



Supplement of

Nonlinear effects of the stratospheric Quasi-Biennial Oscillation on ENSO modulating PM_{2.5} over the North China Plain in early winter

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Section S1

Figures S1 to S13

Definition of ENSO events by Jan Null in their website of <https://ggweather.com/enso/oni.htm>

The Oceanic Niño Index (ONI) is the de facto standard used by NOAA to classify El Niño (warm) and La Niña (cool) events in the eastern tropical Pacific. It is defined as the running three-month mean sea surface temperature (SST) anomaly in the Niño 3.4 region (5°N–5°S, 120°–170°W). An El Niño event is identified when the SST anomaly equals or exceeds +0.5°C for five consecutive overlapping three-month periods, while a La Niña event is defined by anomalies at or below –0.5°C over the same duration.

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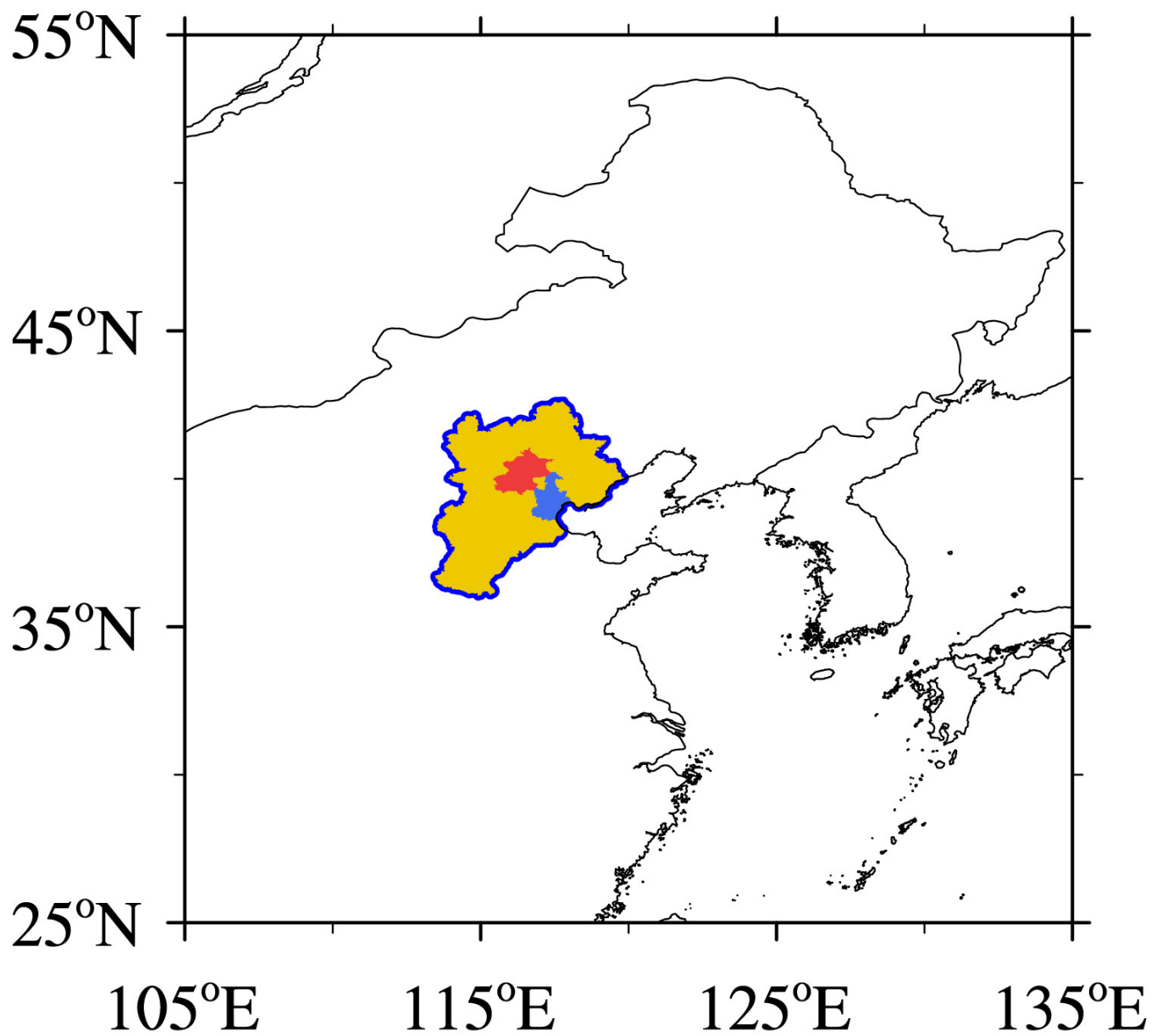


Figure S1: Map showing Hebei (yellow shading), Beijing (red shading), and Tianjin (blue shading), China. The area enclosed by the blue curve corresponds to the Beijing–Tianjin–Hebei region.

