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**Supplement**

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Table S1. PMIP4-LGM simulations and their variable accessibility

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **PI** | | | | | **LGM** | | | | **references** | **Duration(y)** |
|  | tas | sea ice | Zg | slp | tas | sea ice | zg | slp |  |  |
| **MIROC-ES2L** | **500** | **500** | **500** | **500** | **100** | **100** | **100** | **100** | Ohgaito et al. (2021) | 2200 |
| **AWI-ESM-1-1-LR** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | Lohmann et al. (2020) | 600 |
| **MPI-ESM1-2-LR** | **1000** | **1000** | **1000** | **1000** | **500** | **500** | **500** | **500** | Mauritsen et al. (2019) | 3850 |
| **CESM2-FV2** | **500** | **500** | **500** | **500** | **500** | **500** | **500** | **500** | Zhu et al., 2021 | **500** |
| **CESM2-WACCM-FV2** | **500** | **500** | **500** | **500** | **100** | **100** | **100** | **100** | Zhu et al., 2022 | 500 |
| **INM-CM4-8** | **530** | **530** | **530** | **530** | **100** | **○** | **○** | **100** | Volodin et al. (2018) | 50 |
| **IPSLCM5A2** | **250** | **250** | **250** | **250** | **○** | **○** | **○** | **○** | Sepulchre et al. (2020) | 1200 |
| **UoT-CCSM4** | **○** | **○** | **○** | **○** | **○** | **○** | **○** | **○** | Chandan & Peltier (2017) | 2900 |
| **HadCM3B-M2.1aD** | **○** | **○** | **○** | **○** | **○** | **○** | **○** | **○** | Valdes et al. (2017) | 400 |
| **iLOVECLIM1.1.4** | **○** | **○** | **○** | **○** | **○** | **○** | **○** | **○** | Lhardy et al. (2020) | 5000 |

NB: Numbers indicate the duration of monthly variable, and circles indicate no available data. Shading color marks four model used in this study.

