What water vapor back-trajectory analysis can tell us about climate variability

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Of the Heat That Is in the World

Where vital heat is, there is movement of vapour … heat always draws to itself damp vapours and thick mists as opaque clouds, which it raises from seas as well as lakes and rivers and damp valleys …

Heat and moisture cannot exist with cold and dryness; and where the first portion stops the rest settle … thick and dark clouds are formed. They are often wafted about and borne by the winds from one region to another, where by their density they become so heavy that they fall in thick rain.

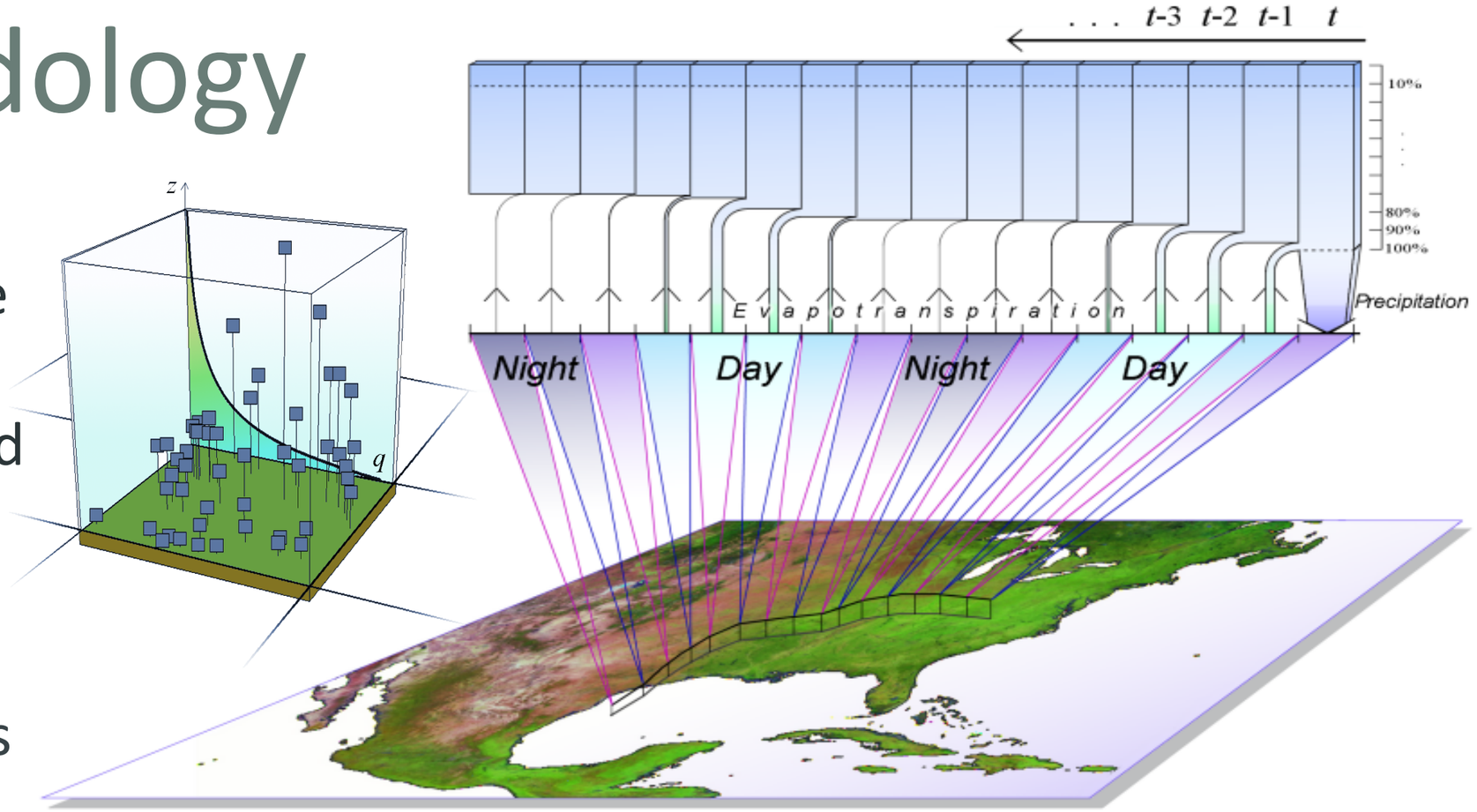
If the heat of the sun is added… the clouds are drawn up higher still and find a greater degree of cold, in which they form ice and fall in storms of hail.

Quasi-Isentropic Back Trajectories

- The idea for the technique is borrowed from air pollution meteorology (cf., 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

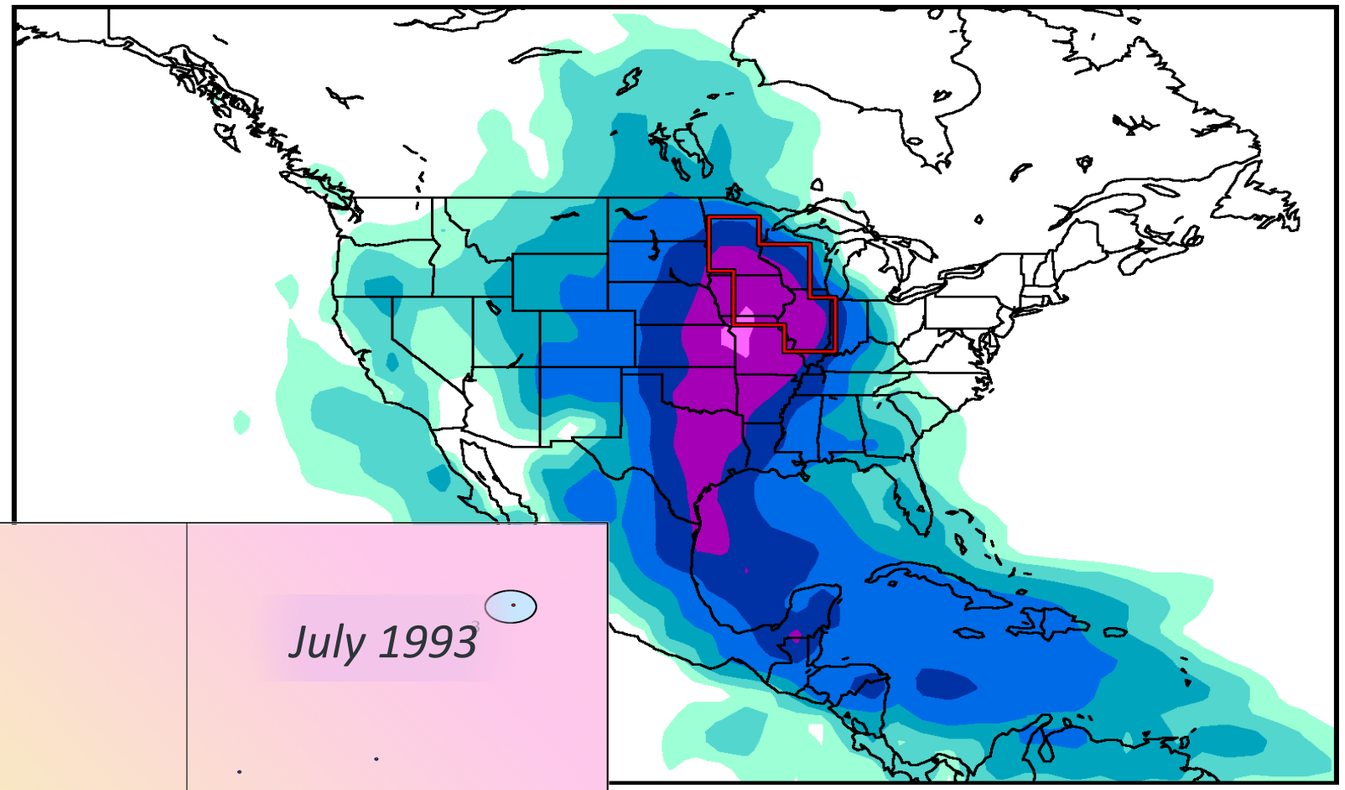
- Lagrangian "parcels" are used to estimate moisture transport *a posteriori*.
- Many parcels are launched at random humidity-weighted altitudes at times of precipitation.
- 3-D atmospheric reanalysis data are used to trace parcels backward in time.
- Evaporative contribution during each time step is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

