

Supplementary Information

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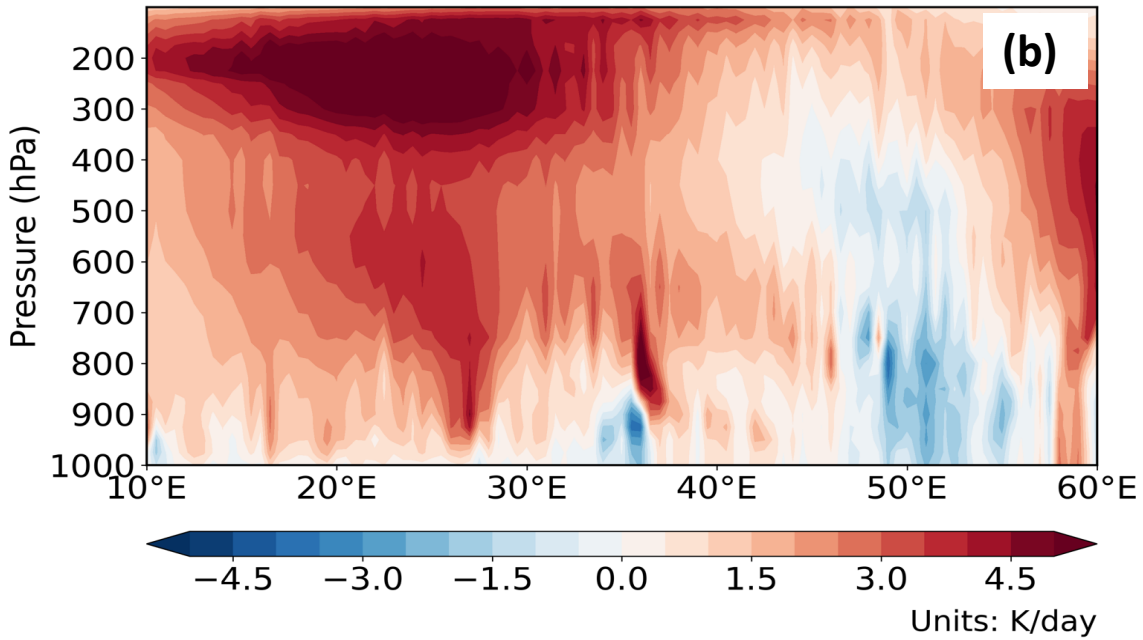
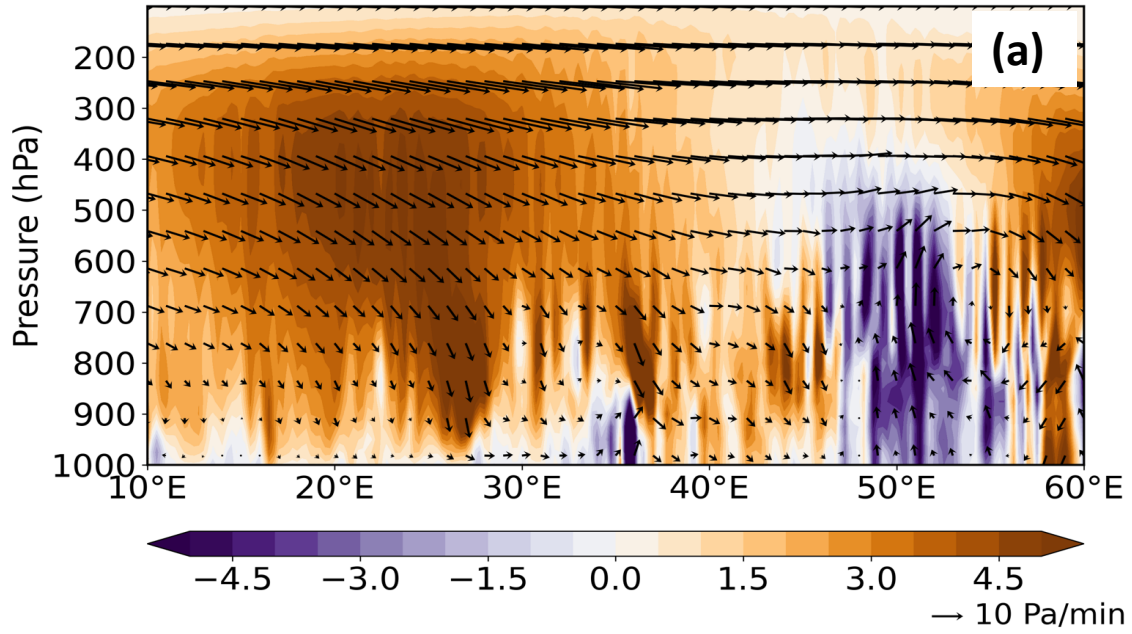