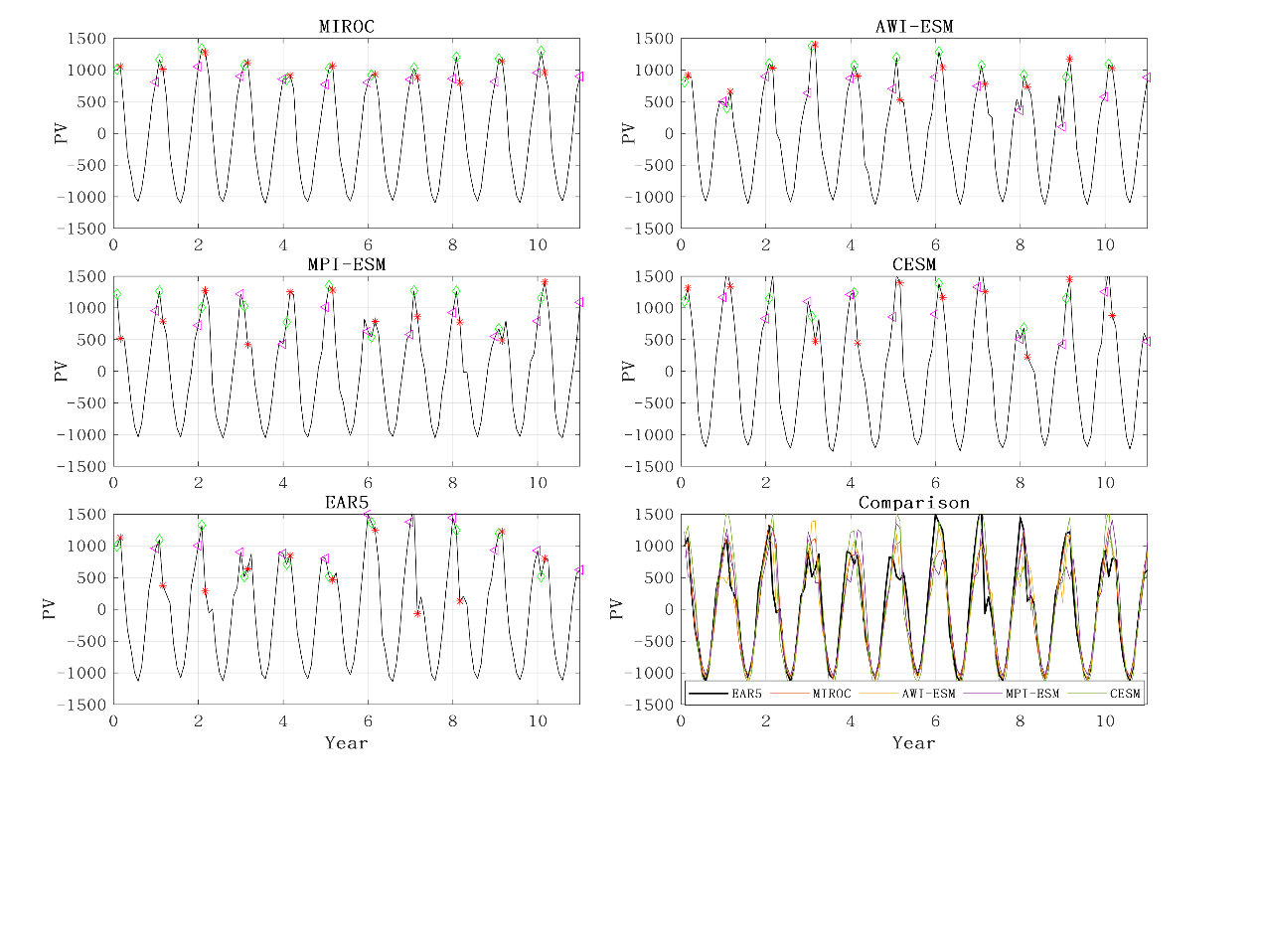


Figure S1. Seasonal change of VSI of the PI simulations and ERA5 re-analysis data, illustrating strong PV and their large variation during the winter. The green, red and magenta markers mark Jan, Feb and Dec VSI in turn.