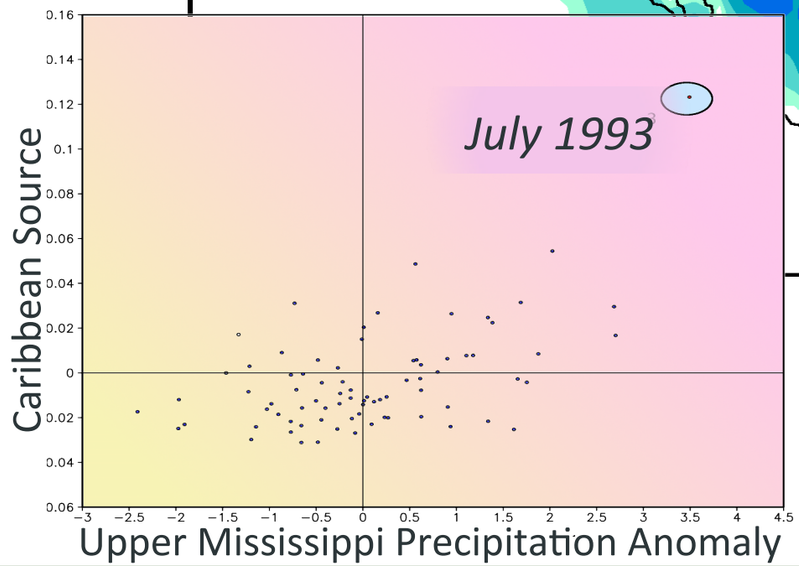


Dirmeyer & Brubaker, 1999: *J. Geophys. Res.*
Brubaker et al., 2001: *J. Hydrometeor.*
Reale et al. 2001: *Geophys. Res. Lett.*
Sudradjat et al., 2003: *J. Geophys. Res.*
Turato et al. 2004: *J. Hydrometeor.*
Dirmeyer & Brubaker, 2006: *Geophys. Res. Lett.*
Dirmeyer & Brubaker, 2007: *J. Hydrometeor.*
Dirmeyer & Kinter, 2009: *EOS Trans. AGU.*
Dirmeyer & 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.*
Wei et al. 2016: *Geophys. Res. Lett.*
Hoyos et al. 2016: *Climate Dyn.*

Early Work

- A link between moisture from the Caribbean Sea and the flooding over the Great Plains during 1993 was established in early work.
- 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.



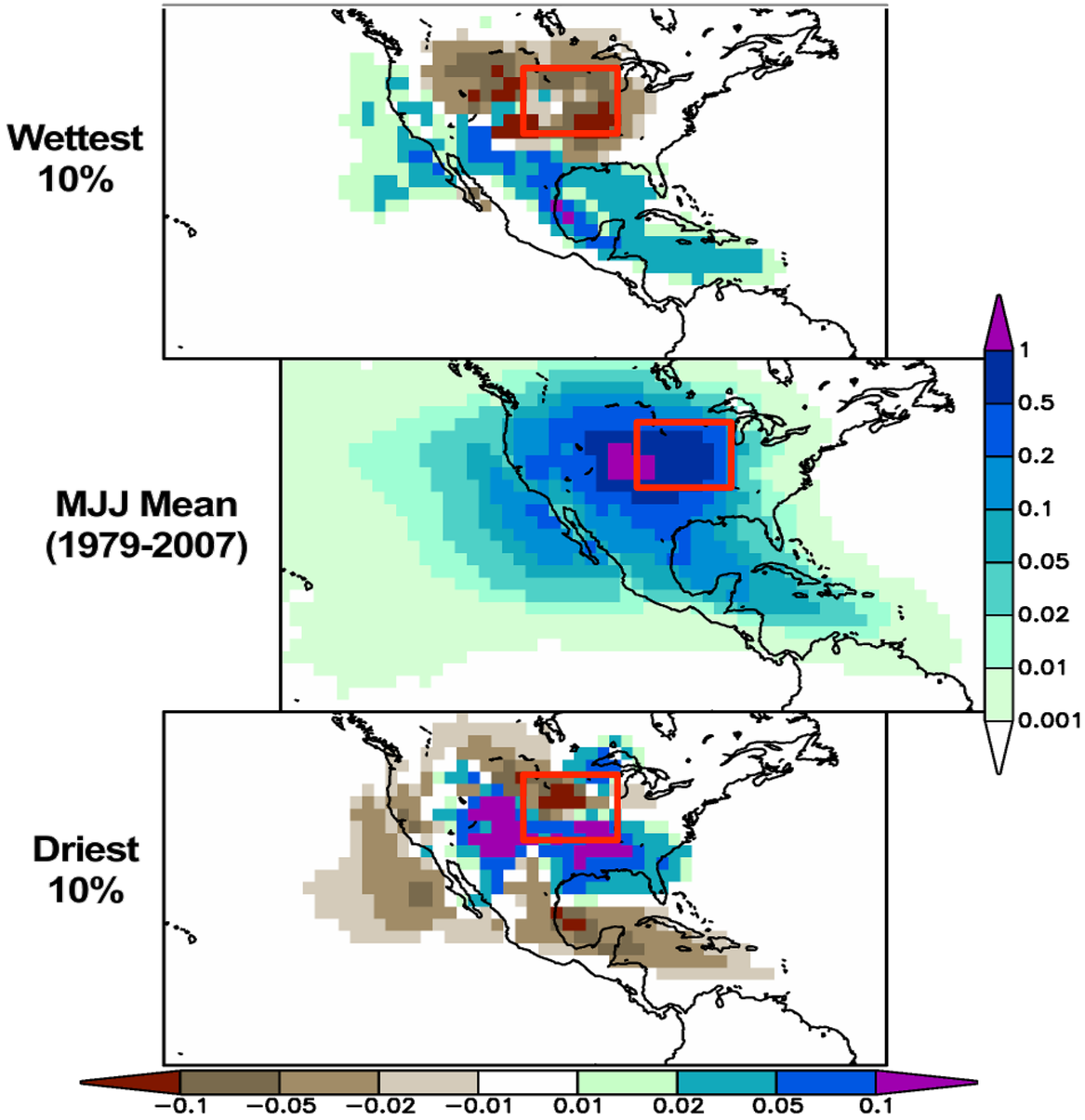


Dirmeyer & Brubaker, 1999: *J. Geophys. Res.*

Maya Express

- The MJJ climatology of evaporative moisture sources supplying the rainfall over the red box (NCEP/DOE-based; center) shows oceanic sources of moisture from the Atlantic (Gulf of Mexico and Caribbean), Pacific and land sources.
- Anomalies composited for the wettest and driest 10% of months show the fraction of from within the box (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 below-average fractions of moisture coming from ocean sources.

