

SUMMARY

Atmospheric moisture-source diagnostics are widely used to investigate hydroclimatic variability, yet it remains unclear which source features are robust across tracking formulations and contrasting hydroclimatic conditions. Here, we compare seven Lagrangian formulations applied to common ERA5-driven FLEXPART trajectories and the Eulerian WAM2layers framework to characterise seasonal moisture sources for northeastern South America (NES) during 1983–2023. All formulations identify the tropical Atlantic, particularly the tropical South Atlantic east and southeast of NES, as the dominant external moisture source. Its geometry varies seasonally, from a broad Atlantic–continental configuration in DJF and a meridionally extended tropical Atlantic source in MAM to a compact South Atlantic corridor in JJA and a transitional configuration in SON. Source location is consistently more robust across formulations than source magnitude. Seasonal moisture uptake also covaries with NES precipitation, revealing a distinction between climatological source strength and hydroclimatic relevance: during DJF, the tropical North Atlantic (TNA), although comparatively weak in the climatological source field, becomes prominent in the precipitation–uptake relationship and in the contrasting dry and wet composites. SPI3-based composites show that source sectors weakened during severe dry conditions generally strengthen during severe wet conditions. This sign reversal occurs in all seasons and is reproduced by all eight formulations, although its amplitude and peripheral structure remain method dependent. These results show that the NES moisture-source system is organised around a robust South Atlantic core that persists across tracking formulations, while climatologically secondary regions such as the TNA can become more relevant under anomalous hydroclimatic conditions.

