Higher model resolution alters the winter precipitation response to past and future warming in the western U.S.

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1. Motivation

- Atmospheric rivers (ARs) drive extreme precipitation and flooding in the western US—and are projected to intensify under future warming
- Past warm intervals offer insight into future AR behavior in the region, but paleo-AR research has been limited by coarse model resolution
- Low-resolution (LR) simulations underestimate AR strength and precipitation; high-resolution (HR) better captures integrated vapor transport and orographic effects
- Thermodynamic (water vapor) increases robustly drive more AR activity under warming, but the dynamic (wind-driven) response remains uncertain

How do thermodynamic and dynamic changes control ARs and precipitation in the western US across a range of warming transitions?

2. Simulations & surface warming

Figure 1. Surface temperature anomalies for the Cenozoic based on proxy reconstructions (Evans et al. 2024, *Paleo&Paleo*; Osman et al., 2021, *Nature*). The time periods simulated with HR and LR iCESM1.3 are preindustrial, Last Glacial Maximum (LGM, 21 ka), mid-Pliocene (Pliocene, ~3 Ma). We also include MESACLIP RCP 6.5 and 8.5 ensembles (2070-2100) for comparison (Chang et al. 2020, *JAMES*). **HR-iCESM1.3 has a ~0.25° atm/lnd and ~0.1° ocn/ice components; LR-iCESM1.3 has all ~1° components. PaleoWeather simulations performed with NWSC Accelerated Scientific Discovery project on Derecho.**