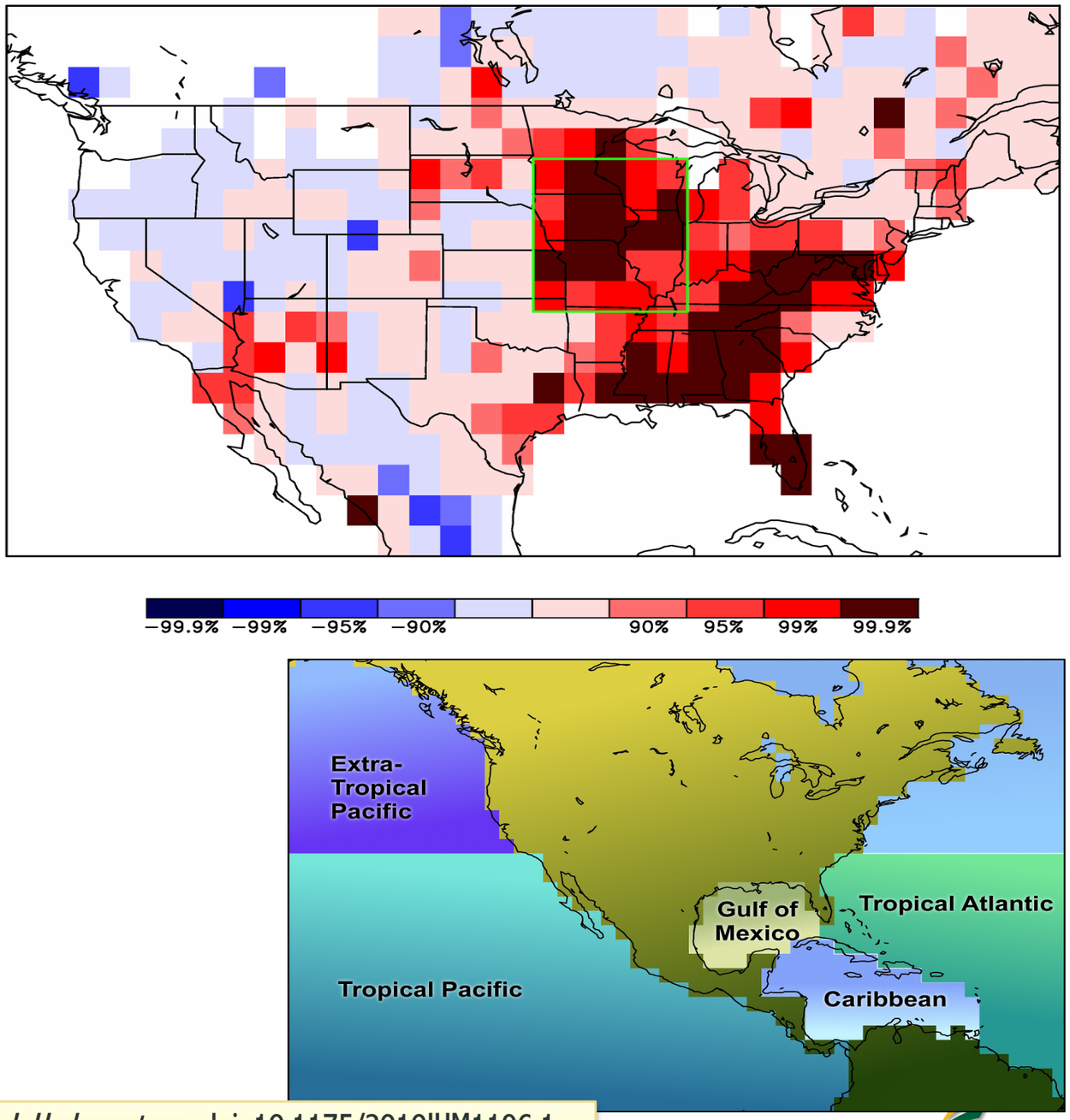
Units are the percentage of total water mass falling over the box – the global integral equals 100%.



Dirmeyer & Kinter, 2010: *J. Hydrometeor.*, doi: 10.1175/2010JHM1196.1.

Caribbean Source

- The correlation between MJJ precipitation anomalies within the Midwest box and the Caribbean source of moisture (region defined in lower 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.

