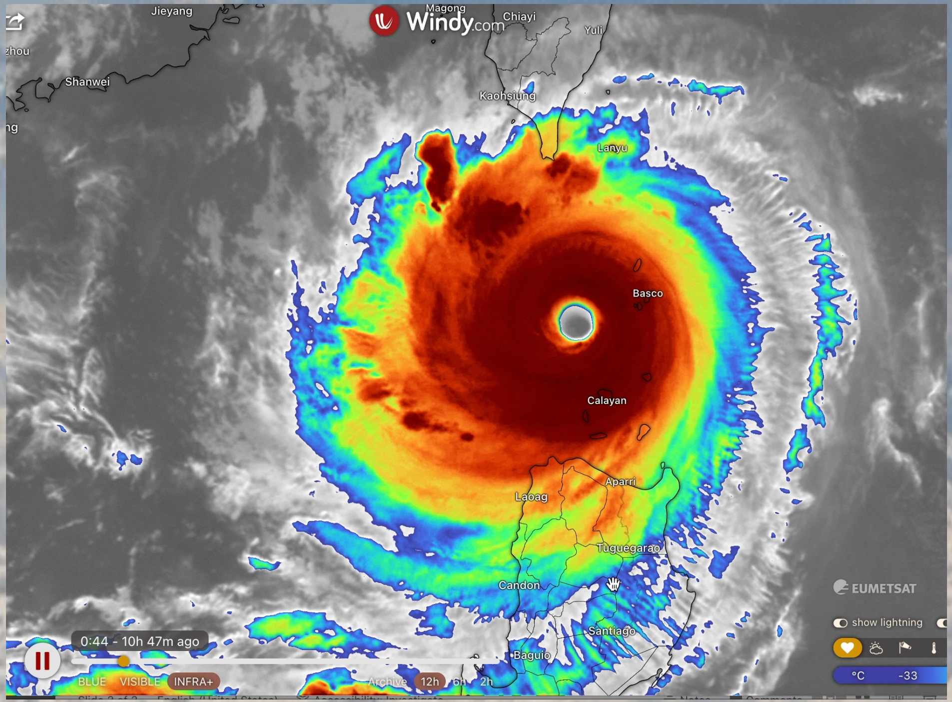
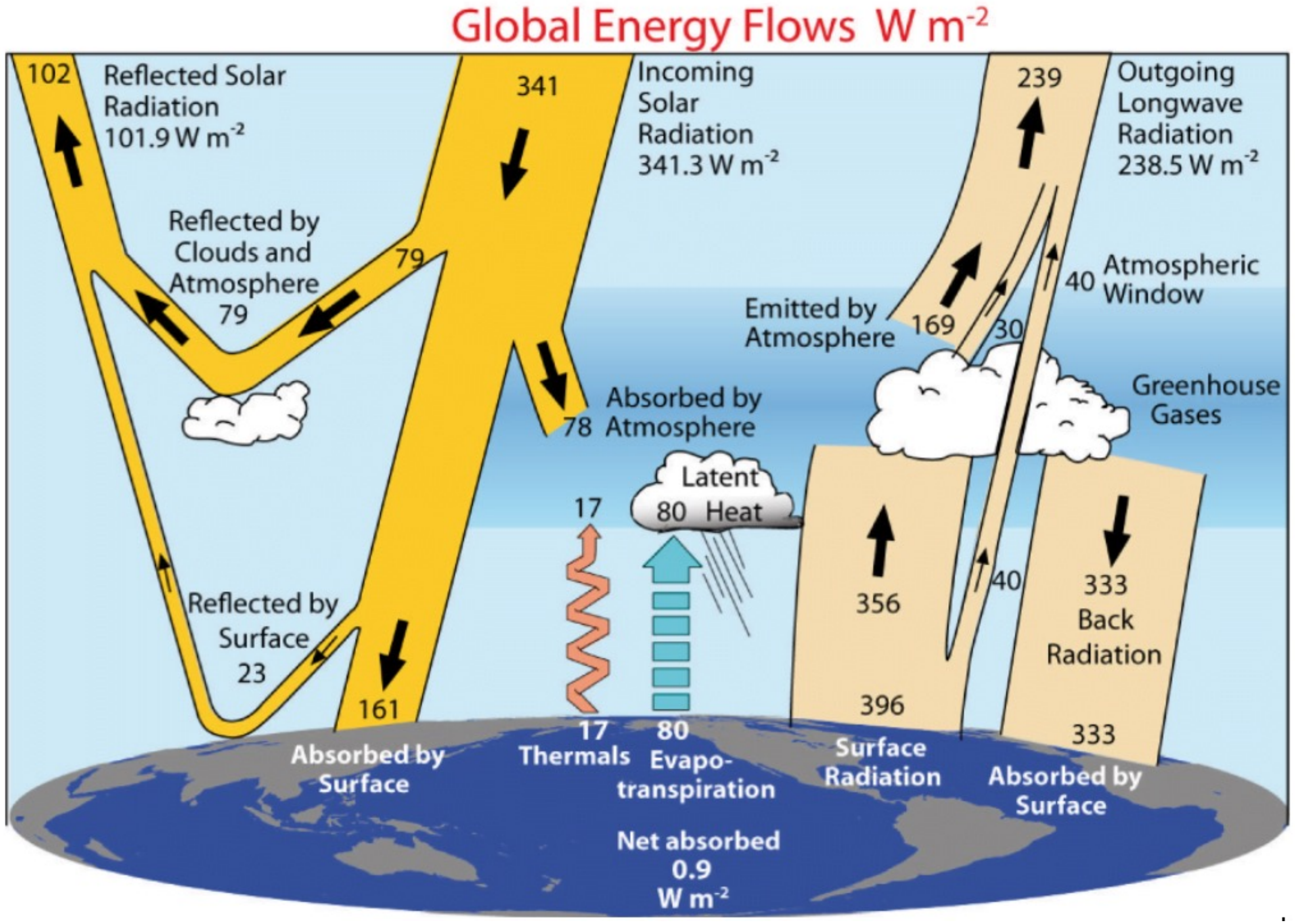
Deep convection organisation idealized and real: from self aggregation through squall lines to hurricanes and tropical coupled waves

Adrian Tompkins (ICTP)

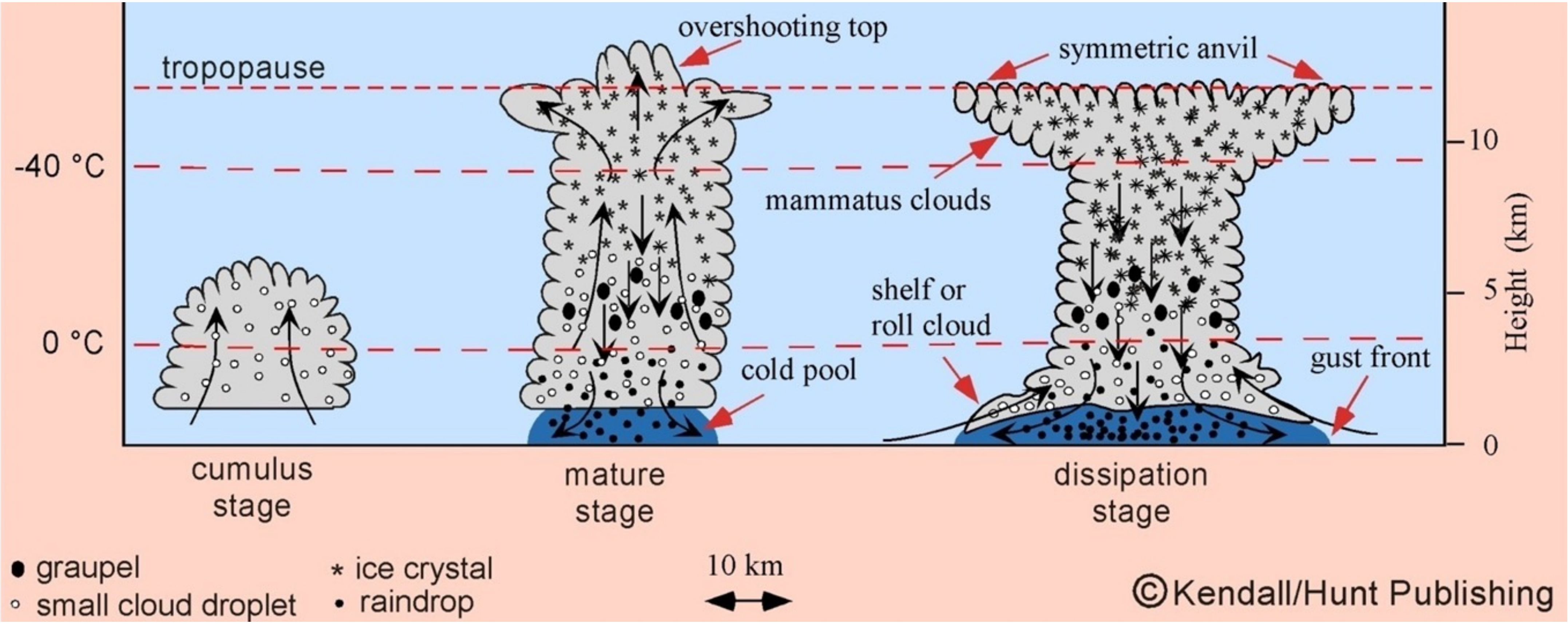




clouds are black bodies in IR, and reflect SW efficiently

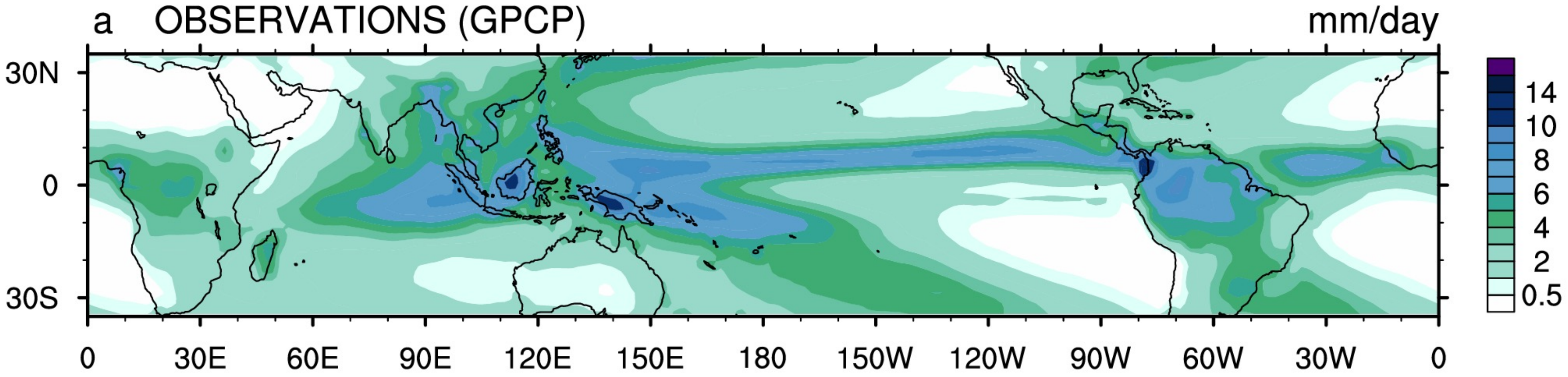
Water vapour is the most important greenhouse gas

Reminder: components of a deep convective storm

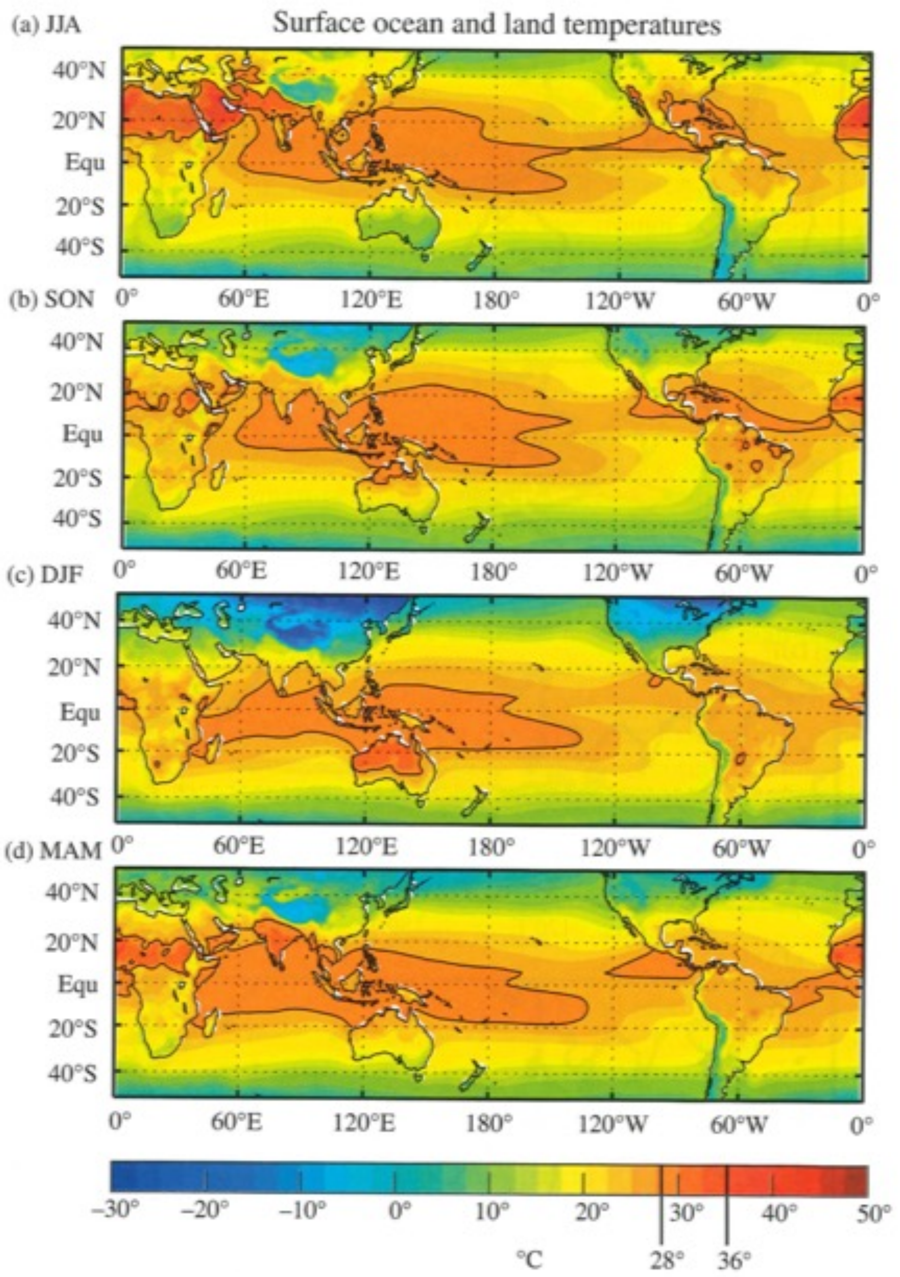


- Creates cloud (=> radiation)
- Produces rain!
- But locally moistens the atmosphere...
- heats the atmosphere and induces a circulation (gravity waves)
- Increases winds (cold pools)

Rainfall in the tropics in focused in a narrow band, the inter tropical convergence zone



Bellon 2023

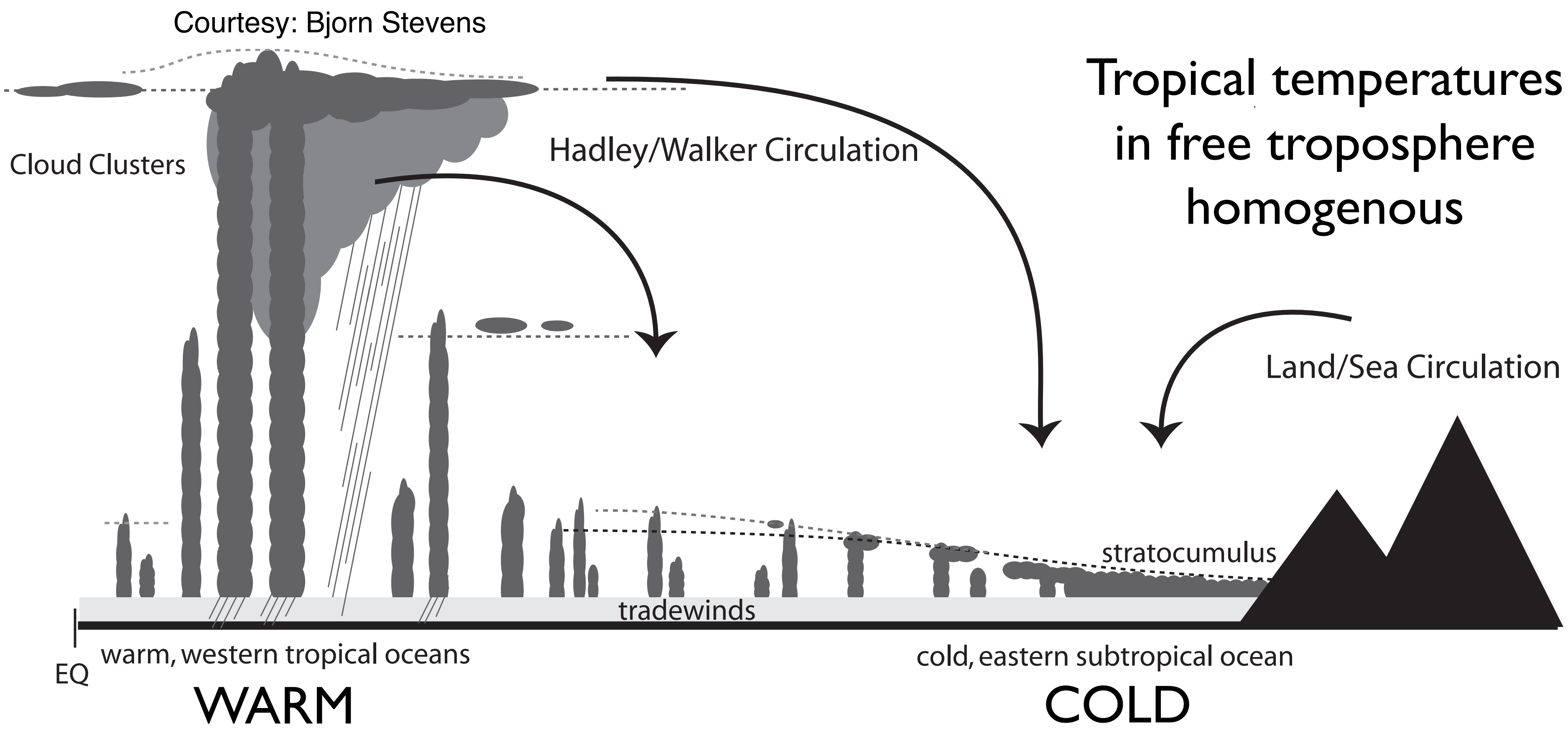


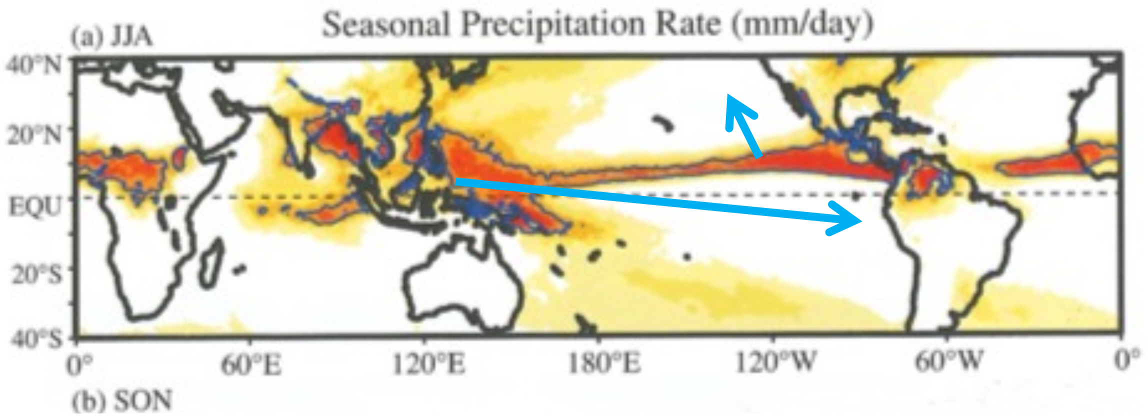
Courtesy Dennis Hartmann Global Climatology

Temperature at surface impacted by ocean dynamics

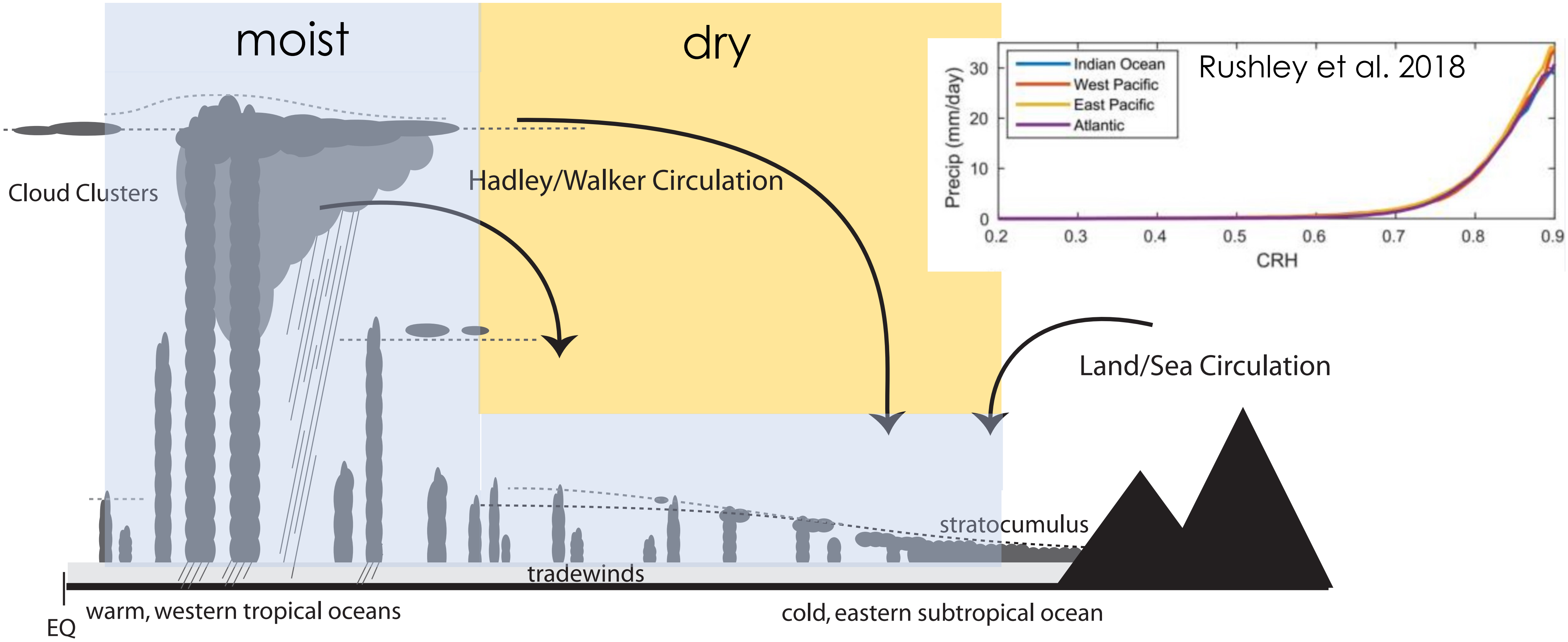
In free troposphere, temperature is set by the profile of the warmest regions (no rotation) and gradients are small (<3K)

Tropical temperatures in free troposphere homogenous





What is the impact on the water vapour field?