1. STUDY AREA

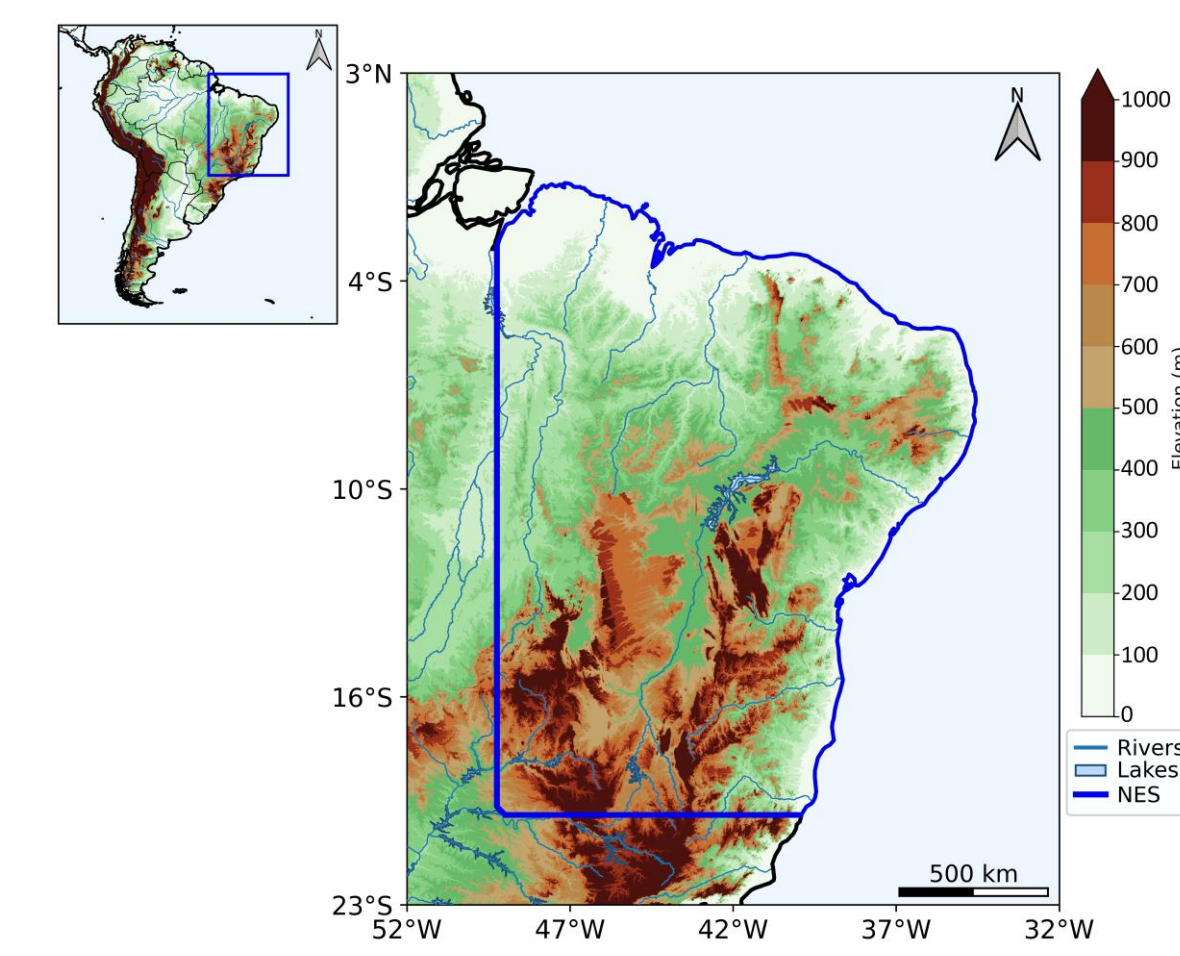


Figure 1. Northeast South America (NES)

2. METHODOLOGY

FLEXPART v10.4 model [1] + Meteorological reanalysis data from ERA5 Project [2]. Period 1981–2023.

For one parcel

Integrating all the parcels in the vertical column

By integrating over all parcels residing in the atmospheric column over a target area, we obtain ($E-P$). Integration for $K=10$ days [1].

($E-P$) > 0 in a backward experiment indicates moisture gain and regions acting as moisture sources, while ($E-P$) < 0 obtained in a forward experiment indicates a moisture contribution to precipitation.

$$e - p = m \frac{dq}{dt} \quad E - P \approx \sum_{k=1}^K \frac{(e - p)}{A}$$

$E \rightarrow$ evaporation
 $P \rightarrow$ precipitation
 $K \rightarrow$ No parcels

Table 1. Criteria used by the seven Lagrangian moisture-tracking formulations to identify moisture changes along trajectories, together with the corresponding Eulerian WAM2layers representation.

Method	Precipitation parcels at target region		Moisture uptake		Losses in route		ABL restriction	Reference
	Δq^*	RH^*	Δq_{net}	ΔRH	Δq_{loss}	RH		
SJ05	-	-	-	-	-	-	No	Stöhl and James, 2004, 2005
SJ05_F	< -0.1	> 0	-	-	-	-	No	Sorí et al., 2019
SOD08	< -0.2	> 80	> 0.2	-	< -0.2	-	Yes	Sodenmann et al., 2008
FAS19	< -0.1	> 80	> 0.1	-	< -0.1	-	No	Fremme and Sodenmann, 2019
JK22	< 0	> 80	> 0	< 20	< 0	-	Yes	Keune et al., 2022
APA22	< -0.1	> 0	> 0	-	< 0	-	No	Pérez-Alarcón et al., 2022
APA25	< 0	> 65	> 0	< 20	< 0	> 65	No	Pérez-Alarcón et al., 2025
WAM2layers	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Two layers (lower/upper troposphere)	Kalverla et al., 2025

3. RESULTS AND DISCUSSION

The results show that across all four seasons, the eight formulations consistently identify the tropical Atlantic, and particularly the tropical South Atlantic, as the dominant external moisture source for NES (Figure 2 for DJF and JJA). The principal uptake region remains broadly located east and southeast of NES, while its intensity and spatial extent vary through the seasonal cycle. The VIMF fields represented in these figures also provide a dynamically consistent representation of the prevailing easterly and southeasterly transport towards northeastern South America, although they are interpreted here as transport pathways rather than as a direct source diagnostic. This persistent Atlantic contribution agrees with previous Lagrangian and water-budget studies identifying the tropical South Atlantic as the main external moisture supply to Northeast Brazil. The patterns of moisture uptake for MAM and SON show intermediate seasonal configurations, while preserving the same dominant Atlantic source across all formulations.