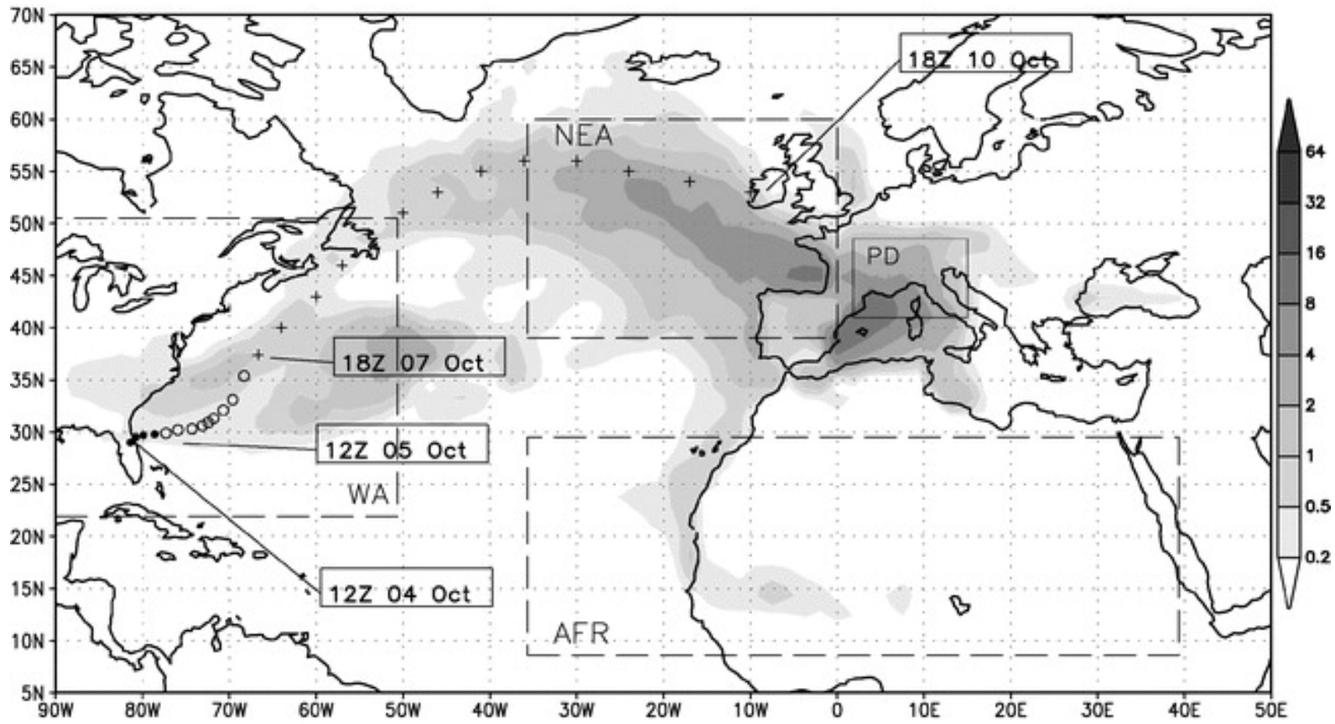


Dirmeyer & Kinter, 2010: *J. Hydrometeor.*, doi: 10.1175/2010JHM1196.1.

Tracking Moisture to Floods

- Moisture supplying the Piedmont floods of 2000 were tracked to North Atlantic sources, including water vapor carried by TS Leslie from the East Coast of the US.
- Floods are particularly linked to advection of moisture from distant locations.

Evaporative Sources for rain falling
from 18Z 09 Oct to 18Z 14 Oct 2000



Total Precipitation=881.6 mm
Total Evaporation=871.2 mm

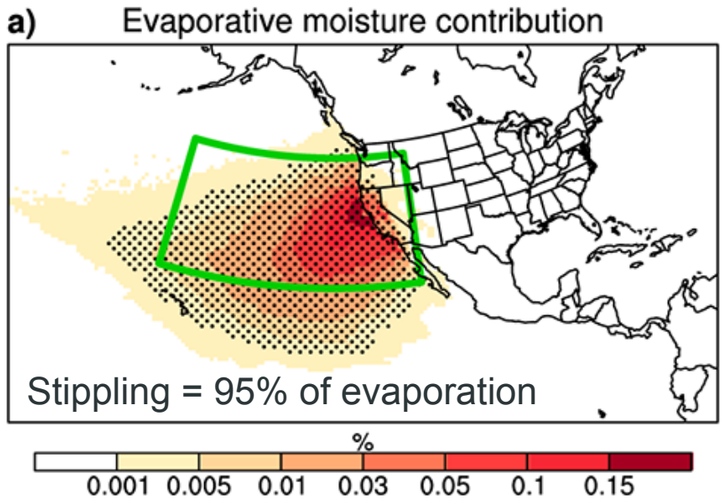
A=65.4 %
M=19.5 %
L=13.9 %

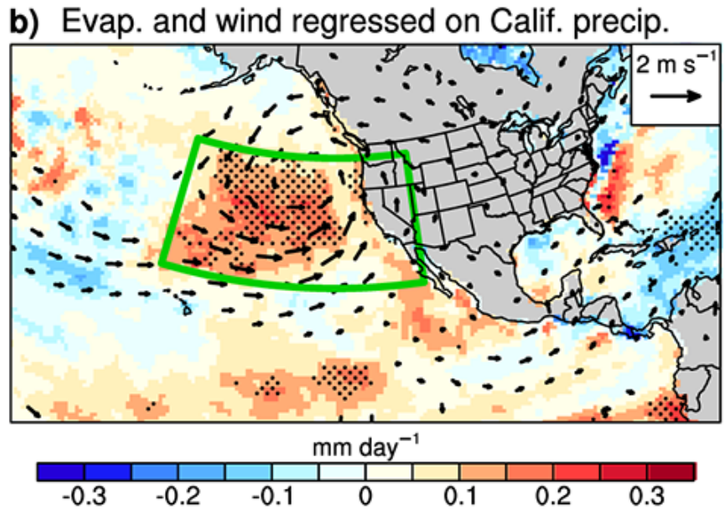
WA=11.8 %
NEA=41.6 %
AFR=3.2 %

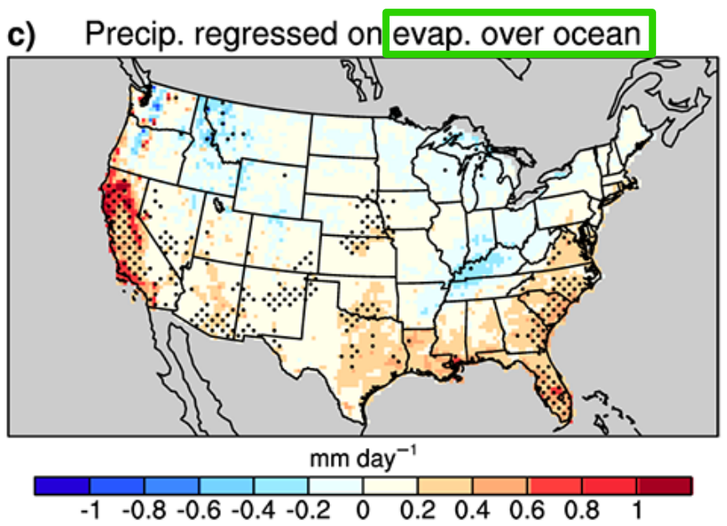
Turato et al. 2004: *J. Hydrometeor.*

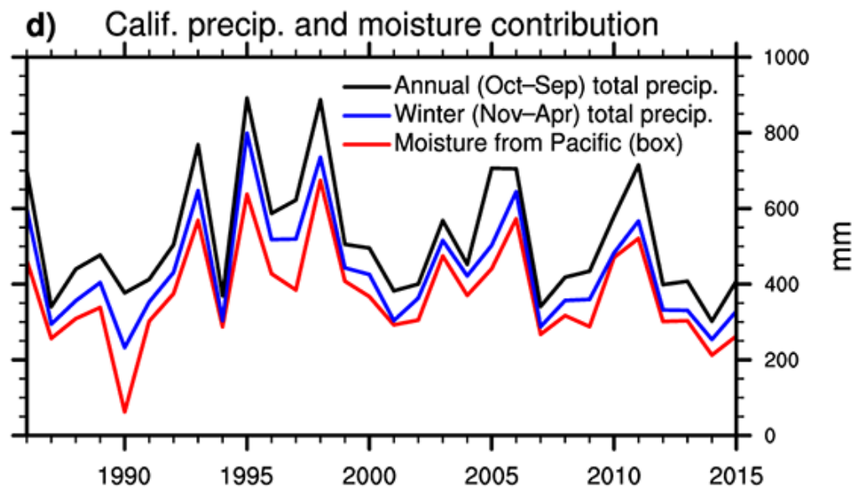
Evaporation, Transport, and Floods

- Relationship between California precipitation and its moisture supply from evaporation during winter (November–April) 1985-2015.
- Ocean evaporation rates correlate with floods better than with drought.
- The intensity of low-level wind is both the driver of evaporation changes and transport (e.g., atmospheric rivers).