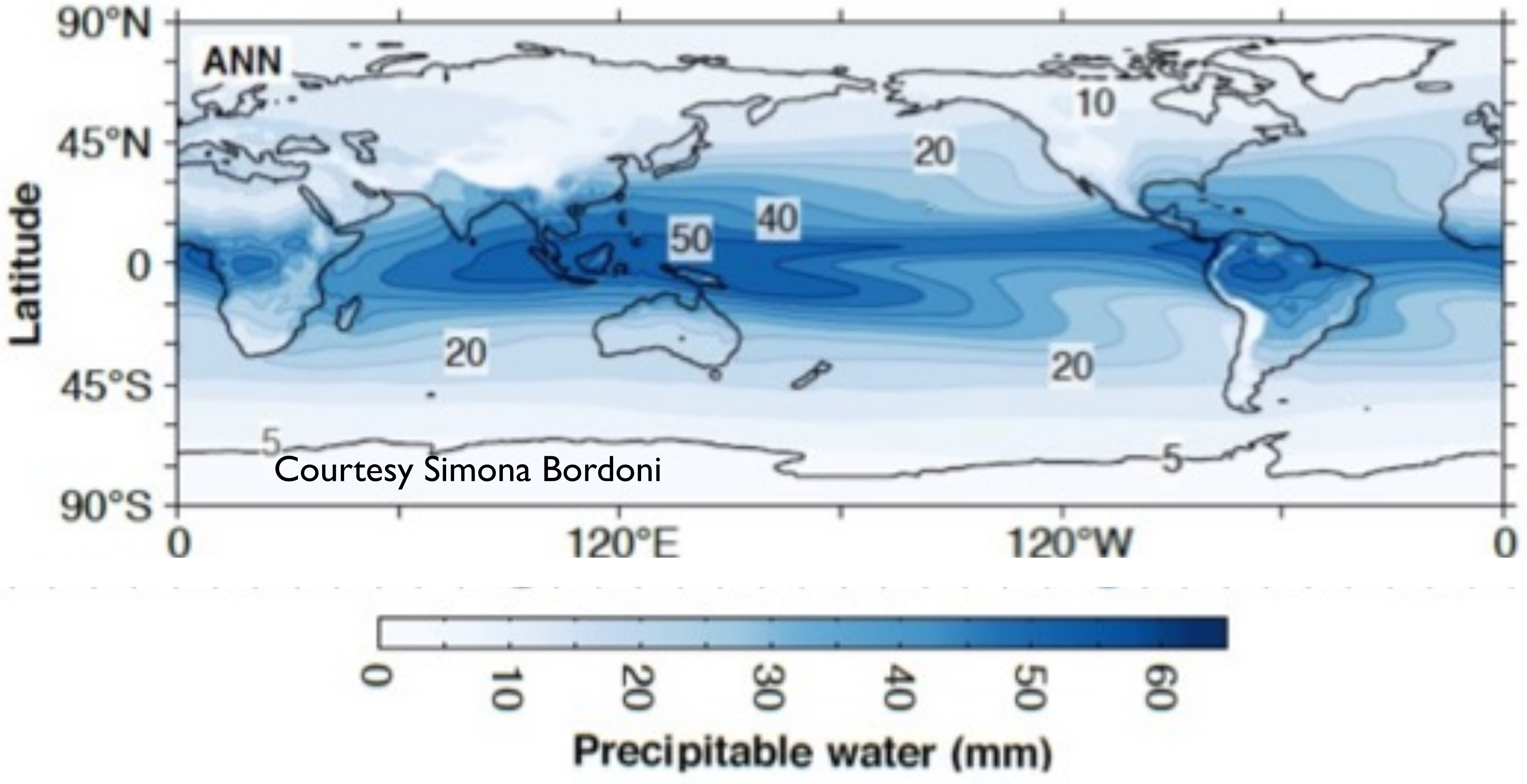


Convection dries in mean (produces precipitation!)

a) Locally moistens

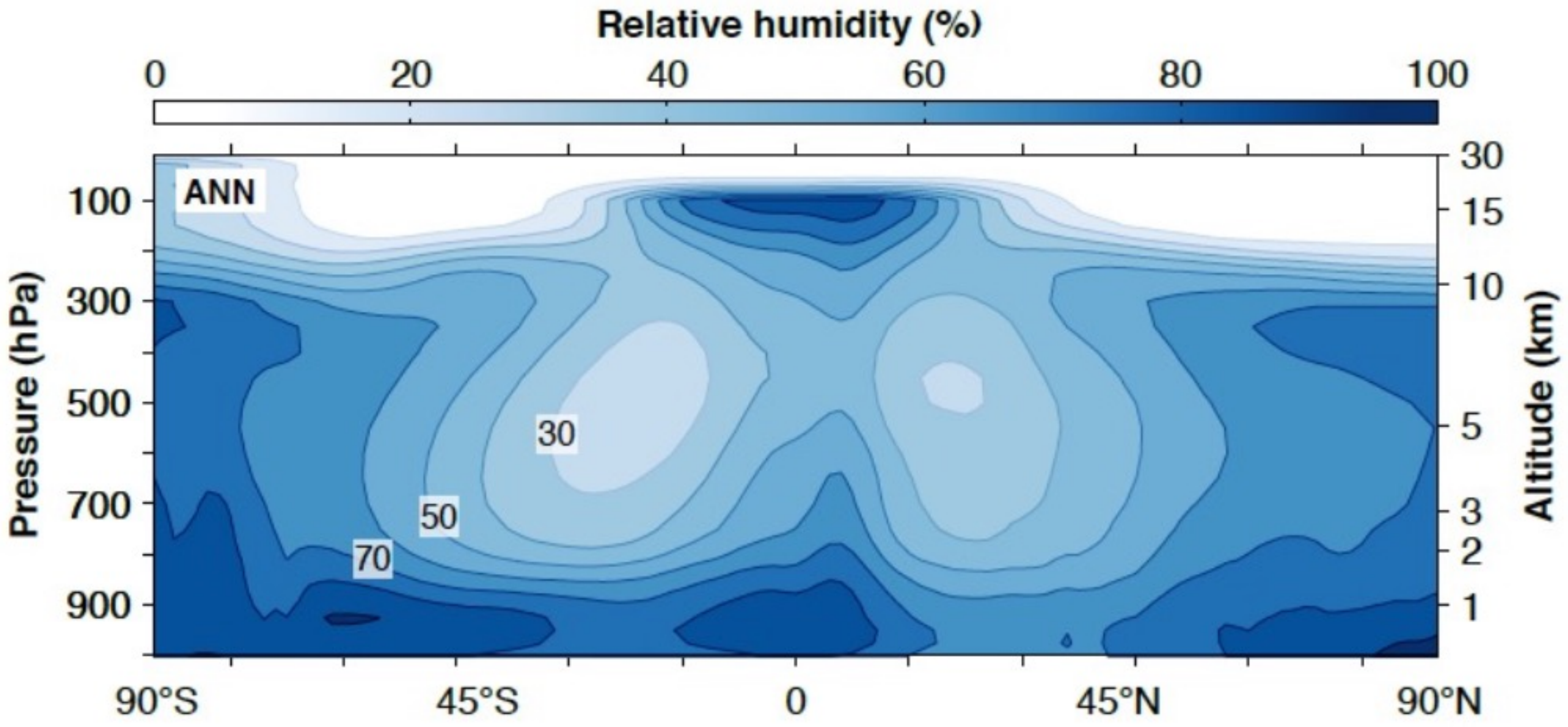
Courtesy: Bjorn Stevens

b) drying far field through subsidence (fast gravity wave)

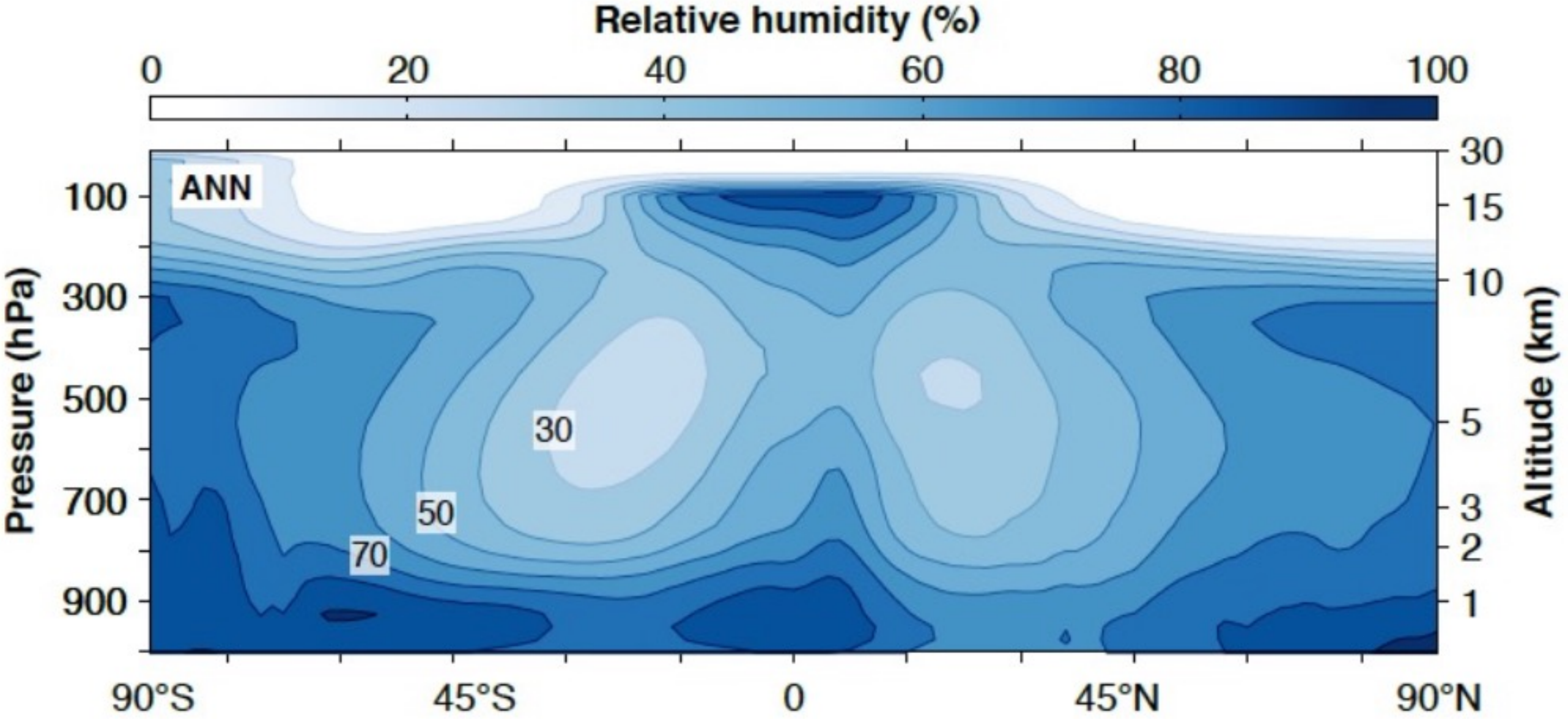


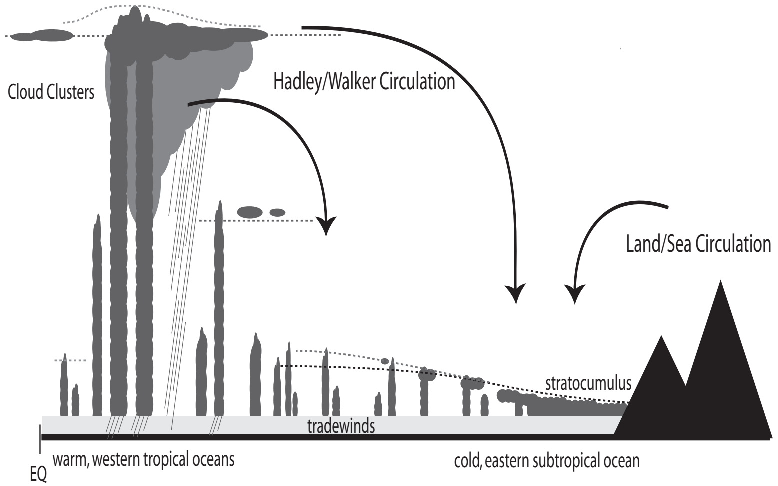
Total Column water vapor much higher in convecting regions

Pierre Humbert 1995 “Radiator Fins” highlights importance of dry descending regions to allow tropics to cool