Figure S1: Summer climatology of meridional mean zonal distribution of (a) vertical velocities and (b) Vertical temperature advection averaged over EMME (31–40°N) during 1990–2019.

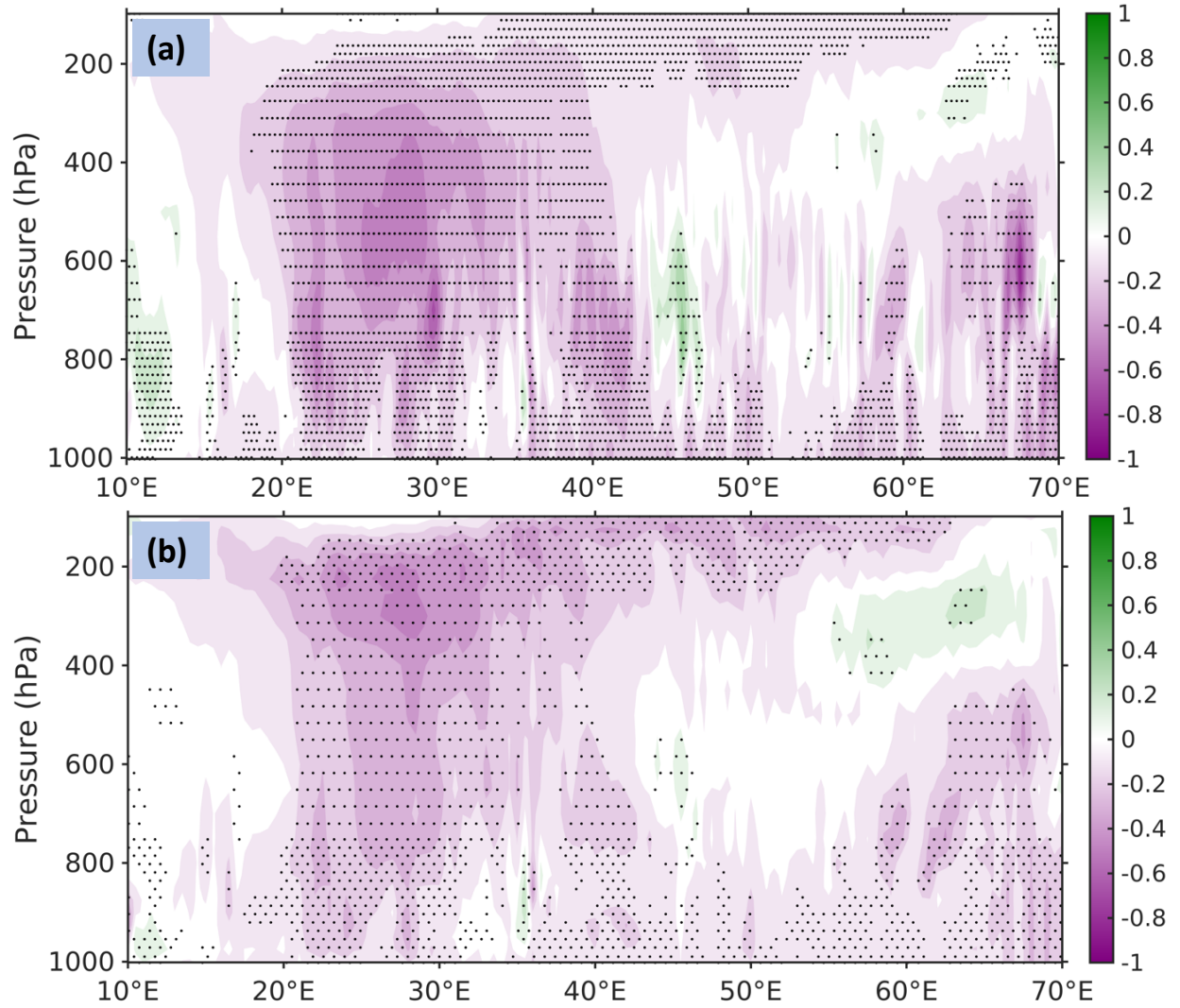


Figure S2: Long-term (1980–2024) trends in the summer mean (a) vertical velocity (units: Pa/min), and (b) vertical advection of temperature (units: K/day) averaged over the EM region (31–40°N).