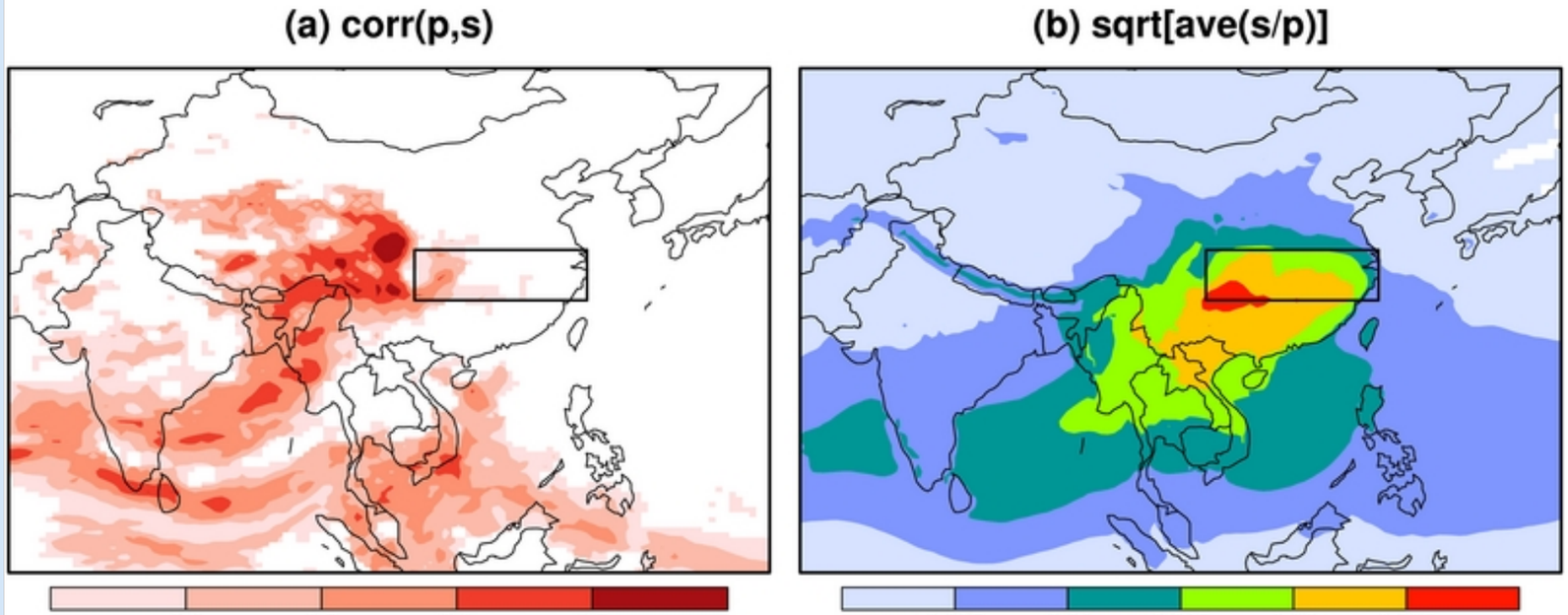






Wei et al. 2016: *Geophys. Res. Lett.*, doi: 10.1002/2016GL069386

Chinese Rainfall Variability – Bay of Bengal



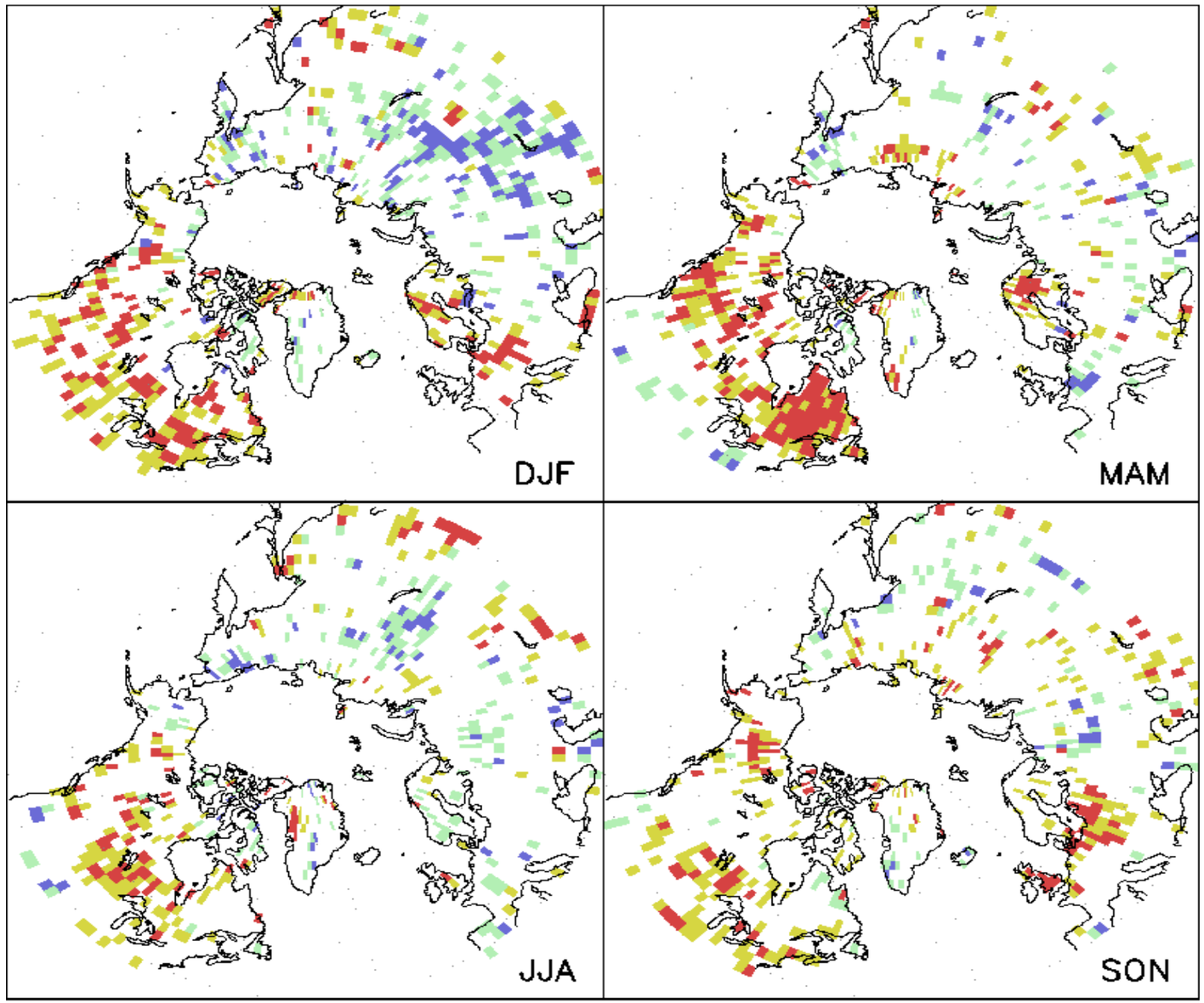
- Evaporative source for rain in the Cháng Jiāng Basin (rectangle, right) Apr-Sep 1979-2010.
- Left panel shows correlation between Cháng Jiāng precipitation and surface evaporative source at each location.
- Although most moisture comes from evaporation over southern and central China, interannual variability correlates with moisture from western China and the Bay of Bengal.

