Water Cycle Linkages Between the Intra-American Seas and Continental Areas

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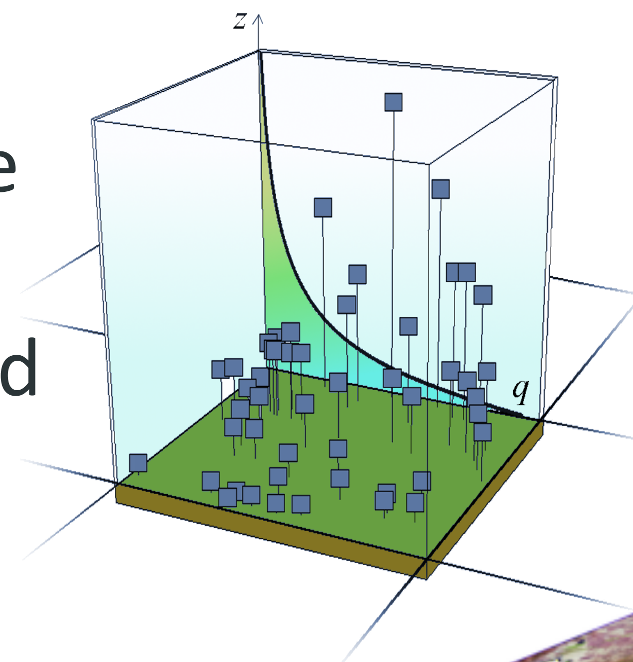
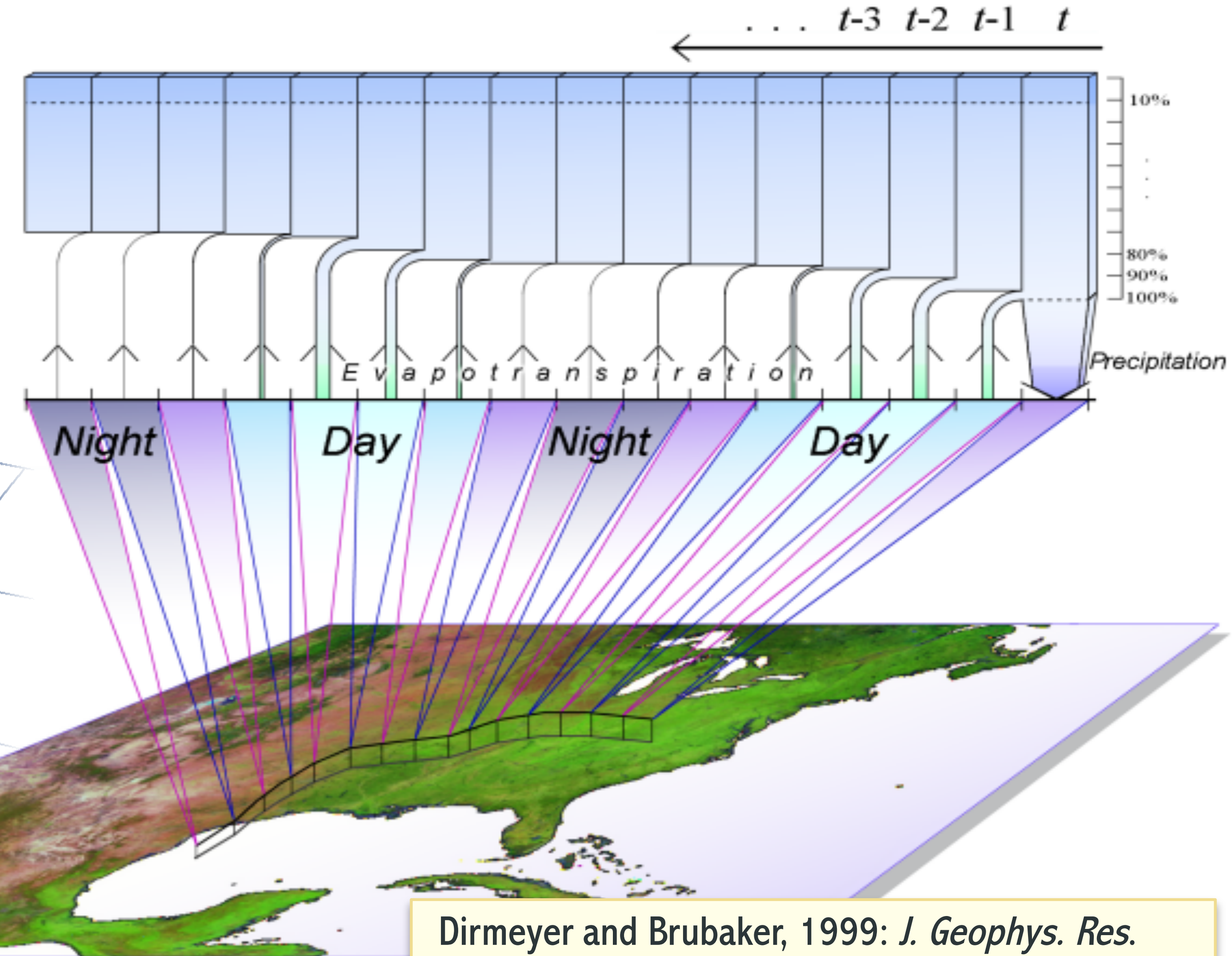
Quasi-Isentropic Back Trajectories

- The idea for the technique is borrowed from air pollution meteorology (e.g., Merrill et al. 1986 *Mon. Wea. Rev.*).
- Water vapor is treated as a passive tracer between the time of evaporation from the surface and the time of condensation/ precipitation.
- The key to the technique is treatment of the endpoints.
  - Traces begin at precipitation events, go backwards in time.
  - Each trace generates a PDF of evaporative sources; these are aggregated over many traces for each grid point, pentad.
  - Further aggregation can be performed in space or time to estimate sources for regions, months, seasons, etc.

QIBT Methodology

- Lagrangian "parcels" are used to estimate moisture transport *a posteriori*.
- Many parcels are launched at random humidity-weighted altitudes at times of precipitation.
- 6-hourly 3-D atmospheric data are used to trace parcels backward in time (45-minute time steps).
- Evaporative contribution during each time step is proportional to ET/PW.



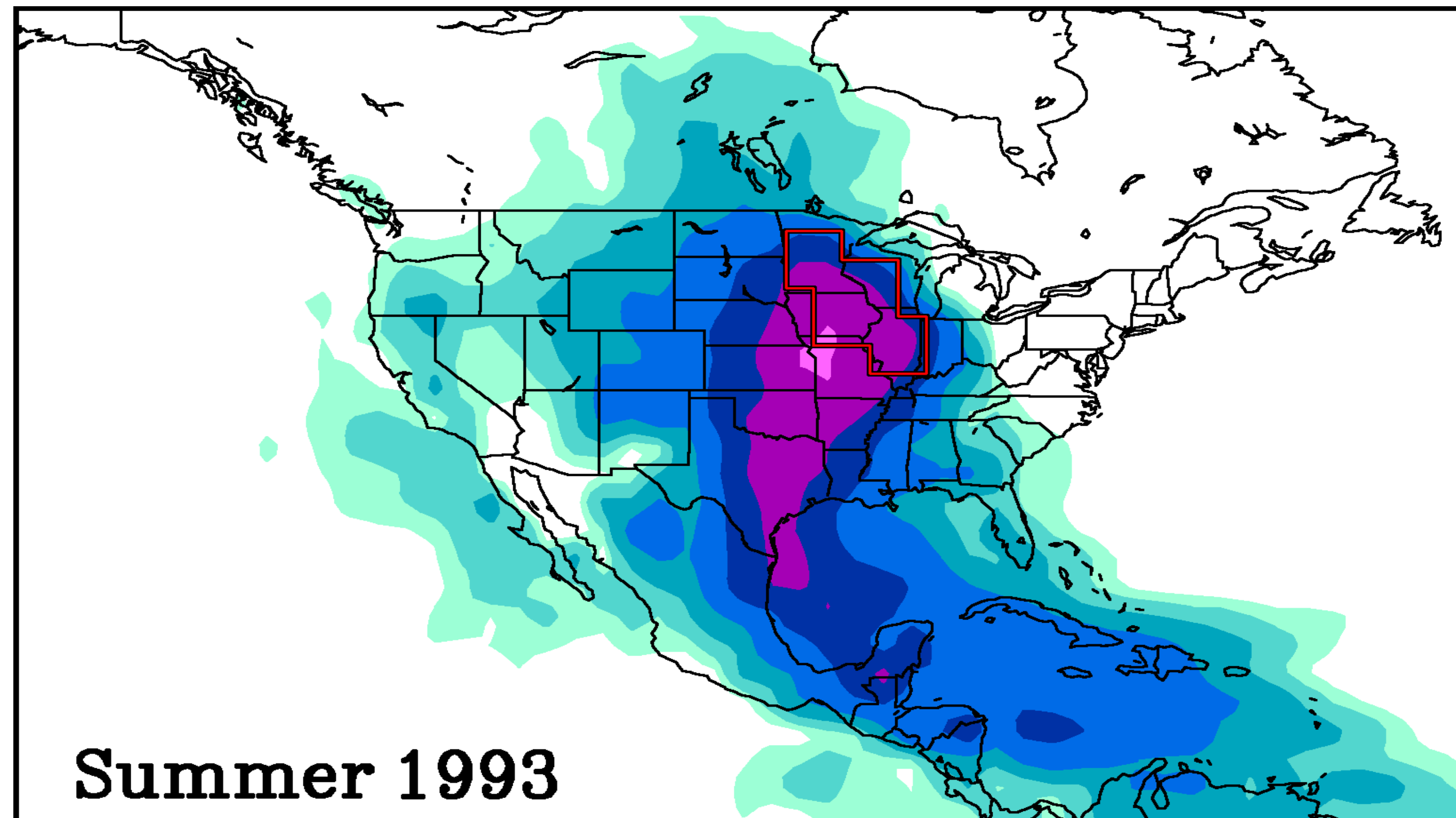


Period: 1979-2005

Dirmeyer and Brubaker, 1999: *J. Geophys. Res.*
Brubaker et al., 2001: *J. Hydrometeor.*
Sudradjat et al., 2003: *J. Geophys. Res.*
Dirmeyer and Brubaker, 2006: *Geophys. Res. Lett.*
Dirmeyer and Brubaker, 2007: *J. Hydrometeor.*
Dirmeyer and Kinter, 2009: *EOS Trans. AGU.*
Dirmeyer and Kinter, 2010: *J. Hydrometeor.*
Dirmeyer et al., 2011: *J. Hydrometeor.*
Wei et al., 2012: *J. Geophys. Res.*
Bagley et al. 2012: *Env. Res. Lett.*
Wei et al., 2013: *J. Hydrometeor.*
Dirmeyer et al., 2014: *J. Hydrometeor.*