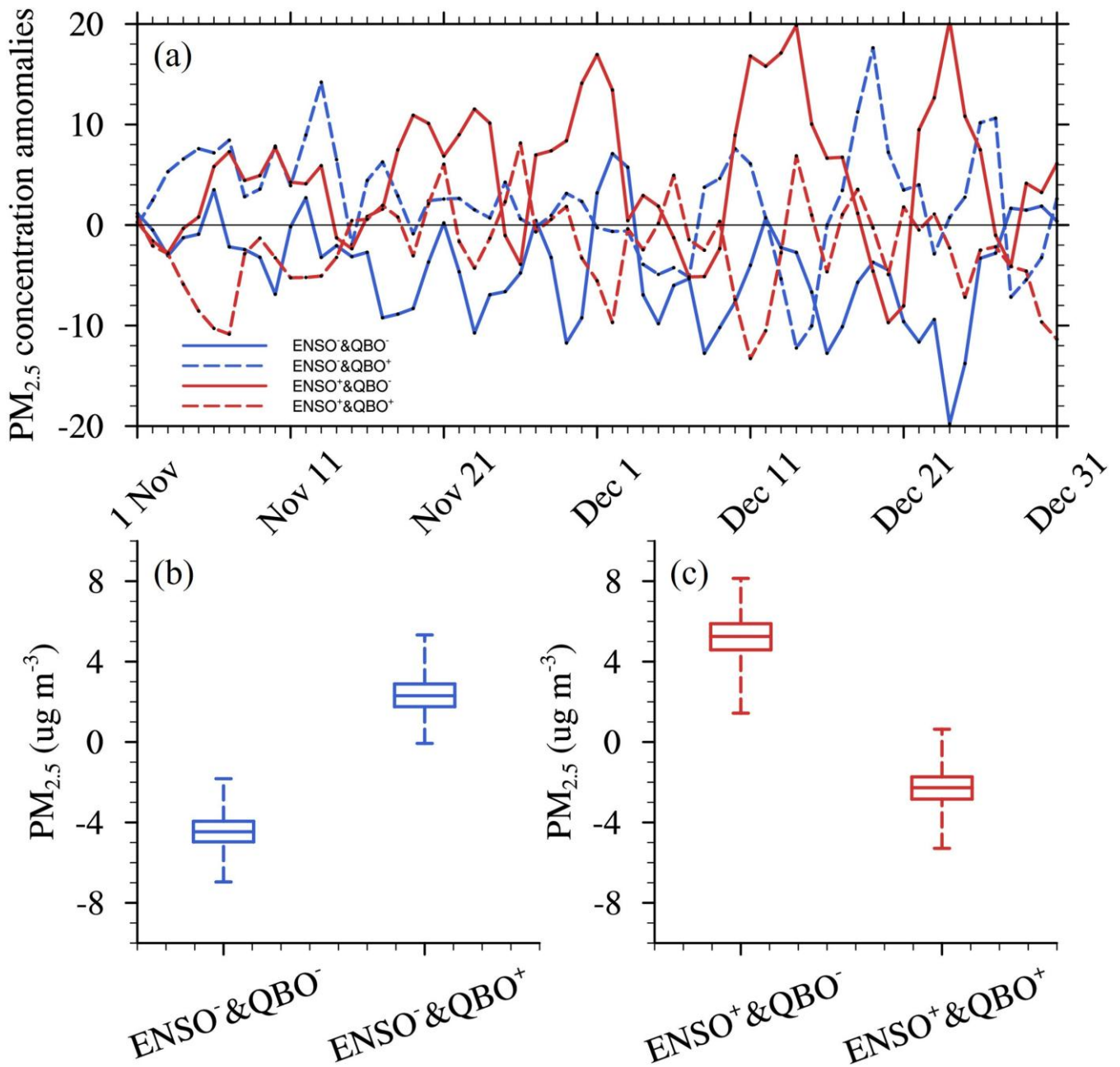


Figure S2: (a) Composite daily PM_{2.5} time series ($\mu\text{g m}^{-3}$) during November–December for La Niña & EQBO (blue solid line), La Niña & WQBO (blue dashed line), El Niño & EQBO (red solid line), El Niño & WQBO (red dashed line). (b, c) Same as Figure 3 in the main text, but based on daily PM_{2.5} data. The daily PM_{2.5} data were provided by Yang (2020).