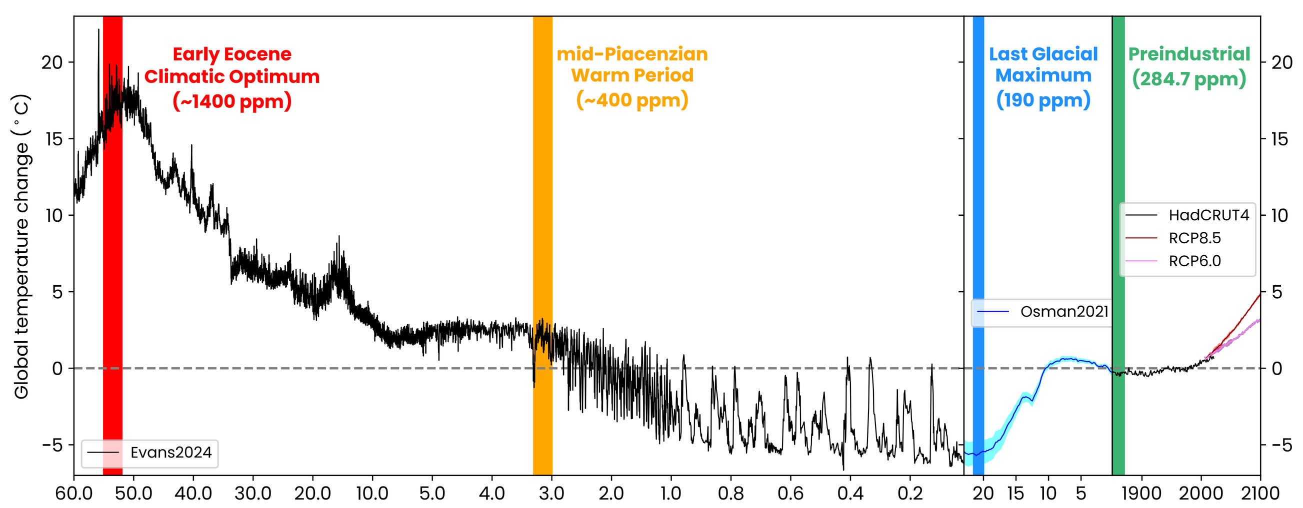
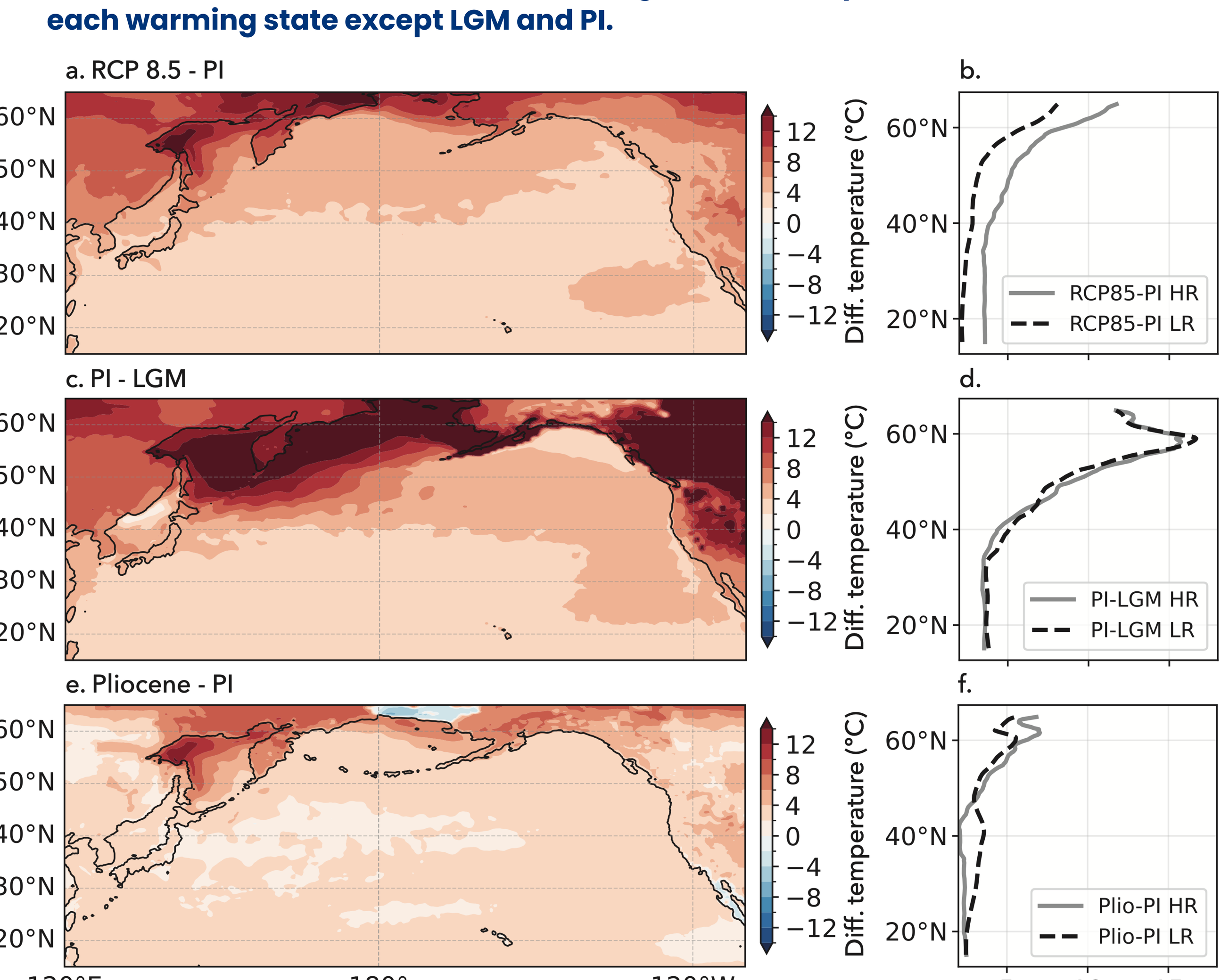


Figure 2. Surface temperature warming patterns over the North Pacific in the HR simulations (a, c, e). Meridional changes in surface temperature are shown for LR and HR (b, d, f). **HR features stronger Arctic amplification than LR for each warming state except LGM and PI.**



3. Drivers of atmospheric river change

Figure 3. The total, thermodynamic, and dynamic components of AR frequency and integrated vapor transport (IVT) over the North Pacific in the HR simulations. ARs are tracked using the Lora_v2 (Skinner et al. 2020, *EPSL*) and TempestExtremes (Ullrich & Zarzycki 2017, *GMD*) detection tools. **Overall, increases in AR activity are primarily driven by systematic increases in water vapor, whereas state-dependent differences in winds amplify or dampen this signal.**