To identify the moisture-source regions that are most consistently represented across formulations, inter-method agreement was evaluated at formulation- and season-specific percentile thresholds of climatological moisture uptake (p10–p90; Figure 3 for DJF (a) and JJA (b)).

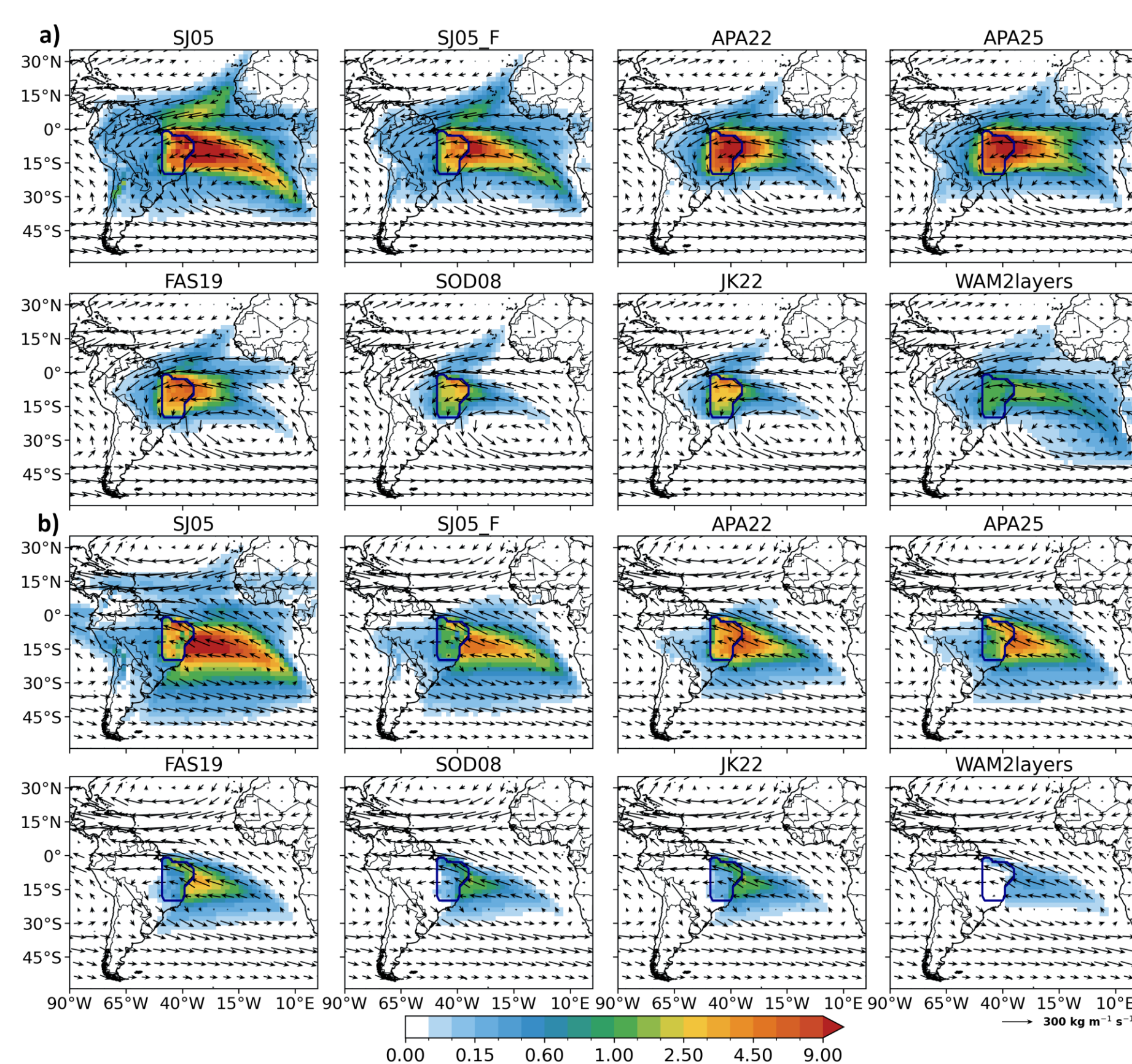


Figure 2. (a) DJF and (b) JJA moisture sources and Moisture flux across the moisture-tracking formulations