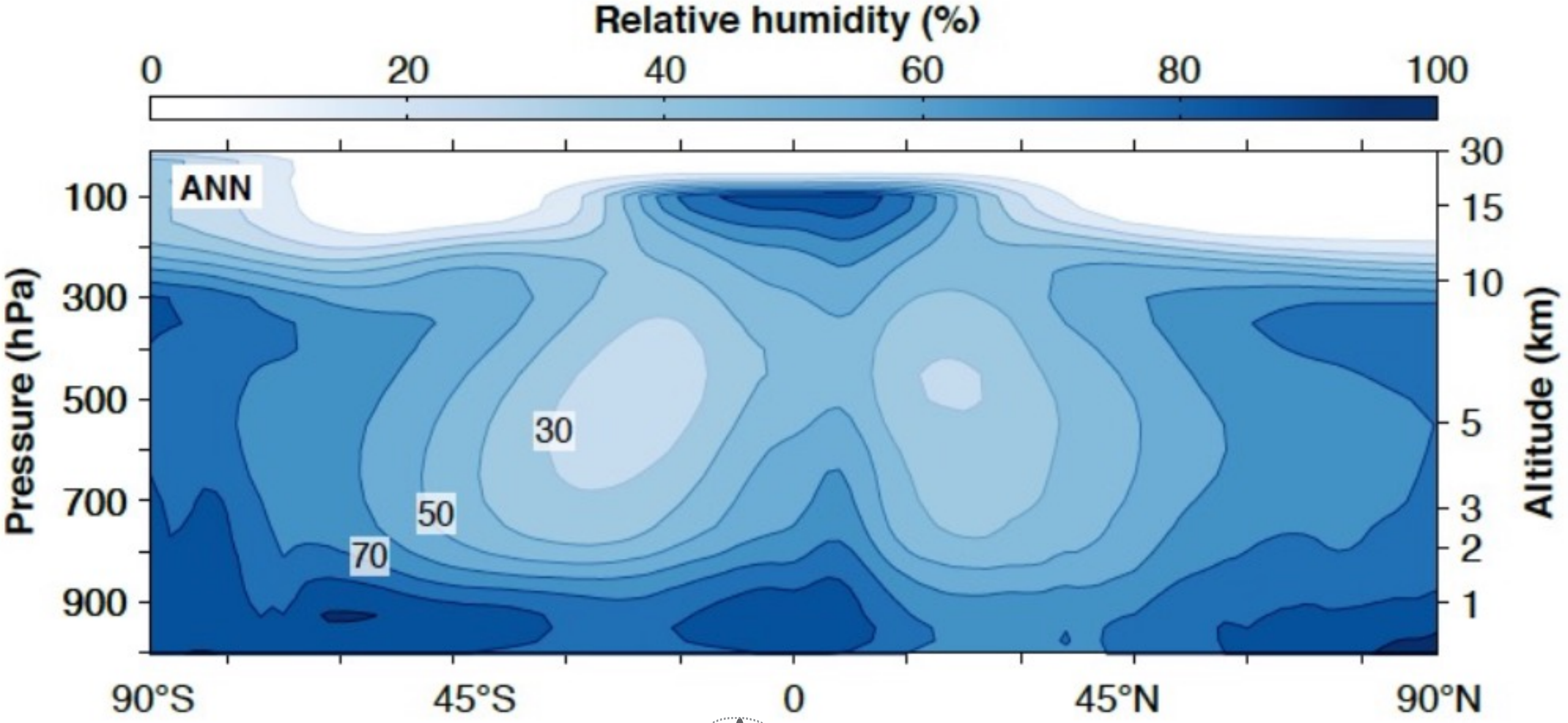


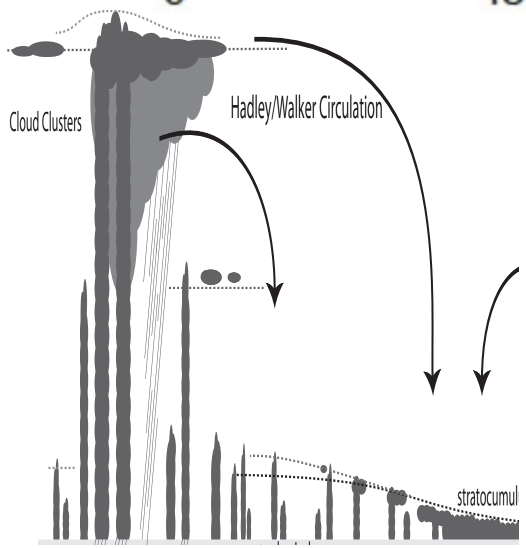
Courtesy Simona Bordoni



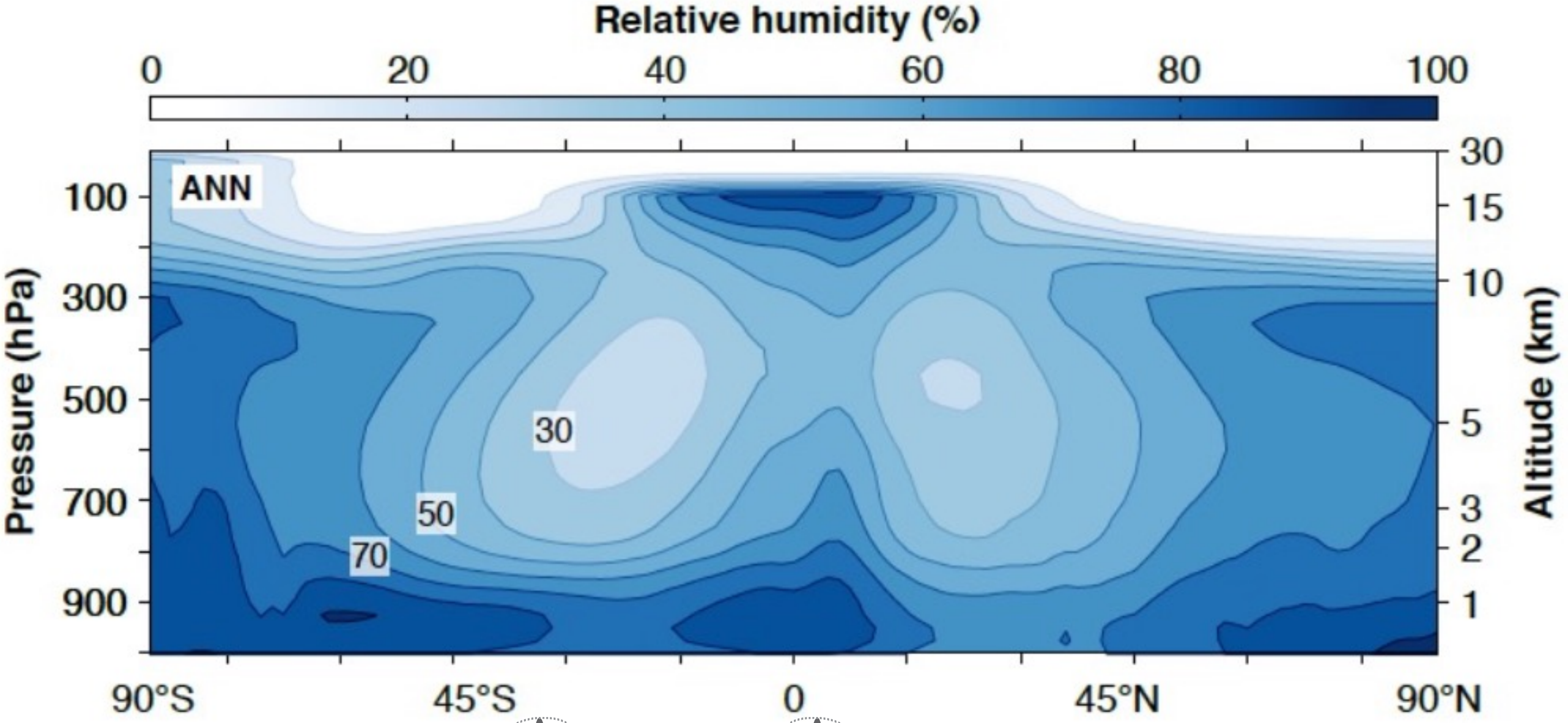


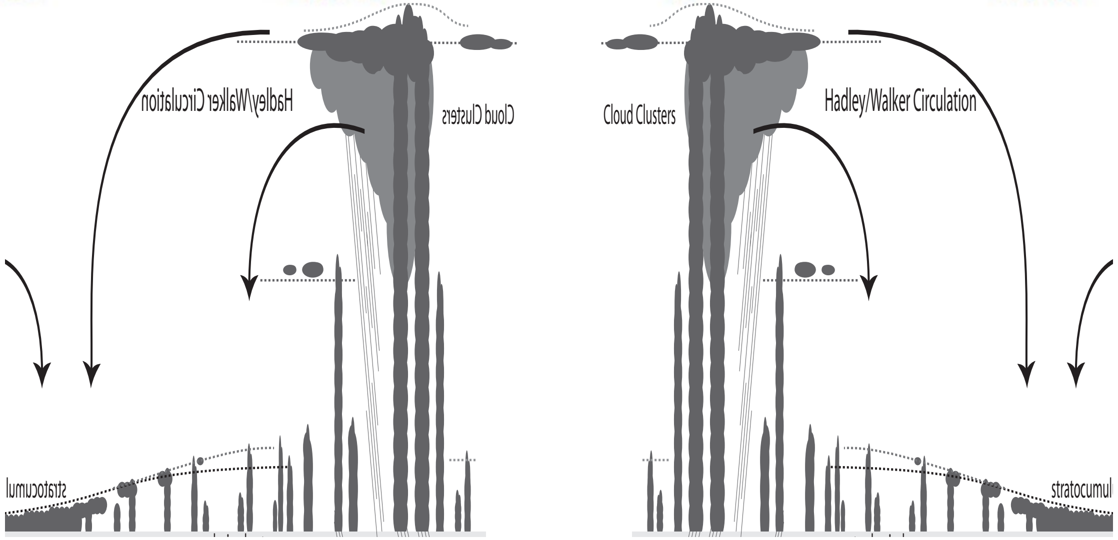
Courtesy Simona Bordoni



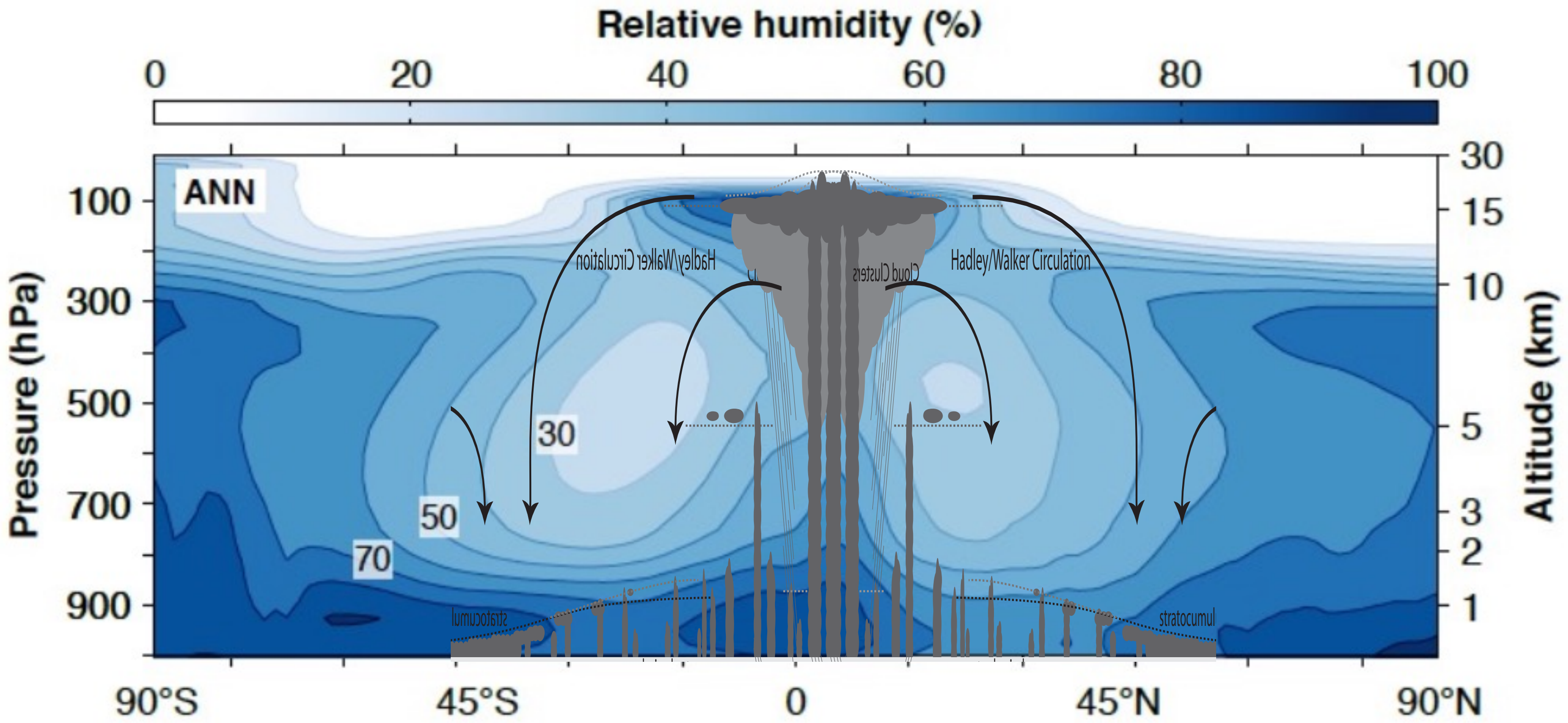


Courtesy Simona Bordoni



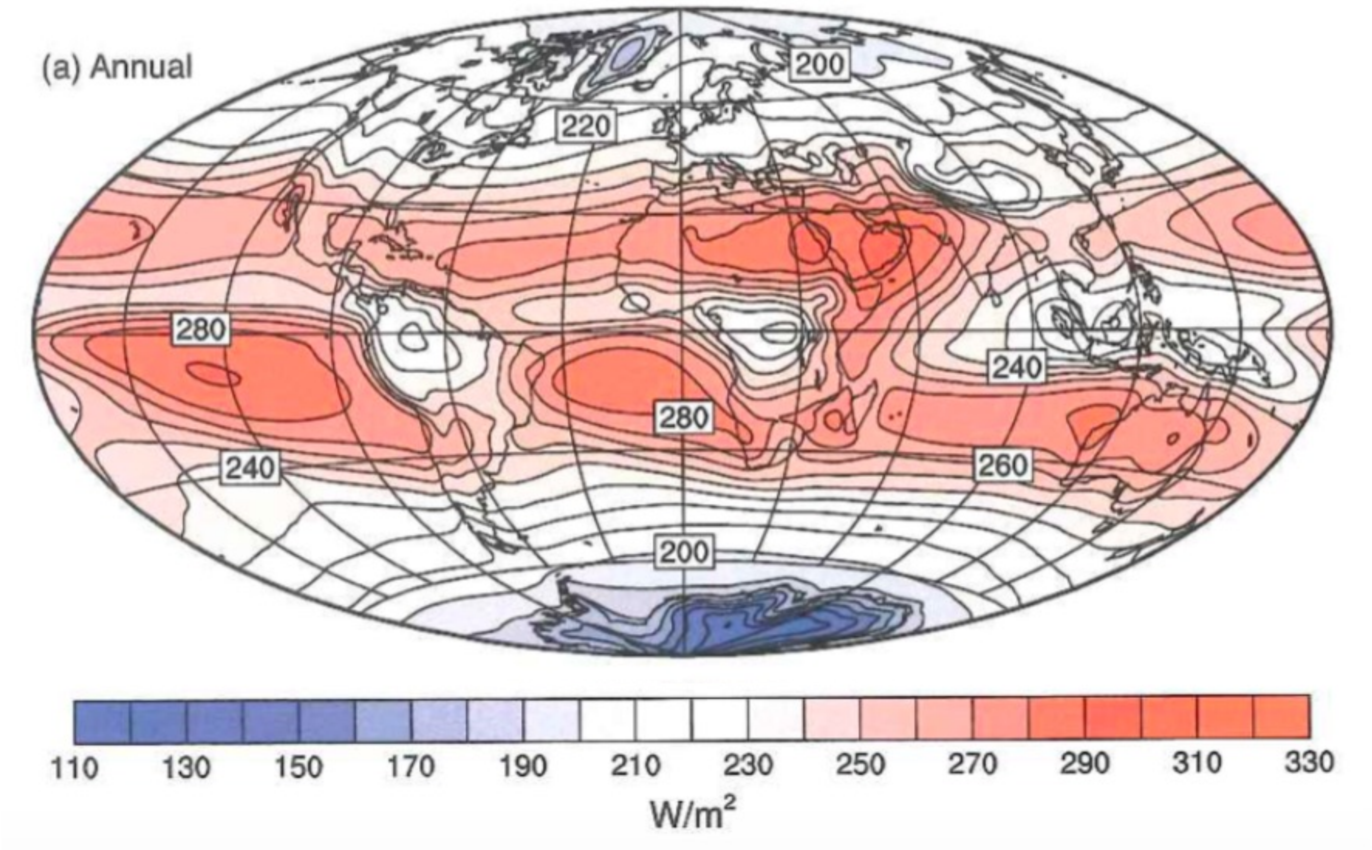


Courtesy Simona Bordoni



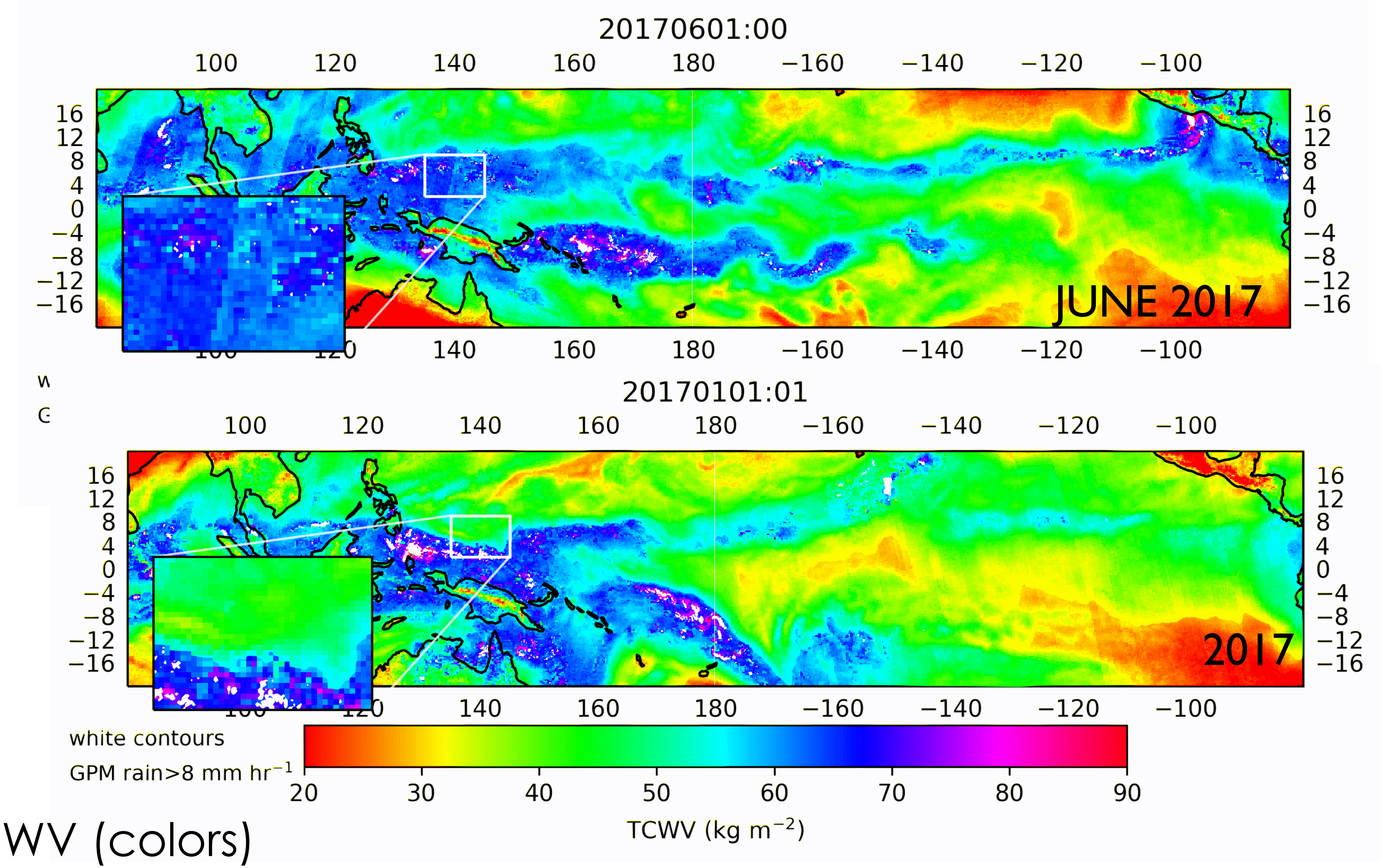
Courtesy Simona Bordoni

The dryness of the subtropics means these are the regions of maximum OLR



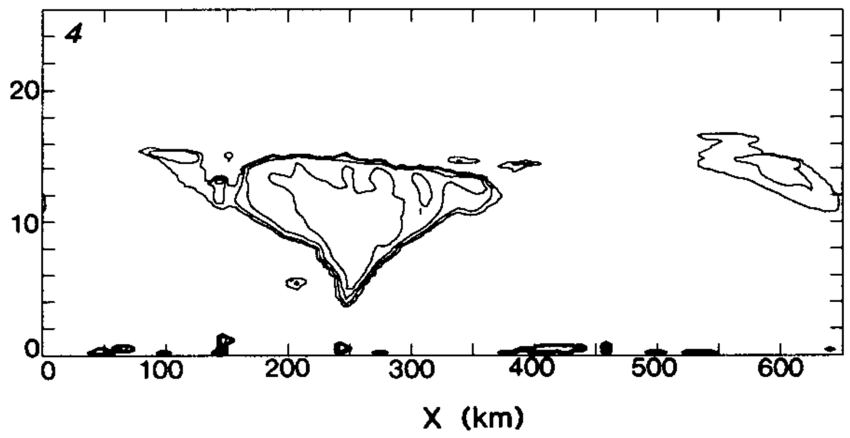
Dennis Hartmann Global Climatology

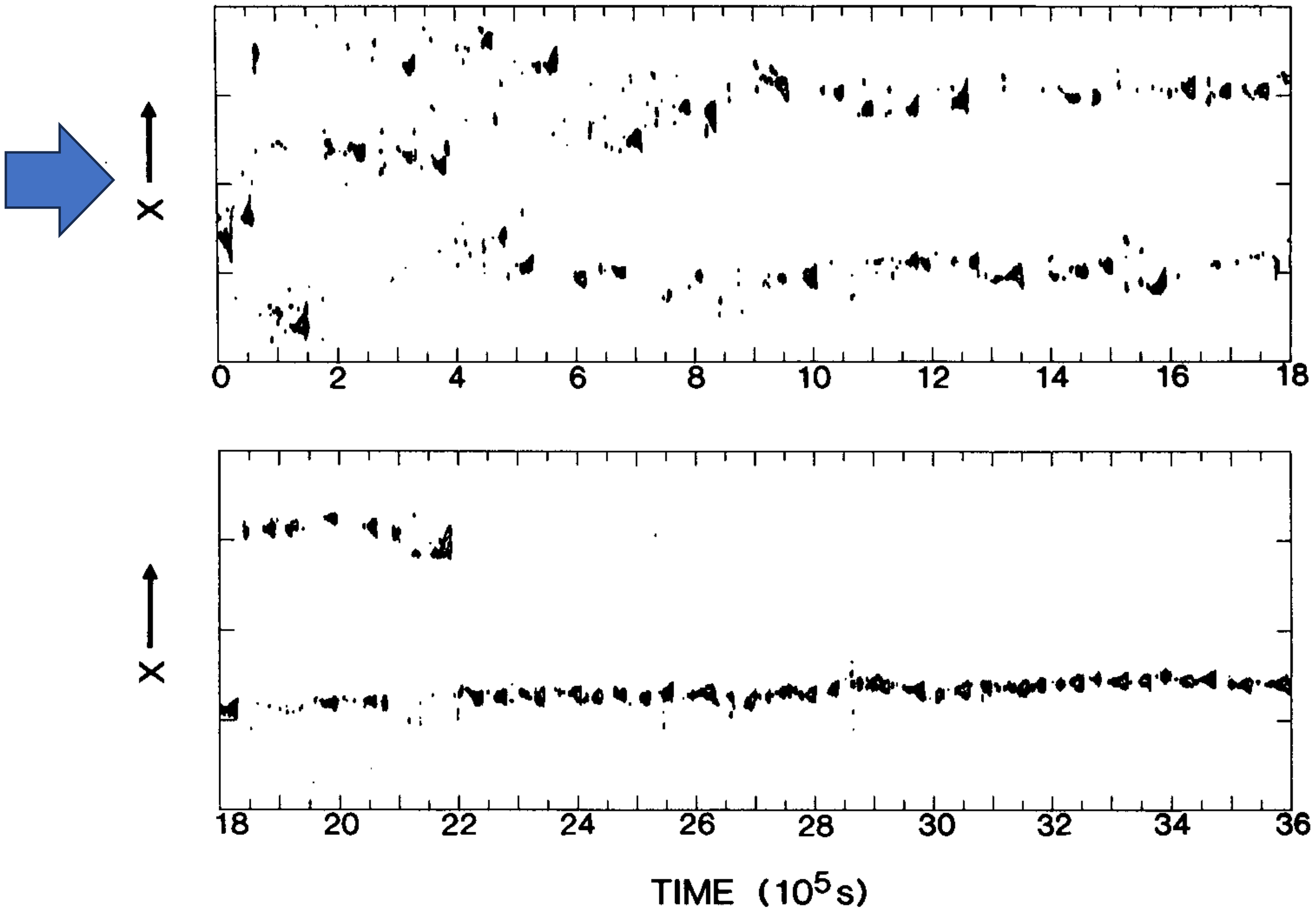
but much more complex than this at spatial scales O(100-500)km



Mimic TCWV (colors)
Imerg rain (white)

1. What is convective organisation?



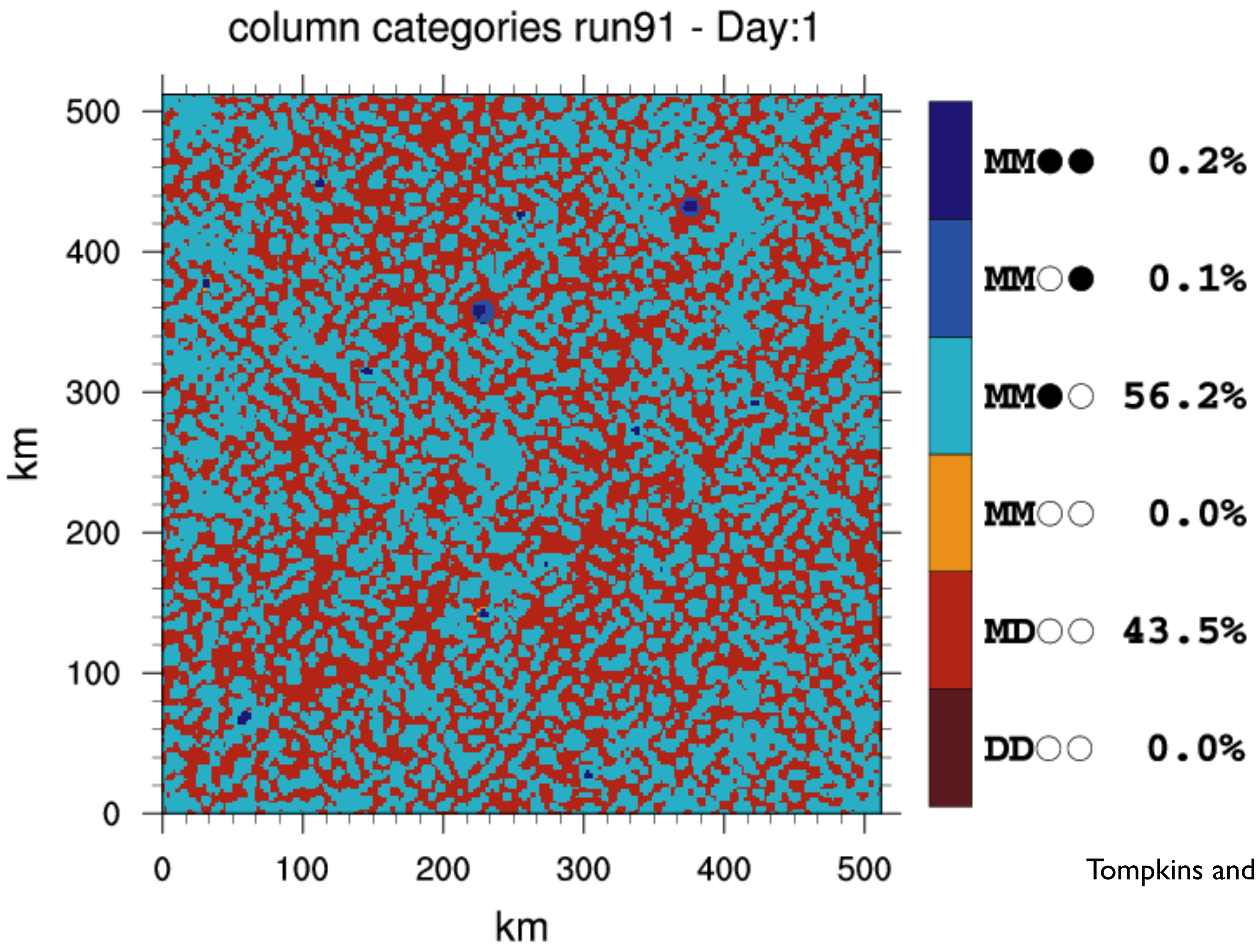


- Held et al. 1993 640km 2D cloud model with 5km resolution
- Surface fluxes over fixed sea surface temperature, radiative cooling
- Convection collapses to a single cell