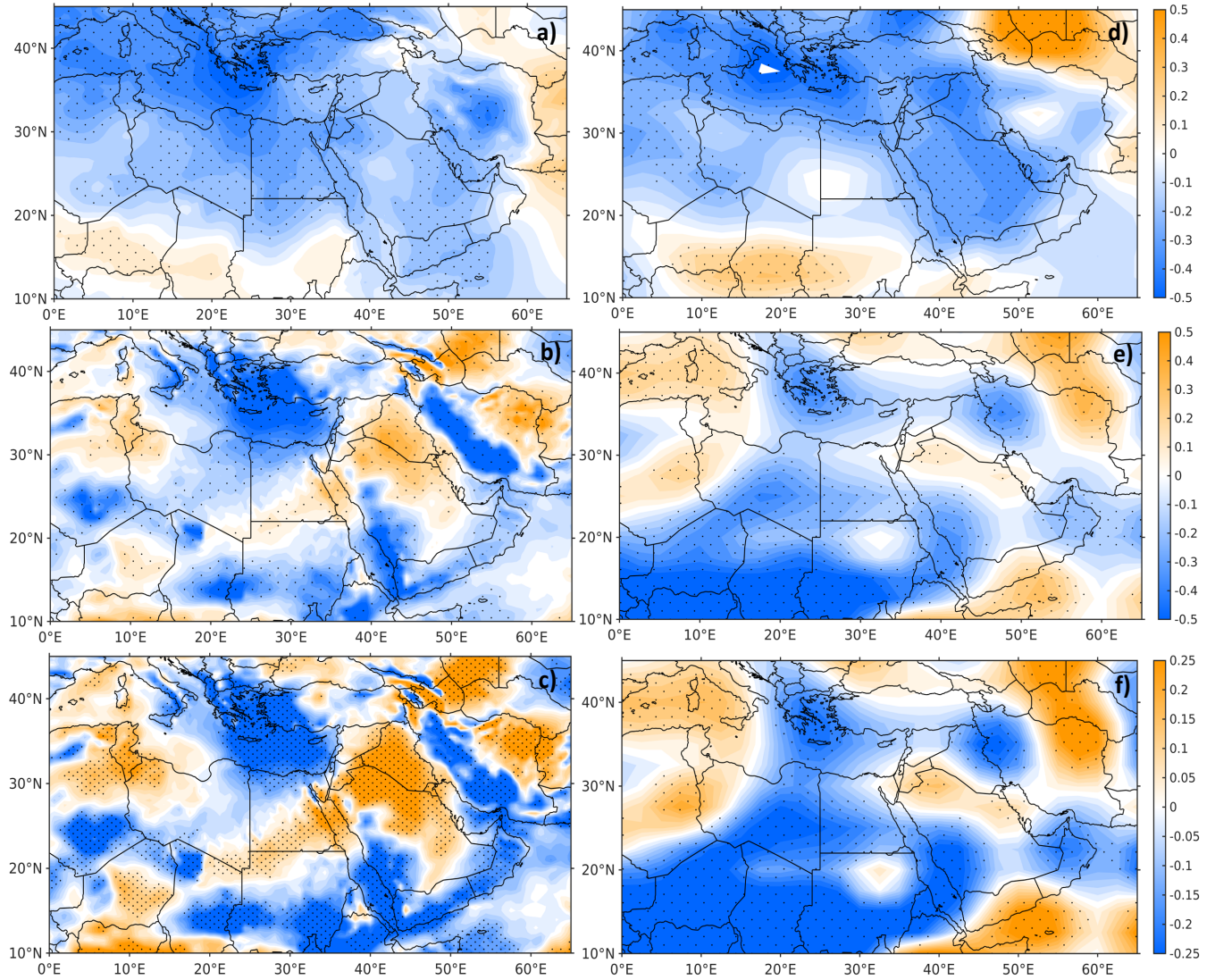