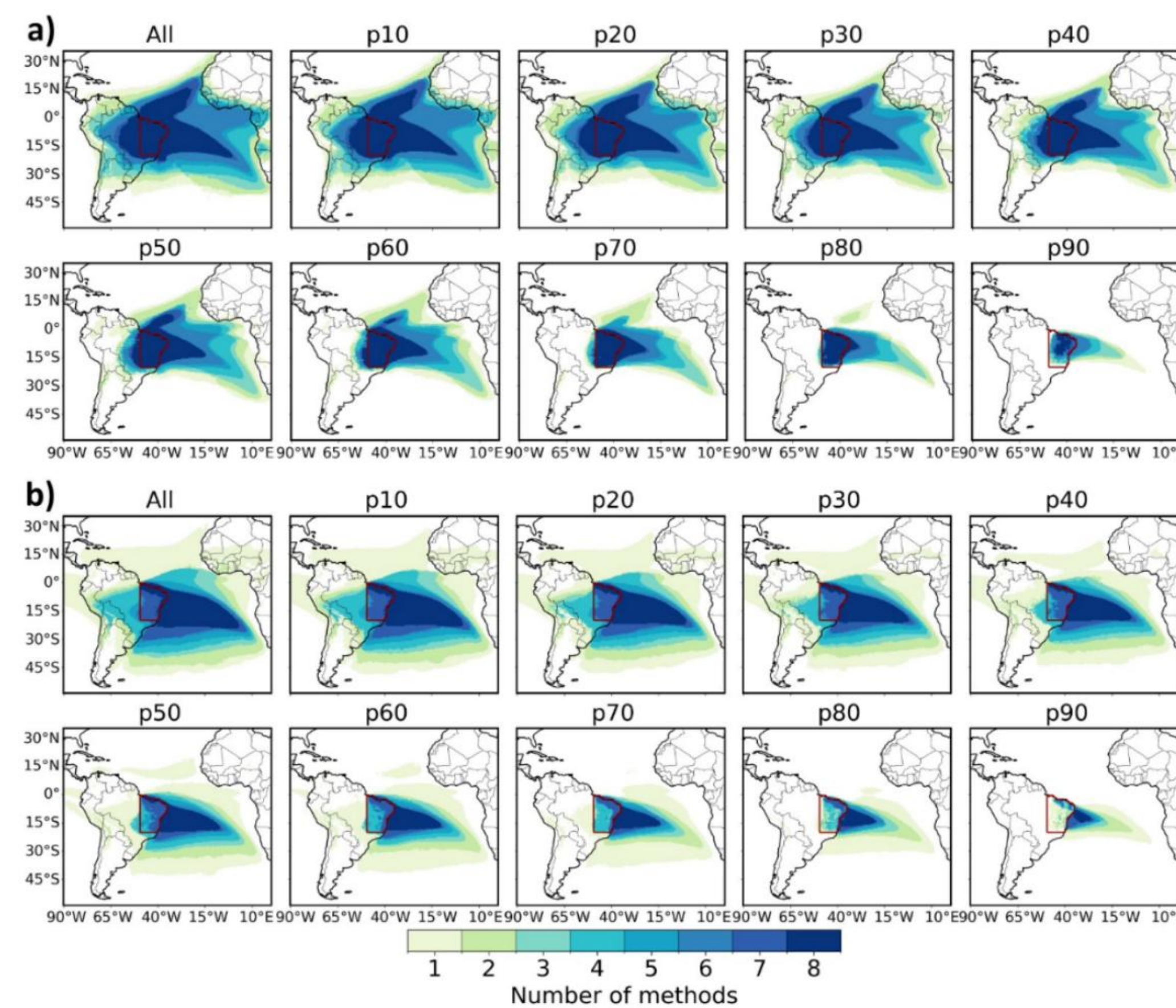


Figure 3. Spatial agreement among the eight methods for (a) DJF and (b) JJA

We examined seasonal Spearman correlations between NES precipitation and grid-point moisture uptake within each formulation-specific 99% climatological source footprint (Figure 4). During DJF, significant positive correlations extend across much of the tropical Atlantic, including the northern tropical Atlantic, although their spatial extent varies among formulations. This indicates that wetter seasons tend to coincide with enhanced moisture uptake across a broader Atlantic domain than the climatological high-intensity source core.

The extensive correlations over the northern tropical Atlantic are particularly relevant because they suggest that regions contributing relatively less moisture in the climatology may nevertheless covary substantially with interannual rainfall variability.