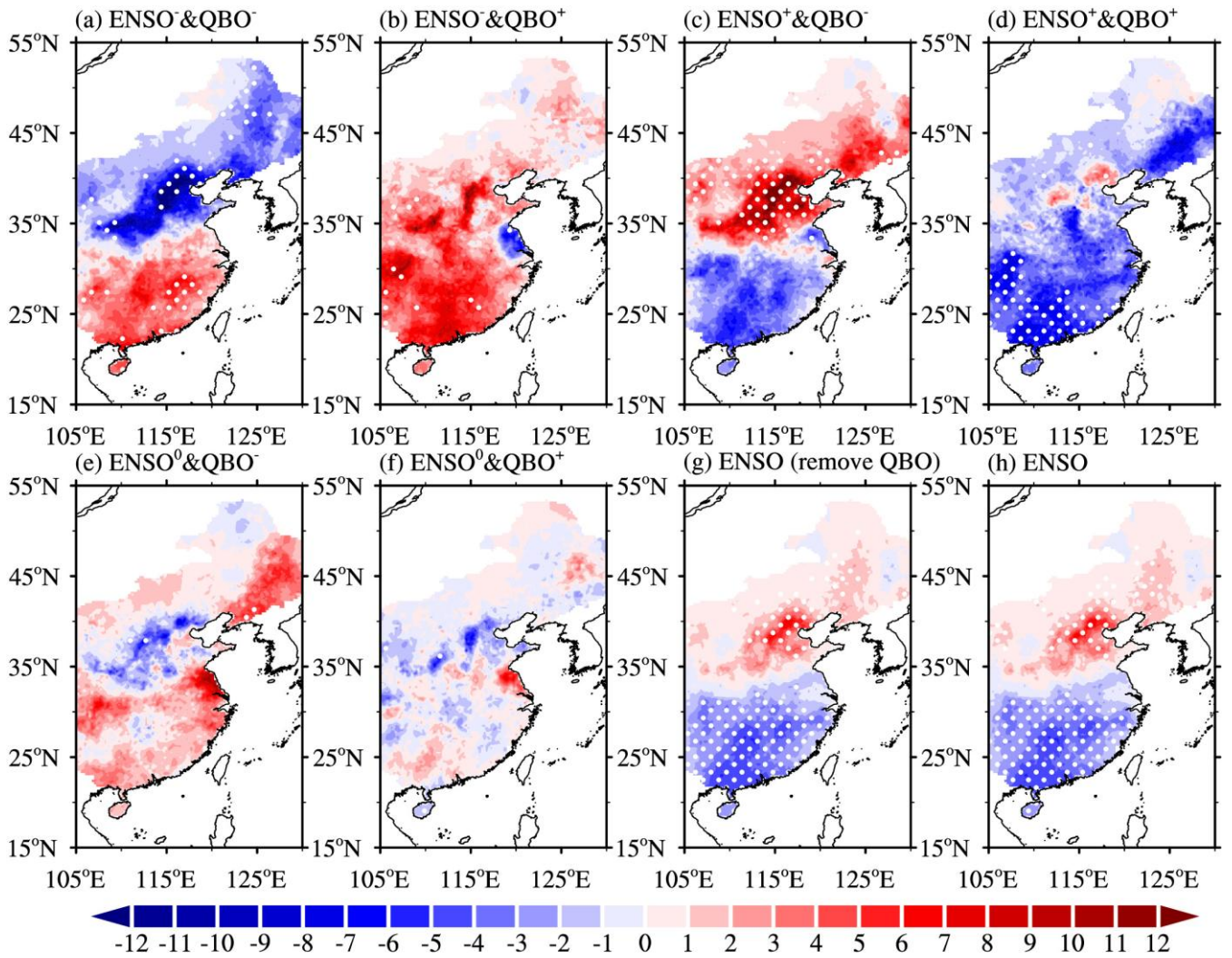


Figure S3: Composite patterns of anomalous $PM_{2.5}$ concentrations (shading; unit: $\mu g m^{-3}$) provided by Zhong et al. (2022) for (a) La Niña & EQBO, (b) La Niña & WQBO, (c) El Niño & EQBO, (d) El Niño & WQBO, (e) non-ENSO & EQBO, (f) nENSO & WQBO. (g-h) Regression coefficients of anomalous $PM_{2.5}$ concentrations onto the Niño3 index (QBO signals removed) and Niño3 index shown in Figs. 1b and c. White dotted areas indicate significant values at the 90% confidence level.

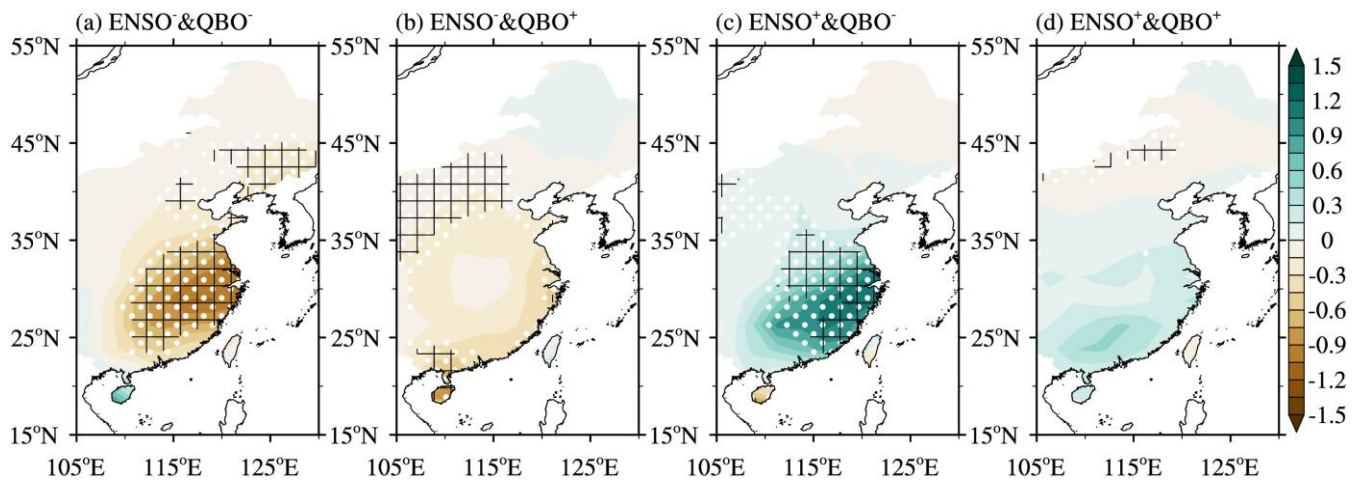


Figure S4: Composite patterns of precipitation (shading; unit: mm day^{-1}) for (a) La Niña and EQBO, (b) La Niña and WQBO, (c) El Niño and EQBO, and (d) El Niño and WQBO. White dotted (black grid) areas indicate significant values at the 80% (90%) confidence level.