Wei et al. 2012: *J. Geophys. Res.*, doi: 10.1029/2011JD016902.

25-Year Trend

Trends in recycling ratio (%/yr) reflect:

- Milder Canadian winters, weaker baroclinicity in summer.
- The earlier onset of spring over high latitudes of Canada, Alaska, N. Europe.
- Possible later onset of autumn over some locations.



Trend in the recycling ratio (during 1979-2003) scaled to a common reference area of $10^5 km^2$. Trends significant at the 98% confidence limit (Cox-Stewart test) are shown in shades of red (positive) and blue (negative), 93% in yellow (positive) and green (negative).

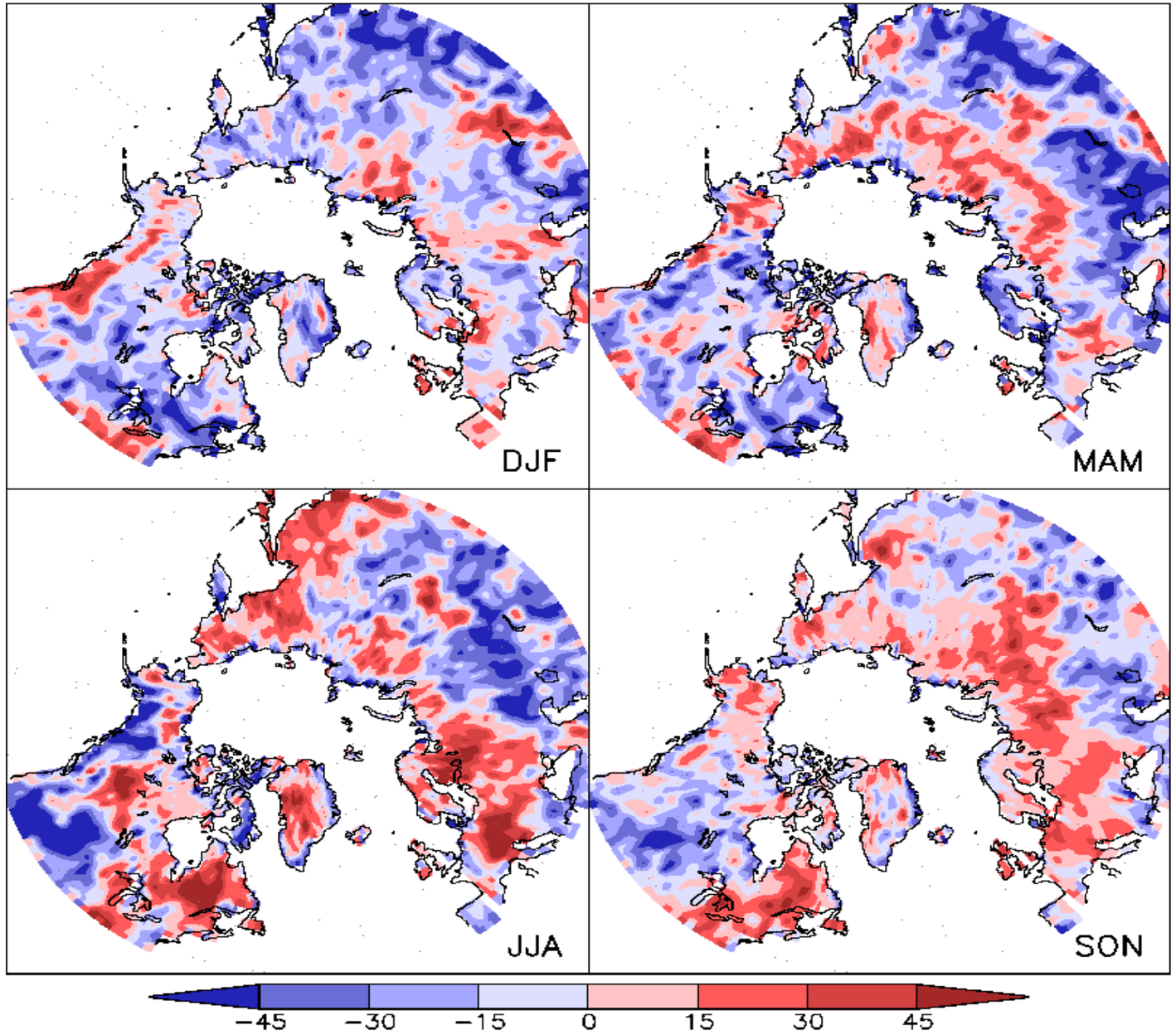
Dirmeyer & Brubaker, 2006: *Geophys. Res. Lett.*

Source of Trend

Red: Transport dominant

Blue: ET dominant

- At higher latitudes, trends are driven by weakening of circulation (ET small anyway).
- Mid-latitudes are dominated by ET trends, but circulation changes exist too.

