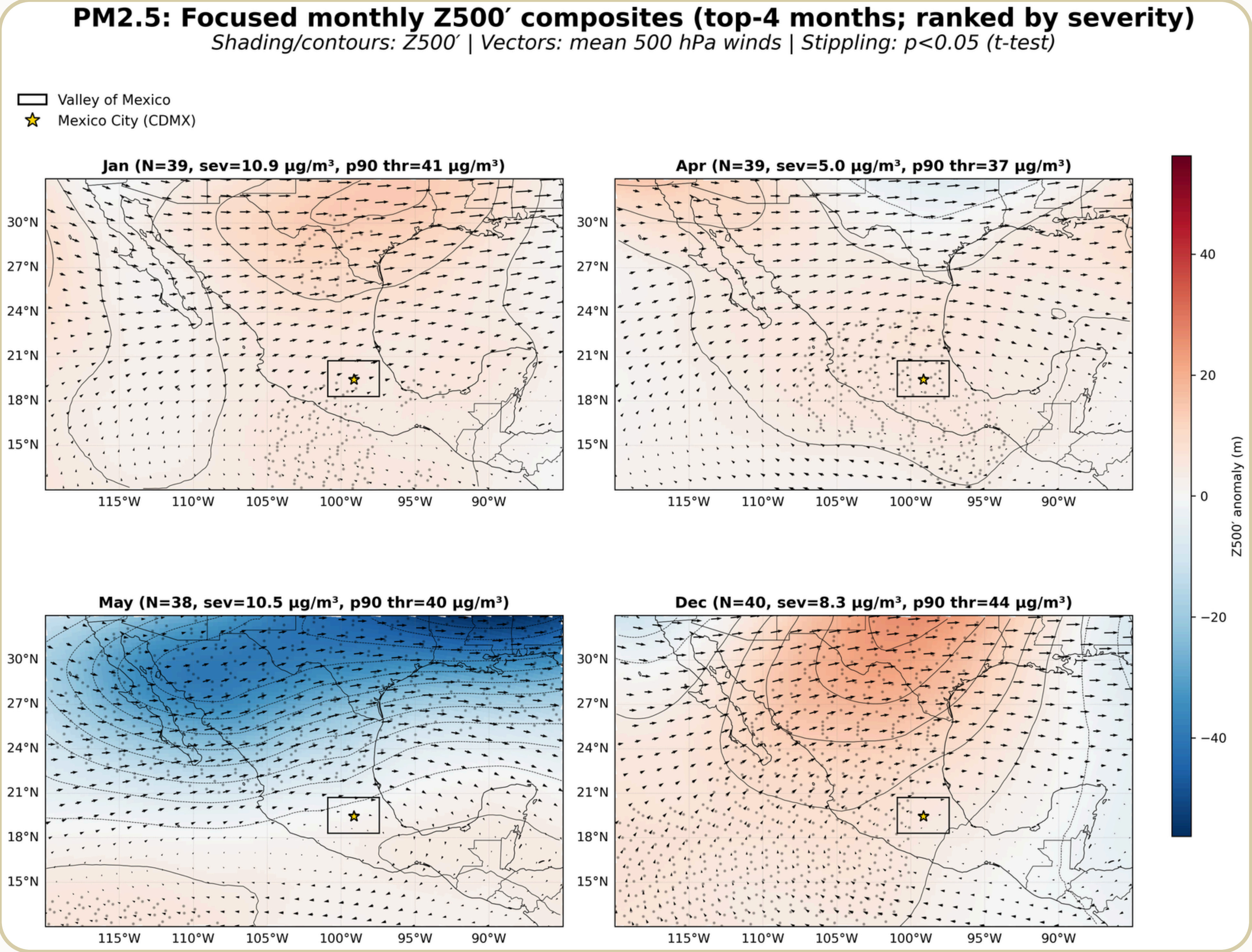

Figure 10. Z500′ composites for top 4 months ranked by severity (PM2.5).