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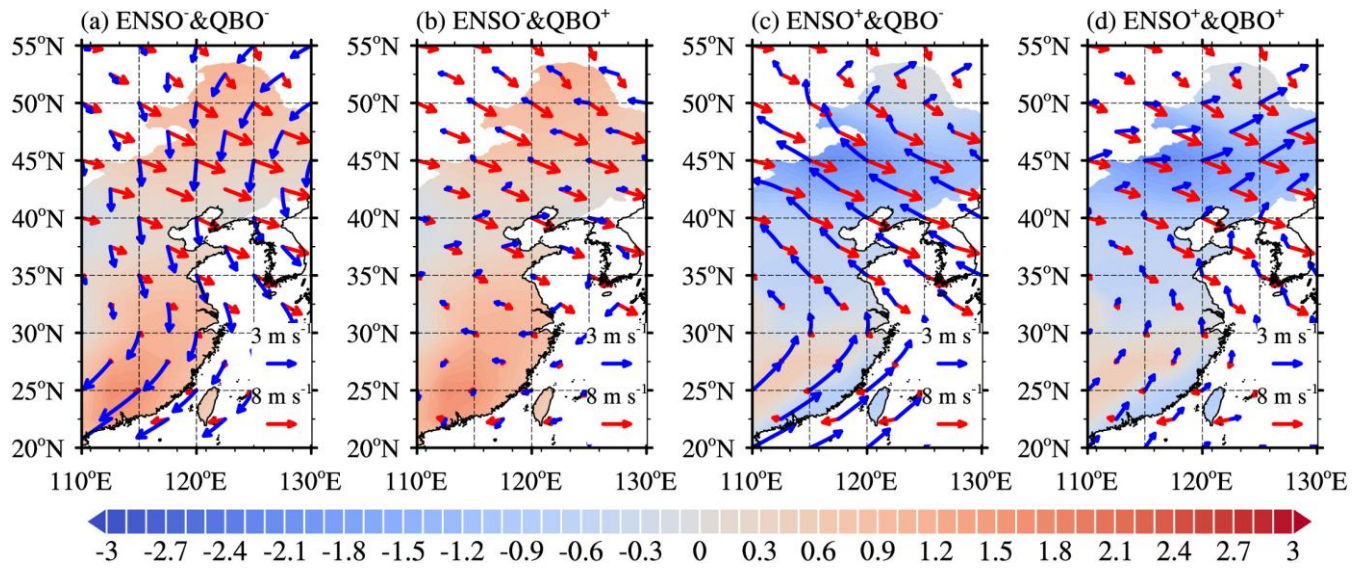


Figure S5: Same as Figure 4 in the manuscript, but for NCEP data.

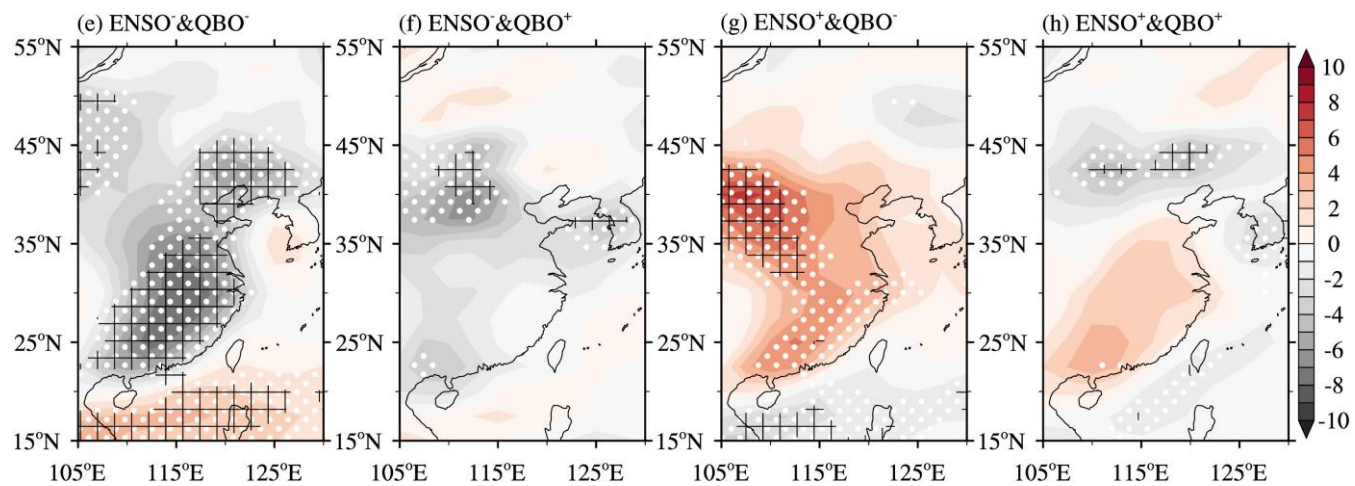


Figure S6: Same as Figure 5e–h in the manuscript, but for NCEP data.