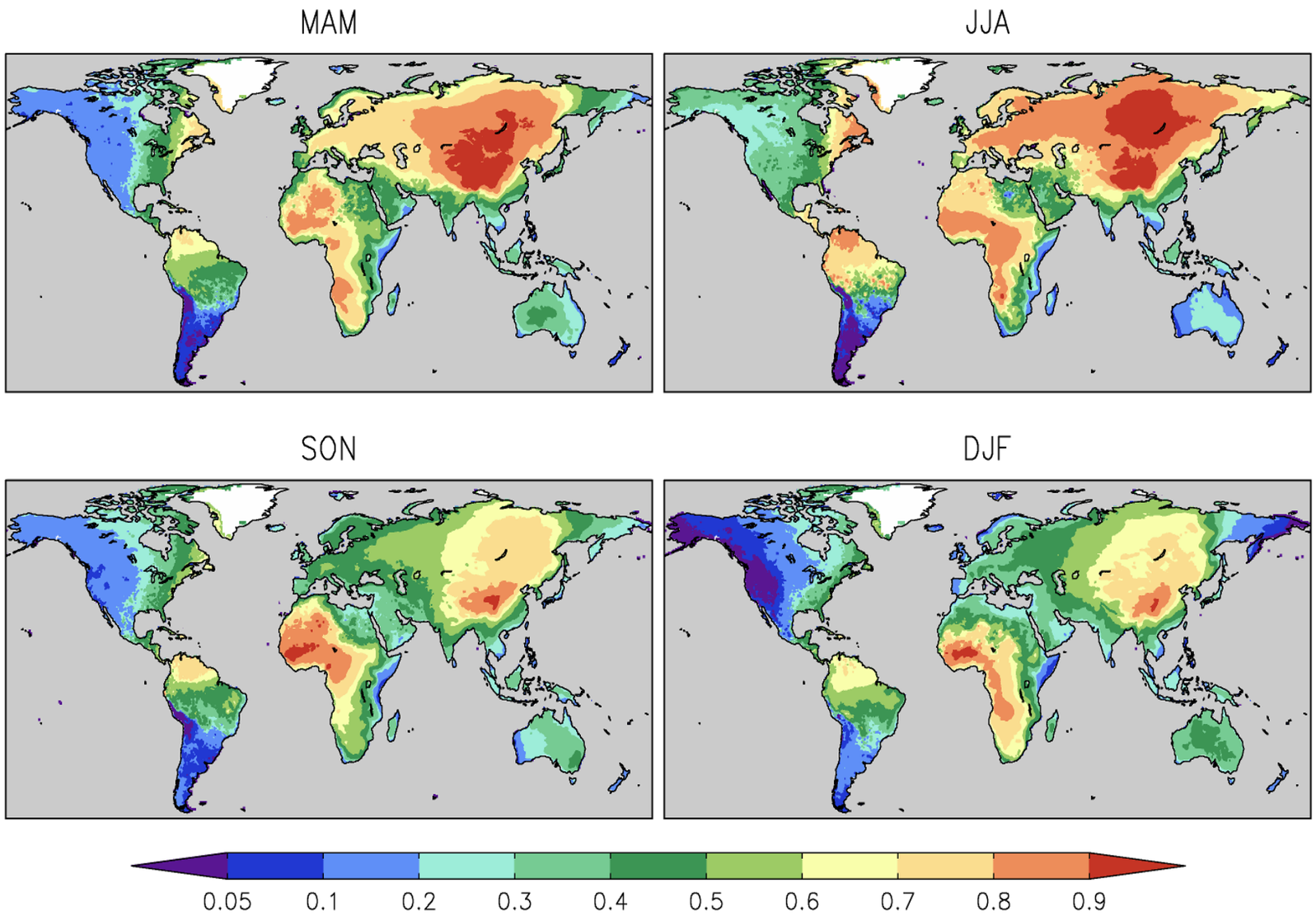


Difference in the explained variance (%) from [the temporal correlation of seasonal mean moisture transport with recycling ratio] *minus* [the correlation of total surface evapotranspiration with recycling ratio].

Dirmeyer & Brubaker, 2006: ***Geophys. Res. Lett.***

Global Sources of Precipitating Water

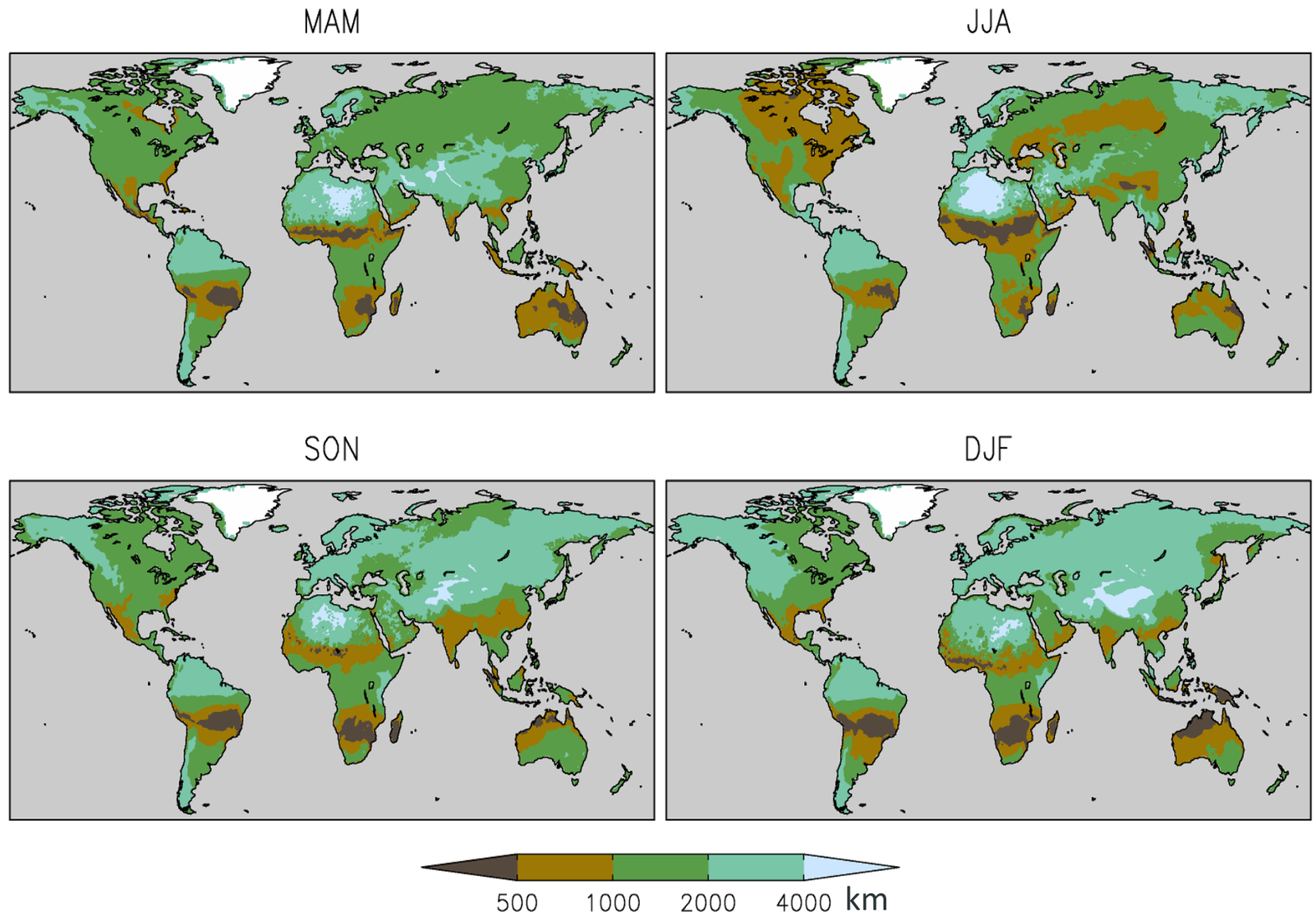
- Seasonal estimates of the fraction of precipitation coming from land evaporation.
- Maritime influence (blue) where flow is onshore.
- Western NA, southern SA are the most oceanic.
- Central Asia, West Africa are most continental.
- Most locations have pronounced annual cycles.



Dirmeyer et al. 2014: *J. Hydrometeor.*, doi: 10.1175/JHM-D-13-053.1.

