Atmospheric Rivers as Key Drivers of Global Extreme Precipitation: The observed analysis from 1979 to 2024

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Introduction

- Atmospheric rivers (ARs) are narrow corridors of concentrated moisture in the atmosphere that transport vast amounts of water vapor from tropical and subtropical regions to mid-latitudes. When these moist air masses encounter topography or atmospheric instability, they can release intense and prolonged precipitation, often resulting in extreme rainfall events, floods, and associated hazards (Zhu and Newell, 1998; Ralph et al., 2018).
- Recent studies have shown that ARs contribute significantly to total seasonal precipitation in many regions, including the west coasts of North and South America, western Europe, South Asia, and parts of southern Africa. The intensification of ARs due to global warming is a growing concern, as warmer air holds more moisture (Clausius–Clapeyron relationship), potentially increasing the frequency and severity of extreme precipitation events (Payne et al., 2020; Gershunov et al., 2019).
- Emerging research indicates a poleward shift and intensification of ARs in future climate scenarios, with important implications for water resources and disaster risk management (Paltan et al., 2021; Viale et al., 2023). Furthermore, the interaction of ARs with large-scale modes of variability, such as ENSO and the Madden–Julian Oscillation (MJO), modulates the spatial and temporal characteristics of extreme rainfall (Gershunov et al., 2017; White et al., 2023).