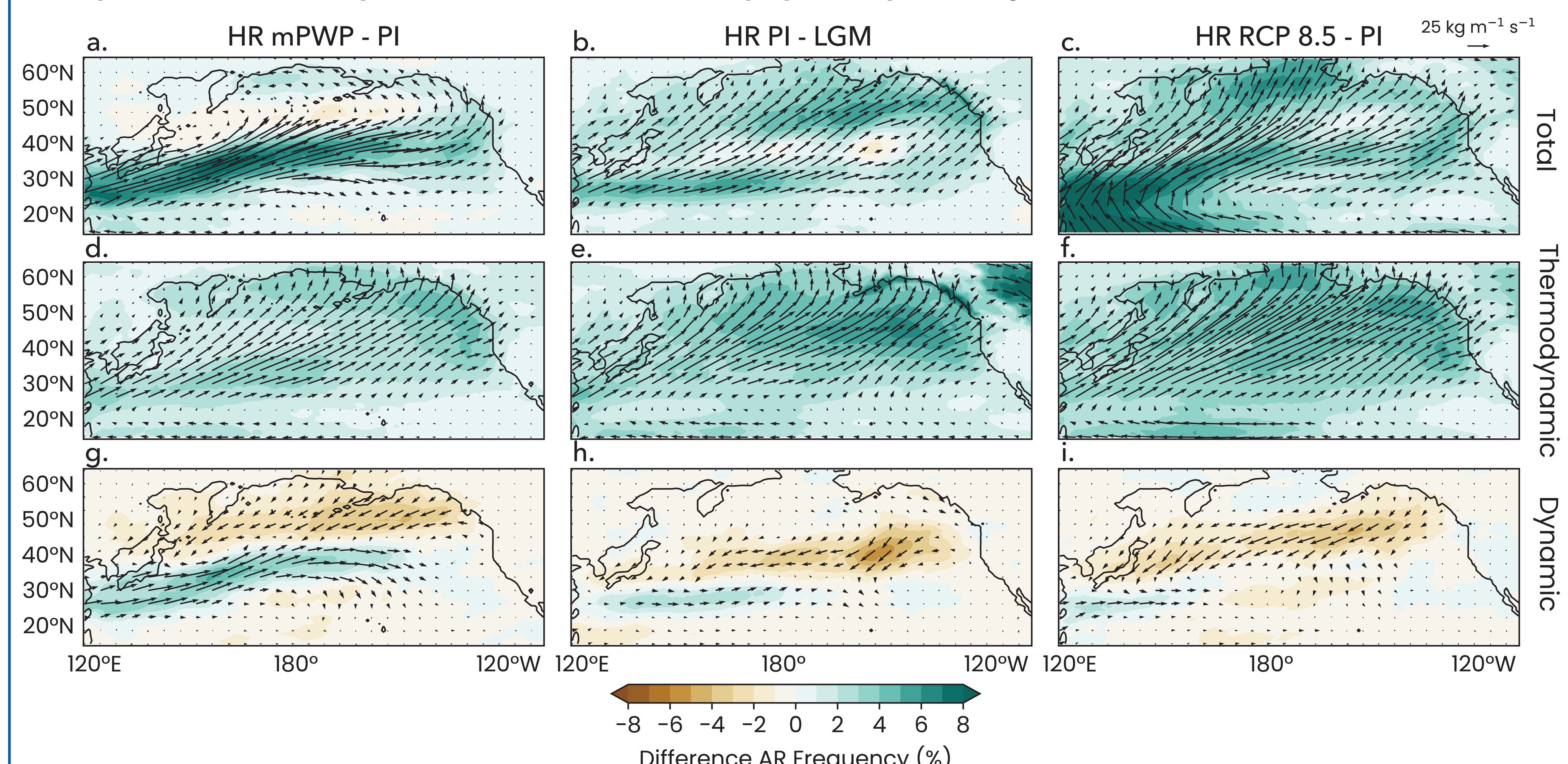