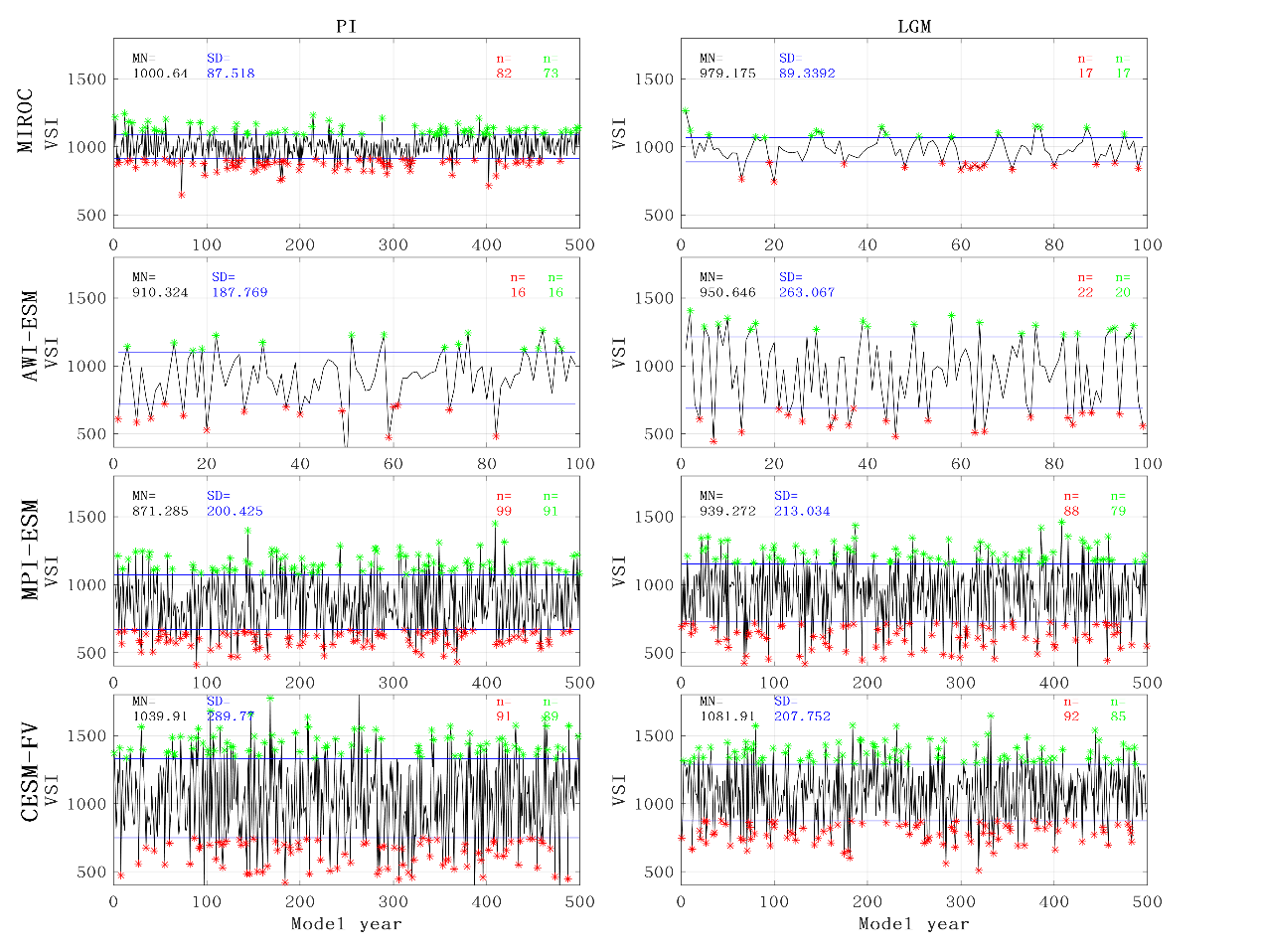


Figure S2. Time series of the vortex strength index (VSI) and composite for weak (red stars) and strong (green stars) PV years. Mean and standard deviation has been shown in black and blue color.

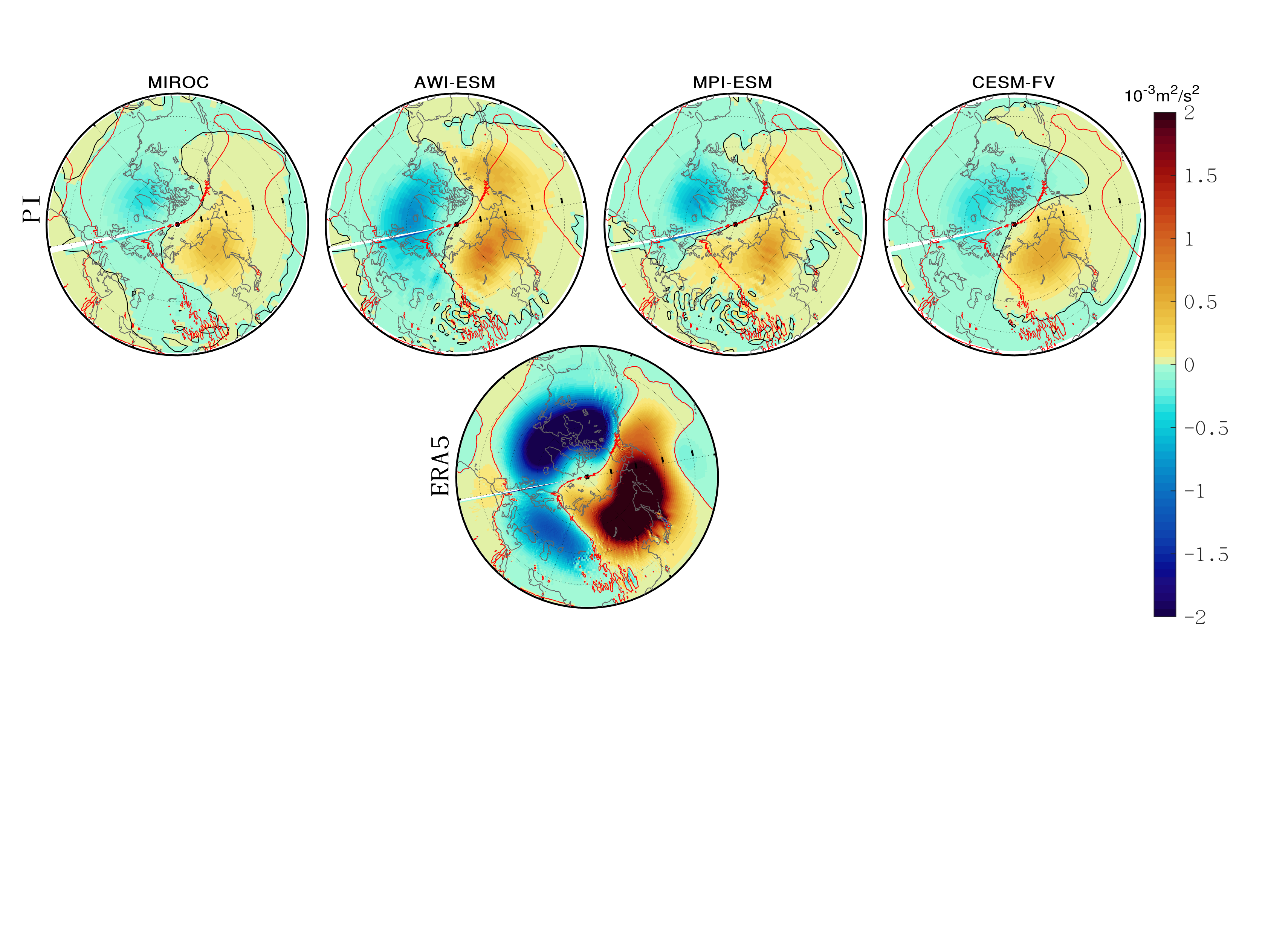


Figure S3. December Plumb wave activity flux anomalies at 100 hPa in the PI simulations and in ERA5 re-analysis data for the period of 1940-2024. Positive values indicate upward wave energy flux that vertically propagates from Rossby waves, and negative values give downward reflected planetary waves. The zero contour is shown in red for ERA5.