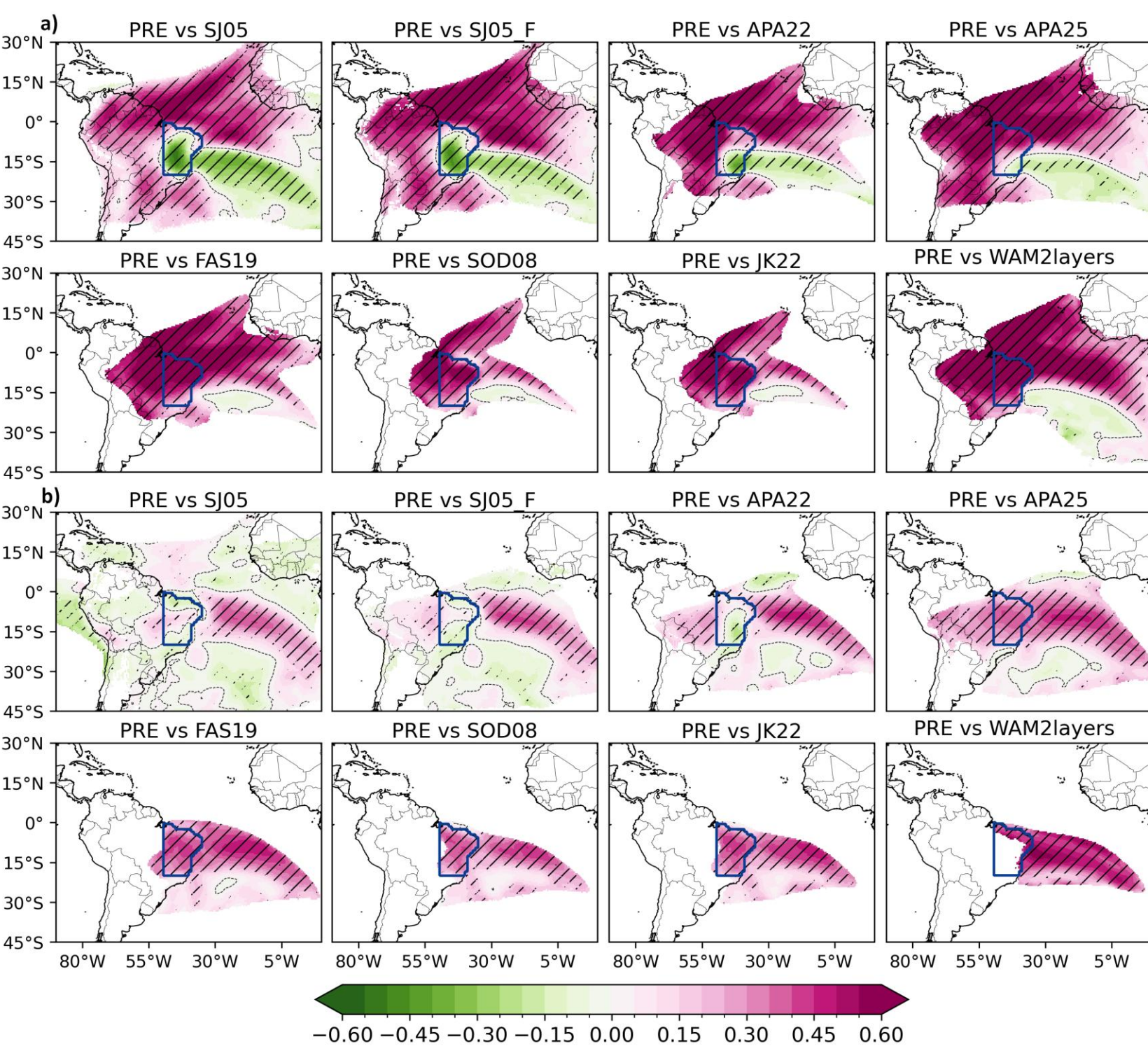


Figure 4. Spatial Spearman correlations between standardised seasonal precipitation anomalies over the NES target region and grid-point moisture-uptake anomalies for DJF (a) and JJA (b) across the eight Lagrangian–Eulerian formulations.

4. CONCLUSIONS

The tropical South Atlantic is the dominant and most persistent external moisture source for NES, while the source footprint varies seasonally from a broader Atlantic–continental configuration in DJF to a more confined South Atlantic pathway in JJA. During anomalous conditions, secondary regions such as the tropical North Atlantic and continental sectors over Amazonia also become relevant, showing consistent dry–wet responses across formulations. All eight methods diagnose reduced integrated source contributions during severe-dry conditions and enhanced contributions during severe-wet conditions, indicating that the direction of the hydroclimatic response is highly robust across tracking approaches. Overall, methodological robustness is strongest for the geographical organisation of the main source regions and the sign of their dry–wet modulation, whereas the magnitude and peripheral spatial structure remain more formulation dependent.

Table 2. Seasonal dry and wet conditions based on February, May, August, and November SPI3 values. Grey shading denotes severe-to-extreme dry and wet events identified using SPI-3 thresholds of ≤ -1.28 and $\geq +1.28$, respectively.

Season	Dry events (SPI-3 ≤ -1.28)	Wet events (SPI-3 $\geq +1.28$)
DJF	1987, 2013, 2015	1985, 1986, 1990, 1992, 2004