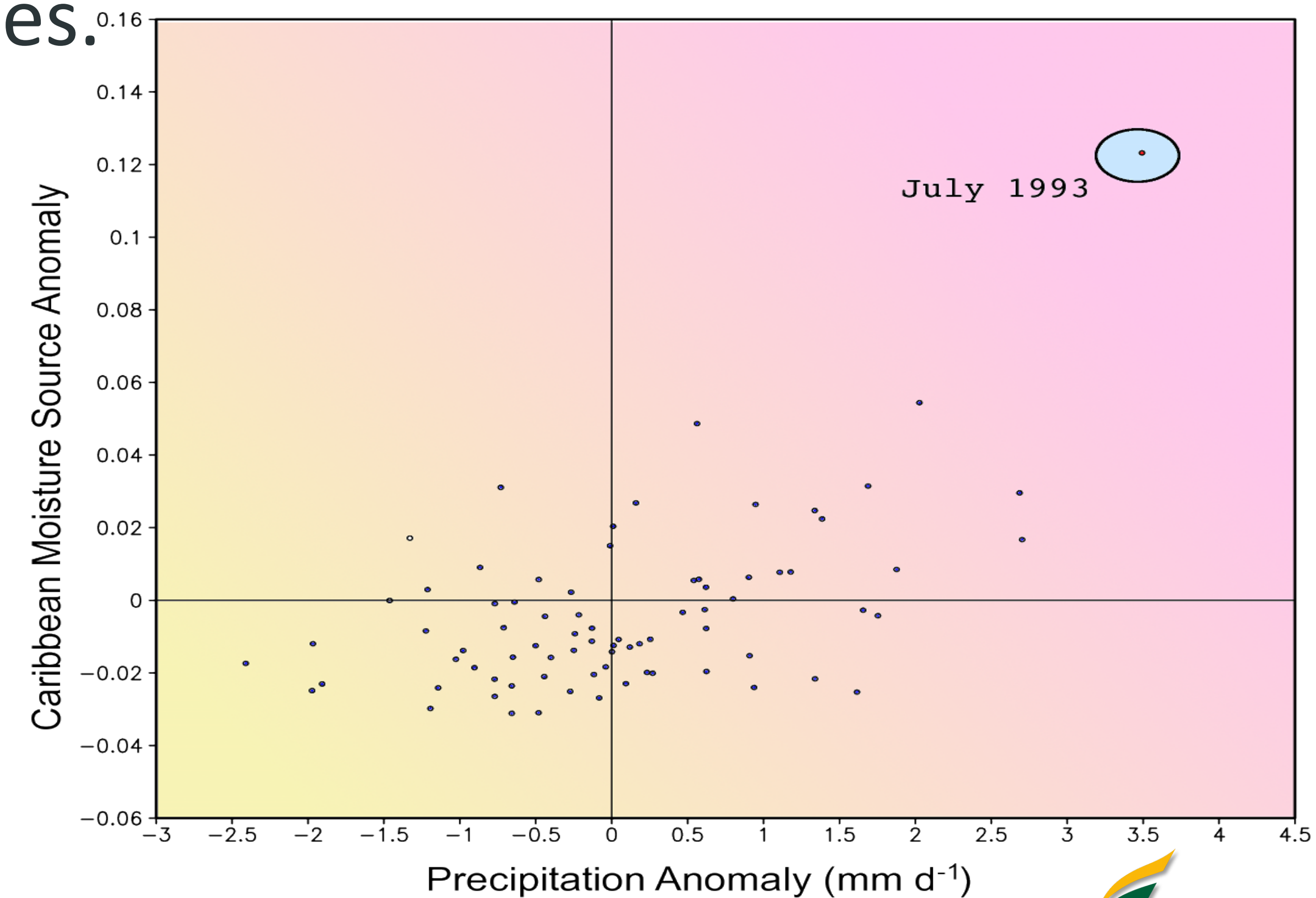
Early Work

- A link between moisture from the Caribbean Sea and the flooding over the Great Plains during 1993 was established in early work (Dirmeyer and Brubaker, JGR, 1999).
- Over the years, this work has been updated (originally using NCAP/NCAR reanalysis data, later NCEP/DOE and most recently MERRA, each anchored by observed precipitation analyses).
- Extended to global coverage, new applications relating to water cycle, circulation anomalies, etc.



The Flood of 1993

- A scatter plot of the Caribbean moisture source anomaly (expressed as a percentage of total moisture) against Midwestern rainfall anomalies for MJJ 1979-2004 shows that July 1993 was an exceptional case. Severe flooding occurred during late June and July over much of the central United States.



- Dirmeyer and Brubaker (1999) showed that it was associated with a strong source of moisture advected from the Caribbean Sea region.

- <u>What about the floods of 2008?</u>

Maya Express

- Severe flooding in 2008 over approximately the same region as in 1993 prompted an investigation into whether similar conditions existed (Dirmeyer and Kinter, EOS, 2009).

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PAGES 101–108

The "Maya Express": Floods in the U.S. Midwest

PAGES 101–102

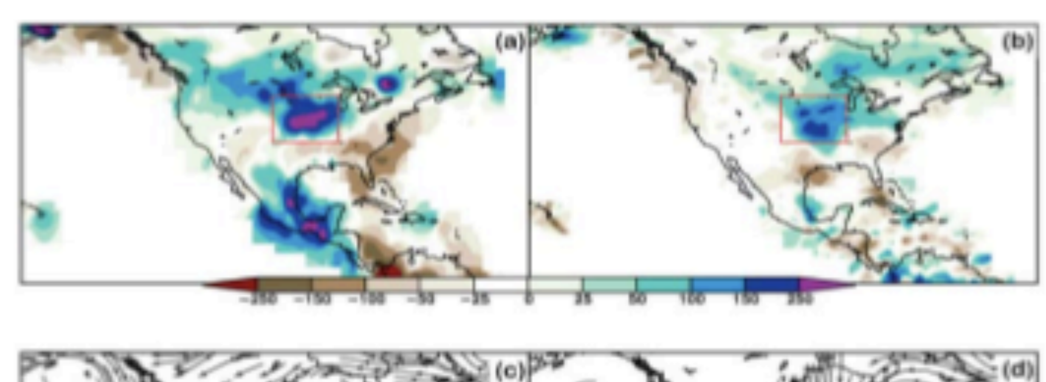
The 2008 floods in the U.S. Midwest culminated in severe river flooding, with many rivers in the region cresting at record levels during May and particularly June. Twenty-four people were killed and more than 140 were injured as a result of the floods. Nine states were affected: Illinois, Indiana, Iowa, Kansas, Minnesota, Missouri, Nebraska, South Dakota, and Wisconsin. In Iowa, 83 of the state's 99 counties were declared disaster areas. Cedar Rapids, Iowa, was among the cities hardest hit by flooding. At one point, water covered 1300 city blocks across 24 square kilometers, inundating 3900 homes and most of the city's infrastructure and municipal facilities. The flood, which also damaged the Midwest's corn and soybean crops, was presaged by unusually heavy snowpack the preceding winter and by anomalously heavy rainfall during the spring.

It is natural to compare the events of

Back-trajectory calculations that attribute the moisture that falls as rain to specific locations where evaporation supplied that moisture have shown that a tropical source of moisture fed the 1993 floods [*Dirmeyer and Brubaker*, 1999]. Specifically, advected moisture (from an upstream area, or "fetch") was identified as coming from the western Gulf of Mexico and the western Caribbean Sea, well outside the usual sources of moisture for rainfall over the region. Did the floods of 2008 share these characteristics? Are there attributes that are common to the most severe Midwest floods?

Floods in 1993 Compared to 2008

Figures 1a and 1b show precipitation anomalies for June and July 1993 and for May and June 2008, respectively, using data from the Global Precipitation Climatology Project of the World Climate Research Programme. Both flood events were characterized by wet conditions in the months prior to



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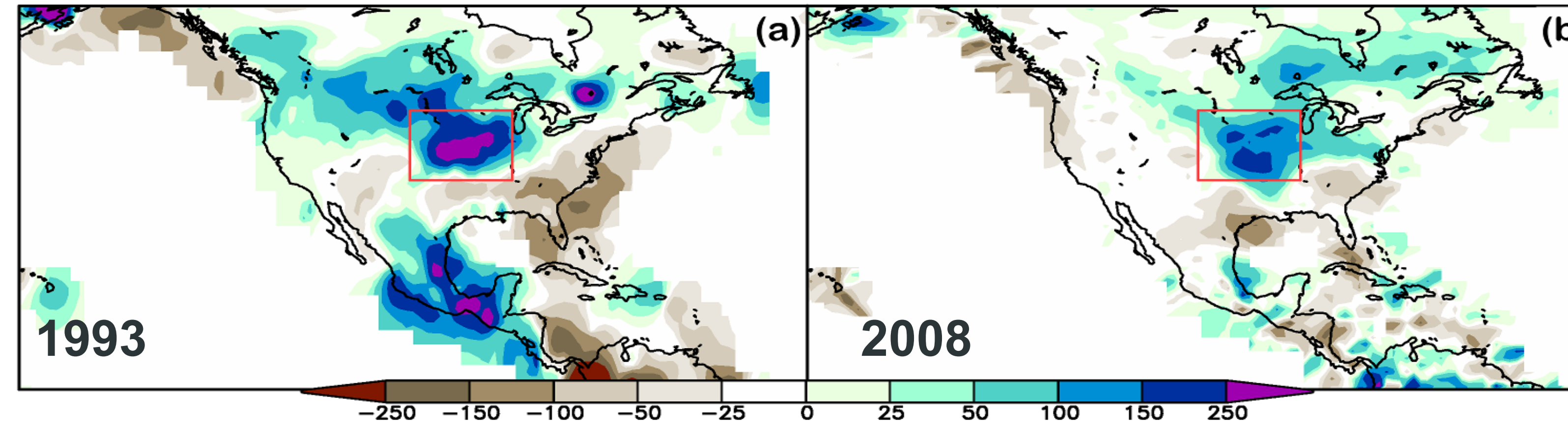
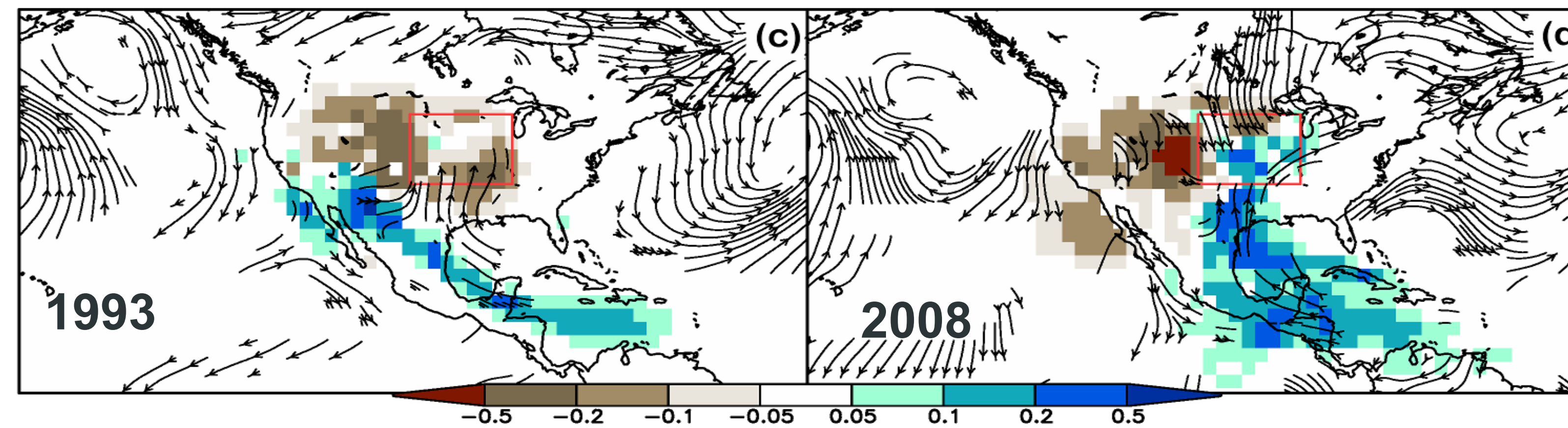
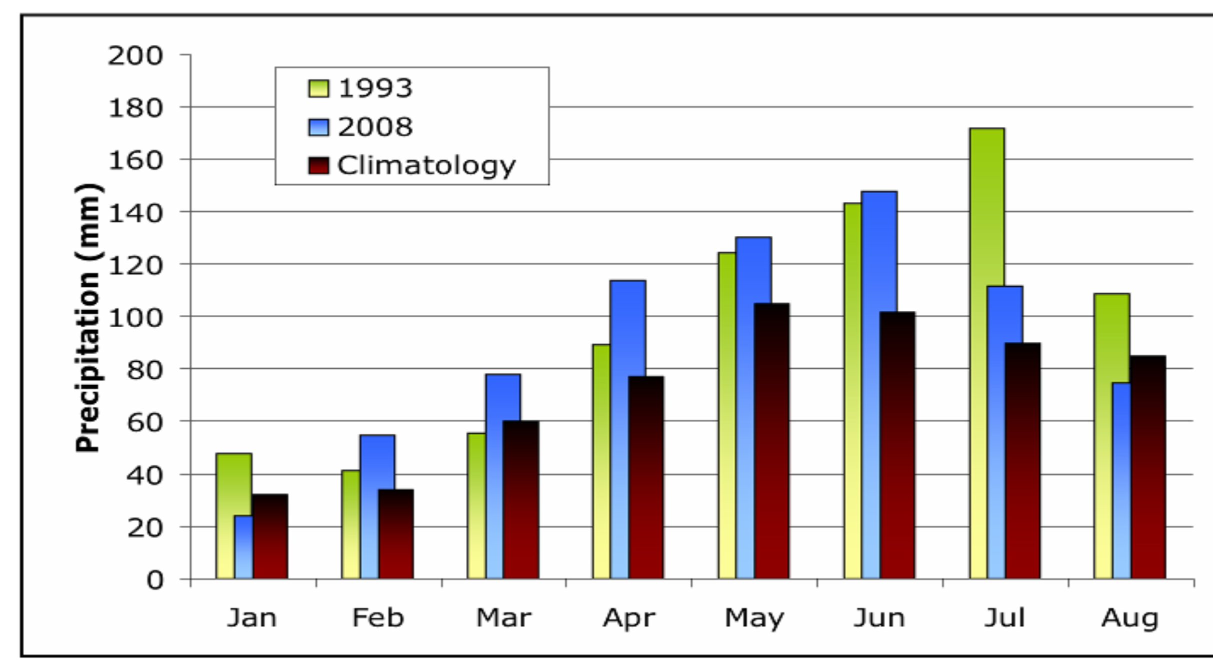
IAS Sources