Part IV: Seasonal Synthesis

Aggregating monthly composites into seasonal (DJF/MAM/JJA/SON) summary patterns

Table 2. Seasonal summary of p90 extreme events: frequency (N), mean severity, and mean p90 threshold.

Season	N (PM10)	Sev (PM10)	p90 thr (PM10)	N (PM2.5)	Sev (PM2.5)	p90 thr (PM2.5)
DJF	115	9.7 μg/m³	80 μg/m³	115	8.0 μg/m³	40 μg/m³
MAM	118	11.3 μg/m³	70 μg/m³	118	6.3 μg/m³	37 μg/m³
JJA	117	5.2 μg/m³	47 μg/m³	116	3.4 μg/m³	26 μg/m³
SON	114	7.6 μg/m³	55 μg/m³	115	4.3 μg/m³	30 μg/m³

Seasonal Z500′ Composites During PM10 p90 Event Days (2012–2024)

- DJF: Strongest and most statistically significant ridge over Mexico (+10-20 m); subsidence-driven inversions trap PM10.
- MAM: Light ridge; highest severity (11.3 μg/m^3) due to combined stagnation + fire/dust emissions.
- JJA: No clear pattern; no stippling over central Mexico. Monsoon rains dominate → events are local/mesoscale phenomena.
- SON: Weak transitional pattern; ridge beginning to build as dry season approaches.
- The winter ridge pattern is the dominant synoptic driver. Spring combines synoptic + emission factors for maximum severity.