3D CRM domain. First convection is random
But if you wait after 5-20 days something remarkable happens

3D experiment typical framework

- Convection permitting resolutions 0.5-2 km [2km]
- 100-10000 km dimensions (square or "bowling alley") [500-1000]
- Interactive radiation
- Fixed (sea) surface lower boundary (also land and slab oceans)
- Period boundary conditions
- No imposed mean wind conditions (or even removed)

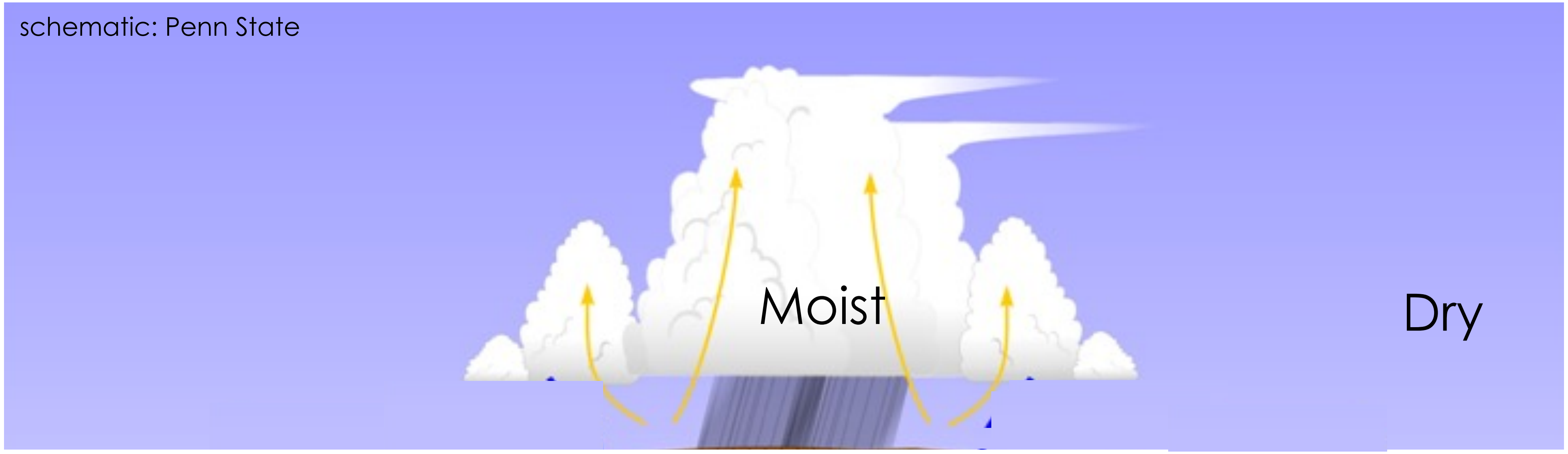


Tompkins and Semie 2017

Convection forms cluster surrounded by clear areas

Clustering: Thermodynamic and dynamic

Water vapor feedback



Convection Moisten local environments

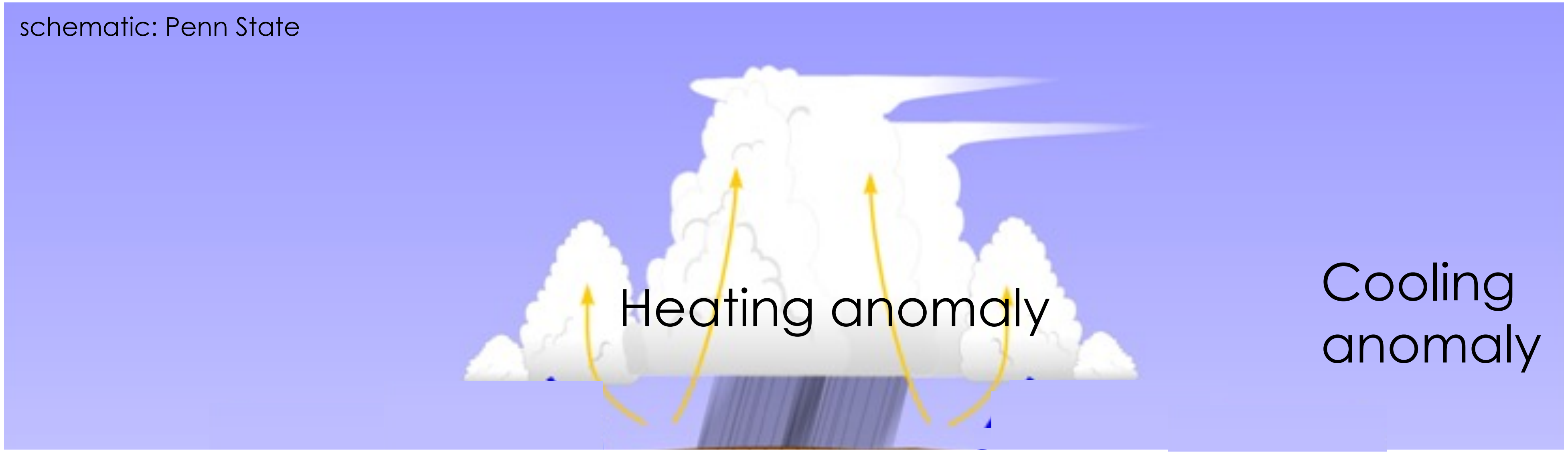
Dry Environments inhibit convection

Moisture Modes: advective and diabatic processes sustain a net import of column moist static energy

See Lucas et al. 20 … Back and Bretherton 2006 and Raymond…

Clustering: Thermodynamic and dynamic

Radiative Feedback

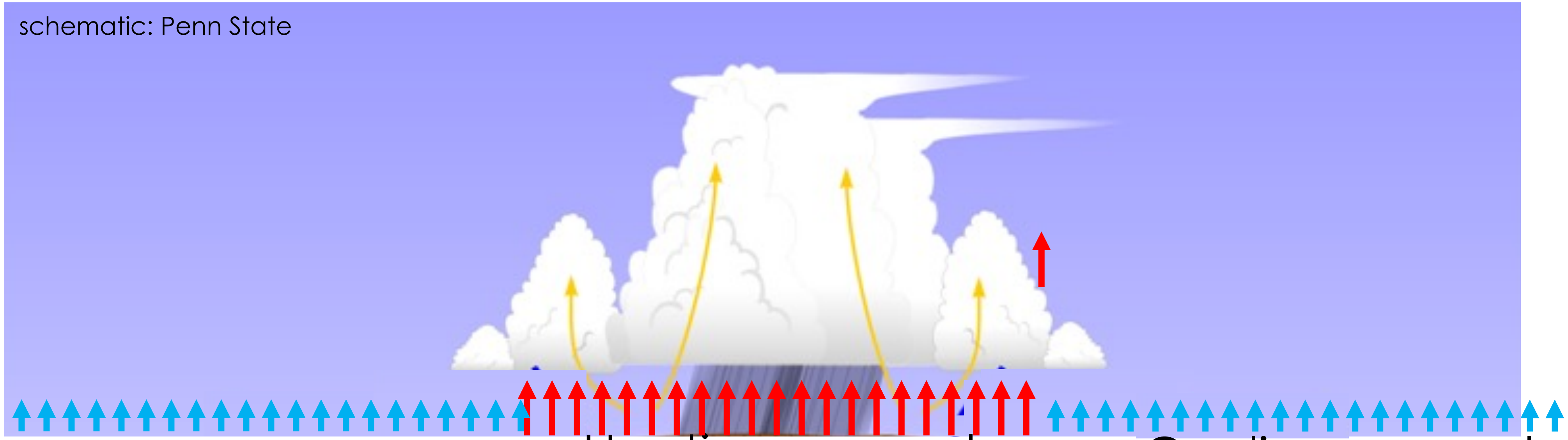


Convection creates heterogeneity in clouds/humidity fields

Radiative heating response drives convergence to convective regions

Clustering: Thermodynamic and dynamic

Surface Flux Feedback



Heating anomaly

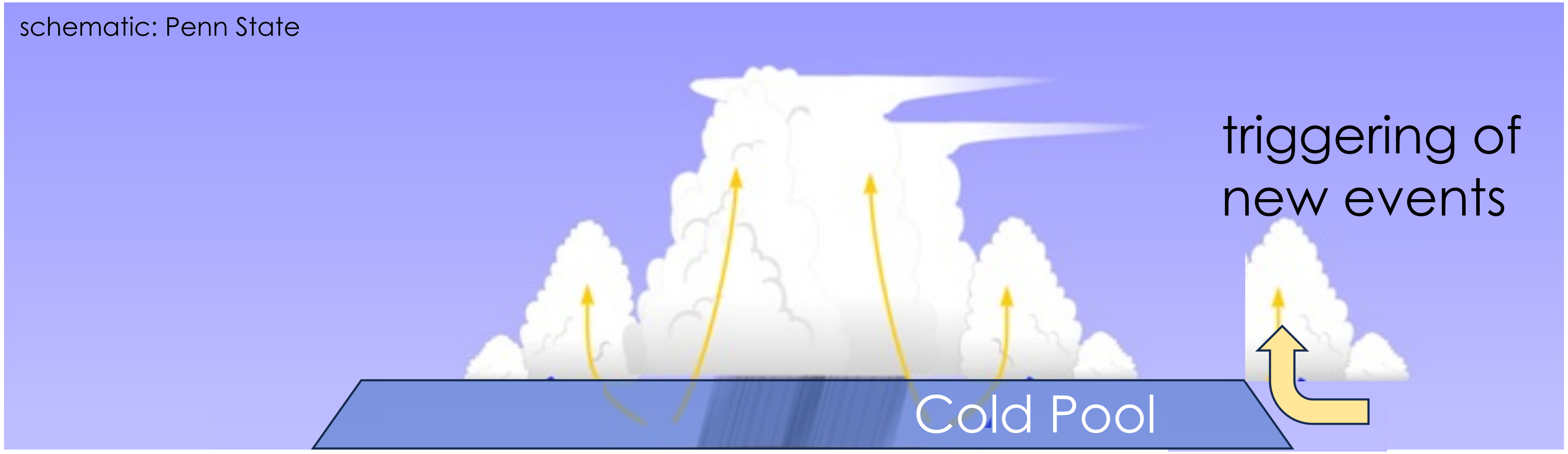
Cooling anomaly

Convection impacts winds (and boundary layer stability

surface fluxes enhanced in convection region/import of energy

Clustering: Thermodynamic and dynamic

Role of Cold Pools

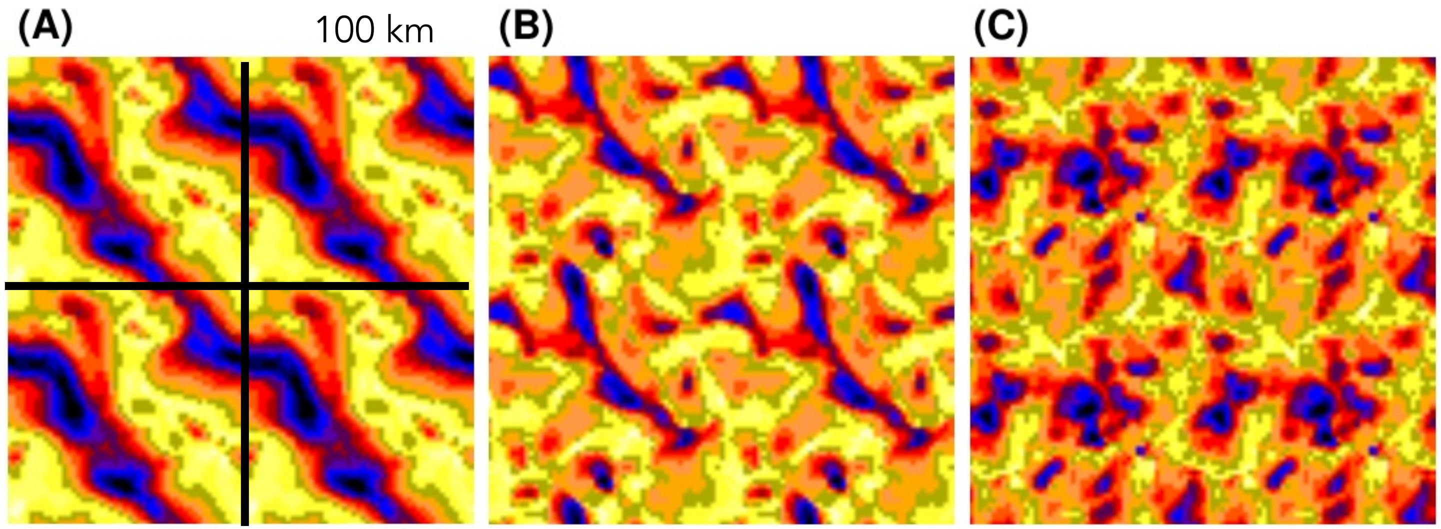


Convection cold pools create boundary layer thermodynamic and dynamic heterogeneity

This triggers new convection at edge of mature cold pools / colliding pools

Which processes contribute to organisation?

boundary layer humidity

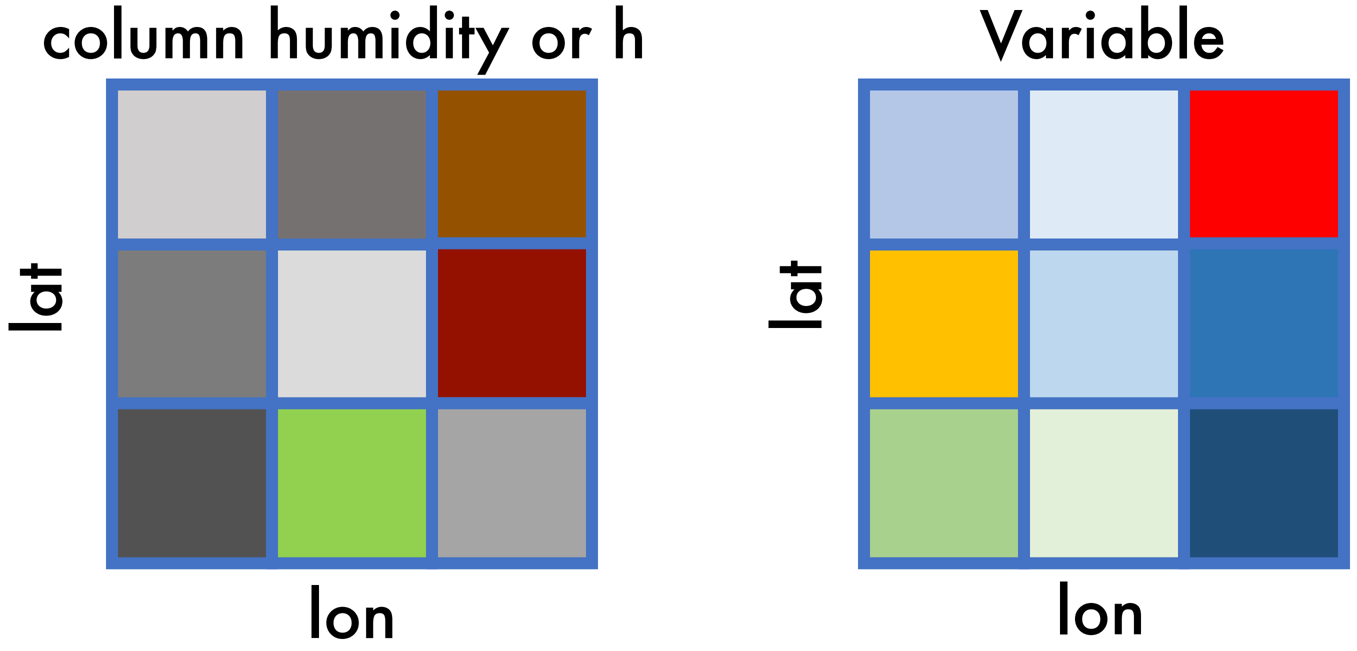


Tompkins and Craig 98a

Interactive Radiation and surface fluxes | Homogenize surface fluxes | Homogenize radiation

these early "mechanism denial" experiments indicated that radiative fluxes were key to clustering, but that surface fluxes played a secondary role

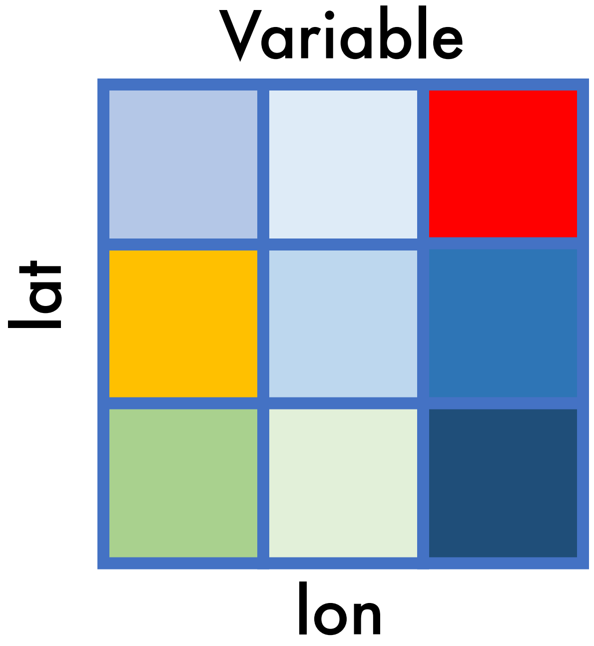
We can examine variables ordered by column humidity or (moist static) energy

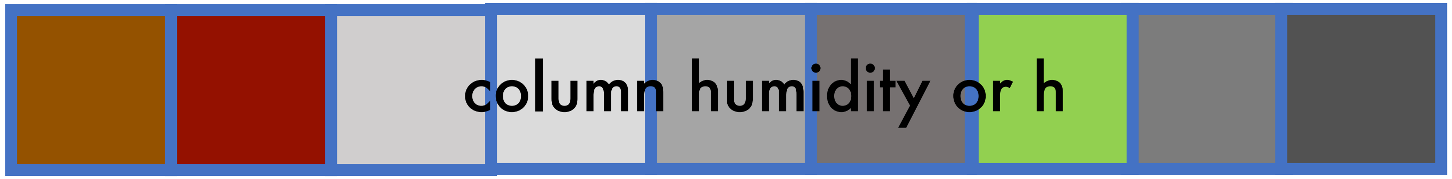


This approach pioneered by Bretherton and later Wing et al.