- Rainfall anomalies (mm) for JJ1993 and MJ2008 (top) for two recent Midwest flood years.
- The moisture source <u>anomalies</u> (middle) show reduced source from the west, and enhanced sources from the south ("Maya Express"), from the western GoM and Caribbean Sea.
- Both 1993 and 2008 were characterized by above average rainfall during the preceding months (bottom) and anomalously high soil moisture consistent with a local positive feedback from the land surface.

Streamlines show wind anomalies in the lowest 30 hPa that exceeded 1 ms^{-1}.



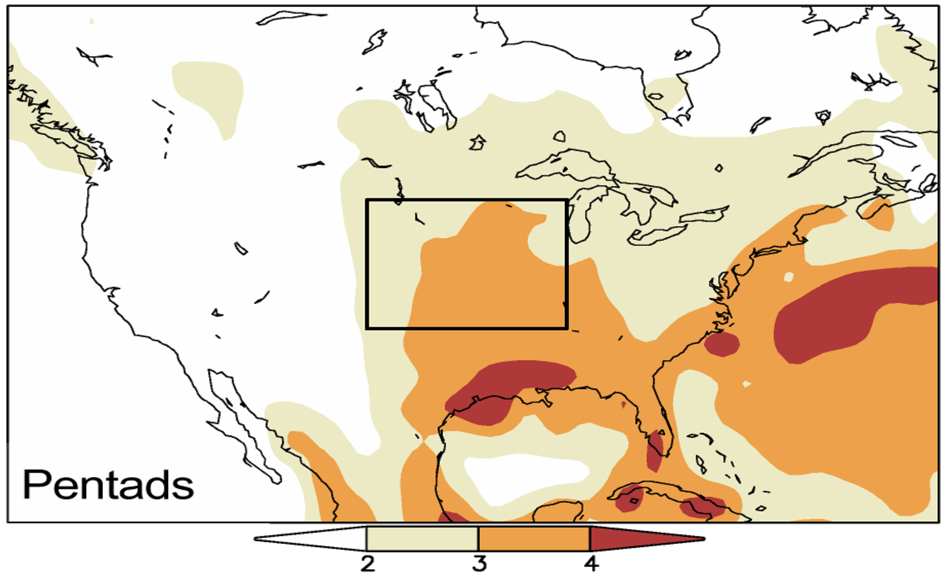


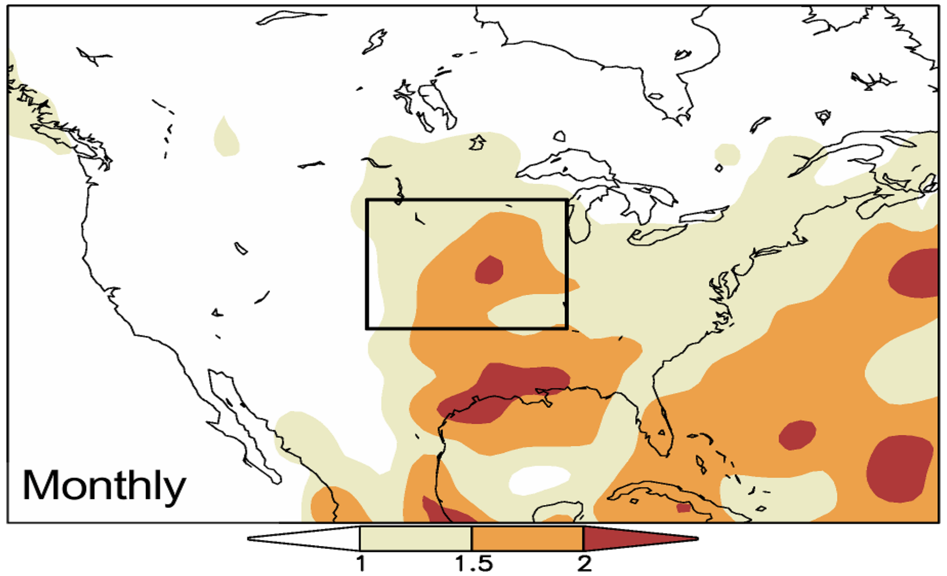


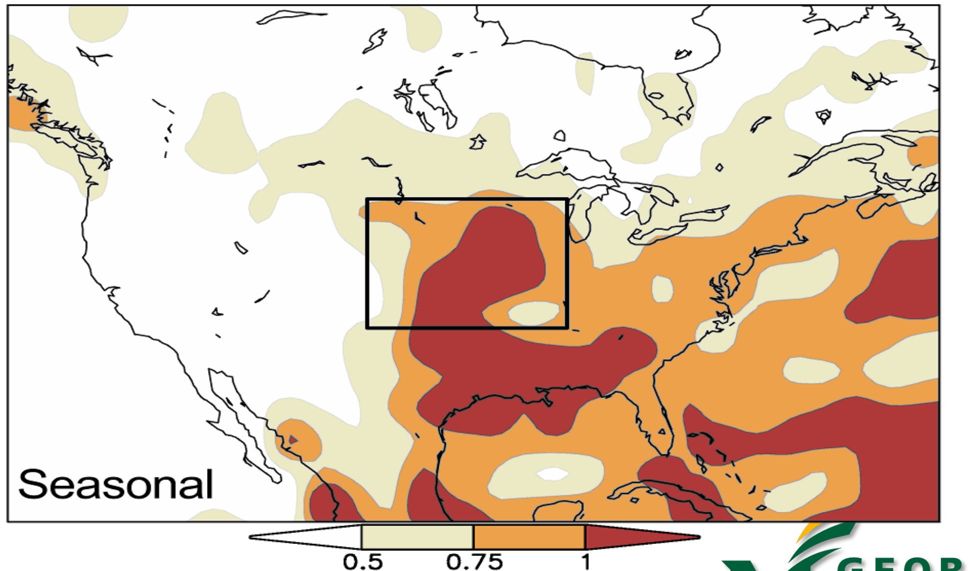
Dirmeyer & Kinter, 2009: *Eos*, 101-102.
Dirmeyer & Kinter, 2010: *JHM*, 1172-1181.

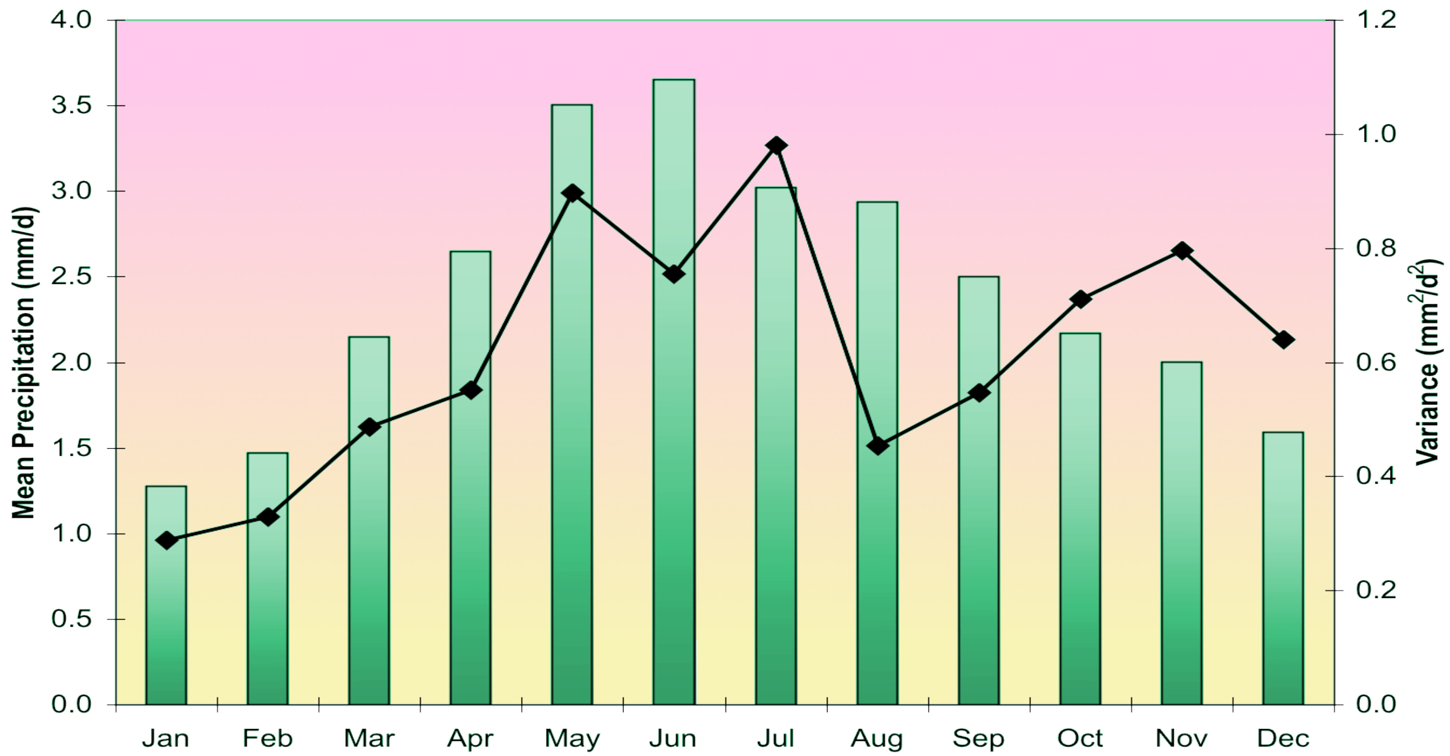
Water Cycle "Hot Spot"

- Variability in rainfall is locally high over the Mississippi Valley at all time scales (right)
- Precipitation (bars) and variability peak in late spring and early Summer (below)