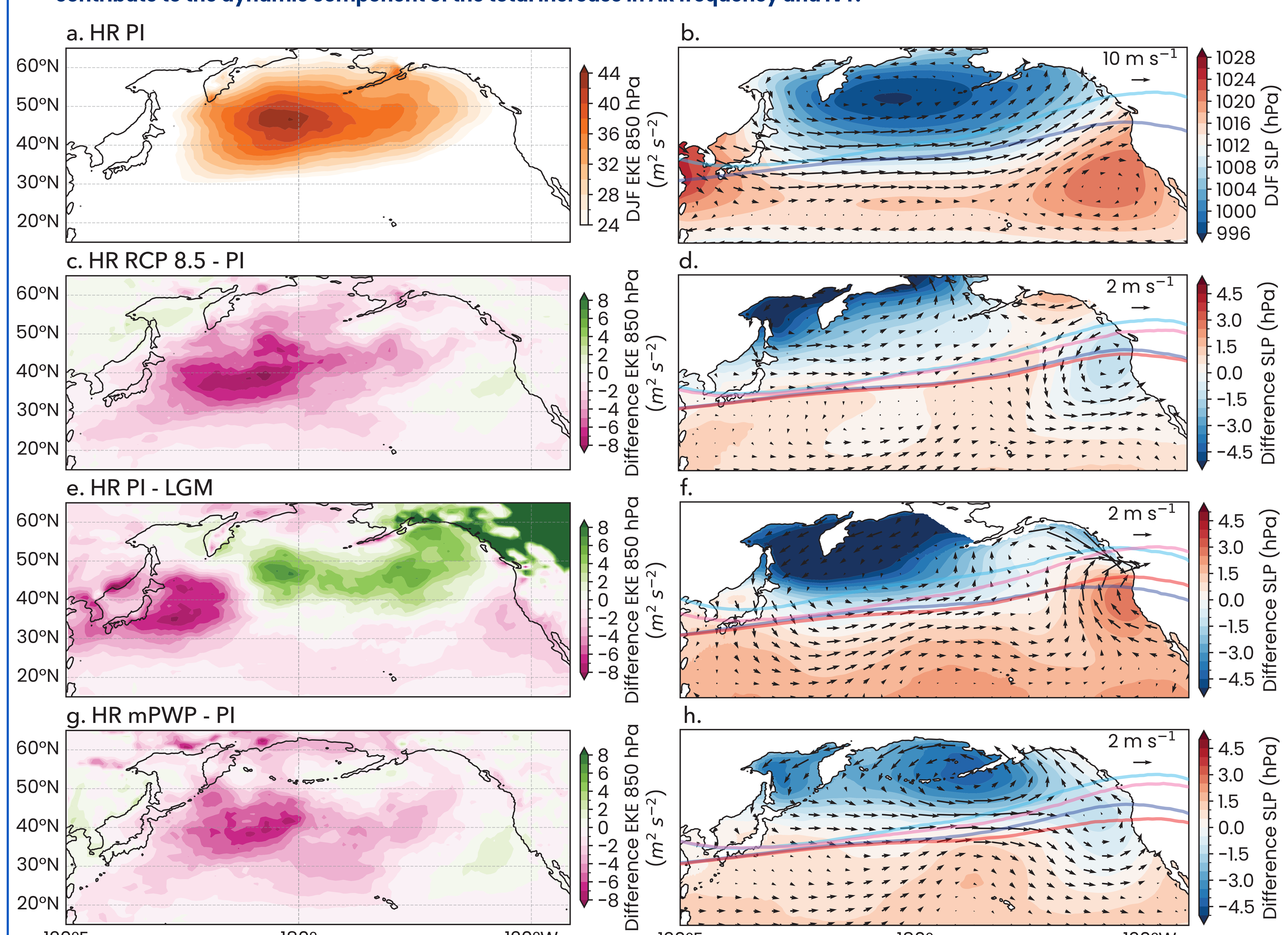