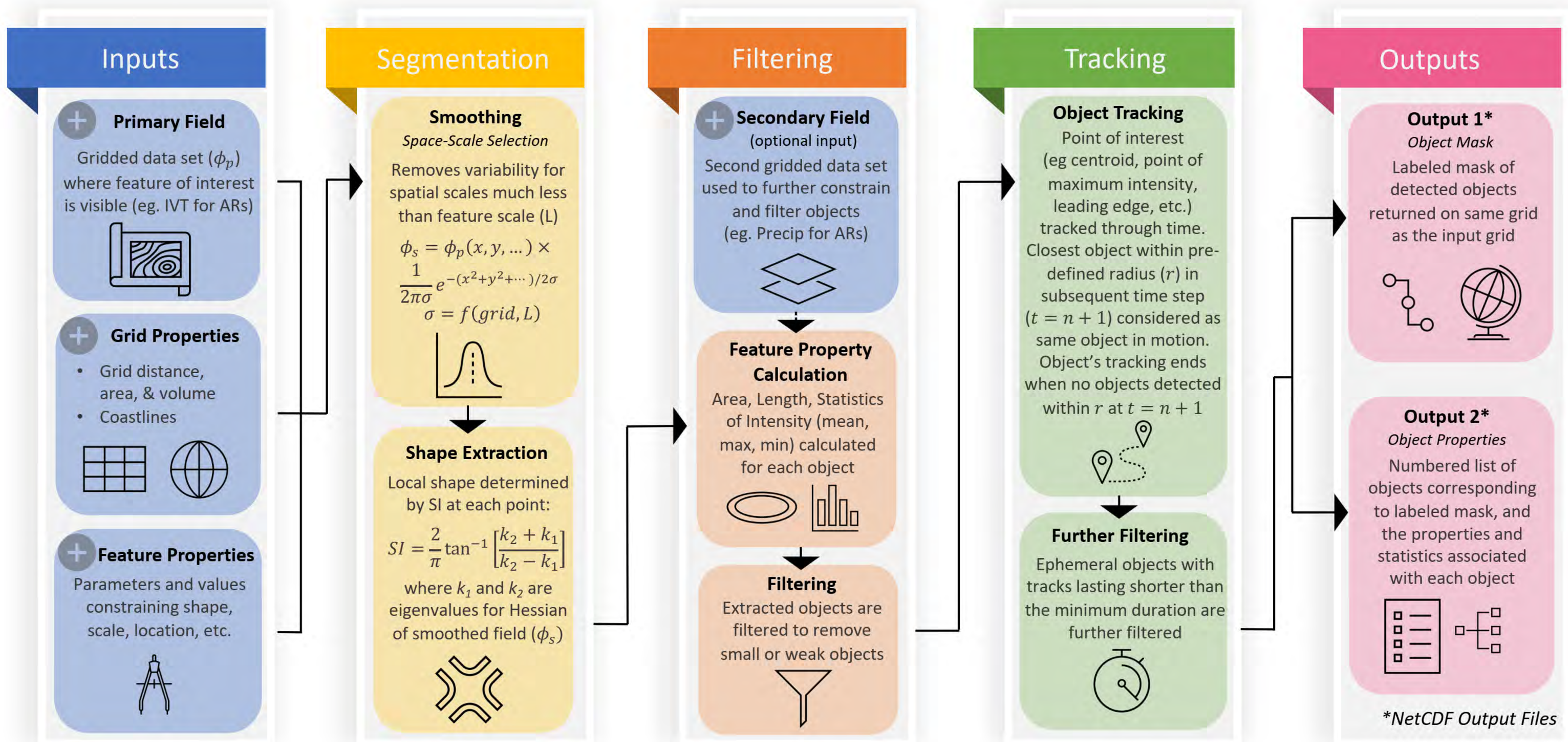
Data and Methods

- Daily mean of ERA5 data for the period of 1979 to 2024 is used.

Boreal Summer: May to September **Boreal Winter: November to March**

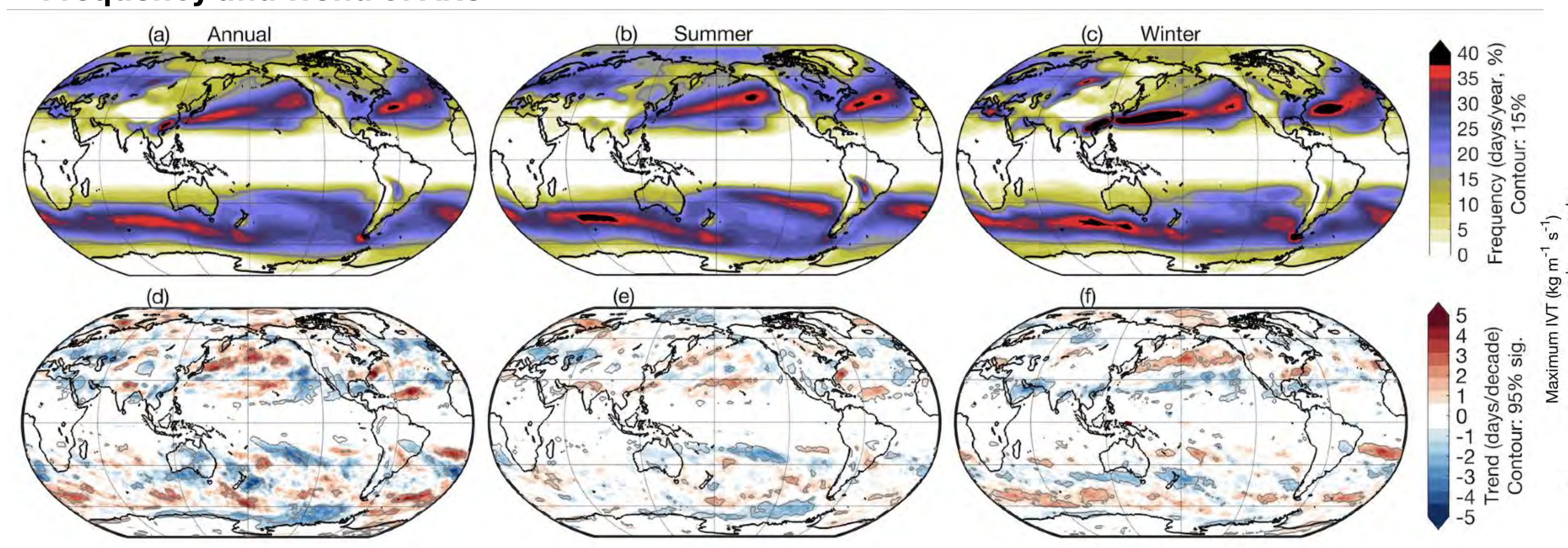
$$IVTx = -\frac{1}{g}\int_{1000\,hPa}^{300\,hPa} q\,u\,dp \qquad IVTy = -\frac{1}{g}\int_{1000\,hPa}^{300\,hPa} q\,v\,dp \qquad |IVT| = \sqrt{IVTx^2 + IVTy^2}.$$