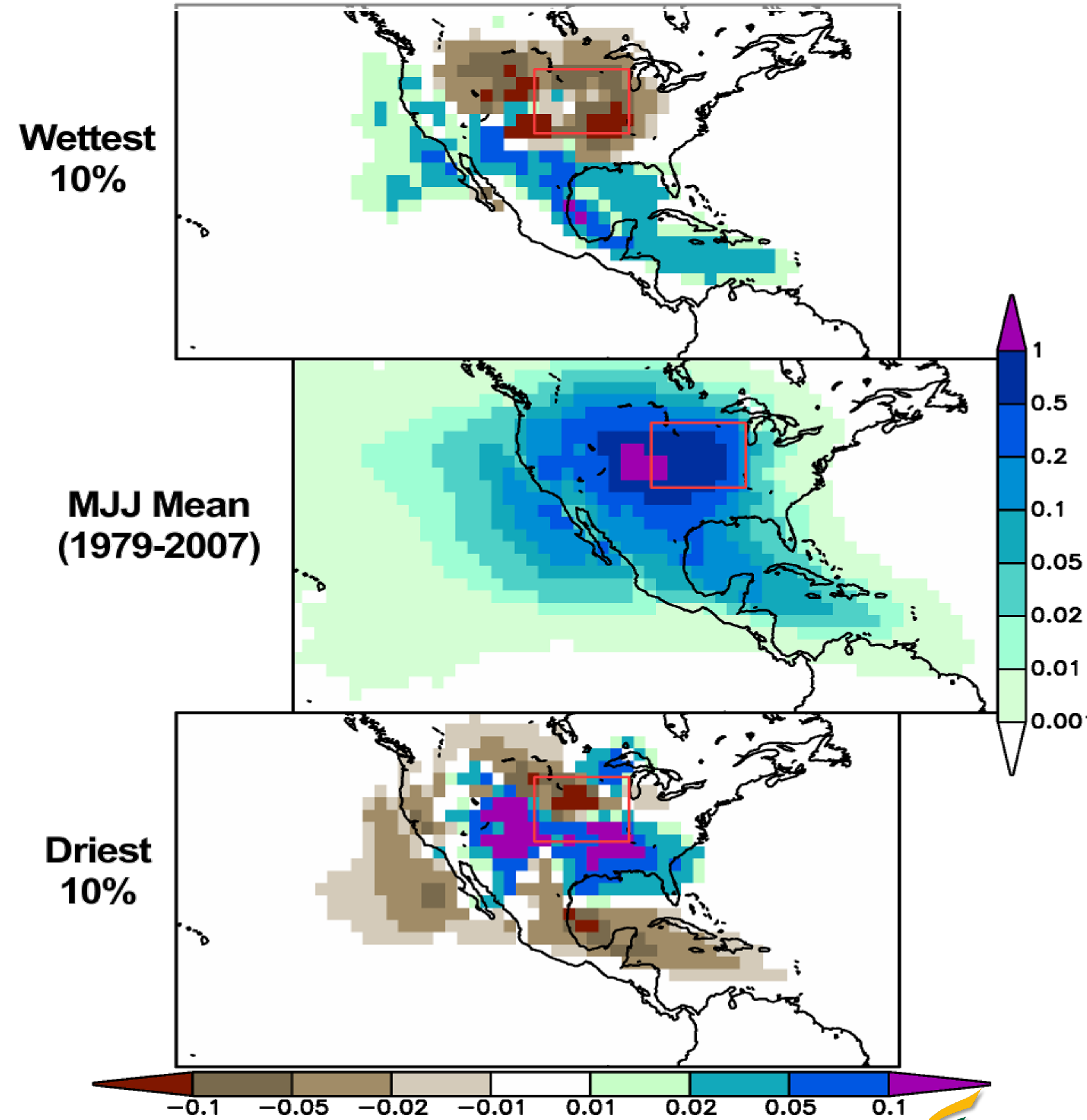




Moisture Sources

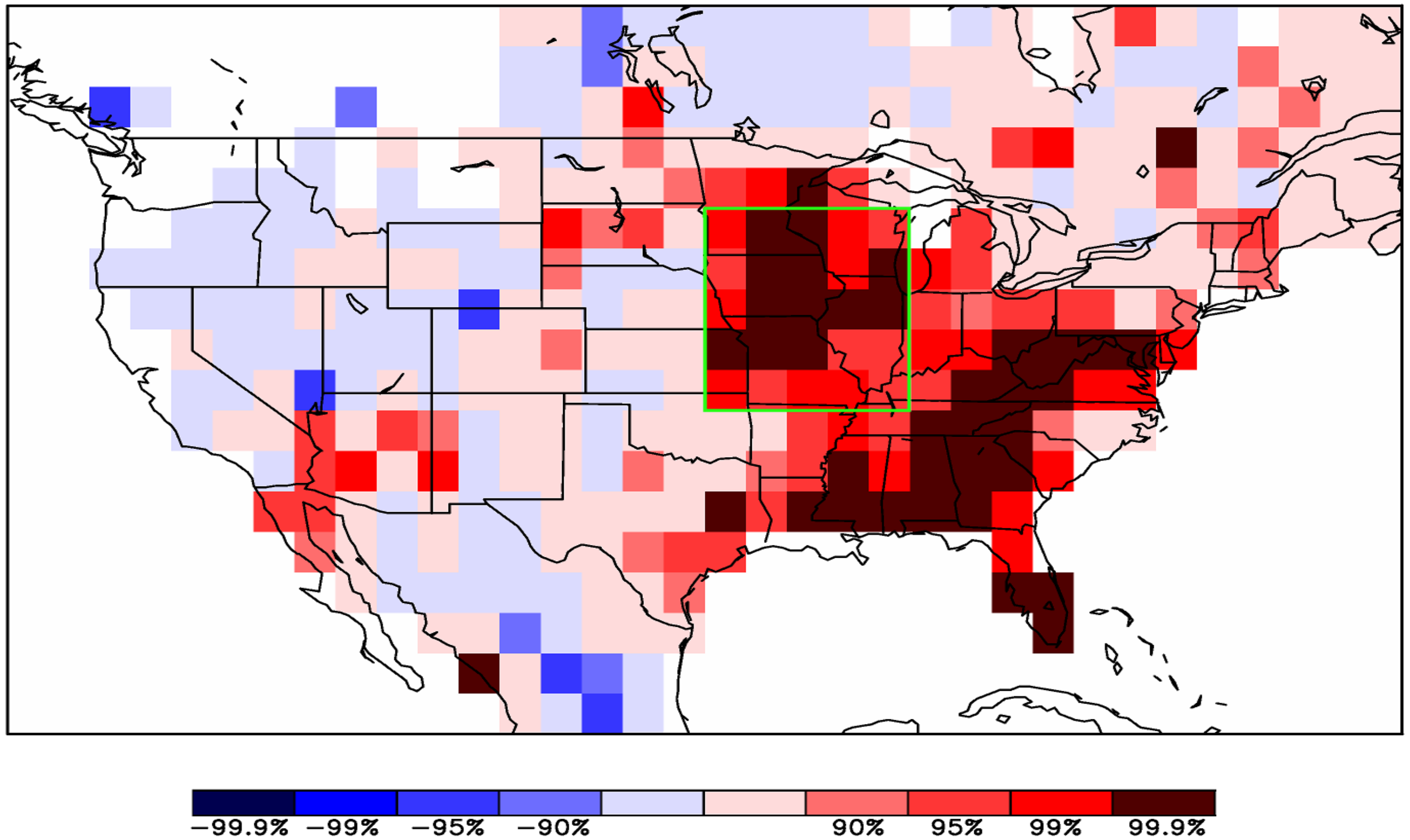
- The MJJ climatology of evaporative moisture source supplying the rainfall over the red box (NCEP/DOE-based; center) shows oceanic sources of moisture from both the Atlantic (Gulf of Mexico and Caribbean) and Pacific and terrestrial sources.
- Anomalies composited for the wettest and driest 10% of months show that the fraction of evaporative source from within the region (i.e., the recycling ratio), is below average in both extremes.
- Floods show a strong source from regions to the south, especially the western Gulf of Mexico.
- Droughts show above-average fractions of moisture coming from evapotranspiration over land.

Units are the percentage of total water mass falling over the box – the global integral equals 100% by definition.



Caribbean Source

- The correlation between MJJ precipitation anomalies within the Midwest box and the Caribbean source of moisture (region defined in under-laid map) shows that much of the Eastern U.S. east of 97°W has a strong link between tropical moisture and rainfall. This appears to be associated with either an enhanced or displaced subtropical ridge over the North Atlantic.



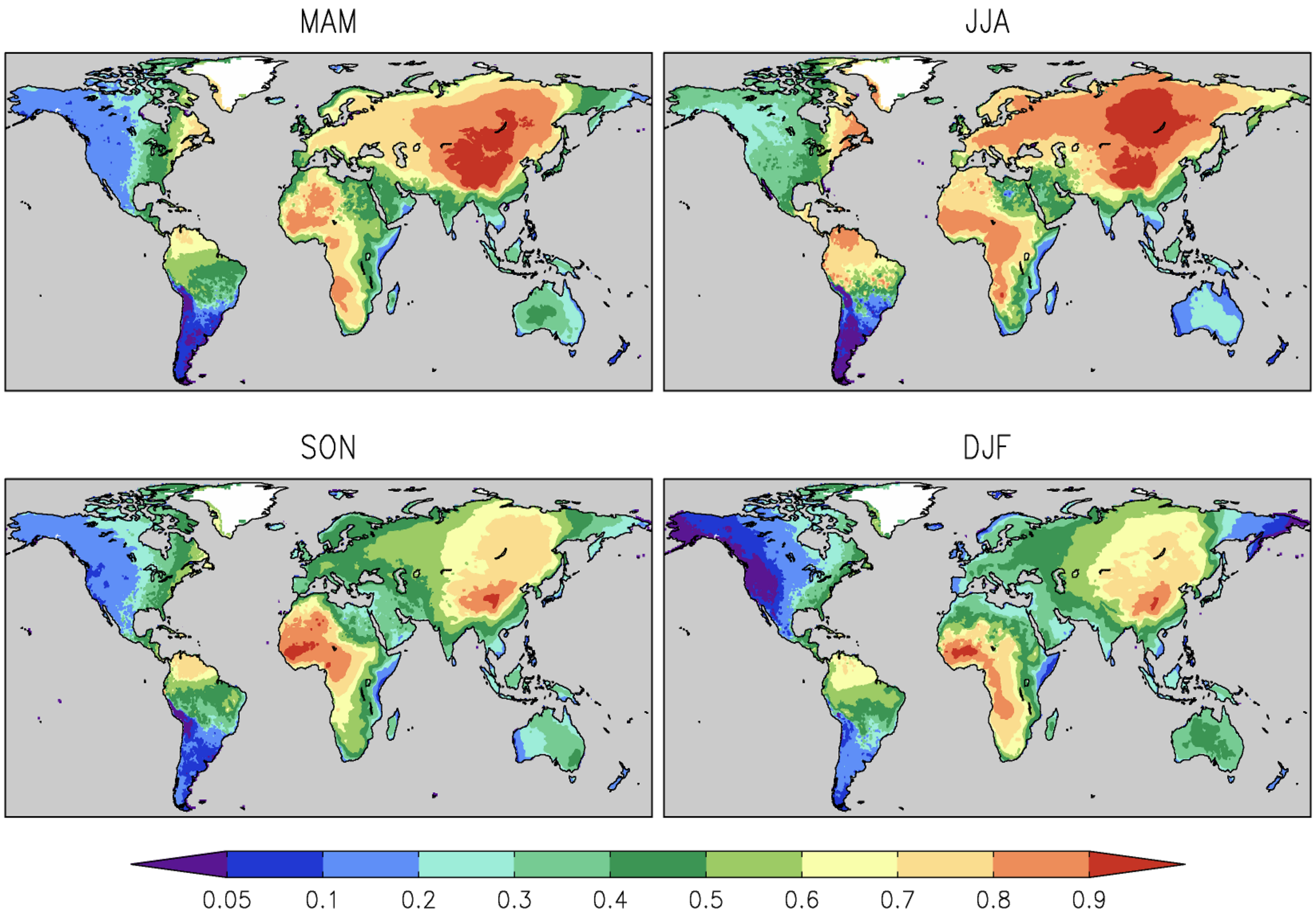
Most Recent Study – Data Used

- NASA MERRA Reanalysis:
  - 3-D fields of Temperature, Humidity, Wind (U and V)
  - Precipitation is corrected by CPC Unified precipitation at pentad timescale to remove biases, errors
  - ET (corrected by MERRA-Land* at pentad timescale)
- 6-hourly data, Jan 1979 – Dec 2005
- 2/3° x 1/2° resolution (540x360 grid)

* Reichle et al., 2011: *J. Climate*.