MAM	1990, 1992, 1993, 1998, 2012, 2016	1985, 1995, 1997, 2006, 2009
JJA	1983, 1997, 2007, 2016	1985, 1986, 1989, 1990, 2000, 2009
SON	2002, 2004, 2007, 2015, 2019, 2023	1992, 1996, 1999

While the correlation analysis characterises the continuous interannual relationship between moisture uptake and NES precipitation, it does not reveal how the source system behaves during the strongest departures from normal hydroclimatic conditions. To address this, seasonal dry and wet conditions were identified using seasonal SPI3 values over 1983–2023 (Table 2).

During dry DJF conditions in NES, the largest agreement in negative anomalies of moisture uptake by the methods occurs over a broad tropical Atlantic sector, particularly located to the north and northeast of NES (Figure 9). The agreement is also observed over a pronounced continental region extending across Amazonia and around the southwest margin of NES. A similar spatial structure appears with the opposite sign during wet DJF conditions, when most formulations diagnose enhanced source contributions over these same oceanic and terrestrial sectors.

The spatial organisation differs markedly in JJA. Under dry conditions, the highest agreement is concentrated along the tropical South Atlantic east and southeast of NES, while agreement over the tropical North Atlantic and the continental interior is much weaker, in consensus with anomalies shown in Figure 8. Wet conditions show a closely corresponding pattern of positive agreement, again centred on the South Atlantic source sector.