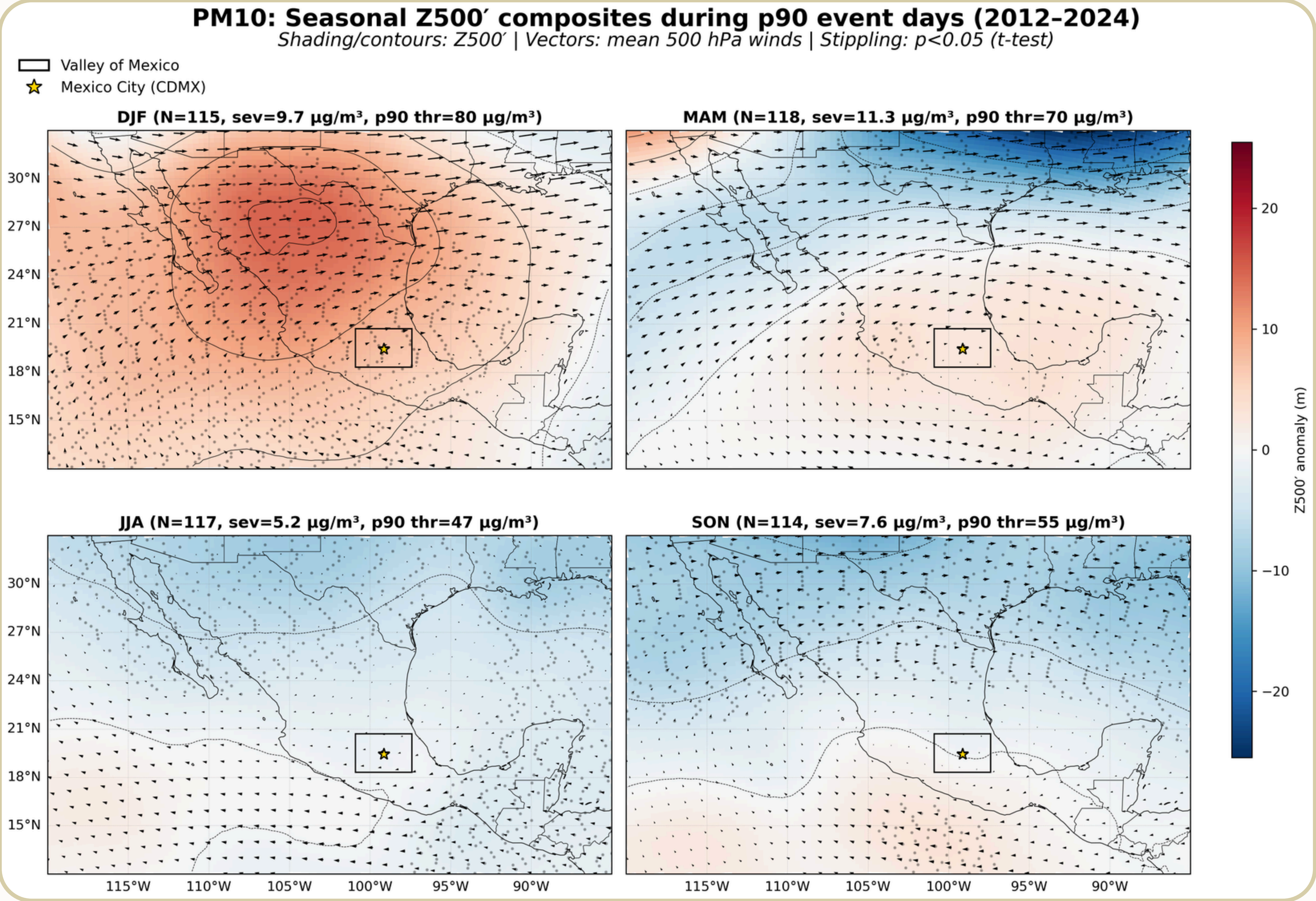

Figure 11. Monthly Z500′ composites during PM10 p90 event days (12-panel).

Seasonal Z500′ Composites During PM2.5 p90 Event Days (2012–2024)

- DJF: Very similar to PM10, strong ridge with extensive stippling; highest PM2.5 severity (8.0 µg/m^3).
- MAM: A similar ridge is present but of different severity than PM10-MAM, with a clear core in the south; PM2.5 depends more on atmospheric stability than surface emissions.
- JJA: No clear positive signal (same as PM10); p90 threshold drops to 26 µg/m^3 → wet deposition dominates.
- SON: Emerging ridge over the Pacific.