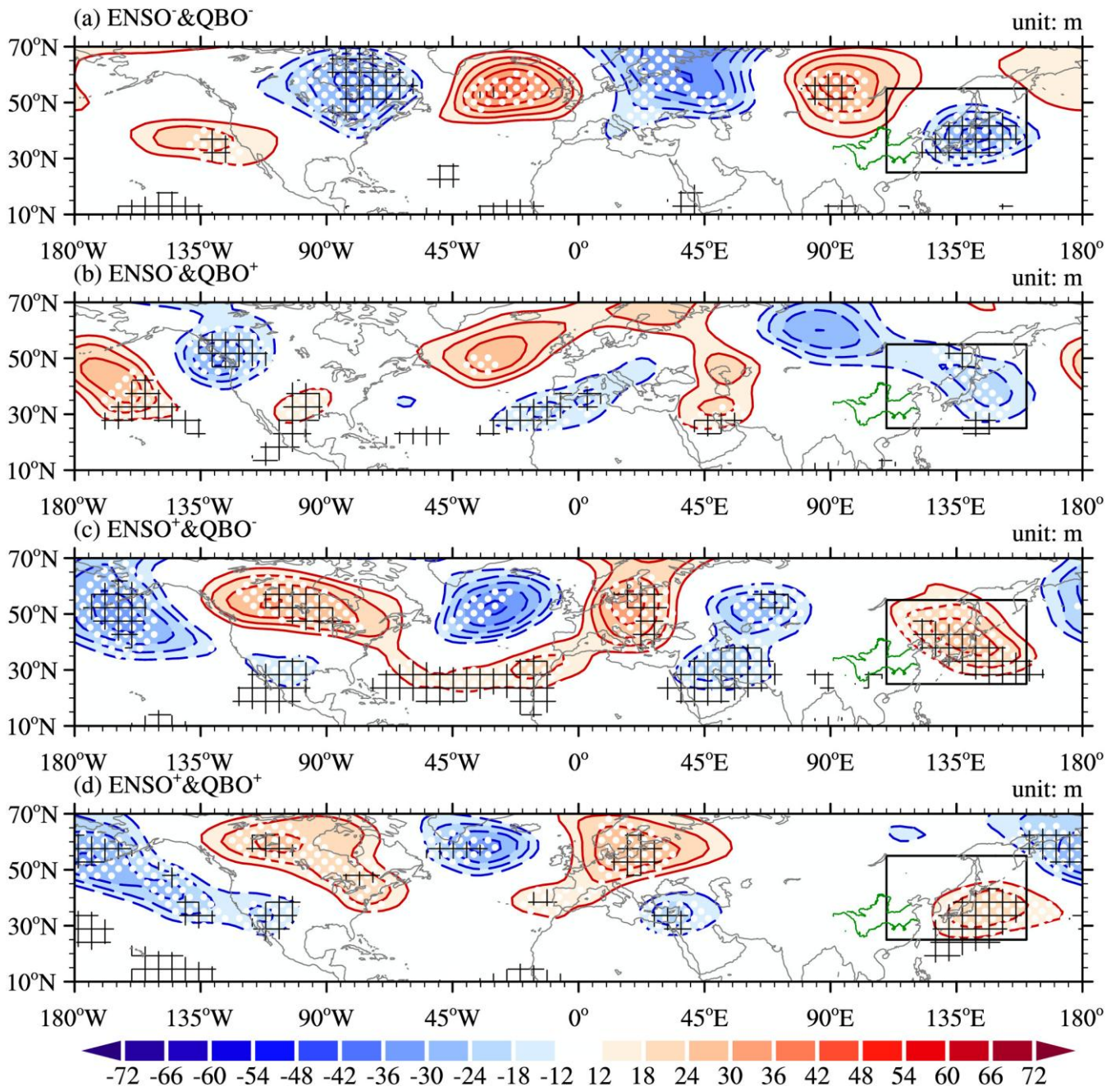


Figure S7: Same as Figure 6 in the manuscript, but for NCEP data.