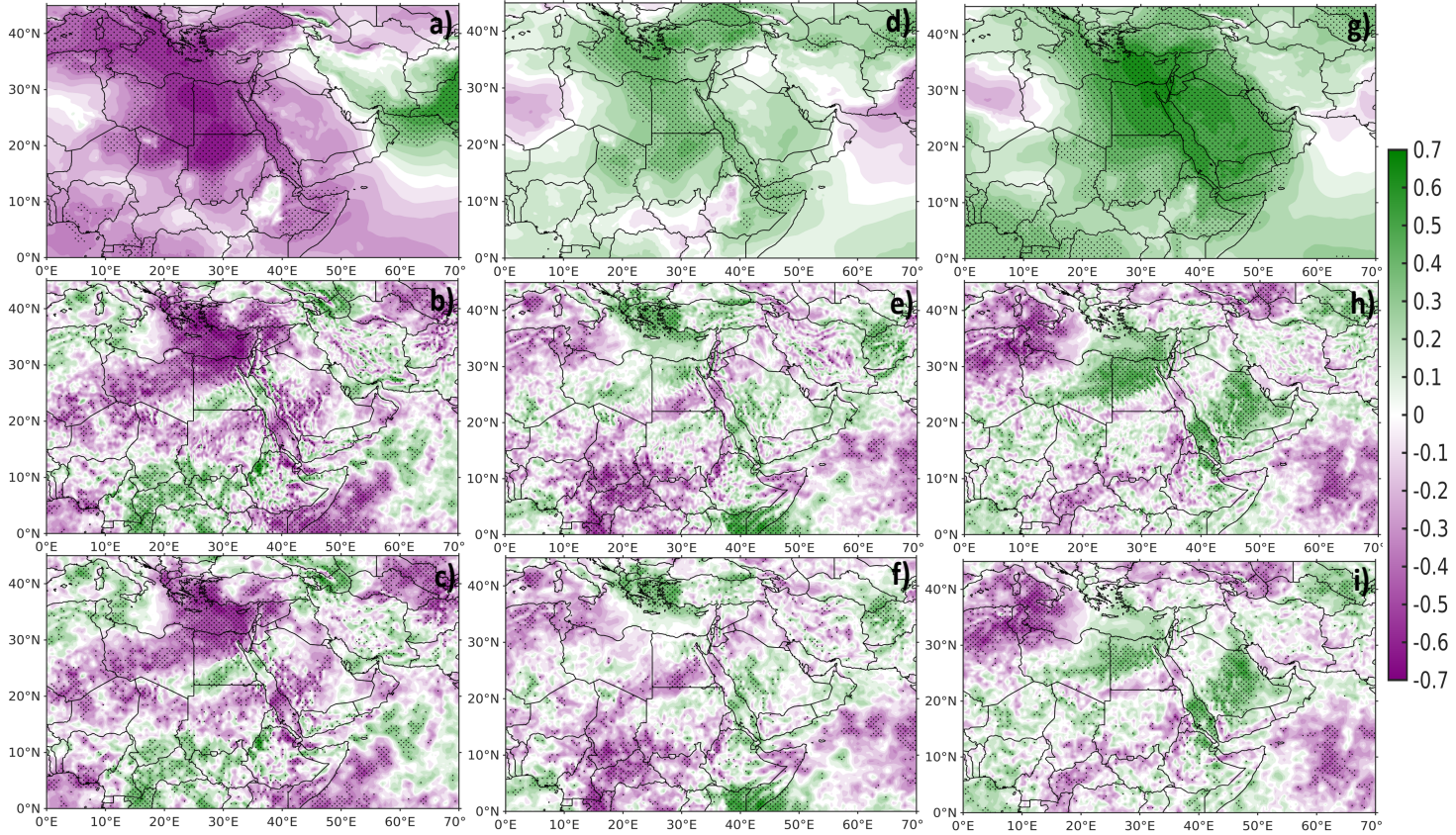