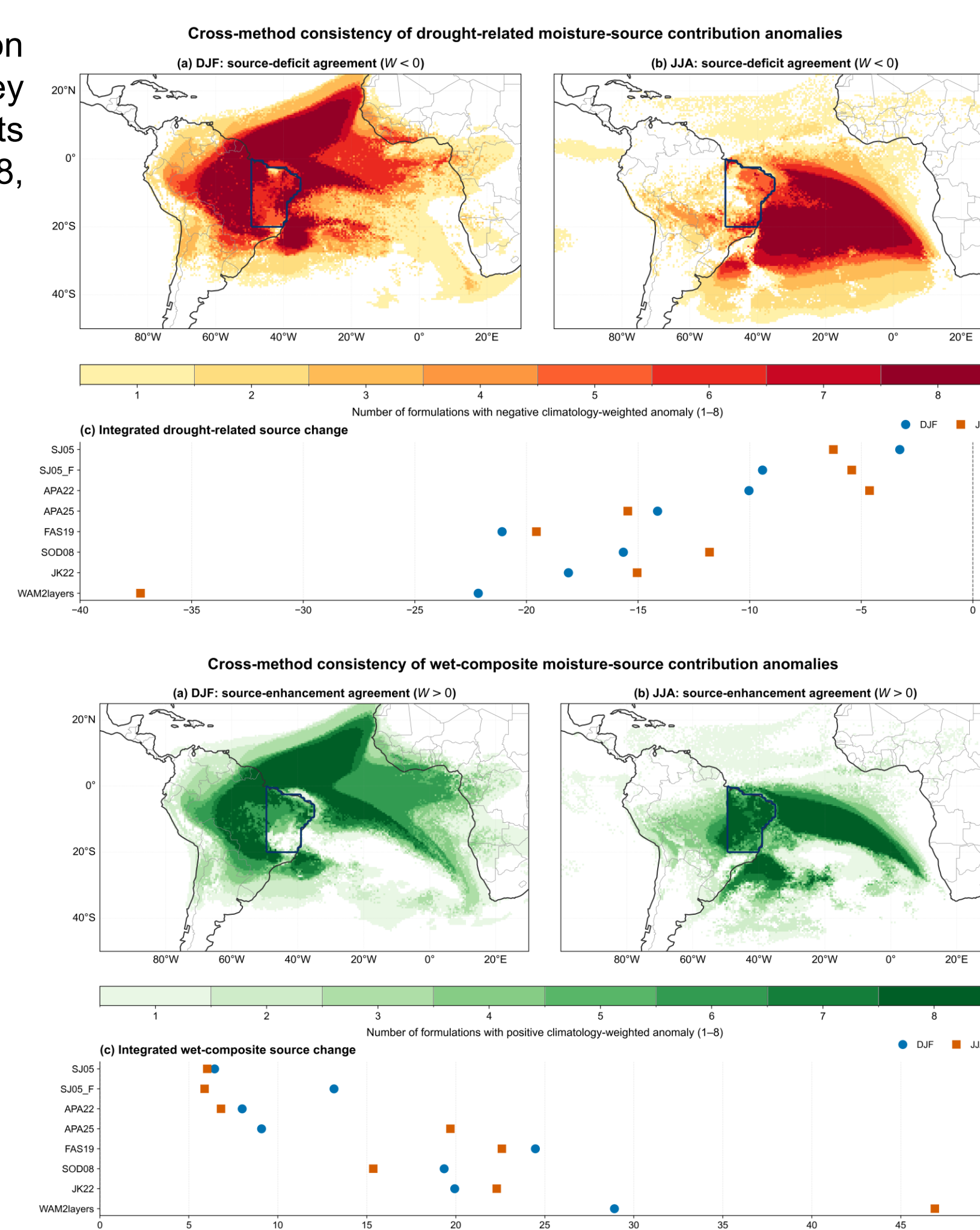


Figure 9. Cross-method consistency of drought (top) wet (bottom) related moisture-source contribution anomalies during DJF and JJA.

REFERENCES

- [1] Pissot et al. (2019). The Lagrangian particle dispersion model FLEXPART version 10.4 Geosci. Model Dev. 12 4955–97 <https://doi.org/10.5194/gmd-12-4955-2019>.
[2] Hersbach et al. (2023). ERA5 monthly averaged data on pressure levels from 1940 to present Copernicus Climate Change Service Climate Data Store <https://doi.org/10.24381/cds.6860a573>.

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