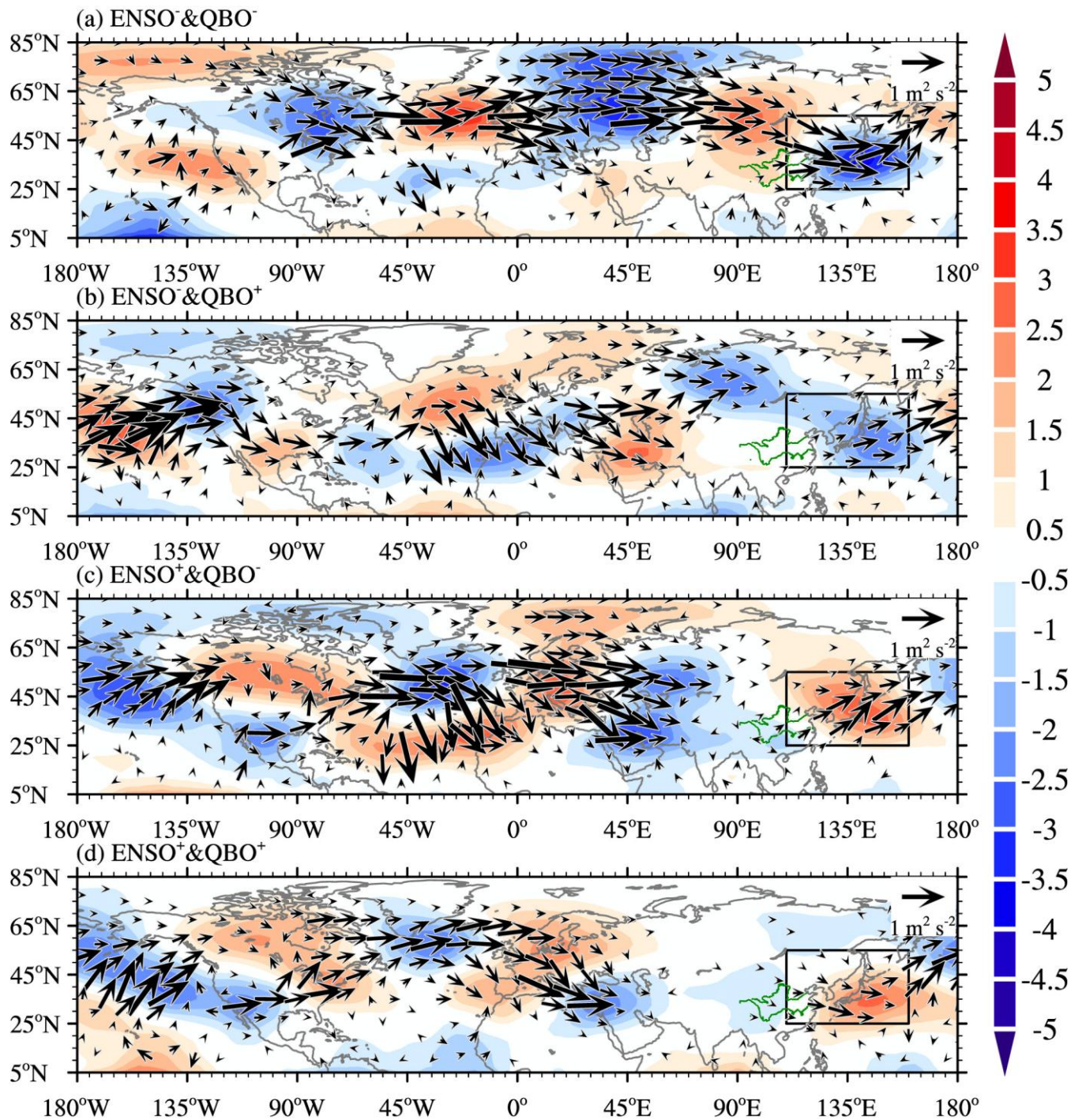
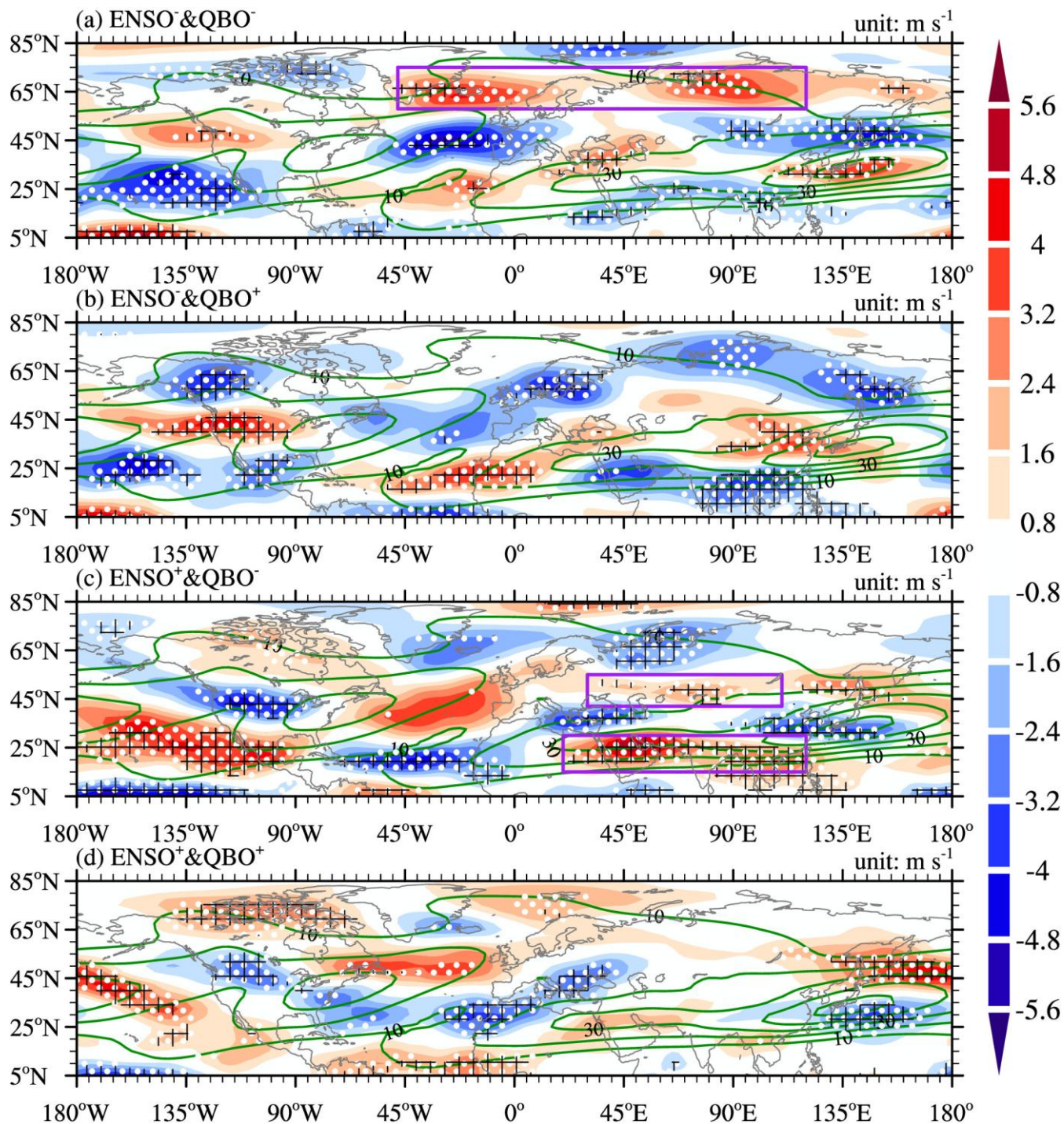


Figure S8: Same as Figure 7 in the manuscript, but for NCEP data.