Figure S3: Long-term trends (1980–2024) in summer mean (a) mean sea-level pressure, (b) vertical velocity, and (c) vertical temperature advection at 500 hPa derived from the MERRA-2 reanalysis. Corresponding results derived from the NCEP-2 reanalysis are shown in right panel (d–f). Pixels with trends significant at the 95% confidence level ($p < 0.05$) are indicated by dots.



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51 **Figure S4:** Spatial correlation patterns between key climate modes and summer atmospheric
 52 circulation features over the period 1980–2024. Panels (a–c) display correlations with the Atlantic
 53 Multidecadal Variability (AMV) for surface pressure (a), vertical velocity at 500 hPa (b), and
 54 vertical temperature advection at 500 hPa (c). Panels (d–f) show corresponding correlations with
 55 Arctic sea ice concentration, and panels (g–i) illustrate correlations with the Pacific Decadal
 56 Oscillation (PDO). Stippling denotes regions where correlations are statistically significant at the
 57 $p < 0.05$ level.

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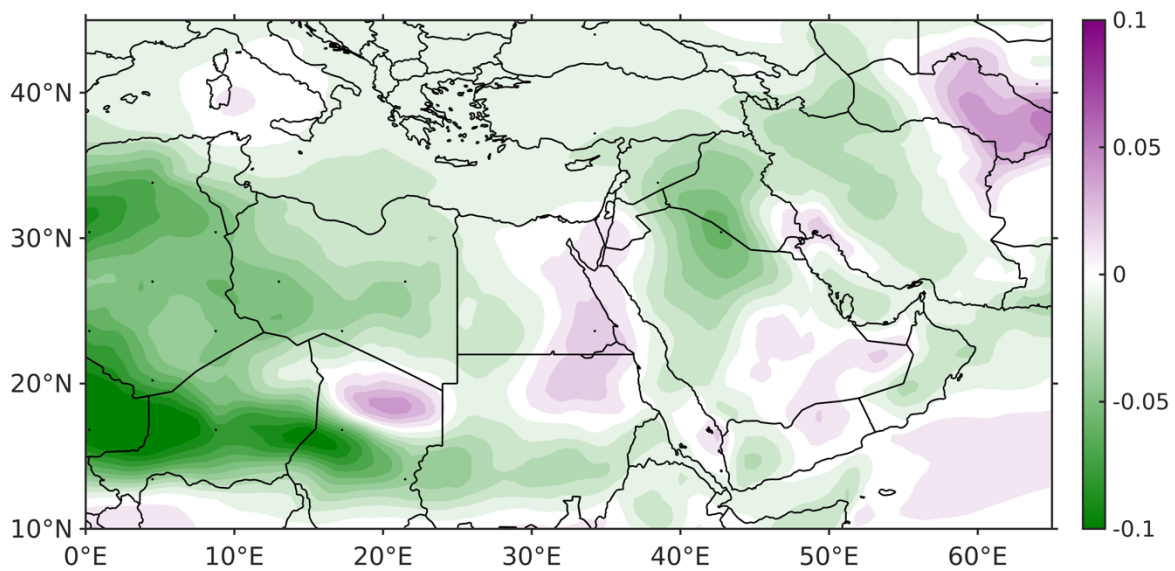


Figure S5: Recent (2000–2024) trends in the summer mean dust load in atmospheric column (units: g/m^2) over the EMME region. The dots indicate the trends with $p\text{-value} < 0.1$