Scalable Feature Extraction and Tracking (SCAFET)

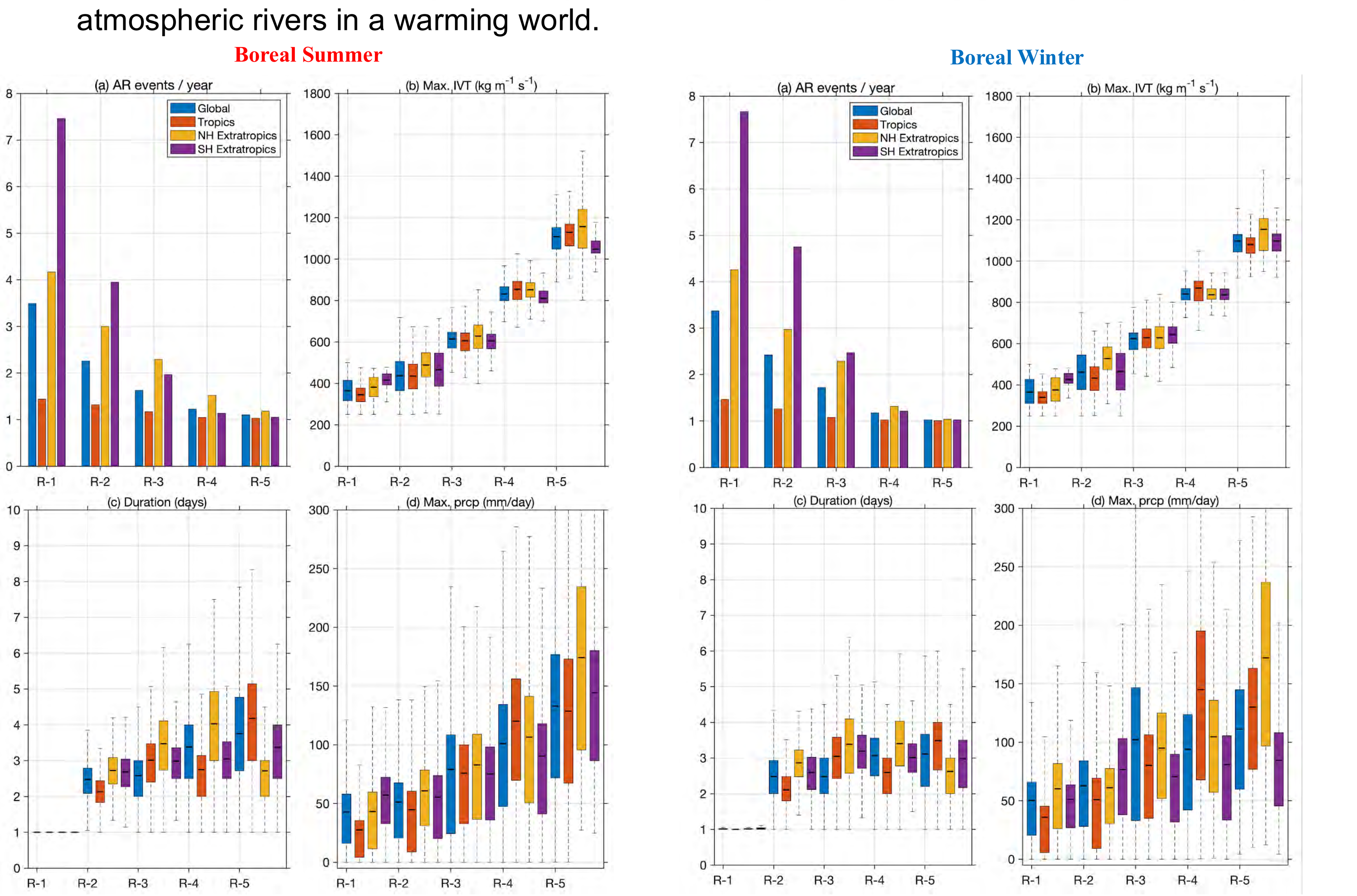


Results

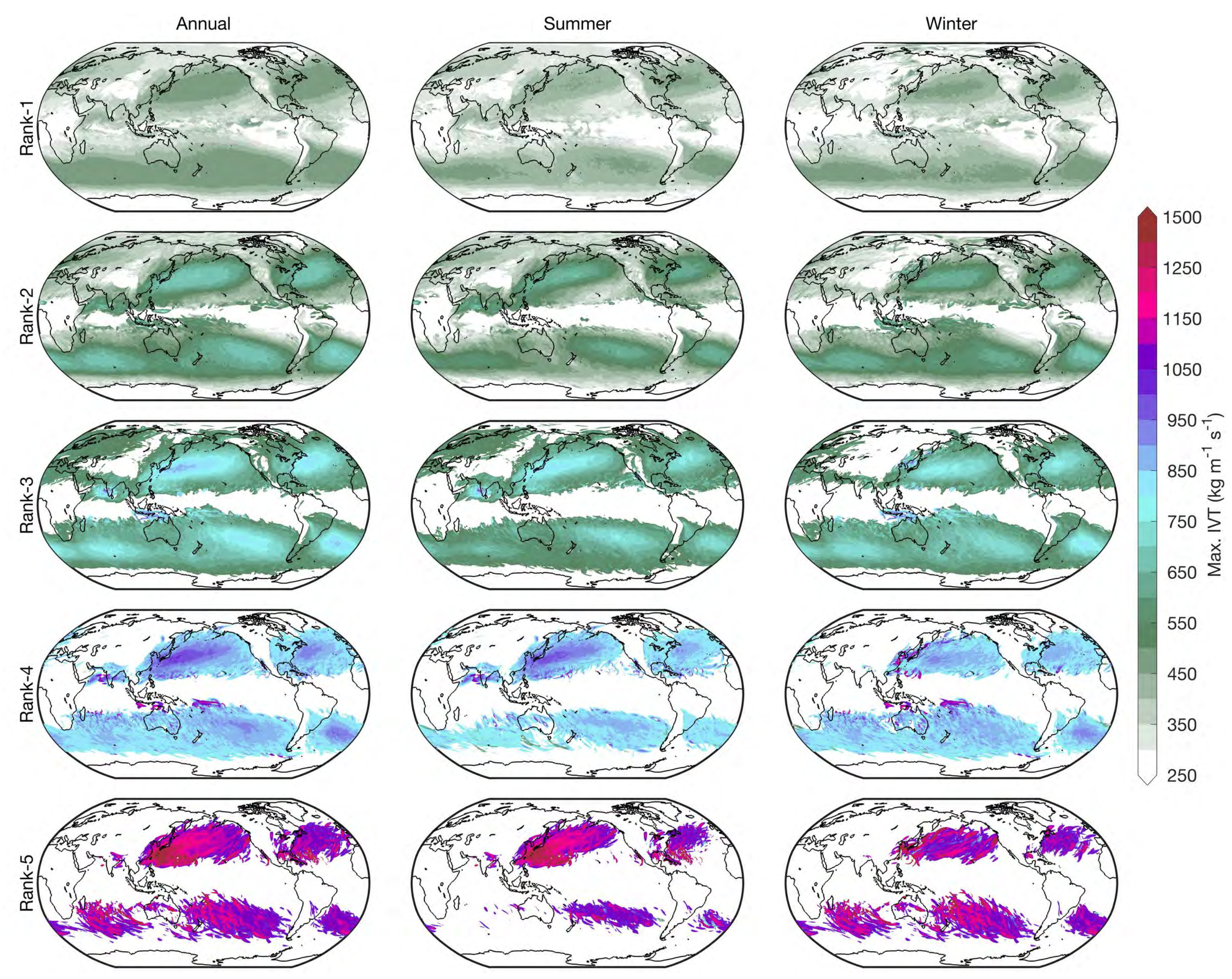
Frequency and Trend of ARs



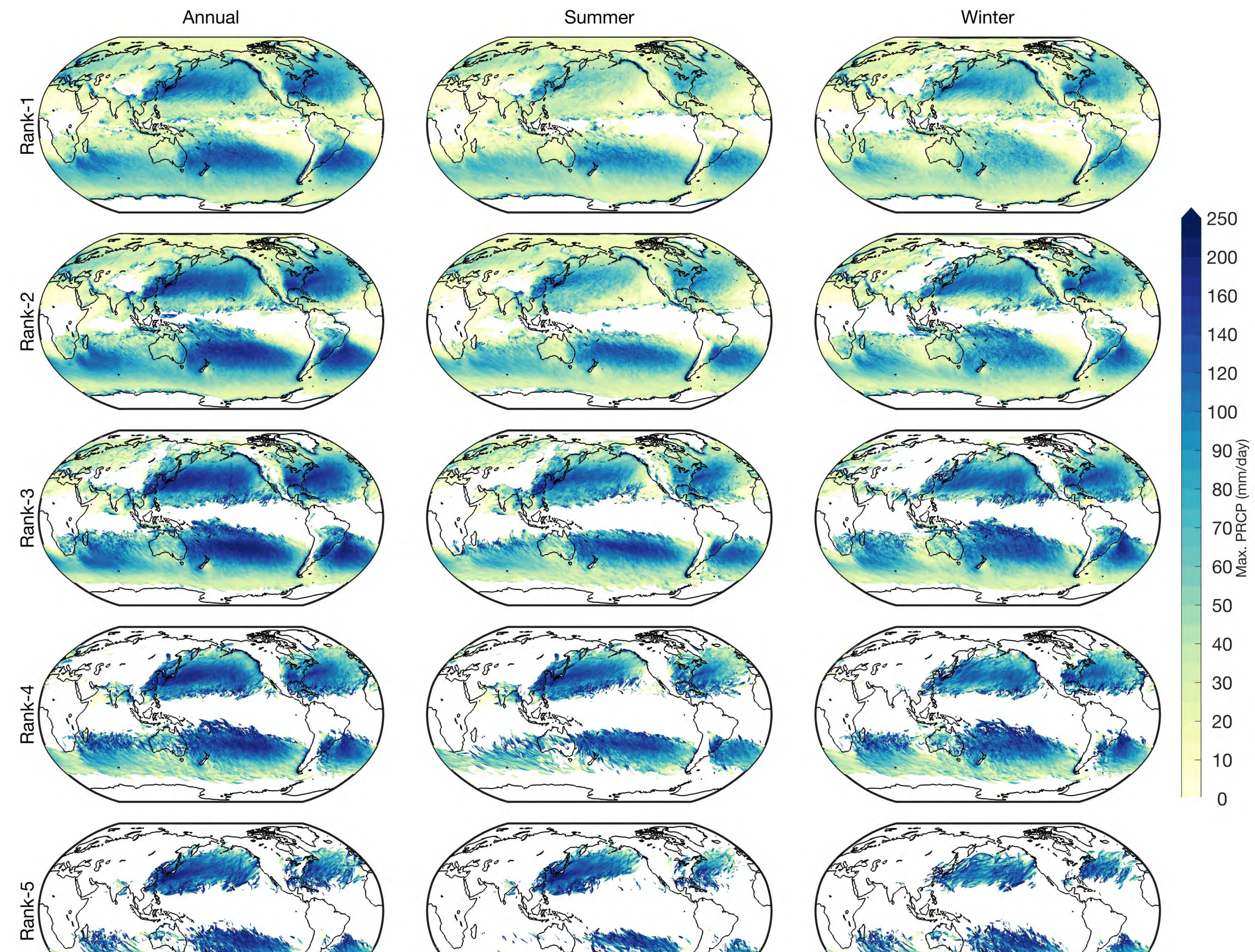
- The observed northward shift in summer AR activity over East Asia and the western Pacific aligns with monsoon circulation and subtropical jet changes, while winter exhibits peak AR frequencies along intensified storm tracks, emphasizing the strong influence of seasonal atmospheric dynamics on AR distribution.
- Over the past four decades, significant positive trends in AR frequency—particularly in the North Pacific, western U.S., and parts of East Asia—suggest enhanced moisture transport and storm track shifts likely driven by climate change, highlighting growing regional impacts of atmospheric rivers in a warming world.