Moisture Modes: advective and diabatic processes sustain a net import of column moist static energy

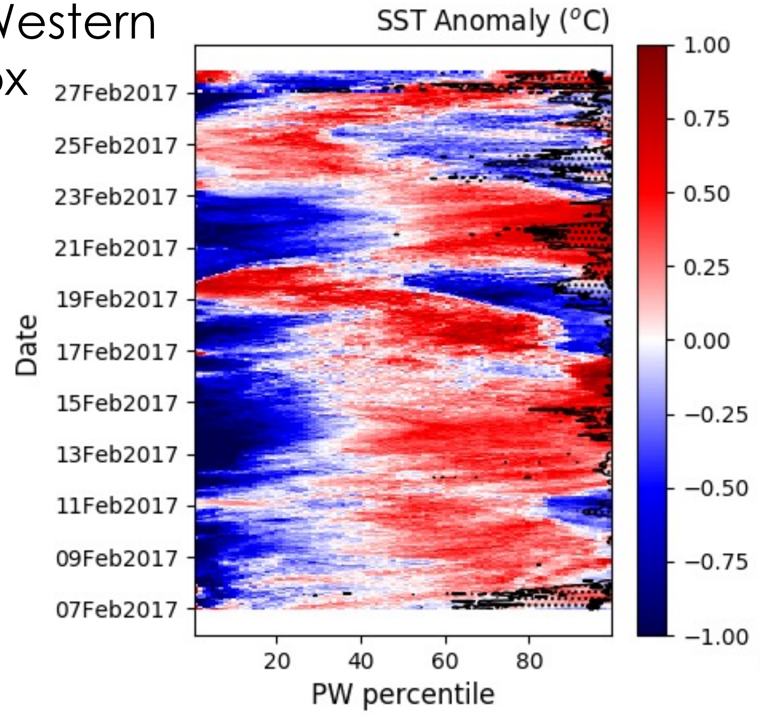
We can examine variables ordered by column humidity or (moist static) energy

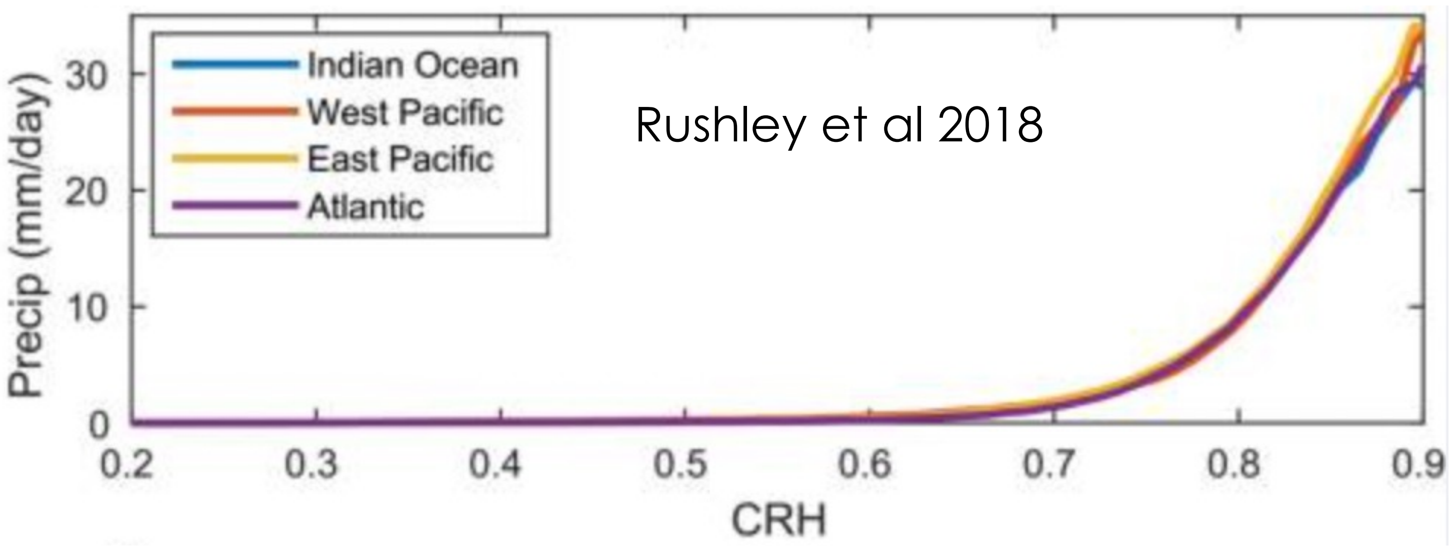




We can examine variables ordered by column humidity or (moist static) energy

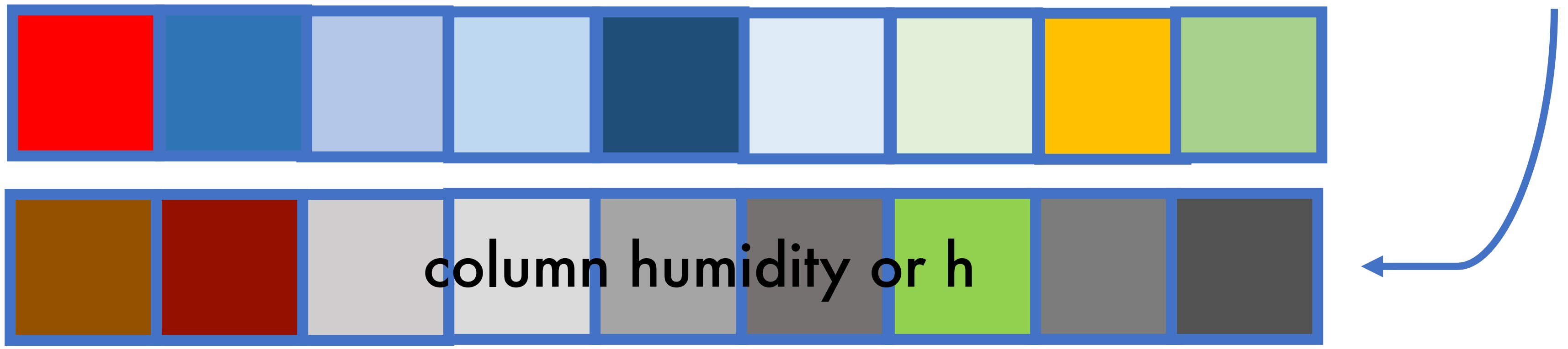
Tropical Western Pacific Box





Rushley et al 2018

Variable



Convection occurs here!

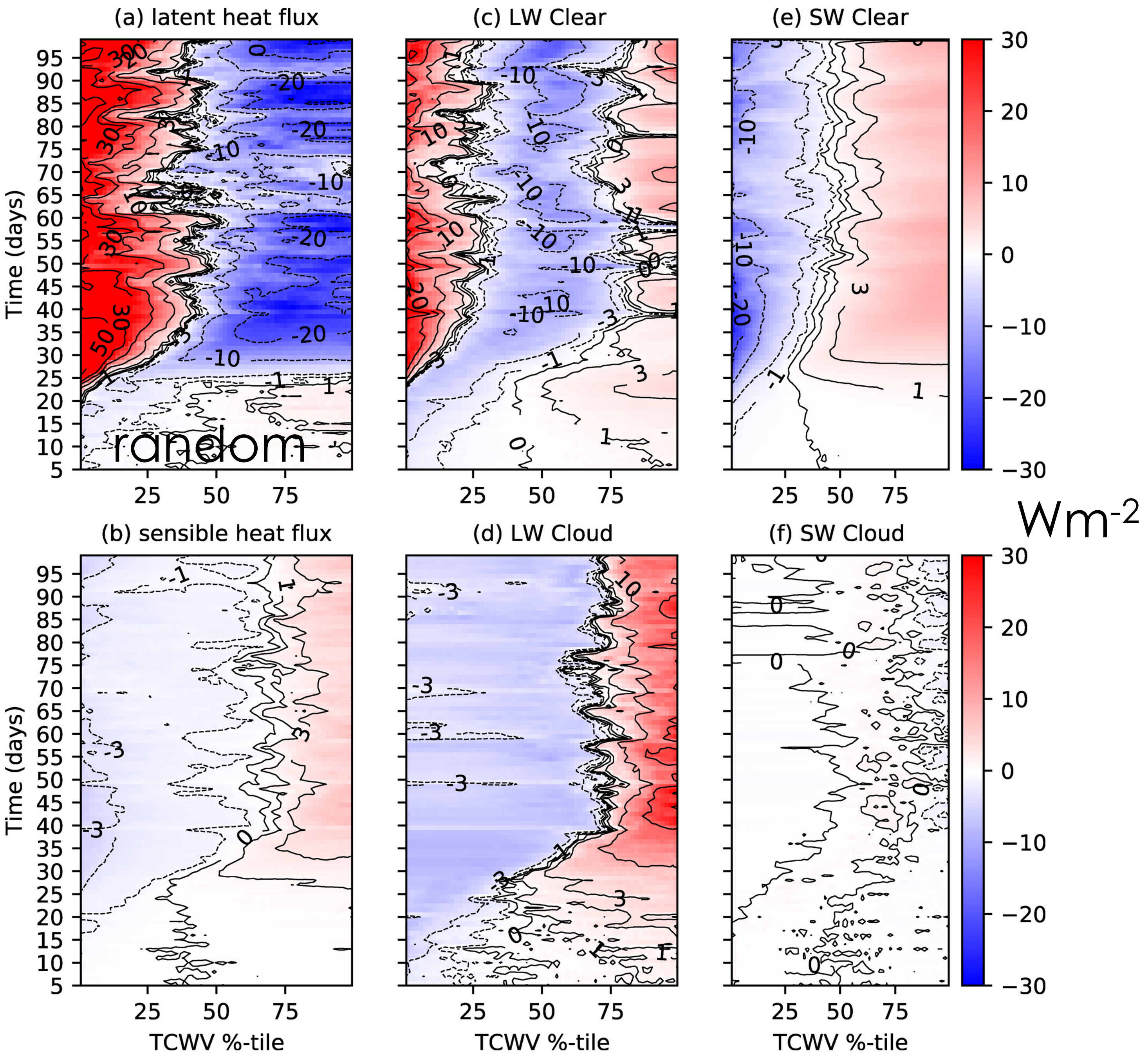
day 1-20 random
day 30+ clustered

Longwave-cloud forcing key (clouds black body in infra-red and thus high-cloud heat column.

Latent heat flux secondary

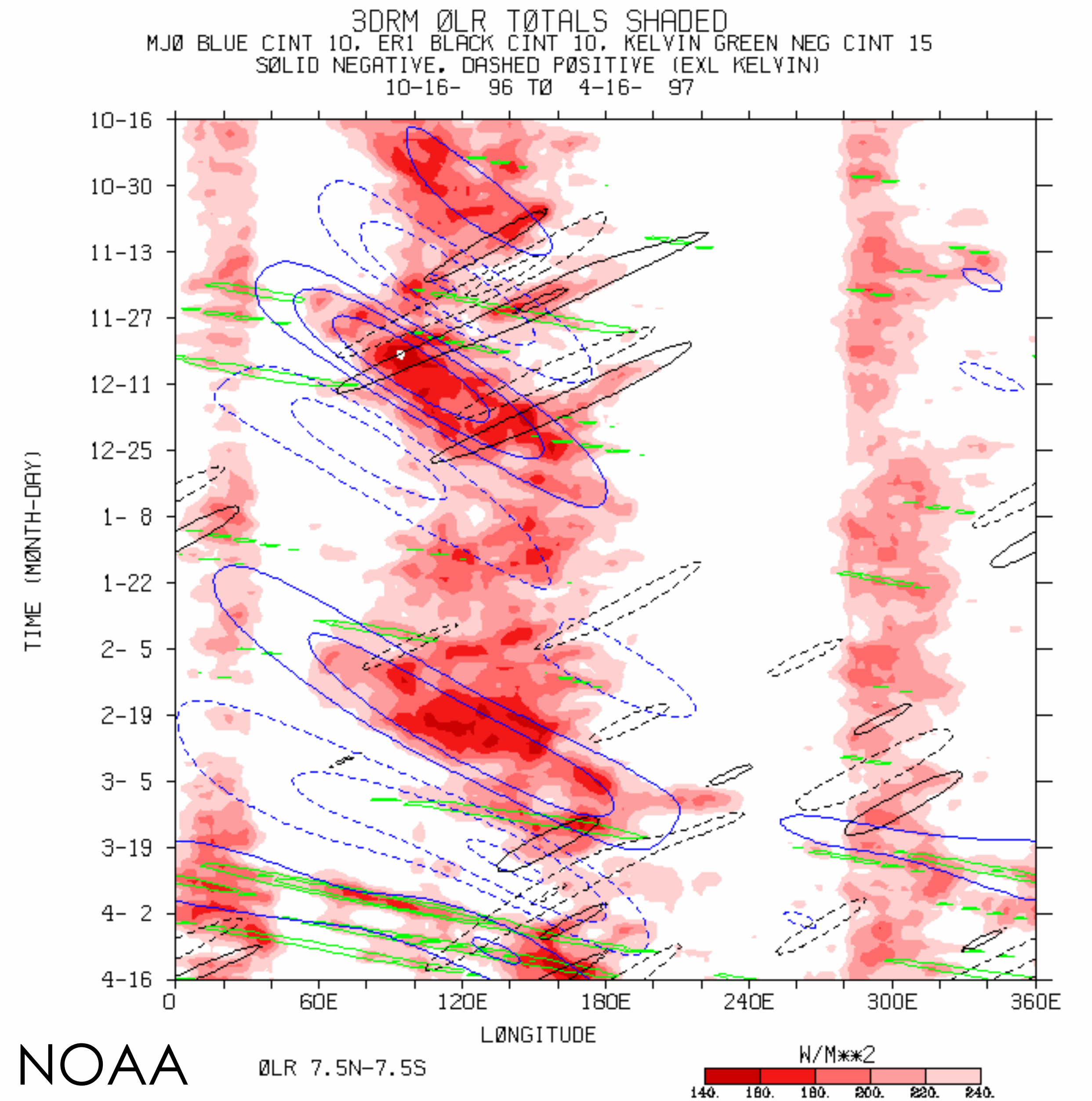
See also Wing et al 2014

Note: Difficult to isolate impact of cold pools or role of water vapor feedback with this method



Tompkins and Semie 2021

What about "real" convective organization?
What role do these mechanisms play?



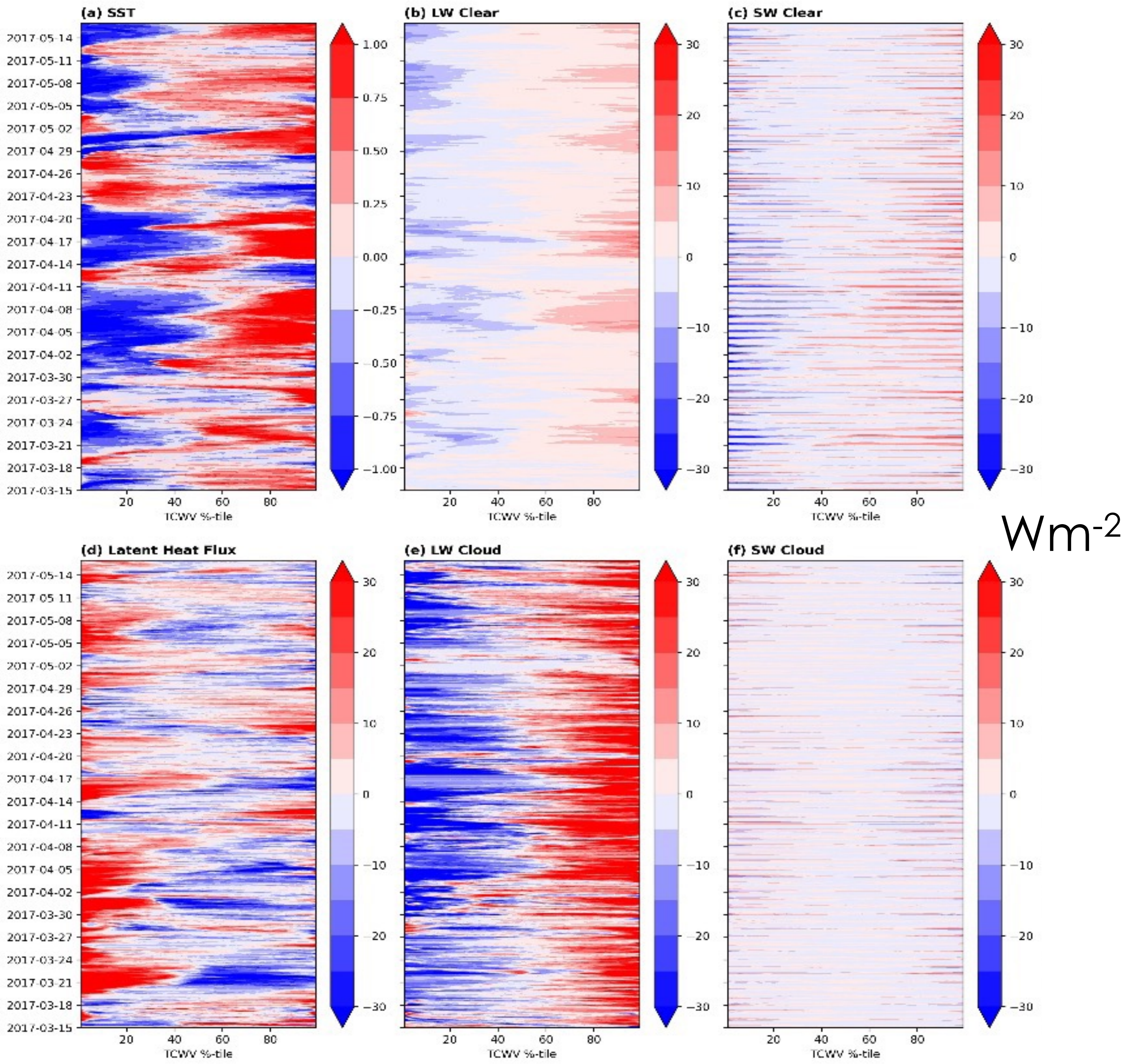
PSL NOAA

135E-145E, 2-9N box

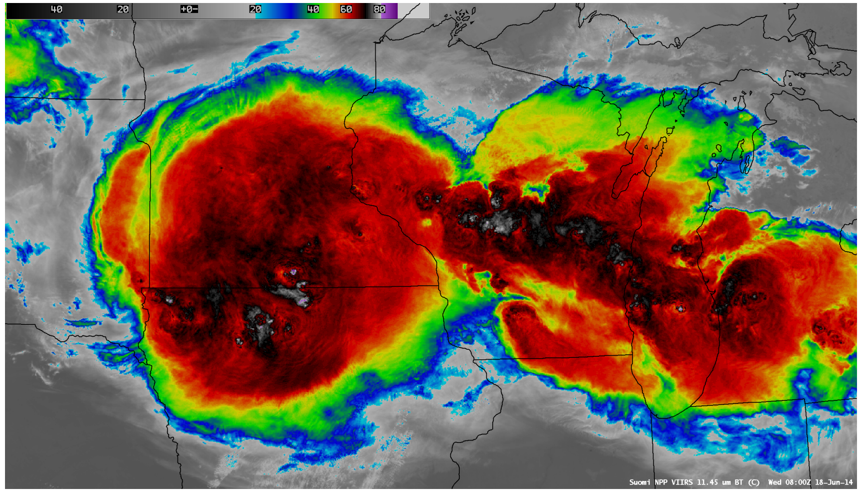
Diabatic Forcing in the tropical Western Pacific

The diabatic forcings are very similar to idealized simulations!

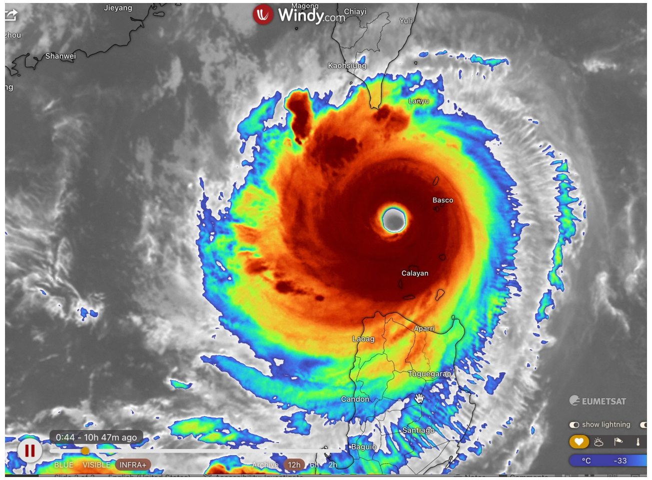
(Casallas et al. in prep)



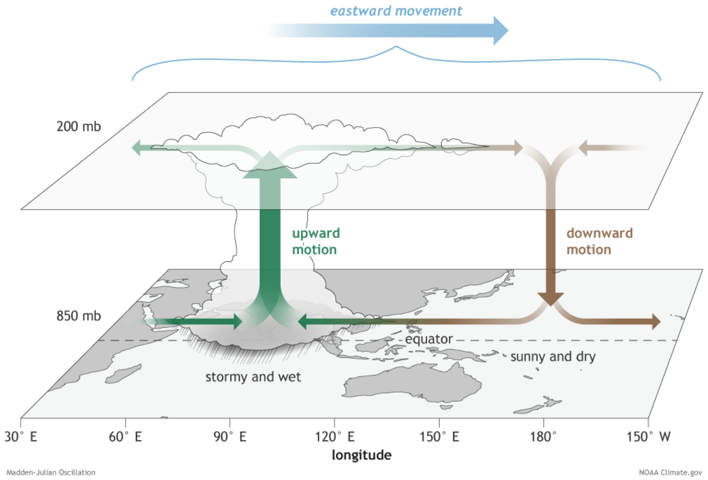
What about "real" convective organization? What role do these mechanisms play?