Distance Travelled

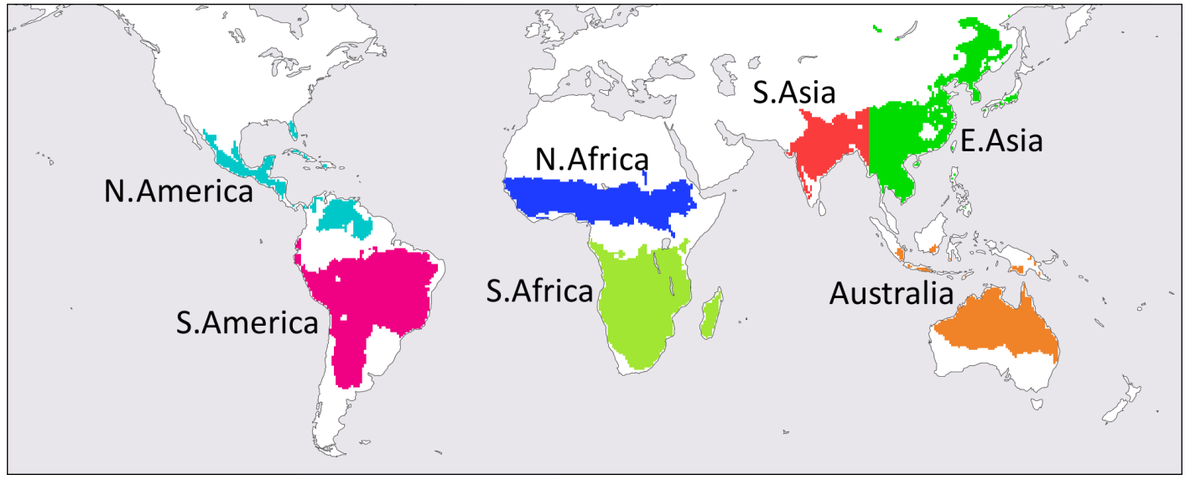
- The mean distance between the source of evaporation and where it falls over land.
- Shortest distances are usually in the humid subtropics.
- Interior deserts have the longest paths.

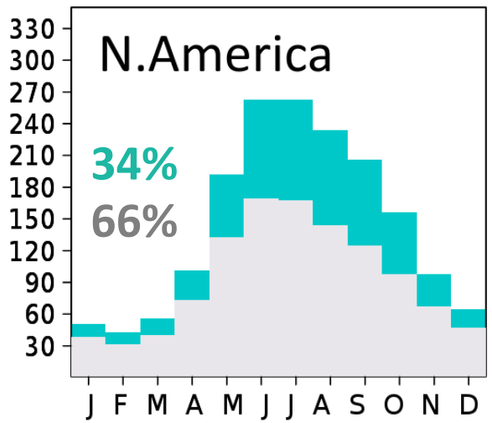


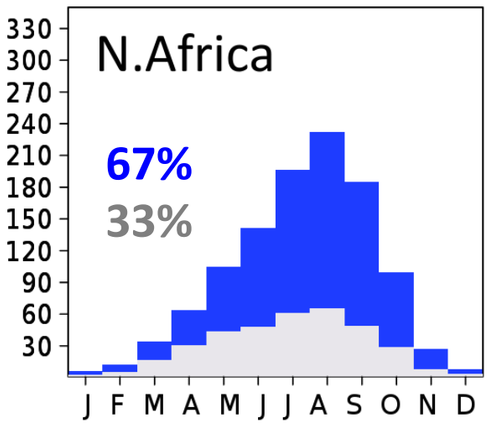
Dirmeyer et al. 2014: *J. Hydrometeor.*, doi: 10.1175/JHM-D-13-053.1.

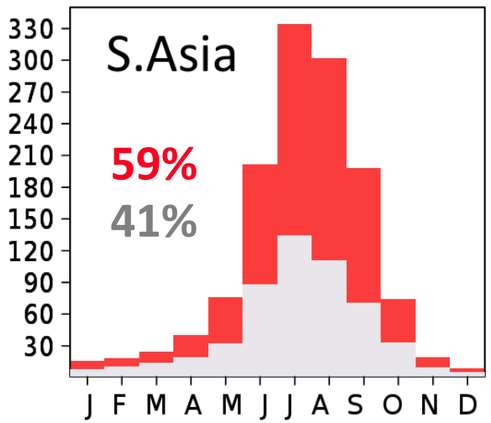
Monsoon Sources

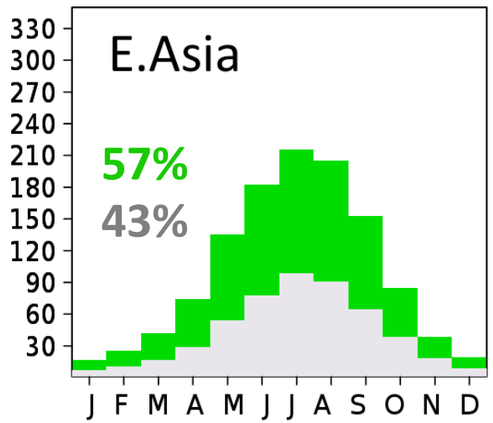
- Terrestrial (color) and ocean (grey) contributions to precipitation in monsoon regions.

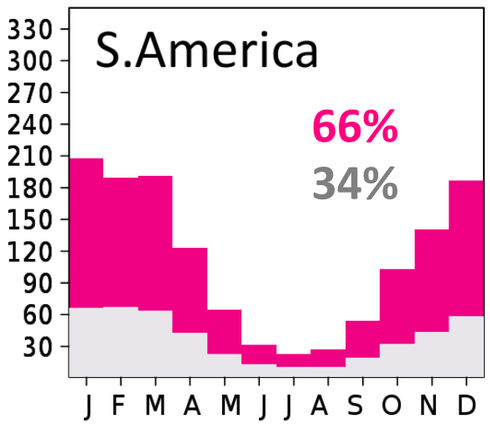


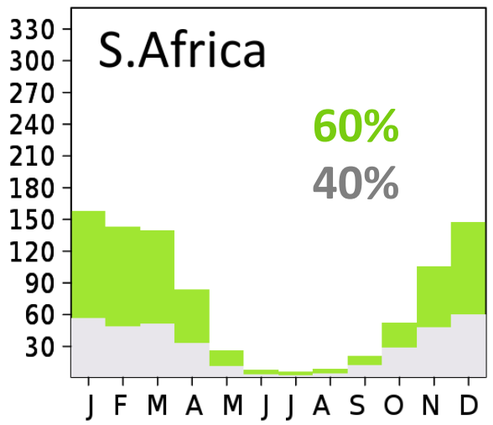


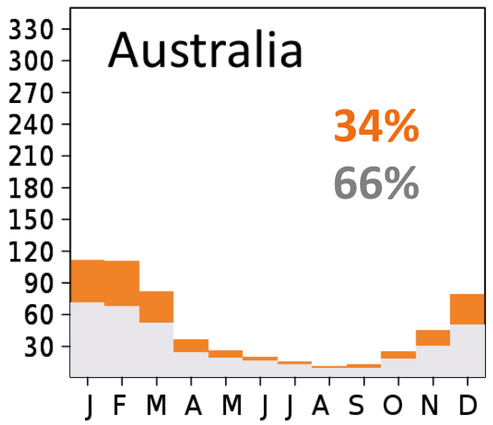












Monsoon regions defined using B. Wang's definition based on C. Willmott (U. Del.) rainfall data

Summary

- Oceanic moisture sources are linked to precipitation over land, particularly floods, but not always as strongly as many believe.
- Monsoons are not uniformly supplied by oceanic moisture sources – only the relatively weak North American and Australian monsoon systems are strongly driven by oceanic moisture sources.
- QIBT has found other applications – estimating recycling, water vapor transport distances, even climate change detection.

Grazas