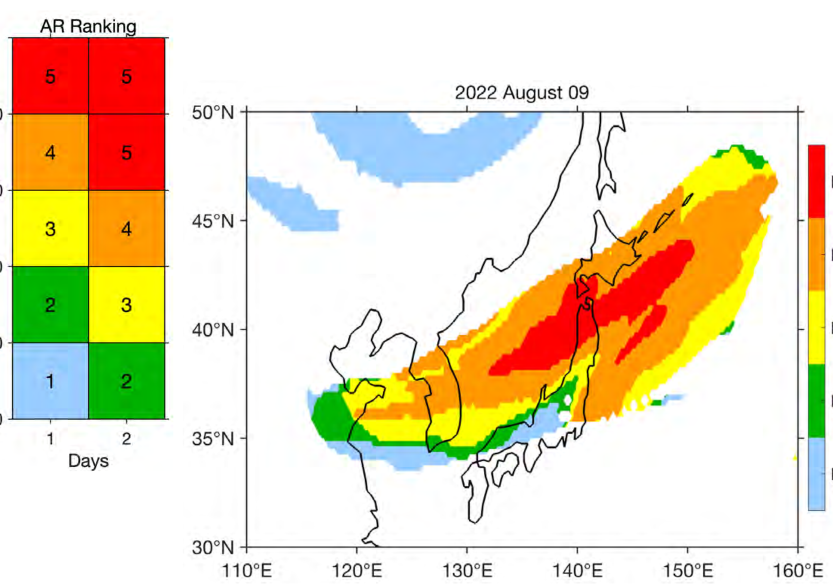


- The high-rank ARs occur less frequently in winter, they are substantially more intense, aligning with stronger baroclinic conditions and enhanced moisture transport in the cold season. The SH extratropics dominate AR frequency in summer, particularly for weak events (R-1 and R-2), whereas the NH extratropics and tropics lead in winter, especially for higher-ranked ARs (R-3 to R-5). This reflects a seasonal shift in dominant AR regions — summer ARs are more persistent but less intense and mostly SH-driven, while winter ARs are fewer but stronger, concentrated in NH midlatitudes and tropics.