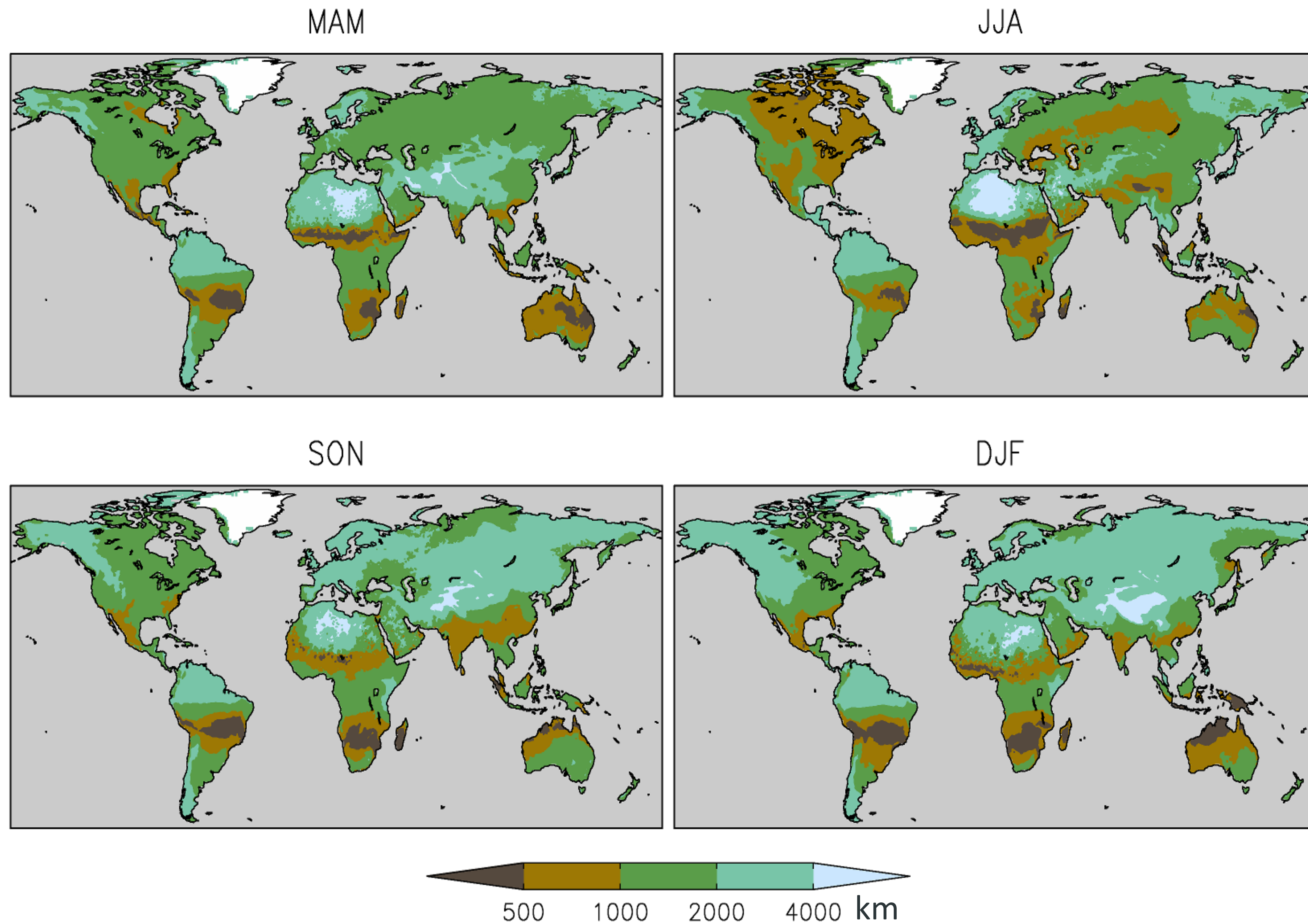
Terrestrial Sources

- Seasonal estimates of the fraction of precipitation coming from land evaporation.
- Maritime influence (blue) where flow is onshore.
- Central Asia, West Africa are most continental.
- Stark contrast between northern SA, other continental regions bordering the IAS.



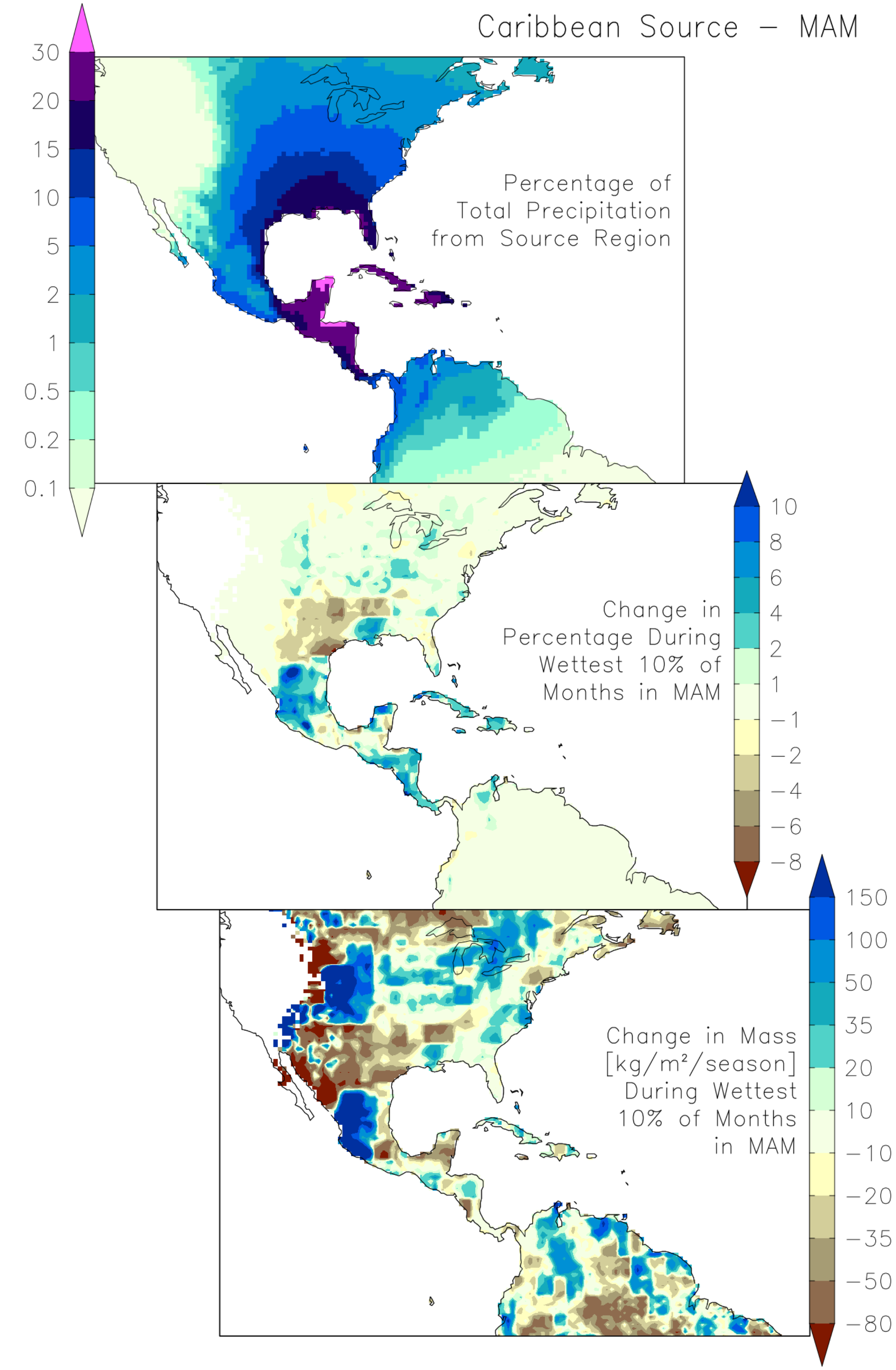
Distance Travelled

- The mean distance between the source of evaporation and where it falls over land.
- Shortest distances are usually in the humid subtropics.
- Interior deserts have the longest paths.



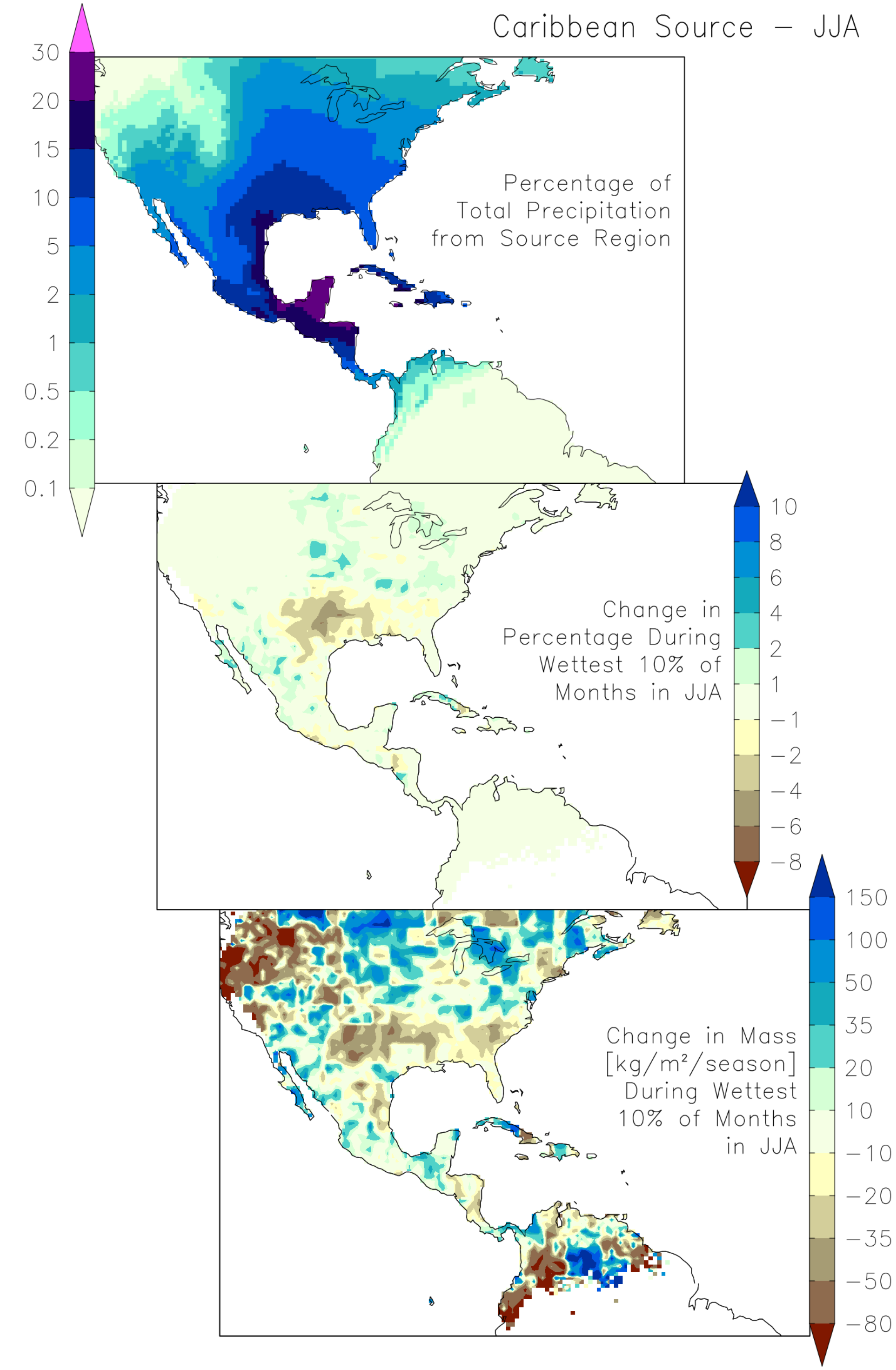
Sources and Floods

- The Caribbean Sea supplies evaporated moisture to precipitation to a large area (top for MAM)
- The wettest months over Mexico, Central America, Louisiana, Greater Antilles are associated with a greater fraction of moisture from Caribbean.
- When Texas is wet, it gets relatively less moisture from Caribbean.
- Little connection to South America.