40 Figure S9: Same as Figure 8 in the manuscript, but for NCEP data.

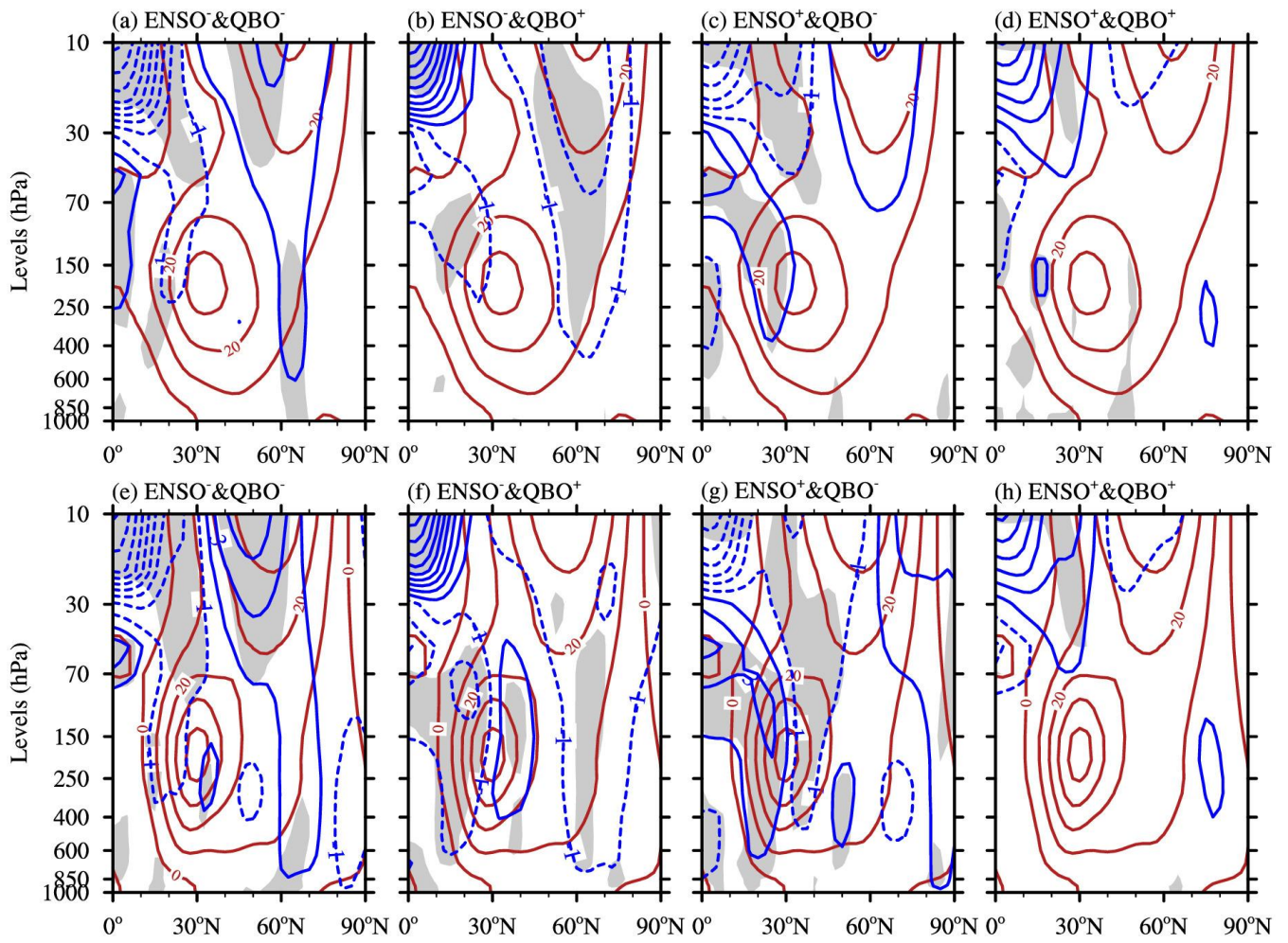


Figure S10: Same as Figure 9 in the manuscript, but for NCEP data.

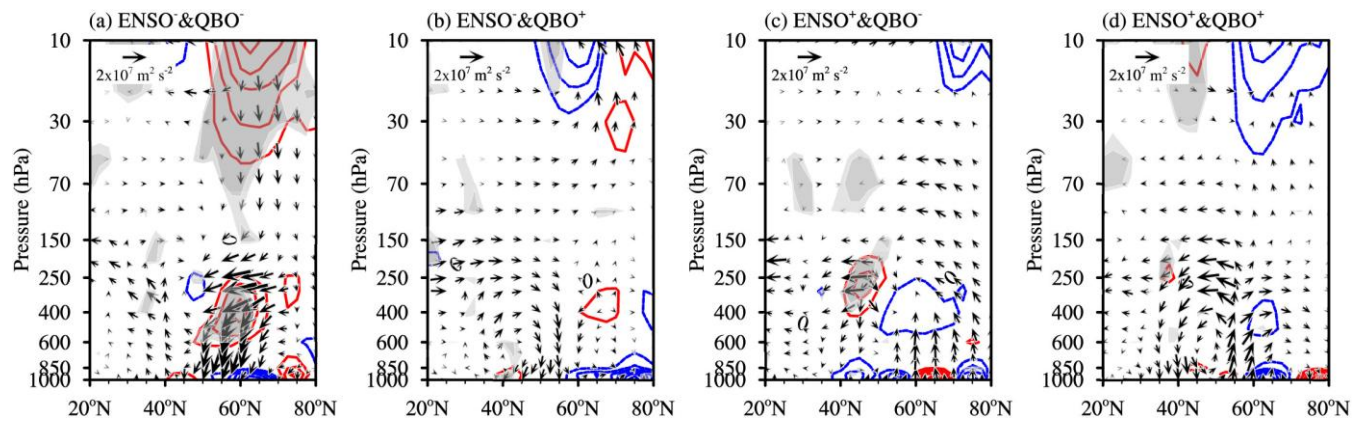


Figure S11: Same as Figure 10 in the manuscript, but for NCEP data.