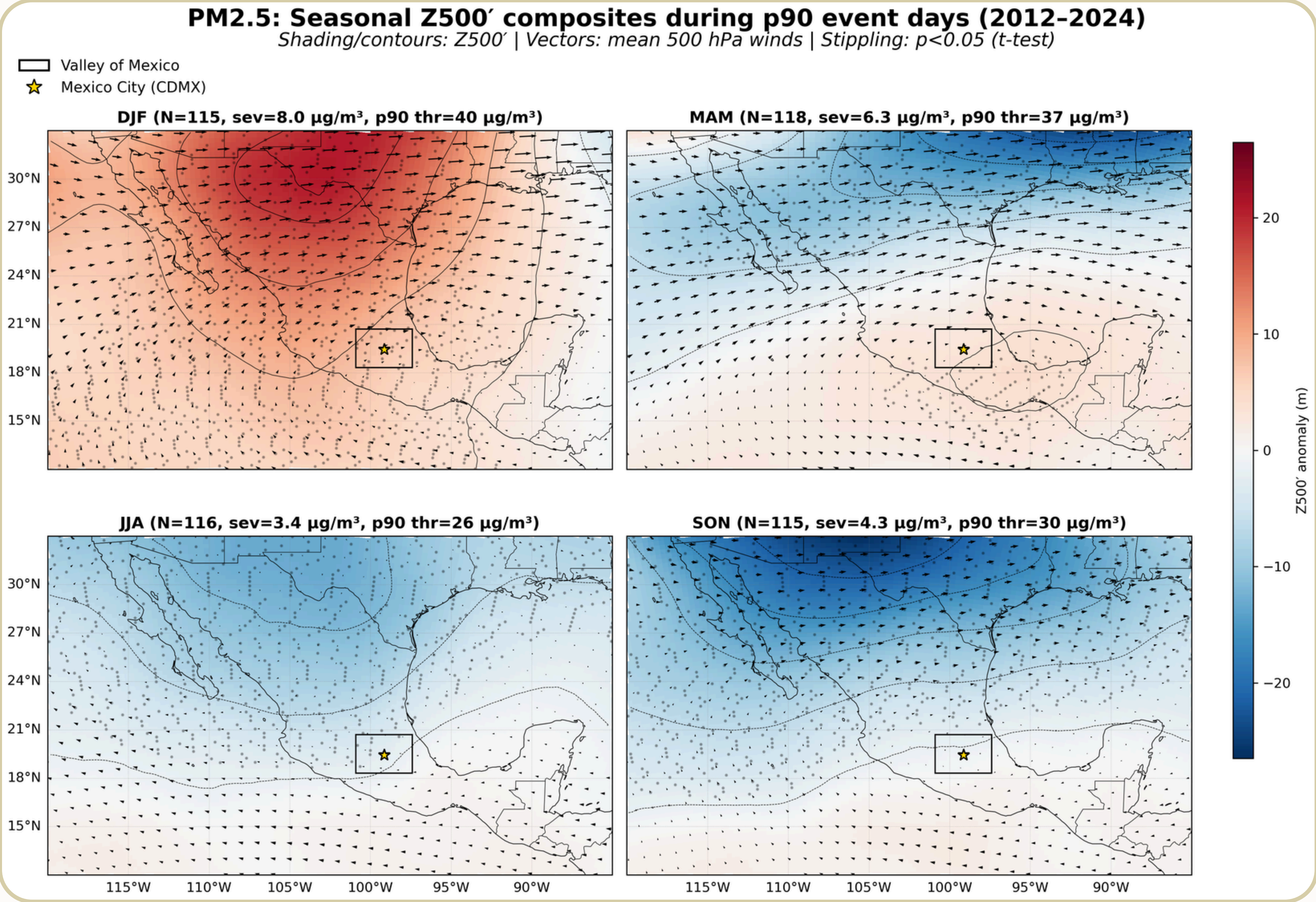

Figure 12. Monthly Z500′ composites during PM2.5 p90 event days (12-panel).

Conclusions + Discussion

- Primary finding: Extreme PM events in CDMX during the dry season (Nov-May) are strongly associated with positive Z500 anomalies (ridges) → large-scale subsidence → enhanced thermal inversions → pollutant trapping.
- Seasonal contrast: DJF shows the most intense, persistent, and statistically significant ridge pattern; JJA shows no coherent synoptic signal, and monsoon precipitation is the dominant control.
- PM10 vs. PM2.5: Both pollutants respond to the same synoptic forcing, but PM10 has an additional sensitivity to spring fire/dust emissions (MAM = highest severity for PM10 but not for PM2.5)
- Temporal trend: Event-day counts have declined dramatically since 2013, especially for PM10, suggesting regulatory improvements. However, the synoptic patterns identified remain climatologically relevant for future event forecasting.
- Implications: Forecasting extreme PM days could leverage Z500 anomaly patterns as predictors, particularly during winter season when the ridge signal is most robust.
- Multi-day persistence: ~10% of episodes last ≥3 days (max 10), indicating sustained synoptic forcing, not isolated daily events.
- Finally, the ridge-like configurations observed in several high-PM months may be dynamically consistent with reduced moisture inflow and limited wet deposition, although explicit moisture diagnostics are beyond the scope of Stage 2. Future work will test whether ridge-dominated composites coincide with reduced moisture inflow and precipitation (wet deposition proxy), using 850 hPa humidity/flow and precipitation composites.

Next Steps

(Stage 2 → Stage 3: Synoptic Regime Classification)

- Apply objective regime classification to 500 hPa circulation patterns.
- Identify dominant large-scale circulation modes over the Mexico domain.
- Associate p90 event-days with specific synoptic regimes.
- Quantify regime frequency, persistence, and pollutant-specific differences.
- Evaluate whether extreme PM events cluster within particular circulation states.

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thank you!