Figure 4. DJF (Dec-Jan-Feb) transient eddy kinetic energy (EKE) at 850 hPa (a) and sea level pressure (SLP, contours) and wind vectors at 850 hPa (b) over the North Pacific in the HR PI simulation. Differences in EKE and SLP are plotted for the other simulations (c-h). The blue/light blue (red/pink lines) delineate the latitude of maximum zonal winds at 250 and 500 hPa for the relatively cool (warm) interval, respectively. **A combination of short-term and long-term mean changes in winds contribute to the dynamic component of the total increase in AR frequency and IVT.**



This material is based upon work supported by the NSF National Center for Atmospheric Research, which is a major facility sponsored by the U.S. National Science Foundation under Cooperative Agreement No. 1852977. Any opinions, findings and conclusions or recommendations expressed in this material do not necessarily reflect the views of NSF.

4. Regional precipitation change

Figure 5. Differences in cool-season (Oct-Mar) precipitation (a, b, c) and the proportion of AR precipitation to total precipitation (d, e, f) in the HR simulations. Changes that are not significant (p > 0.05, Welch's ttest) are white. Markers are proxy-based qualitative changes in precipitation (teal=wetter, brown=drier, white=no change, gray=inconclusive; Oster et al. 2015, *Nature Geo.* and Ibarra et al. (2018), *Geology*). The average number of landfalling ARs in the Pacific Northwest (PNW, g) and California (CAL, h) for each AR category.

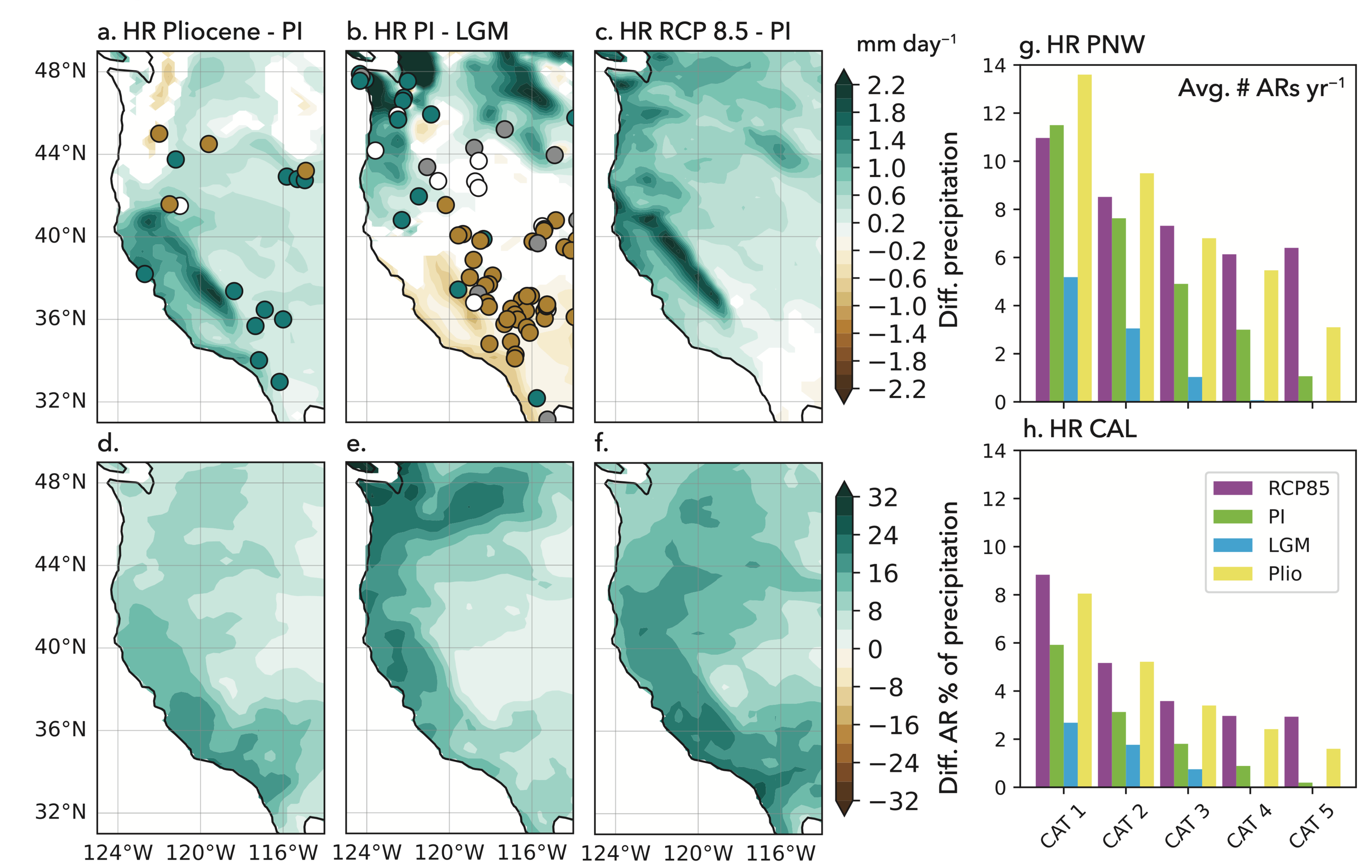
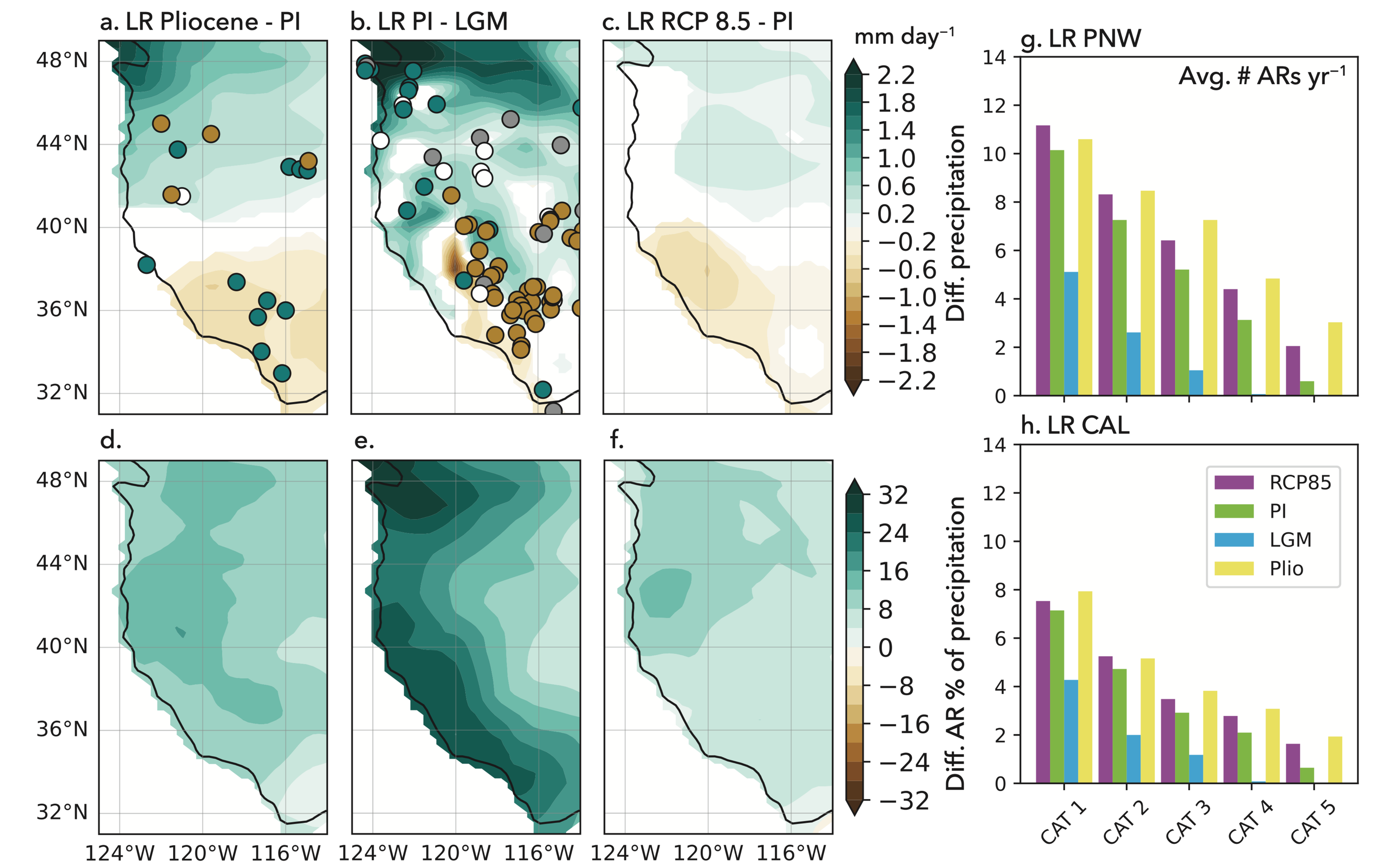


Figure 6. Same as Fig. 5 but for the LR simulations. **HR simulations show improved agreement with direction of proxy-inferred precipitation change compared to LR.**



5. Summary

- AR frequency and IVT increase in the North Pacific under past and future warming, primarily due to enhanced water vapor
- Yet, atmospheric circulation responses to warming are state-dependent. Changes in winds can amplify/dampen increases in AR activity and steer ARs to new locations, leading to different cool-season precipitation responses in the western US across warming transitions
- HR-CESM improves the precipitation response to warming compared to LR relative using paleo-data from the Pliocene and LGM
- In the western, hazardous ARs increase more than beneficial ARs under warming across all transitions