MCS



hurricanes



MJO

- Mesoscale convective systems, squall lines (cold pools)
- hurricanes (surface fluxes, radiation)
- tropical waves (moisture feedback, radiation)
- MJO (water vapor, radiation, surface fluxes)

tropical cyclones

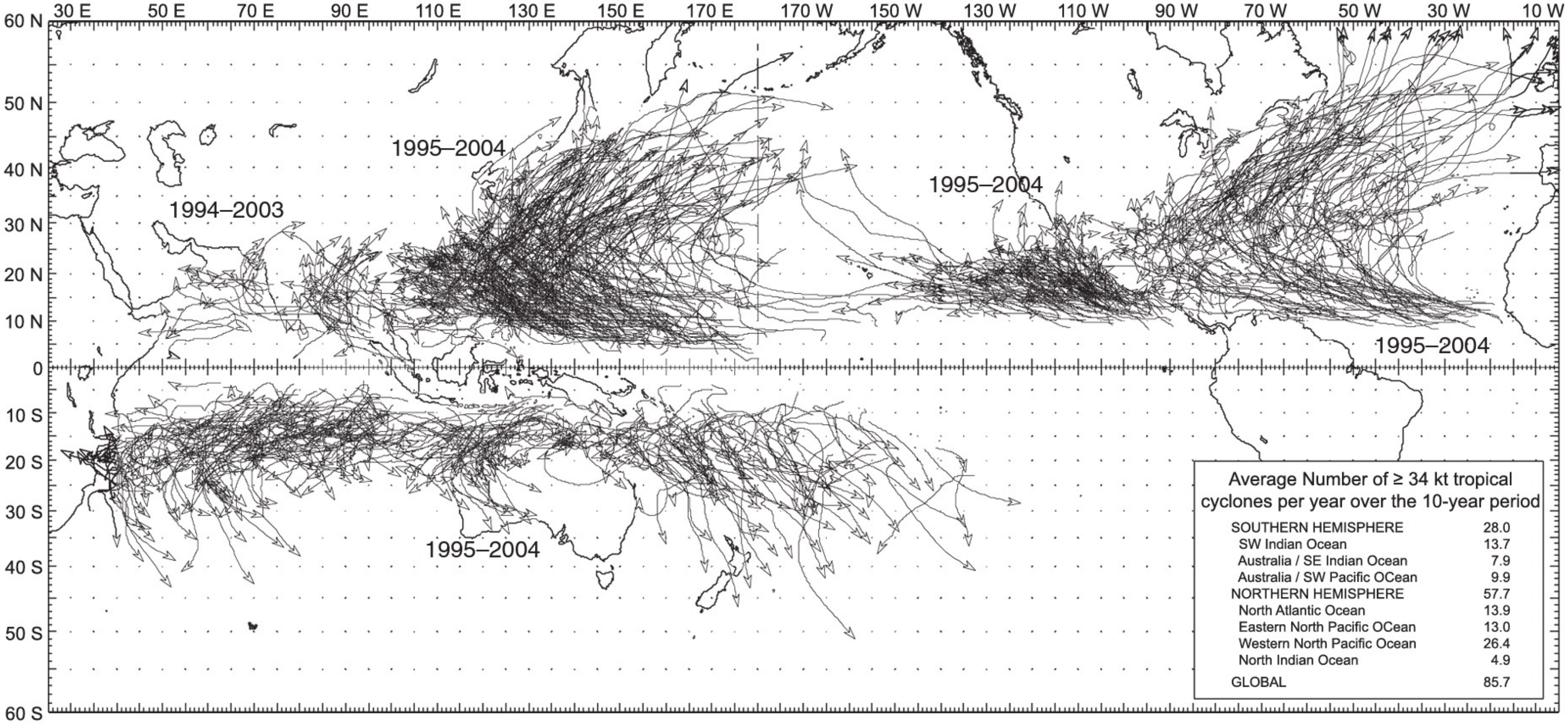
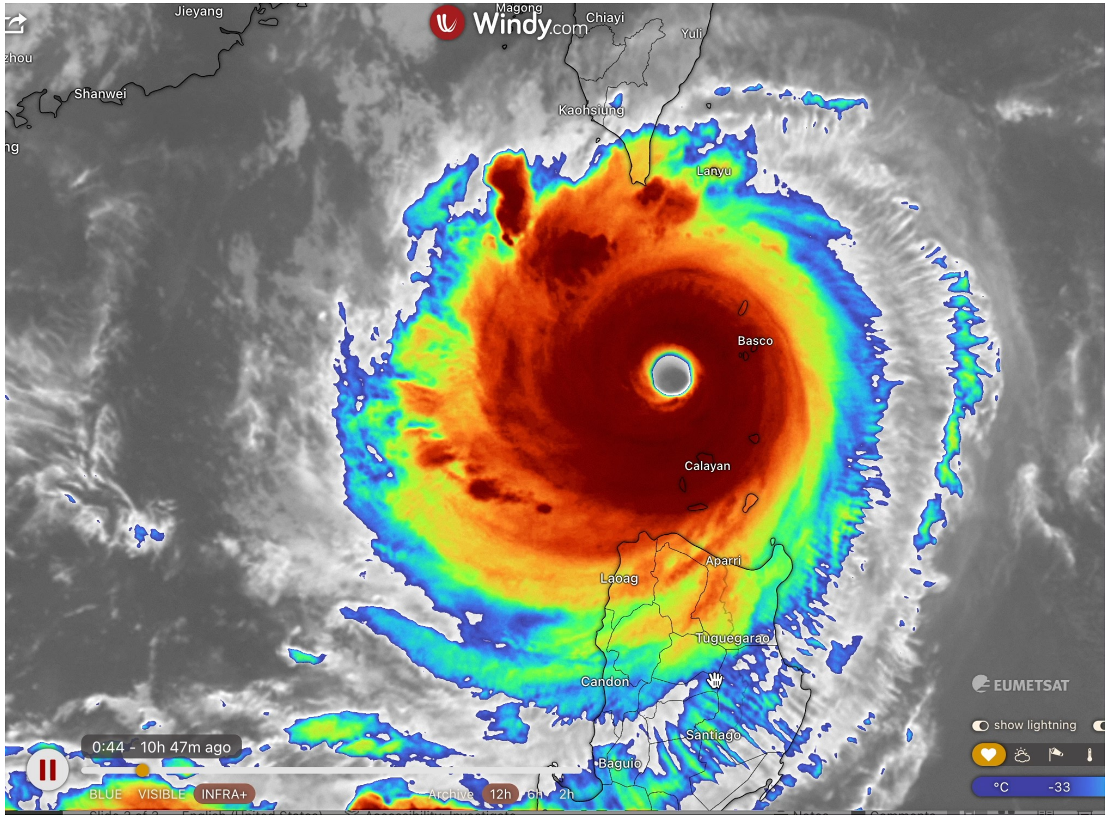
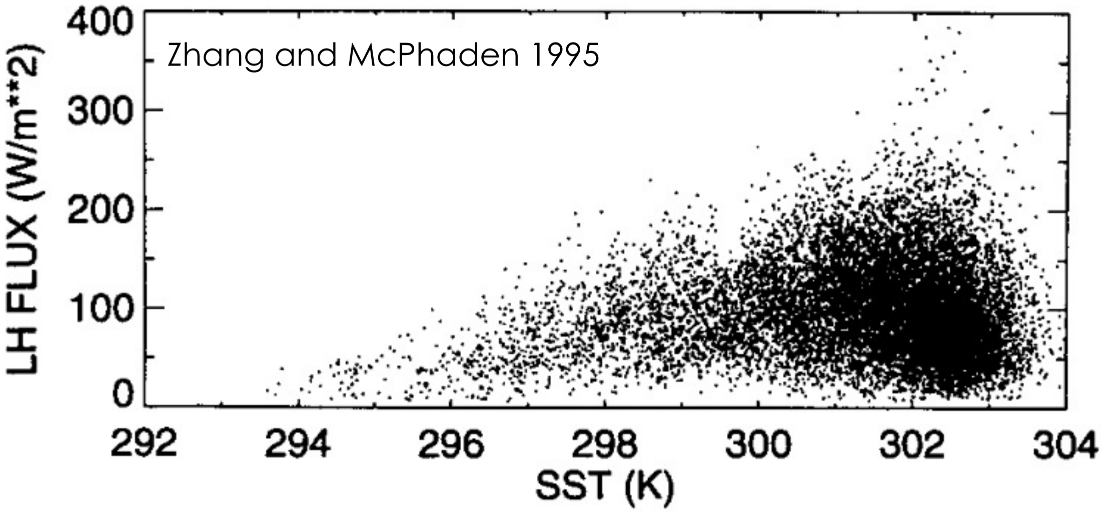


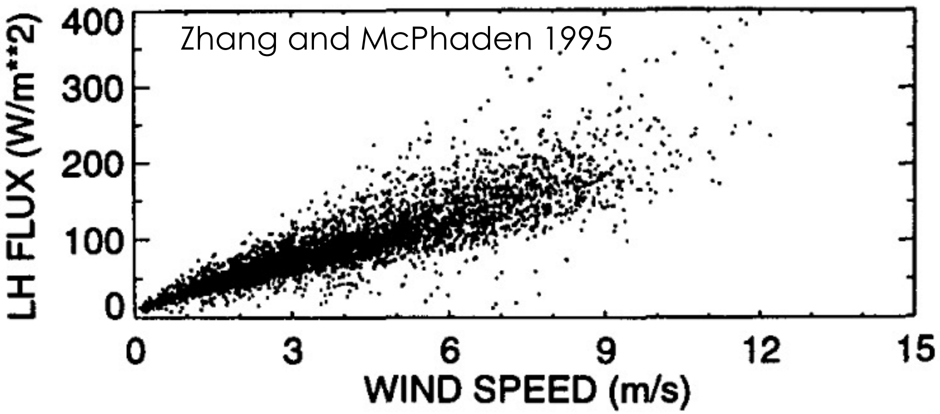
Fig. 9.17 Genesis locations and tracks of tropical cyclones with wind speeds of at least $17\,\mathrm{m\,s^{-1}}$ for the period of 1995–2004. (Adapted after Neumann 1993; Courtesy of Dr. Charles Neumann.)

typhoon (last week)

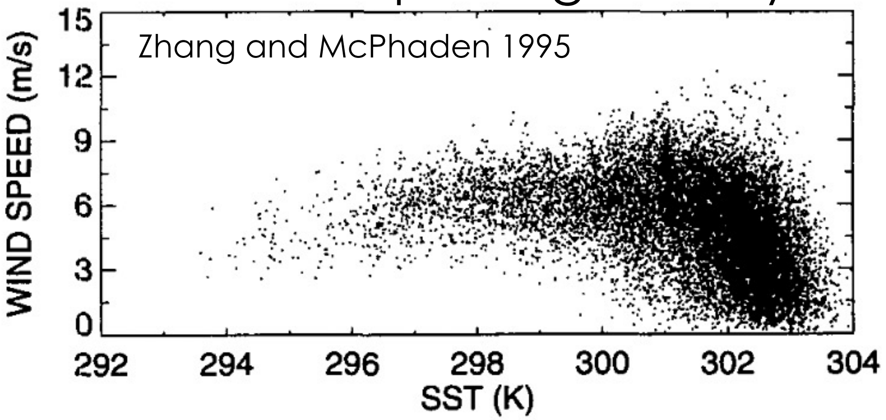




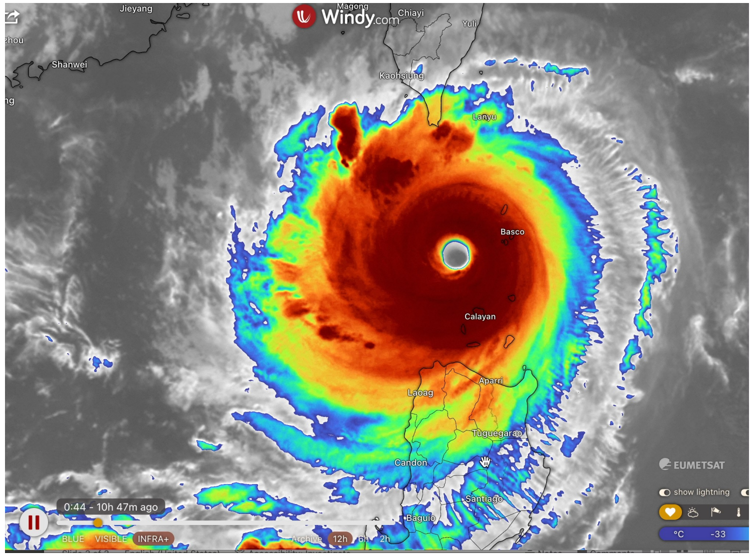
in general fluxes reduce over warmest SST (why?)



because wind speed generally lower



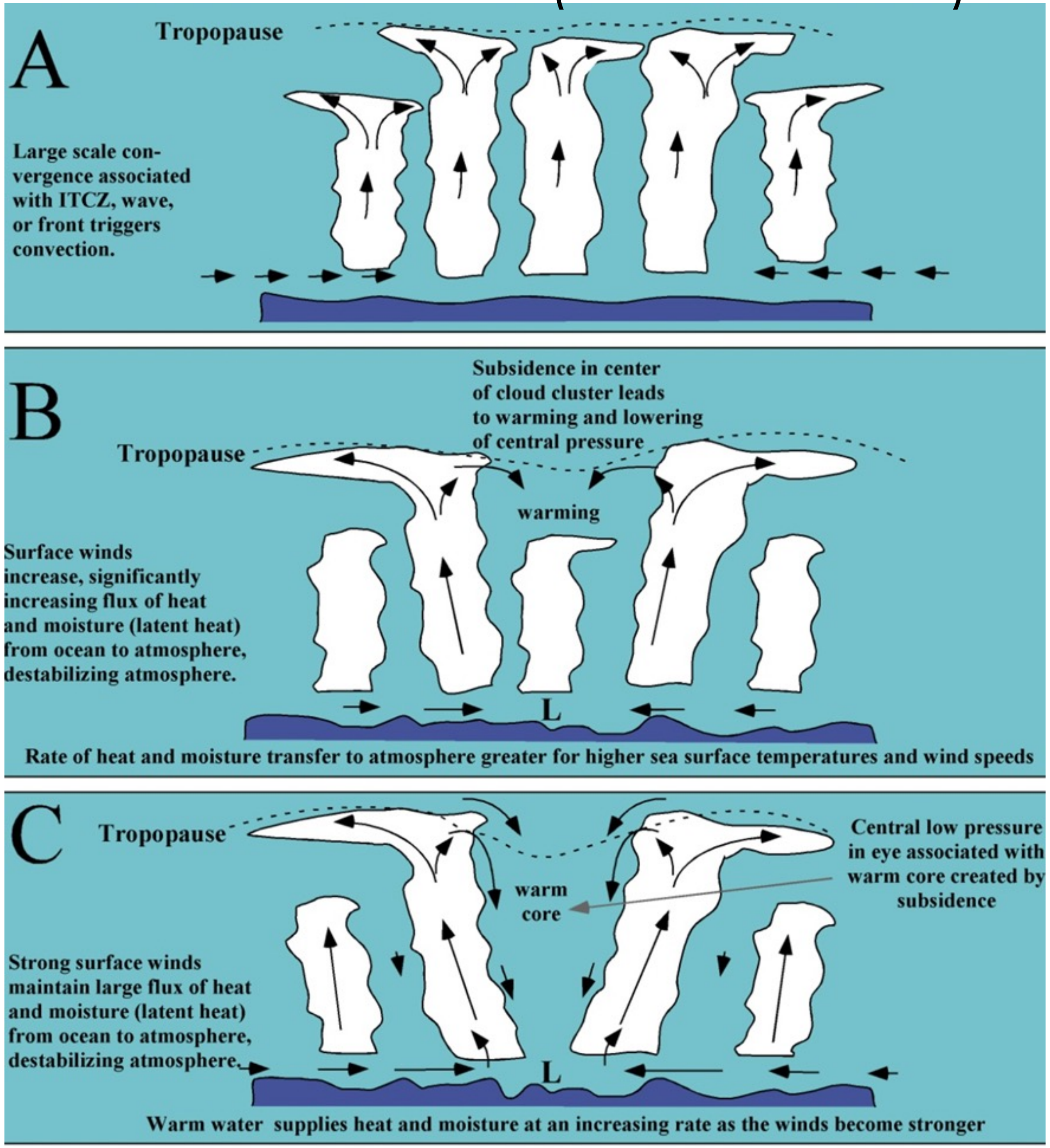
typhoon (last week)



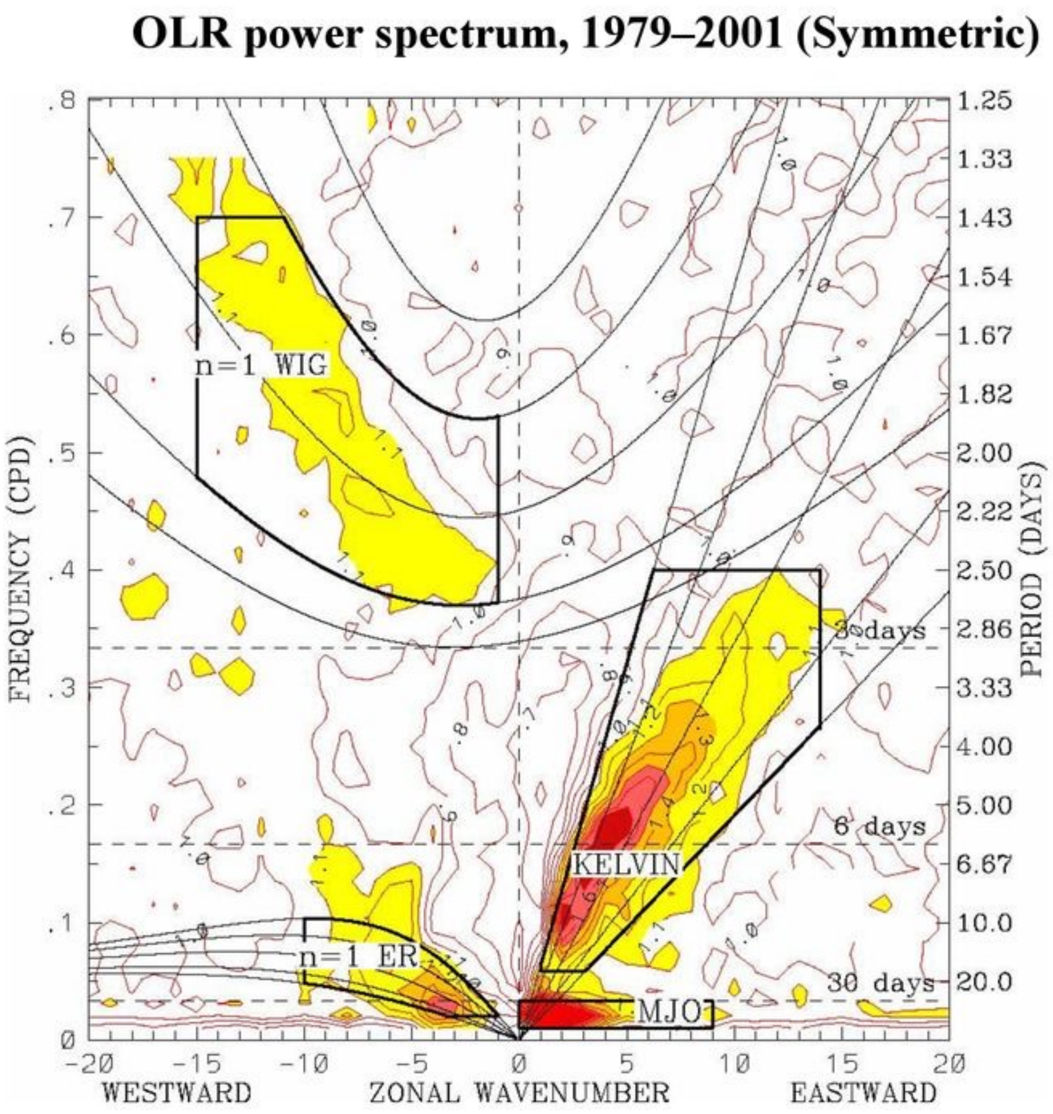
Hurricanes increase wind speed!
Role of surface flux feedback.
requires temperatures >27C

But studies also show role of radiative feedback (OLR-cloud), e.g. Ruppert et al 2020, PNAS

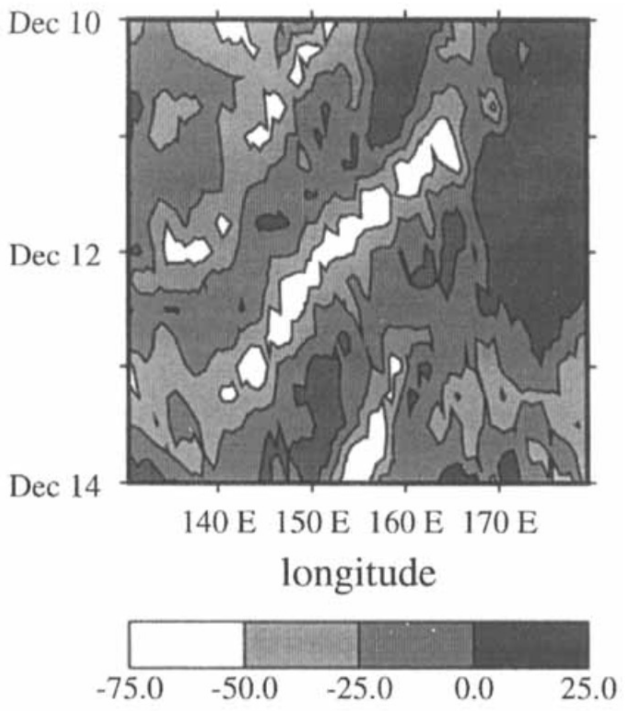
WISHE feedback (Emanuel 1987)