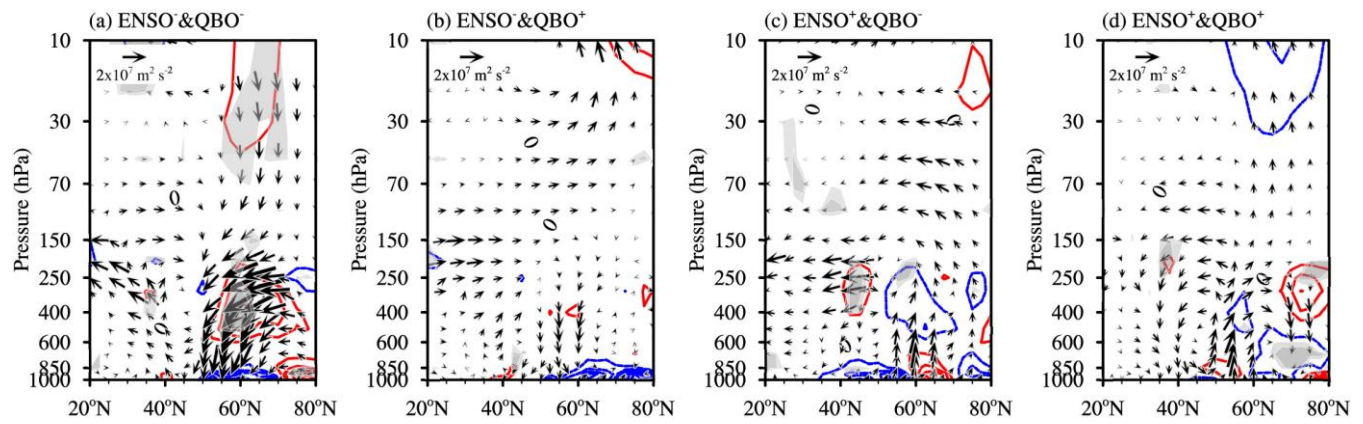
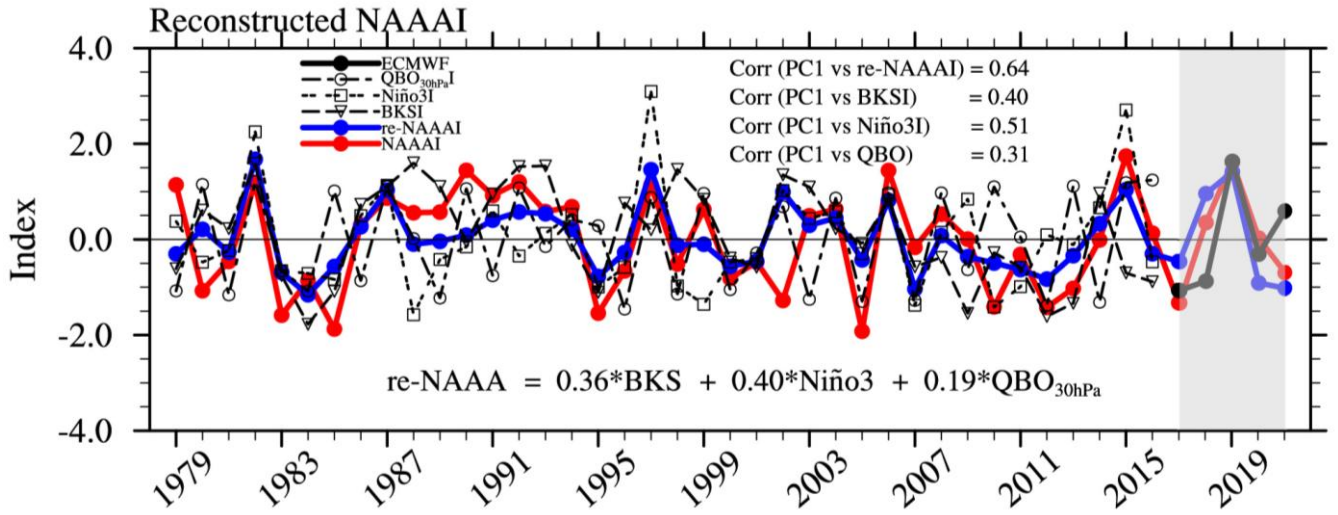


Figure S12: Same as Figure S11 in the manuscript, but for daily ERA5 data.



50 Figure S13: Linear regression of the time-series of the first EOF (representing the northeast Asian anomalous
 55 anticyclone (NAAA)) of November to January mean geopotential height anomalies at 500 hPa over the domain 25°–
 55°N, 100°–160°E during 1979–2019, with multiple variables including the Barents–Kara Sea sea-ice index (BKSI),
 Niño3 index (Niño3I) and 30-hPa QBO index (QBO_{30hPaI}). The red solid line represents the NAAA index (500-hPa
 geopotential height anomaly averaged over 25°N–50°N, 120°E–160°E) based on reanalysis data, the blue solid line is
 the re-NAAAI reconstructed by multiple linear regression, the black dashed line is BKSI, the black dotted line is
 Niño3I, and the black dash-dotted line is QBO_{30hPaI}. The black thick line represents 500-hPa geopotential height
 anomaly averaged over 25°N–50°N, 120°E–160°E based on ERA5 seasonal forecast products provided by the
 ECMWF. The gray shading indicates the period when hindcast experiments were carried out for verification. Please
 refer to An et al. (2023a) for more details.