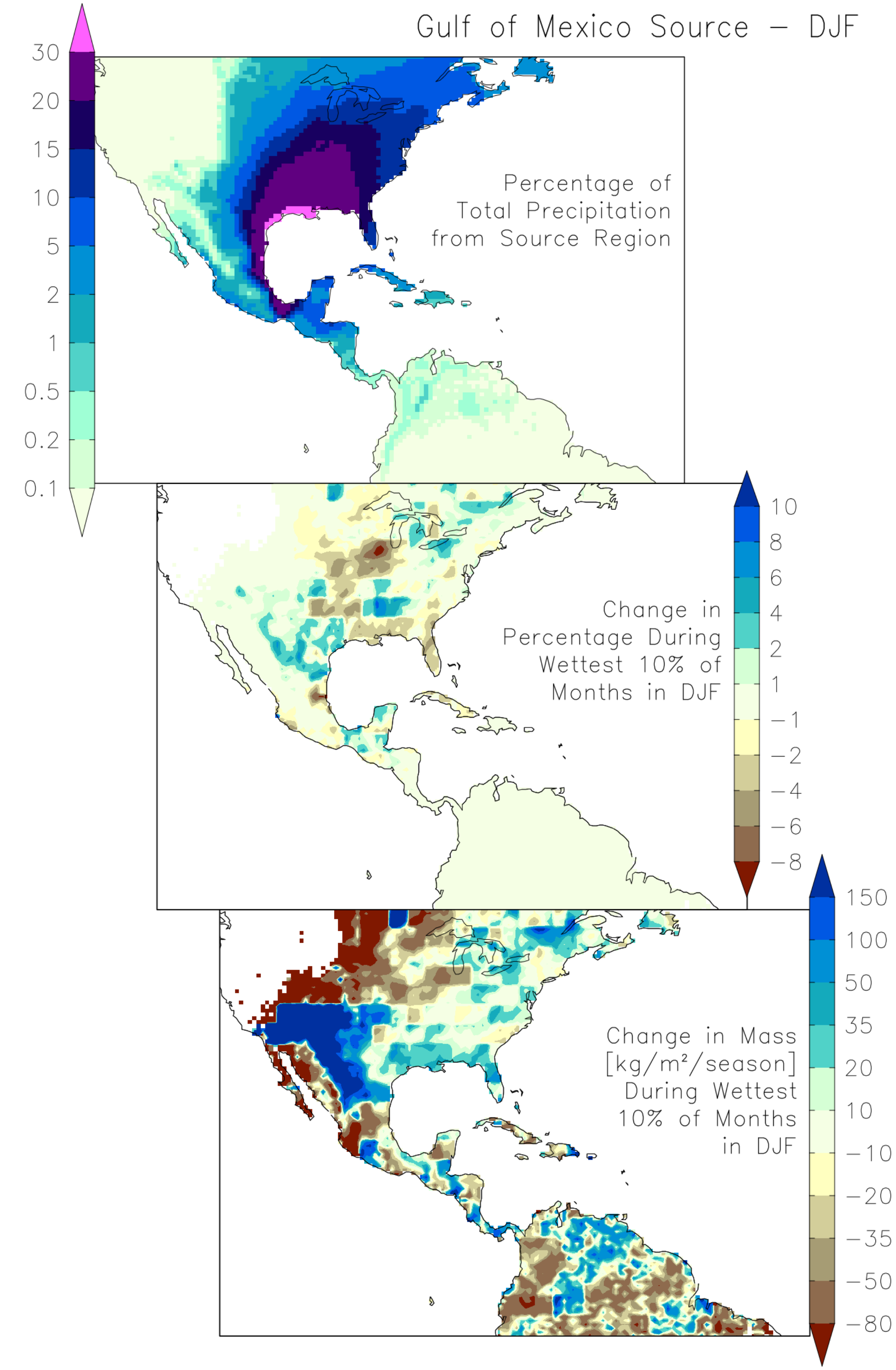
Summer Flooding

- The signal in MERRA is less clear than in previous studies, but can still see that flooding in the upper Midwest is connected to Caribbean source.
- At the same time, flooding in the southern half of US less connected to Caribbean.
- Transports of moisture are stronger for northern Mississippi Basin.



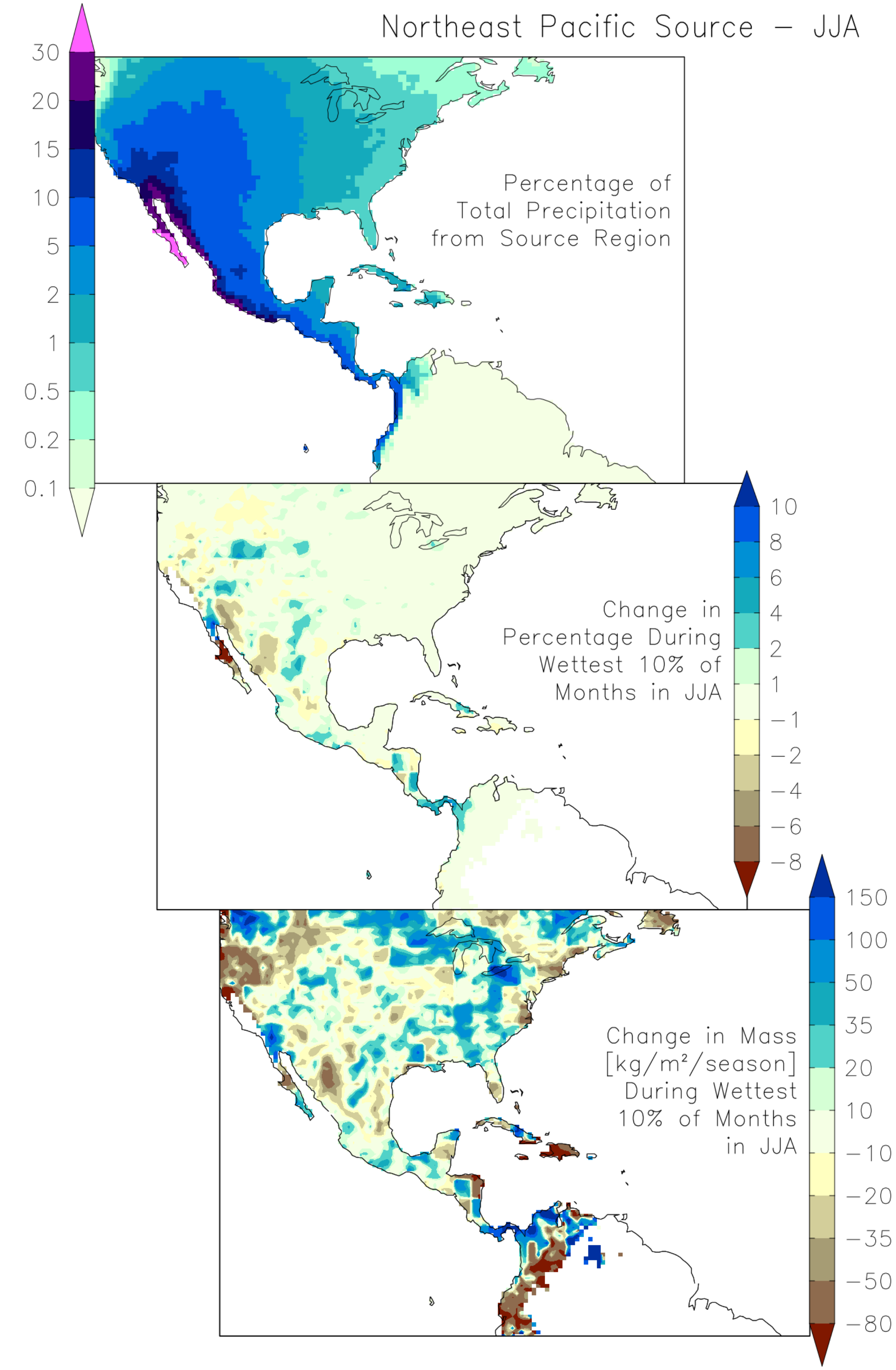
Sources and Floods

- The Gulf of Mexico source appears to be more connected to wet periods nearer afield (southern and southwestern US).



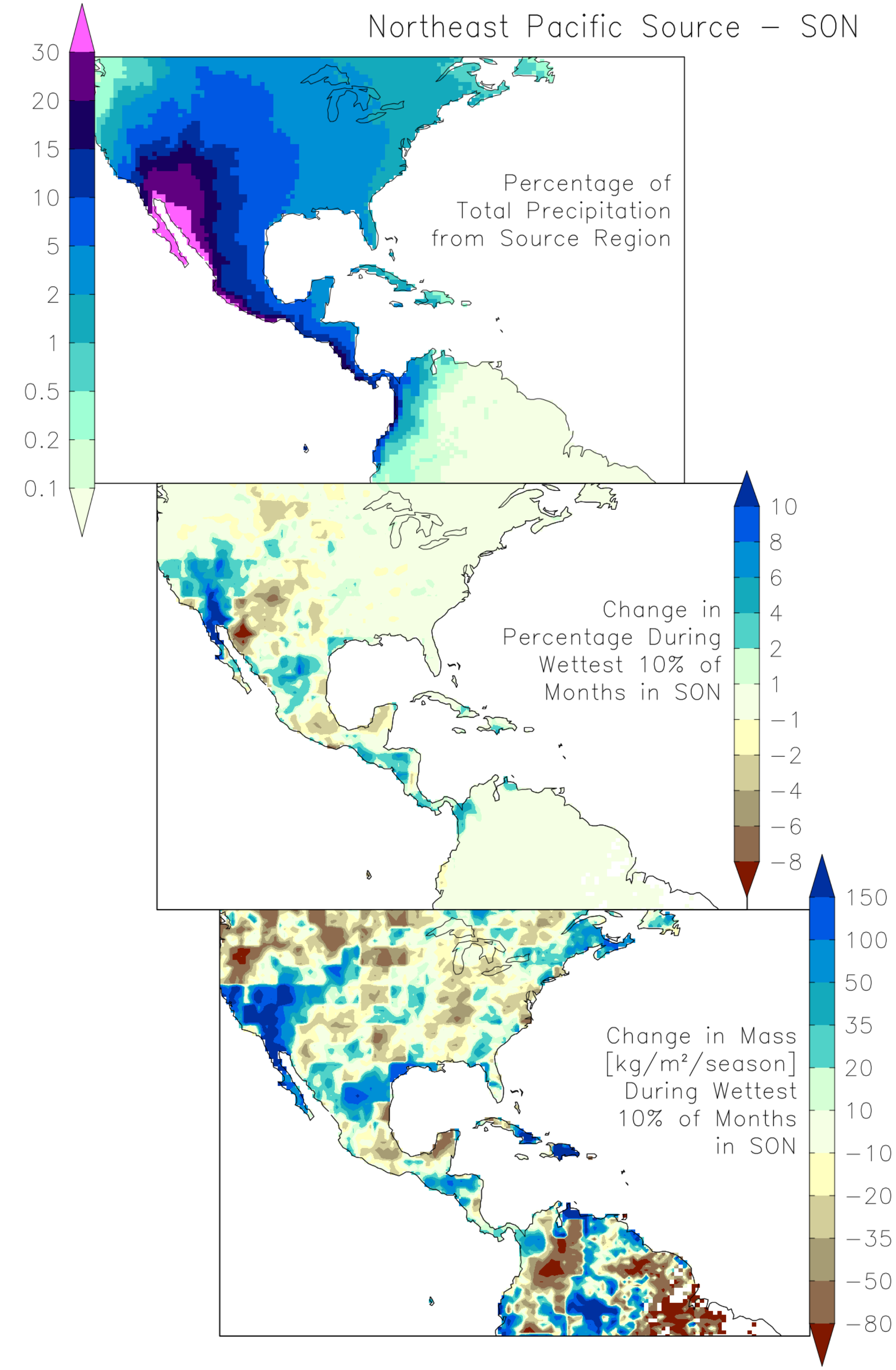
N.A. Monsoon

- During the monsoon season, there appears to be little connection between wet periods and moisture sources from the Pacific southwest of Mexico and Central America.
- This is not the case in other seasons…