Tropical convectively coupled waves



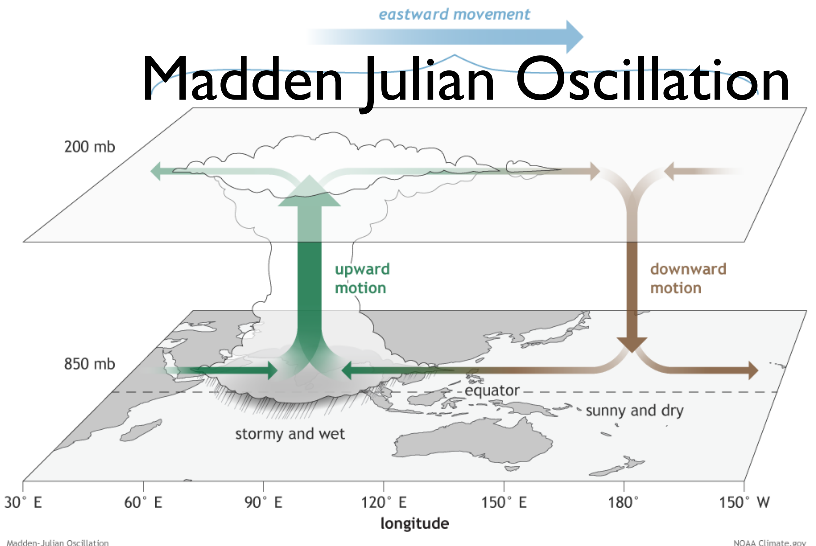
wheeler and Kiladis 1999

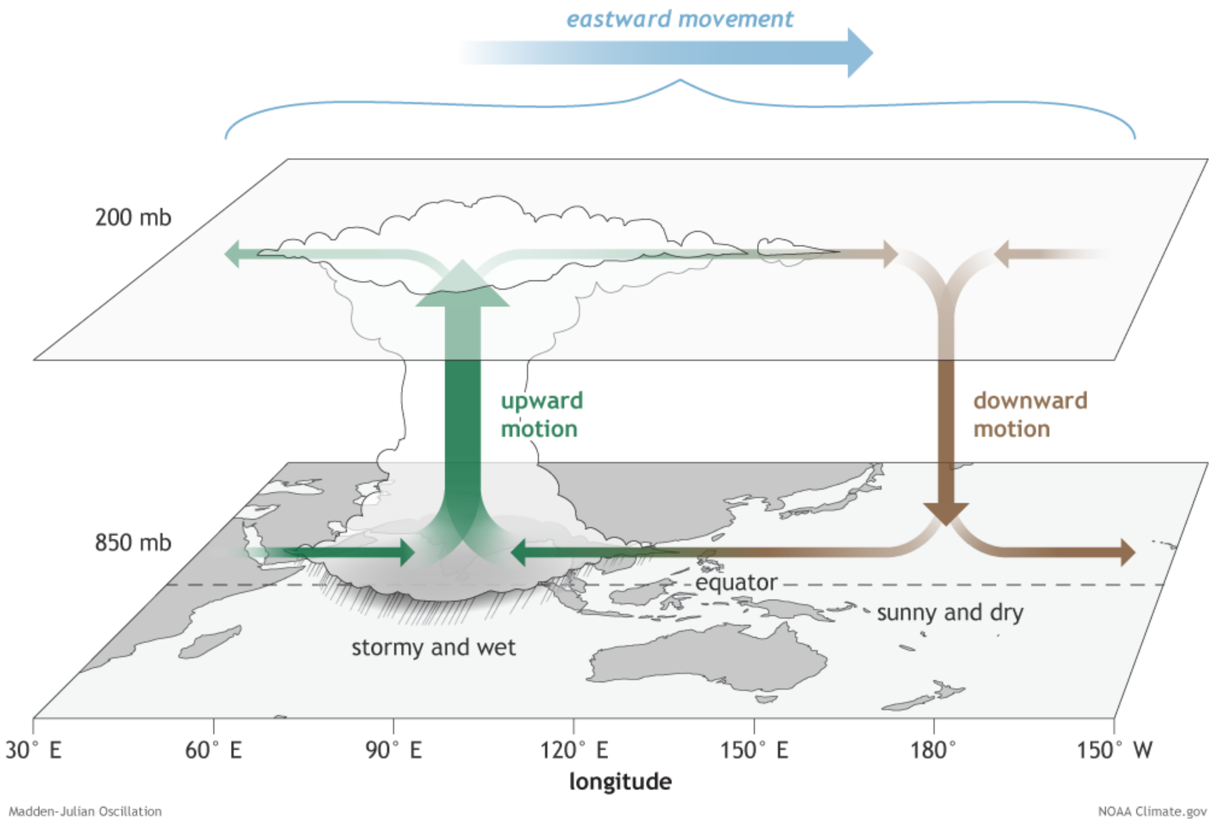


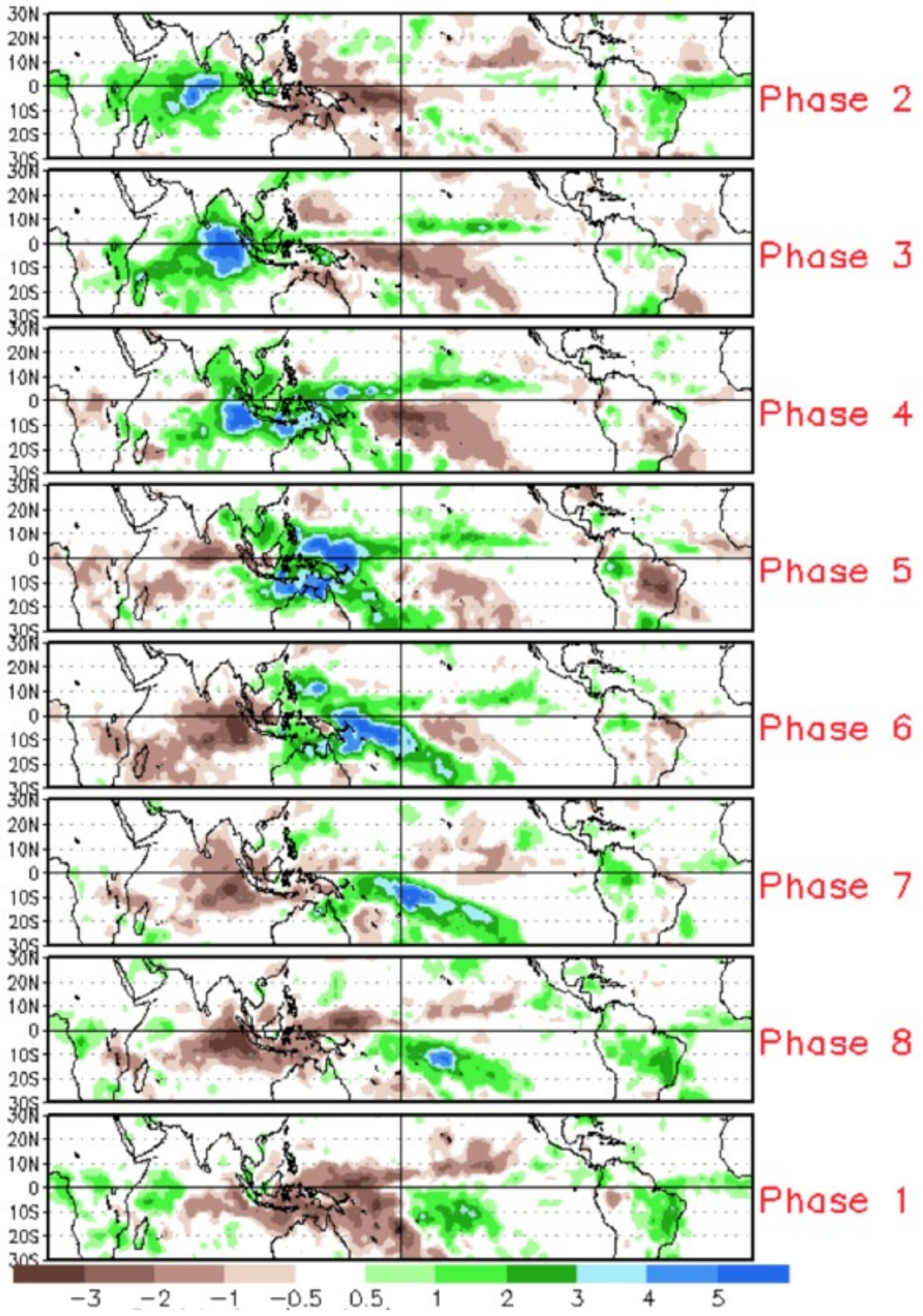
Haertel and Johnson 1998b citations

2D-5D Rossby-like waves

Madden Julian Oscillation





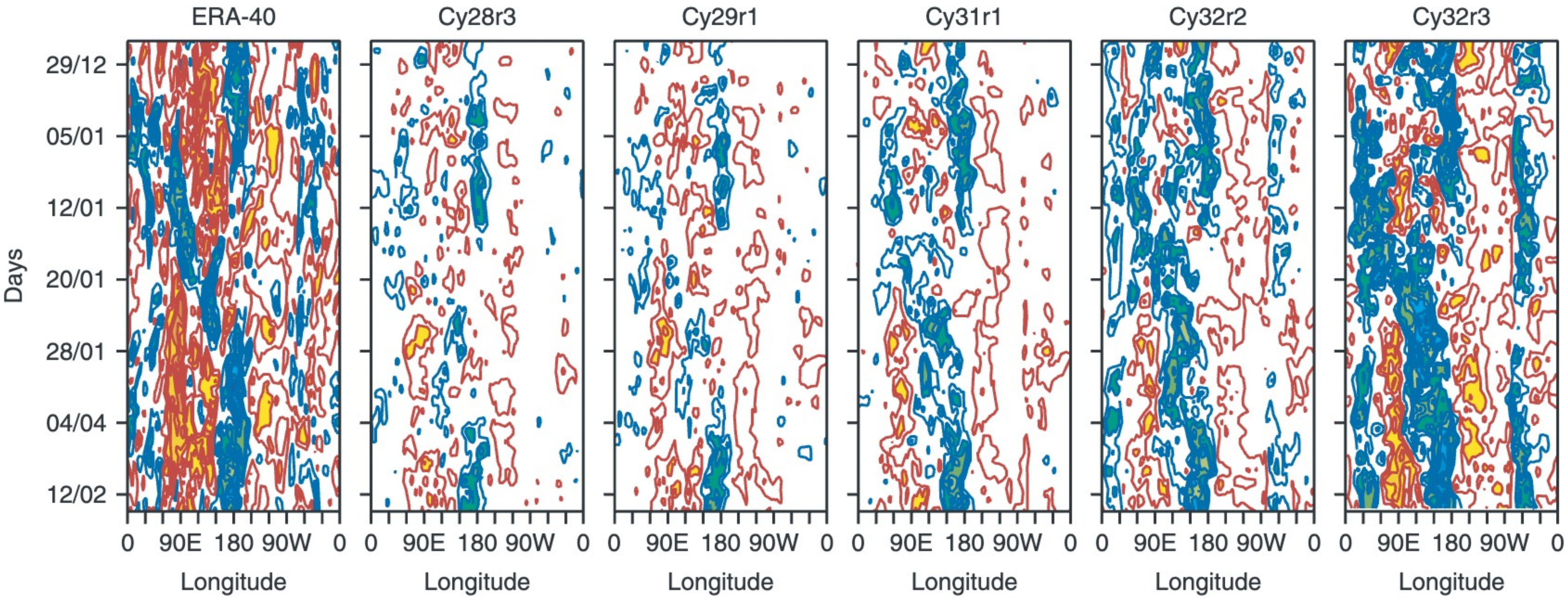


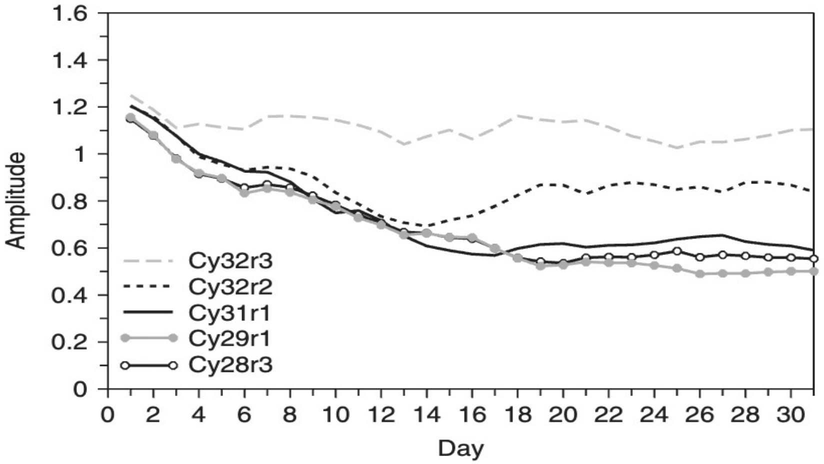
MJO:
water vapor feedback (Thayer Calder and Randall 2009, ECMWF model)

Radiation feedback (e.g. Benedict et al. 2020)

Surface flux feedback (Woolnough et al. 2001)

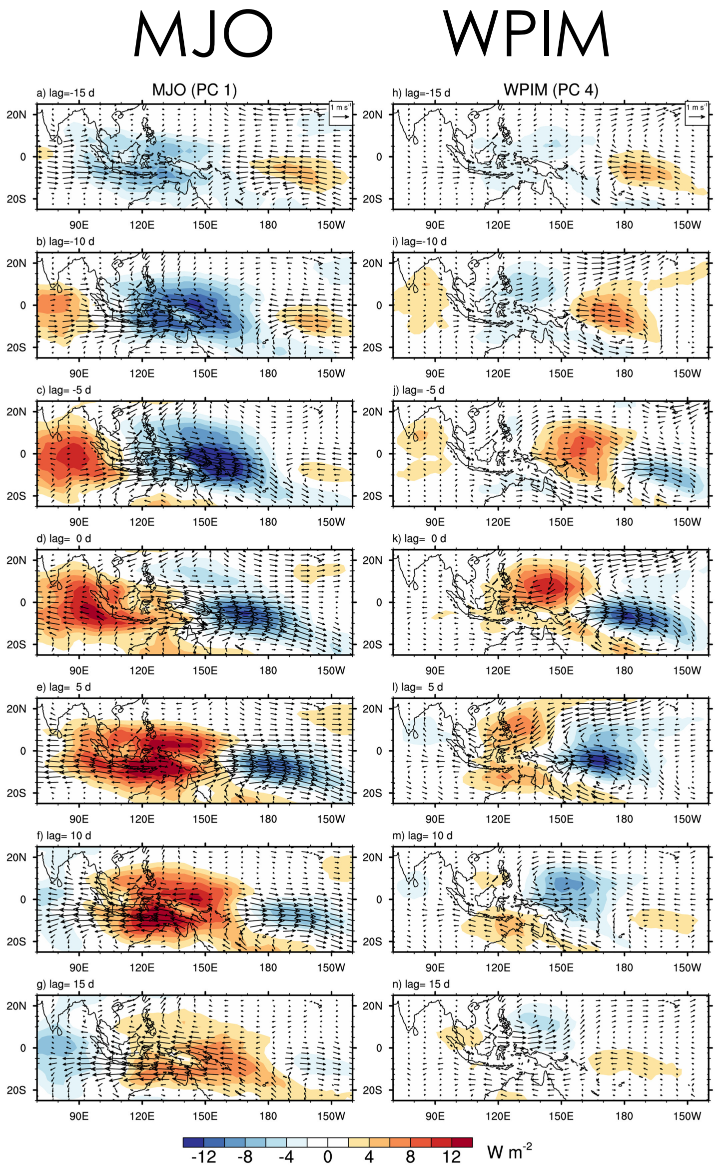
Water vapor feedback: Improvements to ECMWF convective entrainment

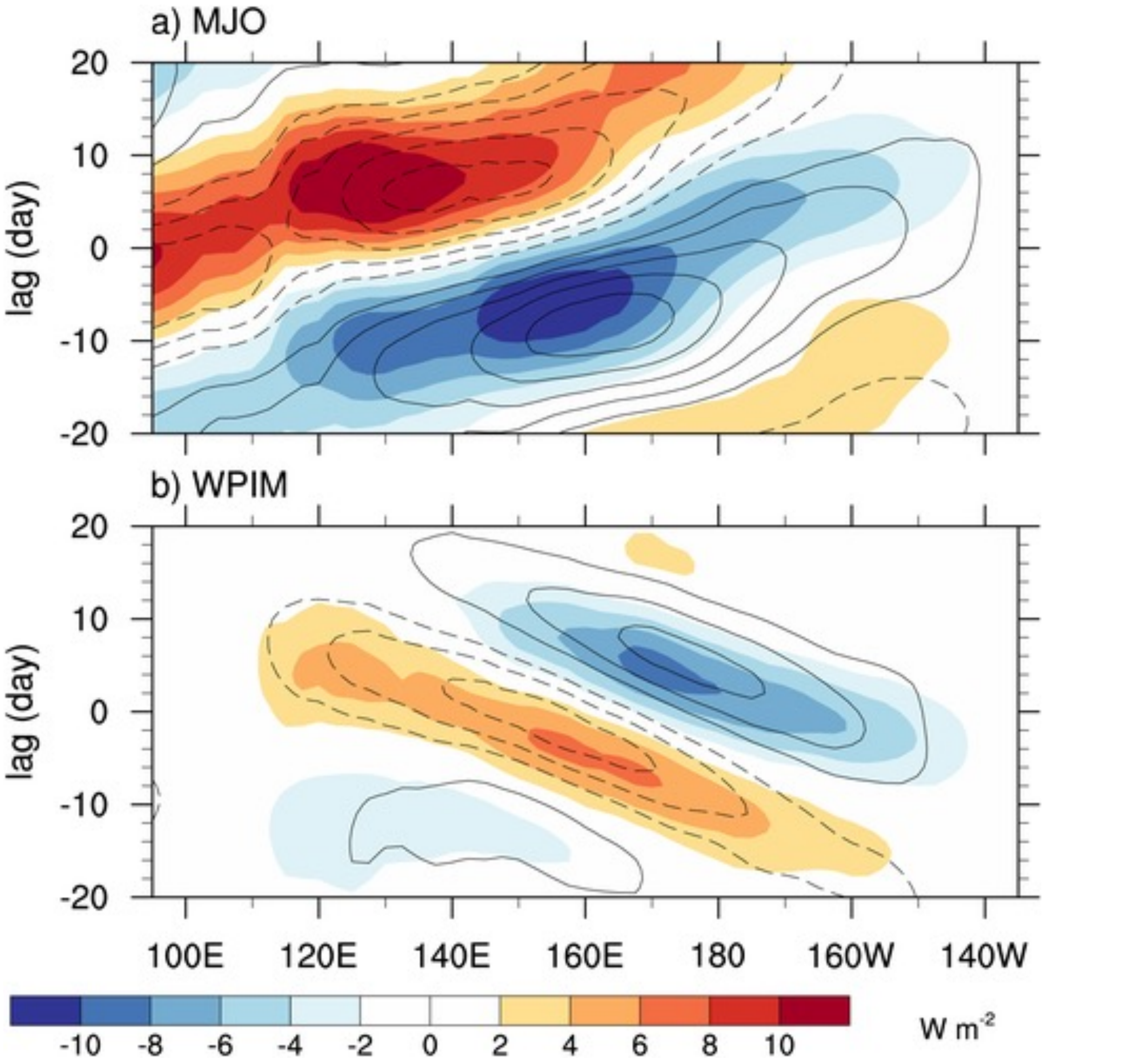




Bechtold et al. 2009

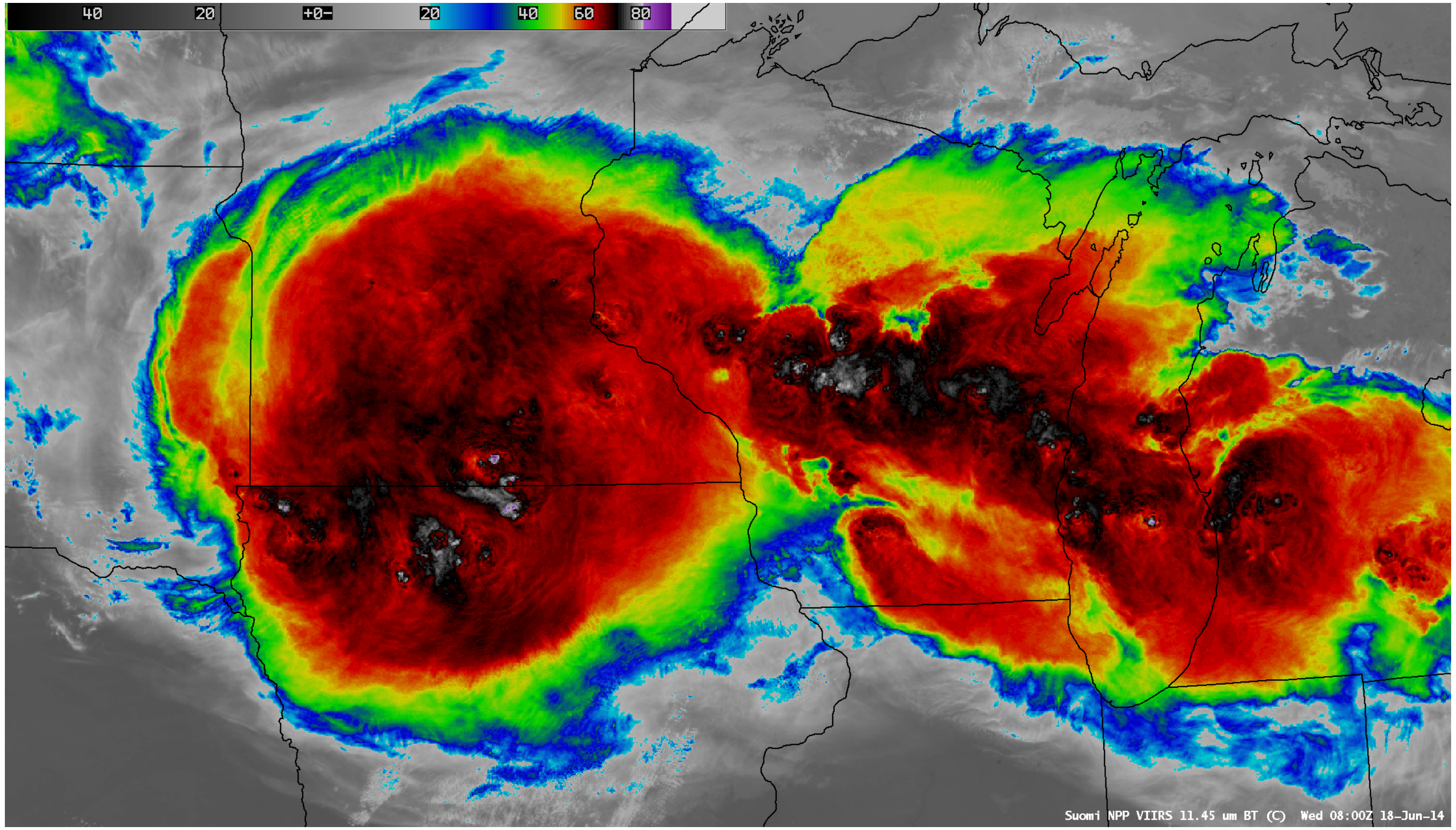
Gonzalez and Jiang 2019
Show both as "moisture mode"

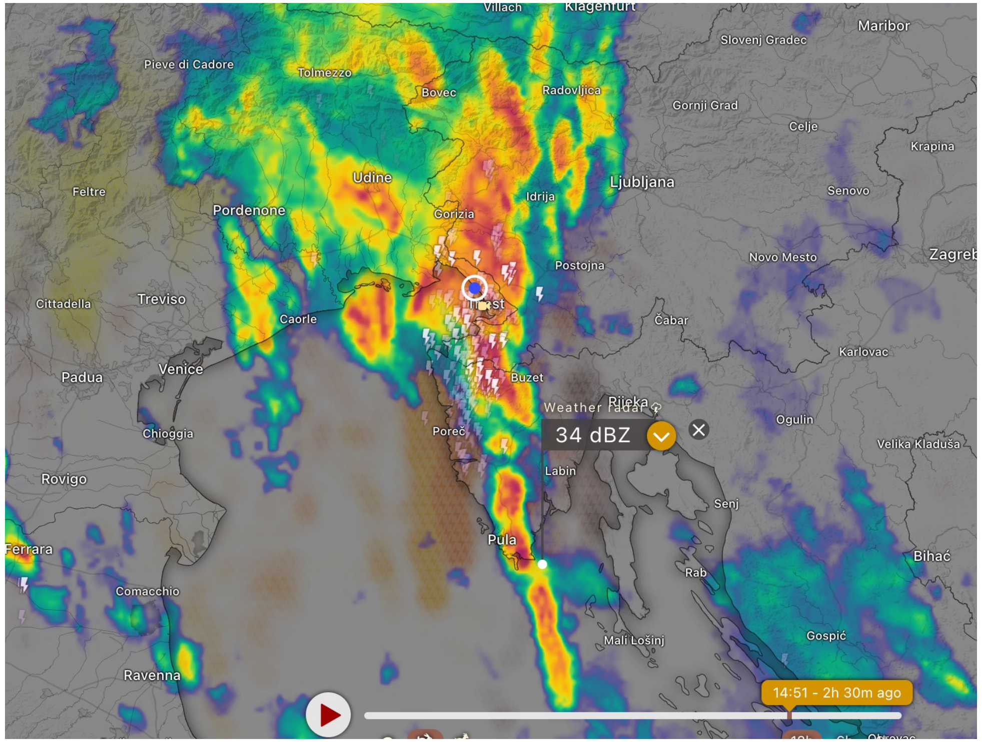




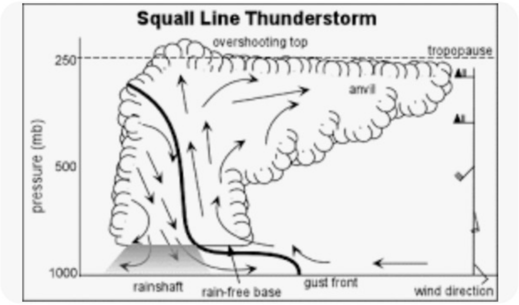
Longitude-lag anomalies of 15°S–5°N averaged unfiltered OLR (shading) and unfiltered column-integrated MSE (contour lines) lag regressed onto (a) PC 1 (normalized, MJO) and (b) PC 4 (normalized, WPIM). For the MSE isolines, the contour interval is 1×10^6 J/m^2, negative values are dashed and the zero line is omitted.