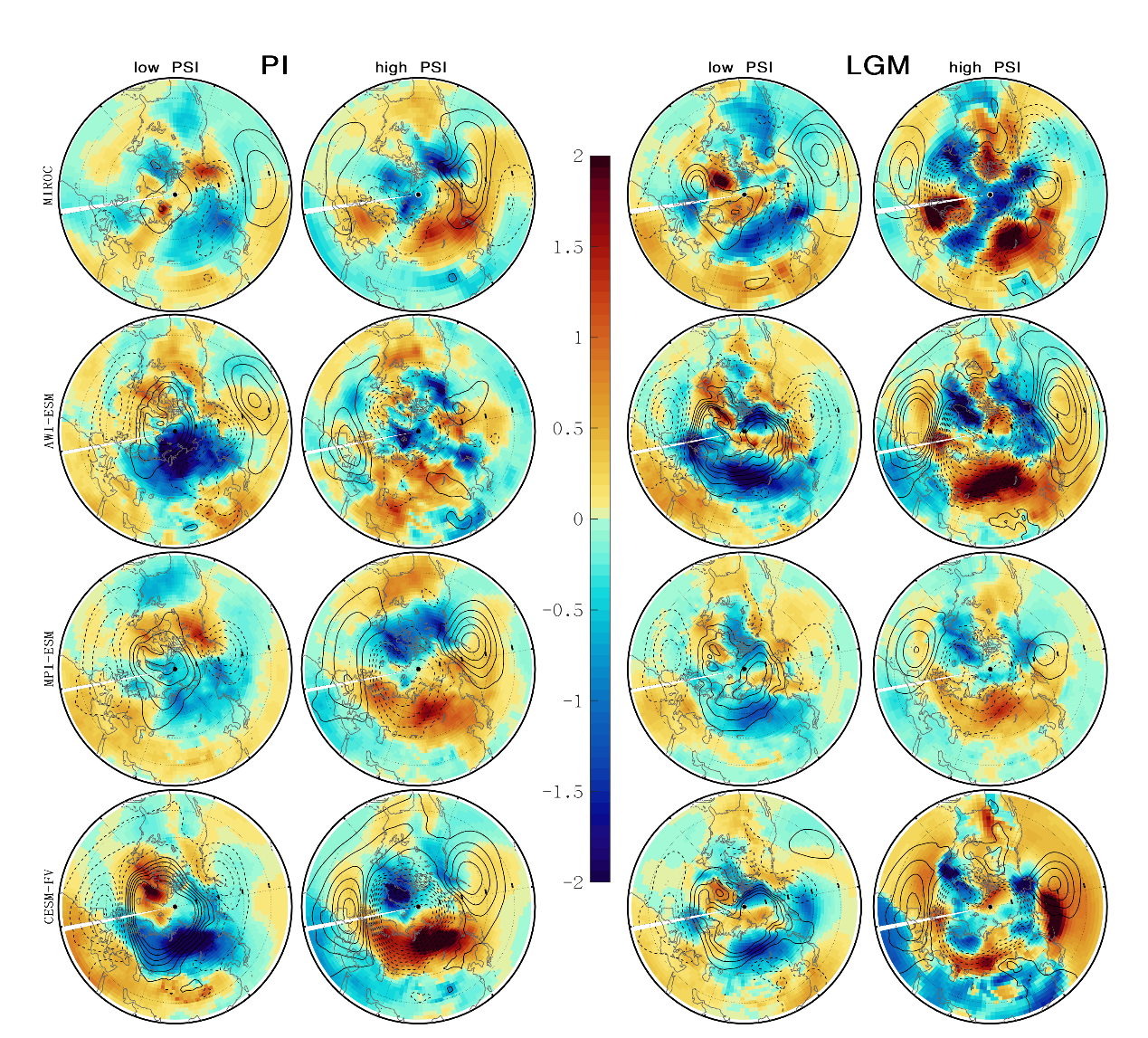


Figure S4. DJF Surface air temperature (SAT) differences between the weak PV (low PSI) and strong PV (high VSI) composites, shown as the anomalies of the corresponding composites from their full-time climate mean fields (coloured, in ℃). The corresponding sea level pressure (SLP) anomalies are shown as contours, with the interval of 60 hPa.