Outside the Wet Season

- For example, during SON we see that wet conditions in north-central Mexico, Greater California and the southwestern U.S. are linked to the Pacific moisture source.



Summary

- Back trajectories of water vapor from precipitation (sinks) to evaporation (sources) reveal a new perspective on the atmospheric water cycle (mean and variability).
- We can quantitatively compare variations in source regions during dry/wet periods to elucidate causes.
  - We can see links between extremes and moisture sources in some situations that suggest circulation and advection changes.
  - More interestingly, we see situations where there are no links, suggesting extremes don't always come from circulation changes.

Thank You!

Tool: Relative Entropy (RE)

- Relative entropy (also called Kullback-Leibler Divergence or Information Divergence) measures the difference between two probability distributions (PDF) p and q:

$$RE(x) = \int p(y \mid x) \ln \frac{p(y \mid x)}{q(y)} dy$$

- This measure from information theory is often applied in statistics, communications, finance.

- x can be multidimensional – for data on a finite grid:

$$RE_{p,q} = \sum_i p(i) \ln \frac{p(i)}{q(i)} \quad \text{provided} \quad \sum_i p(i) = \sum_i q(i) = 1$$

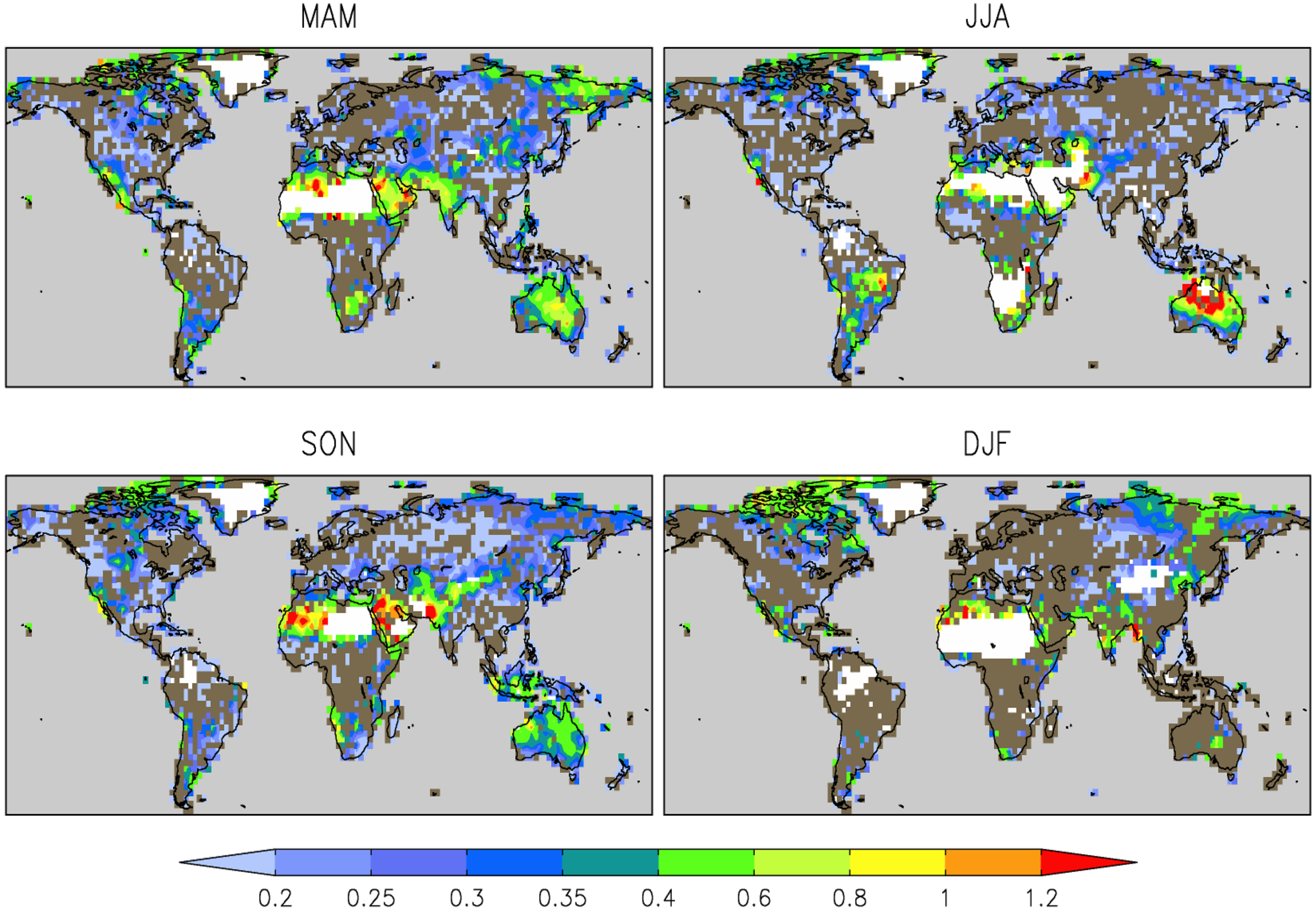
Properties of RE

$$RE_{p,q} = \sum_i p(i) \ln \frac{p(i)}{q(i)}$$

- $RE \geq 0$
- $RE = 0$ only if the two distributions p and q are identical.
- $RE_{p,q} \neq RE_{q,p}$, but ranking is preserved, and RE is invariant to nonlinear transformations.
- Here, p is the climatological evaporative source for rainfall over a given area, and q is the source conditioned on extremes in precipitation ("drought" and "flood" deciles).
- At every land grid box we calculate RE based on its evaporative sources – plot maps of RE.

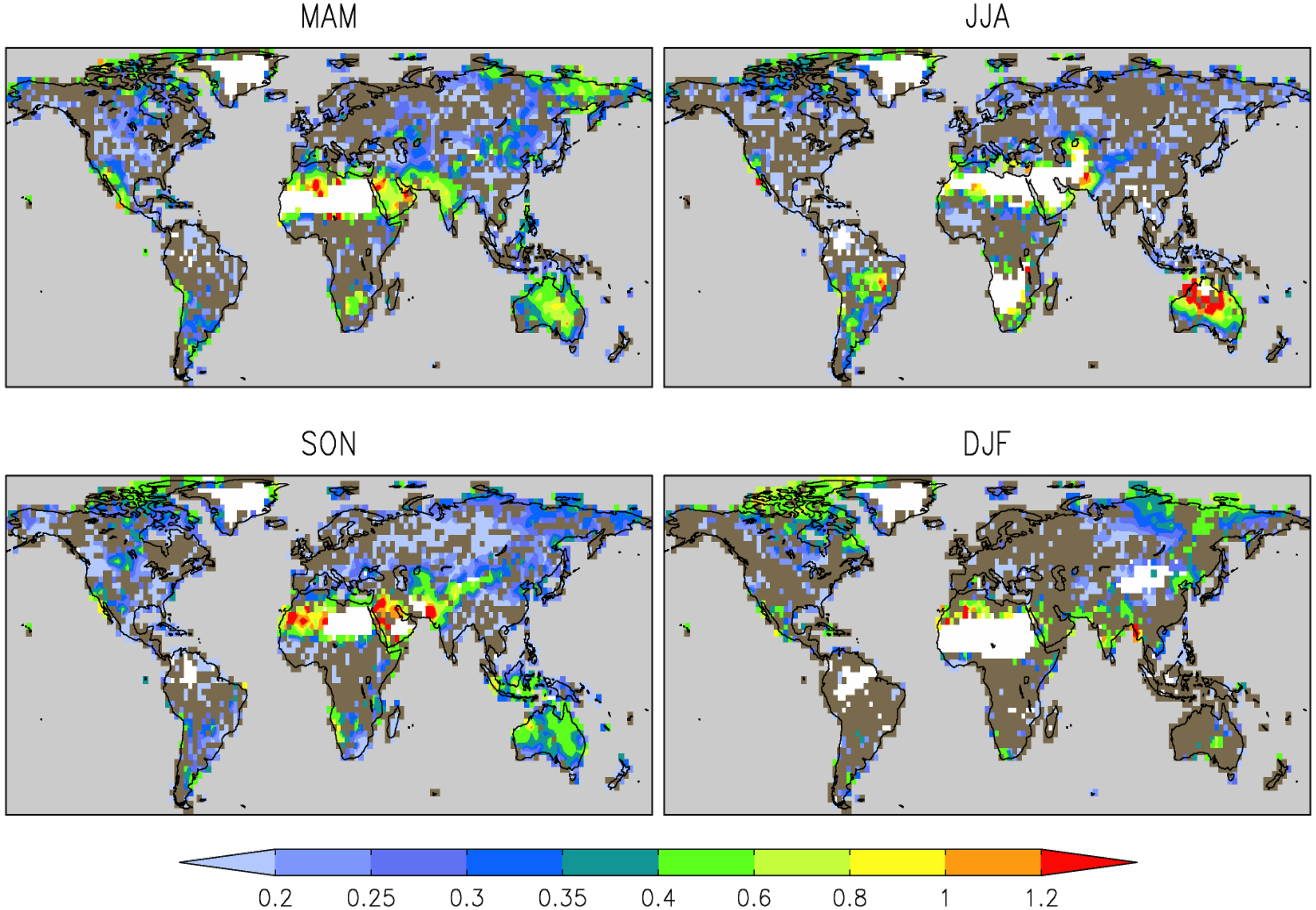
Drought Years vs. Climatology

- Maps show RE between monthly climatological evaporative moisture sources calculated at each point and the sources for the 3 driest years.
- Only areas with significantly large RE ($\rho \leq 0.05$ based on bootstrap sampling) and $p > 0.1$ mm/d are shaded with colors.