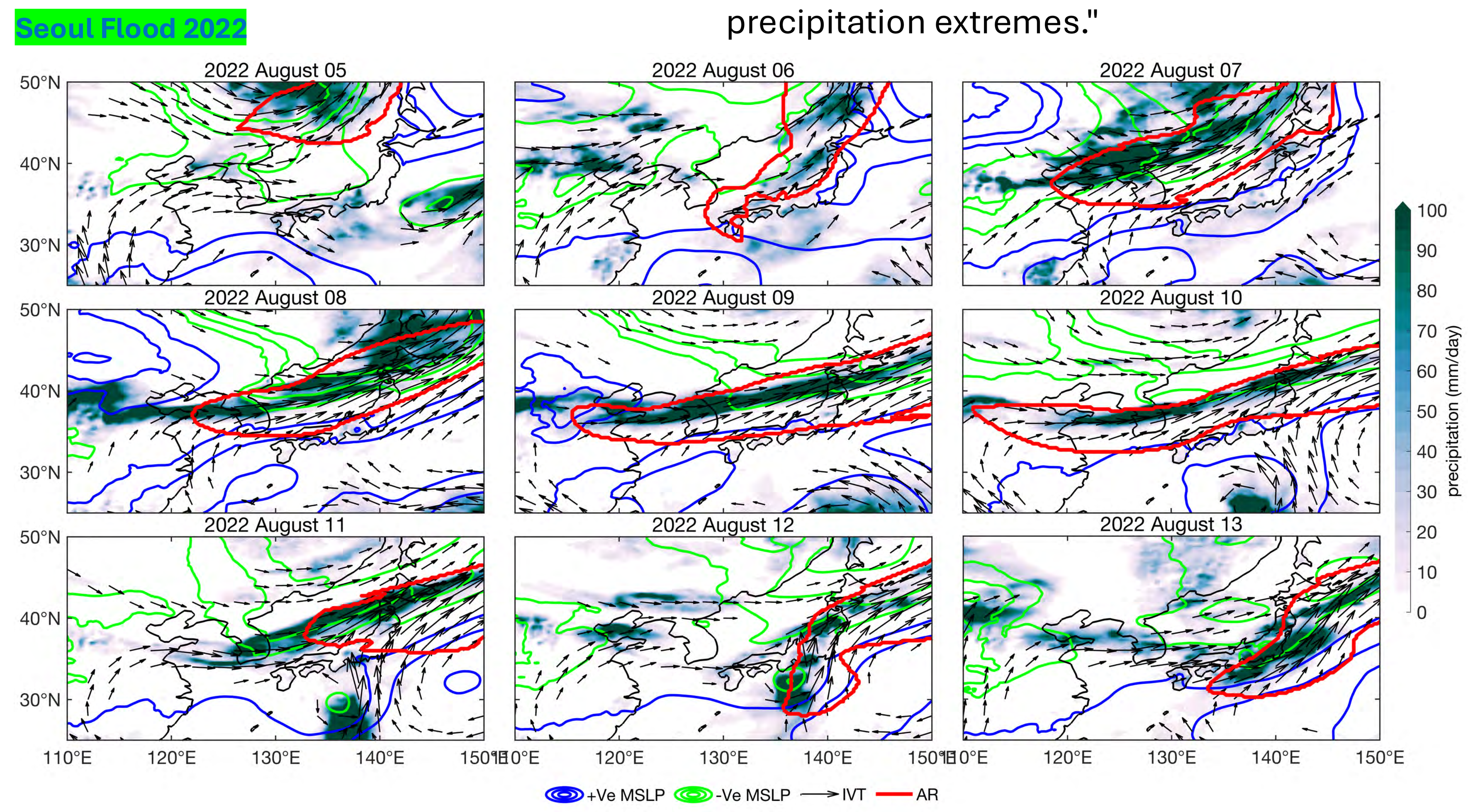
The seasonal variability in IVT magnitudes, with low-to-mid-ranked ARs (R1–R3) contributing to widespread, year-round moisture transport across midlatitude storm tracks, while higher-ranked ARs (R4–R5) are rarer, winter-dominant, and regionally concentrated over the North Pacific, North Atlantic Gulf Stream region, and western-central Pacific, reflecting the enhanced baroclinicity and jet dynamics that drive extreme IVT events in these key global hotspots.





The highest-ranked ARs (Ranks 4–5) yield sharply confined precipitation maxima exceeding 150 mm/day, particularly over climatologically active corridors such as the North Pacific, Gulf Stream region, and South Pacific Convergence Zone. This spatial confinement becomes most pronounced during boreal winter, driven by stronger synoptic forcing and enhanced moisture flux convergence, underscoring the dominant hydrological imprint of rare, high-intensity ARs on global precipitation extremes."

Seoul Flood 2022



Summary

Intensity and Duration Increase with Category: Higher-category ARs show stronger IVT and longer durations—up to ~4 days for Rank 5.

Rising Trends in AR Activity: Statistically significant increases in Category 1–3 ARs are observed globally, driven mainly by extratropical regions under warming.

Stronger Role in Extreme Rainfall: ARs increasingly contribute to seasonal extremes, especially in winter and midlatitude storm tracks like the North Pacific and South Atlantic.

Seoul Flood: The 2022 Seoul flood was primarily driven by a persistent, high-intensity AR event, peaking on August 8–9. Exceptional moisture transport via IVT, aligned with favorable synoptic pressure patterns, resulted in record-breaking precipitation over the region.

SCAFET: Nellikkattil, A.B., Lemmon, D., O'Brien, T.A., Lee, J.Y. and Chu, J.E., 2024. Scalable Feature Extraction and Tracking (SCAFET): a general framework for feature extraction from large climate data sets. *Geoscientific Model Development*, *17*(1), pp.301-320.
Categorization: Guan, B., Waliser, D.E. and Ralph, F.M., 2023. Global application of the atmospheric river scale. *Journal of Geophysical Research: Atmospheres*, *128*(3), p.e2022JD037180.

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