NOAA NSSL: “A ***Mesoscale Convective System (MCS)*** *is a collection of thunderstorms that act as a system. An MCS can spread across ~1000km and last more than 12 hours. On radar one of these monsters might appear as a solid line, a broken line, or a cluster of cells. This all-encompassing term can include many storm types*”

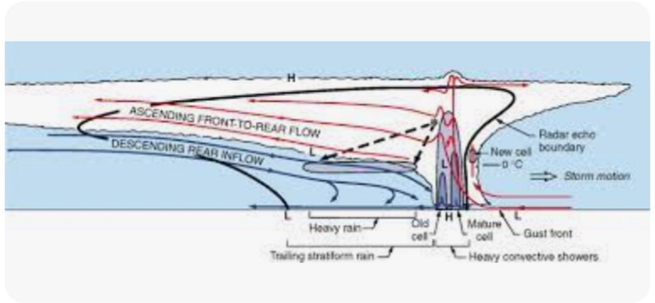




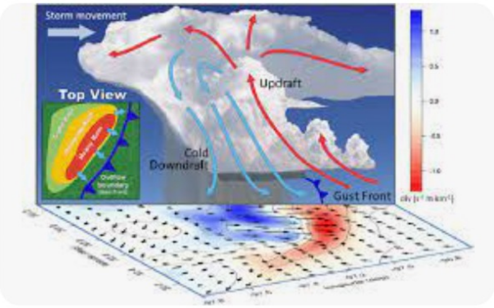
What is the common element?



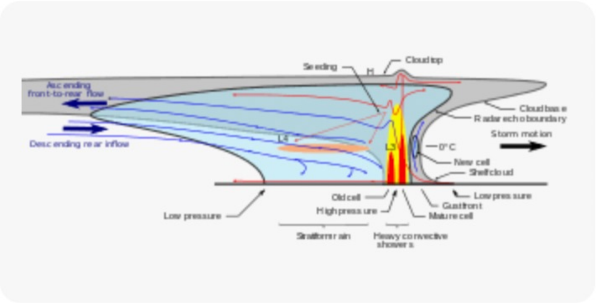
WW2010
Squall Lines:



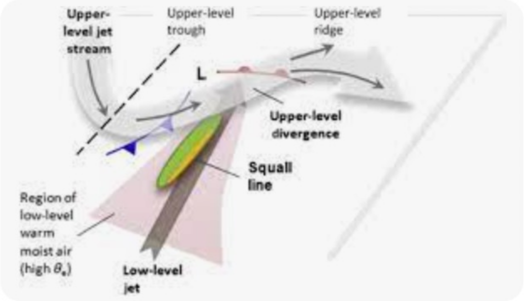
ScienceDirect.com
Squall Line - an overview ...



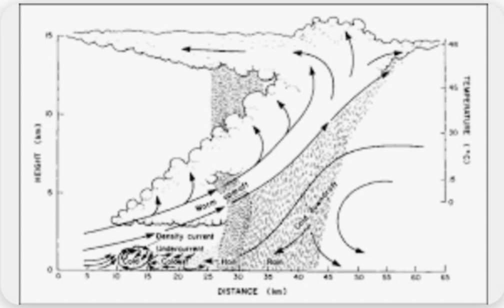
ResearchGate
squall-line vertical structure ...

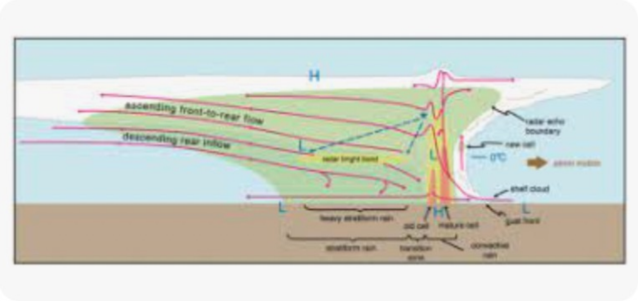


Wikipedia
Squall line - Wikipedia

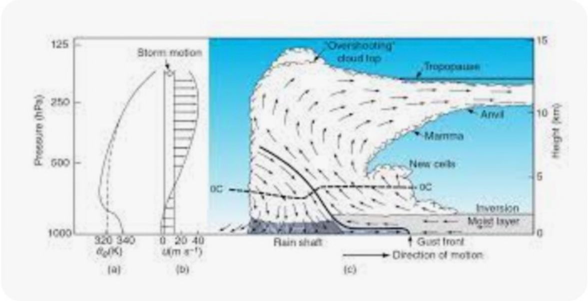


ResearchGate
2: Schematic of a dust storm of the ...

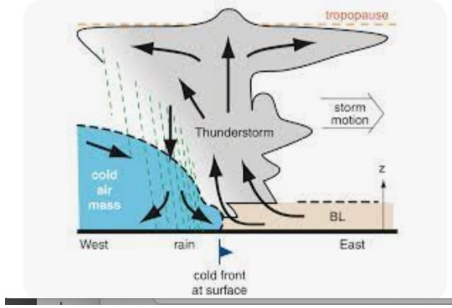


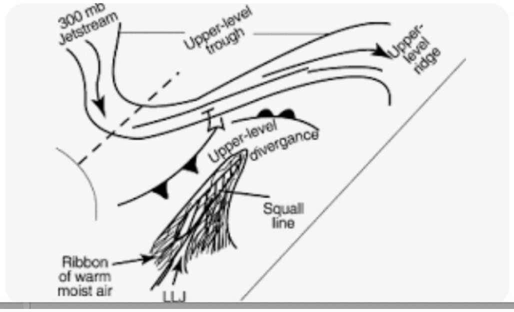


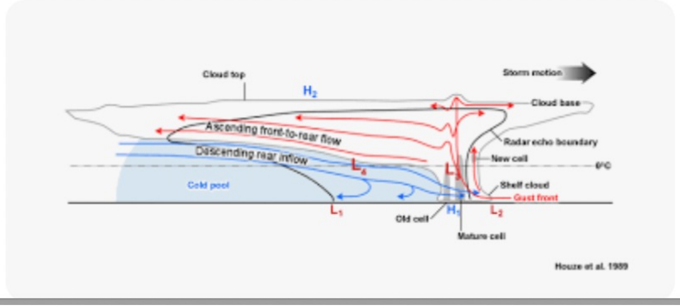
www.stratusdeck.co.uk
Squall lines

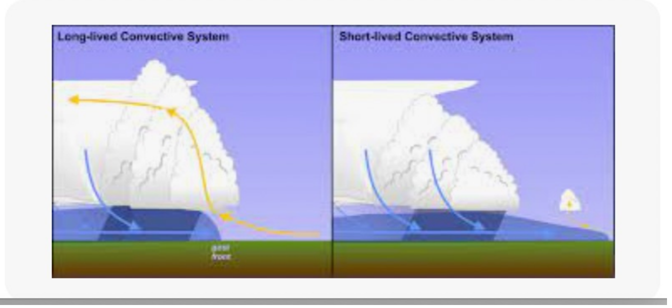


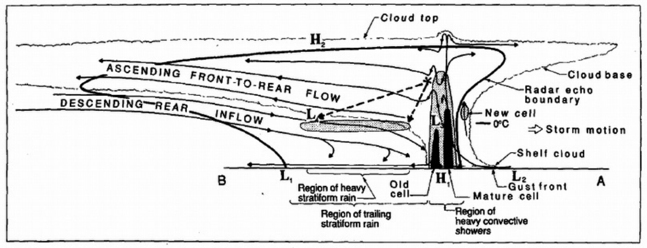
Weather Academy
Squall Line Severe Thunderstorms ...

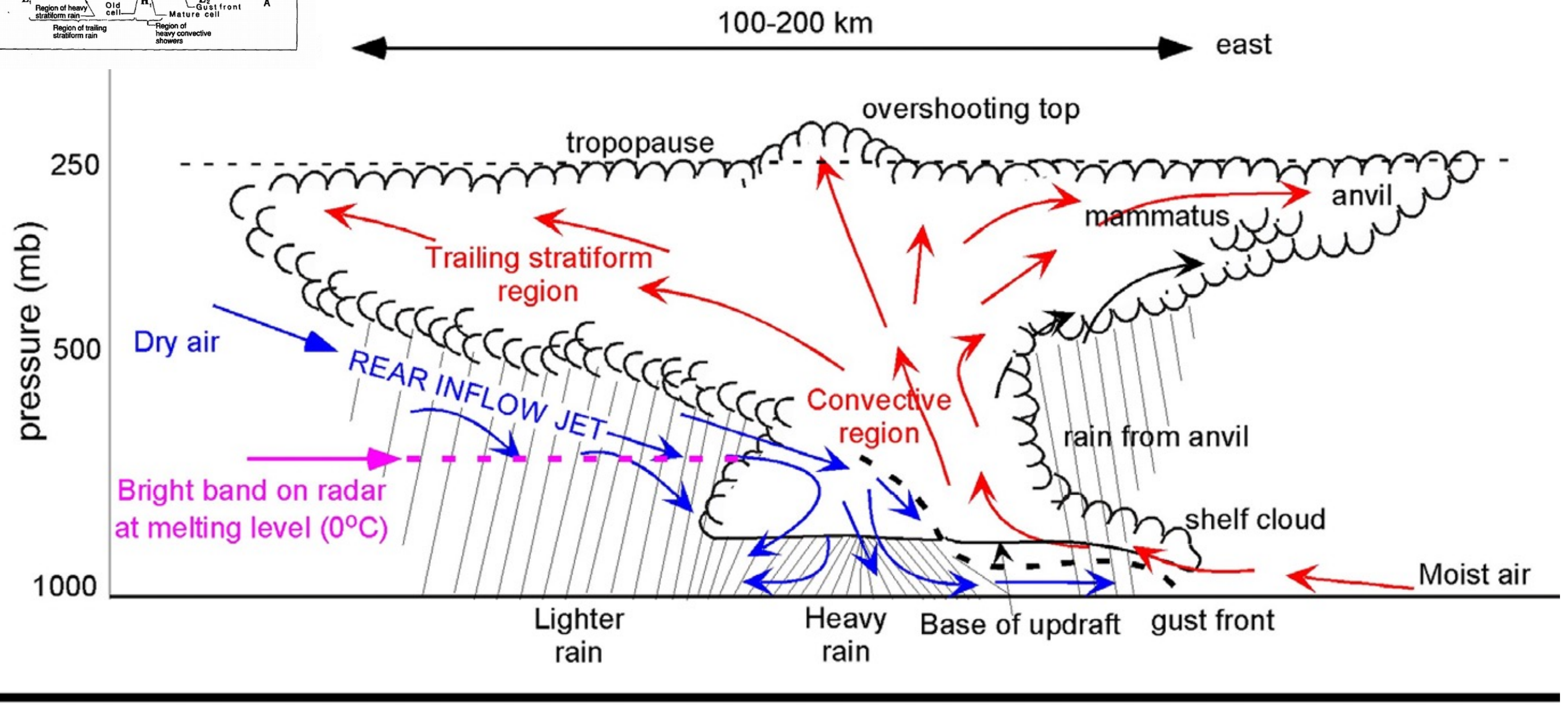






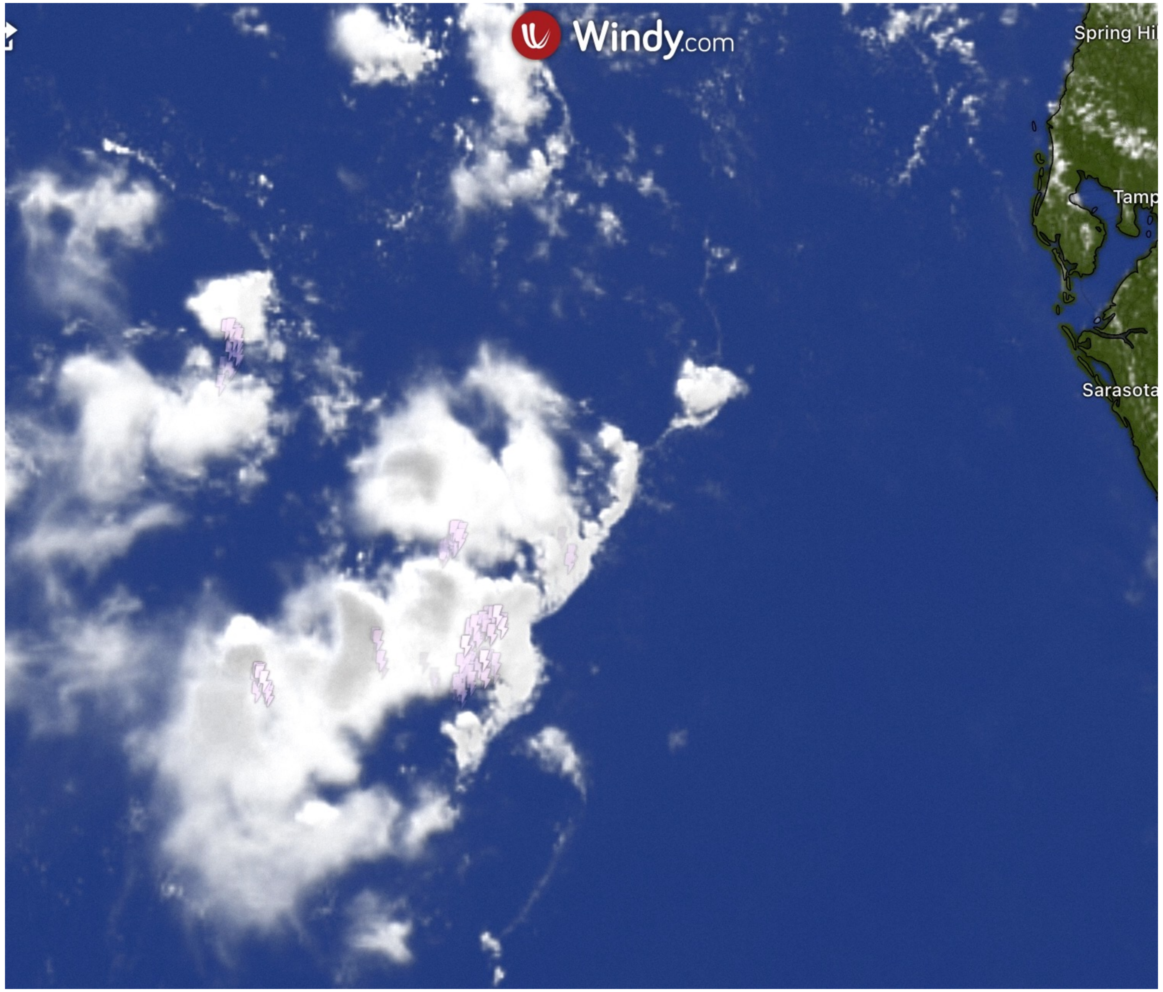




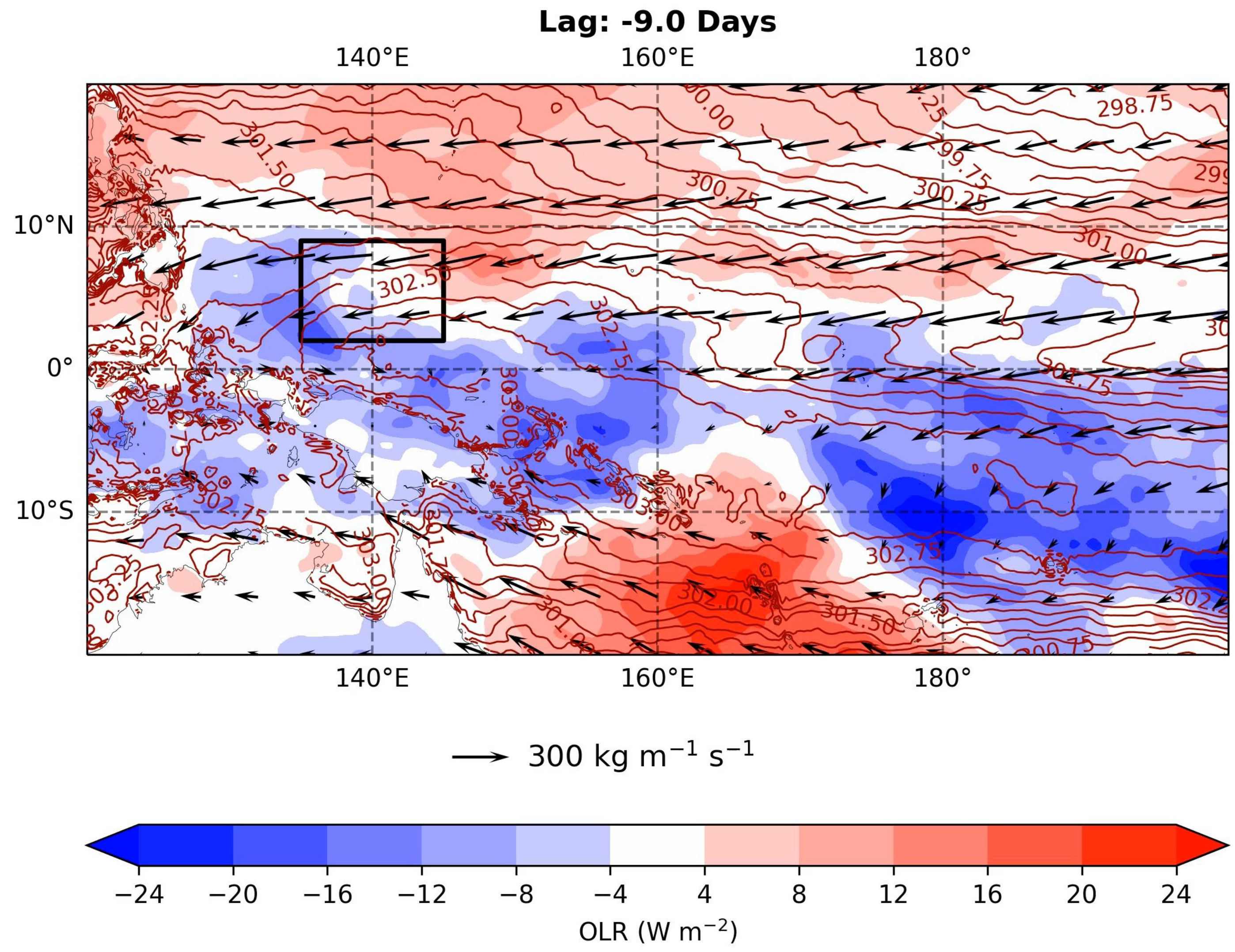


Schematics always emphasize the role of the cold pool/ gust front
Wind shear is also important to ensure long lived events

Next: Cold pools!



extra slides



Composite of 44 westward propagating equatorial Rossby wave-like events

Refer to recent work of these “moisture modes” waves

(e.g. Mayta et al 2022)

Casallas et al. (in prep)