Drought Years vs. Climatology

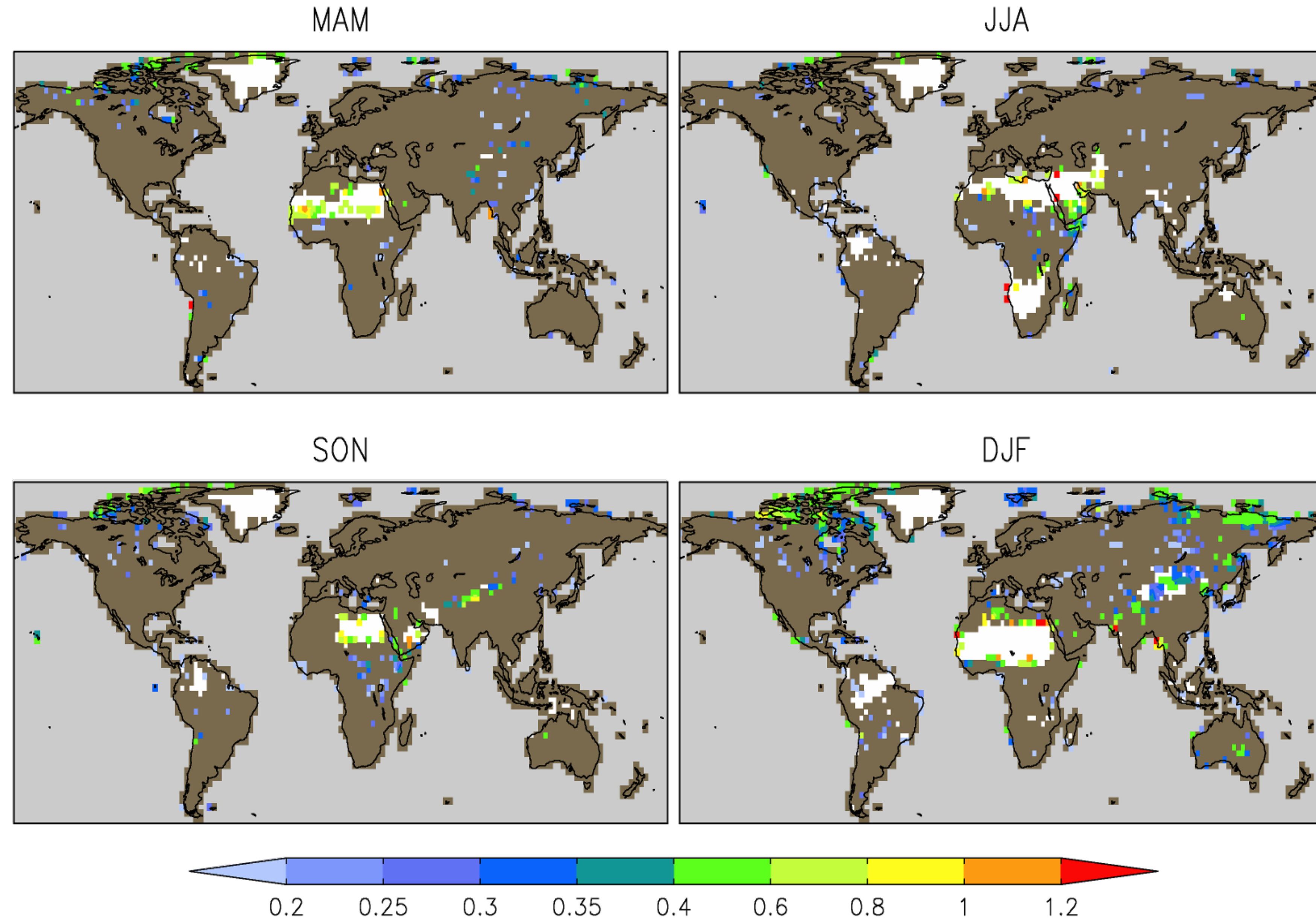
- Maps show RE between <u>monthly</u> climatological evaporative moisture sources calculated at each point and the sources for the 3 driest years.
- Small values ≈ moisture source (circulation) changes are <u>not</u> associated with drought.



- Must be another cause (e.g., stability, subsidence, L-A feedback).

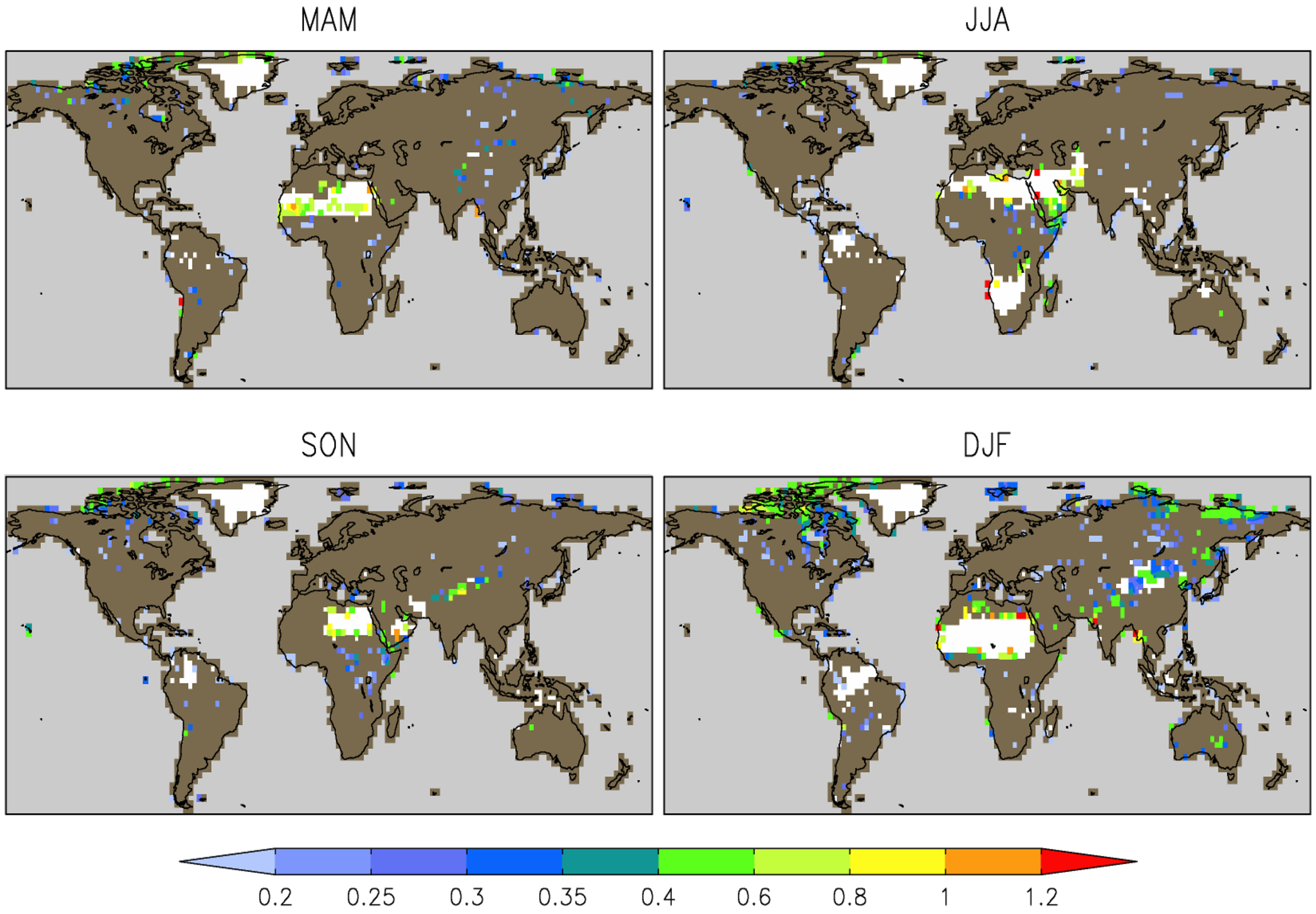
Wet Years Signal

- Wet years show very little significance.



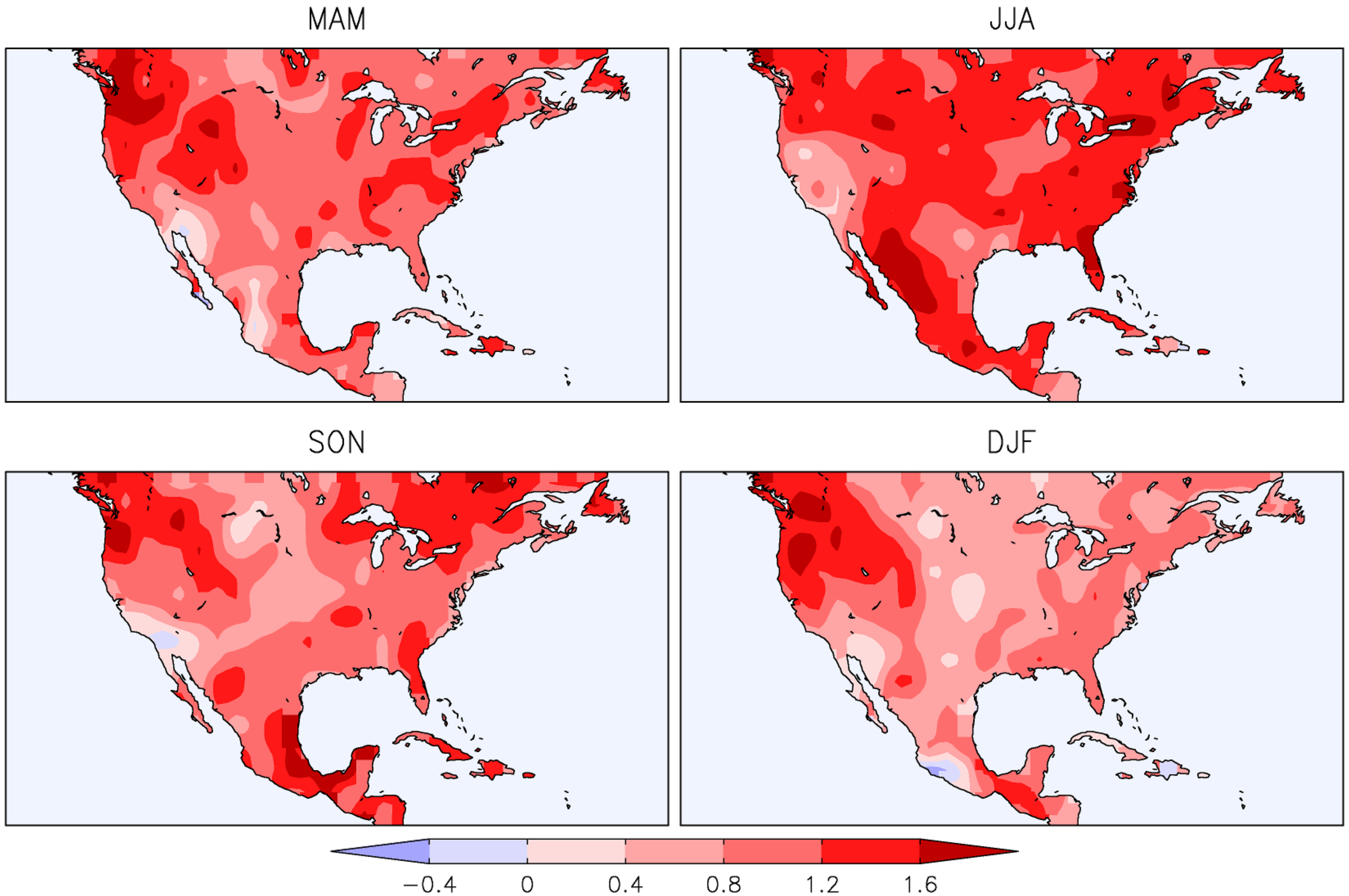
Wet Years Signal

- Wet years show very little significance.
- Reason? We are using monthly data. Droughts are long-term phenomena, but a wet month can result from 1 or 2 days of heavy rain.



RE Based on Pentads (N. America)

- Seasonal averages based on wettest of pentads show generally higher values than monthly.
- For many places, summer is most likely to have a wet season caused by brief anomalous fetches of moisture (atmospheric rivers).
- For DJF it's N. Cal. and Pacific NW.



ln of ratio: RE[pentad] / RE[monthly] for wet versus climatology.